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Microwave Heating of Lossy Films on Metal Surface

PhD
2010

Swinburn
Abstract

Finite element calculations have been performed on a T-septum waveguide to investigate the possibility of heating a lossy dielectric film coated on a metal surface using microwaves. The results indicate that additional lossless dielectric loading is required above the septum to provide the necessary electric field to heat the lossy film. A parametric study reveals that significant power deposition can occur in the film provided the permittivity of the dielectric loading is high. Measurements on an applicator have shown that the temperature of a lossy film painted on a metal surface can be increased by more than 40°C. The temperature is related to thickness of the film, septum height, and the position and permittivity of the low loss dielectric loading. It has been also been shown that the necessary electric field in the coated film can further be increased by using a nonlinear distribution of permittivity of the dielectric loading. The power loss in the film is again related to various distributions of permittivity of the loading as well as the height of the T-septum.

Finite element method was used to compute the field structure inside the waveguide applicator. Two symmetrical portions are assumed for the applicator and analysis are done by considering one of the half sections formed by introducing a magnetic wall. A novel compact Y-septum waveguide applicator is proposed for the single mode microwave heating of loads of small dimensions (e.g. a printed circuit board or a film) and is compared to a T-septum waveguide applicator of the same dimensions by
varying the septum height, septum width, septum thickness and septum angle.

Power Frequency Characterisation of different types of paints such as Solar Acrylic, Polyester Resin, Wattyl Instant Estapol and Metal Gloss Polypropylene with three different thicknesses (1.5 mm, 1.0 mm and 0.05 mm) was conducted using two different types of Variable Frequency Microwave (VFM) facilities. Temperature characterisation was also done in two different power outputs of 30W, 60W and 90W and all the above studies were done in both the VW1500 with frequency range of 6.5GHz to 18GHz and Microcure 2100 facilities with frequency range of 2.5GHz to 8GHz VFM facilities. After analysing the diagrams and data collected it was found that all different materials behaved in a different way to parameters like thickness, power input, bandwidth frequency and sweep time. Results also showed that special care should be taken when designing a microwave applicator with variable frequency for heating various materials and VFM facility is a very useful tool to identify these parameters and design an applicator for most favourable conditions so that hot spots and thermal run away can be avoided for specific materials.

A simple fibre optic probe has been developed to measure temperature in microwave environment. The basic principle of operation of the probe is
discussed together with its structure and construction. Temperature characteristics of the probe are analysed as well as the prediction of its temperature range and characteristics. The construction of a fibre optic thermal switch is presented. A new constant called the 'temperature bandwidth - sensitivity product' of the probe is defined which determines the temperature range and sensitivity of the fibre optic probe. Also stability studies were conducted by thermally cycling the temperature probe as well as the construction of a temperature probe is explained to carry out measurements near liquid nitrogen temperature.
ACKNOWLEDGEMENTS

To my beloved Alfhild who encouraged me to complete this work.
DECLARATION BY CANDIDATE

I, Paul Antony, hereby declare that the thesis:

- contains no material which has been accepted for the award to the candidate of any other degree or diploma, except where due reference is made in the text of the examinable outcome

- to the best of the candidate's knowledge contains no material previously published or written by another person except where due reference is made in the text of the examinable outcome; and

- where the work is based on joint research or publications, discloses the relative contributions of the respective workers or authors

(Signature)                                      20 May 2010

(Date)
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Chapter 1
Introduction

1.1 Thesis Objective

This thesis provides a novel approach to investigate the possibility of heating a lossy dielectric film mounted on a metal surface using microwaves and describes the development of an inexpensive fibre optic temperature probe to use in the microwave environment. Also thesis looks at the possibility of characterising materials using Variable Frequency Microwave facility to have an understanding of how materials behave to variable frequency sweeping around a central frequency so that a time averaged uniform heating can be achieved, which can assist in building applicators of special design.

There are several types of geometry in which it is difficult to use microwave power for heating. The first type includes low loss dielectric materials in any configuration. The second include lossy dielectrics adjacent to metal surfaces on which the tangential electric field vanishes. Low loss dielectrics adjacent to metal surfaces comprise the third type. However, some progress has been made in the first category by using a “transient wave” applicator [94] where heating is obtained incrementally for each transient wave (forward or reflected) which passes through the dielectric.

A solution for the second type is proposed in this thesis [52] based on the so called “air gap effect” originally introduced by others [95]. In the past no studies or solutions were reported on this type of problem of heating a lossy dielectric film coated on a metal surface using microwaves. The boundary conditions require that the tangential component of electric field is zero on a perfect metal and hence the film does not heat up as the heat generated depends on the magnitude of the electric field. This technique involves “pulling” the electric away from the metal wall by creating an air gap of
critical dimension to minimise losses in the metal waveguide. The air gap which is
created between the metal wall and a dielectric slab has the effect of rearranging the
electric field depending on the dimension of the air gap and dielectric slab and its
relative permittivity. Instead of a sine or cosine field distribution which exists in the
waveguide prior to the dielectric slab, the modified electric field profile can be very
high near the wall but quickly drops and vanishes at the wall.

In this thesis a T-septum waveguide [62] is examined as a device to heat lossy films of
high dielectric constant using microwave power. When a film is placed on a metal
surface within the waveguide, boundary conditions require that the tangential electric
field on the metal surface be zero and heating can be difficult to achieve. In the
following analysis, it is shown that a low loss dielectric placed in parallel above the
septum can increase the tangential component of electric field in the vicinity of the film.
Finite element method calculations have been performed for the analysis of the problem.
The numerical analysis indicates that power loss is related to the thickness and
permittivity of the dielectric and height of the T-septum. A waveguide applicator has
been fabricated using the optimum parameters obtained from the numerical analysis. S-
parameter measurements confirm that significant power can be deposited in a lossy film
painted on the inside surface of the waveguide above the septum. When operating at
high power, an appreciable temperature rise in the film was observed which was related
to the thickness of the film as well as the position and dielectric constant of the loading.
Finite element method calculations have been performed for the analysis of the problem.

Existing waveguide applicators of rectangular, ridged, T-septum or any other cross
sections are generally large when a thin small sheet or film has to be heated using
microwaves. A novel Y-septum waveguide applicator has been proposed which is very
compact and has the size of approximately 4% of that of a rectangular waveguide
applicator and 35% of that of a T-septum applicator at a microwave frequency of 2450
MHz. This Y-septum applicator has a much larger bandwidth (65% larger) than that of
a T-septum applicator at the above mentioned microwave frequency. Because of its
higher bandwidth, the Y-septum waveguide applicator is ideal for single mode
microwave heating.

A simple and hence inexpensive fibre optic temperature probe has been developed to
sense temperature in a microwave environment. It is not possible to use conventional temperature probes such as thermo-couples, thermistors etc. in microwave fields, as they are all made of metals and affect the field distribution. The types of fibre optic temperature sensors available in the market are very expensive as they need a design that requires miniaturised optoelectronics with optical filters, micro lenses and signal processing. The fibre optic temperature probe discussed in this dissertation uses an inexpensive standard multimode communication fibre and the variation in temperature is measured by a simple amplitude detector mounted on one end of the fibre. Hence the advantage of the developed temperature probe is its simplicity in construction and can be manufactured with a fraction of the cost of those probes available in the market.

1.2 Advantages of Microwave Heating

Microwave heating and drying processes for various industrial applications have been well established and in many cases are replacing less efficient, less economical and less convenient conventional methods in the past ten to twelve years. There are many advantages in using microwaves which are not found in other types of heating [53, 54, and 55]. Heat generated by the microwave energy occurs principally in the product and not on the oven walls or atmosphere. Hence the heat losses from the oven walls to the surroundings are much lower and results in reduced running costs. In conventional ovens, the product must have a high temperature at the surface. This provides the gradient necessary to heat the interior and can result in damaging the product. The surface damage is minimised in microwave heating as the heat is generated directly in the product without requiring such temperature gradients and hence the product has a better quality. The electric power level determines the degree of product heating or drying. So a better control of temperature and dryness is possible. Various advantages of microwave heating over conventional heating are tabulated in Table 1.1.

1.3 Background to Applicator Design

The use of microwave power for heating purposes requires an applicator of specific design. Large metallic chambers are commonly used but heating can be non-uniform because of the complicated internal multimode field structure. Single mode resonant
cavities provide higher field strengths than multimode chambers for the same applied power and have been found suitable for the treatment of low loss dielectrics [53, 54, and 55]. However, many applications, because of dielectric properties of the load or their variation during processing, require special design. For example, in travelling wave or waveguide systems, heat deposition can be quite uniform because the occurrence of standing waves is minimised. Power is partially absorbed within the extended load as it travels down the waveguide towards a non-reflecting termination. Such applicators have been used for heating material in the form of thick dielectric sheets suspended within the waveguide [56, 57, and 58].

Table 1.1   Advantages of microwave energy over conventional techniques [88]

<table>
<thead>
<tr>
<th>No.</th>
<th>Advantages</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>More efficient in drying within the falling rate period</td>
<td>Reduced running costs</td>
</tr>
<tr>
<td>2.</td>
<td>Reduced drying times</td>
<td>Increased throughputs</td>
</tr>
<tr>
<td>3.</td>
<td>More compact than conventional systems</td>
<td>Reduced space requirements</td>
</tr>
<tr>
<td>4.</td>
<td>Energy is transferred in a clean manner</td>
<td>Cleaner environment</td>
</tr>
<tr>
<td>5.</td>
<td>Selective energy absorption by lossy constituents</td>
<td>Result in moisture levelling of web materials</td>
</tr>
<tr>
<td>6.</td>
<td>Puffing of materials such as doughnuts and food products by internal pressure</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>Heat transfer is independent of air stream and mass transfer is increasingly independent of air stream as load temperature increases</td>
<td>High velocity air flows are not required which may result in fan power energy savings</td>
</tr>
<tr>
<td>8.</td>
<td>Energy dissipated rapidly throughout the volume of the material</td>
<td>Deeper penetration and reduced surface damage</td>
</tr>
<tr>
<td>9.</td>
<td>Avoids over drying</td>
<td>Lower losses</td>
</tr>
<tr>
<td>10.</td>
<td>Substitution of cheaper raw material for more expensive material used conventionally</td>
<td>Reduced raw material costs</td>
</tr>
<tr>
<td>11.</td>
<td>Relatively low maintenance costs</td>
<td></td>
</tr>
</tbody>
</table>
A rectangular waveguide with internal ridges is useful for large bandwidth and wide mode separation [59, 60, and 61]. T-septum waveguides [62] have lower cut-off frequencies and broader bandwidth than those of the conventional ridged guides with the same geometries and can produce field distributions suitable for microwave heating of lossy materials. A T-septum is further capable of concentrating the electric field into a much smaller area above the septum.

Even though thick dielectric sheets could be heated using microwaves [56, 57, and 58], heating of thin dielectric sheets are much difficult to achieve. The heating of a film of dielectric material coated on a metal surface is difficult to achieve as the tangential component of electric field is zero on a perfect metal and no published literature is available in this case. In this dissertation it is demonstrated that the concept of loading an additional dielectric material of low loss and high permittivity below the coated metal surface can increase the tangential component of electric field inside the film and hence heat the film. A T-septum waveguide applicator has been designed for the purpose. Finite element method [45] was used to analyse the problem by determining the field structure inside the waveguide applicator.

A waveguide applicator has been built using the optimum parameters obtained from the finite element method analysis. S-parameter measurements using a network analyser confirm that significant power can be deposited in a lossy film coated on the metal surface. When operating at high power, an appreciable temperature rise in the film was observed which was related to the thickness of the film as well as the position and dielectric constant of the loading.

1.4 Background to Temperature Sensing

Sensing temperature is always a problem when measurements have to be carried out in electric and magnetic environments. It is not possible to use conventional temperature probes such as thermo-couples, thermistors etc. as they are all made of metals and affect the field distribution. As well, the presence of a microwave field can affect the measured temperature readings of those types of conventional temperature probes. Fibre optic cables are electrical insulators and information transmitted along them is not
affected by normal electrical interference. Hence they can be used in situations where high fields are present.

Several fibre optic sensing concepts have been applied to temperature measurement; reflective [2, 3, 4], micro bending [5], intrinsic [6, 7, 8, 9] and phase modulated concepts [10, 11, 12, 13]. In the reflective type of fibre optic sensors where a bimetallic element is attached as a transducer and hence being metal, they are not suitable for temperature measurement in a microwave environment. The reflective type of sensors using liquid crystals has a limited temperature range \((35^0 C - 50^0 C)\) and hence useful only to monitoring biological processes. Another reflective concept is spectral modulation. Implementation of this concept involves optical components to detect distinct wavelengths and can be very expensive. Materials with high thermal expansion are generally metals and hence micro bending concept is not suitable for temperature monitor in microwave environment. In intrinsic type black body fibre optic temperature sensors, the intensity and wavelength of radiation is a function of temperature. At low temperatures \((<100^0 C)\) the wavelength of transmission is above 4 microns so that most conventional fibres are not effective and hence suitable only for temperature measurement over the range of \(500^0 C - 2000^0 C\). Interferometric temperature sensors are sensitive to both changes in wavelength and refractive index. Even though the sensitivity of this approach was calculated to have values of \(10^{-8}\), it is extremely expensive to implement.

The small number of commercially available fibre optic temperature probes currently available on the market operates on the principle of photoluminescence [10, 11] or photo absorption [12, 13]. Both these type of sensors need a design that requires miniaturised optoelectronics with optical filters, micro lenses and signal processing. These precision devices make this type of fibre optic temperature probe particularly expensive.

The fibre optic temperature probe developed and presented in this dissertation uses an inexpensive standard multimode communication fibre that transmits signal pulses to the sensor. The sensor is made of an optical fibre whose cladding is made of a material
which has a refractive index very sensitive to temperature. As the light pulses propagate through the sensor, a part of the light leaks into the cladding depending on its refractive index, which is determined by the temperature. Hence the variation in temperature is measured by a simple amplitude detector mounted on the other end of the fibre. The advantage of this type of temperature sensor is its simplicity in construction and can be manufactured with a fraction of the cost of those probes available in the market.

1.5 Background to Compact Waveguide Applicators for Heating Loads of Small Dimensions

The frequencies used for industrial microwave heating are 2450 MHz, 915 MHz and 434 MHz [77]. The penetration depth of microwave power inside a load increases with decreasing frequencies [77]. In order to effectively utilise microwave energy, the bulk of the material should be penetrated, which requires relatively low frequency. Hence the size of the waveguide applicator should be large to support the low cut off frequency. The result is a bulky applicator especially in the case of heating small loads (e.g. a printed circuit board or a film).

For the same power applied, a single mode applicator will establish much higher electric field strength than a multimode applicator [78] and for this reason the former is most useful for the treatment of low loss dielectrics. These fundamental mode applicators are in general more compact with extremely high power densities ($10^7 W/m^3$).

Furthermore, a single mode applicator is capable of transferring more power from the generator onto the dominant mode than a multimode applicator.

Waveguides of rectangular or circular cross section are generally used as single mode applicators. A ridged waveguide applicator is used to increase the value of electric field in the vicinity of the work load and was used for the continuous flow heating of extruded rubber [77]. Bleackley et al. [79] have presented various configurations of ridged structures, where electric field around the ridge was increased to enhance the coupling of microwave energy to a low loss web material. This resulted in a more compact applicator than the equivalent structure without ridges, which have a good
coupling of energy for drying narrow strips of glue. A T-septum applicator has also been proposed [80] which is suitable of microwave heating of materials and is more compact than a ridge waveguide.

Work is in progress on waveguides of different structures to allow reduced size. Ridged waveguides [81, 82] were developed as a result and have lower cut-off frequencies and wider bandwidth for the same size rectangular waveguide. Because of their higher bandwidth, they are suited for single mode microwave heating. A significant improvement in the ridged waveguide can be obtained by changing the shape of the ridge into a T-shaped septum and was suggested by Mazumder and Saha [86].

In this dissertation a novel Y-septum waveguide applicator is proposed. This Y-septum applicator can further reduce the size of the waveguide compared to a T-septum applicator as well as a ridged applicator for the same cut-off frequency. A 95.6% improvement in reducing the space has been achieved over the rectangular waveguide and 65% over the T-septum. The bandwidth of the Y-septum is more than 7 times as wide as the rectangular and 1.7 times that of the T-septum guide.

1.6 Background to Heating Characterisation of Paints Using Variable Frequency Microwave Facility

Microwave heating is generally established using a single microwave frequency of 2.45 GHz. Other frequencies generally used are 915 MHz and 434 MHz [77]. However these frequencies have inherent non-uniformity problems like hot spots and thermal run away. A new technique called Variable Frequency Microwave (VFM) technique [92] has been used to solve this problem of inherent in the fixed frequency by using a preselected bandwidth of frequencies sweeping around a central frequency. As more than one thousand frequencies are launched into the cavity sequentially, each incident frequency sets up its own electric field pattern at different locations at different time intervals, a time averaged uniform heating can be achieved with proper selection of sweep frequency and range. So prior to building special microwave applicators with variable frequency, it is advantages to do characterisation the paints used using VFM. Unfortunately not a lot of data is available on many materials how they behave on
variable frequencies. This data is very crucial when designing applicators suitable for various frequencies as design of this type of applicators require more care on how various microwave energy is reflected at various frequencies. Two of the most important characteristics needed in designing applicators with variable frequencies for various materials are Power Frequency characteristics, which determines how microwave power is reflected at various frequencies and Temperature characteristics which determine how heating occurs with variable frequency.

Power Frequency Characterisation was conducted using two different types of VFM facilities. Four totally different types of paints that includes water based, oil based and even resin are included in the study. The samples selected are Solar Acrylic, Polyester Resin, Wattyl Instant Estapol and Metal Gloss Polypropylene. Also studies were conducted with the paints with three different thicknesses (1.5 mm, 1.0 mm and 0.5 mm). Temperature characterisation was also done in two different power outputs of 30W, 60W and 90W and all the above studies were done in both the VW1500 with frequency range of 6.5GHz to 18GHz and Microcure 2100 facilities with frequency range of 2.5GHz to 8GHz VFM facilities.

After analysing the diagrams and data collected it was found that all different materials behaved in a different way to parameters like thickness, power input, bandwidth frequency and sweep time. Results also showed that special care should be taken when designing a microwave applicator with variable frequency for heating various materials and VFM facility is a very useful tool to identify these parameters and design an applicator for most favourable conditions so that hot spots and thermal run away can be avoided for specific materials.

1.7 Thesis Review and Organisation

Chapter 2 presents the development of a new fibre optic probe for the measurement of temperature in a microwave environment. The basic principle of operation of the temperature probe is discussed. The structure and construction of two versions of temperature probe are explained. Temperature characteristics of the two versions of the sensor are analysed together with the construction of a fibre optic thermal switch. The
prediction of temperature range as well as characterisation of the temperature probe is also included. Construction of a computer board to display temperature is briefly described. A new constant called the 'temperature bandwidth - sensitivity product' is defined which determines the temperature range or sensitivity of the fibre optic temperature probe. Also a temperature probe was constructed to sense measurements near liquid nitrogen temperature. Stability studies were conducted by thermally cycling the temperature probe.

Chapter 3 first briefly explains the finite element method, which is used for the numerical calculations throughout the dissertation. The formulation of the higher order finite element analysis for dielectric loaded waveguides is discussed. Application of the finite element method to solve a dielectric loaded T-septum waveguide applicator is presented. Due to symmetry only one half of the waveguide need to be analysed. The applicator was divided into triangular sub regions and the solution of the waveguide eigen value problem has been obtained for the TE_{10} mode. From the eigen vectors obtained, corresponding electric field components were calculated. The advantage of the tangential component of electric field (E_x) over the normal component (E_y) for heating a lossy dielectric film coated on a metal surface using microwaves is demonstrated. The electric field distribution in the dielectric loaded T-septum waveguide applicator was calculated. It is shown that an additional tangential component of electric field can be generated by loading a dielectric material of high permittivity. This generated tangential component of electric field is responsible for the heating of a film coated on a metal surface. It is shown that a lossy film coated on a metal surface can be heated using microwaves by placing a dielectric of low loss and high permittivity below the film. A dielectric loaded T-septum waveguide applicator was proposed to heat the film on the metal. Numerical analysis of the applicator has been done by using the finite element method explained. The analysis indicates that an additional tangential component of electric field can be generated in the coated film thereby producing significant heat deposition through power loss. The power loss is related to the thickness and permittivity of the dielectric loading and the height of the T-septum. Also it has been demonstrated that the tangential electric energy in the coated film can further be increased by using a nonlinear distribution of permittivity of the dielectric loading. The power loss in the film is again related to various distribution of
permittivity of the loading as well as the T-septum height.

Chapter 4 deals with the construction of a dielectric loaded T-septum waveguide applicator to heat a film of paint coated on a metal surface. The design of the applicator is based on the cross-sectional dimensions obtained (explained in Chapter 3) by finite element method. A pilot model of the waveguide applicator was made with polystyrene and aluminium tape to allow easy modifications. This design was perfected for a minimum reflected power by making standing wave as well as scattering parameter measurements. Using these dimensions, a T-septum waveguide applicator was made of aluminium for high power applications. Low power measurements were analysed by measuring scattering parameters using a Hewlett Packard Network Analyser 8720A and a various characteristics were tabulated. High power performance was examined by using a 1.2 kW variable power magnetron source and it was demonstrated that a film of paint coated on a metal surface can in fact be heated. The temperature rise in the film was related to the thickness of the film and the position and permittivity of the low loss dielectric loading. The temperature distribution inside the paint was measured. The temperature measurements were done using the fibre optic probe explained in Chapter 2. Measurements on the applicator have shown that the temperature of the lossy film painted on a metal surface can be increased by more than \(40^\circ C\). A practical waveguide applicator was also proposed to heat painted metal sheet for industrial applications.

Chapter 5 deals with the application of a new technique called Variable Frequency Microwave (VFM) technique [92] to solve the problem of non-uniformity in heating like hot spots and thermal run away inherent in the fixed frequency microwave heating. Two of the most important characteristics needed in designing applicators with variable frequencies which are Power Frequency characteristics, which determines how microwave power is reflected at various frequencies and Temperature characteristics which determine how heating occurs with variable frequency are measure. Power Frequency Characterisation was conducted using two different types of VFM facilities. Four totally different types of paints that includes water based, oil based and even resin are included in the study. The samples selected are Solar Acrylic, Polyester Resin, Wattyl Instant Estapol and Metal Gloss Polypropylene. Also studies were conducted
with the paints with three different thicknesses (1.5 mm, 1.0 mm and 0.5 mm). Temperature characterisation was also done in two different power outputs of 30W, 60W and 90W and all the above studies were done in both the VW1500 with frequency range of 6.5 GHz to 18 GHz and Microcure 2100 facilities with frequency range of 2.5 GHz to 8 GHz VFM facilities. Data collected were analysed and plotted and it is related to parameters like thickness, power input, bandwidth frequency and sweep time for four different materials and the results also showed that in order to design an applicator for microwave heating with variable frequency for various materials, special care should be taken in designing an applicator for most favourable conditions so that hot spots and thermal run away can be avoided.

In Chapter 6 a novel compact Y-septum waveguide applicator is proposed for single mode microwave heating of loads of small dimensions (e.g. a printed circuit board or a film). The Y-septum waveguide applicator is more compact and has higher bandwidth compared to the existing rectangular, ridged or T-septum waveguide applicators. The higher bandwidth of the Y-septum waveguide is an advantage for ensuring a single mode heating for a wider range of variation of dielectric properties during microwave processing. The proposed Y-septum waveguide applicator is compared with the existing T-septum applicator for cut off wavelength and extended bandwidth capabilities using the finite element analysis explained in Chapter 2. The Y-septum waveguide was analysed for various septum angles. Parameters like size and bandwidth of a rectangular, a T-septum and Y-septum applicators were compared at a microwave frequency of 2450 MHz and the advantages of Y-septum over the other applicators were highlighted.

Conclusions are presented in Chapter 7.

1.8 Original Contributions of this Thesis

The original contributions of the present work in evolving this thesis are summarised below and the relevant author's publications are referenced.

* A novel idea of heating a lossy dielectric film coated on a metal surface using
microwaves by loading an additional dielectric material of high permittivity below the film is proposed [52]. A significant amount of tangential component of electric energy can be concentrated on the film. The tangential component of electric energy is absent when there is no additional dielectric loading and hence the film cannot be heated.

* Design and construction of a practical dielectric loaded T-septum waveguide applicator [52] to demonstrate the above stated concept. Measurements on the applicator have shown that the temperature of a lossy film painted on a metal surface can be increased by more than $40^0 C$.

* A simple and inexpensive fibre optic temperature probe has been proposed [1]. The developed fibre optic temperature probe is suitable for the measurement of temperature in electric and magnetic environments. As the probe is made of a standard multimode communication fibre and the variation in temperature is measured by a simple amplitude detector, it can be manufactured with a fraction of the cost of those probes available on the market. A patent for this device has been issued for this development.

* A new constant called 'temperature bandwidth - sensitivity product' of the developed fibre optic temperature probe which determines its temperature range or sensitivity (or both) has been defined. The temperature bandwidth - sensitivity product of temperature probes constructed by the same optical fibres is constant. Only way to improve the temperature range or sensitivity of the probe is to use optical fibres of larger temperature range - sensitivity product.

* Power – Frequency characterisation and Temperature characterisation of four different materials Solar Acrylic, Polyester Resin, Wattyl Instant Estapol and Metal Gloss Polypropylene are conducted using a new technique called Variable Frequency Microwave (VFM) technique [92] to solve the problem of non-uniformity in heating like hot spots and thermal run away inherent in the fixed frequency microwave heating. These characteristics are essential in designing applicators for microwave heating of using variable frequencies.
A novel Y-septum waveguide applicator has been proposed [89] which has a lower cut-off frequency and larger bandwidth than any of the existing waveguide applicators. A 96% improvement in reducing the space has been achieved over the rectangular waveguide applicator and 65% over T-septum waveguide applicator. The bandwidth of the Y-septum is more than 7 times as wide as the rectangular guide and 1.7 times that of a T-septum guide. The Y-septum applicator is suitable for heating loads of very small dimensions.
Fibre Optic Probe for Measuring Temperature in Microwave Environment

2.1 Introduction

Sensing temperature is always a problem when measurements have to be carried out in electric or magnetic environments. There has been considerable interest in microwave processing of various industrial materials and food stuffs. Also microwaves are used in many chemical reactions and biomedical applications. It is not possible to use conventional temperature probes like thermo-couples, thermistors etc. because microwaves affect the reading as they are all made of metals. A possible answer to this question is to use optical fibres. Fibre optic cables are electrical insulators and information transmitted along them is not affected by normal electrical interference. For this reason they can be used in situations where there are high voltages present.

Several fibre optic sensing concepts have been applied to temperature measurement such as reflective, micro bending and intrinsic and phase modulation concepts. A bimetallic element attached as a transducer to a bifurcated reflective fibre optic probe can be designed to provide a snap action at a specific temperature, moving abruptly relative to the probe tip, thus resulting in a switching action at a set temperature point [2]. As the sensor is made of metal, this type of sensor may be unsuitable for temperature in a microwave environment.

Liquid crystals exhibit colour changes and reflective changes at a fixed wavelength due to temperature changes. Light passes through the input fibre and is reflected from the liquid crystal. The reflected light is detected and the intensity is a function of temperature. The working range is quite limited, (35°C to 50°C) and this concept is
limited to monitoring biological processes [3]. Another reflective concept involves spectral modulation [4]. The sensing target element acts as a spectral mirror, changing the spectral reflectance over the light source bandwidth. The ration of two of the discrete component wavelengths varies in a manner proportional to the temperature. Implementation of this concept involves optical components to detect the distinct wavelengths and can be very expensive.

Micro bending can be used as a temperature monitor [5]. The change in bend radius with temperature can easily provide a sensing function by using a bending mechanism device with a high thermal expansion. A fibre is wrapped around a pipe that can expand or contract. This type of sensor could be relatively bulky. Materials with high thermal expansion are generally metals and hence this concept may be unsuitable for measuring temperature in microwave environment.

Blackbody fibre optic temperature sensors are based on the fact that thermal radiation is emitted when a material is heated [6, 7, and 8]. The intensity and wavelength of the radiation is a function of temperature. At low temperatures (<100° C) the wavelength of transmission is above 4 microns so that most conventional fibres are not effective because of the absorption and hence suitable only to high temperatures over the range of 500° C to 2000° C. Interferometric temperature sensors are sensitive to both changes in wavelength and refractive index [9]. If the parameters in the sensing fibre change relative to the reference fibre, a phase change occurs. Even though sensitivity of this technique approaches 10^-8 C, it is extremely expensive to implement.

The small number of commercially available fibre optic temperature probes currently on the market operates on the principle of photoluminescence [10, 11] or photo absorption [12, 13]. In the first type, the sensor absorbs the incident light and emits fluorescent radiation. The sensor uses a single fibre made of pure quartz to maximise the transmission of input UV light. The fibre tip is coated with a phosphor layer and encapsulated. The light is filtered and focused on to the fibre with a series of optical elements. The UV light excites the phosphor and fluorescent radiation in the visible region of the spectrum is carried back to the electro-optic interface via the same fibre. The incoming and outgoing beams are of different wavelengths. A beam splitter is used
to separate two beams by interference filters. The detected intensity of each beam is
determined and fed to a microprocessor, which calculates the intensity ratio, which is a
function of temperature of the phosphor. The phosphor that has been used successfully
in a fluorescent sensor is europium-activated gadolinium oxysulphide [10]. In photo
absorption type of sensors, rare earth materials such as neodymium (Nd) and europium
(Eu) when added to glass result in an absorption spectra with temperature sensitive
properties. Two wavelengths were found with unique temperature behaviour for Nd-
doped fibres. The intensity of each of the two wavelengths is determined and the ratio
provides a measure of temperature. Both these types of sensors need a design that
requires miniaturised optoelectronics with optical filters, micro lenses and signal
processing. These precision devices make this type of fibre optic temperature probe
particularly expensive.

The fibre optic temperature probe to be discussed in this chapter uses an inexpensive
standard multimode communication fibre that transmits signal pulses to the sensor. The
sensor is made of an optical fibre whose cladding is made of a material which has a
refractive index very sensitive to temperature. As the light pulses propagate through the
sensor, a part of the light leaks into the cladding depending on its refractive index,
which is determined by the temperature. Hence the variation in temperature is measured
by a simple amplitude detector mounted on the other end of the fibre. The advantage of
this type of fibre optic temperature sensor is its simplicity in construction and can be
manufactured with a fraction of the cost of those probes available in the market. The
basic principle of operation of the fibre optic temperature probe is discussed in this
chapter. The structure and construction of two versions of temperature probe, one with
50 / 125 micron fibre and the other with 200 micron fibre are discussed. Temperature
characteristics of the sensor are analysed, together with the construction of a fibre optic
thermal switch. The prediction of temperature range of the sensor is also included.
Construction of a computer board to display temperature is briefly discussed. Stability
studies were conducted by thermally cycling the temperature probe. A new constant
called the temperature bandwidth - sensitivity product of the sensor which basically
depends on the core diameter and refractive index profile of the fibre is defined. This
constant determines the temperature range or sensitivity of the fibre optic probe. As a
second contribution, a fibre optic temperature probe was constructed to sense
measurements near liquid nitrogen temperature. This temperature probe could be used
in industrial applications as a temperature control when liquefying explosive gases.

2.2 **Principle and Basics**

Optical fibres have the capability to support a number of guided waveforms called modes [14, 15]. Single mode fibres are used when extremely high signal bandwidth is required. A single mode fibre supports only one electromagnetic mode which can exist in two mutually orthogonal polarizations, whereas multimode fibres support hundreds to thousands of modes.

2.2.1 **Optical Fibres**

2.2.1.1 **Step Index Fibres**

For step index optical fibres, the refractive index profile is a step function [16-18]. The wave equation for a cylindrical waveguide (having coordinates r, θ, z) with a step index profile n(r) can be written as [15]

\[
[\nabla^2 + k_0^2 n^2 (r)] \psi = 0
\]  

(2.1)

where \( \nabla^2 \) is the Laplacian operator, and \( e^{j\omega t} \) dependency is assumed. \( k_0 \) is the amplitude of the propagation vector in free space and \( r \) is the radius vector. Because of the axial and circular symmetry of the fibre, a solution of equation (2.1) is of the form

\[
\psi = \psi(r) \exp\left[ j(l\theta + \beta z) \right]
\]  

(2.2)

where \( l \) is the azimuthal eigen value and \( \beta \) is the propagation wave number along the \( z \) axis of a fibre with a core radius \( a \). Substituting equation (2.1) in (2.2), it can be obtained for the case of a step index profile:

\[
\frac{d^2 \psi}{dr^2} + \frac{1}{r} \frac{d \psi}{dr} + \left( k_0^2 n_0^2 - \beta^2 - \frac{l^2}{r^2} \right) \psi = 0 \quad r \leq a
\]  

(2.3)
\[
\frac{d^2 \psi}{dr^2} + \frac{1}{r} \frac{d \psi}{dr} + \left( k_0^2 n_c^2 - \beta^2 - \frac{l^2}{r^2} \right) \psi = 0 \quad r \geq a \tag{2.4}
\]

where \( n_0 \) is the refractive index of the core and \( n_c \) is that of the cladding.

To simplify the equations above, it can be defined as

\[
u^2 \equiv (k_0^2 n_0^2 - \beta^2)a^2
\]  

(2.5)

\[
\gamma^2 \equiv (\beta^2 - k_0^2 n_c^2)a^2 
\]  

(2.6)

An important parameter \( V \) for the fibre can be obtained as:

\[
V = \left( u^2 + \gamma^2 \right)^{\frac{1}{2}} = k_0 a \left( n_0^2 - n_c^2 \right)^{\frac{1}{2}}
\]

\[
= \frac{2\pi a}{\lambda} (NA) 
\]  

(2.7)

where \( NA \) is known as the numerical aperture of a step index fibre.

The solutions of equations (2.3) and (2.4) are well known. For bounded solutions, the Bessel function of the first kind of order \( l \) can be chosen for equation (2.3) and the modified Bessel function of the second kind of order \( l \) for equation (2.4) and these are

\[
\psi(r) = AJ_l \left( \frac{\nu r}{a} \right) \quad \text{for} \quad r<a
\]  

(2.8)

\[
\psi(r) = BK_l \left( \frac{\gamma r}{a} \right) \quad \text{for} \quad r>a
\]  

(2.9)

2.2.1.2 Graded Index Optical Fibres
The refractive index profiles of graded index fibres are often approximated by a power law as [15]

\[
n(r) = n_0 \left[ 1 - 2 \left( \frac{r}{a} \right)^g \Delta \right]^{\frac{1}{2}} \quad \text{for } r < a
\]

\[
n(r) = n_0 \left[ 1 - 2 \Delta \right]^{\frac{1}{2}} = n_c \quad \text{for } r > a
\]  

(2.10)

where \( n_0 \) is the peak refractive index in the core, \( n_c \) is the cladding refractive index, and \( a \) is the core radius. \( \Delta \) is a measure of the relative difference between the maximum refractive index and its cladding value \( n_c \) and is defined as

\[
\Delta = \frac{n_0^2 - n_c^2}{2n_0^2}
\]

or

\[
\Delta \approx \frac{n_0 - n_c}{n_0} \quad \text{for } \Delta << 1
\]  

(2.11)

The wave equation for a graded index fibre is of the form [15]

\[
\frac{d^2 \psi}{dr^2} + \frac{1}{r} \frac{d \psi}{dr} + \left( n^2(r)k_0^2 - \beta^2 - \frac{l^2}{r^2} \right) \psi = 0 \quad r \leq a
\]  

(2.12)

where \( n(r) \) is a very slowly varying function of \( r \). Therefore, a general solution can be assumed, which is a superposition of plane waves, of the form

\[
\psi(r) = e^{ik_0 \phi(r)}
\]  

(2.13)

where \( \phi(r) \) can be expanded in a power series in terms of \( \frac{1}{k_0} \) as

\[
\phi(r) = \phi_0 + \frac{1}{k_0} \phi_1 + .......
\]  

(2.14)
Substituting equation (2.13) into (2.12) and collecting terms in accordance with the power of \( \frac{1}{k_0} \), two equations belonging to the zeroth and the first order can be obtained:

\[
k_0^2 \left( \frac{d \phi_0}{dr} \right)^2 - \left[ k_0^2 n^2(r) - \beta^2 - \frac{l^2}{r^2} \right] = 0
\]

(2.15)

And

\[
i \left( \frac{d^2 \phi_0}{dr^2} + \frac{1}{r} \frac{d \phi_0}{dr} \right) - 2 \frac{d \phi_0}{dr} \frac{d \phi_1}{dr} = 0
\]

(2.16)

From equation (2.15) it can be obtained that

\[
k_0 \phi_0(r) = \int_0^r \left[ k_0^2 n^2(r) - \beta^2 - \frac{l^2}{r^2} \right]^{1/2} dr
\]

(2.17)

Substituting equations (2.17) into (2.16), we obtain

\[
\phi_1(r) = \frac{i}{4} \ln \left[ \frac{r_2 n^2(r) - \frac{\beta^2 r^2}{k_0^2} - \frac{l^2}{k_0^2}}{\frac{r_1 n^2(r) - \frac{\beta^2 r^2}{k_0^2} - \frac{l^2}{k_0^2}}{2}} \right]
\]

(2.18)

It can be observed that the real limits of the integral in equation (2.17) are two turning points inside the fibre \( r_1 \) and \( r_2 \) at which the integrand vanishes and they represent the turning points, which separate regions of oscillatory and evanescent field variation. One of the conditions for establishing guided wave modes is that on two consecutive reflections, the total phase angle must be integer multiple of \( 2 \pi \). By integrating equation (2.17) from \( r_1 \) and \( r_2 \), only one-half of the cycle for a skew ray can be obtained; therefore,
The integer $m$ is associated with the $m^{th}$ mode number. Equation (2.19) is useful for determining the number of modes in a given range. However, some comments and corrections to this equation must be made. First, the validity of the method is good only for the ray optics picture, in which the phase changes at the turning points $r_1$ and $r_2$ are ignored.

Second, there are two fold degeneracy associated with each lm mode: one with the clockwise or counter clockwise rotation and the other with the orientations of the linear polarization. These degeneracy increase the mode number by 4 from what has been already accounted for by equation (2.19). Thirdly, for each $m$ value, there exist a set of $l$ numbers with an upper limiting value $l_{\text{max}}$ at which the wave is no longer bound. Since the largest $l$ value for a given $m$ occurs for the mode near its cut-off point, $\beta$ shall be replaced by $k_0 n_c$. Therefore we can write

$$l_{\text{max}} = k_0 r \left[ n^2(r) - n_c^2 \right]^{\frac{1}{2}}$$  \hspace{1cm} (2.20)

By taking these corrections into account and treating $l$ as a continuous variable, the sum over $l$ can be replaced by an integer and thus obtain from equation (2.19) the total number of modes as expressed by

$$M = \frac{4k_0}{\pi} \int_0^{l_{\text{max}}} \left[ n^2(r) - n_c^2 - \frac{l^2}{k_0^2 r^2} \right]^{\frac{1}{2}} dldr$$

After integrating over $l$ and using equation (2.20),
In equation (2.21), $\beta$ has been replaced by $k_0 n_c$ and the integral has been extended over the entire core. By substituting equation (2.10) into (2.21), the number of modes propagating in a graded index fibre with a profile can be obtained. The number of modes propagating in a step index fibre can be obtained by letting $g = \infty$. For a graded index fibre, $g \approx 2$, which indicate that the number of modes in a graded index fibre is only about one-half of that in a step index fibre of identical core diameter.

Multimode fibres have advantages compared to single mode fibres for this type of applications. Their larger core radii facilitate launching of light and splicing of similar fibres. An additional advantage is that multimode fibres can be excited with light emitting diodes (LEDs), while single mode fibres must be excited with lasers. Light emitting diodes are easier to make and have longer lifetimes than semiconductor lasers, making their use desirable in some applications. Also for LEDs, the failure is gradual.

### 2.2.3 Leaky Modes

Modes that fail to be guided by the fibre are called cut-off modes. From equation (2.21), it can be seen that a cut-off condition occurs when

$$n_0 < n_c$$

(2.22)

where $n_0$ and $n_c$ are the refractive indices of the core and the cladding respectively. When this inequality is satisfied the energy radiates away into the cladding space as leaky modes. In terms of light guidance in fibres it can be said that light energy tunnels and emerges in the cladding as radiant energy.

### 2.3 Principle of Operation of the Developed fibre Optic Temperature Probe
For the developed fibre optic temperature sensor the leaky modes are of prime importance as it depends on the principle of modes radiating into the cladding. The cladding is chosen of a material whose refractive index is very sensitive to temperature. This prepared material is coated as a cladding on to a specially drawn silica fibre of refractive index 1.457. At very low temperature the refractive index \( n_c(t) \) of the prepared cladding material is high compared the core refractive index \( n_0 \) and all modes satisfy the condition given in equation (2.22) and thus leak into the cladding material. As the temperature increases, \( n_c(t) \) decreases and so lower order modes start being guided inside the fibre. At very high temperature many thousands of modes will be guided in the fibre and hence the light power arriving at a detector is also very high. The temperature at which all the higher order modes propagate is the higher limit of the temperature probe. The value of the propagation constant \( \beta \) decreases with increasing mode order and reaches the value \( \beta_c = n_c(T)k \) where at cut-off \( n_c \) is the refractive index of the prepared cladding material at temperature \( T \). As temperature decreases, \( n_c(T) \) increases and higher order modes with lower propagation constants (\( \beta \)) satisfy the equation (2.22) and leaks into the cladding material and hence number of propagating modes \( M \) decreases. At a very low temperature, \( M \) becomes zero, because all the modes leak into the cladding material. This temperature \( T \) is the lower limit of the temperature probe. The distribution of energy in modes is of no significant importance as it can be taken care of when calibrating the temperature probe.

### 2.3.1 Variation of the Number of Propagating Modes with Sensor Core Radius

The number of propagating modes \( M \) shown in equation (2.21) determines the operating temperature range of the probe. The equation (2.21) is used to calculate \( M \) by increasing the cladding refractive index from 1.43 to 1.457 for 125 micron and 200 micron fibres and is shown in figure 2.1. The core refractive index is 1.457. The results suggest that a 200 micron fibre can propagate more than twice the number of modes than that of a 125 micron fibre for the same change in refractive index of the cladding material. Hence by proper selection of a cladding material, either the temperature range
or sensitivity (or both) of a temperature probe using 200 micron fibre sensor can be made larger than that using a 125 micron fibre sensor.

Figure 2.1 No. of propagating modes of 200 micron and 125 micron step index optical fibres for various cladding refractive indices. The core refractive index is 1.457.

2.3.2 Measurement of Refractive Index of Various Cladding Materials
Refractive index characteristics of the cladding material determine the temperature characteristics of the sensor (equations 2.10, 2.11 and 2.21). Refractive index characteristics of a number of cladding material with varying temperature have been experimentally determined using an optical refractometer. A small amount of the sample cladding material is placed in the refractometer. The temperature of the sample can be kept constant at a desired value by constant temperature water circulation. By varying the water temperature, the sample temperature also can be varied. The refractive index characteristics of these materials thus measured are plotted and shown in figures 2.2 and 2.3.
Figure 2.2 The refractive index - temperature characteristics of materials W2080 and C1. The constituents of the materials are tabulated in Table 2.1. The measurement is done using a refractometer.

Figure 2.3 The refractive index - temperature characteristics of various materials. The constituents of the materials are tabulated in Table 2.1. The measurement is done using a refractometer.
The materials selected for the refractive index measurement are labelled for simplicity and are shown in Table 2.1. Some of the materials selected are obtained by mixing materials of different properties. For example W2080 was obtained by mixing 20% of W1 and 80% of C1. Also NONANENOL5050 was made by mixing 50% of NONANE and 50% of NONANOL and DECNOL5050 is a mixture of 50% NONADECANE and 50% NONANOL. As the optical refractometer did not permit the taking of measurements at higher temperatures, the measurement was limited to $65^\circ C$.

**Table 2.1 Constituents of various labels used as cladding materials.**

<table>
<thead>
<tr>
<th>No</th>
<th>Label</th>
<th>Constituents (by mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>W1</td>
<td>Paraffin wax (industrial)</td>
</tr>
<tr>
<td>2</td>
<td>W2</td>
<td>Paraffin wax (commercial)</td>
</tr>
<tr>
<td>3</td>
<td>C1</td>
<td>Solidified coconut oil</td>
</tr>
<tr>
<td>4</td>
<td>WC2080</td>
<td>20% W1 and 80% C1</td>
</tr>
<tr>
<td>5</td>
<td>WC8020</td>
<td>80% W1 and 20% C1</td>
</tr>
<tr>
<td>6</td>
<td>NONANE</td>
<td>Nonane</td>
</tr>
<tr>
<td>7</td>
<td>NONANOL</td>
<td>Nonanol</td>
</tr>
<tr>
<td>8</td>
<td>NONANENOL5050</td>
<td>50% Nonane and 50% Nonanol</td>
</tr>
<tr>
<td>9</td>
<td>NONADECANE</td>
<td>Nonadecane</td>
</tr>
<tr>
<td>10</td>
<td>DECNOL5050</td>
<td>50% Nonadecane and 50% Nonanol</td>
</tr>
<tr>
<td>11</td>
<td>L1</td>
<td>Lanolin</td>
</tr>
<tr>
<td>12</td>
<td>G1</td>
<td>Glycerol</td>
</tr>
<tr>
<td>13</td>
<td>VO1</td>
<td>Vegetable oil</td>
</tr>
<tr>
<td>14</td>
<td>LP1</td>
<td>Liquid paraffin</td>
</tr>
<tr>
<td>15</td>
<td>SO1</td>
<td>Machine oil</td>
</tr>
<tr>
<td>16</td>
<td>WC2080-NON</td>
<td>20% W1, 80% C1 and 50% Nonane</td>
</tr>
</tbody>
</table>
2.4 Construction of the Temperature Probe

2.4.1 Structure of Version I Probe

The first version of the probe developed has a structure shown in figures 2.4 and 2.5. Two ends of a sensing fibre of diameter 125 microns (shown in the middle in figure 2.4)

Figure 2.4 Schematic of the fibre optic temperature probe Version I implemented using 50/125 micron fibres and associated circuitry.
are fusion spliced to two pig-tails of a standard 50 / 125 graded index multimode communication fibre. These connectors fit to SMA device mounts. Fibre optic communication grade light emitting diode and PIN diode of peak frequency response of
Figure 2.5  (a) Photograph of the fibre optic temperature probe Version I implemented using 50/125 micron fibres and (b) enlarged view of the sensor.

850 nm are fitted to each device mount so that light could be coupled into the fibre pig-tail from one end and detected on the other. The light emitting diode is driven by a 555 timer as shown in figure 2.10 and light pulses of 1 KHz are pumped into one end of the fibre. On the other end of the fibre the PIN diode detects the out coming light pulses which are amplified by a Tran conductance amplifier (figure 2.11). All noise is filtered out of the amplified signal, which is further amplified and fed to a computer board for processing and the temperature is displayed using LED displays which will be explained in detail in a later section.

The intensity of light that is detected by the PIN diode on the end of the fibre is also a function of temperature. Well below room temperature, all light leaks into the material and hence no light is detected by the PIN diode. As the temperature increases, more and more light starts being guided by the sensing fibre. At a very high temperature, well above 200°C, almost all the light is being guided by the sensing fibre. The advantage of this system is that the light intensity detected by the PIN diode is directly related to the temperature of the sensing material as it depends on the number of propagating modes \( M \) (equation 2.1) and it is not necessary to use any wavelength de-multiplexer or miniaturised optoelectronics such as the optical filters and micro lenses used in those types of probes that are available on the market.

The sensitivity of the temperature probe could be further increased by many parameters such as the refractive index of the sensing fibre, thermal coefficient of refractive index of the sensing material, initial refractive index of the sensing material (i.e. the refractive index at the cut-off condition), wavelength of the light used, and the diameters of the communication as well as the sensing fibres used. This is clearly outlined in the theoretical explanation in section 2.3.

2.4.2  Structure of Temperature Probe Version II
2.4.2.1 Implementation Using 50/125 Micron Optical Fibre

An improved version has been made by reducing the two fusion splicing used in version I to one. The modified structure is shown in figure 2.6 and 2.7. This version has a number of structural advantages over version I. It looks similar to a mercury thermometer but is many times smaller in diameter and length. In this version, one end of a silica (sensing) fibre is fusion spliced into pig-tail of a standard multimode 50/125 graded index multimode communication fibre. The other end of the sensing fibre is mirrored by coating gold using vacuum evaporation so that light guided through this

Figure 2.6 Schematic of the fibre optic temperature probe Version II implemented using 50/125 micron fibres and associated circuitry.
fibre is reflected back to the standard communication fibre. The other end of the communication fibre is connected to the single port of a 2x1 optical star coupler which is also shown in figure 2.6. The other two ports of the star coupler are connected to a light emitting diode and a PIN diode as used in version I. It is important to note that the version II should be more sensitive and compact as light travels twice through the sensing fibre.

![Figure 2.7 Photograph of the fibre optic temperature probe Version II implemented using 50/125 micron fibres.](image)

2.4.2.2 Implementation using 200 Micron Optical Fibres

The Version II temperature probe has been implemented using a 200 micron step index optical fibre instead of a 50 micron graded index fibre and is shown in figures 2.8 and 2.9. A light emitting diode and a PIN diode are connected to two branches of Y-splitter using 200 micron fibres. The common terminal of the Y-splitter is connected to another 200 micron optical fibre. A sensor is made on the other end of this 200 micron by
peeling off the acrylic coating and coating the fibre with a cladding material. The sensor head is encapsulated.

From equations (2.10) and (2.11) it can be noted that a step index fibre propagates twice the number of modes than a graded index fibre with a parabolic profile ($g = 2$ for a graded index fibre whereas $g = \infty$ for a step index fibre). As the number of propagating modes $M$ increases, the temperature range or sensitivity (or both) of the temperature

![Figure 2.8 Schematic of the fibre optic temperature probe Version II implemented using 200 micron fibres.](image)
probe also increases. Also equation (2.21) shows that as the radius $a$ of the core of the fibre increases, the number of propagating modes $M$ also increases and hence the temperature range and sensitivity increase. The above are the two main reasons for selecting a 200 micron step index fibre instead of a 50 micron graded index fibre with much lower core radius.

The special material for cladding on the 200 micron fibre is easily removable leaving a uniform refractive index core. Thus there is no need to splice an undoped section of fibre as is required in the 50 micron fibre temperature probe, which makes the temperature probe very easy to fabricate. Abnormalities and loss in the spice are therefore totally eliminated.

2.4.3 Electronic Hardware for Display of Temperature

A computer board has been built [19] to process the thermomodulated light output from the PIN diode and display the temperature on a 4 digit 8 segment LED display. The
constructed board is shown in figure 2.13. This computer board consists of an Intel 8052 Basic central processing unit which allows the information to be processed by writing programs directly in BASIC language or Assembly language or both. The programs as well as a look-up table of temperature are stored in an erasable/programmable read only memory (EPROM). The amplified output of the PIN diode is fed to an A/D converter of the board which digitises the analogue signal into eight bits. Using the Lagrangian interpolation technique to interpolate temperature points above and below this address stored in the EPROM, the actual temperature could be found and displayed in a seven segment LED display. Hence this board can take care of the nonlinearities of the temperature characteristics of the sensor.

A look-up table of temperature could be constructed by calibrating the probe with the help of another standard thermometer. This was done in plotting the characteristics shown in figures 2.15 – 2.23 and the table was stored in the EPROM. This look-up table consists of data relating to temperatures corresponding voltages that are fed into the analogue input of an A/D converter chip on the computer board. The input of the A/D converter comes from an amplifying circuit following the PIN diode, which is
Figure 2.10 Circuit diagram of the light emitting diode driver. 1 KHz pulses of light are generated using this circuit.
shown in the schematic in figure 2.11. As the Lagrangian interpolation technique was used to calculate the temperature corresponding to an analogue voltage input, it was not necessary to incorporate all the points in the temperature characteristics of the probe; it was sufficient to store only a few points, say from three to ten or fifteen. In the linear section of the graph only two or three points need to be stored, whereas when the curve

Figure 2.11 Circuit diagram to amplify the light signal that is detected by the PIN diode. The signal is first amplified using a transconductance amplifier and is further amplified. A low pass filter and a high pass filter are provided to eliminate noises in the signal.
bends, two or three points have to be stored on the bend itself for greater accuracy. Thus with the help of values corresponding to all the chosen points of the characteristics, an approximating polynomial equation like the Lagrangian polynomial equation can be obtained. The order of the interpolating equation depends on the number of points chosen in the characteristics. Once the polynomials are known, the temperature can be calculated by substituting the value of the analogue input in the interpolating equation.

The converted digital value of the analogue input from the A/D converter is fetched by the processor, and substituted into the approximating polynomial equation. The temperature value is calculated and can be displayed in the 4-digit 8-segment display.

When the temperature characteristics of the probe are highly nonlinear, more than ten or fifteen points are considered. In such situations, instead of choosing a higher order polynomial equation, the characteristics are split into three or four smaller sections. In each section, separate approximating low order polynomial equations are considered. The processor can select the appropriate section by comparing the input value of analogue voltage from the A/Digital converter and calling the appropriate code in the program. The complexity of calculations involved in deriving polynomials for a high order approximating equation is more laborious than calculating large number of smaller approximating equations of low orders; for this reason the whole region is split into many smaller sections.

2.4.3.1 Analogue to Digital Converter

An analogue to digital converter (A/D) takes the analogue input signal (temperature information), samples it, and then produces as its output, a coded digital word which corresponds to the level of that sample of the analogue signal being examined. The A/D converter encodes a given analogue voltage into a digital output of predetermined bit length. The A/D converter is incorporated in the computer board shown in figure 2.12.

2.4.3.2 Microcomputer Board

A microcomputer board was designed based on the 8052AH-BASIC chip. The chip
contains an 8K ROM (read-only-memory) resident BASIC interpreter. The development system is a single board shown as schematic diagram in figure 2.13 which contains 17 chips in a compact 144 by 216 millimetres including 8052AH processor.

Figure 2.12 Photograph of the computer board developed using 8052AH-BASIC chip. An A/D converter of this board digitises the input analogue signal (temperature information), which is processed using Lagrangian interpolation techniques, with the help of a look-up table previously stored in an EPROM. A 4-digit 8-segment LED display outputs the temperature.

24K bytes of RAM/EPROM (random access memory/erasable programmable ROM), EPROM programmer and a serial port with automatic data transmission rate selection.

The computer board has a programmable interface chip 8255, which consist of three ports A, B and C. Each of these ports can be programmed as input or output ports and each port can be selected by addressing it from the 8052AH processor. Port A of the 8255 is programmed as an input port and is connected to the A/D converter. Port B of 8255 is programmed as an output port and used to display temperature.

### 2.4.3.3 Display of Temperature

Information of temperature is calculated, using the Lagrangian interpolating equations, by processing the information available in port B of the 8255 chip. Port B (8 lines) of the 8255 is connected to a display controller chip 74C911, an interface element with
Figure 2.13 Circuit diagram of the 8052AH-BASIC controller to display temperature.
memory that drives a 4-digit, 8-segment LED display as shown in figure (2.12). The 74C911 chip allows individual control of any segment in the 4-digit display. The display controller receives data information through 8 data lines and digit information through 2 address inputs K1 and K2, which are connected to the two lower bits of the address lines of the microcontroller 8052AH. The input data are written into the register selected by the address information when chip enable CE and write enable WE are low and are latched when either CE or WE return high. Software is written in assembly language to convert the temperature value to a coded binary that is understood by the display controller 74C911. This controller in turn selects the appropriate LED segments to display the temperature. This code converter is stored in EPROM.

2.4.3.4 Software Design

The program is divided into two major parts, a main program and two sub-routines. The main program is written in BASIC language and the sub-routine is written in Intel-8051 assembly language. The latter only controls the input and output operations. The main program has three functions. It calls the assembly language subroutine to get the temperature information from the analogue input of the A/D converter, process it using Lagrangian interpolation technique by taking the temperature probe characteristics data already stored in the EPROM, and calls the appropriate assembly language routine to display the temperature in the 4-digit 8-segment display.

The sub-routines are written in assembly language and consist of two routines, one an input routine, which by addressing the port A of 8255A takes the voltage information of temperature from the analogue input of the A/D converter. It must be mentioned that the 8052AH-BASIC processor has a special function for converting binary numbers to decimal numbers to help process the data from the A/D converter. The controller reads the data from the A/D converter located at #EA00H and converts the data by using the function code (#09AH) to automatically convert binary numbers to floating point decimal numbers which can be easily sent back to the BASIC program to be further calculations. The second routine has two parts, one an output routine, which addresses both the port B of 8255A and the display controller 74C911 to display the temperature. The second part of the second routine is a data conversion program. This program
should be called before an output operation is performed, converts the temperature information, which is in the form of binary numbers, to coded information which properly displays the proper segments in the 4-digit 8-segment display to show the temperature.

2.4.4 Prediction of Temperature Range of the Probe

From equation (2.21) it is clear that the lower limit of the temperature probe will be reached when the refractive index of the cladding \( n_2(T) \) equals that of the core \( n_0 \) of the sensing fibre. Since the refractive index of the core of the fibre is 1.457, the cut-off condition occurs at the temperature when the refractive index of the cladding material becomes 1.457. The upper limit occurs at the temperature when the refractive index of the cladding material saturates (in other words there is no appreciable change of refractive index with temperature) and hence the number of propagating modes \( M \) in equation (2.21) do not increase.

From the equation 2.21, it is clear that the number of modes propagating in the fibre and hence the higher temperature range of the probe increase in correlation to the diameter of the fibre.

Refractive index characteristics of the cladding material also determine the temperature characteristics of the sensor (equations 2.10, 2.11 and 2.21) and are shown in section 2.3.2.

From an extrapolation of figure (2.2) it can be seen that the refractive index of sample W2080 becomes 1.457 at 22.5\(^0\)C; therefore it could be predicted that the lower limit of this particular temperature probe should be at 22.5\(^0\)C. Thermal characteristics of the probe shown in figure (2.17) clearly confirm this prediction. Also from the refractive index characteristics shown in figure (2.2) of the sample C1, it can be predicted that the lower limit is 20.25\(^0\)C and the thermal characteristics shown in figure (2.16) supports this prediction with an experimental error less than 2\(^0\)C. It is probable that the major portion of this error was caused by the inaccuracy of keeping
the temperature of the refractometer at a constant value using the constant temperature water supply. Since the refractometer did not allow the taking of measurements above $65^\circ C$, it was not possible to do any studies to find the upper limit of the temperature probe. Nevertheless refractive index characteristics will give a lot of information about temperature range and characteristics of the temperature probe.

Figure 2.3 shows the refractive index temperature characteristics of two cladding materials NONANOL and NONANE. These two materials are mixed at a ratio of 50% each and the refractive index characteristics of the mixture labelled as NONANENOL5050 are shown in figure 2.3. From the figures it is seen that the mixture has a characteristics somewhat in between the two. By interpolating the data it can be concluded that the cut-off condition of the mixture occurs at a lower temperature than that of nonanol, but at a higher temperature than that of nonane. So the lower limit of the temperature can thus be designed to suite a particular requirement. Figure 2.3 also shows refractive index characteristics of materials NONADECANE and NONANOL. Their mixture is labelled as DECNOL5050 and shown in figure. This figure again confirms that the refractive index characteristics can be designed by mixing suitable materials of different characteristics. The upper limit of the temperature probe also can be tailored for a specific requirement. The upper limit of a many of the materials studied basically depend on the evaporation temperature. So by mixing a material of low evaporation temperature (with appropriate refractive index) with a material of a high evaporation temperature, a higher range temperature probe can be designed. As the optical refractometer did not permit the taking of measurements at higher temperatures this could not be studied in detail.

2.4.5 Characterisation of the Sensor

The refractive index characteristics of cladding material W2080 shown in figure 2.2 can be used to characterise the sensor as for any particular sensor with a particular wavelength, the refractive index of the cladding material is the major contributing parameter in equation (2.21) that determine the number of propagating modes $M$. The sensor fibre has a step index profile of core refractive index 1.457 with a diameter of 125 microns. The wavelength of light used was 850 nm. Substituting these values
together with the refractive index values of figure 2.2 in equation (2.21), the number of propagating modes \( M \) can be calculated for various refractive indices of the cladding material. Using the known temperature values for the corresponding refractive indices from the figure, the variation in the number of propagating modes with temperature is calculated and is shown in figure 2.14. Using the figure a Lagrangian polynomial equation is calculated as

\[
T_p = L_0 T_0 + L_1 T_1 + L_2 T_2 + L_3 T_3 + L_4 T_4 + L_5 T_5
\]  

(2.23)

where

\[
L_0 = \frac{(M_p - M_1)(M_p - M_2)(M_p - M_3)(M_p - M_4)(M_p - M_5)}{(M_0 - M_1)(M_0 - M_2)(M_0 - M_3)(M_0 - M_4)(M_0 - M_5)}
\]  

(2.24)

\[
L_1 = \frac{(M_p - M_0)(M_p - M_2)(M_p - M_3)(M_p - M_4)(M_p - M_5)}{(M_1 - M_0)(M_1 - M_2)(M_1 - M_3)(M_1 - M_4)(M_1 - M_5)}
\]  

(2.25)

\[
L_2 = \frac{(M_p - M_0)(M_p - M_1)(M_p - M_3)(M_p - M_4)(M_p - M_5)}{(M_2 - M_0)(M_2 - M_1)(M_2 - M_3)(M_2 - M_4)(M_2 - M_5)}
\]  

(2.26)

\[
L_3 = \frac{(M_p - M_0)(M_p - M_1)(M_p - M_2)(M_p - M_4)(M_p - M_5)}{(M_3 - M_0)(M_3 - M_1)(M_3 - M_2)(M_3 - M_4)(M_3 - M_5)}
\]  

(2.27)

\[
L_4 = \frac{(M_p - M_0)(M_p - M_1)(M_p - M_2)(M_p - M_3)(M_p - M_5)}{(M_4 - M_0)(M_4 - M_1)(M_4 - M_2)(M_4 - M_3)(M_4 - M_5)}
\]  

(2.28)

\[
L_5 = \frac{(M_p - M_0)(M_p - M_1)(M_p - M_2)(M_p - M_3)(M_p - M_4)}{(M_5 - M_0)(M_5 - M_1)(M_5 - M_2)(M_5 - M_3)(M_5 - M_4)}
\]  

(2.29)

\( T_0, T_1, T_2, T_3, T_4, T_5 \) are the temperature values and \( M_0, M_1, M_2, M_3, M_4, M_5 \) are the corresponding number of propagating modes that are obtained from figure 2.14. \( M_p \) in these equations is the number of propagating modes that can be calculated for any particular cladding refractive index \( n_c \) using equation 2.21 and \( T_p \) is the corresponding temperature which can be calculated using the polynomial equation 2.23.
Figure 2.14 Calculated temperature - number of propagating modes characteristics. The refractive index characteristics of W2080 and equation (2.21) are used to calculate this graph. This graph is useful to obtain the Lagrangian polynomials which are useful in the characterisation of the sensor using various cladding materials and to predict the temperature range and profile.
2.4.6 The Prediction of Temperature Profile for the Cladding Material C1

The Lagrangian polynomial equation (2.23) is useful to predict the temperature characteristics of any sensor and hence predict the temperature range of the sensor. The Lagrangian polynomials $L_0, L_1, L_2, L_3, L_4, L_5$ are again calculated using figure 2.14. 

To predict the temperature range of any sensor using this equation (2.23), the measured refractive index values for the cladding material C1 shown in figure 2.1 were substituted in equation (2.21) and the corresponding number of propagating modes were calculated. The polynomial equation was then used to calculate temperature values. The predicted temperature values together with the measured values are shown in Table 2.2. The error shown in the table probably occurred due to the inaccuracy in the measurement of refractive index using refractometer. This inaccuracy is unavoidable as it is only possible to measure up to three decimal places; however an error in the third decimal place significantly affect the temperature characteristics. Nonetheless the temperature characteristics are predicted to with reasonable accuracy.

<table>
<thead>
<tr>
<th>Refractive Index of Cladding Material</th>
<th>Estimated Temperature $^0\text{C}$</th>
<th>Measured Temperature $^0\text{C}$</th>
<th>Error $^0\text{C}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.446</td>
<td>44.3</td>
<td>45.0</td>
<td>-0.7</td>
</tr>
<tr>
<td>1.448</td>
<td>40.4</td>
<td>41.0</td>
<td>-0.6</td>
</tr>
<tr>
<td>1.450</td>
<td>35.9</td>
<td>35.0</td>
<td>+0.9</td>
</tr>
<tr>
<td>1.453</td>
<td>30.6</td>
<td>28.0</td>
<td>+2.6</td>
</tr>
<tr>
<td>1.455</td>
<td>27.0</td>
<td>24.5</td>
<td>+2.5</td>
</tr>
</tbody>
</table>

The shape of the output characteristics of the temperature probe is related to energy distribution of modes and the sensitivity function of the detector diode. As the energy distribution of modes and the sensitivity function of the detector diode depends
primarily on the refractive index of cladding materials and not on any other material properties for the same type of fibre, a single calibration of the probe using any one of the cladding material is sufficient to predict the temperature profile of the temperature probe using any cladding material once the refractive index profile of the cladding material is known.

2.4.7 Temperature Bandwidth Sensitivity Product

We define a constant for our temperature sensors called 'the temperature bandwidth - sensitivity product'. The temperature bandwidth – sensitivity product of a particular fibre is a constant, as it basically depends on the core radius and refractive index profile (step index or graded index). By choosing a proper cladding material, the temperature range of the sensor could be increased at the cost of the sensitivity or vice-versa.

From section 2.2.2 it can be seen that a step index optical fibre supports twice the number of modes $M$ than a graded index fibre. Also from equation (2.21) it can be seen that $M$ is proportional to the square of the core radius. Hence for the same core and cladding refractive indices, the temperature bandwidth – sensitivity product of step index fibre is proportional to $a^2$ whereas that of a graded index fibre is proportional to $\frac{1}{2} a^2$, where $a$ is the radius of the core. Therefore, the temperature bandwidth – sensitivity product of the 200 micron step index fibre is 32 times larger than that of a 50 micron graded index optical fibre.

2.5 Results

2.5.1 Temperature Characteristics of Version I Probe

The PIN diode output is amplified using a trans-impedance amplifier and is plotted against temperature for different types of cladding materials. In order to calibrate the probe, it was used in conjunction with a mercury thermometer. Some of these characteristics of different types of cladding materials are shown in figures 2.15-2.20. Figure 2.15 shows the temperature characteristics of a material W1 which has a

48
Figure 2.15 Temperature characteristics of the fibre optic temperature probe Version I implemented using 50/125 micron fibres.

Figure 2.15 shows a sensitive range of $55^0C$ to about $160^0C$. Also in the figure it can be seen that the temperature characteristics of the material L1 range from $93^0C$ to well above $160^0C$.

Figure 2.16 shows a temperature characteristic of C1 range $20^0C$ to above $85^0C$. The materials W1 and C1 were mixed in different proportions. In figure 2.17 a mixture of 80% of W1 and 20% of C1 (WC8020) and a mixture of 20% of W1 and 80%
of C1 (WC2080). The slope of the characteristics of W1 thus can be modified and improved for a better thermal response by adding a required amount of C1. The lower limit of the temperature range of the device has been improved from above $53^\circ C$ shown in figure 2.15 to below $22^\circ C$ shown in figure 2.17. When 20% of W1 is added to 80% of C1 the upper limit of the device is now modified to well above $180^\circ C$. Characteristics above $180^\circ C$ were not plotted as our temperature measurement equipment could not be used beyond this temperature. The characteristics of WC2080
Figure 2.17 Temperature characteristics of the fibre optic temperature probe Version I implemented using 50/125 micron fibres.

are well suited for a temperature probe of range $22^0C$ to $180^0C$. These characteristics are used in our temperature probe version I and the temperature is displayed in four digit eight segment display with the help of Lagrangian interpolation techniques implemented in a developed computer board. So it could be seen from figures 2.17 that by proper selection and preparation of materials any suitable characteristics can be obtained to meet different requirements. In figures 2.18 and 2.19 it can be seen that more linear thermal characteristics ranging from approximately
Figure 2.18 Temperature characteristics of the fibre optic temperature probe Version I implemented using 50/125 micron fibres.

Also the careful selection of material enables us to have a highly accurate temperature probe for a low temperature range or a relatively low accurate temperature probe for a very large temperature range (an explanation is given with the help of a newly defined term 'temperature bandwidth - sensitivity product' explained in section 2.4.7. The only way to improve this product is to use a different type of fibre. The accuracy of the probe could be further increased by increasing the sensitivity and amplification factor of the electronics following the probe.
Figure 2.19 Temperature characteristics of the fibre optic temperature probe Version I implemented using 50/125 micron fibres.

2.5.2 Temperature Characteristics of Version II Probe

The temperature characteristics using the cladding material WC2080 are again measured in the same way as before using Version II 50/125 micron probe and plotted in figure 2.21. Comparing figures 2.17 and 2.21 it is obvious that both versions have similar pattern of the curve even though the PIN diode output level was different. This
Figure 2.20  Temperature characteristics of the fibre optic temperature probe Version I implemented using 50/125 micron fibres. This characteristic is ideal for the development of a fibre optic thermal switch.

is because the power level output of the light emitting diode which is coupled into the fibre is different in each case. It should also be noted that the loss of optical star coupler as well as the length of the sensing fibre will cause losses. As the pattern of the curve is the same (as it is the material property for a particular wax), the output of the light emitting diode or the gain of the PIN diode amplifier output can be adjusted for
calibration.

Figure 2.21  Temperature characteristics of the fibre optic temperature probe Version II implemented using 50/125 micron fibres.

A Version II temperature probe using 200 micron fibres is used to characterise the cladding material WC2080-2N and is shown in figure 2.22. The temperature range extends from $0^\circ C$ to above $100^\circ C$ (although measurements are not taken beyond
Figure 2.22 Temperature characteristics of the fibre optic temperature probe Version II implemented using 200 micron fibres.

$100^0 \text{C}$, it can be expected its upper temperature range to extend to $200^0 \text{C}$ and the temperature characteristics are more linear than those obtained previously.

2.5.3 **Fibre Optic Thermal Switch**

From the characteristics shown in figures 2.15 (W1) and 2.20 (W2), it can be seen that these materials are well suited to the fabrication of a thermal switch, with a switching
temperature of $60^0C$ in the former case and $50^0C$ in the latter case. It could also be concluded from all these figures that by proper selecting materials as well as mixing different quantities, a thermal switch could be designed to operate at a required temperature. The critical control parameter for the design of device for either temperature measurement or switching is the dependence of the refractive index of the material with temperature as explained in section 2.3. The switching speed of these devices is faster than that of a mercury thermometer because of low thermal mass and they are well suited for situations where an on line switching of microwave ovens or devices are required.

### 2.5.4 Measurements near Liquid Nitrogen Temperature

A Version II fibre optic temperature probe was made using 200 micron optical fibres as described above in section 2.4.2.2 for measuring temperatures near liquid nitrogen. The sensing material (NONANOL) in the probe tip was selected to allow operation at a low temperature because of its refractive index at low temperature. Since there was no temperature measuring device available to calibrate our probe, the probe was cooled to liquid nitrogen temperature, and allowed the temperature to rise slowly. Measurements were taken at regular time intervals until the temperature was approximately $-10^0C$. The temperature characteristics are shown in figure 2.23. If it is assumed that the temperature rises linearly with time, the results suggest that the probe provides an output that is rising with temperature above $-185^0C$. Measurements were not recorded above $-10^0C$ as the output amplifier was approaching saturation. However, the characteristics demonstrate that the probe will operate above $-10^0C$ if a gain reduction is added to the output circuit.

The 200 micron probe can be configured to operate over a desired temperature range by appropriate selection of the temperature sensing material placed in the probe tip. It has been demonstrated that this range can be as low as $-196^0C$ and up to at least $200^0C$. This temperature probe could be used in such industrial applications as temperature control in liquefying explosive gases.
2.5.5 Temperature Cycling of Fibre Optic Temperature Probe

Stability studies have been conducted for the Version II temperature probe using 200 micron fibre that is described in the section 2.4.2.2. The physico-chemical properties of high quality waxes like paraffins, nonanes, decanes and undecanes are very stable under normal operating temperatures [89]. A temperature probe was made as described in the above section and measurements were taken with increasing temperature. The probe
was then thermally cycled by heating and cooling between $0^\circ C$ and $100^\circ C$.
Measurements were taken every 20 thermal cycles and these characteristics are shown in figure 2.24. Since there was no significant change in the characteristics when the probe is cycled more than 20 times, it was concluded that the probe had stabilised. However it is advisable to cycle the probe more than 20 times as well as at higher temperatures as a precaution to ensure stability.

Figure 2.24 Thermal cycling of a fibre optic temperature probe Version II implemented using 200 micron fibres. The probe was heated and cooled between $0^\circ C$ and $100^\circ C$ and measurements were taken after every twenty cycles.
The thermal cycling is required because of the following reasons.

1. The sensor contains a mixture of thermally sensitive materials and cycling ensures a uniform mixture.
2. Cycling helps spread the material uniformly over the sensing fibre.

2.6 Concluding Remarks

A novel inexpensive fibre optic temperature measuring probe has been developed. As fibre optic cables are electrical insulators and information transmitted along them is not affected by normal electrical interference, they can be used in situations where very high voltages are present, unlike the traditional thermocouple temperature measuring probes which, being electrical conductors, have limited use in this type of environment. The developed fibre optic probe is particularly suitable for monitoring the operating temperature of large power transformers, alternators, switch gear, in-situ temperature measurements in microwave ovens and RF heaters, temperature measurements involving radioactive materials, applications in explosive and highly inflammable environments as they are based on a non-electrical operation, highly corrosive environments, because of their structural nature, biomedical applications, and temperature control in liquefying explosive gases at low temperature. Unlike commercially available fibre optic devices currently on the market the developed fibre optic temperature probe uses an inexpensive standard multimode fibre that transmits signal pulses to the sensor. Variations in temperature are measured straight from a PIN diode, and a patent had been issued for this device to the Illawarra Technology Corporation Ltd., on behalf of the University for the Inventors. As the device can be manufactured very cheaply, such applications as temperature measurement in domestic microwave ovens becomes a commercial possibilities, while more advanced models can be used for control and monitoring of industrial processing. It can be also used in refrigeration applications.

The basic principle behind the operation of the developed temperature sensing system is
discussed together with the structure and construction of two versions of the
temperature probe, one using 50/125 micron fibre and the other using 200 micron fibre.
Temperature characteristics of both versions have been experimentally determined and a
fibre optic thermal switch has been constructed. It was shown that the temperature
range of the probe could be predicted, if certain parameters of the fibre as well as
sensing material were known. A computer board which is capable of handling the
nonlinearities of the temperature characteristics of the fibre optic probe was constructed
to display the temperature. Stability studies of the temperature probe were conducted
and it was found that the temperature probe stabilises after 20 thermal cycles from
$0^0C$ to $100^0C$. A new constant called 'temperature bandwidth - sensitivity product'
has been defined and this constant depends on the core radius and refractive index
profile of a fibre. By choosing a proper cladding material, the temperature range of the
sensor could be increased at the cost of the sensitivity or vice-versa. Also a fibre optic
temperature probe has been constructed to do measurements near liquid nitrogen
temperature, which ranges from $-196^0C$ to $-10^0C$. This probe is suitable for
industrial applications such as temperature control in liquefying explosive gases.
3.1 Introduction

Heating and drying processes using microwaves for various industrial applications have been well established and in many cases are replacing conventional methods which are less efficient, less economical and less convenient. Because of the rapid and effective conversion of electrical energy into thermal energy within the product, microwave energy was initially utilized in food processing. Increasing utilization in processing dielectric and biological materials has occurred in the past ten to twelve years.

There are many advantageous features of microwave processing which are not found in other types of heating. Because heat generated by the microwave energy occurs principally in the product and not in the oven walls or oven atmosphere, energy losses from the oven to the surroundings are much lower. Heat is generated in the product by electromagnetic waves, and hence heating can be immediately started or stopped by automatic control. The electric power level determines the degree of product heating or drying, which can be rapidly adjusted to control temperature, dryness, etc.

In conventional hot air heating systems, the product must have a high temperature at the surface thereby providing the gradient necessary to heat the interior rapidly. High surface temperature can damage the product. Microwave energy generates heat directly in the product without requiring such temperature gradients and hence surface damage is minimised.
The use of microwave power for heating purposes requires an applicator of specific design. Large metallic chambers are commonly used but heating can be non-uniform because of the complicated internal multimode field structure. Single mode resonant cavities provide higher field strengths than multimode chambers for the same applied power and have been found suitable for the treatment of low loss dielectrics [52, 53, and 54]. However, many applications, because of dielectric properties of the load or their variation during processing, require special design. For example, in travelling wave or waveguide systems, heat deposition can be quite uniform because the occurrence of standing waves is minimised. Power is partially absorbed within the extended load as it travels down the waveguide towards a non-reflecting termination. Such applicators have been used for heating material in the form of thick dielectric sheets suspended within the waveguide [55, 56, and 57].

3.2 Power Dissipation

The process of microwave heating of dielectric sheets placed inside a waveguide applicator consists of dissipating part of the microwave energy flow in a heated material. Dielectric losses can be formally described by considering the dielectric constant $\varepsilon^*$ to be a complex number in the form

$$\varepsilon^* = \varepsilon_0 (\varepsilon' - j\varepsilon'') = \varepsilon_0 \varepsilon' (1 - j \tan \delta)$$  \hspace{1cm} (3.1)

where $\varepsilon_0$ is the dielectric constant in vacuum, $\varepsilon'$ and $\varepsilon''$ are the real and imaginary components of the dielectric constant.

The power dissipated in the heated body, $P_{\text{diss}}$ is related to the DC conductivity $\sigma$ and losses due to polarisation, i.e.

$$P_{\text{diss}} = -\frac{1}{2} \int_{\nu} \sigma E \varepsilon^* dv$$
\[ P_{\text{diss}} = -\frac{1}{2} \omega \varepsilon_0 \int \varepsilon_r |E|^2 \, dv = 2.78 \times 10^{-12} f \int \varepsilon_r^\prime |E|^2 \, dv \] \hspace{1cm} (3.3)

where \( P_{\text{diss}} \) is in Watts, \( f \) is frequency in Hertz, and \( E \) is electric field intensity (peak value) in volts/meter.

In a rectangular waveguide carrying a TE mode, the normal component of electric field \( E_y \) will be large compared to the tangential component \( E_x \). When a dielectric film of relative permittivity \( \varepsilon_r \) is present inside the waveguide, because of the boundary conditions at the air-dielectric interface, the normal component of electric field inside the film will be decreased by a factor \( \varepsilon_r \) and is shown in figure 3.2 (a). But the tangential component of electric field is not affected by the boundary conditions at the air-dielectric interface as is shown in figure 3.2 (b). Hence for the maximum power dissipation in the dielectric film, the component of electric field tangential to the surface of the dielectric film is more significant than the normal component.

### 3.3 T-septum Waveguides

A rectangular waveguide with internal ridges is useful for large bandwidth and wide mode separation [58, 59, and 60]. T-septum waveguides [62] have lower cut-off frequencies and broader bandwidths than conventional ridged guides with the same geometries and can produce field distributions suitable for microwave heating of lossy materials. Better electric field uniformity and enhanced power dissipation concentrated at the inserted material can be obtained through the use of a single-mode applicator [62].
In a single mode waveguide, because there is only one mode of propagation, maximum power can be coupled into the waveguide applicator from a magnetron into this mode at the mid-plane of the wider dimension of the waveguide. A T-septum is further capable of concentrating the electric field into a much smaller area above the septum. Placing a sample above the septum will ensure that it resides in the vicinity of the maximum field and thus interacts fully with the stored energy within the waveguide applicator.

In engineering practice, TE modes of propagation are usually preferred because they have lower cut-off frequencies compared with TM modes. Also, the polarisation of the electric field is well defined within the cross section, which may be necessary for

Figure 3.1 Dielectric loaded T-septum waveguide applicator designed to heat a lossy film coated on a metal surface. A lossless dielectric sheet of thickness \( t_2 \) is placed between the T-septum and the upper wall. A lossy dielectric film is placed on the waveguide wall above the dielectric sheet in the air gap \( g_1 \). Dimensions: \( a=86 \text{ mm}, b=43 \text{ mm}, a_2=48 \text{ mm}, a_3=24 \text{ mm} \) and \( w=8 \text{ mm} \).
certain applications such as microwave heating. Among the various TE modes, the TE\textsubscript{10} mode is of primary interest. Throughout this dissertation TE\textsubscript{10} is designated as the dominant TE mode and have several advantages:

1. It has the lowest cut-off frequency in contrast to other modes.
2. The separation of the cut-off wavelength between the TE\textsubscript{10} mode and the next higher mode, TE\textsubscript{20}, is larger than that between any other adjacent modes.
3. Within its normal operating frequency range, for a given aspect ratio, the TE\textsubscript{10}
mode offers the smallest attenuation due to skin effect or surface resistance of the metal.  

4. The electric field is strictly confined to the transverse plane passing from top to bottom of the guide. This type of unidirectional polarisation may be essential for certain application.

3.4 Dielectric Loaded T-septum Waveguide for Heating of Lossy Films

There are several types of geometry in which it is difficult to use microwave power for heating. First type includes low loss dielectric materials in any configuration. The second type includes lossy dielectrics adjacent to metal surfaces on which the tangential component of electric field vanishes. Low loss dielectrics adjacent to metal surfaces comprise the third type. However, some progress has been made in the first category by using a transient wave applicator [94] where heating is obtained incrementally for each transient wave (forward or reflected) which passes through the dielectric. A solution for the second type is proposed in this dissertation [52]. The technique involves “pulling” the electric field away from the metal wall by placing a dielectric material of critical dimensions to maximise tangential component of the electric field on the film. The dielectric material which is placed in the waveguide has the effect of rearranging the electric field depending on the dimensions of the dielectric slab and its relative permittivity. Instead of a sine or cosine distribution which exists in the waveguide prior to the dielectric slab, the modified electric field profile can be very high on the dielectric film, but quickly drops and vanishes at the wall.

In this chapter the T-septum waveguide is examined as a device to heat lossy films of high dielectric constant using microwave power. When the film is placed on a metal surface within the waveguide, boundary conditions require that the tangential component of electric field on the metal surface is zero and heating can be difficult to achieve. In a T-septum waveguide carrying a TE mode, as shown in figure 3.1, the normal component of electric field $E_y$ in the gap above the T-septum will be large compared to the tangential component $E_x$. When the dielectric film of relative
permittivity $\varepsilon_r$ is loaded inside the waveguide, because of the boundary conditions at the air-dielectric interface, the normal component of electric field inside the film will be decreased by a factor of $\varepsilon_r$ whereas the tangential component of electric field is not affected by the boundary conditions at the air-dielectric interface. For dielectric heating of films on the metal surface, an applicator must be designed that maximises the component of electric field tangential to the surface of the dielectric film. In the following analysis, it is shown that an additional loading of a low loss dielectric of high relative permittivity placed above the septum can increase the tangential component of electric field in the vicinity of the film. Numerical analysis indicates that power loss is related to the thickness and permittivity of the dielectric and height of the T-septum.

### 3.5 Finite Element Analysis of Dielectric Loaded Waveguide Applicator

#### 3.5.1 Introduction to Finite Element Analysis

In the finite element method (FEM) continuous functions are discretised into polynomials or other piecewise approximations. The FEM has its origin from structural engineering and has since found applications in many areas of engineering, science, and applied mathematics. The FEM was first applied in electrical engineering was in the analysis of accelerator magnets by Winslow [23] but the method progressively expanded into various areas of electrical engineering. Even though, only comparatively simple waveguide problems were analysed initially, it has since been employed in many areas where two-dimensional scalar potentials or wave functions need to be determined. First order elements initially used in the analysis have been replaced in many applications later on by elements of higher orders because of their relatively low accuracy. FEM continued to very useful when material nonlinearities or complicated geometric shapes are encountered, especially in problems that involve analysing the magnetic fields of electric machines, or the charge and current distributions in semiconductor devices.

#### 3.5.2 Theoretical Basis of Finite Element Method
When analysis is done using the finite element method, its solution region is divided into non-overlapping elements of well defined shape (triangle or quadrilateral shapes). The finite element analysis of any problem can be described by four basic steps [24]:

a) Discretising the solution region into a finite number of elements
b) Deriving the governing equations for a typical element
c) Assembling all the elements of the solution region
d) Solving the system of equations obtained.

3.5.3 Analysis of Waveguides with Arbitrary Cross Section

An electromagnetic energy is guided from one point to another using waveguides. Waveguides of cross-sectional shapes other than rectangular, circular or elliptical are often desirable in many situations. In order to analyse the behaviour of such waveguides, it is required to solve the eigen value problem of Helmholtz's equation

\[(\nabla^2 + \lambda^2) = 0\]

subject to homogeneous Dirichlet or Neumann boundary conditions [25]. Only for the three shapes mentioned above, an analytical solution by separation of variables is possible. A different solution technique is required for other shapes as the Helmholtz equation is not separable. The cut-off frequency and field pattern of the dominant propagating mode need to be determined to understand the propagation properties of a waveguide. Motz [26] and Davies and Muilwyk [27] have solved the Helmholtz equation for uniform hollow waveguides with boundaries of arbitrary shape, but hey calculated only the dominant mode. Beaubien and Wexler [28] accomplished the determination of higher order modes and substantial program modification was required to achieve this. With these iterative methods, considerable computational effort was needed. Also convergence difficulties often arise when degenerate modes are involved. Hence attempts have been made to develop explicit methods rather than iterative methods. They are usually based on variational principles, to determine complete sets of waveguide modes.
Analyses are comparatively easy for certain cross-sectional shapes to find conformal transformations that map the given shape into a rectangle. In such case, a more complicated elliptical differential operator is used to replace the Helmholtz differential operator, subject to conditions imposed on an inconvenient boundary, but on a very simple region. Rayleigh-Ritz method can be used to solve the latter problem using sines and cosines as trial functions. Meinke, Lange and Ruger [29] and Meinke and Baier [30] explored this approach extensively. When the guide shape becomes a union of rectangles, a direct method of variation of parameters may be used (Skiles and Higgins [31], Krange and Haddad [32]) and it has gained popularity.

### 3.5.4 Numerical Solution of Dielectric Loaded

Except for a few simple geometries, analytic solution of dielectric loaded waveguides is also prohibited like the homogeneous waveguides [25], [50], because of the difficulty of matching the electric and magnetic fields at the air-dielectric interface. Consequently, efforts were made to obtain solutions using numerical methods. A common characteristic in these numerical methods is the formation of a matrix eigen value equation that is solved for the frequency, propagation constant, and fields in the waveguide.

The first general method for the solution of dielectric loaded waveguides was reported by Collins and Daly [40]. They used the finite difference method to discretise the Helmholtz equation for inhomogeneous waveguides. This method was refined by Hannaford [41] by discretising a corresponding variational expression. In order to obtain sufficient accuracy, solution of a prohibitively large matrix eigen value is needed and hence the finite difference method is inherently inefficient when applied to dielectric loaded waveguides.

With the use of continuous analytic trial functions, solutions of dielectric loaded waveguides have also been obtained by minimising a variational expression for the electromagnetic fields using the Rayleigh-Ritz procedure. Works of English [42] and of Thomas [43] have to be noted for these calculations. This method has the advantage of only requiring the solution of a small matrix eigen value problem, but it required the
evaluation of lengthy analytic expressions as each set of trial functions is limited to a particular geometry.

These deficiencies are not involved when the finite element method is used in approximating a space function. In this method, the region of interest is first divided into a number of elements, triangular, quadrilaterals or any other shape, and in each element; a polynomial approximation is made of the function. Ahmed and Daly [44], has already made attempts for dielectric loaded waveguides in a limited sense, however, their work seems to be unnecessarily restricted to special geometries by imposing a regular mesh spacing. It also limited in computational efficiency by confining their polynomial approximation to first order. The great advantages of the finite element method is the freedom to fit any polynomial shape by choosing triangular element shapes and sizes and the extremely accurate approximations provided by high-order polynomials. First or second order elements do not provide accurate results compared to third or higher order elements. Both of these advantages are retained in the finite element formulation by Csendes and Silvester [45]. Hence, this formulation was used in the calculations of the results presented in Chapters 4 as well as the analysis done on Y-septum waveguides shown in chapter 6.

3.5.5 Functional Formulation

In a uniform dielectric loaded waveguide there are several homogeneous regions of different permittivity have to be considered. In each of these homogeneous regions, the electric and magnetic fields must satisfy the homogeneous Helmholtz equation subject to boundary conditions and Maxwell's equations are to be satisfied on the boundaries. Hence, the electromagnetic behaviour of this system is determined by the boundary value problem formed by the combination of these regions.

A variational formulation of this boundary value problem can be derived [45] from the behaviour of the physically realisable electromagnetic fields in dielectric loaded waveguides. A source-free Maxwell field equation governs these fields which assume a sinusoidal variation in time and in the direction of propagation.
The interface conditions are

\[
\frac{1}{k^2} M \frac{\partial \psi}{\partial n} = \frac{\beta}{\omega k^2} J \frac{\partial \psi}{\partial t} + \frac{i}{\omega} J \xi \tag{3.4}
\]

where

\[
\psi = \begin{bmatrix} E_z \\ H_z \end{bmatrix} \tag{3.5}
\]

\[
\xi = \begin{bmatrix} E_\tau \\ H_\tau \end{bmatrix} \tag{3.6}
\]

\[
M = \begin{bmatrix} \varepsilon & 0 \\ 0 & \mu \end{bmatrix} \tag{3.7}
\]

\[
J = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \tag{3.8}
\]

\[
k^2 = \omega^2 \varepsilon \mu - \beta^2 \tag{3.9}
\]

and \(\tau, z\) are the orthogonal directions tangent to the interface and \(n\) normal to them.

Across a boundary, \(\xi\) and \(\frac{\partial \psi}{\partial n}\) are continuous even if \(\varepsilon\) and \(\mu\) change discontinuously.
It is easily found that the axial field components satisfy the homogeneous Helmholtz equation for a homogeneous region \( r \). This may be written in operator form as

\[
M \left( \frac{1}{k^2} \nabla^2 + 1 \right) \psi = 0
\]  

(3.10)

From the theorems of mathematical physics [46] a variational solution of the system \( L_x = g \) results by extremising the functional \( F = \langle t \mid L \mid t \rangle - 2\langle t \mid g \rangle \). Consequently, the functional

\[
F(\phi) = \frac{1}{k^2} \langle \phi \mid M \nabla^2 \mid \phi \rangle + \langle \phi \mid M \mid \phi \rangle
\]  

(3.11)

is stationary if and only if the variational solution \( \phi \) equals the true physical solution \( \psi \).

Since only at the true solution the function is stationary, at this stationary value (3.4) may be applied. By using a suitable integral definition of the scalar product and two appropriate vector identities, at the stationary value the first term in (3.11) becomes

\[
\frac{1}{k^2} \int_r \psi^T M \nabla^2 \psi \, dr = -\frac{1}{k^2} \int_r \nabla \psi^T M \nabla \psi \, dr + \frac{1}{k^2} \oint_r \psi^T M \frac{\partial \psi}{\partial n} \, d\tau
\]

\[
= -\frac{1}{k^2} \int_r \nabla \psi^T M \nabla \psi \, dr + \frac{\beta}{\omega k^2} \oint_r \psi^T J \frac{\partial \psi}{\partial \tau} \, d\tau + \frac{j}{\omega} \oint_r \psi^T J \xi \, d\tau
\]

\[
= -\frac{1}{k^2} \int_r \nabla \psi^T M \nabla \psi \, dr + \frac{\beta}{\omega k^2} \oint_r (\nabla \psi^T J X \nabla \psi) \cdot \hat{a}_z \, d\tau + \frac{j}{\omega} \oint_r \psi^T J \xi \, d\tau
\]  

(3.12)
In the last integral on the right side of equation (3.12), the boundary integral is zero on external boundaries that are either metal, where \( E_z \) and \( E_t \) vanish, or lines of symmetry, where \( H_z \) and \( H_\tau \) vanish. Also, the functional for the union of many homogeneous regions will be the sum of the contributions from each. It can be seen that all of the internal boundaries are to be travelled twice, in opposite directions, and since the values of \( \psi \) and \( \xi \) must be continuous, there can be no net contribution to the functional from this integral. Therefore, the expression

\[
F(\phi) = -\int_R \nabla \phi^T \frac{1}{k^2} M \nabla \phi dR + \int_R \phi^T M \phi dR + \frac{\beta}{\omega} \int_R (\nabla \phi^T \frac{1}{k^2} J X \nabla \phi) \cdot \hat{a}_z dR
\]

(3.13)

where the region of integration is over the whole waveguide cross section \( R \) is stationary at the true solution. The entire boundary conditions are contained the third integral for dielectric loaded waveguides and above cut off it couples the electric and magnetic fields on the interfaces between regions of different media.

### 3.5.6 The Rayleigh-Ritz Procedure

The Rayleigh-Ritz method may be applied to solve equation (3.10) by determining the stationary condition of the functional (3.13). The solutions are sought of the form

\[
E_z = \sum_{i=1}^{n} e_i \alpha_i(x, y)
\]

(3.14)

\[
H_z = \sum_{i=1}^{n} h_i \alpha_i(x, y)
\]

(3.15)
where \( \alpha_i(x, y) \) are a set of linearly independent functions. Substituting these values in equation (3.13), differentiating with respect to \( e_i \) and \( h_i \) and setting the result equal to zero, 2n simultaneous equations are obtained as

\[
\sum_r \frac{1}{k_r^2} \sum_{i=1}^{n} \varepsilon_r S_{ki} e_i + \frac{\beta}{2\omega} U_{ki} h_i = \sum_r \varepsilon_r \sum_{i=1}^{n} T_{ki} e_i \tag{3.16a}
\]

\[
\sum_r \frac{1}{k_r^2} \sum_{i=1}^{n} \mu_r S_{ki} h_i + \frac{\beta}{2\omega} U_{ki} e_i = \sum_r \mu_r \sum_{i=1}^{n} T_{ki} h_i \tag{3.16b}
\]

where

\[
S_{ki} = \int_r \nabla \alpha_k \cdot \nabla \alpha_i \, dr \tag{3.17}
\]

\[
T_{ki} = \int_r \alpha_k \alpha_i \, dr \tag{3.18}
\]

\[
U_{ki} = \int_r \left( \alpha_k \frac{\partial \alpha_i}{\partial \tau} - \alpha_i \frac{\partial \alpha_k}{\partial \tau} \right) \, d\tau \tag{3.19}
\]

In matrix form these equations can be written as

\[
V \Psi = \omega^2 T \Psi \tag{3.20}
\]

where \( V \) and \( T \) are the partitioned matrices.
Here it can be written as $\delta = \frac{B}{\omega}$. Equation (3.20) may be solved for the frequency of propagation and field distribution in the waveguide at any value of phase velocity.

### 3.5.7 Finite Element Discretization

Although an arbitrary set of trial functions is used to perform the Rayleigh-Ritz expansion, for each set of trial functions that is chosen the integrals in equations (3.4)-(3.6) must be evaluated, it is wise to choose trial functions that minimize such calculations. In the finite element method this can be done by splitting the region of integration into a number of simple elements. The integration over each element of some particular sets of trial functions may then be reduced to the evaluation of a few parameters. The calculation of the total integral may be performed by a simple combination of these parameters.

By using the triangular interpolation polynomials of [47], the approximating functions are
\[ \alpha_{ijk} = P_i(\zeta_1) + P_j(\zeta_2) + P_k(\zeta_3) \]  \hspace{1cm} (3.22)

where the \( z_i \) are triangular coordinates and

\[
P_m(z) = \prod_{i=1}^{2} \left( \frac{N_z - i + 1}{i} \right), m \geq 1
\]

\[ P_0(z) = 1 \]  \hspace{1cm} (3.23)

It is evident that these polynomials possess the desired Newton-Cotes interpolation property

\[
\alpha_{ijk}(\frac{i}{N}, \frac{j}{N}, \frac{k}{N}) = 1
\]

if \( I, j, k \) are integers satisfying

\[ i + j + k = N, 0 \leq i, j, k \leq N \]  \hspace{1cm} (3.24)

and

\[
\alpha_{ijk}(\frac{l}{N}, \frac{m}{N}, \frac{n}{N}) = 1
\]

if \( l, m, n \) are integers that satisfy (3.25) but have

\[ l \neq i, m \neq j, n \neq k \]  \hspace{1cm} (3.27)

Hence, the coefficients in a finite element approximation are identical to the potential values on the interpolation point set.
Since the matrix elements of $V$ and $T$, $S_{ik}$ and $S_{jk}$ have been used to solve the homogeneous Helmholtz equation and are therefore known and tabulated [47] for polynomial approximations up to the fourth order. To evaluate the remaining element $U_{ik}$, it is necessary to find an expression for the tangential derivatives in (3.19). This may be obtained by finding the derivative of the polynomial (3.23)

$$\frac{\partial P_m(z)}{\partial z} = \sum_{i=1}^{m} \frac{P_m(z)}{N_{i+1}}, m \geq 1$$

$$\frac{\partial P_0(z)}{\partial z} = 0$$  \hspace{1cm} (3.28)

And using the relationship

$$\zeta_p + \zeta_q = 1$$  \hspace{1cm} (3.29)

valid on triangular-element edges. After a little algebraic calculations results in

$$\frac{\partial \alpha_{0jk}}{\partial \alpha_{\tau1}} = \begin{cases} 
N \sum_{n=1}^{k} \frac{P_n(\zeta_3)P_{N-k}(1-\zeta_3)}{N\zeta_3 - n + 1} - \sum_{n=1}^{N-k} \frac{P_k(\zeta_3)P_{N-k-n}(1-\zeta_3)}{N(1-\zeta_3) - n + 1}; k \neq 0, k \neq N \\
-N \sum_{n=1}^{N} \frac{P_N(1-\zeta_3)}{N(1-\zeta_3) - n + 1}; k = 0 \\
N \sum_{n=1}^{N} \frac{P_N(\zeta_3)}{N\zeta_3 - n + 1}; k = N
\end{cases}$$  \hspace{1cm} (3.30)

Now $U_{ik}$ can be evaluated to any order of polynomial approximation and for any triangular shape by substituting this expression into (3.19) and integrating the resulting expression around the perimeter of a triangle using triangular coordinates. Although this appears complex, much symmetry exists and the necessary computations are
relatively few. The U matrix has been evaluated independently by Daly [48].

3.5.8 Finite Element Analysis of Dielectric Loaded T-septum Waveguide Applicator

The microwave applicator shown in figure 3.1 consists of a rectangular waveguide with T-septum that is to be used to heat a lossy dielectric film coated on the top wall of the applicator. A lossless dielectric material is supported above the T-septum and there are air gaps between the dielectric and the metal surfaces.

The dimensions of the T-septum waveguide are $a=86$ mm, $b=43$mm, $a2=48$ mm, $a3=24$ mm and $w=8$ mm. Calculations have been performed by varying the remaining parameters shown in figure 3.1. The lossless dielectric loading is shown as the shaded region in the figure.

The finite element method discussed in section 3.5.4 was used to determine the field structure in the region above the septum. A computer code has been developed to do the analysis. Two symmetrical portions are assumed for the applicator and analysis are done by considering one of the half sections formed by introducing a magnetic wall along the dotted lines in the middle of the x-dimension of the waveguide cross section as shown in figure 3.3. The aspect ratio of the half section is $\frac{b}{2a}$.

In the study of guided waves along a uniform waveguide, it is assumed that the waveguide applicator is infinitely long, and that the electromagnetic field has been somehow introduced into the waveguide. The field solutions may be classified into two basic types. Solutions containing an electric field component but no magnetic field component in the direction of propagation are known as transverse magnetic (TM) modes. The other type of potential is referred to as transverse electric (TE) modes, which have a magnetic field component but no electric field component in the direction of propagation. In a waveguide with complex boundaries, there often exist hybrid modes, which are considered to be a coupling of TE and TM modes.

In engineering practice, TE modes of propagation are usually preferred because they
have lower cut-off frequencies compared with TM modes. Also, the polarisation of the electric field is well defined within the cross section. In this dissertation, a TE mode is designated by the notation $TE_{mn}$, where $m$ is the number of half cycle variations in the $x$ direction and $n$ is that in the $y$ direction. Each combination of $m$ and $n$ values

Figure 3.3 Subdivision of the cross section of the T-septum waveguide applicator into triangular elements. Due to symmetry, only one-half of the waveguide is analysed by considering one of the half sections formed by introducing a magnetic wall along the dotted lines. The cross section is divided into 40 triangular subregions and the shaded area represents the dielectric loading.
represents a different field configuration (mode) in the guide. For $TE_{10}$ mode, the field components in the guide do not change with respect to $y$ but have a half cycle variation with respect to $x$. Although a waveguide applicator is capable of carrying various modes of fields, a single mode of propagation is preferred for high power microwave heating because multimode propagation makes it difficult to introduce the fields into the guide and to extract the energy out of it. Also a single mode applicator provides a much more uniform field distribution compared to a multimode applicator. Hence in single mode microwave heating only the $TE_{10}$ mode called the dominant is used and hence only this mode is considered in the following analysis. When $TE$ modes are analysed, the boundary condition required at the applicator walls is Neumann.

One half of the waveguide cross section was subdivided into 40 triangular sub-regions as shown in figure 3.3. A finer mesh of triangular elements would have increased the accuracy of the solution, but would otherwise require more computing power. Each triangular element is uniquely identified by its three vertices. To make up data for the computer program, all vertices are numbered and the vertex numbers and the corresponding coordinates are fed to the program as data. The elements themselves are not uniquely specified by its vertex list. Therefore a second set of data is used to communicate to the program which vertices define each element. Solution of the waveguide eigen value problem was then obtained by finding the polynomial coefficients in each triangle using the variational procedure explained in the above section. A set of eigen vectors are obtained for each eigen value. Each of these eigen values represents the cut-off wavelengths of each $TE$ mode. The corresponding eigen vectors are the magnetic field distribution ($H_z$) in the propagation direction.

From $H_z$, other electric field components are calculated as [51]

$$Ex = \frac{1}{j\omega k} \frac{\partial H_z}{\partial y}$$

(3.31)

and
\[ E_y = \frac{1}{j \omega k} \frac{\partial H_z}{\partial x} \quad (3.32) \]

were \( k \) is the wave number in free space and \( \omega \) is the angular frequency.

In this analysis, the lossy dielectric film was not included as it was assumed to be thin and hence did not significantly affect the eigen value and eigen vectors of the problem. Even though the lossy film has a high dielectric constant, its thickness is significantly small compared to the rest of the applicator. Hence the electrical distance, which is a product of the square root of dielectric constant and the thickness, is very small compared to the rest of the applicator. When an additional dielectric loading of high permittivity is placed below the lossy film, the electrical distance of the lossy film becomes further insignificant and hence the film need not be considered in the analysis. The aim was to compute the electric field components near the metal surface on which the film was placed.

### 3.6 Advantage of Tangential Component of Electric Field for the Heating of Film on Metal Surface

Electric fields must satisfy boundary conditions on a perfect metal so that only the normal (\( y \)) component is non-zero. As well, the continuity conditions on an air-dielectric interface for normal and tangential components require that

\[
\varepsilon_0 E_{y0} = \varepsilon_1 E_{y1} \quad (3.33)
\]

\[
E_{x0} = E_{x1} \quad (3.34)
\]

The subscripts 0 and 1 refer to air and dielectric, respectively. Equation (3.33) shows that if the dielectric constant of the film is large then \( E_y \) in the film will be proportionally less than that in air, but the tangential component \( E_x \) will be unchanged.
Thus if the lossy dielectric (of loss tangent $\tan \delta$) is thin, the component of electric field tangential to the film surface will produce the most significant heat deposition through power loss given by $\omega \varepsilon_\perp E_x^2 \tan \delta$. For a dielectric film coated on a metallic surface, volumetric heating will be accomplished mainly by the tangential electric field, which must be zero on the metal surface. Heat deposition will necessarily be non uniform in depth with most heat deposited in the film close to the air-film boundary.

### 3.7 Electric Field Distribution in a Dielectric Loaded T-septum Waveguide Applicator

The finite element calculations have been performed for the dielectric loaded T-septum waveguide applicator shown in figure 3.1. The permittivity of the dielectric loading is chosen as 50 and the loading is placed inside the applicator in such a way that there is a 1 mm air gap above and below the loading. The tangential component of electric field ($E_x$) was calculated above the septum and plotted in figure 3.4. The figure shows the contours of tangential electric fields of equal magnitude. The contours are plotted for the region above the septum. It should be noted that when the dielectric loading was absent there was no tangential component of electric field; all the energy were stored in the normal electric component ($E_y$). When the dielectric material of high permittivity was loaded inside the applicator above the septum, an additional tangential component of electric energy was generated and the generated electric energy is responsible for the heating of the lossy film coated on the metal surface. It can be from the figure 3.4 that the tangential component of electric field is not concentrated on the middle of the upper portion of the applicator, but more uniformly spread along the x direction on the upper region of the waveguide septum. This uniform spread of the tangential electric field ensures uniform heating of the coated film on the metal.

### 3.8 Analysis of the Dielectric Loaded Waveguide Applicator

The microwave applicator shown in figure 3.1 consists of a rectangular waveguide with T-septum that is to be used to heat a lossy dielectric film placed near the top wall. A lossless dielectric material is supported above the T-septum and there are air gaps
between the dielectric and the metal surfaces.

The permittivity and thickness of the dielectric loading determines the strength of the tangential electric field $E_x$ within the upper air gap. Calculations done in the following analysis using the finite element method have shown that the maximum rms $E_x$ can be up to one tenth of that for $E_y$. When a high loss dielectric film (such as Titanium dioxide based paint with $\varepsilon_{rf} \geq 50$) is placed in the centre of gap $g_1$, the fractional component of $E_x$ electric energy inside the film compared to the total electric energy inside the waveguide cross section can be written as

![Calculated contour plots of the tangential component of electric field of equal magnitude. The permittivity of the lossless dielectric loading is 50. The tangential component is quite uniform along the x direction and hence can produce uniform heating of the lossy film coated on the top wall of the applicator above the septum. When the dielectric loading is removed the tangential component of electric field is absent.](image)

84
\[
\frac{E_{xf}^2}{E_{Tot}^2} = \frac{E_{xf}^2}{E_{xf}^2 + \left(\frac{E_{yf}}{\varepsilon_{rf}}\right)^2}
\]

where \(E_{Tot}^2\) is the rms total electric energy averaged over the cross section of the applicator and, \(E_{xf}^2\) and \(E_{yf}^2\) are the x component and y component respectively of the rms electric energy inside the high loss dielectric film. The factor \(\varepsilon_{rf}\) appears in the equation because of the continuity conditions of equations (3.37) and (3.38). Substituting \(E_y\) to be 10 times \(E_x\) and \(\varepsilon_{rf}\) as 50 results in

\[
\frac{E_{xf}^2}{E_{Tot}^2} = \frac{E_{xf}^2}{E_{xf}^2 + \left(10E_{xf}/50\right)^2} = 96\%
\]

Hence the tangential component of rms electric energy inside the high loss dielectric film increases by a dielectric loading and provide the major contribution to heating of the film. When the film is placed on the upper wall, the fractional x-component energy will necessarily be less because of the metal-film boundary condition. However, on the film-air boundary, there will remain significant tangential energy which will provide heating on the surface of the film. Exact analytical solutions are available [90] for the case of a rectangular waveguide loaded with a dielectric material and substitution of appropriate values in the analytical solution shows that a significant tangential electric field can be present close to the metal surface. To obtain a measure of heating efficiency in the film, the ratio

\[
R = \frac{\int_{\text{upper air gap}} \varepsilon_0 E_x^2 \, dv}{\int_{\text{total}} \varepsilon_r \left(E_x^2 + E_y^2\right) \, dv}
\]

(3.35)
is maximised by varying geometrical factors and dielectric constant. This maximises the $E_x$ energy component in the upper air gap relative to the total stored energy per unit length.

### 3.7 Results

#### 3.7.1 Effect of Variation of Thickness of the Dielectric Loading

The T-septum waveguide has been analysed for the following dimensions: $a=86$ mm, $b=43$ mm, $a_2=48$ mm, $a_3=24$ mm and $w=8$ mm. Calculations have been performed where the thickness of the dielectric loading has been varied with a fixed permittivity and T-septum height. A 1 mm gap is left at the top of the guide to allow room for the film. Studies are not conducted with varying air gap; 1 mm gap is chosen because it is very difficult to maintain a distance less than 1 mm and a gap more than 1 mm will decrease the heating effect that results due to the dielectric loading. Figure 3.5 shows the fractional component of electric energy in the $E_x$ field as the thickness of the dielectric material $t_2 \ (\varepsilon_r = 5)$ is varied from 1 mm to 11 mm. It can be seen that the amount of electric energy in the 1 mm gap which is responsible for heating the film increases as $t_2$ increases, but suddenly drops when the bottom of the dielectric touches the T-septum. When the dielectric loading touches the metallic wall of the T-septum, the air dielectric boundary which existed on the bottom of the dielectric loading is eliminated and hence the dielectric sheet effectively spreads the field. A narrow air gap $g_2$ of approximately 1 mm between the dielectric material and the T-septum is sufficient to provide a significant $E_x$ component.

#### 3.9.2 Effect of Variation of Permittivity of the Dielectric Loading

Calculations performed by varying the thickness and permittivity of the dielectric
loading with a fixed T-septum height are shown in figure 3.6. The results suggest that the maximum electric energy in $E_x$ occurs when the loading fills the region above the septum except for air gaps of widths approximately 1mm above and below, and has a relative permittivity in the range of 4 to 10. The relatively large value of $R$ corresponding to $\varepsilon_r = 1.0$ may have occurred because the tangential components of electric fields are averaged over the volume above the T-septum whilst the local value of this electric field component is mainly large at the T-septum edges.

3.9.3 Effect of Varying the T-septum Height

The effect of varying the height of the T-septum has been investigated. The air gaps $g_1$ and $g_2$ are fixed at 1 mm and the thickness of the dielectric loading is varied between
Figure 3.5  Numerical evaluation of the percentage of tangential energy in the upper air gap relative to the total energy as the thickness of the dielectric loading is varied. The septum height is 31 mm and the permittivity of the dielectric loading is 5. At point A the lossless dielectric is in contact with the T-septum.

10 and 1 mm by changing the height of the T-septum from 31 to 40 mm. The dielectric constant is varied from 1 to 50 and the design criterion R shown in equation (3.35) is calculated over the same volume in each case. The results are plotted in figure 3.7

Figure 3.6  Numerical evaluation of the percentage of tangential energy in the upper air gap relative to the total energy as the permittivity
of the dielectric loading is varied for two different thicknesses \((t_2)\). The upper air gap \((g_1)\) is 1 mm, and the T-septum height is 31 mm. The curves labelled \(R\) refer to the relative electric energy in equation (4.7) whilst those labelled \(E\) give the ratio of the rms tangential and normal electric field components in the air gap.

which shows that the \(E_x\) energy component in the upper air gap is highest for the highest septum. For a given septum height the presence of dielectric loading maximises the energy component provided the relative permittivity is in the range 4 to 10.
3.9.4 Effect of Nonlinear Distribution of Permittivity of the Dielectric Loading

Figure 3.7 Numerical evaluation of the percentage of tangential energy in the upper air gap relative to the total energy as the permittivity of the dielectric loading is varied for different T-septum heights (t₁). There are 1 mm air gaps above and below the dielectric sheet.
Here it can be demonstrated that the fractional component of electric energy in the $E_x$ field could further be improved by using a nonlinear distribution of permittivity of the dielectric loading instead of the linear distribution used in previous sections. The dielectric loading is symmetrically split into 6 equal parts with three different dielectric constant values $\varepsilon_1$, $\varepsilon_2$ and $\varepsilon_3$ as shown in figure 3.8.

### 3.9.4.1 Effect of Simultaneous Variation of Permittivity of Dielectric Loadings 1 and 2

Calculations have been performed to find the effect of varying the dielectric constants $\varepsilon_1$ and $\varepsilon_2$ of loadings 1 and 2 simultaneously from 1 to 50. The permittivity of the third loading ($\varepsilon_3$) is kept constant at 1. The dielectric materials are placed in such a way that there is an air gap of 1 mm above and below the dielectric loading and the height of the T septum are selected as 38 mm. The results are plotted in figure 3.9. It can be seen that the design criterion R increases and reaches a maximum value of 0.114% as $\varepsilon_1$ and $\varepsilon_2$ reach 11.

### 3.9.4.2 Effect of Variation of Permittivity of Dielectric Loading 3

Analysis is carried out by varying the permittivity of dielectric loading 3 ($\varepsilon_2$) from 1 to 5. The permittivity of loadings 1 and 2 are fixed at 1. The T septum height is again 38 mm and there is an air gap of 1 mm above and below the dielectric loadings. The results are shown in figure 3.10. The analysis shows that when the permittivity of loading 3 increases, the design criterion R decreases. So $\varepsilon_2 = 1$ is the best for a maximum performance in heating provided the permittivity of the loadings 1 and 2 are of value 1. A further improvement in R could be expected by increasing the permittivity of dielectric loadings 1 and 2, while keeping that of loading 3 at a minimum value of 1. These possibilities are analysed in the following sections.
3.9.4.3 Effect of Variation of Permittivity of Dielectric Loading 1

Calculations are performed by increasing the permittivity of dielectric loading 1 to a value of 100. The permittivity of loading 3 is kept at a minimum value of 1 and that of loading 2 at a reasonably high value of 6. The results are shown in figure 3.11. It can be seen that the design criterion $R$ increases as $\varepsilon_1$ increases from 12 and reaches a saturation point at $\varepsilon_1 = 40$ at a maximum $R$ value of 0.178%. This distribution of permittivity of the dielectric loading shows an improvement of the value of $R$ over the previous cases. Air gaps of 1 mm are again provided above and below the dielectric loadings and the height of the T septum is 38 mm.
Figure 3.9  Numerical evaluation of the percentage of tangential energy in the upper air gap relative to the total energy as the permittivity of the dielectric loadings 1 and 2 are simultaneously varied. The permittivity of the third material is kept constant at 1.

3.9.4.4 Effect of Variation of Permittivity of Dielectric Loading 2

From sections 3.6.4.2 and 3.6.4.3 it is obvious that a high value of $R$ is obtained when the permittivity of loading 1 is 22 or higher and that of loading 3 is at a minimum value.
of 1. Keeping $\varepsilon_1$ and $\varepsilon_3$ at these values, analyses have been carried out by varying the permittivity of loading 2 from 1 to 8. The dielectric loadings are again placed with an air gap of 1 mm above and below the dielectric materials and the height of the T septum is 38 mm. The results are shown in figure 3.12. It can be seen that R is the highest at a value of 0.205% when the permittivity of loading 2 is at a minimum value of 1. Further improvement could be obtained by adjusting the permittivity of dielectric loading 1 by

Figure 3.10 Numerical evaluation of the percentage of tangential energy in the upper air gap relative to the total energy as the permittivity of the dielectric loading 3 is varied. The permittivity of the loadings 1 and 2 are kept constant at a minimum value of 1.
Figure 3.11 Numerical evaluation of the percentage of tangential energy in the upper air gap relative to the total energy as the permittivity of the dielectric material 1 is varied. The permittivity of the dielectric loadings 2 and 3 are kept constant at 6 and 1 respectively. Calculations are performed by varying the permittivity of the loading 1 from 1 to 30 and results are shown in figure 3.13. It can be seen that the design criterion increases as $\varepsilon_1$ increases until it saturates at approximately 16.
Figure 3.12 Numerical evaluation of the percentage of tangential energy in the upper air gap relative to the total energy as the permittivity of the dielectric loading 2 is varied. The permittivity of the dielectric loadings 1 and 3 are kept constant at 22 and 1 respectively.

3.9.4.5 Effect of Variation of the T-septum Height for Nonlinear Dielectric Loading
The effect of varying the height of the T-septum height for a nonlinear distribution of permittivity of the dielectric loading has been investigated. The air gaps $g_1$ and $g_2$ are fixed at 1 mm and the thickness of the dielectric loading is varied from 3 to 1 mm by changing the height of the T-septum from 38 to 40 mm. The permittivity of dielectric loading 1 is varied from 1 to 30 and the design criterion $R$ is calculated over the same volume in each case. The permittivity of loadings 2 and 3 are kept at a minimum value of 1. The results are shown in figure 3.14, which indicates that the $E_x$ energy component in the upper air gap is highest for the highest septum. For a given septum height the dielectric loading maximises the energy component provided the permittivity of loading 1 is more than 10. The value of the design criterion is at a maximum of 0.25%, when the T-septum height is 40 mm. Also from figures 3.7 and 3.14, it can be clearly seen that a nonlinear distribution of permittivity increases the design criterion $R$ from a value of 0.092 % to 0.24 %, which is an increase of 160%, when the T-septum height is at 40 mm. Also in the latter case, $R$ remains high for a wider range of $\varepsilon_1$.

3.10 Concluding Remarks

There are several types of geometry in which it is difficult to use microwave power for heating. First type includes low loss dielectric materials in any configuration. The second type includes lossy dielectrics adjacent to metal surfaces on which the tangential component of electric field vanishes. Low loss dielectrics adjacent to metal surfaces comprise the third type. However, some progress has been made in the first category by using a transient wave applicator [Bhartia et. al. 1975] where heating is obtained incrementally for each transient wave (forward or reflected) which passes through the dielectric. A solution for the second type is proposed in this dissertation [Paul Antony and F.Paoloni, 1992]. The technique involves “pulling” the electric field away from the metal wall by placing a dielectric material of critical dimensions to maximise tangential component of the electric field on the film. The dielectric material which is placed in the waveguide has the effect of rearranging the electric field depending on the dimensions of the dielectric slab and its relative permittivity. Instead of a sine or cosine distribution which exists in the waveguide prior to the dielectric slab, the modified
electric field profile can be very high on the dielectric film, but quickly drops and vanishes at the wall.

Figure 3.13 Numerical evaluation of the percentage of tangential energy in the upper air gap relative to the total energy as the permittivity of the dielectric loading 1 is varied. The permittivity of the dielectric loadings 2 and 3 are kept at a minimum value of 1.

A dielectric loaded T-septum waveguide applicator has been proposed to heat lossy dielectric films. The major contribution to the heating is the electric field component
tangential to the film surface, which has been maximised by selecting the geometry and dielectric loading. Both linear and nonlinear distributions of dielectric loading have been investigated. The results suggest that a lossy film with high permittivity can be heated even if it is in contact with the upper metal surface of the waveguide. Calculations done using finite element method by varying the thickness of the dielectric

Figure 3.14 Numerical evaluation of the percentage of tangential energy in the upper air gap relative to the total energy as the permittivity of the dielectric loading 1 is varied for various T-septum heights ($t_1$). The dielectric loadings 2 and 3 are kept at a minimum value of 1 and there are 1 mm air gaps above and below the dielectric loading.
loading has shown that the maximum heating occurs when the dielectric loading fills the region above the septum except for air gaps of approximately 1 mm above and below. When the relative permittivity of the dielectric loading was varied, the maximum heating occurred at the value of the relative permittivity was in the range of 4 to 10. Also studies on the effect of the T-septum height showed that the highest heating occurred with the highest T-septum.

Performance can be further improved by using a nonlinear distribution of the permittivity of the dielectric loading. The dielectric loading was symmetrically split into 6 equal parts with three different dielectric constant values. Calculations were performed by varying the dielectric constants of each part. The effect of variation of the T-septum height for the nonlinear dielectric loading is also studied which showed that for the highest heating, the highest T-septum height is required. An improvement in performance in heating of 160% was obtained for the nonlinear dielectric loading over the linear dielectric loading for a T-septum height of 40 mm. The trend shows that an improved performance in heating could have been achieved by increasing the T-septum height above 40 mm. Any non uniform heating of the film due to the nonlinear dielectric loading can be solved by moving the film along the tangential direction of the waveguide applicator.
4.1 Introduction

It is well known that many materials absorb microwave radiation and produce heat. The heat is generated due to the imaginary component of the dielectric constant which can be due to either dielectric absorption or ohmic heating. A large amount of dielectric data for a wide variety of materials has been published in the literature [64, 65, and 66]. This type of heating is known as dielectric heating by which a large increase in temperature in materials can be obtained in a short period of time. Rapid heating using microwaves can be used for a wide variety of specialised applications. During the late forties and early fifties, a considerable attempt was made to obtain reliable data on material properties of many organic and inorganic materials pioneered by von Hippel [66]. Gourdenne [67, 68] used microwaves at 2450 MHz to cure a glass filled epoxy system. Williams [69] also investigated the curing of epoxy-impregnated pipe using microwaves. In addition to this large amount of data on material properties, significant developments in the design of magnetrons, power supplies and ancillary equipment have made microwave heating techniques more reliable.

The most important characteristic for the microwave heating of a material is the dipole moment, either locally (on the molecular chain) or for the entire molecule. Molecules without a complex dipole moment will not absorb microwave energy [70].

In this chapter, it is dealt with the practical implementation of the concept, discussed in detail in chapter 3, to heat a film of paint on a metal surface. A pilot model of the
applicator was made with polystyrene foam and aluminium tape to allow easy modification. This design was optimised for minimum reflected power by making standing wave as well as scattering parameter measurements. Using the optimised dimensions, a T-septum waveguide applicator was made of aluminium for high power applications. Low power performance was analysed by measuring scattering parameters using a Hewlett Packard Network Analyser 8720A and various characteristics were tabulated. High power performance was examined by using a 1.2 kW variable power magnetron source. It was shown that the complex problem of heating a film of paint on metal surface can be solved with the help of a dielectric loading placed underneath the paint. The temperature distribution in the paint was measured using a fibre optic temperature probe developed by the author and discussed in detail in Chapter 3. Measurements on the applicator have shown that the temperature of a lossy film painted on a metal surface can be increased by more than $40^\circ C$. The temperature rise is related to the thickness of the film and the position and permittivity of the low loss dielectric loading. A practical waveguide applicator was also proposed to heat painted metal sheet for industrial applications.

### 4.2 Dipolar loss mechanism

Dipolar polarisation is the most significant form of loss mechanism occurring in industrial heating applications at frequencies above 1 GHz. Absorption can be described by first breaking up the dielectric constant into real and imaginary part as

$$
\varepsilon^* = \varepsilon' - j\varepsilon''
$$

where $\varepsilon'$ is the dielectric constant associated with electromagnetic conduction and $\varepsilon''$ relates to the strength of absorption [70]. Both $\varepsilon'$ and $\varepsilon''$ are functions of frequency.

Absorption depends on how the dipoles respond to the oscillating electric field. At frequencies $\omega \ll \frac{1}{\tau}$, the dipoles have a more rapid motion than that of the electric field and absorption will not occur. $\tau$ is the relaxation time which indicates the amount of
time required for a collection of dipoles in an electric field to revert to a random orientation once the field is removed. At $\omega = \frac{1}{\tau}$, the dipoles and the electric field have the same frequency of motion, although the motions are not in phase with one another. The dipole response lags behind the electric field thereby causing energy transfer from the field to the material. At high frequencies when $\omega \gg \frac{1}{\tau}$, the dipoles can no longer respond quick enough to the electric field and absorption does not occur.

The ratio of the absorbing part to the non-absorbing part is called the loss tangent given by

$$\tan \delta = \frac{\varepsilon''(\omega)}{\varepsilon(\omega)}$$

(4.2)

The absorption is often referred to as dielectric loss and high loss tangent results in high absorption [70]. The power loss ($P_{\text{diss}}$) due to absorption can be written as

$$P_{\text{diss}} = \omega \varepsilon'' E^2 \tan \delta$$

(4.3)

4.3 Applicator Design for Heating a Film of Paint on a Metal Surface

4.3.1 Low Power Performance

4.3.1.1 Initial Design using Polystyrene Model

A 1 metre long waveguide applicator has been designed to heat a film of industrial enamel paint on a metal surface and is shown in figures 4.1, 4.2 and 4.3. The cross section of the middle of the applicator shown in figure 4.3 (section C C) consists of a T-septum waveguide of sides $a = 86$ mm and $b = 43$ mm. The height of the T-septum is $t_1 = 40$ mm with an air gap of $3\text{ mm (} g_1 + t_2 + g_2\text{)}$ above the septum and the upper
The width of the upper side of the T-septum \( a_2 = 48 \text{ mm} \) and the lower side \( a_3 = 24 \text{ mm} \) with arm thickness \( w = 8 \text{ mm} \). The dimensions of the waveguide are the same as those analysed numerically in chapter 3 (shown in figure 3.1). The height of the T-septum inside the waveguide is constant over the central 150 mm region of the applicator but is symmetrically tapered toward either end over a length of 400 mm (the elevation is shown in figure 4.1). The tapering of several wavelengths long is provided to minimise reflection of microwave energy for a source connected to either port. The top wall of the waveguide above the central region is removable and a film of paint can be coated on the inner side. As well, a sheet of alumina of thickness 1.6 mm (or any other dielectric) can be suspended a distance 0.3 mm above the flat portion of the septum.

A pilot model of the waveguide was constructed using polystyrene with aluminium tape wrapped around to simulate waveguide metal boundaries (a photograph is shown in figure 4.4). Polystyrene foam was selected because its dielectric constant is close to that of air \( (\varepsilon_r = 1.004) \). This model was ideal to select the dimensions of the waveguide as it is very easy to make modifications. Standing wave measurements have been done using a Hewlett Packard 8620C sweep oscillator, Marconi Instruments 6593 VSWR amplifier and a VSWR probe and are tabulated in Table 4.1 for a frequency range of 2.4 to 2.5 GHz. Measurements were taken with unloaded waveguide as well as loaded with dielectric and paint. It can be seen from the table that unloaded waveguide reflects only 2.2% of the power at 2.45 GHz. When loaded with dielectric and paint, the reflected power is still only 5.7%.

In order to quickly test the model, a Hewlett Packard Network Analyser 8720A was used as shown in figure 4.5. A wet paper was used instead of the paint as it was easy to
Figure 4.1 The T-septum waveguide applicator - section AA elevation.
Figure 4.2 The T-septum waveguide applicator - section BB.
(cross-section of the ends of the waveguide)
Figure 4.3  The T-septum waveguide applicator - section CC.
(cross-section of the middle of the waveguide)
Table 4.1 Standing wave measurements on polystyrene model of T-septum waveguide.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>VSWR</th>
<th>Power Reflection Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V</td>
<td>S11 (%)</td>
</tr>
<tr>
<td></td>
<td>GHz</td>
<td>(%)</td>
</tr>
<tr>
<td>Waveguide with no load</td>
<td>2.4</td>
<td>2.45 (2.2%)</td>
</tr>
<tr>
<td>Waveguide with paint</td>
<td>1.15</td>
<td>1.35 (1.12%)</td>
</tr>
<tr>
<td>Waveguide with dielectric</td>
<td>1.235</td>
<td>1.37 (1.165%)</td>
</tr>
<tr>
<td>and paint</td>
<td>1.775</td>
<td>1.625 (2.1%)</td>
</tr>
</tbody>
</table>

Table 4.2 Absorption characteristics using polystyrene model. Teflon is used as the dielectric to concentrate tangential electric field on to a thin wet paper (instead of paint) placed on the top metal wall of the waveguide.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>S11 (%)</th>
<th>Reflected Power (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unloaded Waveguide</td>
<td>4.57</td>
<td>2.14</td>
</tr>
<tr>
<td>Waveguide loaded with dielectric alone</td>
<td>5.21</td>
<td>2.28</td>
</tr>
<tr>
<td>Waveguide loaded with dielectric and wet paper</td>
<td>18.62</td>
<td>4.32</td>
</tr>
<tr>
<td>Waveguide loaded with wet paper alone</td>
<td>4.01</td>
<td>2.00</td>
</tr>
</tbody>
</table>
use in the delicate polystyrene model. Scattering parameter $S_{11}$ (reflection coefficient) and Smith Chart are measured for different conditions and shown in Appendix B. A representative example of the measured scattering parameters $S_{11}$ and $S_{21}$ of the polystyrene model is given in figures 4.6. From the scattering parameter $S_{11}$ obtained in dB, the percentage value is calculated and shown in Table 4.2. From the table, it can be noted that in the worst case, when loaded with dielectric and wet paper, the Power reflection coefficient is only 4.3%. It can be seen from tables 4.1 and 4.2 that both the standing wave measurements and the network analyser measurements agree to a considerable accuracy.
Figure 4.5  Set-up for the measurement of scattering parameters of the polystyrene model of the T-septum waveguide applicator using Hewlett Packard Network Analyser 8720A.

4.3.1.2  Aluminium Model

A waveguide was made of aluminium with the same dimensions as the polystyrene model so that high power could be applied (shown in figure 4.7). The top wall of the waveguide above the plane portion of the T-septum is made of a separate sheet of aluminium and is bolted in place to allow easy removal. Two pieces of copper braid are used to ensure electrical contact between this sheet and the applicator walls. Low power measurements were again done using the Hewlett Packard Network Analyser.

4.3.1.2.1  Effect of the Position of the Dielectric Loading

A thin sheet of alumina of thickness 1.6 mm and dielectric constant of approximately 9 is used to concentrate the tangential component of electric field onto a thin sheet of
lossy paint, coated on the top wall above the flat portion of the T-septum. The S-parameter measurements were performed on ports 1 and 2 at 2.45 GHz using Hewlett Packard 8720A Network Analyser and are shown in Appendix A. In the experimental setup, the waveguide applicator was fitted with two waveguide to coaxial converter, one on each side, so that the applicator could be connected to the ports of the network analyser. The two waveguide to coaxial converters are connected to each other without the applicator and the S-parameter measurements are again performed in this case, which is shown in Appendix A. The measurements show that 11.64% of microwave
Table 4.3  Effect of the position of the dielectric loading. Alumina of thickness 1.6 mm is used as the loading.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Absorbed Power (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No paint</td>
<td>9.53</td>
</tr>
<tr>
<td>Paint</td>
<td>13.25</td>
</tr>
<tr>
<td>No paint</td>
<td>18.58</td>
</tr>
<tr>
<td>Paint</td>
<td>36.07</td>
</tr>
<tr>
<td>Paint</td>
<td>17.11</td>
</tr>
</tbody>
</table>

Table 4.4  The effect of variation of permittivity of the dielectric loading on absorption of paint. Equal dimensions of Alumina of permittivity approximately 9 and Teflon of 2.1 were used for the analysis. Both dielectric loadings were placed 0.5 mm below the film.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Absorbed power (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumina of permittivity approximately 9 placed below the paint</td>
<td>36.07</td>
</tr>
<tr>
<td>Teflon of permittivity approximately 2.1 placed below the paint</td>
<td>14.3</td>
</tr>
</tbody>
</table>
Table 4.5. The effect of dryness of the paint on absorption. Alumina of thickness 1.6 mm is used as a dielectric loading and is placed 0.5 mm below the coated paint film of thickness approximately 0.1 mm.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Absorbed power (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet paint</td>
<td>36.07</td>
</tr>
<tr>
<td>Partially dry paint</td>
<td>20.85</td>
</tr>
</tbody>
</table>

Figure 4.7 Photograph of the aluminium model of the T-septum waveguide applicator. The metal plate in the centre of the applicator can be easily removed for coating the paint.
power is lost in the waveguide to coaxial converter. Table 4.3 provides some results examining the percentage of power lost between ports with different configurations. The calculated power lost can be correlated to the absorption of power in the paint. In this table, the power loss due to the waveguide to coaxial connector has already been subtracted to show the net power loss.

The results suggest that approximately 10% of the input power is dissipated in the waveguide. This high figure is most likely caused by the resistivity of the wall material (aluminium) and high wall currents in the vicinity of the septum. Transmission losses increases slightly when the dielectric loading alumina is present indicating small additional dielectric loss, but when the paint film is also present with an air gap of 0.5 mm between them, the loss increases to almost 36%. Thus a significant fraction of the input power is dissipated in the paint film. However, when the air gap between the paint and the dielectric loading is increased to 1.4 mm, the power loss decreased to a value of 17% showing the effect of the position of the dielectric loading. When the dielectric loading was removed and paint alone was present, the loss decreased to about 13% suggesting that only 3% of the power is absorbed in the paint.

4.3.1.2.2 Effect of Variation of Dielectric Constant

The effect of permittivity of the dielectric loading has been studied. Equal thicknesses (1.6 mm) of alumina of dielectric constant approximately 9 and Teflon of 2.1 were placed 0.5 mm below the coated paint film, one at a time. The S-parameter measurements were again performed on ports 1 and 2 at 2.45 GHz using the network analyser (shown in Appendix A). Table 4.4 shows results examining the percentage of power lost between ports with dielectric loadings of different permittivity.

Results shows that when Teflon loading of lower permittivity is used, the input power lost in the waveguide is approximately 14%, which is only slightly more than that with no dielectric loading present (refer Table 4.3), whereas when the Teflon is replaced with the alumina of higher permittivity the power loss is almost 36%. Thus a significant fraction of the input power is dissipated in the paint film when the permittivity of the dielectric loading is increased.
4.3.1.2.3 Effect of Dryness of Paint on Absorption

The effect on absorption of input power while the paint dries has been studied in this section. A dielectric loading (alumina) of thickness 1.6 mm was placed 0.5 mm below the coated paint film of thickness approximately 0.1 mm. S-parameter measurements were again performed on ports 1 and 2 at 2.45 GHz using the network analyser (shown in Appendix A). Table 4.5 provides results examining the percentage of power lost between ports with paints of different dryness.

Results suggest that approximately 36% of the input power is lost when the paint film is wet. When the paint film is allowed to dry partially, the input power absorbed in the system decreases to almost 21%.

4.3.2 High Power Performance

The high power performance of the T-septum waveguide applicator was examined using a 1.2 kW variable power magnetron source connected to one side of the applicator as shown in figure 4.7. A terminating load was connected to the other end so that no power was reflected back, hence preventing a standing wave forming in the T-septum. A film of paint of approximately 0.05 mm thick was coated inside the top wall of the waveguide above the flat portion of the septum. Microwave power was applied and the temperature on the painted metal surface was measured over time using a fibre optic temperature probe explained in chapter 2.

4.3.2.1 Effect of Position of the Dielectric Loading and Input Power

A thin sheet of alumina of thickness 1.6 mm has again been used as the dielectric loading and is placed below the paint film. The air gap between the film and the loading has been varied and the temperature measurement has been taken using the developed fibre optic probe for an input microwave power of 350 W. Results are shown in figure 4.8. It was found that when no dielectric loading was present there was a
Figure 4.8 The temperature rise in the paint film over time for different input powers and widths of the upper air gap (g1). The paint thickness is 0.1 mm.

temperature rise of only $2^0 C$ during a 16 minute period. When the alumina was placed 0.5 mm under the paint, the temperature rise was $11^0 C$ for the same microwave power. Application of higher microwave power was restricted when the T-septum waveguide applicator was not loaded with alumina because of arcing between the T-septum and the upper wall of the waveguide applicator. However, a microwave power of 1.2 kW could easily be applied when the alumina was present, resulting in a temperature rise of $20^0 C$. 
4.3.2.2 Effect of Variation of Paint Thickness

The effect of varying the paint thickness was studied using an input power of 1.2 kW and an air gap of 0.5 mm with alumina loading. In figure 4.9, the 0.02 mm thick paint film underwent only a $15^0C$ temperature rise whereas when the thickness was 0.25 mm the temperature rise was $42^0C$. Also, majority of the heating occurred in the first 3 to 4 minutes. When no paint was used, temperature rise was less than $5^0C$.

Since the paint film was in intimate thermal contact with the metallic upper wall of the applicator, the final measured temperature must have been an underestimate of the surface temperature of the paint. If air flow was maintained down the waveguide to remove the evaporated solvents, the film was 'touch dry' within two minutes of the application of power.

4.3.2.3 Temperature Distribution on the Paint

Information of the temperature distribution within the paint is essential in order to design an applicator to heat a painted metal uniformly. The developed fibre optic probe was again used for this purpose. Five rows of equally spaced holes of diameter 2 mm were drilled 20 mm apart on a sheet of aluminium with each row containing six holes. One side of the sheet is coated with a film of paint approximately 0.05 mm thick in such a way that the paint can be in contact with the temperature probe. The sheet was bolted to the applicator above the T-septum and microwave power of 1.2 kW was applied from one end of the applicator with a terminating load readings were taken. In order to ensure that the temperature probe does not heat by itself, the temperature probe was inserted in a region where there was no paint and it was found that it did not record any increase in temperature. The temperature distribution inside the paint is shown in figure 4.10. The results show that the temperature distribution inside the paint is quite uniform even though a higher temperature was observed in a region closer to the magnetron than that in a region further away. Also paint in the middle of the applicator parallel to the
Figure 4.9 The temperature rise in paint films of various thicknesses. The input power is 1.2 kW, the upper air gap width is 0.5 mm and the dielectric loading is alumina of thickness 1.6 mm.

line of propagation heated to a higher temperature relative to the edges. This probably might have occurred as the thermal mass of the metallic applicator wall is much higher than that of the film of paint and hence the heat generated in the paint near the applicator wall edges can be conducted away more rapidly that at the middle.

4.4 Design of a Practical Waveguide Applicator to Heat a Painted Sheet of Metal
A practical applicator is proposed in order to heat a long sheet of painted metal more uniformly. The design consists of two parallel T-septum waveguides interconnected using two waveguide corners as shown in figure 4.11. A magnetron is mounted at one end of the waveguide and a terminating load at the other. There is a flat T-septum in the centre of each waveguide. The waveguides are slowly tapered to both sides of several wavelengths long so that there is very little reflection of the microwave power. A painted sheet of metal is designed to move over the flat portion of each T-septum with the help of rollers. Low loss dielectric materials like alumina are loaded on the T-septums to concentrate the tangential component of electric field. Waveguide corners are designed to change the direction of microwave energy flow as shown in figure 4.11 [72]. Waveguide corners must be carefully designed to avoid impedance mismatches and to prevent voltage breakdown. Four microwave chokes were attached one on each side of the paint drying section, to prevent microwave leakage. Uniformity of microwave heating occurs as microwaves enter opposite sides of the paint in the two applicators.

### 4.4.1 Choke Design

The problem of designing a choke for a waveguide operating in the $TE_{10}$ mode is discussed in considerable detail by Ragan [72]. Since this mode is a symmetrical one, the current flow in the waveguide wall is of uniform density. The choke type most frequently used is shown in figure 4.12. The path lengths $l$ and $d$ in figure 4.12 are

\[ l = d = \frac{\lambda_g}{4} \]  \hspace{1cm} (4.4)

where $\lambda_g$ is the guided wavelength. In the design, the main waveguide is assumed to be terminated in its characteristic impedance $Z_0$. The input impedance of the branch lines can be made very small compared to $Z_0$ so the gaps will not present an appreciable mismatch to waves transmitted along the main line. This will be the case if
Figure 4.10 The measured contours of the temperature distribution of a paint film of thickness 0.05 mm using the developed fibre optic temperature probe. Alumina of thickness 1.6 mm is used as the dielectric loading and is placed 0.5 mm below the paint film. The contours on the middle of the left hand side have a higher magnitude than those on the right hand side.

the branch lines are made one half wave lengths long, since the input impedance for a half-wavelength line terminated in a short circuit is zero, neglecting losses.
Furthermore, in such a line section, the current is high at the short circuit, zero at a point
Figure 4.11 Proposed design of a practical T-septum waveguide applicator to heat painted metal
Figure 4.12 Choke design to stop microwave leakage for the proposed T-septum waveguide applicator to heat painted sheet of metal.
a quarter wavelength away and high again at the half-wavelength point. If the break in the branch lines is made at the quarter wavelength point, it will not be necessary to provide good contact since no current is flowing at that point. Additional microwave absorbers are placed in the far end of the choke to absorb any small leaks not blocked by the choke.

4.5 Concluding Remarks

Heating using microwave power is difficult to achieve in several types of geometry. First type includes low loss dielectric materials in any configuration. Lossy dielectric adjacent to metal surfaces on which the tangential component of electric field vanishes includes the second type and low loss dielectrics adjacent to metal surfaces comprise the third type. Some progress has been made in the first category by using a transient wave applicator [Bhartia et. al. 1975] where heating is obtained incrementally for each transient wave (forward or reflected) which passes through the dielectric. We propose a solution for the second type is proposed in this dissertation [Paul Antony and F.Paoloni, 1992]. The technique involves “pulling” the electric field away from the metal wall by placing a dielectric material of critical dimensions to maximise tangential component of the electric field on the film. The dielectric material which is placed in the waveguide has the effect of rearranging the electric field depending on the dimensions of the dielectric slab and its relative permittivity. Instead of a sine or cosine distribution which exists in the waveguide prior to the dielectric slab, the modified electric field profile can be very high on the dielectric film, but quickly drops and vanishes at the wall.

A dielectric loaded T-septum waveguide has been designed to heat lossy dielectric films. The design is based on the observation by numerical analysis that a dielectric loading placed below the film has the ability to concentrate the tangential component of electric field on the film. A polystyrene model of the applicator was initially designed using polystyrene and aluminium tape to replace air and metal respectively to determine the optimum geometry for minimum reflection of incident energy, as this type of construction is easily modified. Using the dimensions obtained, an applicator was made of aluminium. S-parameter measurements using a network analyser indicates that a lossy film of high permittivity can absorb significant amount of microwave power even
if it is in contact with the upper metal surface of the waveguide applicator. The maximum absorption of microwave energy on the film occurs when the dielectric loading is closer to the paint. Effect of variation of dielectric constant of the dielectric loading has also been studied. Higher absorption of microwave power in the film occurs when the loading has a higher permittivity. The effect of dryness of the paint on the amount of absorption was also studied.

High power performance of the applicator was conducted by applying microwave power up to 1.2 kW. Temperature measurements on the paint were carried out using a developed fibre optic temperature probe which indicated that the maximum absorption of microwave energy on the paint occurred when the dielectric loading was closer to the paint as predicted. A temperature rise of $11^0C$ was measured when the air gap between the dielectric loading and the paint was 0.5 mm when a microwave power of 350 W was applied. A rise of only $5^0C$ was observed when the air gap was 2.3 mm for the same microwave power. With the application of 1.2 kW of microwave power, a 0.25 mm thick film of paint underwent a temperature rise of $42^0C$ but a rise of only $19^0C$ was observed when the thickness of the paint was 0.1 mm. The application of the higher power was restricted when the applicator was not loaded with alumina because of arcing between the T-septum and the upper wall of the waveguide applicator, whereas a microwave power of 1.2 kW could easily be applied when the alumina was present. Temperature distribution inside the paint was measured which shows that the heating of the paint film was quite uniform even though a higher temperature was observed in a region closer to the magnetron. A practical waveguide applicator was also proposed for the industrial heating of long sheets of painted metal.
5.1 Introduction

In the previous chapters studies were conducted only at a microwave frequency of 2.45 GHz as this is the most established used frequency of microwave heating. Other microwave frequencies commonly used are 915 MHz and 434 GHz [77]. However these frequencies have inherent non-uniformity problems like hot spots and thermal run away. Variable Frequency Microwave (VFM) technique is a new technique [92] developed to solve this problem of inherent in the fixed frequency. In this technique rapid, uniform and selective heating is accomplished by using a preselected bandwidth of frequencies sweeping around a central frequency. There are three series of VFM facilities produced by the manufacturers namely VW1500, Microcure 2100, Microcure 5100. In the Industrial Research Institute, Swinburn University of Technology, there are two sets of VFM facilities VW1500 and Microcure 2100 [93] and both these facilities are used in these studies. VW1500 has a bandwidth range of 6-18 GHz at a nominal power of 125 W with cavity dimensions 250 mm x 250 mm x 300 mm (figure 5.1). The Microcure 2100 has cavity size of 300 mm x 275mm x 375 mm with frequency bandwidth of 2-7 GHz at a power of 250W (figure 5.2).

5.2 VFM Facilities

5.2.1 Interaction of VFM Fields
When fixed frequency microwave energy say 2.45 GHz is launched in to a cavity containing a material, some areas of the material would have higher electric field strength than the other areas. Areas with higher electric strength are heated more creating hot spots which eventually lead to thermal run away. When variable frequencies are used, as more than one thousand frequencies are launched into the cavity sequentially, each incident frequency sets up its own electric field pattern and therefore results in hot spots generated at different locations at different time intervals, resulting in different areas

![Variable Frequency Microwave (VFM) facilities VW1500 from Lambda Technologies Inc.](image)

Figure 5.1  Variable Frequency Microwave (VFM) facilities VW1500 from Lambda Technologies Inc.

heating at different times. Hence time averaged uniform heating can be achieved with proper selection of sweep frequency and range.

5.2.2  Hardware of Microcure 2100

The Microcure 2100 has many more advanced control subsystems compared to VW1500. The subsystems [93] consist of curing cavity, oven control
system, signal generator and high power amplifier system, transmission system, and fibre optic based temperature monitoring system as shown in figure 5.3.

5.2.2.1 Curing Cavity

The curing cavity is the metal enclosure where microwave processing of material takes place. The cavity contained four pass through ports for fibre optic temperature probes. The samples being processed was supported off the bottom of the cavity floor at a minimum distance of 20 mm by a suitable microwave transparent material such as Teflon block [93].

5.2.2.2 Oven Control System

Oven control is driven by software. It supervises and controls the Microcure operations. A personal computer serves as the central control system and data collection. It also
interfaced with all the subsystems of the facility. It has a graphical user interface that maintains the input and output functions of the VFM facility.

5.2.2.3 Signal Generator and High Power Amplifier

Unlike most microwave ovens where the microwave source is a magnetron, Microcure 2100 uses a Yig oscillator. It also has a voltage control attenuator, PC data acquisition and VFM interface board [93]. It generates all the system’s low level microwave energy and controls all the system’s high level energy. The high power amplifier (HPA) amplifies the low level microwave energy generated from the signal generator section to levels high enough to provide adequate molecular excitation in the curing cavity. The HPA consists of a travelling wave tube, a high voltage power supply, and a solid state amplifier that serves as an intermediate power amplifier, and control logic. It communicates with the PC using an RS-232C serial communication link.

5.2.2.4 VFM Safety Printed Circuit Board (PCB)

This is a stand alone device which senses the high level microwave energy in the transmission system and also monitors the cavity door safety interlocks and all the other high level radio frequency (RF) safety interlocks. If the system detects a dangerous level of energy in the transmission system while the interlock was tripped or the cavity over heated, PCB activates the interlock line in the HPA. This stops the high level microwave energy produces until a safe condition was selected [93].

5.2.2.5 Transmission System

The transmission system routes the high power microwave energy from the HPA to the cavity. It consists of a high power isolator, a dual directional coupler (combined with crystal detectors to provide power sampling for the system), waveguide, and an iris-style launcher.

5.2.2.6 Temperature Monitoring System
Two types of temperature monitoring systems were available for the Microcure 2100. A single channel fibre optic measurement system was provided as standard. This included a fibre optic probe to be placed in contact with the surface of the material that is monitored. An additional 3 (4 total) fibre optic channels were also installed. It also has a second temperature device comprising of an infrared non-contact temperature measurement unit that provided specific surface temperature reading without making physical contacts with the materials being processed.

5.2.2.7 Software System

5.2.2.7.1 Introduction

The Microcure 2100 system software controls all the functions of the Microcure 2100. However, most of the functions were controlled by a combination of manual and software controls. The main screen shown in figure 5.3 [93] is grouped into three main categories: status displays, quantitative displays, and controls. The utilities and the event menus are the two most important ones and are described in more detail below.

5.2.2.7.1.1 Utilities Menu

Characterisation and graphics are the two most important sub-menus under the utilities menu. The characterisation menu is used to measure the characteristics of the cavity when the sample was loaded. Also it can be seen graphically how the cavity performed over the operating frequency range. The input power selected depends on the estimated loss tangent of the material. Higher the estimated loss, lower was the power level selected. During the characterisation of the loaded cavity, the variation in temperature and incident power as well as reflected power can be monitored.
5.3 Heating Characterisation of Paints using VFM

Only one microwave frequency of 2.45GHz was used in developing applicators discussed in the previous chapters for heating paints. However when paints with large surface areas are used, these can create hot spots which results in thermal run away. When large bandwidth of microwave frequencies are used this problem of hot spots can be reduced and more time averaged microwave heating can be achieved. So prior to
building special microwave applicators with variable frequency, it is advantageous to do a heat characterisation the paints used using VFM.

5.3.1 Characterisation of Different Paints

Four totally different types of paints that includes water based, oil based and even resin are studied. The samples selected are Solar Acrylic, Polyester Resin, Wattyl Instant Estapol and Metal Gloss Polypropylene as shown in figure 5.4. Before a study of the temperature characteristics of paints with time can be made, a number of parameters need to be understood like how the paints loaded in the cavity behave with input microwave power at various frequencies. These include the microwave central frequency used, frequency bandwidth, sweep time, input and reflected power, maximum temperature etc. So power frequency characteristics have been done prior to temperature characteristics measurement. Also studies were conducted with paints of three different thicknesses (1.5 mm, 1.0 mm and 0.05 mm). Temperature characterisation was also done in different power outputs of 30W, 60W and 90W and all the above studies were done in the VW1500 with frequency range of 6.5GHz to 18GHz and Microcure 2100 with frequency range of 2.5GHz to 8GHz VFM facilities.

5.3.1.1 Requirements of the Power - Frequency Characterisation

When microwave power is induced into the loaded cavity, a portion of the power is absorbed inside the cavity and a portion of the power is reflected back from the cavity. In order to do the characterisation of the loaded material, measurements need to be done on the forward microwave power $P_f$, the reflected power $P_r$, percentage of reflected power or the reflection coefficient $R_c$ with various frequency $f$ needed to be measured. Also the microwave power is proportional to the temperature increase in the material $\Delta T$ and inversely proportional to incremental time $\Delta t$ to reach this increase in temperature. It is also essential to make sure that there is minimal reflected power $P_r$ and the power level as low as possible so that there is no change in the material structure of the loaded material. It is also noted that higher uniformity in heating occurs when higher the bandwidth of microwave frequencies used and higher the sweep rate of
the frequency of the microwave source. However there are limitations in using higher bandwidths as at some frequencies the reflected microwave power is very high. At

Figure 5.4 The samples selected for the characterisation (Solar Acrylic, Polyester Resin, Wattyl Instant Estapol and Metal Gloss Polypropylene) using the Variable Frequency Microwave (VFM) facilities from Lambda Technologies Inc.

higher bandwidth of frequencies the VFM facility may not have the capacity to have higher sweep rates. So it is essential to identify optimal values of these parameters.

5.3.2 Power - Frequency Characterisation of Paints using VW1500 VFM Facility

The total operational bandwidth for VW1500 is from 6.5 GHz to 18 GHz. For keeping the reflected power low, the characterisation bandwidth is split into four equal parts namely 6.5 GHz to 9.375 GHz, 9.375 GHz to 12.25 GHz, 12.25 GHz to 15.125 GHz, 15.125 GHz to 18 GHz. For each quarter of the operational bandwidth three tests were
performed to make sure effect of position was not large and spectra for each test were very similar and average power in each region is approximately 60W.

5.3.2.1 Power - Frequency Cavity Characterisation of VW1500VFM Facility with Teflon

Prior to making measurements to characterise various paints, characterisation of the cavity with a block of Teflon is done. Teflon is used because it is a microwave transparent material and it is used to support off the various paints from the bottom of the cavity floor at a minimum distance of 20 mm. Again the operational bandwidth has been divided into four equal parts and it was found with trial and error that the forward power of approximately 60W through out the entire bandwidth can be achieved if forward powers were set at 21W at 6.5 GHz, 103W at 9.38 GHz in the first section of the bandwidth, 83W at 9.38 GHz and 40W at 15.13GHz at the second section, 76W at 12.25 GHz and 40W at 15.13 GHz in the third section, and 105W at 15.13 GHz and 21W at 18 GHz. The forward power $P_f$, the reflected power $R_c$ and the calculated reflected power ($R_e$) are shown in figure 5.5. Polynomial approximation of both forward power and reflected power are also calculated and plotted for clarity.

5.3.2.2 Power - Frequency Characterisation of Solar Acrylic Paint using VW1500 VFM

Measurements are carried out to characterise Solar Acrylic paint using VW1500 VFM, by placing three samples of the paint on the block of Teflon. Again the operational bandwidth has been divided into four equal parts and by trial and error it was found that the forward power of approximately 60W through out the entire bandwidth can be achieved if forward powers were set at 26W at 6.5 GHz, 94W at 9.38 GHz in the first section of the bandwidth, 83W at 9.38 GHz and 42W at 15.13GHz at the second section, 76W at 12.25 GHz and 42W at
Figure 5.5 Power Frequency Characteristics of the Variable Frequency Microwave (VFM) facility VW1500 with Teflon. $P_f$ is the forward power, $(P_f)$ is smoothened using polynomial approximation for clarity, $P_r$ is the reflected power, $R_c$ is the reflected power and $(R_c)$ is smoothened by polynomials.

15.13 GHz in the third section, and 107W at 15.13 GHz and 8W at 18 GHz. The forward power $P_f$, the reflected power $P_r$ and the calculated reflected power $P_r$ are shown in figure 5.6. Polynomial approximation of both forward power and reflected power are also calculated and plotted.
5.3.2.3 Power - Frequency Characterisation of Polyester Resin using VW1500 VFM

Measurements are carried out to characterise Polyester Resin using VW1500 VFM, by placing three samples of the paint on the block of Teflon. Again the operational bandwidth has been divided into four equal parts and by trial and error it was found that the forward power of approximately 60W through out the entire bandwidth can be achieved if forward powers were set at 27W at 6.5 GHz, 94W at 9.38 GHz in the first section of the bandwidth, 83W at 9.38 GHz and 41W at 15.13GHz at the second section, 75W at 12.25 GHz and 40W at 15.13 GHz in the third section, and 107W at 15.13 GHz.
and 10W at 18 GHz. The forward power $P_f$, the reflected power $P_r$ and the calculated reflected power $\overline{P}_r$ are shown in figure 5.7. Polynomial approximation of both forward power and reflected power are also calculated and plotted.

![Power Frequency Characteristics](image)

Figure 5.7  Power Frequency Characteristics of Polyester Resin using the Variable Frequency Microwave (VFM) facility VW1500. Samples are placed on a block of Teflon. $P_f$ is the forward power, $(P_f)$ is smoothened using polynomial approximation for clarity, $P_r$ is the reflected power, $R_c$ is the reflected power and $(R_c)$ is smoothened by polynomials.

**5.3.2.4 Power - Frequency Characterisation of Wattyl Instant Estapol using VW1500 VFM**
Measurements are carried out to characterise Wattyl Instant Estapol using VW1500 VFM, by placing three samples of the paint on the block of Teflon. Again the operational bandwidth has been divided into four equal parts and by trial and error it was found that the forward power of approximately 60W through out the entire bandwidth can be achieved if forward powers were set at 27W at 6.5 GHz, 95W at 9.38 GHz in the first section of the bandwidth, 83W at 9.38 GHz and 40W at 15.13GHz at the second section, 75W at 12.25 GHz and 50W at 15.13 GHz in the third section, and 107W at 15.13 GHz and 10W at 18 GHz. The forward power $P_f$, the reflected power $P_r$ and the calculated reflected power $P_r$ are shown in figure 5.8. Polynomial approximation of both forward power and reflected power are also calculated and plotted.

5.3.2.5 Power - Frequency Characterisation of Metal Gloss Polypropylene using VW1500 VFM

Measurements are carried out to characterise Metal Gloss Polypropylene paint using VW1500 VFM, by placing three samples of the paint on the block of Teflon. Again the operational bandwidth has been divided into four equal parts and by trial and error it was found that the forward power of approximately 60W through out the entire bandwidth can be achieved if forward powers were set at 26W at 6.5 GHz, 95W at 9.38 GHz in the first section of the bandwidth, 83W at 9.38 GHz and 41W at 15.13GHz at the second section, 75W at 12.25 GHz and 44W at 15.13 GHz in the third section, and 107W at 15.13 GHz and 9W at 18 GHz. The forward power $P_f$, the reflected power $P_r$ and the calculated reflected power $P_r$ are shown in figure 5.9. Polynomial approximation of both forward power and reflected power are also calculated and plotted.
5.3.3 Power - Frequency Characterisation of Paints using Microcure 2100 VFM Facility

Now the experimental study conducted in the section 5.3.2 was repeated using Microcure 2100 VFM facility. The total operational bandwidth for Microcure 2100 VFM facility has an operational bandwidth from 2 GHz to 8 GHz. It also has a much more sophisticated control system so that the whole study can be done in one sweep unlike VW1500 VFM facility. Tests were done to identify operating parameters so that the average power in the cavity is
Figure 5.9 Power Frequency Characteristics of Metal Gloss Polypropylene using the Variable Frequency Microwave (VFM) facility VW1500. Samples are placed on a block of Teflon. $P_f$ is the forward power, $(P_f)$ is smoothened using polynomial approximation for clarity, $P_r$ is the reflected power, $R_c$ is the reflected power and $(R_c)$ is smoothened by polynomials.

approximately 60W. Three samples of the paint were simultaneously placed to eliminate the effect of the position of the sample in the cavity as shown in figure 5.10.

5.3.3.1 Power – Frequency Cavity Characterisation of Microcure 2100 VFM Facility with Teflon

Prior to making measurements to characterise various paints, characterisation of the cavity with a block of Teflon is done as before. Teflon is once again used because it is a microwave
Figure 5.10 Placement of samples to study the Power Frequency Characteristics using the Variable Frequency Microwave (VFM) facility Microcure 2100. Three samples are placed on a block of Teflon and measurements are averaged to eliminate the effect of the positions of the samples.

transparent material as it is used in the following experiments to support off the various paints from the bottom of the cavity floor at a minimum distance of 20 mm. The rest of the experiments are conducted using the same Teflon so that the variation in the results due to the variation of distance from the bottom of the cavity can be eliminated. Also as the frequency bandwidth of the microwave are varied, the variation in results due to the position of the three samples are very negligible. The forward power is selected as 60W. The forward power $P_f$, the reflected power $P_r$ and the calculated reflected power $P_r$ are shown in figure 5.11. Polynomial approximation of both forward power and reflected power are also calculated and plotted as before.
Figure 5.11 Power Frequency Characteristics of the Variable Frequency Microwave (VFM) facility Microcure 2100 with Teflon.  $P_f$ is the forward power, $(P_f)$ is smoothened using polynomial approximation for clarity, $P_r$ is the reflected power, $R_c$ is the reflected power and $(R_c)$ is smoothened by polynomials.

5.3.3.2 Power - Frequency Characterisation of Solar Acrylic Paint using Microcure 2100 VFM

Measurements are carried out to characterise Solar Acrylic paint using Microcure 2100 VFM, by placing three samples of the paint on the block of Teflon. Again the forward power is selected as 60W. The forward power $P_f$, the reflected power $P_r$ and the calculated reflected power $P_r$ are shown in figure 5.12. Polynomial approximation of both forward power and reflected power are also calculated and plotted.
Figure 5.12  Power Frequency Characteristics of Solar Acrylic paint using the Variable Frequency Microwave (VFM) facility Microcure 2100. Samples are placed on a block of Teflon. $P_f$ is the forward power, $(P_f)$ is smoothened using polynomial approximation for clarity, $P_r$ is the reflected power, $R_c$ is the reflected power and $(R_c)$ is smoothened by polynomials.

5.3.3.3  Power - Frequency Characterisation of Polyester Resin using Microcure 2100 VFM

Measurements are carried out to characterise Polyester Resin using Microcure VFM, by placing three samples of the Polyester Resin on the block of Teflon. Again the forward power is selected as 60W. The forward power $P_f$, the reflected power $P_r$ and the calculated reflected power $P'_r$ are shown in figure 5.13. Polynomial approximation of both forward power and reflected power are also calculated and plotted.
Figure 5.13  Power Frequency Characteristics of Polyester Resin using the Variable Frequency Microwave (VFM) facility Microcure 2100. Samples are placed on a block of Teflon. \( P_f \) is the forward power, \( (P_f) \) is smoothened using polynomial approximation for clarity, \( P_r \) is the reflected power, \( R_c \) is the reflected power and \( (R_c) \) is smoothened by polynomials.

### 5.3.3.4 Power - Frequency Characterisation of Wattyl Instant Estapol using Microcure 2100 VFM

Measurements are carried out to characterise Wattyl Instant Estapol using Microcure 2100 VFM, by placing three samples of the Estapol on the block of Teflon. The forward power once again is selected as 60W. The forward power \( P_f \), the reflected power \( P_r \) and the calculated reflected power \( P_r \) are shown in figure 5.14. Polynomial approximation of both forward power and reflected power are also calculated and plotted.
Figure 5.14 Power Frequency Characteristics of Wattyl Instant Estapol using the Variable Frequency Microwave (VFM) facility Microcure 2100. Samples are placed on a block of Teflon. $P_f$ is the forward power, $(P_f)$ is smoothened using polynomial approximation for clarity, $P_r$ is the reflected power, $R_c$ is the reflected power and $(R_c)$ is smoothened by polynomials.

5.3.3.5 Power - Frequency Characterisation of Metal Gloss Polypropylene Paint using Microcure 2100 VFM

Measurements are carried out to characterise Metal Gloss Polypropylene paint using Microcure 2100 VFM, by placing three samples of the polypropylene paint on the block of Teflon. Again the forward power is 60W and the forward power $P_f$, the reflected power $P_r$.
Figure 5.15 Power Frequency Characteristics of Metal Gloss Polypropylene using the Variable Frequency Microwave (VFM) facility Microcure 2100. Samples are placed on a block of Teflon. $P_f$ is the forward power, $(P_f)$ is smoothened using polynomial approximation for clarity, $P_r$ is the reflected power, $R_c$ is the reflected power and $(R_c)$ is smoothened by polynomials.

and the calculated reflected powers $P_r$ are shown in figure 5.15. Polynomial approximation of both forward power and reflected power are also calculated and plotted.

5.3.4 Temperature Characterisation of Paints
The Power – Frequency characteristics obtained from section 5.3.3 is most useful in conducting temperature characterisation of paints. When doing temperature characterisation it is essential to make sure that the power reflected from the cavity is minimal. In order to get uniform heating, both the frequency bandwidth used and the frequency sweep rate is as high as possible so that the time averaged uniform heating can be achieved. But these two parameters contradict to each other as one parameter can be increased at the expense of the other due to the limitation of electronics and microwave source. So it is necessary to obtain optimal values for the frequency bandwidth and sweep rate and this can be identified from the Power – Frequency characteristic obtained before. The other parameters need to note in doing temperature characteristics are power output, initial temperature, final temperature, processing time.

Temperature characteristics were done for all the four sets of paints, Solar Acrylic, Polyester Resin, Wattyl Instant Estapol and Metal Gloss Polypropylene studied before. Also the studies were done on both VW1500 and Microcure 2100 VFM facilities. Also experiments were conducted with two different power levels, 30W and 60W in the case of VW1500 VFM facility and 60W and 90W for Microcure 2100 VFM facility. Also studies were done on three different thicknesses of each paint sample (1.5 mm, 1.0 mm and 0.5 mm). For Teflon substrates were used and paints were painted on it at various thicknesses. For each experiment, once again three samples of each paint were placed at various location of the oven as shown in figure 5.16 to prevent errors occurring due to location of placement of the sample and the average values are taken.

5.3.4.1 Temperature Characterisation of Solar Acrylic Paint using VW1500 VFM

Temperature characteristics of the Solar Acrylic paint were done for three different thickness 1.5 mm, 1.0 mm and 0.5 mm and two different input power levels 30W and 60W and are shown in figure 5.17. In the figure T1 represents thickness of the paint of 1.5 mm; T2 represents thickness 1.0 mm and T3 thickness 0.5 mm. Also 30 represents 30W power level and 60 represents 60W power level. As an example T1_30 means a sample of thickness 1.5 mm and microwave power level used is 30W.
Figure 5.16 Placement of samples to study the Power Frequency Characteristics using the Variable Frequency Microwave (VFM) facility Microcure 2100. Three different thicknesses of each sample are painted on a Teflon substrate which in turn is placed on a block of Teflon and measurements are averaged to eliminate the effect of the positions of the samples.

For both 30W and 60W power inputs, the central frequency used in the experiment was 12.25 GHz and the frequency bandwidth is 5.75 GHz. The sweep time was 1 sec and the processing time was set at 10 minutes.

The flat portion of the curve represents the stabilised region for microwave processing of the sample. In the case of T1_30, it can be seen that the stability is achieved at above 300 seconds where as in the case of T1_60 is obtained at around 500 seconds. Also higher heating also takes place when power is increased from 30W to 60W. If compared between, T1_60,
Figure 5.17 Temperature Characteristics of Solar Acrylic paint using the Variable Frequency Microwave (VFM) facility VW1500. T1, T2, T3 represents thicknesses 1.5 mm, 1.0 mm and 0.5 mm of the paints and 30 and 60 represents the input microwave powers of 30W and 60W. For example T1_30 represents a paint of thickness 1.5 mm and applied input power of 30W.

T2_60 and T3_60, it can be seen that for the same power level, when the thickness were 1.5 mm and 1.0 mm, the characteristics remains quite the same, but when the thickness is decreased to 0.5 mm, the heating decreased considerably. This is very consistent with the theories we explained in previous chapters.

5.3.4.2 Temperature Characterisation of Polyester Resin using VW1500 VFM

Temperature characteristics of the Polyester Resin were done for three different thickness 1.5 mm, 1.0 mm and 0.5 mm and two different input power levels 30W and 60W as before and are shown in figure 5.18. In the figure T1 represents thickness of the
paint of 1.5 mm; T2 represents thickness 1.0 mm and T3 thickness 0.5 mm. Also 30 represents 30W power level and 60 represents 60W power level.

Figure 5.18 Temperature Characteristics of Polyester Resin using the Variable Frequency Microwave (VFM) facility VW1500. T1, T2, T3 represents thicknesses 1.5 mm, 1.0 mm and 0.5 mm of the paints and 30 and 60 represents the input microwave powers of 30W and 60W. For example T1_30 represents a paint of thickness 1.5 mm and applied input power of 30W.

For 30W power input, the central frequency used in the experiment is 12.25 GHz and the frequency bandwidth is 5.75 GHz. The sweep time was 1 sec and the processing time was set at 10 minutes. In the case of 60W power input, the central frequency used in the experiment is 13.5 GHz and the frequency bandwidth is 4.55 GHz. The sweep time was 1 sec and the processing time was set at 10 minutes. The bandwidth in the case of 60W power has to be limited as there is large reflected energy at lower frequencies.
It can be noted that the samples are not adequately stabilised compared to the previous case with solar acrylic paint and thermal run away may be possible. There is considerable increase in heating as the thickness of the sample increases as well as the input power increases.

### 5.3.4.3 Temperature Characterisation of Wattyl Instant Estapol using VW1500 VFM

Temperature characteristics of the Wattyl Instant Estapol were done for three different thickness 1.5 mm, 1.0 mm and 0.5 mm and two different input power levels 30W and 60W and are shown in figure 5.19. In the figure T1 represents thickness of the paint of 1.5 mm; T2 represents thickness 1.0 mm and T3 thickness 0.5 mm. Also 30 represents 30W power level and 60 represents 60W power level.

For both 30W and 60W power inputs, the central frequency used in the experiment was 12.25 GHz and the frequency bandwidth is 5.75 GHz. The sweep time was 1 sec and the processing time was set at 10 minutes

It can be noted that the samples are not adequately stabilised compared to the previous case and thermal run away may be possible when power increased. To process this material efficiently, it should be noted from the figure that the thickness of the material and power levels should be kept at a minimum.

### 5.3.4.4 Temperature Characterisation of Metal Gloss Polypropylene Paint using VW1500 VFM

Temperature characteristics of the Metal Gloss Polypropylene paint were done for two different thickness 1.5 mm and 1.0 mm and two different input power levels 30W and 60W and are shown in figure 5.20. In the figure T1 represents thickness of the paint of 1.5 mm, and T2
Figure 5.19 Temperature Characteristics of Wattyl Instant Estapol using the Variable Frequency Microwave (VFM) facility VW1500. T1, T2, T3 represents thicknesses 1.5 mm, 1.0 mm and 0.5 mm of the paints and 30 and 60 represents the input microwave powers of 30W and 60W. For example T1_30 represents a paint of thickness 1.5 mm and applied input power of 30W. T2_30 represents thickness 1.0 mm. Also 30 represents 30W power level and 60 represents 60W power level.

For both 30W and 60W power inputs, the central frequency used in the experiment was 12.25 GHz and the frequency bandwidth is 5.75 GHz. The sweep time was 1 sec and the processing time was set at 10 minutes.

It can be noted from the figure that the thickness of the material is 1.5 mm and power level 30W the material adequately stabilised very quickly.
Figure 5.20 Temperature Characteristics of Metal Gloss Polypropylene using the Variable Frequency Microwave (VFM) facility VW1500. T1, T2, T3 represents thicknesses 1.5 mm, 1.0 mm and 0.5 mm of the paints and 30 and 60 represents the input microwave powers of 30W and 60W. For example T1_30 represents a paint of thickness 1.5 mm and applied input power of 30W.

5.3.4.5 Temperature Characterisation of Solar Acrylic Paint using Microcure 2100 VFM

This time, the temperature characteristics of the Solar Acrylic paint were done using Microcure 2100 for three different thickness 1.5 mm, 1.0 mm and 0.5 mm and two different input power levels 60W and 90W and are shown in figure 5.23. In the figure T1 represents thickness of the paint of 1.5 mm; T2 represents thickness 1.0 mm and T3 thickness 0.5 mm. Also 60 represents 60W power level and 90 represents 90W power level. As an example T1_60 means a sample of thickness 1.5 mm and microwave power level used is 60W.
Figure 5.21 Temperature Characteristics of Solar Acrylic paint using the Variable Frequency Microwave (VFM) facility Microcure 2100. T1, T2, T3 represents thicknesses 1.5 mm, 1.0 mm and 0.5 mm of the paints and 30 and 60 represents the input microwave powers of 30W and 60W. For example T1_30 represents a paint of thickness 1.5 mm and applied input power of 30W.

For both 60W and 90W power inputs, the central frequency used in the experiment was 5.75 GHz and the frequency bandwidth is 2.25 GHz. The sweep time was 0.1 sec and the processing time was set at 600 seconds.

The flat portion of the curve represents the stabilised region for microwave processing of the sample. It can be seen very clearly that at higher thickness of 1.5 mm, the sample stabilised very quickly at around 60 secs irrespective of the power level. But when the thickness of the material was below 1.5 mm proper stabilisation is not achieved.
5.3.4.6 Temperature Characterisation of Polyester Resin using Microcure 2100 VFM

Temperature characteristics of the Polyester Resin were done for three different thickness 1.5 mm, 1.0 mm and 0.5 mm and two different input power levels 30W and 60W as before and are shown in figure 5.22. In the figure T1 represents thickness of the paint of 1.5 mm; T2 represents thickness 1.0 mm and T3 thickness 0.5 mm. Also 60 represents 60W power level and 90 represents 90W power level.
For both 60W and 90W power inputs, the central frequency used in the experiment was 5.75 GHz and the frequency bandwidth is 2.25 GHz. The sweep time was 0.1 sec and the processing time was set at 600 seconds.

It can be noted that the samples are not adequately stabilised and there is higher chances for thermal run away at a higher power of 90W.

5.3.4.7 Temperature Characterisation of Wattyl Instant Estapol using Microcure 2100 VFM

Temperature characteristics of the Wattyl Instant Estapol were done for three different thickness 1.5 mm, 1.0 mm and 0.5 mm and two different input power levels 30W and 60W and are shown in figure 5.23. In the figure T1 represents thickness of the paint of 1.5 mm; T2 represents thickness 1.0 mm and T3 thickness 0.5 mm. Also 60 represents 60W power level and 90 represents 90W power level.

For both 60W and 90W power inputs, the central frequency used in the experiment was 5.75 GHz and the frequency bandwidth is 2.25 GHz. The sweep time was 0.1 sec and the processing time was set at 600 seconds.

It can be noted that when the thickness of the material is as small as 0.5 mm and at a low power of 60W the material stabilises at around 2 minutes. Thermal run away might occur if the material thickness or the power input increased.

5.3.4.8 Temperature Characterisation of Metal Gloss Polypropylene Paint using Microcure 2100 VFM

Temperature characteristics of the Metal Gloss Polypropylene paint were done for two different thickness 1.5 mm and 1.0 mm and two different input power levels 60W and 90W and
Figure 5.23 Temperature Characteristics of Wattyl Instant Estapol using the Variable Frequency Microwave (VFM) facility Microcure 2100. T1, T2, T3 represents thicknesses 1.5 mm, 1.0 mm and 0.5 mm of the paints and 30 and 60 represents the input microwave powers of 30W and 60W. For example T1_30 represents a paint of thickness 1.5 mm and applied input power of 30W.

are shown in figure 5.24. In the figure T1 represents thickness of the paint of 1.5 mm, and T2 represents thickness 1.0 mm. Also 60 represents 60W power level and 90 represents 90W power level.

For both 60W and 90W power inputs, the central frequency used in the experiment was 5.75 GHz and the frequency bandwidth is 2.25 GHz. The sweep time was 0.1 sec and the processing time was set at 600 seconds.
Figure 5.24 Temperature Characteristics of Metal Gloss Polypropylene using the Variable Frequency Microwave (VFM) facility Microcure 2100. T1, T2, T3 represents thicknesses 1.5 mm, 1.0 mm and 0.5 mm of the paints and 30 and 60 represents the input microwave powers of 30W and 60W. For example T1_30 represents a paint of thickness 1.5 mm and applied input power of 30W.

It can be noted from the figure that the thickness of the material is 0.5 mm and at a lower power level 60W the material adequately stabilised very quickly.

5.4 Concluding Remarks

Microwave heating is generally established using a single microwave frequency of 2.45 GHz. However these frequencies have inherent non-uniformity problems like hot spots and thermal run away. A new technique called Variable Frequency Microwave (VFM) technique [92] has been used to solve this problem of inherent in the fixed frequency by
using a preselected bandwidth of frequencies sweeping around a central frequency. As more than one thousand frequencies are launched into the cavity sequentially, each incident frequency sets up its own electric field pattern at different locations at different time intervals, a time averaged uniform heating can be achieved with proper selection of sweep frequency and range. So prior to building special microwave applicators with variable frequency, it is advantageous to do characterisation the paints used using VFM.

Power Frequency Characterisation was conducted using two different types of VFM facilities. Four totally different types of paints that includes water based, oil based and even resin are included in the study. The samples selected are Solar Acrylic, Polyester Resin, Wattyl Instant Estapol and Metal Gloss Polypropylene. Also studies were conducted with the paints with three different thicknesses (1.5 mm, 1.0 mm and 0.05 mm). Temperature characterisation was also done in two different power outputs of 30W, 60W and 90W and all the above studies were done in both the VW1500 with frequency range of 6.5GHz to 18GHz and Microcure 2100 facilities with frequency range of 2.5GHz to 8GHz VFM facilities.

After analysing the diagrams and data collected it was found that all different materials behaved in a different way to parameters like thickness, power input, bandwidth frequency and sweep time. From the results the sweep frequency, bandwidth and input power can be appropriately selected for uniform heating of different materials. Results also showed that special care should be taken when designing a microwave applicator with variable frequency for heating various materials and VFM facility is a very useful tool to identify these parameters and design an applicator for most favourable conditions so that hot spots and thermal run away can be avoided for specific materials.
Chapter 6

A Novel Y-Septum Waveguide Applicator for Single Mode Microwave Heating

6.1 Introduction

Waveguides are commonly used as applicators for industrial microwave heating of lossy dielectric materials [77]. The frequencies used for industrial microwave heating are 2450 MHz, 915 MHz and 434 MHz [77]. The penetration depth of microwave power inside a load increases with decreasing frequencies [77]. In order to effectively utilise microwave energy, the bulk of material should be penetrated, which requires relatively low frequency. Even though power absorbed into the load decreases with decreasing frequency, to maintain the same heating rate at lower frequencies, it would be necessary to increase the field intensity to the limit of arcing.

For the same power applied, a single mode waveguide applicator will establish much higher electric field strength than a multimode waveguide applicator [78] and for this reason the former is most useful for the treatment of low loss dielectrics. These fundamental mode waveguide applicators are in general more compact with extremely high power densities ($107\frac{KW}{m^2}$). Furthermore, a single mode waveguide applicator is capable of transferring more power from the generator onto the dominant mode than a multimode waveguide applicator.

Waveguides of rectangular or circular cross section are generally used as single mode applicators. A ridged waveguide applicator is used to increase the value of electric field in the vicinity of the work load and was used for continuous flow heating of extruded rubber [77]. Bleackley et al. [79] have presented various configurations of ridged structures, where electric field around the ridge was increased to enhance the coupling of microwave energy to a low loss web material. This resulted in a more compact
applicator than the equivalent structure without ridges, which gave good coupling of
energy for drying narrow strips of glue. A T-septum applicator has also been proposed
[80] which is suitable of microwave heating of materials and is more compact than a
ridge waveguide applicator.

6.2 Existing Waveguide Applicators and their Problems in Microwave
Single Mode Heating of Small Film Loads

Waveguides, because of their properties of low attenuation, small radiation loss, simple
structure, and high power capability, are used extensively for transferring high intensity
microwaves. In applications such as single mode heating of small materials such as a
film of paint, these applicators are bulky at low frequencies.

From waveguide theory, the cut-off wavelength $\lambda_c$ is $2a$ for a rectangular waveguide
($\lambda_c$ is independent of $b$ for the dominant mode) where $a$ is the width of the guide and
$b$ is the height as shown in figure 6.1 (a). As an example, at microwave frequencies
2450 MHz, 915 MHz and 434 MHz, rectangular waveguides of width at least 80 mm,
220 mm, 450 mm and height 40 mm, 110 mm, 225 mm respectively are needed (in
practice, a waveguide is designed with a cut-off frequency approximately 30% less than
the operating frequency for minimum attenuation) Work is in progress on waveguides
of different structures to allow reduced size. Ridged waveguides [81, 82] were
developed as a result of this research as shown in figure 6.1 (b). This type of
waveguides has some advantages over the conventional rectangular waveguide. It has a
lower cut-off frequency and wider bandwidth for the same width rectangular waveguide.
Because of its higher bandwidth, it is suited for single mode microwave heating. When
a microwave frequency at 520 MHz is to be used with the ridged waveguide, the width
$a$ of the waveguide has to be 205 mm and the height $b$ 92 mm (for $t/b = 0.3$, $b/a = 0.45$
and $s/a = 0.5$) [83], which is 45 percent smaller than the rectangular waveguide that
would have to be used. A significant improvement in the ridged waveguide can be
obtained by changing the shape of the ridge into a T-shaped septum. This was
suggested by Mazumder and Saha [86] in their preliminary analysis of a double T-
septum wave guide, which showed a decrease in the cut-off frequency of the dominant
Figure 6.1(a) Rectangular waveguide (b = 0.5 a) and (b) single ridged waveguide.

mode, and an increase in the bandwidth when compared with the conventional ridged guides with the same geometries. If a double T-septum waveguide is used at 520 MHz, its width a would be 178 mm and the height b 89 mm, (for b/a = 0.5, t/b = 0.3, and s/a =
0.5), which is 13 percent smaller than the ridged waveguide, and 52 percent smaller than the rectangular waveguide. This is a tremendous improvement in reduction of the size.

In the following sections, finite element analysis [45] was used to analyse the T-septum waveguide and the results were compared with the known analytical results.

6.3 A Novel Y-septum Waveguide Applicator for Microwave Heating of Thin Film

A novel Y-septum waveguide applicator is proposed. This Y-septum applicator can further reduce the size of the waveguide compared to a T-septum applicator as well as a ridged applicator for the same cut-off frequency. It will be shown that the Y-septum waveguide applicator has a higher cut-off wavelength (at least 68% larger than that of a T-septum waveguide applicator as seen in figures shown later) and bandwidth (65% larger than that of a T-septum waveguide applicator) for the dominant mode. This type of waveguide could be used in microwave heating of thin films coated on metal surfaces and would be superior to other types of waveguides for single mode heating because of the higher bandwidth which reduces the possibility of forming higher modes. Analysis comparing a T-septum waveguide and a Y-septum is shown in the following sections.

6.4 Analysis of Proposed Y-septum Waveguides

The geometry of a Y-septum waveguide is shown in figure 6.2. Two symmetrical portions are assumed for the waveguides and analysis is done by considering one of the half sections formed by introducing a plane, as shown by the dashed line in the figure. The aspect ratio of the half section is \( \frac{2b}{a} \). When using the finite element method to analyse these two types of waveguides, due to symmetry, only one-half of the waveguide is needed to be analysed.

It is assumed that the waveguide is made of perfect conductors and the boundary conditions require that the tangential electric field vanish on a metallic boundary and normal magnetic field vanish on a magnetic boundary. The computer code based on the
finite element formulation gives an output which contains eigen values and corresponding eigen vectors, beginning with the dominant mode. The eigen values are called the cut-off wave numbers and eigen vectors are the corresponding field distribution

Figure 6.2 Proposed Y-septum waveguide of (a) positive angle and (b) negative angle.
6.5 Cut-off Wavelength and Extended Bandwidth Capabilities of T-septum and Proposed Y-septum waveguides

One of the important properties of waveguides is their bandwidth, which is the frequency range over which single-mode propagation is ensured. The useful bandwidth is the separation of the cut-off frequencies between $TE_{10}$ and $TE_{20}$ modes. In the study of waveguides, however, the term bandwidth is customarily defined as the ratio of the cut-off wavelengths of the fundamental mode and the next higher mode, i.e,

$$BW = \frac{\lambda_{c_{10}}}{\lambda_{c_{20}}} = \frac{f_{c_{20}}}{f_{c_{10}}}$$  \hspace{1cm} (6.1)

where $\lambda_{c_{10}}$ is the cut-off wavelength for the $TE_{10}$ mode, and $\lambda_{c_{20}}$ that of the $TE_{20}$ mode.

By solving the eigen value of the waveguide, the cut-off wavelength will be determined.

The normalized cut-off wavelengths of $TE_{10}$, $TE_{20}$ and bandwidth characteristics of a T-septum waveguide were calculated and plotted as a function of s/a, with t/b as a parameter. The aspect ratio b/a for these curves is fixed at 0.25, w/a = 0.1 and w'/b = 0.05. Figure 6.3 is shown as an example and is obtained by finite element method explained in chapter 3. From the figure, it is evident that there is agreement between the published values [87] and the calculated values of the finite element program.

It should be noted from figure 6.3 (a) that the cut-off wavelength of $TE_{10}$ mode increases monotonically with s/a for fixed t/b. The peaks of the bandwidth curves are shifted toward higher values of s/a. If a T-septum waveguide is designed with s/a in the range between 0.4 and 0.7, the advantages of both longer cut-off wavelength and wider bandwidth will be appreciated.
6.5.1 Properties of Y-septum Waveguides

In figures 6.4 and 6.5, the normalized cut-off wavelengths of the $TE_{10}$ and $TE_{20}$ modes are plotted for a Y-septum waveguide, with $\theta = 10^0$, as a function of $s/a$ for various $t/b$ ranging from 0.1 to 0.4. The aspect ratio $b/a = 0.25$, $w/a = 0.1$ and $w'/b = 0.05$. It should be noted by comparing figures 6.4 and 6.3 (a) that the cut-off wavelength increases more rapidly for a Y-septum waveguide than for a T-septum waveguide. When $s/a = 0.7$ and $t/b = 0.1$ the cut-off wavelength of a Y-septum waveguide is 68.8% longer than that of a T-septum waveguide. This means that for the same cut-off frequency, the Y-septum waveguide will be much smaller in size compared to a T-septum guide. The bandwidth characteristic is shown in figure 6.6. It should be noted comparing with figure 6.3 (b) that the Y-septum waveguide has a bandwidth 64.9% greater than that of a T-septum guide of similar size when $s/a = 0.7$ and $t/b = 0.1$. These calculations obviously demonstrate the advantages of a Y-septum waveguide over a T-septum waveguide.

6.5.2 Analysis of Y-septum Waveguides with Different Septum Angles

Figure 6.2 (b) shows a negative Y-septum waveguide with septum angle $\theta = -10^0$. In figures 6.7-6.15 the normalized cut-off wavelengths of $TE_{10}$ and $TE_{20}$ modes and the bandwidth characteristics are plotted as a function of $s/a$ for different septum angles $\theta$. The aspect ratio $b/a = 0.25$, $w/a = 0.1$ and $w'/b = 0.05$. Figures 6.7, 6.10 and 6.13 indicate that as the septum angle $\theta$ increases from $-10^0$ to $+10^0$, the cut-off wavelengths for the dominant mode also increases. In this study, interest is only in a trend and hence studies were not conducted above $+10^0$ or below $-10^0$. The septum angle is chosen arbitrarily between $-10^0$ to $+10^0$ because we only need to find a trend on how bandwidth characteristics and cut-off wavelength behave when the septum angle is changed. The increase in cut-off wavelength is highly predominant for larger $s/a$. The bandwidth characteristics shown in figures 6.9, 6.12 and 6.15 also show that the bandwidth increases as the septum angle $\theta$ increases. The increase in bandwidth is again predominant for larger values of $s/a$. It should be appreciated that with $s/a$
ranging from 0.4 to 0.7, there is an advantage in larger cut-off wavelength as well as bandwidth with the septum angle $\theta$ close to $10^0$. When the septum angle $\theta$ becomes zero the Y-septum becomes a T-septum waveguide. When $\theta$

![Graph](image)

Figure 6.3  (a) Variation of normalised cut-off wavelength ($\frac{\lambda_{c10}}{a}$) of dominant TE$_{10}$ mode with gap width ratio (s/a) of a T-septum wave guide  (b) Variation of bandwidth ($\frac{\lambda_{c10}}{\lambda_{c20}}$)
characteristics with gap width ratio \((s/a)\) of the T-septum wave guide.

is less than \(10^0\), the advantages of higher cut-off wavelength and bandwidth are not only lost but also worse compared to a T-septum waveguide.

6.6 Comparison of Waveguides

In this section an example is furnished to show how to use the curves presented in the previous sections when a Y-septum waveguide is designed as an applicator at a microwave frequency of 2450 MHz. The results of the
Figure 6.4 Variation of normalised cut-off wavelength ($\lambda_{c10}/a$) of dominant TE$_{10}$ mode with gap width ratio (s/a) of a Y-septum waveguide with septum angle $\theta = +10^\circ$.

eample will then be compared with T-septum, ridged and rectangular waveguides for which the same frequency is used. The advantages of the Y-septum waveguide are discussed through the comparison.

Figure 6.5 Variation of normalised cut-off wavelength ($\lambda_{c20}/a$) of TE$_{20}$ mode with gap width ratio (s/a) of a Y-septum waveguide with septum angle $\theta = +10^\circ$.

Suppose a microwave power of 2450 MHz is to be used with a $TE_{10}$ mode
in a Y-septum waveguide. As the minimum attenuation of the power occurs in the vicinity of \( f = \sqrt{3} f_c \), the cut-off frequency is chosen to be \( \sqrt[3]{3} \) times the microwave source frequency,

\[
\lambda_{c10}/\lambda_{c20}
\]

Figure 6.6 Variation of bandwidth (\( \lambda_{c10}/\lambda_{c20} \)) characteristics with gap width ratio (s/a) of a Y-septum waveguide with septum angle \( \theta = +10^\circ \).

the cut-off frequency is then

\[
f_c = \frac{f}{\sqrt{3}} = \frac{2450}{\sqrt{3}} = 1415.5 MHz
\]

or \( \lambda_c = 211.9 \) mm. The waveguide parameters may be chosen as b/a = 0.25, t/b = 0.1, s/a = 0.7, w/a = 0.1 and w'/b = 0.05. The dimensions and the properties of the Y-septum
guide can be determined from the figures presented in earlier sections. From figure 6.4 it can be found that $\lambda_{c10} = 13.5$, which yields $a = 15.70$ mm, $b = 7.85$ mm, $s = 10.99$ mm, $t = 0.785$ mm, $w = 1.57$ mm, $w' = 0.785$ mm.

Figure 6.7 Variation of normalised cut-off wavelength ($\lambda_{c10}/a$) of dominant TE10 mode with gap width ratio $(s/a)$ of a Y-septum waveguide of gap height ratio $(t/b = 0.2)$ for various septum angles ($\theta$).
Figure 6.8 Variation of normalised cut-off wavelength ($\lambda_{c20}/a$) of TE$_{20}$ mode with gap width ratio (s/a) of a Y-septum waveguide of gap height ratio (t/b = 0.2) for various septum angles ($\theta$).
Figure 6.9  Variation of bandwidth ($\lambda_{c10}/\lambda_{c20}$) characteristics with gap width ratio (s/a) of a Y-septum waveguide of gap height ratio (t/b = 0.2) for various septum angles ($\theta$).

The bandwidth of the waveguide is found from figure 6.6 as:

$$\frac{\lambda_{c10}}{\lambda_{c20}} = 14.5$$
Figure A.10 Variation of normalised cut-off wavelength ($\lambda_{c10}/a$) of dominant TE$_{10}$ mode with gap width ratio ($s/a$) of a Y-septum waveguide of gap height ratio ($t/b = 0.3$) for various septum angles ($\theta$).
Figure 6.11 Variation of normalised cut-off wavelength ($\lambda_{c20}/a$) of TE$_{20}$ mode with gap width ratio (s/a) of a Y-septum waveguide of gap height ratio (t/b = 0.3) for various septum angles ($\theta$).

In order to compare the advantages of the Y-septum guide applicator with those of the T-septum applicator and the rectangular applicator, calculations were made on the T-septum guides (from figures 6.3 and 6.4) and the rectangular guides with identical cut-off frequency and aspect ratio. The results are listed in Table 6.1. The parameters compared are size and bandwidth. The values in percentages are the corresponding parameters normalised to those of the rectangular waveguide applicator. It is obvious
Figure 6.12 Variation of bandwidth ($\lambda_{c10}/\lambda_{c20}$) characteristics with gap width ratio ($s/a$) of a Y-septum waveguide of gap height ratio ($t/b = 0.3$) for various septum angles ($\theta$).

from the table that the Y-septum waveguide applicator is much smaller than a T-septum or rectangular waveguide applicators with the same cut-off frequency. The cross-sectional area of the Y-septum waveguide applicator is only 4.4 percent of the rectangular waveguide applicator and 35 percent of the T-septum waveguide applicator. A 95.6 percent improvement in reducing the space has been achieved over the rectangular waveguide applicator and 65 percent over the T-septum waveguide applicator. The bandwidth of the Y-septum applicator is more than 7 times as wide as the rectangular applicator and 1.7 times that of the T-septum applicator.
Figure 6.13 Variation of normalised cut-off wavelength ($\lambda_{c_{10}}/a$) of dominant TE$_{10}$ mode with gap width ratio ($s/a$) of a Y-septum waveguide of gap height ratio ($t/b = 0.4$) for various septum angles ($\theta$).
Figure 6.14 Variation of normalised cut-off wavelength ($\lambda_{c20}/a$) of TE$_{20}$ mode with gap width ratio ($s/a$) of a Y-septum waveguide of gap height ratio ($t/b = 0.4$) for various septum angles ($\theta$).
Figure 6.15 Variation of bandwidth ($\lambda_{c10}/\lambda_{c20}$) characteristics with gap width ratio (s/a) of a Y-septum waveguide of gap height ratio (t/b = 0.4) for various septum angles ($\theta$).
Table 6.1. Comparison of three types of wave guides at a microwave frequency of 2450 MHz

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Y-septum</th>
<th>T-septum</th>
<th>Rectangular</th>
</tr>
</thead>
<tbody>
<tr>
<td>b/a = 0.25</td>
<td>s/a = 0.7</td>
<td>t/b = 0.1</td>
<td>w/a = 0.1</td>
</tr>
<tr>
<td>s/a = 0.7</td>
<td>t/b = 0.1</td>
<td>w/a = 0.1</td>
<td>w/b = 0.05</td>
</tr>
<tr>
<td>t/b = 0.1</td>
<td>w/a = 0.1</td>
<td>w/b = 0.05</td>
<td>θ = 10°</td>
</tr>
<tr>
<td>w/a = 0.1</td>
<td>w/b = 0.05</td>
<td>θ = 10°</td>
<td></td>
</tr>
<tr>
<td>w/b = 0.05</td>
<td>θ = 10°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ψ = 10°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size (mm²)</td>
<td>a x b</td>
<td>15.70 x 7.85</td>
<td>26.49 x</td>
</tr>
<tr>
<td>Normalized</td>
<td>4.39%</td>
<td>12.50%</td>
<td>100%</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>λ&lt;sub&gt;ε=10^3&lt;/sub&gt;λ&lt;sub&gt;ε=20&lt;/sub&gt;</td>
<td>14.5</td>
<td>8.5</td>
</tr>
<tr>
<td>Normalized</td>
<td>72.5%</td>
<td>425%</td>
<td>100%</td>
</tr>
</tbody>
</table>

6.7 Concluding Remarks

A novel Y-septum waveguide applicator ideal for single mode microwave heating of small loads like film of paint is proposed, which has a much higher cut-off wavelength and bandwidth compared to existing waveguide applicators such as a rectangular, ridged or T-septum waveguide applicators. Also its high bandwidth characteristics are appreciable to ensure single mode heating when the dielectric properties of the load vary during processing. It is shown that for a septum angle of 10°, the proposed Y-septum waveguide applicator has the cut-off wavelength 68.8% larger than that of a T-septum waveguide applicator of the same dimensions. Also it is shown that the bandwidth of the proposed Y-septum waveguide applicator is 64.9% larger than a T-septum waveguide applicator of the same cut-off frequency.

Calculations performed comparing the rectangular, T-septum, and Y-septum waveguide applicators have shown that the cross-sectional area of the Y-septum waveguide applicator is only 4.4% of the rectangular waveguide applicator and 35% of that of the T-septum waveguide applicator. A 95.6% improvement in reducing the space has been
achieved over the rectangular waveguide applicator and 64% over the T-septum waveguide applicator. The bandwidth of the Y-septum waveguide applicator is more than 7 times as wide as the rectangular waveguide applicator and 1.7 times that of the T-septum waveguide applicator.

Further studies on the Y-septum waveguides may include the consideration of two or more septa on one or both sides of the waveguides, and loading the guide with dielectrics, which would further improve the characteristics of the waveguide. Y-septum applicator can be expected to have regions of better uniform field distribution compared to a T-septum guide. The uniformity in the field distribution probably could be controlled by adjusting the septum angle.
Conclusions

The work described in this thesis aimed at the possibility of heating a lossy dielectric film coated on a metal surface using microwaves, development of a simple and inexpensive fibre optic temperature probe for the measurement of temperature in the microwave environment. Also thesis looks at the possibility of characterising materials using Variable Frequency Microwave facility to have an understanding of how materials behave to variable frequency sweeping around a central frequency so that a time averaged uniform heating can be achieved, which can assist in building applicators of special design.

Heating a lossy dielectric film coated on metal surface using microwaves is a difficult problem because the tangential component of electric field is absent on the metal surface. No relevant literature is available in the solution of the problem. So the major goal of this thesis is to find an answer to this difficult problem. In pursuit of this goal, it has been necessary to first understand numerical techniques like finite element method, which then could be used to solve the Helmholtz equation for dielectric loaded applicators of different shapes. The finite element method formulation of dielectric loaded waveguides by Csendes and Silvester was used for the analysis of the problem. The application of the method on a dielectric loaded T-septum waveguide has revealed that an additional tangential component of electric field can be created above the septum for the dominant mode when loaded with a dielectric material of high permittivity. The tangential component of electric field was absent when there was no dielectric loading. The distribution of the generated tangential component of electric field was also plotted for a dielectric loading of permittivity 50.
A novel concept of heating a lossy dielectric film coated on a metal surface using microwaves by loading an additional dielectric material of high permittivity below the film is proposed. The major contribution to the heating is the generated tangential component of electric field by the additional dielectric loading, which has been maximised by selecting the geometry and the dielectric loading. Both linear and nonlinear distributions of the dielectric loading have been investigated. The results indicate that a lossy film with high permittivity can be heated even if it is in contact with the upper metal surface of the waveguide applicator. Calculations using finite element method varying the thickness of the dielectric loading have shown that the maximum heating occurs when the dielectric loading fills the region above the septum except for air gaps of approximately 1 mm above and below. When the relative permittivity of the dielectric loading was varied, the maximum heating occurred when the value of the relative permittivity was in the range of 4 to 10. Also studies on the effect of the T-septum height showed that the highest heating occurred with the highest septum.

Performance can be further improved by using a nonlinear distribution of the permittivity of the dielectric loading. The dielectric loading was symmetrically split into 6 equal parts with three different dielectric constant values. Calculations were performed by varying the dielectric constant of each part. The effect of variation of the T-septum height for the nonlinear dielectric loading is also studied which showed that for the highest heating, the highest T-septum height is required. An improvement in performance in heating of 160% was obtained for the nonlinear dielectric loading over the linear dielectric loading for a T-septum highest of 40 mm. Any non uniform heating of the film due to the nonlinear dielectric loading can be solved by moving the film along the tangential direction of the waveguide applicator.

Based on the results obtained by numerical analysis a dielectric loaded T-septum waveguide applicator has been constructed to heat lossy dielectric films coated on a metal surface. A polystyrene model of the applicator was initially designed using polystyrene and aluminium tape to replace air and metal respectively to determine the optimum geometry for minimum reflection of incident energy, as this type of construction can be easily modified. Using the dimensions obtained, an applicator was
made of aluminium. S-parameter measurements using a network analyser indicate that a lossy film of high permittivity can be heated even if it is coated on the upper metal surface of the waveguide applicator. The maximum absorption of microwave energy on the film occurs when the dielectric loading is closer to the paint. Effect of variation of dielectric constant of the dielectric loading has also been studied. Higher absorption of microwave power in the film occurs when the loading has a higher permittivity. The effect of dryness of the paint on the amount of absorption was also studied.

High power performance of the applicator was conducted by applying microwave power up to 1.2 kW. Temperature measurements on the paint were carried out using a developed fibre optic temperature probe, which indicated that the maximum absorption of microwave energy on the paint occurred when the dielectric loading was closer to the paint as predicted. A temperature rise of 11°C was measured when the air gap between the dielectric loading and the paint was 0.5 mm when a microwave power of 350 W was applied. A rise of only 5°C was observed when the air gap was 2.3 mm for the same microwave power. With the application of 1.2 kW of microwave power, a 0.25 mm thick film of paint underwent a temperature rise of 42°C when the dielectric loading was placed 0.5 mm below the paint, but a rise of only 19°C was observed when the thickness of the paint was 0.1 mm. The application of the high power was restricted when the applicator was not loaded with alumina because of arcing between the T-septum and the upper wall of the waveguide applicator, whereas a microwave power of 1.2 kW could easily be applied when the alumina was present. The temperature distribution inside the paint was measured which shows that the heating of the paint film was quite uniform even though a higher temperature was observed in a region closer to the magnetron. A practical waveguide applicator was also proposed for the industrial heating of long sheets of painted metal.

A simple fibre optic temperature measuring probe has been developed to measure temperature in the microwave environment. As fibre optic cables are electrical insulators and information transmitted along them is not affected by normal electrical interference, they can be used in situations where very high voltages are present, unlike the traditional thermocouple temperature measuring probes which, being electrical conductors, have limited use in this type of environment. The developed fibre optic probe is particularly suitable for monitoring the operating temperature of large power
transformers, alternators, switch gear, in-situ temperature measurements in microwave ovens and RF heaters, temperature measurements involving radioactive materials, applications in explosive and highly inflammable environments as they are based on a non-electrical operation, highly corrosive environments, because of their structural nature, biomedical applications, and temperature control in liquefying explosive gases at low temperature. Unlike commercially available fibre optic devices currently on the market, the developed fibre optic temperature probe uses an inexpensive standard multimode fibre that transmits signal pulses to the sensor. Variations in temperature are measured straight from a PIN diode. As the device can be manufactured very cheaply, applications such as temperature measurement in domestic microwave ovens become commercial possibilities; while more advanced models could be used for control and monitoring of industrial processing. This device could also be used in refrigeration applications.

A basic principle behind the operation of the developed temperature sensing system is discussed, together with the structure and construction of two versions of the temperature probe, one using 50/125 micron fibre and the other using 200 micron fibre. Temperature characteristics of both versions have been experimentally determined and a fibre optic thermal switch has been constructed. It was shown that the temperature range of the probe could be predicted, if certain parameters of the fibre as well as the sensing material were known. A computer board which is capable of handling the nonlinearities of the temperature characteristics of the fibre optic probe was constructed to display the temperature. Stability studies of the temperature probe were conducted and it was found that the temperature stabilises after 20 thermal cycles from 0°C to 100°C. A new constant called 'temperature bandwidth - sensitivity product' has been defined and this constant depends on the core radius and refractive index profile of a fibre. By choosing an appropriate cladding material, the temperature range of the sensor could be increased at the cost of the sensitivity or vice-versa. Also a fibre optic temperature probe has been constructed to take measurements near liquid nitrogen temperature, which ranges from -196°C to -10°C. This probe is suitable for industrial applications such as temperature control in liquefying gases.

Microwave heating is generally established using a single microwave frequency of 2.45 GHz. However these frequencies have inherent non-uniformity problems like hot spots
and thermal run away. A new technique called Variable Frequency Microwave (VFM) technique (Lambda Technologies, undated) has been used to solve this problem of inherent in the fixed frequency by using a preselected bandwidth of frequencies sweeping around a central frequency. As more than one thousand frequencies are launched into the cavity sequentially, each incident frequency sets up its own electric field pattern at different locations at different time intervals, a time averaged uniform heating can be achieved with proper selection of sweep frequency and range. So prior to building special microwave applicators with variable frequency, it is advantages to do characterisation the paints used using VFM.

Power Frequency Characterisation was conducted using two different types of VFM facilities. Four totally different types of paints that includes water based, oil based and even resin are included in the study. The samples selected are Solar Acrylic, Polyester Resin, Wattyl Instant Estapol and Metal Gloss Polypropylene. Also studies were conducted with the paints with three different thicknesses (1.5 mm, 1.0 mm and 0.05 mm). Temperature characterisation was also done in two different power outputs of 30W, 60W and 90W and all the above studies were done in both the VW1500 with frequency range of 6.5GHz to 18GHz and Microcure 2100 facilities with frequency range of 2.5GHz to 8GHz VFM facilities.

After analysing the diagrams and data collected it was found that all different materials behaved in a different way to parameters like thickness, power input, bandwidth frequency and sweep time. Results also showed that special care should be taken when designing a microwave applicator with variable frequency for heating various materials and VFM facility is a very useful tool to identify these parameters and design an applicator for most favourable conditions so that hot spots and thermal run away can be avoided for specific materials.

A novel Y-septum waveguide applicator is proposed, which has a much higher cut-off wavelength and bandwidth compared to existing waveguide applicators such as a rectangular, ridged or T-septum waveguide applicators. It is shown that for a septum angle of 10°, the proposed Y-septum waveguide applicator has the cut-off wavelength 68.8% larger than that of a T-septum waveguide applicator of the same dimensions. Also it is shown that the bandwidth of the proposed Y-septum waveguide applicator is
64.9% larger than a T-septum waveguide applicator of the same cut-off frequency.

Calculations performed comparing the rectangular, T-septum, and Y-septum waveguide applicators have shown that the cross-sectional area of the Y-septum waveguide applicator is only 4.4% of the rectangular waveguide applicator and 35% of that of the T-septum waveguide applicator. A 95.6% improvement in reducing the space has been achieved over the rectangular waveguide applicator and 64% over the T-septum waveguide applicator. The bandwidth of the Y-septum waveguide applicator is more than 7 times as wide as the rectangular waveguide applicator and 1.7 times that of the T-septum waveguide applicator.

The Y-septum waveguide applicator is ideal for single mode microwave heating of small loads like a film of paint because of its compact size. The high bandwidth characteristics of the Y-septum waveguide applicator is appreciable in ensuring a single mode heating when the dielectric properties of the load vary during processing.

Further studies on the Y-septum waveguides may include the consideration of two or more septa on one or both sides of the waveguides, and loading the guide with dielectrics, which would further improve the characteristics of the waveguide. Y-septum applicator can be expected to have regions of better uniform field distribution compared to a T-septum guide. The uniformity in the field distribution probably could be controlled by adjusting the septum angle.
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Appendix A

Scattering Parameter Measurements of the T-septum Wave Guide Applicators Using Hewlett Packard Network Analyser 8720A

Figure A.1  Measured scattering parameters $S_{11}$ and $S_{21}$ of the polystyrene model of the T-septum wave guide applicator using Hewlett Packard Network Analyser 8720A. The applicator is unloaded.
Figure A.2  Measured scattering parameters $S_{11}$ and $S_{21}$ in Smith Chart representation of the polystyrene model of the T-septum wave guide applicator using Hewlett Packard Network Analyser 8720A. The applicator is unloaded.
Figure A.3  Measured scattering parameters $S_{11}$ and $S_{21}$ of the polystyrene model of the T-septum wave guide applicator using Hewlett Packard Network Analyser 8720A. The applicator is loaded with low loss dielectric (Teflon)
Figure A.4  Measured scattering parameters $S_{11}$ and $S_{21}$ in Smith Chart representation of the polystyrene model of the T-septum wave guide applicator using Hewlett Packard Network Analyser 8720A. The applicator is loaded with low loss dielectric (Teflon)
Figure A.5  Measured scattering parameters $S_{11}$ and $S_{21}$ of the polystyrene model of the T-septum wave guide applicator using Hewlett Packard Network Analyser 8720A. The applicator is loaded with low loss dielectric (Teflon) and a wet paper is in contact with the top metal wall of the wave guide to represent lossy paint.
Figure A.6  Measured scattering parameters $S_{11}$ and $S_{21}$ in Smith Chart representation of the polystyrene model of the T-septum wave guide applicator using Hewlett Packard Network Analyser 8720A. The applicator is loaded with low loss dielectric (Teflon) and a wet paper is in contact with the top metal wall of the wave guide to represent lossy paint.
Figure A.7  Measured scattering parameters $S_{11}$ and $S_{21}$ of the polystyrene model of the T-septum wave guide applicator using Hewlett Packard Network Analyser 8720A. A wet paper is in contact with the top metal wall of the wave guide to represent lossy paint. Low loss dielectric is not loaded in this case.
Figure A.8  Measured scattering parameters $S_{11}$ and $S_{21}$ in Smith Chart representation of the polystyrene model of the T-septum wave guide applicator using Hewlett Packard Network Analyser 8720A. A wet paper is in contact with the top metal wall of the wave guide to represent lossy paint. Low loss dielectric is not loaded in this case.
Figure A.9  Measured scattering parameters $S_{11}$ and $S_{21}$ of the aluminium model of the T-septum wave guide applicator using Hewlett Packard Network Analyser 8720A. The applicator is not loaded.
Figure A.10  Measured scattering parameters $S_{11}$ and $S_{21}$ of the aluminium model of the T-septum wave guide applicator using Hewlett Packard Network Analyser 8720A. A film of paint is coated on the top wall of the applicator above the T-septum and dielectric loading is used.
Figure A.11  Measured scattering parameters $S_{11}$ and $S_{21}$ of the aluminium model of the T-septum wave guide applicator using Hewlett Packard Network Analyser 8720A. Alumina of thickness 1.6 mm is used as the dielectric loading and the applicator wall is not coated with paint film in this case.
Figure A.12  Measured scattering parameters $S_{11}$ and $S_{21}$ of the aluminium model of the T-septum wave guide applicator using Hewlett Packard Network Analyser 8720A. A film of paint is coated on the top wall of the applicator above the T-septum and alumina (dielectric loading) is placed between the paint coating and the septum, 0.5 mm below the coating.
Figure A.13  Measured scattering parameters $S_{11}$ and $S_{21}$ of the aluminium model of the T-septum wave guide applicator using Hewlett Packard Network Analyser 8720A. A film of paint is coated on the top wall of the applicator above the T-septum and alumina (dielectric loading) is placed between the paint coating and the septum, 1.4 mm below the coating.
Figure A.14  Measured scattering parameters $S_{11}$ and $S_{21}$ of the hats (coaxial to wave guide converter) using Hewlett Packard Network Analyser 8720A.
Figure A.15  Measured scattering parameters $S_{11}$ and $S_{21}$ of the aluminium model of the T-septum wave guide applicator using Hewlett Packard Network Analyser 8720A. A film of paint is coated on the top wall of the applicator above the T-septum and Teflon (dielectric loading) is placed between the paint coating and the septum, 0.5 mm below the coating.
Figure A.16  Measured scattering parameters $S_{11}$ and $S_{21}$ of the aluminium model of the T-septum wave guide applicator using Hewlett Packard Network Analyser 8720A. The film of paint is coated on the top wall of the applicator above the T-septum is partially dry in this case and alumina (dielectric loading) is placed between the paint coating and the septum, 0.5 mm below the coating.