Study of optical drive systems for two-photon optical data storage

A thesis submitted for the degree of
Doctor of Philosophy

by

Md Azim Ullah

Centre for Micro-Photonics
Faculty of Science, Engineering and Technology
Swinburne University of Technology
Melbourne, Australia

Principle Supervisor: Professor Min Gu
Associate Supervisor: Dr. Xiangping Li

2014
Abstract

Optical data storage technologies have undergone significant developments over the past few decades, heavily inspired by the high demand for information storage in areas such as medical studies, historical research, and telecommunications. The demand for data storage continues to increase exponentially. However, the current optical data storage techniques are reliant on compact discs (CDs), digital versatile discs (DVDs) and Blu-ray discs (BDs), where data storage capacities are limited to 0.7 GB, 4.7 GB and 23 GB, respectively. These storage capacities cannot satisfy the current demand. Revolutionary ideas, including the two-photon (2P) excitation technique, have been applied to the optical data storage in three dimensions (3D) to increase the data storage capacity.

By using a surface plasmon of gold nanorod (GNR) in the 2P optical data storage technique, the data storage capacity can be increased to 1.6 Tbytes/disc. However, currently, no compatible optical disc drive (ODD) systems exist to support these techniques. The present research study is focused on the development of such a compatible ODD system.

To this end, we prepared 2P optical discs using a DVD disc substrate, and utilised a DVD optical pickup head (OPUH) as a recording and reading optics. Firstly, we fabricated GNR dispersed 2P optical discs, and performed 2P thickness measurements to check homogeneity and thickness.
Secondly, we characterised the electrical, mechanical, and optical performances of the OPUH to determine the 2P recording and reading performances. The 2P recording performance of the objective lens of the OPUH unit is characterised by coupling high power femtosecond pulsed laser beams. The experimental results proved that our customised OPUH is capable of performing the 2P recording and reading.

Thirdly, we developed a 2P-enabled ODD system. Because of the dynamic operation of the optical disc in the 2P-enabled ODD system, it is difficult to maintain the recording layer of the optical disc in the focal plane of the objective lens. For this reason, the data cannot efficiently record and read from the recording layer of the optical disc. In order to record and extract data from the recording layer effectively, we introduced a servo system. The optical arrangement of the focusing and the tracking servo systems along with the control algorithms, confirmed the data extraction with a high degree of precision. We verified the readout performance of the 2P-enabled ODD system with the servo system.

In order to implement the surface plasmon of GNRs in the 2P recording technique, a sharp selective photo-reshape of GNR is required. To enable the selective photo-reshape of GNR, it is important to know the focal temperature in order to avoid unwanted damage during the recording process. For this purpose, we broke new ground by experimentally using nano-thermometry principle in the focal temperature measurement. In this experiment, we measured the heat generation resulting from the surface plasmon of GNRs in a polyvinyl alcohol (PVA) matrix. The role of the PVA matrix was replaced with the glass substrate to confirm the effect of the PVA on the environmental temperature increment. We demonstrated the effect of numerical aperture (NA) on temperature increment in the focal plane of the objective lens. To the best of our knowledge, this is the first experimental demonstration of focal
temperature measurement employing different surface-to-volume ratios with substrates varying in thermal conductivity.

Subsequently, we performed low energy threshold recording using GNR dispersed discs under the femtosecond pulsed laser beam coupled into the OPUH. In this study, we fabricated a double layer 2P optical disc and performed dual layer 2P recording and reading. The recording density for a double layer disc is equivalent to 69 GB per DVD sized disc.

In conclusion, our designed 2P-enabled ODD system presents a significant innovation in the field of optical data storage and drive systems technology.
Acknowledgement

In the Name of ALLAH, the Most Gracious, the Most Merciful.

In my search for a PhD opportunity in the field of electrical and electronic engineering, I discovered a project on solar cells - my initial area of research interest - conducted by the Centre for Micro-Photonics at Swinburne University, Melbourne, Australia. Professor Min Gu generously offered me one of his prestigious Laureate Fellowship project - ‘Optical disc drive system’, I would like to first give my sincerest thanks to my supervisor, Professor Min Gu, for giving me such an opportunity and inspiring me in the selection of my project. His excellent guidance and encouragement certainly assisted me in completing this research study.

I would like to thank my co-supervisor, Dr. Xiangping Li, for his great effort in training me in research methodology and experimental technique, in problem solving, and for fruitful discussions we have done throughout my PhD candidature. I would like to thank A/Prof. Dr. Baohua Jia for her helpful assistance in a number of areas, particularly in my PhD admission and scholarship applications processing, and in the organising the initial research process.

Special thanks go to Swinburne University of Technology for providing me with a prestigious SUPRA award (Swinburne University Postgraduate Research Award, SUPRA).
I also would like to thank our collaborators Tsinghua University, China and Anwell Ltd for providing me with experimental equipment for this research project.

I would like to thank A/Prof Hiway Wang for his fruitful discussion about the servo system. I also thank to Dr. Masatoshi Tsuji, Prof Xiaojian Hao, Dr. Phillip Dolan and Dr. Dru Morrish for discussions on optics and electronics.

My gratitude goes to Dr. Qiming Zhang, Mr. Haoran Ren and Dr. Yaoyu Cao, who helped me with preparation of disc fabrications materials. A big thank goes to Ms Laura Martinez Maestro for sharing her nano-thermometry research, which assisted in the the focal temperature measurement experiments.

I thank Mr. Mark Kevenin for his excellent mechanics design for the optical systems build up. For smooth administrative support, thanks goes to Mrs Barbara Gillespie, Ms Kerrie Lawrence, and Mrs Amable Lou.

Finally, my heartfelt gratitude goes to my beloved mom, my elder brother Mr Saifullah, and my sisters for their constant unwavering encouragement throughout my PhD study. Without their constant support, it would not have been possible to complete my overseas studies smoothly.

Md Azim Ullah
Melbourne, Australia
October, 2014
Declaration

I, Md Azim Ullah, declare that this thesis entitled:

“Study of optical drive systems for two-photon optical data storage”

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

Md Azim Ullah

Centre for Micro-Photonics
Faculty of Science, Engineering and Technology
Swinburne University of Technology
Australia

Dated this day, 13th October 2014
# Contents

Abstract

Acknowledgements

Declaration

Contents

List of Figures

List of Tables

Nomenclature

1 Introduction
   1.1 Evaluation of optical memory
   1.2 2P process
   1.3 ODD system
      1.3.1 ODD systems for 2D optical data storage
      1.3.2 ODD systems for 2P optical data storage
         1.3.2.1 Concepts of 2P based ODD system
         1.3.2.2 Challenges of the 2P-enabled ODD system
   1.4 Thesis objectives
   1.5 Outline of the thesis

2 Review

vii
2.1 Introduction ................................................. 16
2.2 Principle of optical data storage ............................ 17
2.3 Optical data storage techniques ............................ 19
   2.3.1 Holographic recording ............................... 19
   2.3.2 Near-field recording ................................ 21
   2.3.3 Far-field recording ................................... 22
      2.3.3.1 Conventional optical data storage ............. 22
      2.3.3.2 3D recording ................................... 23
      2.3.3.3 Multi-dimensional recording ..................... 24
2.4 Optical recording disc and drives .......................... 26
   2.4.1 Optical disc ........................................... 27
   2.4.2 Optical pickup head ................................... 29
      2.4.2.1 Optical transfer ................................. 30
      2.4.2.2 Servo system .................................... 32
   2.4.3 Control mechanism .................................... 37
2.5 Chapter conclusion .......................................... 38

3 Two-photon optical discs ...................................... 40
3.1 Introduction ................................................. 40
3.2 Optical discs ................................................ 41
   3.2.1 Disc structure ......................................... 41
   3.2.2 Preparation of recording materials .................... 42
   3.2.3 Disc fabrication ....................................... 43
3.3 Characterisation of the fabricated 2P optical discs ......... 46
   3.3.1 Thickness measurement .................................. 47
   3.3.2 Lateral uniformity measurement ....................... 47
3.4 Chapter conclusion .......................................... 49

4 Characterisation of an optical pickup head ...................... 50
4.1 Introduction ................................................. 50
7.3 Dual layer recording ................................. 103
7.4 Chapter conclusion ................................. 106

8 Conclusions and future outlook .......................... 108
  8.1 Thesis conclusion .................................. 108
  8.2 Future outlook ..................................... 110
    8.2.1 Super-resolution ODD system .................. 111
    8.2.2 Optical storage array ......................... 111

Bibliography ............................................. 114

Appendix A: Spindle motor characterisation ............. 131

Appendix B: Mechanical performance of optical pickup head 136

Appendix C: Servo circuit and controller design .......... 138

Author’s publications ................................... 143
List of Figures

1.2 a) Process of two-photon excitation. b) The density of photons is increased by spatial compression using objectives with high NA. c) The density of photons is increased by temporal compression using ultra-fast lasers [12] ................................. 5
1.3 Schematic of the ODD system ................................. 6
1.4 Basic data readout principle ................................. 7
1.5 Optical disc of CD, DVD and BD and readout (eye) pattern. Images are collected from Wikipedia and [14] ................................. 9
1.6 Flow of this PhD thesis ........................................ 13

2.1 Schematic diagram of the optical recording/reading system. ................................. 18
2.2 Holographic data storage a) writing data and b) reading data [25] ................................. 20
2.3 System of near-field recording using a) SIL and b) Aperture [27] ................................. 21
2.4 Data record in spectra and polarisation domains [13] ................................. 24
2.5 Five-dimensional optical data storage [10] ................................. 26
2.6 Schematic of optical disc drive [33] ................................. 27
2.7 Physical format of an optical disc ................................. 28
2.8 Optical pickup head, Model SF-HD850 [51] ................................. 30
2.9 Block diagram of the optical transfer of the optical pickup head ................................. 31
2.10 Focus error detection [69] ................................. 33
2.11 Track error detection a) 3-beam method and b) differential push-pull method [69] ................................. 35
3.1 Disc structure ................................................. 41
3.2 Gold nanorods synthesis a) recording layer preparation method,
b) absorption absorption of gold nanorods and c) two-photon
emission spectrum of gold nanorods ............................. 43
3.3 Disc fabrication process ....................................... 44
3.4 Disc fabricator a) disc fabricator machine and b) composite of
disc fabricator ....................................................... 45
3.5 Fabricated 2P disc ................................................ 47
3.6 2P thickness of the fabricated gold-nanorods dispersed disc.
Inset shows the absorption spectra of the gold nanorods. ....... 48
3.7 Disc lateral uniformity .......................................... 49
4.1 Experimental setup for OPUH characterisation .................. 51
4.2 Transmission versus wavelength ................................ 53
4.3 Axial response versus wavelength [105] ......................... 54
4.4 Lateral resolution versus wavelength [105] ....................... 56
4.5 2P readout image ............................................... 57
4.6 Fluorescence intensity dependence of the DMNPAA emission
under 2P excitation on a log-log scale. The slope of the linear
fitting is 1.98 ∼ 2. ............................................. 59
4.7 Reconstructed readout image of the two-photon recorded pattern 60
4.8 Bit size and contrast as a function of the recording power .... 60
5.1 Schematic of the 2P-enabled ODD system ......................... 64
5.2 Experimental setup of the 2P-enabled ODD system ............... 65
5.3 Schematic of Z-scanning technique ............................... 67
5.4 Z-scanning simulation .......................................... 67
5.5 Schematic of the servo system ................................... 70
5.6 Surface detection method ........................................ 71
5.7 Schematic of focus servo system ................................ 72
5.8 Quad-photo-detector [107] ........................................ 73
5.9 Simulated beam shape on the QPD as a function of disc deviation. ........................................ 74
5.10 Tracking servo system ........................................ 75
5.11 Generation voltages in the QPD ................................. 77
5.12 Beam shape change as a function of disc deviation .......... 78
5.13 S-curve .......................................................... 79
5.14 RF signal when the disc spinning speed is a) 100 rpm, b) 300 rpm, c) 400 rpm, d) 600 rpm, e) 800 rpm, and f) 1000 rpm ... 81
5.15 Focus error signal ........................................ 83
5.16 Tracking error signal ........................................ 84
5.17 Fluorescence readout with a servo system ................... 85

6.1 Temperature versus quantum dot peak wavelength [124] .... 90
6.2 Schematic diagram of the temperature measurement .......... 92
6.3 Temperature rise on the glass substrate ........................ 93
6.4 Temperature rise in the PVA matrix ............................ 94
7.1 (a) Calculated focal temperature as a function of the number of pulses at a repetition rate of 82 MHz and an energy density of 0.4 mJ cm$^{-2}$. The blue squares and red circles present the calculated temperature rising in GNR-dispersed PVA matrix by objectives with NA = 0.6 and NA = 1.4, respectively. The green triangles represent data for GNR distributed on cover glass. (b) Experimental characterisation of the 2P fluorescence contrast reduction as a function of the energy density by surface melting of GNRs in the PVA matrix with an objective NA = 0.6 (blue), in the PVA matrix with an objective NA = 1.4 (red) and distributed on cover glass with an objective NA = 0.6 (green), respectively. (c) The focal temperature of the PVA matrix after 2000 pulses at different energy-density levels and laser repetition rates.

7.2 (a) Fluorescence readout image of the recorded pattern at different recording power levels. The scale bar is 10 µm. (b) Size defined by the FWHM and (c) the readout contrast of the recorded bits as a function of the recording power and the exposure time.

7.3 2P fluorescence readout images of two letters recorded in the first layer (a) and the second layer (b). The inset shows the zoom in view of the recorded bits indicated by the dashed square. The scale bar is 10 µm. (c) the axial response of the two recorded layers with a layer separation of 15 µm. (d) the cross section plot of the recorded bits as indicated by the dashed line.

8.1 Schematic illustration of the optical storage array

8.2 Electrical equivalent circuit of the spindle motor

8.3 Bode plot of open loop transfer function of the spindle motor

8.4 Speed profile throughout the disc at constant linear velocity
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.5 Transfer function of the focusing actuator</td>
<td>136</td>
</tr>
<tr>
<td>8.6 Transfer function of the tracking actuator</td>
<td>137</td>
</tr>
<tr>
<td>8.7 Block diagram of the servo circuit</td>
<td>138</td>
</tr>
<tr>
<td>8.8 Schematic of servo circuit</td>
<td>139</td>
</tr>
<tr>
<td>8.9 Bode plot of the low pass filter</td>
<td>140</td>
</tr>
<tr>
<td>8.10 Block diagram of the PID controller</td>
<td>141</td>
</tr>
<tr>
<td>8.11 Step response of the focusing controller</td>
<td>141</td>
</tr>
<tr>
<td>8.12 Step response of tracking PID controller</td>
<td>142</td>
</tr>
</tbody>
</table>
List of Tables

3.1 Recipe for the fabrication of the homogeneous recording layer
   a) materials b) spinning parameters . . . . . . . . . . . . . . . . 46

5.1 Parameter of the servo system model . . . . . . . . . . . . . . . 73

8.1 Spindle motor specification . . . . . . . . . . . . . . . . . . . . . 132
Nomenclature

2D  Two-dimension
2P  Two-photon
3D  Three-dimension
BD  Blu-ray disc
CD  Compact disc
CLV Constant linear velocity
DMNPAA 2,5-dimethyl-4-p-nitrophenylazo
DSP Digital signal processor
DVD Digital versatile disc
EB  Exabyte
ECZ 9-ethylcarbazole
FES Focus error signal
GB  Gigabyte
GNR Gold nanorods
HD-DVD High definition digital versatile disc
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDD</td>
<td>Hard disk drive</td>
</tr>
<tr>
<td>ODD</td>
<td>Optical disc drive</td>
</tr>
<tr>
<td>OPUH</td>
<td>Optical pickup head</td>
</tr>
<tr>
<td>PB</td>
<td>Petabyte</td>
</tr>
<tr>
<td>PMT</td>
<td>Photo-multiplier tube</td>
</tr>
<tr>
<td>PS</td>
<td>Un-plasticised polystyrene</td>
</tr>
<tr>
<td>PSA</td>
<td>Pressure sensitive adhesive</td>
</tr>
<tr>
<td>PVA</td>
<td>Polyvinyl alcohol</td>
</tr>
<tr>
<td>QD</td>
<td>Quantum dot</td>
</tr>
<tr>
<td>QPD</td>
<td>Quad-photo-detector</td>
</tr>
<tr>
<td>QWP</td>
<td>Quarter waveplate</td>
</tr>
<tr>
<td>RF</td>
<td>Radio frequency</td>
</tr>
<tr>
<td>rpm</td>
<td>Rotation per minute</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-noise ratio</td>
</tr>
<tr>
<td>TES</td>
<td>Track error signal</td>
</tr>
<tr>
<td>TOC</td>
<td>Table of contents</td>
</tr>
<tr>
<td>TPA</td>
<td>Two-photon absorption</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

Currently, optical data storage is one of the largest applications of optics, which studies light fields and their interaction with matter to store information. Information storage density relies on the nature of the focused light beams, where a focal spot with smaller spot size produces a higher data storage density. Due to the current rapid growth in the global demand for information storage, optical scientists are looking for an array of techniques to improve storage capacity [1–7]. To fulfil the enormous current demand for information storage, the revolutionary idea of “big data storage” offers a potential solution [8]. ‘Big data’ can be described as a massive volume of data that is difficult to process in the conventional techniques; for example, ‘big data’ could be in a volume of petabyte (PB) or exabyte (EB).

In order to support this type of data successfully, ‘big data’ centres have engineered multiple optical drives to increase data storage capacity. However, the current optical disc drive (ODD) is in the range of ∼ gigabytes (GB) capacity, which requires ∼ millions of ODDs of the same capacity in order to assemble a big data centre with a PB data storage capacity. This massive
amount of ODD demands extremely high power consumption, expensive interfacing and driving accessories, as well as low-speed; this makes the system extremely costly, bulky and less efficient. In order to reduce the systems cost and to increase the systems speed, fewer high speed ODD units should be used. To achieve high data storage capacity with fewer ODD units, the individual ODD unit should be capable of producing high density data storage.

To have high capacity data storage, a large volume of data is required to be stored in a small spatial location of the storage medium. In such a condition, the smallest size of each data bit is required. However, current optical data storage technologies, such as the compact disc (CD), the digital versatile disc (DVD) and the Blu-ray disc (BD) store the information on the two-dimensional (2D) surface of the recording medium. These technologies use a diffraction limited focal spot to store information, which limits the capacity of the optical data storage to the \( \sim \) GBs range.

By adding axial layers on the 2D surface of the recording medium, and by using shorter wavelengths of laser beams, the data storage capacity is greatly enhanced. Due to the strong scattering effect of the short wavelengths of the laser beam in the deeper layers of the recording medium, substantial amounts of layers cannot be efficiently added [9]. These problems can be solved with the revolutionary idea of 2P technology, in which the recording into the deep layer can be possible without distorting the laser beam [9].

In addition, optical data storage capacity can be increased to 1.6 Tbytes/disc by using the surface plasmon properties of gold nanorod (GNR) [10]. However, no such ODD systems exist to support this technique. Thus, the motivation for and advisability of researching the development of a 2P-enabled ODD system became clear.

In this introductory chapter, we introduce current optical data storage
techniques and ODD systems that lead us to develop the concepts of 2P optical data storage and a 2P-enabled ODD system. The main challenges for 2P-enabled ODD systems are presented. We also have presented the thesis objectives and a summary of the structure of the thesis.

1.1 Evaluation of optical memory

The groundbreaking history of optical data storage is not more than a few decades old. Before that, it was a in the realm of science fiction to think of the storage of GBs of information. Nowadays, several GBs of information storage are evident even in a tiny secure digital (SD) card, universal serial bus (USB) stick, MP3 players, and other hand-held devices. It is interesting to look back and compare some of the early storage devices to present day existing data storage discs and devices [11].

Figure has been removed

**Figure 1.1** Evaluation of data storage [11]

Fig. 1.1 shows the evaluation of data storage throughout the 20th century [11]. In 1932, Austrian scientists invented magnetic drum memory, the capacity of which was around 10 kB; this was widely used in computer memory until the 1960s. The first magnetic tape was used in the data storage of computer systems in 1951. The recording density of the magnetic tape was 128 characters per inch, which was 1200 feet long and heavy. The lighter version of the magnetic tape, of which the data transfer rate was 2000 bits/sec, was called ‘compact cassette’; it came into existence in the 1970s. IBM invented the easy removal storage media, called a ‘floppy disk’, in 1971; this was popular until late 1990s. The storage capacity of the floppy disk was 79.7 kB. The first hard disk drive (HDD) was invented in 1956, where the storage capacity was less
than 5 MB. Until 1979, the HDD capacity was 256 MB. The first GBs capacity HDD came into existence in 1980.

In 1958, David Paul Gregg and James Russell invented the first optical disc, called a ‘laser disc’. The first market-available laser disc was introduced in 1978. It consisted of a transparent disc, in which contents were completely analog. It was also known as a ‘laser video disc’ and the size of the laser disc was 30 cm in diameter.

The CD was launched into the market in 1982, four years after the invention of the laser video disc. The recording and the reading information of the CD is the digital form or binary values. It was designed to support audio recording. The CD size is 12 cm in diameter, of which the data storage capacity is 700 MB.

A high data storage capacity optical disc is required to have the video recording and reading capability. Philip, Sony, Toshiba, and Panasonic invented the ‘digital videodisc’ or DVD, in 1995, to fulfill the requirement of high-density optical data storage for video data storage. A DVD disc is the same size as a CD and is 12 cm in diameter. The storage capacity of a DVD is 4.7 GB.

The BD was invented in early 2003 to provide a high definition video resolution, of which the size is 12 cm in diameter, a size similar to CD and DVD discs. The storage capacity of the BD disc is 23 GB per layer. The first BD discs came into the market in 2006.

### 1.2 2P process

In 1931, Marie Goeppert - Mayer first predicted the process of two-photon absorption (TPA) [12]. TPA is the process of the simultaneous absorption of two photons to excite the molecule from the ground energy state to the
high energy, or excited, state. It is a non-linear absorption process, where the strength of absorption is equal to the square of the light intensity. In 1961, the TPA process was experimentally verified [12].

To describe the TPA, two different excitation mechanisms, such as sequential excitation and simultaneous excitation can be used. The simultaneous excitation process of TPA is shown in Fig. 1.2a.

The high density of photons is required to achieve a high probability of such a nonlinear absorption process. By utilising spatial and temporal compression, the high density of photons can be achieved as shown in Fig. 1.2b and Fig. 1.2c, respectively. Because of using spatial and temporal compression in the TPA process, the excitation beam is highly localised within the focal volume. The high-localised excitation beam is the main interest of using over the single photon absorption [12].

![Figure 1.2](image_url)

**Figure 1.2** a) Process of two-photon excitation. b) The density of photons is increased by spatial compression using objectives with high NA. c) The density of photons is increased by temporal compression using ultra-fast lasers [12]
1.3 ODD system

Fig. 1.3 shows the schematic of the basic principle of optical data storage used in most current CD and DVD drive systems. A single intense laser beam is used to record and read data from the optical disc. The laser beam is collimated first, and then directed to the optical disc. A spindle motor is used to spin the optical disc, which consists of a number of tracks spaced by track pitches.

An objective lens used to focus the collimated laser beam onto the track of a spinning optical disc. The focused laser beam is directed at a single track of the spinning optical disc, which forms a continuous spiral on the disc. The spiral track is outward from the disc centre toward the outer edge of the disc.

In relation to the data recording operation, the data signal is, at first, converted
to digital form. Features of the digital forms of the data depend on the encoding algorithm used in the particular ODD systems. Mark-edge recording techniques are commonly used in the commercial CDs, DVDs and Blu-ray discs (BDs). In this technique, transition from land to pit or pit to land is considered as “1” and flat area is “0”.

![Figure 1.4 Basic data readout principle](image)

The laser beam is directed to the spinning optical disc through the same objective lens to retrieve the encoded information from the optical disc. The objective lens collects the laser beam, which is reflected from the optical disc surface. Then the reflected laser beam is directed to the photo-detector, which performs readout operation.

Due to the optical disc is being encoded with lands and pits, the reflected laser beam varies. The variation of the reflected laser beam causes the variation of the current signals generated by the photo-detector as shown in Fig. 1.4. The duration of the current ON/OFF is related to the lengths of pre-recorded lands and pits of the optical disc. The current signal is amplified and then sent to a
microprocessor for interpretation of the data signals.

The ODD system is composed of an optical servo system. The servo system performs two functions:

1. It allows the laser beams to focus exactly on the disc-recording medium. This function is called a ‘focus servo’ system.

2. It stays focused on the track by following a spiral path of the pre-recorded lands and pits. This function of the servo system is called the ‘tracking servo’.

The key element that performs recording and reading in the ODD systems is known as ‘optical pick-up unit’. It consists of a laser source with particular wavelength, an objective lens to focus the laser beam, a beam splitter to direct the reflected beam and a photosensitive detector to detect the reflected signal from the surface of the optical disc.

1.3.1 ODD systems for 2D optical data storage

Conventional ODD systems are capable of performing optical data storage in the 2D surface of the optical disc media. At present, the CD drive, DVD drive and BD drive systems are the most widely used ODD systems. In the 2D recording techniques, data is recorded beneath the surface (x - y- plane) of a recording medium [13]. Data is recorded on the surface as pit (recording area) and land (unrecorded area).

In the data readout process, a detector detects the reflected light beam from the recorded disc. A land is a blank (unrecorded) space, the light beam reflected from the land produces a high intensity reflected light beam. The light beam reflected from the pit is destructive interference and produces a low intensity
A CD drive uses a laser source of wavelength 780 nm and an objective lens of 0.45 NA, that produces the spot size $\sim 1.6 \, \mu \text{m}$. In order to avoid cross-talk, a track pitch of $\sim 1.6 \, \mu \text{m}$ produces the optical disc capacity 700 MB. The recording techniques in a DVD disc drive uses a laser source of wavelength 650 nm and an objective lens of 0.6 NA, which produces the spot size $\sim 1.1 \, \mu \text{m}$. As the size of the focus beam of DVD disc drive systems reduces to $\sim 1.1 \, \mu \text{m}$, a track pitch of the DVD is considered as $\sim 0.74 \, \mu \text{m}$, which produces the disc capacity 4.7 GB. With the invention of the blue-laser source, a BD disc drive uses a laser source of wavelength 405 nm and an objective lens of 0.85 NA,
which produces the spot size $\sim 0.48 \, \mu\text{m}$. The track pitch of the BD is $\sim 0.32 \, \mu\text{m}$, which produces the disc capacity 23 GB.

The readout signal is expressed as an eye pattern. Opening of the eye pattern determines the signal-to-noise ratio (SNR) of the readout signal. The data readout from the CD, DVD and BD systems are shown in Fig. 1.5 (bottom side). As data storage density increases from CD to DVD to BD, eye pattern becomes closer, which indicates that the sacrifice of the SNR. The requirement of the high SNR is one of the limitations in the current ODD systems.

1.3.2 ODD systems for 2P optical data storage

Introducing multi-layer recording can greatly enhance the data storage capacity of the optical disc recording system. Due to the strong scattering losses of the laser beam in the deep layers of an optical disc medium, current optical data storage techniques cannot increase the layer number by more than a few layers [9]. In order to reduce the scattering losses of the laser beam, a localised laser beam on the recording medium is required. The 2P process is one of the most promising techniques, as discussed in Section 1.2, because it has the strength of the absorption, which is equal to the square of the light intensity. Even though the principles of 2P recording have been introduced by a few authors [1, 10, 15], no 2P-enabled ODD system is currently being investigated. In this section, we will discuss the concept of and the challenges to developing a 2P-enabled ODD system.

1.3.2.1 Concepts of 2P based ODD system

Owing to its high spatial confinement, the 2P process can be implemented in an optical disc drive (ODD) system to enable high density optical data storage. An ODD system which can performs data recording by two-photon
(2P) absorption, and data readout by fluorescence detection, can be defined as a 2P-enabled ODD system. The 2P-enabled ODD system can be called a second-generation ODD system (where CD, DVD, and BD drives are the first generation ODD system). The concept of a 2P-enabled ODD system introduces 2P recording technology into the ODD system to perform high density optical data storage. In a 2P-enabled ODD system, the readout signal is the fluorescence beam, whereas, it is a reflected light beam in the current ODD systems. The servo system of the conventional ODD systems is related to the reflected light beams, where the reflected light beam is used for the data readout and the servo system. However, in a 2P-enabled ODD system, the data readout beam is fluorescence dependent. Hence, the servo system of the conventional ODD system cannot be implemented in the 2P-enabled ODD system. A new servo system is required to perform the 2P-enabled ODD operation. In this thesis, we have investigated the design of a 2P-enabled ODD system, including a recording system, a readout system, and a servo system.

1.3.2.2 Challenges of the 2P-enabled ODD system

The challenges of the ODD system for 2P optical data storage can be summarised as follows:

2P optical disc: There are two major challenges involved in 2P based optical disc fabrication. The first challenge is the preparation of the material in order to have a high sensitivity in response to the incident laser beams. The second challenge is to fabricate a disc that has a homogeneous layer thickness. If the disc is inhomogeneous, the unwanted signal can be introduced. In this case, the signal processing of the readout signal can be difficult, in terms of judging why unwanted signals are being introduced.

Optical pickup head (OPUH): Even though an optical disc is capable of
generating fluorescence, it is important for the OPUH to collect fluorescence efficiently. A basic OPUH is designed for the specific wavelength of the laser beam. However, in the case of 2P-enabled ODD system, two laser beams are used, where a pulsed laser beam for the recording and the reading operation, and a continuous-wave (CW) laser beam with a different wavelength is used for the servo operations. Therefore, the OPUH should be carefully characterised for the properties such as transmission, axial and lateral behaviours as a function of the wavelengths of the laser beams.

**Servo system:** The performance of the ODD system depends on the precision of the servo system. Care should be taken to select the wavelengths of the laser sources so that the fluorescence signal coming to the servo system’s photodetector can be avoided. Another aspect for consideration in the selection of the servo laser beam is the avoidance of the servo beam coming to the readout photo-detector, if it is within the range of the fluorescence generation signal. The optics of the servo system should be designed in such a way to ensure precision in the axially and radially. In order to maintain the robust servo system, a control algorithm is required.

**Recording system:** The main challenge of the recording system is to introduce the recording threshold power of the pulsed laser beam. Another difficult part of the recording system is to maintain the synchronisation between disc spinning, shutter speed and the laser beam.

**Reading system:** The most challenging part of any ODD system is the data readout process. The basic readout process relates to the precision of the servo system. In the readout process, the power of the pulsed laser beam should be such that there is no re-record happening but enough fluorescence signals are generated.
1.4 Thesis objectives

The ODD is an example of a complete opt-electro-mechanical device. Even though the invention of the ODD is a few decades old, there are many branches of physics, optics, electronics and mechanics that need to be investigated. With the high demand for information storage, scientists are constantly inventing new methods to improve the data storage capacity. In order to transform the updated science into consumer products, engineers are developing suitable ODDs. It is worth doing research in this field as it presents a wide array of challenges in the fields of physics and engineering; currently, these questions remains unsolved. The objective of this thesis is to develop an ODD system to complement the revolutionary idea of 2P high-density optical data storage.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{flowchart.png}
\caption{Flow of this PhD thesis}
\end{figure}

In this thesis, we have chosen the following research methodology, illustrated in Fig. 1.6. In order to design such a novel 2P-enabled ODD system, we have taken a DVD OPUH as a recording / reading objective and DVD disc substrates to fabricate 2P optical disc.
1.5 Outline of the thesis

This thesis has the following structure:

Chapter 2, Review: This chapter begins with a review of the state-of-the-art results of current optical data storage techniques. We then review recent research developments in the investigation of promising data storage techniques. ODD systems available in the current consumer market that fit current optical data storage techniques are then reviewed. Then we review the design of the ODD system needed to support 2P optical data storage; such a design is currently absent in the present research. Finally, we show why 2P-enabled ODD system is excellent blueprints for developing high-density optical data storage.

Chapter 3, 2P optical discs: In this chapter, we discuss the geometrical structure of the 2P optical disc. The preparation of the required 2P recording materials is then discussed. Then the process of the fabrication of the 2P optical disc is explained in detail. We then perform the measurement of the quality of the fabricated 2P optical discs. Finally, we show that the fabricated 2P optical discs are suitable for the 2P-enabled ODD system.

Chapter 4, Optical pickup head: This chapter focuses on the key features of the OPUH of the ODD system. We then experimentally characterise the optical performances of the objective lens of the OPUH, in terms of transmission, axial resolution, and lateral resolution as a function of wavelength under the illumination of broadband femtosecond pulsed laser beams. Importantly, we experimentally demonstrate the innovative femtosecond coupled OPUH for the first time. We finally characterise the feasibility of 2P recording and reading using the OPUH.

Chapter 5, 2P ODD system: In this chapter, we design a 2P-enabled
ODD system. In order to have such a precise 2P-enabled ODD system, we introduce the servo systems. We experimentally verify the servo system in the 2P-enabled ODD system.

Chapter 6, Focal temperature measurement: In this chapter, we investigate the measurement of focal temperature. Firstly, the principle of focal temperature measurement is discussed. Then, we perform experimental validation of the focal temperature measurements.

Chapter 7, Low energy density recording using gold nanorod dispersed discs: In this chapter, we concentrated on the three-dimensional (3D) recording under the 2P recording mechanism using the OPUH. GNRs are used as the 2P recording medium. We then experimentally demonstrate that the low NA objective can be used for the low energy density recording. Finally, we demonstrate the double layer recording using the advantage of the low energy density recording.

Chapter 8, Conclusion: In this chapter, we provide a summary and discussion of the results of this thesis. We then discuss the outlook of this research and propose future research based on the findings of this thesis.
Chapter 2

Review

2.1 Introduction

The two-photon (2P) technique, a revolutionary concept in current high-density optical data storage, has generated many scientific reports and articles [1, 2, 10, 16–20] which demonstrate the significant improvements it has contributed to this field of inquiry. However, compatible optical disc drive (ODD) systems are limited in their ability to transfer the promising optical data storage techniques to the consumer endpoint. The innovation of suitable 2P-enabled ODD system can plays an important role in the development of the consumer-applicable high-density ODD industry. In this thesis, we introduce the development of a 2P-enabled optical disc and drive system. In order to have a better understanding and the highly innovative nature of this thesis, a review of the-state-of-the-art developments in the field of optical data storage discs and drive systems is necessary. This chapter reviews the current developed techniques of optical data storage and ODD systems. This chapter is arranged as follows: Section 2.2 reviews the principle of optical data storage; Section 2.3 reviews the different recording methods and materials for optical data
storage techniques; Section 2.4 discusses the advances in the optical disc and drive technology, as well as the key to improving consumer-applicable ODD systems; and, finally, Section 2.5 summarises and discusses optical data storage and ODD systems.

2.2 Principle of optical data storage

Optical data storage is the technique of storing data on a medium, where a laser beam is used for the storing and retrieval of data. The principle of optical data storage and retrieval can be described as a two-step process [21]; the first step is the process of the recording of optical data marks on the surface of the recording medium, as shown in Fig. 2.1. To record the information on a disc medium, the information is first converted to the digital form, which is then encoded and modulated to act as a driving signal of the intense laser source. The laser source produces an intense light beam with the particular wavelength, which contains the encoded digital data information in a modulated form. The intense laser beam is first collimated, and then directed to the recording optics to accomplish the recording process on the surface of the storage medium. The objective lens of the recording optics focuses the collimated laser beams, and due to the focused intense laser beam, a small localised region of the surface is heated by the absorption of energy from the intense laser beam. When the heat under the small localised region reaches a critical writing threshold, the reflective properties of the localised surface changes and it forms a single recorded bits. The data encoding methods used in the information recording process can determine the amount of information recorded in a single recorded bit under the localised region.

The second step is the process of the optical data retrieval from the pre-
recorded medium. The process of the optical data readout from the pre-recorded disc is illustrated in Fig. 2.1 (dashed line marked as data read). In this process, an intense laser beam scans the surface of the pre-recorded medium. To avoid re-recording in the readout laser beams scanning processes, the power of the laser beams are used at a constant output level that does not heat the data surface medium beyond its thermal recording threshold. As the pre-recorded data marks passes under the scanning laser beams spot, the reflected laser beam is modulated due to the land-pit combination or the data marks. The illumination optics collects the modulated laser beam and then directs it to the data detection optics by a beam splitter. The data detection optics consists of a few focusing optics and a photo-detector. The photodetector in the data detection optics changes the reflected modulated laser beams into the current modulation form, which then amplified with a certain gain and sent to the decoder to perform data decoding operations. The decoder decodes the amplified current modulation signal and then produces the output
data stream. The output data stream is the final readout data.

2.3 Optical data storage techniques

The refractive index change of the material is used in the optical data storage process; the higher the change of the refractive index, the higher the contrast of the recorded data. The refractive index change of the material is the function of the interaction between the electric field of the focused laser beam and the responses of materials. Depending on the electric field property of the focused laser beam illumination on the recording medium, the optical data storage techniques can be categorised as ‘far-field’, ‘near-field’, and ‘holographic’ recording. In this section, we will introduce different types of the optical data storage techniques available in the present research field.

2.3.1 Holographic recording

In the field of high-capacity optical data storage, another potential technology is holographic data storage [22–24]. In this data storage technology, the information is recorded throughout the volume of the recording medium. The idea of holographic data storage is to record information within a thick photosensitive optical recording material by using the optical interference. In this method, a single laser beam is divided into two separate optical patterns of bright and dark pixels respectively. Multiple holograms can be formed and stored on a single recording volume by adjusting the reference beam angle, the wavelength or the media position. This technology is capable of storing multiple states of information in the same recording area by adjusting the light beam at different angles.
In order to read pre-stored data, a reference beam is used to reproduce the holograms. When the reference light beam is focused on the photo-sensitive material, the light diffracts on the interference pattern and projects on the detector. Fig. 2.2 shows the basic data writing and reading mechanisms of the holographic data storage techniques. Fig. 2.2a, depicts the writing process of the holographic data storage, where a laser beam is split into two paths; one beam acts as a reference beam and the other beam is used for the writing beam. The writing beam is modulated by the spatial light modulator to modulate the recording pattern and to store it in the recording medium. The readout process is explained in Fig. 2.2b, where only the reference beam is used to read the recorded data. In the readout process, the storage medium is placed between the reference beam and the photo-detector. The photo-detector detects the
readout data and reconstructs the image.

### 2.3.2 Near-field recording

Obviously, a small spot size can increase the storage capacity. However, due to the diffraction limit, the spot size cannot reduce further. The near-field recording mechanism [26] is a potential candidate for increasing storage capacity, because of its small focus spot. In order to produce extremely small focal spot in near-field optical recording, evanescent energy is used.

![Figure 2.3 System of near-field recording using a) SIL and b) Aperture [27]](image)

Because of the relatively smaller spot size and the higher throughput, compared to a conventional ODD system [27], a solid immersion lens (SIL) [28] is used in the near-field optical data recording and reading system, as shown in the Fig. 2.3a). Another attractive technique to reduce the spot size is to use the aperture system [29] shown in Fig. 2.3b). Recently, a plasmonic lens [30] and a super lens [31] have been used to break the diffraction limit in the near-field optical data storage.

In near field recording, size of the recorded bit significantly is reduced. The
reduced bit size increases the storage capacity. However, to build such a system is extremely complex. It is due to the very close distance between the near-field writing optics and the storage disc. In this system, it is required external mechanism to transfer disc to and from the system, which makes the system extremely bulky and costly.

2.3.3 Far-field recording

The widely used focal lengths of the objective lens in far-field recording is a few times the illumination laser beam wavelength, which forms a diffraction limited spot on the storage medium. The use of the far-field optical recording techniques is of particular interest to ODD recording technology, where replacing the recording medium is a frequent requirement. However, the wavelength of the light beam and the NA of the objective lens limit the resolution of the far-field recording technique. In this section, we will review the currently available far-field recording techniques and its storage capacity.

2.3.3.1 Conventional optical data storage

In conventional optical data storage technology, the CD [21], DVD, BD, and the high definition digital versatile disc (HD-DVD) are examples of far-field recording [32] technology, where the spot size of the recording medium is diffraction limited. The size of the spot is \( d = \frac{\lambda}{2\tan(\text{NA})} \), where \( \lambda \) is the wavelength of the laser beam and \( \text{NA} \) is the numerical aperture of the objective lens. In order to increase the recording density, a shorter laser beam wavelength and a higher \( \text{NA} \) of the objective lens are highly desirable. The storage capacity of the conventional optical data storage were discussed in the previous chapter (see Section 1.1 and Section 1.3.1).
2.3.3.2 3D recording

Conventional optical data storage technology is based on the storage information contained on the 2D surface of the recording medium. Due to the diffraction limit, the spot size is limited to the laser wavelength for the given NA of the objective lens. In order to achieve high-density optical data storage, researchers are looking for alternatives techniques to overcome the diffraction limit. Gu et al [9] indicated that conventional 2D surface recording mechanism uses only 0.01% of the volume of the recording disc. By adding axial dimensions $x - y - z$ in the disc, the recording density can be greatly increased. The use of the $x - y - z$ space of the recording medium is called the ‘3D recording’.

One drawback of this multi-layer or 3D recording is the strong scattering loss from the different layer of the recording medium. When a recording laser beam focused inside the volume of the recording medium, the laser beam is scattered. The scattering effect is stronger for the shorter wavelength of the laser beam. Due to the scattering effect in the different layers, the energy of the laser beam cannot be used efficiently for the multi-layer or 3D recording [9]. This obstacle can be overcome by the revolutionary idea of 2P excitation under the illumination of an infrared femtosecond pulsed laser beam. Walker et al. [16–18] demonstrated the 3D recording, where recording capacity achieved 1 Tbytes using a 2P optical recording medium in 200 layers.

In 3D recording, data recorded in three-dimensional surface of the recording medium. In this recording technique, storage capacity eventually increases. However, due to the strong scattering losses of laser beam into the deeper layer, recording layer is limited. This is the one of the disadvantages of 3D recording technique.
2.3.3.3 Multi-dimensional recording

The diffraction limitation predicts that the maximum storage capacity induced by 2P excitation is approximately $3.5 \text{Tbitcm}^{-3}$ [9] for an objective lens of $\text{NA} = 1.4$ after aberration correction. Another approach to increase the storage capacity without breaking the diffraction limit is to encode multi-states of information in other physical dimensions of the recording beam, such as polarisation and spectra.

![Spectral and polarisation encoding](image.png)

**Figure 2.4** Data record in spectra and polarisation domains [13]

Multi-dimensional optical data storage is third-generation optical data storage (CD is the first generation optical data storage and DVDs, BDs and 3D data storage are second generation) and the concept of multi-dimensional optical recording is to record multi-states of information in the same spot of a recording medium. The information can be multiplexed into different dimensions of a recording beam, such as spectra, polarisation, and three spatial dimensions. The basic principles of spectral and polarisation encoding are shown in Fig. 2.4, expressed by the three-colour (red, blue and green) spectral encoding and
the two polarisation states (0 and 45) of the polarisation encoding system. Three letters are encoded in the same spot with three different colours in the spectral recording system; C is recorded with red laser beam, M with blue laser beam and P with the green laser beam within the same spot. Owing to the sharp spectral sensitivity, the recorded patterns C, M and P can be distinctively addressed by corresponding reading wavelengths of red, blue and green laser beams respectively. Two polarisation angles - 0 and 45 degrees - are used to record two letters A and D, respectively, for polarisation encoding techniques. In polarisation readout system, A and D can be distinctively readout with corresponding polarization angles.

Li [13] demonstrated the four-dimensional (three spatial dimensions and polarisation encoding) optical recording, using 2P excitation. Two polarisation angles are used to record information in each layer, with each pattern consisting of 24 x 24 bits, with bit separation of 2.6 µm. The spacing between the adjacent layers is 20 µm. It has been demonstrated that it is possible to encode two states of polarisation information in the same spatial region. The storage capacity achieved is approximately 50 Gbits/disc. It is possible to increase the recording density by multiplexing more states of information in the same spatial region provided that the recording material has a sharp photosensitivity.

Zijlstra et al. [10] demonstrated an integration technique of spectra, polarization and three spatial dimensions, called a ‘five-dimensional (5D) optical data storage’. The concept of the 5D optical recording technique is illustrated in Fig. 2.5. Eighteen images in three layers are shown in Fig. 2.5. A single femtosecond pulsed laser beam at wavelengths of 700 nm, 840 nm and 980 nm, in both horizontal and vertical polarization states, is used in this pattern recording and readout system. Ten recording and readout layers with 10 µm spacer layer and a bit spacing equal to the bit diameter of 0.75 µm leads to the
recording density of 1.1 Tbit cm$^{-3}$ and is equivalent to the storage capacity of 1.6 Tbyte for a DVD sized disc. This bit-by-bit multi-dimensional recording technique is compatible with optical data storage techniques currently in existence in the ODD industry.

### 2.4 Optical recording disc and drives

Reliable data can be recorded and readout from the conventional ODD system, regardless of its low capacity. In order to design a high-capacity 2P-enabled ODD system, an understanding of the basic construction, operation and the limiting factors of the current reliable ODD systems is required. In this section, we will discuss the advancement of recording media and techniques from the early stages of information storage technology to the present day. The construction and operation of the compatible ODD system is also reviewed and we discuss the challenges of realising a next-generation ODD system.

Fig. 2.6 shows the schematic of the architecture of an ODD system [33].
basic ODD system is composed of an optical disc, an optical pickup unit, a servo system and the control mechanism. Section 2.4.1 discusses the optical disc format, optical disc construction, fabrication, and the materials used in the current ODD. The optical pickup head (OPUH) architectures, working principles and transfer functions are described in section 2.4.2.

![Schematic of optical disc drive](image)

**Figure 2.6** Schematic of optical disc drive [33]

### 2.4.1 Optical disc

The most popular types of optical discs available are CDs, DVDs and BDs. These discs can be found in different formats, such as read-only memory (ROM), write-once read-many (WORM), re-writable (RW), mass-replication moulded and so on. In the ROM format, the pre-recorded data cannot
be altered or modified. Based on the ROM format, the optical discs are categorised as CD-ROM, DVD-ROM and BD-ROM [34–36] respectively. In WORM format, the unrecorded area can be recorded, but previous recorded data is not erasable. The optical discs with WORM format are known as the recordable discs; the latter can be found as CD-R, DVD-R and BD-R [37, 38]. In the RW format, the data can be re-writable with the erasing of pre-recorded data. Similar formats for the optical discs are available in the consumer markets as CD-RW, DVD-RW, and BD-RW [39, 40].

The physical dimension of the optical discs (CDs, DVDs and BDs) are constructed with a 120 mm diameter and a 1.2 mm thick poly-carbonate substrates [34, 38, 41].

![Physical format of an optical disc](image)

**Figure 2.7** Physical format of an optical disc

The optical discs information zone is subdivided into three parts:

**Lead in zone:** The lead in zone of the optical discs contains the table of contents (TOC), which contains all the information on the disc, such as data starting point, data end point, the data format etc [42]. The lead in zone starts at diameter 45.2 mm and ends at diameter 48.0 mm.

**Data zone:** The data zone starts after the lead in zone. The data zone of the optical disc starts at diameter 48 mm and ends at diameter 116 mm.

**Lead out zone:** The lead out zone is the end zone of the optical disc. The
lead out zone of the optical disc starts from at diameter 116 mm and ends at diameter 120 mm.

Fig. 2.7 depicts the physical format of the current optical disc. The disc is constructed using a transparent poly-carbonate plastic substrate. The substrate is composed of spiral land-groove structures, which are used to perform tracking and focusing activities. The pitch of the land-groove is called the tracking pitch, which is the function of the information storage capacity. To have high-density optical data storage, minimisation of the track pitch is required. The track pitch of the CD, DVD, HD-DVD and BD are 1.6 µm, 0.74 µm, 0.46 µm, and 0.32 µm, respectively.

### 2.4.2 Optical pickup head

The optical pickup head (OPUH), which is used to perform recording and reading, is the key component of the ODD system. It consists of a laser source, a photo-detector, a beam splitter, an objective lens, a focusing actuator and a tracking actuator. Depending on the application, an OPUH is designed by considering laser beam wavelength, the NA of the objective lens and the actuators. An OPUH is designed for the specific laser wavelengths: for example, CD OPUH - 780 nm laser beam [43–45]; DVD OPUH - 650 nm laser beam [38, 39, 46]; and BD OPUH - 405 nm laser beam [47–50].

The schematic of the OPUH is shown in Fig. 2.8. When the optical disc is in the spinning mode of operation, the dynamic movement of the focus point of the objective lens is necessary to track the movements. The focus point movement of the objective lens in the dynamic mode is known as the actuator. Such an actuator is a 2D actuator.

In order to move the lens in the axial and the radial direction, the OPUH
comprises two actuators (focusing actuator and tracking actuator). The major components of the OPUH consists of the optical, servo, and electric components [42], which are described in details in the following sections.

2.4.2.1 Optical transfer

When a disc is spinning, the relative position between the disc and the focus of the objective lens deviates. The deviation of the focal position happens in both the axial and the radial directions of the focus. In order to compensate for the deviation, a precise measurement is required, and this inspection of the spinning disc deviation needs to be non-contact.

Optical transfer is the mechanism of transferring the information of the spinning disc deviation in the form of a feedback signal, where optics is used for the non-contact measurement. In the optical transfer, a quad-photo-detector
Fig. 2.9 shows the block diagram of the optical transfer in the OPUH. The function of the optical transfer is to send a signal to the actuator to move the required position in the axial and radial direction. The objective lens of the OPUH collects the reflected laser beam from the spinning optical disc. The reflected laser beam contains the information both of the axial \((z_{\text{disc}})\) and the radial directional \((x_{\text{disc}})\) deviations. The reflected laser beam is directed to the optical transfer block. The QPD in the optical transfer block translates the optical signal into the electrical signal. The QPD generates two types of electrical signals; one for the axial deviation - called the focus error signal (FES), \(e_{\text{axial}}\), and the other for the radial deviation - called the radial/tracking error signal (TES), \(e_{\text{radial}}\). The focus error signal, \(e_{\text{axial}}\) and the track error signal, \(e_{\text{radial}}\) are then directed to the feedback loop.

For focus error signal,
\[
e_{\text{axial}}(s) = z_{\text{disc}}(s) - z_{\text{actuator}}(s) \tag{2.1}
\]
where, \(z_{\text{actuator}}(s)\) is the position of the actuator.
For track error signal,

\[ e_{\text{radial}}(s) = x_{\text{disc}}(s) - x_{\text{actuator}}(s) \]  (2.2)

where, \( x_{\text{actuator}}(s) \) is the track coil of the actuator position.

The feedback loop introduces the required gain to the FES and the TES, and they are then directed to the actuator, which moves the objective lens to the required axial and the radial position.

To drive the actuator, the focus error control signal is

\[ z_{\text{fes}}(s) = K_{\text{fes}} e_{\text{axial}}(s) = K_{\text{fes}} (z_{\text{disc}}(s) - z_{\text{actuator}}(s)) \]  (2.3)

and the radial/track error control signal is

\[ x_{\text{tes}}(s) = K_{\text{tes}} e_{\text{radial}}(s) = K_{\text{tes}} (x_{\text{disc}}(s) - x_{\text{actuator}}(s)) \]  (2.4)

Where \( K_{\text{fes}} \) and \( K_{\text{tes}} \) are the feedback loop of the FES and the TES, respectively.

### 2.4.2.2 Servo system

The system that supports optical transfer is called the servo system, which consists of the optics and the feedback loop. The servo system in the ODD system is needed to establish the stability of the axial and radial deviation. The section of the servo system performing the focusing stability is called the ‘focusing’ servo system and the section performing the radial stability is called the ‘tracking’ servo systems.

There are several methods of the focusing servo system [52–65] introduced in the current ODD systems. The most popular method of the focusing servo system is the astigmatic method [56, 59, 62, 63, 66–68]. In this method, a QPD is used to sense the disc deviation from the focus of the objective lens. Fig. 2.10 show the focus error (FE) detection using the astigmatic method. The QPD is composed of four channels - A, B, C and D. The summation of the signal of
all the channels is called the ‘radio frequency’ (RF) or ‘high frequency’ (HF) signal. When the optical disc is located exactly in the focus of the objective lens, the reflected beam spot is evenly distributed over the four quadrants. In this case, each quadrants of the QPD generates an equal amount of current signals, where RF signal become the maximum. If the disc deviates too-far from the focus of the objective lens, the spot of the reflected beam changes to an ellipsoid shape and it is oriented along the B-D channels. As the size of the shape decreases, so the RF signal decreases. In contrast, if the disc is too-close to the focus of the objective lens, the ellipsoid-shaped spot is oriented along the A-C channels. Similarly, the RF signal magnitude decreases.

![Focus error detection](image)

**Figure 2.10** Focus error detection [69]

Each quadrant of the QPD may not be equally sensitive. In this case, the signals need to be calibrated properly with sufficient gain. The RF signal can
be defined as

\[ RF = k_a A + k_b B + k_c C + k_d D \]  (2.5)

where, \( k_a, k_b, k_c, \) and \( k_d \) are the calibration coefficient of channels \( A, B, C, \) and \( D, \) respectively. The RF signal is used to measure the signal strength in order to trust the error signals. The possible error signals are guaranteed only if the RF signal is greater than the threshold value, \( RF_{\text{thres}} \) [69]. Based on the RF signal characteristics, the focus error signal can be defined, when \( RF \geq RF_{\text{thres}}, \) as follows :

\[ FE = k_{fe} \{(k_a A + k_c C) - (k_b B + k_d D)\} \]  (2.6)

where \( k_{fe} \) is a calibration coefficient of the FES. The calibration of the channel signal and the FES are conducted by the digital signal processor (DSP).

As the spinning optical disc deviates from the focus of the objective lens, the generated FES behaves as an S-curve around the focus of the objective lens, as shown in Fig. 2.10. The linear region of the S-curve is the detection window of the optical discs FE. Beyond this linear detection window, the reflected signal becomes diffuse, which turns the FE signal back to zero. The linear region of the FE is within a few microns. It is about 10 \( \mu \)m for CD [69].

In addition, the optical disc deviates both axially and radially. The error due to the radial deviation is called the ‘track error’ (TE) signal. The TE is the process of the measuring possible radial deviation of the optical discs. Several methods of the TE detection for different optical disc media have been reported in the literature previously [33, 52, 57, 60, 63, 70–87]. The most popular methods of TE detection are: the 3-beam method; the phase-detection method; and the differential push-pull (DPP) method.

The method of 3-beam TE detection was developed for the CD-ROM, where CDs are in pre-recorded condition. Fig. 2.11a) shows the TE detection using the 3-beam method. In this method, a laser beam is split into three beams
through diffraction grating. The central beam is reflected from the disc, which generates the channel signals by a photo-detector; whereas, the two sub-beams generates the E-channel and F-channel signals in the photo-detector. The two sub-beams are separated by a quarter of the track pitch; hence, two different intensities are produced due to deviation of the disc from the track centre. Therefore, the TE is equivalent to the intensity difference of the two reflected sub-beams. In this case, the TE can be defined as [69]

\[ TE = k_{te}(k_e \cdot E - k_f \cdot F) \]  

where \( k_{te}, k_e, \) and \( k_f \) are the calibration coefficient of the TE signal from the E-channel and F-channel, respectively. This method is comparatively insensitive to disc tilt, lens shift, and defocus [88]. The 3-beam TE detection method requires additional optical instrumentation to support three beams, which makes the system extremely bulky and less cost effective. For this reasons,
this method is not suitable for recording disc.

In general, the recording optical disc media are composed of land-groove architecture. In order to detect the TE for the land-groove structured optical disc, the DPP method was introduced. Ideally, this method is suitable for CD-Recordable (CD-R) or CD-Rewritable (CD-RW) discs. In this method (as shown in Fig. 2.11b), the sub-beams are located half way along the track pitch, which produces the sub beam push pull (PP) signal, as in [69]

\[ SPP = k_e E + k_f F - (k_g G + k_h H) \]  

(2.8)

where \( k_e, k_f, k_g, \) and \( k_h \) are the calibration coefficients of the E, F, G and H-channels, respectively. Due to the height gap between the land and the groove, the main beam PP signal can be defined as [69]

\[ PP = k_a A + k_d D - (k_b B + k_c C) \]  

(2.9)

The resulting differential push-pull track error signal can be defined as [69]

\[ TE = PP - k_{dpp} SPP \]  

(2.10)

where, \( k_{dpp} \) is the calibration coefficient of the PP signal. Compared to the 3-beam TE method, the DPP tracking method is highly robust in the face of disc tilt. As a result, the DPP method has improved reading capability compared to the 3-beam method.

With the advancement of optical storage techniques, in order to fit high-density optical data storage, DVD technology has introduced the narrow track pitch 0.74 \( \mu \)m with the land-groove structure. The DPP method can be used in DVD-Recordable (DVD-R) and DVD-Rewritable (DVD-RW) discs, where the optical disc is formed with the land groove structure. However, the DVD disc without the land-groove structure needs a different TE generation method. In the current DVD technology, a differential-phase-detection (DPD) scheme is used for tracking purposes [89]. The DPD method is applicable for the disc
containing data pits. The phase of the diagonal term defined as

\[ AC = k_a A + k_c C \quad \text{and} \quad BD = k_b B + k_d D \]  

(2.11)

The phase differences between the AC and BD indicate how well the beam spot is located over the track. When the laser beam spot is perfectly located over the track, the detectors A-channel and D-channel, and B-channel and C-channel have equal light intensities. In this case, no phase difference can be observed. If the light beam is slightly off-centre to the right of the track, the detectors B-channel and C-channel have no pits and light intensity is fairly flat. And the detectors A-channel and D-channel have pits, so the light intensity with the phase difference can be observed in A-channel and D-channel. Alternately, if the laser beam spot is slightly off centre to the left of the track, the detectors A-channel and D-channel have no pits, whereas, the detectors B-channel and C-channel have most of the pits. Hence, phase difference can be observed in the B-channel and C-channels of the detectors and flat signal for the A-channel and the D-channel. The TE of the DPD, which is linear with respect to the disc error, and makes the control system simpler [52].

2.4.3 Control mechanism

The application of the control system engineering plays a very important role in the ODD system. The basic control systems required to control the ODD are: spindle speed control; focusing coils control; and, tracking coils control, etc.

In constant linear velocity (CLV), the disc rotates at varying rotation speeds when the OPUH moves from the inner radius to the outer radius of the discs. In this case, high speed is required in the inner radius and the low speed is required in the outer radius of the discs. To solve this problem, an adaptive speed profile design can be employed. In the adaptive speed profile design,
the disc rotation speed is the function of the disc’s radius [90]. The analytical
design of the adaptive speed profile for the tracking, and the seeking of the
ODD can be found in [90–93]. However, there is no control system found
suitable for the 2P-enabled ODD system. We have designed the spindle motor
control for the 2P-enabled ODD system, which is described in Appendix A.

Another important control system is the control of the OPUHs tracking and
focusing actuator based on the signal generated in the servo system. The most
commonly used control system is the robust proportional-integral-derivatives
(PID) control. Some other methods, such as disturbance observers (DOB)
method [33, 94, 95], repetitive control [78, 96–99], iterative learning control
[100], and fault detection and the shock disturbance methods [69, 101]. For
the simplicity, in this thesis, we use the PID control system throughout the
design. The details of the controller design are discussed in Appendix C.

2.5 Chapter conclusion

In this chapter, we have reviewed the current state of the art of the optical data
storage techniques, the optical disc formats, and the ODD systems available
in the current devices. Based on the review of the current state of the art of
the optical data storage, two-photon process is one of the most promising
techniques for the next generation high density optical data storage. In
two-photon optical data storage technique, the data recorded by two-photon
absorption and the data readout by two-photon fluorescence detection. In two-
photon process, the strength of the absorption is proportional to the square of
the light intensity. Two-photon recording can be performed by an infrared
femtosecond pulsed laser beam. It has highly confinement properties and
high efficiency of penetration into the volume of the recording medium, which
assist to record data in multiple layer of the recording medium. Another
important milestone is that, the two-photon recording can be performed by using a high power continuous wave (CW) laser in photochromic and photorefractive material, which eventually replace femtosecond pulsed laser. In addition to this, by choosing a suitable material data can be recorded in the multi-dimensions, which significantly increase the data storage capacity. For example, using gold nanorods as a recording medium, data storage can be increased to 1.6Tbytes/disc by manipulating multi-states of information such as polarization and wavelength in the 3-dimensions of the recording medium. However, there has so far been no demonstration of multi-dimensional recording under 2P excitation in the ODD systems. Therefore, the development of an ODD system to support 2P recording technique became the motivation for the present PhD project.

The basic theory of the optical data storage techniques and systems also reviewed, along with the necessary control algorithms used in the current ODD technology. Finally, an indication of a suitable control system for use in our 2P-enabled ODD system is given.
Chapter 3

Two-photon optical discs

3.1 Introduction

As previously discussed, the enhancement of optical data storage capacity via, two-photon (2P) excitation method is a promising route. The use of the nano-particles inside the optical discs, which performs as a recording medium, enables the optical discs as the 2P recordable optical discs. Even though recent research has shown that the nano-particle based optical recording gives a high-density optical recording capability [10], there is no research on the nano-particle based 2P optical discs. In this chapter, we describe the nano-particle based 2P optical disc fabrication to facilitate the high-density optical recording in the 2P-enabled optical disc drive (ODD) system. To this purposes, this chapter is organised as follows. Section 3.2 discusses the 2P optical discs in details. This discussion includes the disc structures, the recording material preparation procedure and the 2P optical discs fabrication process. The fabricated disc characterised in Section 3.3. Finally, this chapter concludes with Section 3.4.
3.2 Optical discs

In the optical data storage process, the data is stored inside the optical discs. In order to facilitate the efficient information recording inside the optical disc media, a well-designed disc structure is required. In this section, we discuss the design of an optical disc that can support 2P excited optical data recording and reading capabilities.

3.2.1 Disc structure

The optical disc was designed based on the consideration of the working distance of a 0.6 NA objective lens of the DVD optical pickup head (OPUH). A second consideration was to couple two wavelengths of the laser beam. One is for the 780 nm wavelength and the second is for the 658 nm wavelength, which are used for the recording and the reading and the servo system, respectively.

![Disc structure](image)

*Figure 3.1 Disc structure*

The optical disc is 120 mm in diameter and has a 0.6 mm thick substrate and a 0.6 mm thick cover. Fig. 3.1 depicts the cross-section of the designed 2P embedded optical disc. The optical disc substrate was made with the 0.6 mm thick poly-carbonate transparent layer. The substrate was composed of a
land-groove structure. The pitch of the groove was $0.74 \, \mu m$. A 0.01 mm thick glue layer was used as a spacer between the discs substrate and the recording layer. As a recording medium a 0.03 mm thick gold nanorod (GNR) layer was used. In order to add further recording layers or a cover layer, a 0.01 mm thick glue layer was used as a spacer between the recording layer and the recording layer or the cover layer. The disc cover layer was a 0.6 mm thick transparent poly-carbonate layer. The cover was the plain disc, where there are no land-groove structures. The purpose of the cover layer was to protect the optical disc from the external disturbances.

### 3.2.2 Preparation of recording materials

The aim of this section is to prepare the recording material for the 2P optical disc fabrication. In order to perform the high-density recording information, the promising solution is to use surface plasmon of GNR [10]. GNRs are synthesised with the well-known recipe developed by the groups of El-Sayed et al. [102]. In our experiment, at first, we prepared Cetyl-trimethylammonium bromide (CTAB) capped gold seeds. The gold seeds were prepared in a 10 mL aqueous solution; the solution contained 0.1 M CTAB and 0.25 mM $HAuCl_4$. To this solution we added 16 mM ice-cold $NaBH_4$. To grow seeds, the solution was put aside for 1 hour. In the growth solution we added a certain amount of $AgNO_3$ and 0.75 mM freshly prepared ascorbic acid. Nanorods growth was initiated by adding 6 $\mu l$ per mL of the seed solution. The solution was kept aside for 24 hours and measure the absorption spectra to find the aspect ratio of the growth nanorods.

Fig. 3.2 shows the absorption spectra of synthesised GNRs. The absorption peak of the synthesised GNR is at 780 nm. The two-photon emission spectrum of the gold nanorod in PVA matrix shown in Fig. 3.2 c).
3.2.3 Disc fabrication

In order to fabricate 2P optical disc, we use a 600 $\mu$m thick and 120 mm diameter DVD sized optical disc. The optical discs substrate has the similar groove structure as the DVDs optical discs, where the track pitch is 0.74 $\mu$m. A second optical layer of 600 $\mu$m is used as a cover layer, which protects the information materials from the external dust particles. The recording materials and the layer spacing materials are sandwiched between the substrate layer and the cover layer.

Fig. 3.3 shows the basic process of the 2P disc fabrication. The disc fabrication process can be divided into four steps. The first step is to form a $\sim 10$ $\mu$m thick layer on the substrate disc using an ultraviolet (UV) curing resin; the
layer is called spacer layer. Transparent glue is used as a spacer material. In the second step, a $\sim 30 \, \mu m$ thick layer is formed on the spacer employed substrate disc by using UV curing resin; the layer is called recording layer. In order to protect the recording materials from external disturbances, a $\sim 10 \, \mu m$ thick spacer layer is used on top of the recording layer. Finally, a 600 $\mu m$ disc is used as a cover layer. In the disc bonding operation, pressure sensitive adhesive (PSA) is used.

The disc was fabricated using a disc fabrication machine provided by Anwell Technologies Limited. Fig. 3.4 shows the disc fabricator and the composition of the disc fabrication machine used to fabricate 2P disc.

Disc fabrication procedures using the fabrication machine are described below:

1. Space layer dispensing and coating on a substrate at C1.

2. UV curing at C1.

3. Recording layer dispensing and coating on the space layer coated substrate at C2.

4. Space layer dispensing and cover layer bonding on the recording layer at
5. Space layer coating at C1.

6. UV curing at C1.

We optimised a coating speed and dispensing volume of the recording layer at C2. Table 3.1 shows a recipe for the fabrication of a homogeneous recording layer. A 5 ml mixture of the GNRs at 780 nm absorption with poly(vinyl alcohol) (PVA) (10%wt) solution was coated as the recording layer on top of the space layer. We changed acceleration, velocity and time into six stages for the coating. After the PVA coating using this recipe, we could confirm
Table 3.1 Recipe for the fabrication of the homogeneous recording layer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recording material</td>
<td>Gold nanorods @780 nm peak</td>
</tr>
<tr>
<td>Polymer matrix</td>
<td>PVA solution (Sigma Aldrich), 10% wt</td>
</tr>
<tr>
<td>Sample volume</td>
<td>5 ml</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Steps</th>
<th>Acceleration</th>
<th>Velocity</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>500</td>
<td>300</td>
<td>3000</td>
</tr>
<tr>
<td>2nd</td>
<td>500</td>
<td>500</td>
<td>3000</td>
</tr>
<tr>
<td>3rd</td>
<td>1000</td>
<td>1000</td>
<td>5000</td>
</tr>
<tr>
<td>4th</td>
<td>1000</td>
<td>3000</td>
<td>2000</td>
</tr>
<tr>
<td>5th</td>
<td>1000</td>
<td>4000</td>
<td>2000</td>
</tr>
<tr>
<td>6th</td>
<td>1000</td>
<td>1000</td>
<td>3000</td>
</tr>
</tbody>
</table>

3.3 Characterisation of the fabricated 2P optical discs

Fig. 3.5 shows the fabricated 2P optical disc. The bottom layer of the disc is contained highly reflective surface, where servo beam reflected from that surface for the servo operation. On top of the reflected layer, we have incorporated recording layer, where recording and reading beams performed recording and reading operations.

The performance characteristics of the optical disc depend on the thickness and the uniform distribution of the recording materials. The optical disc flatness also has an impact on the disc quality to perform the recording and the reading operation effectively. In order to characterise the fabricated disc, we need to measure the thickness and the uniformity along the disc area.
In this section we will discuss about the developed techniques to measure the thickness of our fabricated 2P optical discs. Second part of the characterisation is the measurement of the uniformity of the fabricated disc from the inner radius to the outer radius.

### 3.3.1 Thickness measurement

We have performed thickness measurement of the designed 2P gold nanorod dispersed disc by using Z-scanning fluorescence detection method. Fig. 3.6 shows the experimental result of the fabricated discs thickness measurement. The absence of the fluorescence indicates the focal beam illuminating outside of the GNRs sample.

The fluorescence can be observed only when the objective lens is focused inside the recording medium. The measured thickness was found $\sim 30 \pm 3 \, \mu m$.

### 3.3.2 Lateral uniformity measurement

To perform record or read from the right surface, it is important to have uniform discs. In order to measure the uniformity we scanned the optical disc
Figure 3.6 2P thickness of the fabricated gold-nanorods dispersed disc. Inset shows the absorption spectra of the gold nanorods.

along the radial direction from the inner radius to the outer radius of the discs. By measuring the thickness of the disc from inner radius to the outer radius, we can perform the uniformity test of the fabricated optical discs.

Fig. 3.7 depicts the lateral uniformity of the fabricated 2P optical disc. The scanning range of the disc is from 35 mm to 58 mm. The variation of the disc thickness along the disc radius is

\[
T_{\text{variation}} = \frac{t_{\text{max}} - t_{\text{min}}}{t_{\text{max}}} \times 100\% = \frac{31.8 - 29}{31.8} \times 100\% = 8.5\%
\]  

(3.1)

where, \( t_{\text{max}} \) is the maximum thickness and \( t_{\text{min}} \) is the minimum thickness of the disc. The thickness variation of the fabricated 2P optical disc is 8.5\%. 


In this chapter, we have discussed properties of the 2P optical discs through the design and the fabrication. The fabrication process includes material preparation for the disc fabrication, the disc structure design, the fabrication process etc. After that, we have characterised the fabricated optical discs thickness and uniformity. The thickness of the fabricated disc was measured to be $\sim 30 \pm 3 \ \mu m$. The thickness variation of the fabricated disc is $8.5\%$. The measurement results indicate that the fabricated disc is suitable for the 2P-enabled ODD system.

3.4 Chapter conclusion

In this chapter, we have discussed properties of the 2P optical discs through the design and the fabrication. The fabrication process includes material preparation for the disc fabrication, the disc structure design, the fabrication process etc. After that, we have characterised the fabricated optical discs thickness and uniformity. The thickness of the fabricated disc was measured to be $\sim 30 \pm 3 \ \mu m$. The thickness variation of the fabricated disc is $8.5\%$. The measurement results indicate that the fabricated disc is suitable for the 2P-enabled ODD system.
Chapter 4

Characterisation of an optical pickup head

4.1 Introduction

The operating band of the gold nanorod (GNR) dispersed discs for two-photon (2P) recording and reading is 600-800 nm. In order to perform 2P recording and reading, the objective lens of the optical pickup head (OPUH) should support the 2P bandwidth. The operating wavelength of the OPUH [51] is 650 nm for digital versatile disc (DVD) and 780 nm for compact disc (CD), which is close to the 2P bandwidth. With these key wavelengths (650 nm and 780 nm) capabilities, we implement the OPUH in the 2P-enabled optical disc drive (ODD) systems. Even though the OPUH is capable of operating at two wavelengths, there are several parameters such as the pulsed laser beam incorporation, the transmission, the axial behaviour, the lateral behaviour, the 2P recording and reading required to characterise before it can be implemented to the 2P-enabled ODD system.

In this chapter, we address the key parameters of the OPUHs. The exper-
mental demonstration of the reading performances such as the transmission, the axial behaviour, the lateral behaviour and the 2P reading is explained in Section 4.2.1. In Section 4.2.2, we demonstrate the 2P recording performance of the OPUH. We conclude the chapter in Section 4.3.

4.2 Optical performance of the OPUH

The OPUH consists of an objective lens of 0.6 NA that has previously been used for the ODD systems. The conventional ODD system is developed based on the reflection microscope systems. However, the characteristics of the objective lens of the OPUH under the 2P excitation are as yet unknown. The characteristics are classified into two key categories - the reading performance and the recording performance. In this section, we experimentally demonstrate the reading and the recording characteristics of the objective lens of the OPUH, which is used in our 2P-enabled ODD system.

![Figure 4.1 Experimental setup for OPUH characterisation](image-url)
Fig. 4.1 shows the experimental setup for OPUH characterisation. It includes a beam splitter, which splits the laser beam reflecting from the optical discs and directs it to the photo-detector. In our study, however, we need to specify the laser beam path optics. In order to fit our experimental condition, we separate the detection optics and electronics from the actuators, where the actuator contains the objective lens, the tracking coils and the focusing coils.

4.2.1 Reading characterisation

The objective lens of the OPUH is designed for the collection of the recording and reading signal from the recordable disc. The recording and reading mechanism of the 2P process is different than the DVD recording and reading mechanism. In our 2P-enabled ODD system, we used DVD OPUH. It is necessary to know that the recording laser source and the readout signal from the 2P disc are suitable for the 2P-enabled ODD system.

4.2.1.1 Transmission

One of the requirements of the 2P recording is to use multiple spectra. To this end, it is important for the objective lens to have a broad bandwidth capability. The transmittance of the objective lens can be defined as [103]

\[ t(x, y) = \frac{U_2(x, y)}{U_1(x, y)} \]  

(4.1)

where \( U_1(x, y) \) and \( U_2(x, y) \) are the light fields in the planes immediately before and after the objective lens respectively.

The experimental results of the transmission characteristics of the objective
lens at different wavelengths are shown in Fig. 4.2. The result shows that the transmission is more than 50% for the incoming laser beams of the wavelengths range between the 700 nm and the 900 nm. The transmittance window of the objective lens is potentially useful for the spectrum encoding when an infrared pulsed laser is employed as the excitation source. The verification of employing multiple wavelengths for our 2P data recording techniques is described in the following sections.

4.2.1.2 Axial response versus wavelength

In the three-dimensional (3D) data storage systems, a layer spacing is required to avoid the interference between the different recording layers. The axial response of the light distribution near the focal region is important as it determines the ability of the 3D imaging of an optical imaging system [104]. Hence, high axial resolution is important to increase the recording density in volumetric recording. The axial behaviour of the light distribution near the
focal region is given by [103]

\[ I (v = 0, u) = (N)^2 \left( \frac{\sin \frac{u}{4}}{u/4} \right)^2 \]  

(4.2)

and

\[ u = \frac{2\pi}{\lambda} \Delta z \left( \frac{a}{f} \right)^2 \]  

(4.3)

where \( N \) is the Fresnel number, \( u \) is the axial coordinate, \( \lambda \) is the wavelength of light, \( a \) is the radius of the lens aperture and \( \Delta z = z - f \), \( z \) is the distance between the objective and the sample.

To characterise the 3D recording capability of such an OPUH by incorporating the femtosecond laser beams, we have performed the axial imaging measurement. The axial resolution of the objective lens of the OPUH was characterised as a function of the excitation wavelength from 700 nm to the 900 nm, as shown
in Fig. 4.3. The axial resolution of the objective lens of the OPUH was found to be in the range of 3 \( \mu m \) to the 9 \( \mu m \) \[105\], which indicates the possibility of the 3D volumetric recording using the low NA DVD micro-optics.

### 4.2.1.3 Lateral resolution versus wavelength

In order to determine the bit separation requirement in the recording system introduced by the objective lens of the OPUH, the lateral distribution characterisation is required. Analysis of the lateral/radial intensity distribution is a method of the study the imaging characteristics in a plane for a given objective lens. After successfully determining the image plane \((z = f)\) (with the help of axial scanning described in Section 4.2.1.2), in-plane (radial/transverse) imaging is analysed. The radial intensity of the point spread function at the focal plane can be expressed as \[103\]

\[
I(v) = (\pi N)^2 \left[ \frac{2J_1(v)}{v} \right]^2
\]

\[4.4\]

\[
v = \frac{2\pi ar}{\lambda f}
\]

\[4.5\]

and

\[
NA = \frac{na}{f}
\]

\[4.6\]

where \(v\) is the radial optical coordinate, \(r\) is the radial position of the image plane.

The purpose of this experiment was to characterise the point spread function of the optical pick-up system. Even though optical pick-up system able to detect fluorescence from the recording material (gold nanorods), the point spread
function of the optical pick-up system cannot be performed. It is because, the illumination of the femtosecond pulsed laser may change the shape of the gold nanorods, which may give inaccurate lateral resolution of the pick-up system. On the other hand, fluorescent microbeads are high quantum yield material, so a low power of femtosecond pulsed laser can emit strong fluorescence from the micro beads. As a result, optical pick-up systems lateral behaviors can be obtained accurately if we use fluorescent micro beads to measure point spread function.

The image quality can be evaluated from the radial intensity distribution. The lateral resolution of the OPUH was characterised by using the fluorescent 1 \( \mu m \) micro-beads dispersed optical discs. The lateral resolution defined by the full width half maximum (FWHMs) was found to be in the range of 0.8 \( \mu m \) to 1.3 \( \mu m \) for the excitation wavelengths from 700 \( nm \) to 900 \( nm \), as shown in Fig. 4.4 [105]. The measured lateral resolution is consistent with the diffraction limited case as [103].
\[ d = \frac{1.22\lambda}{NA} \]  

(4.7)

where, \( \lambda \) is the wavelength of the laser beam and \( NA \) is the numerical aperture of the objective lens of the OPUH.

### 4.2.1.4 Two photon readout

Before implementing the optical pick-up system in the two-photon optical disc drive system, it is important to check whether pick-up system is capable of performing two-photon imaging. The purpose of this experiment was to characterise optical pick-up head for two-photon (2P) readout ability. To investigate the 2P readout characteristics, we used fluorescent micro-beads of size 1 \( \mu m \). The fluorescent micro-beads are a high fluorescence quantum yield material.

![2P readout image](image)

**Figure 4.5** 2P readout image

A femtosecond laser beams at the 780 nm wavelength was coupled to the objective lens of the OPUH to excite the fluorescent micro-beads. Fig. 4.5
Chapter 4

shows the static readout image of the fluorescent micro-beads. The size was found to be $\sim 1.2 \mu m$. This experiment indicates that the selected pick-up system is capable of performing 2P readout. By this experiment, we can the pick-up system is suitable for two-photon optical data storage drive system.

4.2.2 2P recording characteristics

To characterise the 2P recording with the OPUH, we use 2,5-dimethyl-4-p-nitrophenylazo (DMNPAA) doped in un-plasticised polystyrene (PS) with 9-ethylcarbazole (ECZ) as a recording medium. The sample was prepared followed the recipe produced by Li [13] with modification. At first, the mixture of 30 wt. % of DMNPAA and 70 wt. % of PS were dissolved in chloroform. Then to get rid of the solvent, solution was evaporated at 60$^\circ$C for 20 minutes. Then the sample was placed on a 600 $\mu m$ thick DVD poly-carbonate disc substrate between spacers and heated at 200$^\circ$C for 3 minutes. The polymer sample was cooled down to room temperature. Another 600 $\mu m$ thick DVD poly-carbonate disc was glued as a cover layer to protect the recording layer.

In order to confirm DMNPAA as a 2P recording material, we have performed fluorescence intensity measurement as a function of laser intensity. A Ti:sapphire ultra-short pulsed laser beam of pulse width 100 fs at a wavelength of 780 nm was focused by the optical pickup head of NA = 0.6 onto the sample. The fluorescence intensity was collected by the optical pickup head and acquired by a photo-multiplier tube (PMT) for fluorescence images. A short pass filter was used to block the scattered laser beam. The dependence of the fluorescence emission intensity on the excitation laser beam intensity is plotted in Fig. 4.6 on a log-log scale. The slope of the linear fit is 1.98 $\sim$ 2, which confirmed the 2P absorption induced emission.

Now we demonstrate the 2P recording capability of the optical pick up head
using DMNPAA as a 2P recording material. A femtosecond laser beam of wavelength of 780 nm, 80 MHz repetition rate is used for the 2P recording. A mechanical shutter of 25 ms exposure was used to encode information with the laser beam illumination.

Fig. 4.7 shows the reconstructed readout image of the recorded pattern. The recorded pattern was consist of $4 \times 4$ dots with 4 $\mu m$ bit separation. The size of each dot is $\sim 1.45$ $\mu m$. 

**Figure 4.6** Fluorescence intensity dependence of the DMNPAA emission under 2P excitation on a log-log scale. The slope of the linear fitting is $1.98 \sim 2$. 
Fig. 4.8 shows the 2P recording as a function of the recording power. The optimised recording power is 25 mW. The size of the recorded spot is $\sim 1.45 \mu m$, which is matched with the diffraction limited spot size. Fig. 4.8 shows the
bit readout contrast as a function of recording power. The contrast is defined as,

\[ C = \left| \frac{(I_{\text{bit}} - I_{\text{back}})}{(I_{\text{bit}} + I_{\text{back}})} \right| \]  

(4.8)

where \( I_{\text{bit}} \) is the bit intensity and \( I_{\text{back}} \) is the background intensity. At 25 mW laser power, contrast found to be 0.08. We did not observe any contrast if we decrease the power label below 25 mW for recording.

### 4.3 Chapter conclusion

In this chapter, the OPUH was used to characterise the 2P techniques. To utilise DVD OPUH in the 2P-enabled ODD system, we have characterised the axial and the lateral behaviours of the objective lens. Finally, we have characterised the OPUH to perform the 2P recording and the reading. The 2P recording and the reading performance of the OPUH makes it a suitable candidate as an objective lens for 2P-enabled ODD system.
Chapter 5

Two-photon optical drive system

5.1 Introduction

The key parts of the optical disc drive (ODD) are an optical disc and an optical pickup head (OPUH). In the previous Chapters 3 and 4, we have characterised the two-photon (2P) recording capability with the fabricated optical disc and the OPUH, which lead us to develop the 2P-enabled ODD system. The basic requirements of all ODD systems are the recording system, the reading system and the precise servo system. The overview of the 2P-enabled ODD system is discussed in Section 5.2. One of the critical issues in the ODD system for the 2P recording is to maintain the synchronisation between the fluorescence generation in the 2P optical disc, and the fluorescence collection by the detection apparatus. To solve this problem, it is essential to have a speed profile of the spindle motor in the different linear positions on the discs. In order to generate the speed profile of the spindle motor, a detailed understanding of the behaviour of the spindle motor is required. In Appendix A, a detailed description of the spindle motor behaviour and the speed profile generation are provided. The recording and the reading efficiency depends
on the precision of the focusing and the tracking servo systems. Section 5.3
discusses the summary of this chapter.

5.2 Drive system

Fig. 5.1 shows a schematic of the 2P-enabled ODD system. It is composed of
a recording system, a reading system and a servo system. The servo system
consists of a focusing servo, a tracking servo, and a spindle servo. The recording
and the reading medium, called the optical disc, is physically connected with
the spindle motor. Fig. 5.2 shows the experimental setup of the 2P-enabled
ODD system.

The basic recording and reading speeds for high throughput depend on the
characteristics of the spindle motor. The spindle servo ensures the desired
speed and precision of the recording and the reading behaviour. In the ODD
system, the spindle motor (EC 32 flat) is used. The maximum speed of the
spindle motor is 25000 rpm (rotation per minutes). To sense the angular
information, the spindle motor has built-in hall sensors. Details of the spindle
motor selection, control mechanism and spindle servo for the 2P-enabled ODD
system are discussed in Appendix A.

In order to have a linear motion in the 2P-enabled ODD system, a high
precision (0.1 μm resolution) Thorlab (LNR 50SE) translation stage is used.
Compared to the coarse actuator of conventional ODD systems (see Section
2.4, Fig. 2.6), this stage has the same functionality with high precision (0.1 μm
resolution). The travelling range of the stage is 50 mm, making it a suitable
candidate as a substitute of the coarse actuator to cover the whole region of
the disc. To translate the coarse action, we mount the 2P optical disc on top
of the linear translation motor.
As it is a 2P-enabled ODD system, it is important to maintain the position of the optical axis as accurately as possible. To avoid any uncertainty in the optical axis misalignment, we keep the fixed optical alignment throughout the system. In order to perform the robust operation, we keep the objective lens fixed in position, where the movement of the focus position through the Z-scanning technique. With the Z-scanning technique, different focus positions of the objective lens can be achieved without changing the actual position of the OPUH.

![Figure 5.1 Schematic of the 2P-enabled ODD system](image)

After setting the coarse position with the linear translation motor, fine tuning can be done with the help of the tracking and the focusing coils associated with the OPUH. To track the axial and the radial deviations of the recording medium, a system called the tracking and the focusing servo system is developed. In this servo system, a laser source at a wavelength of 658 nm is used.
In order to avoid any destruction in the recording medium, the servo laser beam is focused in the groove structure rather than the recording layer. A movable beam expansion method is introduced to keep the focusing servo beam in different positions to the recording laser beam. When the servo laser beam reflects from the optical disc surface, it contains information about the optical disc rotational speeds, and the axial and radial deviations. To detect the reflected servo laser beam, a quad-photo-detector (QPD) is used. The combination of a spherical lens and a cylindrical lens is used to modulate the reflected servo laser beam to extract the information from the spinning disc.

In order to have 2P recording and reading, a relatively high-powered laser beam is required. To meet this requirement, a pulsed femtosecond laser source is used. It is wavelength tuneable (700 nm -1000 nm) and has a high repetition rate (80 MHz). The recording system includes a femtosecond laser source and beam shaping optics. The beam shaping optics consists of a linear polariser, a half wave plate, a beam expansion optics and a beam focusing optics. The purpose of the beam expansion optics is to perform Z-scanning operation. A mechanical shutter is used to modulate the recording beam. The required modulation of the recording beam is generated by a computer.

![Experimental setup of the 2P-enabled ODD system](image)

**Figure 5.2** Experimental setup of the 2P-enabled ODD system
simulated program. As a control program, LabVIEW is used to compute the speed requirement of the shutter, the linear motion of the linear motor, and the speed of the spindle motor.

A dichroic mirror is used to pass the recording and reading laser beams and to reflect the servo laser beams. To detect the 2P fluorescence, a high sensitive photo-multiplier tube (PMT) is used. Several low pass and band pass filters are used to subtract the unwanted light signal entering into the PMT. The collected light signal by the PMT is weak in magnitude. A pre-amplifier is used to amplify the detected signal before it enters the computer for the readout reconstruction. Care should be taken for the selection of the readout laser power so that destructive reading can be avoided.

5.2.1 Z-scanning

Fig. 5.3 shows the schematic of the designed Z-scanning method. In this method, two additional lens are used, where first one is in fixed position and the second one is used for the focus position movement purposes. The second lens is placed over the precise movable stage. When the stage is moved step-by-step, the corresponding focus position of the objective lens is transferred along the axial directions. The focus position transportation is the function of the second lens movement. By detecting the fluorescence signal from the recording medium, the thickness of the recording medium can be measured.

By considering the lens approximation [106], the focus position shifting can be expressed as

\[ z = \frac{f_0(u_2f_0 + f_2)}{u_2(u_2 + f_2) - D(u_2 - f_2) - f_2f_0} \]  

(5.1)
where, $f_0$ is the focal distance of objective lens, $f_2$ is the focal distance of the moving lens, $D$ is the distance between objective lens and the object position and $u_2$ is the moving distance of the moving lens.

Fig. 5.4 shows the focal position of the objective lens shifting as a function of the moving position of the second lens. Considering the parameters $f_0 = 3.05$ mm, $f_2 = 100$ mm and $D = 500$ mm, for the drive systems, the designed system can transfer focal position to $\sim 400 \mu m$. 
5.2.2 Servo system

When the disc is spinning, vibration of the disc can be introduced. This vibration of the spinning disc is due to the inertia of the spindle motor, and the gravitational force acting on the weighted disc and disc mounting accessories. This external disturbance-like vibration generates the wobbling of the recording disc. The wobbling of the disc causes a deviation from the perfect focusing position in axial and radial directions. The axial response of the focusing spot is 3 to 9 $\mu m$ (see in Chapter 4, Sections 4.2.1.2 and 4.2.1.3). In the case of the disc wobbling, the deviation of the disc varies in the scale of sub 100 $\mu m$ to sub millimetres. Reliable recording cannot be achieved with this large deviation range. In order to maintain the laser beam spot in the recording layer, a highly precise servo system is required to track and correct the disc wobble.

The target of the research of servomechanism of 2P-ODD was to collect fluorescence from the recording and reading surface efficiently. Similar to the commercial CD/DVD/BD servo system, 2P-ODD servo system consist of tracking servo and focusing servo. The purposes of tracking and focusing servo systems are compensating lateral and axial deviations respectively.

In our 2P-ODD system, we have selected longer wavelength at 780 nm pulsed laser beam as a laser source similar to CD’s laser beam, and an optical pick up head of 0.6 NA objective lens similar to DVD’s objective lens. Because of these selections, the precision of the servo system is limited between CD’s and DVD’s precision. In commercial CD, DVD and BD, track pitch precisions are 1.6 $\mu m$, 0.74 $\mu m$ and 0.32 $\mu m$ respectively. In BD drive system, another tilting servo system is used to acquire high precision.

The precision requirement of the tracking servo system is depends on the lateral resolution of the objective lens of the optical pick-up head. Based on the lateral
resolution characterization of the pick-up system the tracking servo’s precision is limited to 1.45 \( \mu \text{m} \).

The precision requirement of the focusing servo system is depends on the axial resolution of the objective lens, which is 3\( \mu \text{m} \) to 9\( \mu \text{m} \) for our optical pick-up head. In order to focus the laser beam on the recording layer efficiently, variation of the focus laser beam should be limited to 9\( \mu \text{m} \).

Since the conventional optical data storage system is the reflective type device, the servo system of the conventional ODD system is not applicable to the 2P-enabled ODD system. The 2P-enabled ODD system requires a multi-colour sensitive servo system. In this section, a detailed description of the design of the servo system and its characteristic performance are discussed.

\section*{5.2.2.1 Servo system design}

Since 2P optical data storage systems store information in a localised spatial position, a servo system with a high precision is key for such high performance.
Fig. 5.5 shows the scheme of the designed servo system. A laser diode at a wavelength of 658 nm is used as the servo laser beam. An OPUH with numerical aperture (NA) of 0.6 is used to record data and follows the tracking and focusing signals through the built-in tracking and the focusing coils. As the recording laser beam and the servo laser beam are operated at different wavelengths, a tunable beam expansion system is incorporated to enable the adjustment of the focal position within the volume of the optical disc. A quarter wave plate (QWP) is used to convert a linearly polarised laser beam to a circularly polarised beam before focusing onto the groove structure of the optical disc. A dichroic mirror is used to combine the servo laser beam and the recording/reading laser beams. The reflected servo laser beam is directed at the QPD by a pair of spherical and cylindrical lenses. The detected signal conveys the information about the radial and axial position of the optical
disc with respect to the OPUH. Through monitoring the shape change of the reflected servo beam, the position of the disc, either in-focus or out-of-focus, can be discerned. A home-built servo circuit with a high sensitivity is used to make the tracking and the focusing signals in the QPD. Before applying the tracking and focusing signals to the actuators, a digital signal processor (DSP) is used to further process the signal.

**Seeking or surface detection servo:** Initial surface detection is performed with the help of the beam expansion process.

![Figure 5.6 Surface detection method](image)

The process of the surface detection is shown in Fig. 5.6. As the optical disc has been fabricated with the highly reflective groove structure, the servo beam is designed to track the highly reflective surface. The movable beam expansion is used to look for the highly reflective surface. Once the servo beam finds the highly reflective surface, the QPD detects a high intensity which is the summation of the four quadrant signals of the QPD. The integrated signals of the four detectors are called the radio frequency (RF) signal. For example, the four quadrants are labeled as A, B, C and D, then RF signal = A+B+C+D. The RF signal is the reference for the servo surface of the optical disc. The
frequency of the RF signal can be used to extract the disc spinning speed.

**Focusing servo:** After the seeking operation, the seeking servo finds the operating disc servo position to track it. When the optical disc starts to spin, it is important to dynamically track the operating position of the disc. The astigmatic method [54, 56, 67] of the focusing servo is used in the focus tracking of the ODD system.

![Figure 5.7 Schematic of focus servo system](image)

Fig. 5.7 shows the scheme of the focus servo system. The combination of a cylindrical lens and a spherical lens is used to define the focusing performance. In order to detect the servo signal we used a QPD (OSI SPOT 4DMI) [107] as shown in Fig. 5.8.

The size of the spot detected by the QPD depends on the combination of a
spherical lens and a cylindrical lens in the servo detection path. To have an efficient response from the QPD, the spot size needs to be matched with the active area of the QPD.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective lens numerical aperture, NA</td>
<td>0.6</td>
<td>-</td>
</tr>
<tr>
<td>Objective lens focal depth, $f_{\text{obj}}$</td>
<td>3.05</td>
<td>mm</td>
</tr>
<tr>
<td>Collimator lens focal depth, $f_{\text{col}}$</td>
<td>50.2</td>
<td>mm</td>
</tr>
<tr>
<td>Distance between collimator and objective lens, $d_1$</td>
<td>150</td>
<td>mm</td>
</tr>
<tr>
<td>Cylindrical lens focal depth, $f_{\text{cyl}}$</td>
<td>100</td>
<td>mm</td>
</tr>
<tr>
<td>Distance between collimator and cylindrical lens, $d_2$</td>
<td>15</td>
<td>mm</td>
</tr>
<tr>
<td>Distance between cylindrical lens and photo-detector, $d_3$</td>
<td>25</td>
<td>mm</td>
</tr>
<tr>
<td>Photo-detector size, $d$</td>
<td>0.25</td>
<td>sq. mm</td>
</tr>
</tbody>
</table>

Table 5.1 Parameter of the servo system model
Fig. 5.9 shows the simulation result for the beam pattern on the QPD. Parameters used in the simulation are shown in Table 5.1. In the simulation, the disc deviation is considered as +/- 20 \( \mu \text{m} \). When the optical disc is in-focus, the shape of the beam is circularly symmetric and, in this condition, the half axis of the beam \( a \) is equals to \( b \). From the simulation result, the red curve shows that the beam is in-focus. In the focus condition, the size of the beam is \( \sim 400 \ \mu\text{m} \). When the optical disc deviates from the focus position, the laser beam on the QPD becomes elliptical in shape.

When the distance between the optical disc and the objective lens is shorter than the focus position, the half axis \( b \) becomes greater than the half axis \( a \), \( (b > a) \). When the disc move far away from the objective lens focus position, the half axis, \( a \), becomes greater than the half axis, \( b \), \( (a > b) \).
**Tracking servo system:** The focusing servo system compensates the axial deviation (or out-of-plane) and tracks focal plane of the objective lens in the recording layer. The uncertainty of the focus position is due to the deviation of the disc in the lateral direction. In order to compensate the lateral walking off, the optical disc substrate is designed as a land-groove structure. In the optical disc substrate, the land-groove structure is fabricated as a spiral form, called the track. The aim of the track is to guide the laser beam spot in the lateral direction. The magnitude of the periodic separation between the land and the groove called the ‘track pitch’. The system, to guide the laser beam spot along the track, is called the ‘tracking servo system’.

![Tracking servo system](image)

**Figure 5.10** Tracking servo system

In this research, we use the push-pull method of the tracking servo system. Fig. 5.10 illustrates the concepts of the push-pull tracking servo system in the ODD systems. When the disc is on-track, the diffracted beam is 0-order and the intensity distribution in the quadrants of the A-D and B-C of the QPD are equal. When the laser beam spot is out-off track, a +1-order or -1-order beam generated, which changes the light intensity distribution in the A-D channel and the B-C channel. According to the push-pull tracking method,
the tracking error signal (TES) is defined as

\[
TES = \frac{(V_A + V_D) - (V_B + V_C)}{V_A + V_B + V_C + V_D}
\]  
(5.2)

where, \(V_A\), \(V_B\), \(V_C\), and \(V_D\) are the voltages generated in the A, B, C and D channels of the QPD, respectively.

The relationship between the tracking error signal and the laser beam tracking can be expressed as

\[
\begin{align*}
TES > 0, & \quad \text{the beam spot is out of the track (+1 order beam)} \\
TES = 0, & \quad \text{the beam spot is on the track (0 order beam)} \\
TES < 0, & \quad \text{the beam spot is out of the track (-1 order beam)}
\end{align*}
\]  
(5.3)

To compensate the tracking error an control algorithm needs to design to have \(TES = 0\). The details of the tracking error control algorithm is discussed in Appendix C.

5.2.2.2 Performance analysis

The performance of a servo system depends on the performance of the servo optics and servo electronics. In this section we experimentally demonstrate the servo performance designed for the 2P-enabled ODD system.

**QPD characterisation:** The QPD is composed of the four channels, which are expressed as A, B, C and D. The performance of the QPD depends on the photo-sensitivity of each channel. In general, each channel is specified as equally photo-sensitive. However, in practice, the photo-sensitivity of each of the channel can be changed. To implement it in the system precisely, the
calibration of the photo-sensitivity of each of the channel is essential. In this section, we have performed the calibration of the photo-sensitivity of each quadrant of the QPD.

**Figure 5.11** Generation voltages in the QPD

Fig. 5.11 shows the QPD’s detection voltages of each of the quadrants as a function of the disc deviation (+/- 20 µm) from the centre of the focused servo laser beam. The voltage produced by the QPD is negative in magnitude. The generated voltage of the QPD is proportional to the summation of the incident laser beam onto the QPD surface [67]. In this section, we have experimentally demonstrated the QPD’s generated voltages. Fig. 5.12 shows the experimental images of the beam shape changes due to the disc deviations.

When the disc is in-focus (z=0), the shape of the reflected beam falling on the QPD is circularly symmetric and an equal amount of voltages is generated from
the each quadrant of the QPD, as illustrated in the inset of Fig. 5.11. When the disc is too-close to the objective, an elliptical beam shape is formed as shown in Fig. 5.11 (top left). In this case, the voltage generated in the quadrants B, \(V_B\) and D, \(V_D\) are greater than the voltage generated in the quadrants A, \(V_A\) and C, \(V_C\). When the disc deviates from too-close position to the too-far position, the elliptical shaped beam changes its orientation. When the disc is too-far as shown in Fig. 5.11 (top right), the voltage generated in the quadrants A and C are greater than the voltage generated in the detectors B and D. Even for the ideal conditions \((V_A = V_C)\) and \((V_B = V_D)\), we have observed \((V_A > V_C)\) and \((V_B < V_D)\). It is because the QPD surface is slightly misaligned at the incident beam.
S-curve: In order to determine the detection range of servo systems, it is important to generate the focus error signal as a function of disc deviation range. The specification of the servo systems depends on the S-curve performance. The quality of the S-curve is determined by the two-parameters: lock-on range and acquisition range [67].

Lock-on-range: The lock-on-range is the area between the two peaks of the S-curve. The physical area between the two peaks represents the physical displacement that a system is able to compensate.

Acquisition-range: The acquisition range is the peak value of the focus, where the magnitude of focus error signal is large enough to attain the focus. It is the physical strength of the signal to move the focus coil according to the
deviation in the focus plane.

Fig. 5.13 is the experimental demonstration of the S-curve in the designed servo system. The experiment is performed with a disc deviation from -60 µm to +60 µm. The focus error signal can be defined as 

\[ e_F = (V_A + V_C) - (V_B + V_D). \]

When the disc is too-close as shown in Fig. 5.13 (top left), the voltage generated in detectors B and D are greater than the voltage generated in detectors A and C, which results in a negative focus error signal. The centre part of Fig. 5.13 shows the disc is in-focus. For in-focus condition, 

\[ V_A = V_B = V_C = V_D, \]

in which the focus error signal, \( e_F \), becomes zero. When the disc is too-far as shown in Fig. 5.13 (top right), the generated detector voltage is 

\[ (V_A + V_C) > (V_B + V_D), \]

in which the focus error signal, \( e_F \), becomes positive in magnitude.

The lock-on range is the linear range of the S-curve. In the experimental characterisation, as shown in Fig. 5.13, the lock-on range is found ±30 µm. When the disc moves too-close (beyond -30 µm) or too-far (beyond +30 µm), the linear shape of the S-curve is broken, the system becomes unstable.

The acquisition range of the servo system is ±0.4 V. If the disc moves closer than -30 µm or further away from +30 µm, the focus error signal becomes close to zero. Even though the focus position is not in-focus, the zero focus error signal indicates the system is not stable. It is because the focus error signal strength is not large enough to lock or acquire the objective lens with the deviation of the disc.

**Surface detection / RF signal:** To detect the surface, the maximum intensity of RF is required. The groove structure of the optical disc is coated with a high reflective material. When the servo beam is focused onto the groove
structure, a high intensity of the reflected beam is expected. The frequency of the RF signal tells the actual disc spinning speed.

![Figure 5.14](image)

**Figure 5.14** RF signal when the disc spinning speed is a) 100 rpm, b) 300 rpm, c) 400 rpm, d) 600 rpm, e) 800 rpm, and f) 1000 rpm

Fig. 5.14 shows the RF signal of the systems, where the disc spinning speed varies from 100 rpm to 1000 rpm. The RF signals plotted in Fig. 5.14 (a to f) are the normalised signal. The peak intensity at different speeds varies within 0.8 V, which is within the acquisition range (the acquisition range can be consider as: ±0.4V ≈ (|−0.40| + |0.40|) V ≈ 0.8V). The peak value of the RF signals represents that the disc is on the surface (or in-focus). The RF signals fluctuation to the level of 0.2 V represents that the disc deviates the surface (or out-of-focus). As the spinning speed of the disc increases, the RF intensity level decreases. This is due to the lower data acquisition time at high speed. Even at high speed, the strength of the RF signal is large enough to acquire the focus via the focusing system.

The optical disc is connected with the rotor of the spindle. The speed of the
disc relies on the speed of the spindle motor. Due to the possible mechanical imperfection between the spindle rotor and the disc, the actual speed of the spinning disc differs from the speed of the spindle motor. The ODD system performance relies on the spinning disc performance. For this, a measure of the actual speed of the spinning disc is required.

The actual speed (or frequency) of the spinning disc is determined by the frequency of the RF signal. In Fig. 5.14 (a to f), the scale bar of the speed indicates the spindle speed. The actual speed of the disc is represented by the fluctuation of the RF signals. The required number of peaks, $N_p$, of the RF signal for the corresponding spindle speed, $N_s$, is related to

$$N_p = \frac{N_s}{60} \quad (5.4)$$

In the experiment, we have shown that the measured frequency of the spinning disc is slightly different from the spindle motors speed. For example, in Fig. 5.14 (c), the spindle speed is 400 rpm. According to Equation 5.4, at the speed of 400 rpm, the required number of peak is $\sim 6$. But, actual number of peaks generated is 5. The differences is due to the less coupling efficiency between the optical disc and the spindle motor. In order to generate the clock, the ideal spindle speed is used. However, in our 2P-enabled ODD system, we use the frequency of the RF signals to generate the system clock.

**Focus error signal:** In order to perform the focusing sensing, the focus error signal is measured when the disc is spinning. The focus error signal is measured using the astigmatic methods.

Fig. 5.15 shows the experimental demonstration of the focusing error signal generation. In this case, the optical disc is spinning at 1000 rpm. The
focus error signal fluctuates from the origin or zero position. The fluctuation indicates that the disc comes close to the objective lens and moves away from the objective lens. The positive acquisition range of the system is found $+0.1\,V$ and the negative acquisition range of the system is found $-0.2\,V$; corresponding disc deviations are $7.5\,\mu m$ and $-15\,\mu m$ respectively. The result indicates that the acquisition range is in the acceptable range of the detection window.

**Track error signal:** We have characterised the tracking performance of the servo system. In order to determine the radial deviation we keep the disc spinning speed at 1000 rpm. When the disc deviates from the track, the tracking error signal fluctuates from the zero position. The tracking error voltage provides the equivalent voltage of the radial deviation.

Fig. 5.16 shows the tracking error signal for the spinning disc. When the disc is on track, the tracking error signal become zero. The sinusoidal nature of the tracking error signal indicates that the disc is wobbling when it is spinning.
Figure 5.16  Tracking error signal

The sinusoidal tracking error signal peak magnitudes are 0.1 V (positive peak) and 0.08 V (negative peak).

**Fluorescence readout signal:** 2P material is used as the recording medium. A femtosecond laser beam is used to excite the fluorescence signal. The detection of the fluorescence signal in the dynamic system is difficult, due to the fluctuation or wobbling when the disc is spinning. The uncertainty of the fluorescence detection can produce the unwanted image during the data readout process. This is because, even in the absence of the fluorescence, the system would treated it as a recorded dot.

Fig. 5.17 shows the fluorescence readout signal, before and after applying the servo signal. The red curve in the Fig. 5.17 shows the fluorescence fluctuation without the servo system. The fluctuation magnitude indicates that, during spinning, the disc is in-focus and out-of-focus. The magnitude near to zero (0) indicates that the disc is out-of-focus, whereas the magnitude level of 0.75
Figure 5.17 Fluorescence readout with a servo system

indicates the disc is in-focus position. The perfect servo system can provide the magnitude level near to 0.75, when the disc is spinning. Under ideal conditions, there should be no fluctuation in the fluorescence detection and the fluorescence level maintain at the magnitude of 0.75 (flat line).

Before applying control signals, the uncertainty of the signal is

\[ S_{\text{without}} = \left( \frac{v_h - v_l}{v_h} \right) \times 100\% = \left( \frac{0.75 - 0.1}{0.75} \right) \times 100\% = 86.67\% \quad (5.5) \]

where, \( v_h \) is the maximum fluorescence level and \( v_l \) is the lowest fluorescence level.

In order to reduce fluorescence fluctuation, we have applied a servo control system. The blue curve of Fig. 5.17 shows the fluorescence detection after the implementation of the servo system.

After applying servo control signals, the uncertainty of the signal is

\[ S_{\text{with}} = \left( \frac{v_h - v_l}{v_h} \right) \times 100\% = \left( \frac{0.75 - 0.7}{0.75} \right) \times 100\% = 6.67\% \quad (5.6) \]
With the servo system, the uncertainty of the fluorescence detection reduced to 6.67%. This uncertainty is due to the disc eccentricity, the non-ideal uniformity of the fluorescence material, and disc inertia.

5.3 Chapter conclusion

In this chapter, we described the design of an ODD system for 2P optical data storage. Our designed 2P-enabled ODD system consists of a spindle servo system, a seeking servo system, a focusing and tracking servo system, a reading and a recording system. To support the recording and reading performances under in-focus and on-track condition, we have designed the servo system.

As mentioned above, the precision of the servo system is required to collected fluorescence efficiently from the recording layer of the two-photon disc. The variation of the fluorescence indicates the disc deviation. Implementing the servo system into the readout system, we have demonstrated that the fluctuation of the fluorescence detection is minimised. Before applying the servo system, the uncertainty of the florescence in the fluorescence readout was 86.67%, whereas after applying servo signal, the uncertainty of the fluorescence in the fluorescence readout was reduced to 6.67%, which is equivalent to 3µm deviation. It is also indicates the disc deviates 1.5 µm from the track of the optical disc, which is close to our design requirement.

Comparing to the CD, DVD and BD drive system, our designed servo system is highly precise than CD but less than DVD and BD. It is because; in DVD and BD comparatively shorter wavelength of laser beam (650 nm ion DVD and 405 nm in BD) and high NA objective lenses (0.6 NA in DVD and 0.85 NA in BD) are used. However, we used longer wavelength of laser beam at 780 nm and low NA objective lens. In our case, the designed precision fulfilled our requirement. Lastly, multilayer recording capability greatly increases the recording density.
in 2P-ODD even though little sacrifice lateral density compared to DVD and BD.
Chapter 6

Focal temperature measurement

6.1 Introduction

Several common laser applications such as device fabrication [108, 109], laser writing technique [108, 110–114], optical data storage [10, 105, 115, 116], and magnetic recording [117, 118] extensively use focused laser beams to change the refractive index of materials [2, 119–122], the shape change of the particular nanoparticle [10, 115, 123] and so on. In this interaction, the energy of the focused laser beam produces heating in the focal region. In all the applications, an understanding of both the process in which heat is generated due to the focused laser beam, as well as a firm knowledge of the manipulation of the amount of the heat, are required in order to achieve the desired outcome.

Unfortunately, there has been no reliable method developed to measure the heat generation in the focal volume of a focused laser beam. In this study, we investigate and compare the amount of the heat produced in the following conditions: (1) with different thermal conducting materials; and (2) with different surface-to-volume ratios caused by varying the numerical aperture (NA) of the objective lens. In the experiments, we focused on the “two-photon
(2P) optical disc” to measure the induced temperature increment where gold nanorods (GNRs) are used as heat sources, and quantum dots (QDs) are used as nano-thermometers.

This chapter is organised as follows: In Section 6.2, the principle of the temperature measurement is discussed; the temperature measurement in the GNRs dispersed disc is investigated in Section 6.3, including the details of the experimental mechanisms, experimental results, and the experiment comparing heat generation using different thermal conductive materials and different surface-to-volume ratios; finally, this chapter is concluded in Section 6.4.

### 6.2 Principle of temperature measurement

The principle of the temperature measurements is based on the idea of the measurements of the focal temperature by observing the red-shifting of QDs emission spectra [124]; in this case, GNRs were used as nano-heaters and QDs as nano-thermometers.

In order to perform thermometry operation, a small amount of QDs can be added with the GNR sample. To avoid significant modification of the GNRs extinction spectra due to the QDs being doped, the QDs concentration should be kept as low as $4 \times 10^9 \text{ cm}^{-3}$ [124]. After illumination of the laser beam onto the sample containing GNRs and QDs, the emission spectra is a broadband, whose emission spectra is centred at 640 nm, and which is shifting linearly at the rate of $0.1 \pm 0.05 \text{ nm/}^0\text{C}$, as shown in Fig 6.1 [124].
6.3 Temperature measurement of GNRs dispersed discs

One of the attractive properties of GNR is its selective surface plasmon resonance. When a laser beam is illuminated on the GNRs, the surface plasmon of GNRs is excited [116]. Depending on the illuminated laser beam’s pulse energy that GNRs absorb, the GNRs heat up. The hot GNRs then release heat to the environment surrounding the focal region of the illuminated laser beam. If a small amount of QDs are employed with the GNRs, the emission spectra of the QD’s become red shifted. The shifting of the peak position of the QD’s emission spectra is proportional to the heat released by the GNRs to the environment as discussed in the previous section (Section 6.2).

The heat dissipation to the environment near to the focal region of the laser beam illumination depends on the thermal conductivity of the environment.
The less the thermal conductivity of the material at the focal region, the more
the heat is localised, and vice versa. In addition to the thermal conductivity
of the laser beam illuminated environment, the surface area of the illuminated
laser beam plays an important role in the temperature release rate.

In this experiment, we investigate the local temperature in the focal volume of
the objective lens as a function of the laser input power. We address the effect
of different NAs of the objective lens on focal temperature increment. We also
address the effect on the focal temperature increment of using various thermal
conduction materials as the environment.

6.3.1 Experimental setup

In order to measure the temperature in the focal volume of an objective lens,
we used a confocal microscopic setup. A spectrometer was used for detecting
purposes.

Fig. 6.2 shows the schematic diagram of the confocal microscope used in the
temperature measurement. An optical disc is connected to the spindle motor,
and a high intensity femtosecond laser beam is used to excite the sample.
A dichroic mirror is placed along the path of the incident femtosecond laser
beam. The dichroic mirror transmits the femtosecond laser beam and reflects
the QD’s fluorescence to the spectrometer.

6.3.2 Results

Glass is a highly thermal conducting material (heat capacity = 840 $JKg^{-1}K^{-1}$)
[125]. When GNRs with CdSe QDs are drop cast on the glass substrate, the
illuminatioin of the laser beam did not increase the focal temperature. It is because the highly thermal conductive glass substrate releases heat quickly, which leads to a slow increase in temperature in the focal region.
Fig. 6.3 depicts the focal temperature increment of the GNRs dispersed on the glass substrate. The temperature increment is up to $3.5^\circ C$ for a 1.4 NA objective lens. Considering the room temperature of 300K, the focal temperature of the 1.4 NA objective is 303.5 K. Reducing the NA of the objective lens or increasing the effective spot size produces a large focal area on which to increase temperature. In the case of 0.6 NA and 0.5 NA objective lenses, the temperature increases to $4.0^\circ C$ and $4.5^\circ C$, respectively. Considering a room temperature of 300 K, the effective temperature for the 0.6 NA and 0.5 NA objective lenses are 304 K and 304.5 K, respectively. The slow increase
of the temperature in the focal volume is due to the high heat conductivity of the glass substrate, on which heat dissipates quickly.

In the second experiment, the sample was prepared in a $\sim 100 \, \mu m$ thick PVA matrix. In this case, the GNRs, along with the QDs were mixed with a PVA matrix. The solution were drop cast on the glass substrate. Now, the axial region of the focal volume was completely inside the PVA matrix.

---

**Figure 6.4** Temperature rise in the PVA matrix

Fig. 6.4 shows the temperature increment when GNRs are dispersed on the
PVA matrix. When the laser power increases from 1 mW to 4.5 mW, the temperature increases to $20^\circ C$ in the focal region of the 1.4 NA objective lens. Considering the room temperature of 300 K, the ultimate focal temperature is 320 K.

For a low NA objective lens of 0.6 NA and 0.5 NA, the temperature rise is higher than that of the high NA objective lens (1.4 NA). When the laser power increases from 1 mW to 4.5 mW, the focal temperature is estimated to increase by $33^\circ C$ for a 0.6 NA objective lens, and $35^\circ C$ for a 0.5 NA objective lens. Considering a room temperature of 300 K, the ultimate focal temperature increases to 320 K for a 0.6 NA objective lens and to 335 K for a 0.5 NA objective lens.

The increase of the temperature in the focal region is caused by the decrease of the surface-to-volume ratio due to the change of the NA of the objective lens used. In the case of a low NA objective lens, the surface-to-volume ratio is smaller than that of the high NA objective lens. The heat can be immediately dissipated to the environment for the high NA objective lens, whereas for the low NA objective lens, the heat dissipation rate is slow. Hence, the focal temperature for the high NA objective lens is less than that for the low NA objective lens. This discovery is particularly relevant to 2P recording by the DVD optical pickup of a low NA objective lens, described in Chapter 7.

6.4 Chapter conclusion

In this chapter, we described the study of the temperature measurement process in the focal region, and detailed the experiments conducted to measure the temperature in the focal volume. In the experiment, we considered different heat conducting materials to verify the results. Using different NA objectives as a means of different focal volumes, we measured the focal temperatures.
The experimental results show that the low NA objective lens produces more significant temperature increment in the focal region than that of the high NA objective lens.
Chapter 7

Low energy density recording using gold nanorod dispersed discs

7.1 Introduction

From the previous Chapters, the performances of the optical pickup head (OPUH), and the characteristics of the fabricated two-photon (2P)-enabled gold nanorod (GNR) dispersed optical disc, were shown to be the promising candidates for a 2P-enabled optical disc drive (ODD) systems. Dynamic fluorescence readout performances of the designed 2P-enabled ODD system indicated that the system is ready for the 2P recording and reading operations. To perform recording operation using the surface plasmon meditated GNR melting technique, a high energy density femtosecond pulsed laser beam and a high numerical aperture (NA) objective lens [10] need to be incorporated. The high energy density femtosecond pulsed laser beam can damage many optics, which is a key obstacle for the ODD systems. In order to avoid damaging
with the high energy density femtosecond pulsed laser beam, a single pulse modulation is necessary [10]. However, the use of single pulse modulator makes the system extremely bulky. To make the ODD system simple and efficient, a low energy density recording is the key.

Using the focal temperature measurement process described in the previous chapter, it was found that the GNR dispersed on the polyvinyl alcohol (PVA) matrix was shown to have a better heat accumulation effect. Also, it was found that the low NA objective lens provided more heat accumulation capability. With these significant findings, it indicates that low energy density optical recording can be possible with a low NA objective lens.

To verify the influence of the focal temperature increment to the recording performance, we have performed temperature simulation model in Section 7.2. Then, we have performed low energy density recording. In Section 7.3, the performance of a dual layer recording is described, and, finally, the chapter is concluded in Section 7.4.

### 7.2 Shape transition by surface melting with a low energy density

In the previous chapter, we demonstrated that the low NA objective lens produces more significant temperature increment in the focal region than that of the high NA objective lens. We also found that, as a substrate, low thermal conducting material produces more heat in the focal region than the high thermal conducting materials. However, in order to perform low energy density recording, an estimation of the amount of temperature in the focal volume is required. In this section, we describe the theoretical simulation to predict amount of temperature required to perform the low energy density recording.
To gain a better insight into the temperature rise of the surrounding matrix on surface melting of GNRs excited by the spatially-stretched energy density at a high repetition rate, the rising of the focal temperature in the medium is modelled by considering GNRs as the heat sources. The position and time dependent temperature change in the focus in the medium is given by [111, 126]

$$\nabla T(r, t) = \sum_{n=1}^{m} \frac{F(r_0)a}{8k(\frac{k}{\rho c_p})^2(\pi nt)^2} exp\left(-\frac{(r - r_0)^2}{4\frac{k}{\rho c_p}nt}\right)$$

(7.1)

Here, $F(r_0)$ is the energy-density distribution given by the objective, is the absorption cross-section of GNRs ($\sim 6 \times 10^{-12} \text{ cm}^2$) [127], $\rho$ is the density of the PVA polymer ($1200 \text{ kgm}^{-3}$), $c_p$ is the heat capacity of PVA ($1650 \text{ Jkg}^{-1}\text{K}^{-1}$), $k$ is the thermal conductivity of the matrix ($0.2 \text{ Wm}^{-1}\text{K}^{-1}$) [115], $t$ is the time interval between two successive pulses ($12 \text{ ns}$ for the repetition rate of $82 \text{ MHz}$), $n$ is the number of pulses, is the relative distance from the GNRs. The GNRs are modeled as a homogeneous distribution in the PVA matrix with a particle separation of $80 \text{ nm}$ to simulate the experimental condition. The initial temperature of $293 \text{ K}$ is assumed. The average focal temperature is obtained by superposing the solutions of every GNR inside the focus. Therefore, at a given energy density and a repetition rate, the rising of the focal temperature is dependent on both the thermal conductivity of the surrounding matrix and the surface-to-volume ratio of the focal region by the spatial stretching. Fig. 7.1(a) shows the calculated focal temperature of the GNR dispersed PVA matrix and the glass matrix excited by a spatially-stretched energy density given by objectives with different values of NA. At a laser energy density of $0.4 \text{ mJcm}^{-2}$ which is 25 times lower than the complete-melting threshold of $10 \text{ mJcm}^{-2}$ under the temporally-stretched excitation [128]. The energy of photons absorbed by a single GNR is approximately $2.4 \text{ fJ}$ given the absorption cross-section of $\sim 6 \times 10^{-12} \text{ cm}^2$, which is far below the complete-
melting energy threshold of $\sim 60 \text{ fJ}$ for a similar sized GNR [129]. The focal temperature under a spatially-compressed excitation by an objective of $NA = 1.4$ rises to $\sim 315 \text{ K}$ within the first 1000 pulses, and then saturates. The surrounding matrix has a negligible influence on the photothermal response of GNRs at this temperature. The 2$P$ fluorescence experiment confirms that there is no distinguishable fluorescence reduction after exposure to a laser energy density at this level (Fig. 7.1(b)). In the focal region of an objective with $NA = 0.6$, the temperature rising of the surrounding matrix plays a significant role in determining the photo-thermal shape transition of nanorods. The calculation shows that the focal temperature rises quickly to $\sim 370 \text{ K}$ within the first 1000 pulses and then slowly increases after 2000 pulses. The ultimate focal temperature is estimated $\sim 1000 \text{ K}$ after pulses corresponding to an exposure time of 25 ms, which is the typical experimental condition. This difference in the focal temperature can be attributed to the different surface-to-volume ratios of the focal regions given by different values of $NA$. The surface-to-volume ratio given by an objective with $NA = 1.4$ is $\sim 2.6$ times larger than that given by a spatially-stretched case for an objective with $NA = 0.6$; thus the heat can dissipate out of the focal region much efficiently before the arrival of the successive pulses and the focal temperature is significantly lower.
Figure 7.1 (a) Calculated focal temperature as a function of the number of pulses at a repetition rate of 82 MHz and an energy density of 0.4 mJ/cm$^{-2}$. The blue squares and red circles present the calculated temperature rising in GNR-dispersed PVA matrix by objectives with NA = 0.6 and NA = 1.4, respectively. The green triangles represent data for GNR distributed on cover glass. (b) Experimental characterisation of the 2P fluorescence contrast reduction as a function of the energy density by surface melting of GNRs in the PVA matrix with an objective NA = 0.6 (blue), in the PVA matrix with an objective NA = 1.4 (red) and distributed on cover glass with an objective NA = 0.6 (green), respectively. (c) The focal temperature of the PVA matrix after 2000 pulses at different energy-density levels and laser repetition rates.

These numerical results physically imply that at a low energy density of 0.4 mJ/cm$^{-2}$, the use of a high NA objective may not produce a surface-melting condition under the high-repetition-rate pulsed illumination. However, under the spatially-stretched excitation by a low NA objective, the temperature rising of the polymer matrix exposed at the same energy-density level can be up to $\sim 400 \, K$, which is comparable to constant heating in a hot
environment at similar temperature [130]. Therefore, the shape transition of GNRs excited by an objective of $NA = 0.6$ at the high repetition rate is now possible. To verify the discovery shown in Fig. 7.1(a), we have conducted the $2P$ fluorescence contrast reduction experiment at a variety of energy-density levels. GNRs with an extinction peak at the wavelength of 790 nm and an optical density of 130 were mixed with 10 wt.% PVA solution, and then dried at room temperature. The femtosecond pulsed laser beam at the wavelength of 780 nm with a repetition rate of 82 MHz was employed as the excitation source. After intense irradiation, the shape transition of nanorods can shift the plasmon resonance and significantly reduce the $2P$ fluorescence intensity of illuminated GNRs.

The $2P$ fluorescence contrast reduction experiment in Fig. 7.1(b) shows that the energy-density threshold for $NA = 0.6$ is indeed 2.5-fold lower than that for $NA = 1.4$, which is consistent with the difference in surface-to-volume ratios. To verify the influence of the temperature rising of the matrix on the surface melting of GNRs, a comparison experiment was performed in a sample where GNRs were distributed on the cover glass ($\rho = 2500 \ kgm^{-3}$, $c_p = 840 \ Jkg^{-1}K^{-1}$ and $k = 1 \ Wm^{-1}K^{-1}$) [125]. Owing to the relatively high thermal conductivity of glass, the heat can efficiently dissipate out of the focal region before the arrival of the successive pulses and the focal temperature rises only to 306 K after 2000 pulses under spatially-stretched excitation at an energy density of 0.4 $mJcm^{-2}$ (Fig. 7.1(a)). Consistent with the calculation, the energy-density threshold in the GNR dispersed PVA sample is reduced compared with that in GNRs distributed on cover glass. At the same energy-density level, the fluorescence contrast reduction in the GNR dispersed PVA sample, indicating the strength of the surface melting, is significantly stronger than that in GNRs distributed on cover glass. The reduced threshold and enhanced strength of surface melting can be attributed to the influence of the temperature rising in the surrounding matrix, which
facilitates the photothermal shape transition of GNRs. This feature may be explained as softened elastic properties at the surface of GNRs by the temperature rise in the matrix [131, 132], which may reduce the surface tension to keep the original shape after the successive femtosecond pulses are absorbed.

Fig. 7.1(c) shows the focal temperature of the GNR dispersed PVA sample after 2000 pulses at a variety of energy density levels and repetition rates. It should be pointed out that the increase in the repetition rate of the pulsed laser beam might lead to a further reduction in the energy-density threshold for surface melting of GNRs facilitated by the matrix temperature rising, enabling ultra-low energy-density recording under spatially-stretched excitation by low NA micro-optics.

7.3 Dual layer recording

The low-energy-density recording under spatially-stretched excitation by a high-repetition-rate pulsed laser beam indicates the feasibility of its application in high density optical memory using a low NA micro-optics system.

Now we demonstrate the reduction of the energy-density threshold of recording in the GNR embedded disc using the DVD OPUH to focus the high-repetition-rate femtosecond pulsed laser beam. The laser wavelength at 780 nm was chosen to match the resonance of the synthesised GNRs. The 2P fluorescence of GNRs can be significantly reduced due to the plasmonic resonance shift as a consequence of the photothermal reshaping [128]. Fig. 7.2(a) shows the 2P fluorescence readout images of recorded bits in the GNR dispersed disc. Each image comprises a pattern of $3 \times 3$ bits. To prevent any interference between the adjacent bits, the bit spacing was kept at 10 $\mu m$. The exposure time of 25 ms was optimised to balance the recording speed and the signal-noise-ratio. Fig. 7.2(b) shows the readout bit size as a function of the excitation power.
Increasing the writing power leads to a gradual increase in the size of recorded bits. Owing to the temperature rising of the surrounding polymer matrix, indeed, the threshold power for recording is significantly reduced to 0.25 mW (corresponding to a focal energy density of $\sim 0.4 \, \text{mJ} \text{cm}^{-2}$). Compared with the complete-melting energy-density threshold of $\sim 10 \, \text{mJ} \text{cm}^{-2}$ with single femtosecond pulses [128], this result yields over one-order-of-magnitude reduction. Once the power exceeds 1.5 mW, corresponding to a laser energy density of $\sim 2.4 \, \text{mJ} \text{cm}^{-2}$, deformation of the PVA matrix is observed where the accumulative heating raises the temperature above $\sim 540 \, \text{K}$ [127].

![Fluorescence readout image of the recorded pattern at different recording power levels. The scale bar is 10 $\mu$m. (b) Size defined by the FWHM and (c) the readout contrast of the recorded bits as a function of the recording power and the exposure time.](image)

The minimum lateral size of the recorded bit was found 1.08 $\mu$m at the threshold recording power of 0.25 mW. The image contrast was calculated from the readout fluorescence images of the recorded bits. The contrast is defined as
$$C = \left| \frac{(I_{\text{bit}} - I_{\text{background}})}{(I_{\text{bit}} + I_{\text{background}})} \right|$$  \hspace{1cm} (7.2)

where $I_{\text{bit}}$ is the readout intensity of the bit and $I_{\text{background}}$ is the readout intensity of the background. Fig. 7.2(c) shows the 2P fluorescence image contrast of the recorded bits as a function of the recording power. Reducing the exposure time from 25 ms to 5 ms improves the recording speed at a cost of degradation of the contrast of recorded bits. The exposure time was optimised at 25 ms to balance the speed and the contrast. The contrast was found to be $\sim 0.14$ at the threshold recording power of 0.25 mW and an exposure time of 25 ms.

![Image](image_url)

**Figure 7.3** 2P fluorescence readout images of two letters recorded in the first layer (a) and the second layer (b). The inset shows the zoom in view of the recorded bits indicated by the dashed square. The scale bar is 10 $\mu$m. (c) the axial response of the two recorded layers with a layer separation of 15 $\mu$m. (d) the cross section plot of the recorded bits as indicated by the dashed line.
As a demonstration of the volumetric recording capability, we show the 2P fluorescence readout images of two patterns recorded at two layers, as shown in Fig. 7.3(a) and Fig. 7.3(b). Letters B and M were recorded in the first and second layer, respectively, with a layer separation of 15 $\mu$m. The recording was conducted at the threshold power of 0.25 mW with an exposure time of 25 ms. The images can be readout distinctly without any cross talks from the neighbouring layer, as shown in the axial scanning in Fig. 7.3(c). The cross section of the recorded bits indicated by the dashed line is shown in Fig. 7.3(d) with a bit separation of 1.25 $\mu$m. According to the bit separation of 1.25 $\mu$m and a layer separation of 15 $\mu$m, the equivalent storage capacity of 69 GB per disc is achieved with low NA DVD micro-optics.

7.4 Chapter conclusion

In conclusion, we have demonstrated both numerically and experimentally that the temperature rise of the surrounding polymer matrix can play a significant role in the photothermal shape transition of GNRs, when using a low NA micro-optics to focus a high-repetition-rate pulsed beam. Consequently, we have characterised the volumetric recording capability of DVD OPUHs by coupling a high-repetition-rate femtosecond pulsed laser beam. Compared with that for a high NA objective under single pulse illumination, the laser-energy density is reduced by over one order of magnitude when a DVD OPUH is employed to focus a femtosecond pulsed laser beam at a repetition rate of 82 MHz. As a result, femtosecond laser beam induced dual-layer recording in a GNR embedded optical disc has been successfully demonstrated by using the DVD OPUH. With the recent advance in the development of low-cost femtosecond laser systems, our results demonstrate the potential of ultra - high density and low-cost 3D storage devices that comprise DVD compatible micro-optics.
systems.
Chapter 8

Conclusions and future outlook

8.1 Thesis conclusion

In this thesis, we investigated an optical disc drive (ODD) system for two-photon (2P) optical data storage. This thesis discussed the design of the ODD system and its optical performance. Our innovative 2P-enabled ODD system facilitated the fluorescence collection in the dynamic ODD system. This PhD thesis has contributed in a number of important aspects towards the development of the 2P-enabled ODD system:

- Firstly, we designed an optical disc with 2P sensitive materials. In this experiment, we have prepared gold nanorods (GNRs), as a 2P recording material. When we achieved the preparation of the required shape of the GNRs, 2P optical discs were made by mixing of the proper ratio of the polyvinyl alcohol (PVA) and the GNRs. In addition to the disc fabrication, we developed a technique to measure the thickness of the fabricated optical disc. We used a fluorescence detection method to identify the thickness variation of the disc from the inner radius (35 mm) of the disc to the outer radius (58 mm). The thickness variations
was found to be 8.5%.

- In the second step, we characterised the optical pickup head (OPUH). To the best of our knowledge, this is the first time the femtosecond laser interaction with the DVD OPUH and the DVD-sized optical disc has been demonstrated. In this characterisation, we coupled the femtosecond laser, at different wavelength, to the DVD OPUH. The objective lens of the OPUH shows the diffraction limited nature, where the axial resolution was found to be $3 \sim 9 \, \mu m$ and the lateral resolution was found to be $0.8 \sim 1.3 \, \mu m$, under a laser beam wavelength range of $700 \sim 900 \, nm$. In addition, we characterised the transmission of the OPUH objective lens. The transmission was found more than 50 % under different wavelength conditions. The results of the experiment indicate that the OPUH is a suitable candidate for femtosecond laser induced recording and reading.

- In the third step, we developed an ODD system to enable 2P optical data storage. In order to perform the dynamic operation, we constructed a servo system to solve any system instability. In case of the focusing servo system, the astigmatic method was used as the optical signal generation in relation to the amount of the disc deviations in the axial path. Conversely, for the tracking servo system, the differential push-pull tracking method is used for the tracking signal generation corresponding to the amount of the lateral disc deviations. To ensure a robust performance, we introduced a control algorithm in the servo actions. After implementing the control algorithm, the fluorescence signal uncertainty was reduced to 6.67 %.

- In the fourth step, we developed a process to measure the focal temperature of the objective lens. Using the nano-thermometer method, we investigated the temperature of the focal volume for different NAs
and employing various thermal conductive materials as a substrate. We demonstrated that a low NA objective generates more heat increment then a high NA objective in a low thermal conductive environment near to the focal region.

- Finally, we investigated the recording and the reading characterisation using the GNRs dispersed optical disc under femtosecond laser illumination. We performed low energy density recording using the low NA (=0.6) objective lens of the DVD OPUH. We achieved the threshold value of the GNRs surface melting temperature at the laser beam power of $250 \mu W$, and the 25 ms shutter exposure. In order to demonstrate the three-dimensional (3D) recording capability, we have performed the dual layer recording at layer spacing $\sim 15 \mu m$. By implementing the experimental axial and lateral resolution, our OPUH and optical disc (similar size of the DVD optical disc) combination can store 69 GB data.

In conclusion, this PhD thesis is an integrated study of the wide range of properties including: the OPUH characterisations; the optical discs fabrication through the recording materials preparations; and the recording and reading performance under the 2P mechanism. This PhD thesis study can contribute to the ODD industry in order to design a ultra-high density 2P optical drive systems and discs.

### 8.2 Future outlook

In order to extent this work in future, two potential projects could be undertaken. As this thesis is the study on the ODD with the 2P technology, the first investigation could be the development of a super-resolution ODD system. The second project could be performed optical storage array, which
will enhance the storage capacity as well as the writing and reading speed.

### 8.2.1 Super-resolution ODD system

Super-resolution recording is a technique that could potentially improve the recording density, and, by creating smaller bit sizes, as a result, storage capacity can significantly increased. The details of the super-resolution imaging can be found [133–139]. In this future work, the development could be focused on stimulated emission depletion (STED) microscopy. Using the technique of STED microscopy, it is possible to modify our developed ODD system to an ultra-high density super-resolution ODD system.

### 8.2.2 Optical storage array

A single ODD could have its own limitation of the stored information. By connecting, in parallel, multiple ODDs, the storage capacity could be increased multiple times. In this case, the aim would to not only increase the storage capacity, but also to increase data recording and reading speeds; the concept of optical storage array (OSA) is similar to the optical disc library [140–142].
Fig. 8.1 shows the scheme of a possible OSA using high density ODDs. An OSA consists of multiple ODDs connected in parallel to perform parallel reading and writing. A host computer can be used to perform the entire control algorithm, including parallel read/write processing, and data management within the discs. The performance of the OSA depends on the number of ODDs connected, access time, latency and the throughput of individual ODDs. Since our ODD system is capable of 2P optical data storage, high capacity OSA can be possible with the incorporation of the 2P-enabled ODD systems as individual units of the OSA.
Bibliography


[34] S. Ecma. Data interchange on read-only 120 mm optical data disks (CD-ROM). 1996.


[41] S.-. Ecma. Data Interchange on 120 mm Optical Disk using + RW Format - Capacity : 3 , 0 Gbytes and 6 , 0 Gbytes. 1999.


Appendix A

Spindle motor characterisation

In Chapter 5, we described the development of an optical disc drive (ODD) system. In the ODD system, we used constant linear velocity (CLV) method to record and read data from the optical disc. The CLV operation was performed by a spindle motor of the ODD system. In order to implement spindle motor in the ODD effectively, we performed simulation of transfer function of the spindle motor and the speed profile simulation for the different area of the optical disc.

A1. Transfer function of the spindle motor

Fig. 8.2 shows the electrical equivalent circuit of a spindle motor. When sufficient supply voltage is applied to the spindle motor, rotor of the spindle induced torque. The rotor torque produces the angular movement of the spindle motor.

![Electrical equivalent circuit of the spindle motor](image)

**Figure 8.2** Electrical equivalent circuit of the spindle motor
The transfer function of a spindle motor is the relationship between the rotor’s angular movement when supply voltage applied. When the supply voltage source $V(s)$ is applied to the spindle motor, an angular movement $\omega(s)$ is produced, and the transfer function $G(s)$ of the spindle motor can be expressed as [143],

$$G(s) = \frac{\omega(s)}{V(s)} = \frac{\frac{1}{K_e}}{\tau_m \tau_e s^2 + \tau_m s + 1}$$  \hspace{1cm} (8.1)$$

where, $\tau_m$ is the mechanical time constant, $\tau_e$ is the electrical time constant, $K_e$ is the electrical torque constant.

<table>
<thead>
<tr>
<th>Value at nominal voltage</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maxon motor data</td>
<td>Maxon motor data</td>
</tr>
<tr>
<td>01 Nominal voltage</td>
<td>01 Terminal resistance phase to phase</td>
</tr>
<tr>
<td>Value</td>
<td>Value</td>
</tr>
<tr>
<td>24.0</td>
<td>1.39</td>
</tr>
<tr>
<td>Unit</td>
<td>$\Omega$</td>
</tr>
<tr>
<td>02 No load speed</td>
<td>02 Terminal Inductance phase to phase</td>
</tr>
<tr>
<td>Value</td>
<td>Value</td>
</tr>
<tr>
<td>11000</td>
<td>0.226</td>
</tr>
<tr>
<td>Unit</td>
<td>mH</td>
</tr>
<tr>
<td>03 No load current</td>
<td>03 Torque constant</td>
</tr>
<tr>
<td>Value</td>
<td>Value</td>
</tr>
<tr>
<td>286</td>
<td>20.5</td>
</tr>
<tr>
<td>Unit</td>
<td>mNm</td>
</tr>
<tr>
<td>04 Nominal speed</td>
<td>04 Speed constant</td>
</tr>
<tr>
<td>Value</td>
<td>Value</td>
</tr>
<tr>
<td>9510</td>
<td>465</td>
</tr>
<tr>
<td>Unit</td>
<td>rpm</td>
</tr>
<tr>
<td>05 Nominal torque</td>
<td>05 Speed/torque gradient</td>
</tr>
<tr>
<td>Value</td>
<td>Value</td>
</tr>
<tr>
<td>45.6</td>
<td>31.5</td>
</tr>
<tr>
<td>Unit</td>
<td>rpm/mNm</td>
</tr>
<tr>
<td>06 Nominal current</td>
<td>06 Mechanical time constant</td>
</tr>
<tr>
<td>Value</td>
<td>Value</td>
</tr>
<tr>
<td>2.37</td>
<td>6.39</td>
</tr>
<tr>
<td>Unit</td>
<td>ms</td>
</tr>
<tr>
<td>07 Stall torque</td>
<td>07 Motor inertia</td>
</tr>
<tr>
<td>Value</td>
<td>Value</td>
</tr>
<tr>
<td>355</td>
<td>20.0</td>
</tr>
<tr>
<td>Unit</td>
<td>gcm²</td>
</tr>
<tr>
<td>08 Starting current</td>
<td>08 No of phases</td>
</tr>
<tr>
<td>Value</td>
<td>Value</td>
</tr>
<tr>
<td>17.3</td>
<td>3</td>
</tr>
<tr>
<td>Unit</td>
<td></td>
</tr>
<tr>
<td>09 Max. efficiency</td>
<td>09 Maximum speed</td>
</tr>
<tr>
<td>Value</td>
<td>Value</td>
</tr>
<tr>
<td>76</td>
<td>25000</td>
</tr>
<tr>
<td>Unit</td>
<td>rpm</td>
</tr>
</tbody>
</table>

Table 8.1  Spindle motor specification

By using the spindle motors specification, the transfer function $G(s)$ becomes
\[ G(s) = \frac{16.198}{3.57155 \times 10^{-9}s^2 + 6.59 \times 10^{-3}s + 1} \] (8.2)

The frequency response of the transfer function give us the maximum achievable speed of the spindle motor. The knowledge of the frequency response assists in to design of the control scheme.

**Figure 8.3** Bode plot of open loop transfer function of the spindle motor

Fig. 8.3 shows the frequency response of the spindle motor used in the system. The 0 dB crossover frequency is $\sim 400 \text{Hz}$, which corresponds to 24000 rpm. The phase margin is less than -90 degree.

### A2. Speed profile simulation

In CLV, to achieve synchronisation, the optical disc is rotated at a varying rotation speeds across the optical disc radius [53, 90]. In order to implement CLV, we simulated the speed profile using the over speed function. The over speed factor $N$ can be define as
\[ N = \frac{v_{\text{ins}}}{v_b} = \frac{2\pi f_{\text{disc}} R_{\text{disc}}}{v_b} \]  

(8.3)

in which \( v_b \) is the basic linear velocity of the disc, \( f_{\text{disc}} \) is the disc rotational frequency, \( R_{\text{disc}} \) is the instantaneous disc surface radius from the centre of the disc, \( v_{\text{ins}} \) is the instantaneous linear velocity of the disc when optical head positioned at \( R_{\text{disc}} \) of the disc surface.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure8_4.png}
\caption{Speed profile throughout the disc at constant linear velocity}
\end{figure}

The simulated speed profile of the spindle motor is shown in Fig. 8.4. In the simulation, we used the disc inner radius, \( R_{\text{in}} = 25 \text{ mm} \) and disc outer radius, \( R_{\text{out}} = 58 \text{ mm} \). We also considered the track pitch as \( t = 0.74 \mu \text{m} \). The over speed factor \( N \) determine the speed of the ODD systems. In Fig. 8.4, the expressions 1X, 2X, 4X, 8X and 16X represent the value of the over speed.
factor $N$ is 1, 2, 4, 8 and 16 respectively. The high value of $N$ indicates the fast drive systems. The effect of the change of the value of the CLV is simulated as shown in Fig. 8.4. In case of linear velocity 1 m/s, the required peak speed of the spindle motors varies from the 6.3 Hz to 102 Hz considering over speed factor 1 to 16 respectively. Similarly, in the case of linear velocity 2 m/s, the requirement of the peak speed values of the spindle motors varies from the 13 Hz to 202 Hz, and in the case of 3 m/s linear velocity, from 20 Hz to 303 Hz. The simulation results shows that the spindle spinning slows down when optical head moves from the inner radius 25 mm to the outer radius 58 mm.
Appendix B

Mechanical performance of optical pickup head

In Chapter 4, we have characterised the optical performance of the optical pickup head (OPUH). However, the mechanical performance of the OPUH is required to design a controller to perform servo operation. The mechanical components of the OPUH are a focusing actuator and a tracking actuator. Here, the transfer function simulation for both of focusing and the tracking actuator were performed, and are expressed in Laplace transform.

B1. Transfer function of focusing actuator

By using the OPUH specification [51] the transfer function of the focusing actuator can be defined as

\[
P_{\text{focus}}(s) = \frac{8.121 \times 10^6}{s^3 + 7.145 \times 10^4 s^2 + 3.35 \times 10^6 s + 1.015 \times 10^{10}}
\]  

(8.4)

Figure 8.5 Transfer function of the focusing actuator
Appendix B: Mechanical performance of optical pickup head

Figure 8.5 shows the frequency response of the focusing actuator of OPUH. The resonance frequency of the focusing actuator was found to be 80 Hz. The control operation of the focusing actuator is discussed in the Appendix C.

B2. Transfer function of tracking actuator

In order to travel the focusing position in the radial direction, the tracking actuator is used. The mechanical transfer of the tracking actuator can be extracted from the specifications of the OPUH [51].

Overall transfer function of the tracking actuator

\[
P_{\text{track}}(s) = \frac{3.624 \times 10^7}{s^3 + 4.11 \times 10^5 s^2 + 1.39 \times 10^7 s + 6.039 \times 10^{10}}
\]  

(8.5)

![Bode Diagram of Tracking Actuator](image)

**Figure 8.6** Transfer function of the tracking actuator

Figure 8.6 shows the frequency response of the tracking actuator of the OPUH. The resonance frequency of the tracking actuator found as 52 Hz. In order to perform track following operation in the radial direction, a control algorithm with the sufficient gain is required, which is discussed in the Appendix C.
Appendix C

Servo circuit and controller design

In Chapter 5, we performed the servo operation. The servo system performs two operations: detection circuitry and control system. Here, we discuss our designed servo circuits and the controller.

C1. Servo circuit design

The servo circuit is designed to extract radio frequency (RF) signal, tracking error signal (TES) and focusing error signal (FES), which are defined as

\[ RF = V_A + V_B + V_C + V_D \] (8.6)
\[ TES = \frac{(V_A + V_D) - (V_B + V_C)}{V_A + V_B + V_C + V_D} \] (8.7)
\[ FES = \frac{(V_A + V_C) - (V_B + V_D)}{V_A + V_B + V_C + V_D} \] (8.8)

Fig. 8.7 shows the block diagram of the servo circuit. The design consideration of the servo circuits are to produce focusing error signal, tracking error signal and the RF signals.
Appendix C: Servo circuit and controller design

Figure 8.8 Schematic of servo circuit
Fig. 8.8 shows the designed servo circuit. In order to eliminate the noise contents from circuits Sallen key low pass filter is used. The transfer function of the designed low pass filter is

\[
G_{\text{filter}}(s) = \frac{100402.260299}{s^2 + 359.982806791s + 63769.0031629}
\] (8.9)

Fig. 8.9 shows the response of the designed low pass filter. The cut-off frequency of the filter is 40 Hz.

**C2. Controller design**

In the servo system, the proportional-integral-derivative (PID) closed loop control system is used. The closed loop PID control system is a robust control system, which can provide the high precision and the high speed control.
The closed loop PID controller is shown in Fig. 8.10. In case of the focusing error controller, the focus error signal is used as a feedback signal of the closed loop system, whereas in the tracking error closed loop control system, the tracking error signal is used as a feedback signal.

Fig. 8.11 shows the step response of the focusing controller. The system is unstable within first 150 µs, it is due to the transient response of the control.
systems.

Fig. 8.12 shows the step response of the tracking actuator when applied closed loop PID control algorithm. In order to have stability, the closed loop tracking PID controller required 30 $\mu$s.
Author’s publications

Journal publications


In preparation

1. “Temperature measurement in the focal position of the gold nanorod dispersed discs” Md. Azim Ullah, Xiangping Li and Min Gu.

2. “Focusing servo system design for the two-photon optical drive system” Md. Azim Ullah, Xiangping Li and Min Gu.

3. “Tracking servo system design for the multi-dimensional optical drive system”, Md. Azim Ullah, Xiaojian Hao, Xiangping Li and Min Gu.
Conference papers

