Fabrication and characterisation of three-dimensional passive and active photonic crystals

A thesis submitted for the degree of

Doctor of Philosophy

by

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The cure for boredom is curiosity. There is no cure for curiosity.

— *Dorothy Parker*

Declaration

I, Michael James Ventura, declare that this thesis entitled :

"Fabrication and characterisation of three-dimensional passive and active photonic crystals"

is my own work and has not been submitted previously, in whole or in part, in respect of any other academic award.

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Abstract

The ability to fabricated highly correlated structures in one, two and three-dimensions with a periodic variation in dielectric contrast comparable to optical wavelengths has allowed for the experimental realisation of the '*photonic crystal*' (PC). Proposed independently by Yablonovitch and John over two decades ago, PCs are analogous to semiconductor materials in which photons are scattered in a similar way to electrons in a crystalline array of atoms. Resonant scattering results in gaps opening up in the electromagnetic spectrum which are referred to as photonic band-gaps (PBGs). These novel materials allow for the microscopic engineering of light and may provide a platform for the realisation of the integrated optical circuits of the future. Furthermore the electromagnetic density within PCs can be manipulated towards wavelength selective modification of spontaneous emission of embedded emitters.

The initial validation of the PBG effect was conducted in the microwave regime where three-dimensional (3D) PCs were easily fabricated using simple millimeter machining. However it has only been in recent years that experimental verification at optical wavelengths have been achievable. This has been due to the global development of new state-of-the-art micro and nano-fabrication techniques. Despite the wealth of experimental results into

the fabrication of 3D PCs, there has been little research into exploiting these materials towards spontaneous emission control. Although early work towards this topic was conducted with spectral changes noted as a function of PBG, researchers were limited to using non-ideal optical wavelength emitters including dyes and ions. In recent years the exciting field of semiconductor nanocrystal synthesis has yielded new nano-materials, quantum dots (QDs), that possess narrow-band, stable emission throughout the visible and into the infrared wavelength regions. These materials unlike dyes and ions can closely resemble two-level systems with near unity quantum efficiency.

By combining these once unrelated fields, it is only now possible to draw valid conclusion towards the investigation of spontaneous emission control of embedded light sources within 3D PCs. Experimental investigations into combining QDs and 3D PC towards spontaneous emission control was recently achieved at visible wavelengths using cadmium-based QDs in 2004. Although wavelength dependent emission control was noted as a function of the PBG position, this is not necessarily amenable towards practical implementation. Furthermore cadmium-based QDs do not exhibit emission at infrared wavelengths.

This thesis addresses the development of a more robust PCs towards the control of spontaneous emission at infrared wavelengths. In particular 3D polymer based PC are to be investigated towards emission control at infrared wavelengths, a region of interest in the fields of telecommunications, biological imaging, quantum systems and terahertz devices. Towards this goal a fabrication technique is required that can produce high-quality, 3D PCs with PBGs at infrared wavelengths. Furthermore the fabrication technique has to allow for the introduction of localised defects within these lattices, a particularly important aspect that is required towards full control of spontaneous emission.

The latest state-of-the-art fabrication technique, direct laser-writing of void channels using tightly focused femtosecond pulsed laser light within solid polymers has been used in this thesis. Unlike other fabrication methods, this technique allows for the rapid fabrication of multi-dimensional PCs. Furthermore the flexibility afforded by this method allows for designed defects to be readily integrated within fabricated PCs.

Theoretical predictions of PBG positions as well as localised defect modes are first calculated using a commercial eigen-solver program (RSoft Design Inc. Bandsolve). Furthermore mode density maps of the electric field within PCs obtained from this software is used towards a further understanding of localised defect fields as well as modal distributions at PBG edges.

The introduction of infrared wavelength emitting QDs within 3D PCs is achieved by the synthesis of high-quality QDs in solution followed by direct doping within a polymer matrix. The development of this novel homogeneous QD-doped polymer nanocomposite allows for a material that possesses emission characteristics unchanged for that of QD in solution and still be amenable to direct laser fabrication of high-quality PCs. This material, consisting of a dispersion of QDs is then used to fabricate 3D PCs, resulting in a random distribution of QDs throughout the lattice. Changes in fluorescence lifetime of embedded QDs is then used to directly validate the hypothesis that 3D polymer based PCs can be used to selectively change the rate of spontaneous emission of embedded light sources. An infrared sensitive, time-correlated single photon counting system was developed in conjunction with a home made confocal microscope. This system will allowed for fluorescence lifetimes to be measured from QDs inside fabricated 3D PCs.

The work presented herein is a step towards the development of new photonic materials. The control of light emitters using materials with features comparable to the wavelength may potentially hold the key to photons replacing electrons in the devices of the future. This technology, the combination of infrared wavelength emitting QDs and polymer based 3D PCs may in the future allow for the manipulation of photons with as much finesse as electrons in the semiconductor devices of today.

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In late October 2002 I was drawing to the end of my honours year whilst wrapping up my first journal paper. My principle supervisor Prof. Min Gu proposed that on completion of my honours thesis that I continue to work over the new years on a follow up paper with my associate supervisor Dr. Martin Straub. After a year of unrelenting supervision from both Min and Martin, a three month stint in a cold, dark lab over summer was far from appealing. A week later my outlook had changed, I was eager to get back to work, feeling rejuvenated and excited about this new paper. Min had shown me the light.

It was during this summer work that Prof. Min Gu proposed that I stay on and undertake a PhD research degree with him. Like three months prior to taking up the summer work I was apprehensive about staying. Two weeks later my outlook had changed, I was eager to get back to work, feeling rejuvenated and excited, this time as a PhD student. Min had shown me the light, again. The appreciation I hold for those people who have guided, taught and listened to me thought my candidature are heartfelt.

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