FABRICATION OF PERIODIC MICROSTRUCTURES ON GLASS AND POLYMER USING LOW POWER CO_2 LASER

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Dedicated to my beloved Mother
And Father

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ABSTRACT

Micromachining on glass and polymers has been a widely attractive approach during the past few decades. In laser micromachining of materials, carbon dioxide (CO_2) laser is one of the most significant lasers used. This thesis describes direct laser writing (DLW) scheme for the fabrication of periodic structures on glass and polymers. The periodic structures are important components in diffractive optics and microfluidic devices. The DLW technology is a modern day machining tool which helps to experimentally investigate the behavior of high power lasers on glass and polymers without lithographic and mask-based techniques. The DLW scheme gives great advantages, making it an efficient and cost effective approach for inducing periodic structures. The experimental observations in this research have urged the use of low power (2.5 W) CO_2 laser irradiation to obtain narrow and fine patterns. The laser power and scanning speed play a vital role in the fabrication process. The current investigation focuses on glass and acrylic for the generation of regular and tidy periodic structures. The whole DLW process is controlled by a computer software program. The structure to be written by the laser is first coded and input into the CAD software, before being written on an actual workpiece. The Gaussian CO_2 laser beam with a maximum power of 2.5 W has been targeted to the workpiece which is placed on the moveable xy translational stage. The laser power used in this process ranged from 1 to 2.5 W and the scanning speed, from 0 to 5 mm/s. A scanning electron microscope (SEM), an optical microscope and a surface profiler were used for observing the surface morphology and the channel cross section. A 632.8 nm HeNe laser was used for observing diffraction patterns of the fabricated periodic structures. The formation of periodic structures depends on laser power and scanning speed. The depth and width of the formed channels for glass ranged from 35 to 45 µm and from 15 to 25 µm, respectively. This research has shown the potential to fabricate periodic structures with a period of 1.5 µm which is less than the laser wavelength of 10.6 µm. These results were analyzed using a high precision, non-contact surface profiler technique developed by Taicaan, United Kingdom. In the case of polymethyl methacrylate (PMMA), the depth of the channels increases with increasing laser power, reaching a maximum value of 2349 µm at a laser power of 2.5 W. The formed structure exhibits the properties of diffraction gratings and hence can be used for diffraction experiments. The direct laser writing technique for the formation of microstructures, proves to be an efficient and effective method. A model for heat transfer inside the material is developed using the COMSOL Multiphysics software. Results from the simulated model give the temperature distribution inside the workpiece and are in good agreement with the experimental data obtained.

ABSTRAK

Mikropemesinan pada kaca dan polimer telah menjadi pendekatan yang menarik secara meluas dalam beberapa dekad kebelakangan ini. Dalam mikropemesinan bahan menggunakan laser, laser karbon dioksida (CO_2) merupakan salah satu laser yang amat penting digunakan. Tesis ini menjelaskan skema penulisan laser secara langsung (DLW) bagi pembuatan struktur berkala pada kaca dan polimer. Struktur berkala merupakan komponen penting dalam optiks belauan dan peranti mikrobendalir. Teknologi DLW muncul sebagai perkakasan pemesinan moden yang membantu dalam mengkaji secara amali ciri laser berkuasa tinggi pada kaca dan polimer tanpa teknik berasaskan litografi dan topeng. Skema DLW mempunyai kelebihan yang besar, menjadikan ia berkesan dan kos efektif untuk menghasilkan struktur berkala. Pemerhatian daripada penyelidikan ini mencadangkan penggunaan sinaran laser CO_2 kuasa rendah (2.5 W) untuk mendapatkan corak yang sempit dan halus. Kuasa laser dan kelajuan imbasan memainkan peranan penting dalam proses fabrikasi. Kajian terkini memberi penumpuan kepada kaca dan akrilik bagi penghasilan struktur yang berkala dan kemas. Keseluruhan proses DLW dikawal oleh program perisian komputer. Struktur yang hendak ditulis dengan laser dibangunkan terlebih dahulu dalam perisian CAD dan kemudian ditulis pada kepingan sebenar. Alur laser CO_2 berbentuk Gaussian dengan kuasa maksimum 2.5 W, telah disasarkan ke arah kepingan sampel yang terletak di atas kepingan bolehalih xy. Kuasa laser yang digunakan dalam proses ini berada antara 1 dan 2.5 W dengan kelajuan imbasan antara 0 dan 5 mm/s. Mikroskop pengimbas elektron, mikroskop optik dan *profiler* permukaan telah digunakan untuk mencerap morfologi permukaan dan keratan rentas saluran. Sebuah laser HeNe 632.8 nm telah digunakan untuk memerhatikan corak belauan yang dibentuk oleh struktur berkala yang telah dibina. Pembentukan struktur berkala bergantung kepada kuasa laser dan kelajuan imbasan. Kedalaman dan lebar saluran yang dibentuk pada kaca masing-masing daripada 35 hingga 45 μm dan daripada 15 hingga 25 μm. Penyelidikan ini telah menunjukan keupayaan membentuk struktur berkala dengan tempoh 1.5 μm, iatu kurang daripada panjang gelombang laser 10.6 μm. Keputusan ini telah dianalisis mengunakan satu teknik *profiler* permukaan tanpa-sentuh berketepatan tinggi yang telah dibangunkan oleh Taicaan, United Kingdom. Dalam kes polimetil metakrilat (PMMA), kedalaman saluran meningkat dengan peningkatan kuasa laser, mencapai nilai maksimum 2349 μm pada kuasa laser 2.5 W. Struktur yang terbentuk mempamirkan sifat parutan belauan dan dengan itu boleh digunakan untuk eksperimen pembelauan. Teknik penulisan laser secara langsung untuk penghasilan mikrostruktur, terbukti sebagai satu kaedah yang cekap dan berkesan. Model bagi pindahan haba di dalam bahan kajian telah dibangunkan menggunakan perisian COMSOL Multiphysics. Keputusan daripada model simulasi memberikan taburan suhu dalam kepingan sampel dan ianya sepadan dengan keputusan ujikaji yang diperoleh.

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LIST OF ABBREVIATIONS

1-D	-	One Dimensional
2-D	-	Two Dimensional
3-D	-	Three Dimensional
CO_2	-	Carbondioxide Laser
CW	-	Continuous Wave
DLW	-	Direct Laser Writing
DOE	-	Diffractive Optical Element
HAZ	-	Heat Affected Zone
HeNe	-	Helium Neon
IR	-	Infra-Red
LIPSS	-	Laser Induced Periodic Surface Structures
LMB	-	Laser Beam Machining
MEMS	-	Micro electro Mechanical System
PC	-	Personal Computer
PMMA	-	Polymethyl methacrylate
PW	-	Power Wizard
RF	-	Radio Frequency
SEM	-	Scanning Electron Microscope
TEM_{00}	-	Transverse Electromagnetic Fundamental Mode
UV	-	Ultraviolet

LIST OF SYMBOLS

α	-	Optical Loss
β	-	Gain Coefficient
μ	-	Absorption Coefficient
P	-	Power
r	-	Radius
I_0	-	Intensity
E	-	Electric Field
R_E	-	Reflection Coefficient
n	-	Refractive Index
L	-	Attenuation Length
R	-	Reflectivity
q	-	Rate of Heat Flow
T	-	Temperature
k	-	Thermal Conductivity
Λ	-	Pitch
θ_i	-	Angle Of Illumination
θ_d	-	Angle Of Diffraction
D	-	Groove Density
θ_m	-	Blaze Angle
λ	-	Wavelength
A	-	Area
z	-	Penetration Depth
$g(r, t)$	-	Rate of Internal Heat Generation
$x0$	-	X-Coordinate
$y0$	-	Y-Coordinate
σ_x	-	X-Standard Deviation

σ_y	-	Y-Standard Deviation
v	-	Laser Velocity
A_c	-	Absorption Coefficient
L_z	-	Depth
L	-	Length
d_{th}	-	Thermal Diffusivity

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CHAPTER 1

INTRODUCTION

1.1 Overview

Laser systems are pre-dominantly employed nowadays in micro system technologies for the applications involve in biomedical engineering, automotive industry, telecommunication and advanced optical instrumentations for not only basic research purposes but also for advanced production environment. With this reference of diverse applications the current era can be renamed as an era of modern technological advancement where every day brings new developments especially in the field of optics. The requirements of lasers in the production industry lead the researchers to work on such key area where they can improve laser techniques for the refinement of the modern needs. The micro and nano fabrication of optical components is gaining considerable importance therefore the perfection in the formation of optical microstructures by lasers is going on for many decades. This is right after the advent of lasers in 1960s; when the research was primarily focused on laser damage in material rather than using the laser light for material processing. The word LASER literally means light amplification by stimulated emission of radiation and in other words it is the ability of light to stimulate the emission of light that creates the situation in which light can be amplified. The invention of lasers in the 20^{th} century is not less than a revolution in the field of optoelectronics. According to an estimate in 2007, the sales of lasers in world market have gone up to 8.6 billion USD with Europe as a leading partner. The most important aspect in laser applications is that laser engraving and marking contributes 43% of total world's market which is quite remarkable in overall lasers applications.

Among lasers and its applications, the formation of microstructures is essential due to the growing wide range applications. The laser surface treatment of the materials is important which may lead to the production of micro components and devices for wide applications like micromechanics, micro-electronics and micro-optics. Laser induced periodic surface structures (LIPSS) were first fabricated on semiconductor surfaces in 1965 (Zheng *et al*. 2009). Most of the research was primarily done to investigate the diffraction effects of formed grooves. Among these components diffractive optical elements are of huge significant in beam shaping and pattern production (Schulz-Ruhtenberg *et al*. 2005). It has been significantly reported that the production of advance micro-components are having an edge in comparison with the conventional machining methods. The laser beams are widely used in many applications including cutting, welding, marking and surface treatment of different materials (Dubey and Yadava, 2008). This chapter presents a brief introduction and overall view of lasers evolution in the past decades and its relation with the current on-going objectives and scope of research.

1.2 Background

The study on laser induced periodic structures is going on for many decades to not only improve our understanding about diffraction phenomenon but also to see the capability of the laser system used for the machining process. Due to the advanced lasers systems available in this era of technological advancement, the laser induced periodic surface structures (LIPSS) has gained new interests in dealing with such rapid micro-processing. The conventional lasers systems have been replaced by fast moving, high efficiency and compact lasers which have the ability to do the micromachining with great accuracy and precision. Due to the transitions in laser systems, the researchers have again shown interest in dealing with the processing efficiency of those systems as well as the physics involved in the overall formation of micro patterning. Among these different types of periodic structures, diffraction gratings appear to be an essential component in optical instrumentation and having various applications in optics, opto-electronics, communication, nano-photonics and nano-bioscience due to their unique properties. The importance of grating lies in the fact that it is used to disperse light into its constituent spectrum which enables many spectroscopic discoveries. The classical diffraction grating consists of one dimensional grooves on the surface with fixed period. In the past many ruling engines were made to engrave such small structures by diamond tip. The diamond tip is used to mark small lines on soft metal surface. In the last century it is reported to have said that diffraction gratings have contributed in the field of modern physics to such an extent where no other instrument has done.

The fabrication of these grating like periodic structures is going on for so many decades. The interaction of laser beam with metallic and non-metallic materials is of same interest. The advent of laser in the formation of gratings have not only brought a new vision but also overruled the ruling technology by bringing the quality and ease to the overall processing. Initially it was difficult to apply the laser optics for such micro cause but later researches have proven it to be worthy tool for such applications. At the same time the semiconductor technology has appeared to be matured enough to offer transmission grating to manufacturing technologies. Not only this, it has also brought the cost effectiveness as well as benefits for the production of gratings at high volumes. Hence afterwards this technology was able to produce transmission grating in fused silica in contrast to its rivals.

The formation of grating like periodic a structure by different lasers is going on for a long time yet the fabrication of these elements is still remains a challenge (Florea *et al*. 2007). Laser micromachining offers a great speed-advantage over other classical micro fabrication techniques and it is starting to be implemented for photo mask fabrication as well (Guay *et al*. 2008).

There are many conventional ways of periodic structure formation but the introduction of lasers in fabrication process makes it more efficient and convenient. In laser matter interaction it has been found that periodic structures on solid surfaces can be made by laser irradiation. These structures are formed as a function of laser parameters and substrate material which is used for the process. Recently laser micro processing has become striking method in glass micromachining. High power UV and CO_2 lasers are usually employed for glass processing, since glass has low absorption in the range of visible wavelength.

The rapid growth in optics with the emergence of technological advancement in science and technology have urged the researcher's community to develop such effective micromachining techniques which not only fulfil the needs of modern era but also serve as a great contribution in the field of photonics. The micromachining of borosilicate, fused silica and crystal quartz has been extensively reported (Tseng *et al*. 2007).

Among all lasers, CO_2 was mostly preferred due to the fact that it has very high electrical efficiency and absorption in material processing for continuous mode. There are various applications of CO_2 laser including engraving, cutting, drilling, scribing, surface heat treatment and others. Due to prominent properties of laser beam such as coherence, spectral purity, monochromaticity and ability to transmit in a straight line hence are preferably utilised mostly in laser material processing applications.

In laser material processing the idea of producing periodic structures not only appear to be attractive but also give new paths in understanding the trends in laser matter interaction. Different properties of laser induce structures are of keen interest among the scientific community therefore the use of glass for CO_2 laser in processing microstructures is remarkably considered to be the most flexible and efficient in terms of temperature capability and general factors regarding the overall process. As it is assumed that glass is opaque to laser irradiation so most of the energy from the laser source is absorbed on the surface of glass. The glass is then verified to be opaque for CO_2 laser without causing any major error (Tian and K.S. Chiu, 2004).

Many researchers have practically demonstrated the applicability of micromachining techniques for fabricating microchannels on quartz and polymethyl methacrylate PMMA. Since most of the microfluidic devices fabricated so far use photolithographic method and wet etching to create a pattern for required configuration therefore these methods are not attractive due to time consuming and creates much debris due to ablation so these techniques are not considered to be ideal for microchannelling in PMMA (Hong *et al*. 2010).

Several groups have investigated the fabrication of micro channels for microfluidic devices. One of the groups has utilised CO_2 laser for inscribing microchannels on polymer substrates. Here the power of 0 to 40 W has been utilised along with the very high scanning speed (Klank *et al*. 2002). Another have demonstrated the approach for removing the bulges during the micromachining process (Chung, 2005). The additional layers of PDMS (photoresist) has been added to the substrate which makes it rather complex machining.

For the development of microfluidic devices for different applications in chemical and biological sciences, microchannelling is required for creating unique designs for required application. The current prevailing methods of making microchannels consist of photo-mask design which consist of many photolithographic steps and which increase the processing time considerably (Yen *et al*. 2006). The laser direct writing has been employed for creating plastic microfluidic chips as well as polymethyl methacrylate PMMA (Cheng *et al*. 2004). In other studies the micromachining of glass and quartz has been described with high energy density using ultrafast femtosecond lasers (Oleschuk *et al*. 2000).

On the other hand these techniques applied above consist of UV lasers which are not easily available and of high cost. Although the micro cracking in BK-7 and quartz by laser treatment is inevitable (Schilling *et al*. 2002), hence careful consideration in processing which consist of long series of hit and trial is mostly adopted. As laser processing is based on heat conduction mechanism, so the thermal analysis of laser induced microstructuring is considered to be of high significance and has been widely studied experimentally as well as theoretically. However due to the different properties of the glass with large temperature gradient of the laser, it is yet challenging enough to study those non-equilibrium effects of glass in such cases (Zhou and Mahdavian, 2004).

Laser micromachining is capable for inscribing microchannels on polymethyl methacrylate PMMA (Nimai C Nayak *et al*. 2008). This current study enables the use of low power CO_2 for the micromachining quartz, BK-7, pyrex glass as well as polymethyl methacrylate PMMA to not only fabricate the microchannels but also for many laboratory and biochip applications. There are several questions which should need to be solved before going into the fabrication process. The system must be suitable and capable of undergoing such experiment along with the cost effectiveness. These current findings will enhance the experimental technique for trench formation which give rise to flexibility, reliability and ease in forming complex microstructures. The heat transfer phenomenon in the formation of periodic structure is modelled using COMSOL software which is considered to be efficient in modelling the various physics processes including laser material interaction. The modelling will be ultimately acting as a tool to visualise the physical process by considering almost all laser and material parameters. Although the CO_2 laser has many commercial applications yet the laser matter interaction in terms of laser parameters is essential to be explored.

1.3 Problem Statement

The earlier approaches regarding the formation of microstructure and micro gratings consists of many photolithographic and photo mask steps. Lately many UV and ultrafast femtosecond lasers have been excessively deployed for micromachining of quartz and polymethyl methacrylate PMMA which is economically unstable approach along with the other issues such as optimization and simplicity. In designing micro grating structures, several key issues have been immerged for researchers over the past few decades. The earlier methods for fabrication are complex and cost of making a simple grating is very high. The previous researches have raised lot of questions for example the techniques are costly, including multiple processing steps, surface precision, limited flexibility as well as rapid scanning speed. The experimental setup given in earlier researches consist of complicated optical arrangements which are difficult to illustrate the complete process. Therefore, there is an urgent need to develop a direct laser writing method which is at the same time cost effective and flexible as well as overcoming the previous hurdles in micromachining processes.

For answering these critical issues, we have introduced the improved method of inducing periodic structures by continuous wave CO_2 laser system. This technique is based on direct laser writing method which is capable of forming microchannels configuration and micro gratings which was difficult to achieve by photolithographic and mask based processes. The laser beam of 10.6 μm wavelength is directly focused on the glass substrate providing optimization, simplicity and flexibility in the overall process. The effectiveness of CO_2 laser is evident which is lying in the fact that it is widely employed in industry, its low cost machining and mostly preferred for fused silica glass due to its high absorption coefficient (Okazaki *et al*. 2010). This study encompasses the development of a model for temperature distribution and penetrating depth inside the work piece while interacting with the laser and proposed the reliable and efficient method of fabricating micro gratings on ordinary plane window glass, optical crown glass and fused quartz.

1.4 Objectives

This main objective of this research focuses on the development of effective and efficient fabrication system for periodic structures. The main objectives of this research are.

1. To fabricate laser induced periodic microstructures using CO_2 laser.
2. To fabricate the microchannels in polymethyl methacrylate PMMA, Quartz, and optical crown glass BK-7 using CO_2 laser.
3. To analyse these microstructure and surface characterization by SEM, Surface Profiler and optical microscope.
4. To develop a model for temperature distribution in workpiece by CO_2 laser.

1.5 Scope of Study

This research covers a review of grating fabrication techniques and introduction to the new method of periodic structure fabrication. This study comprises the fabrication of periodic structures using low power CO_2 laser. PMMA polymer and glass has been utilised in carried out the fabrication process. The study revolves around the analysis techniques such as Scanning electron microscopy (SEM), Optical Microscope and Taicaan Surface profiler. The last part of scope includes the heat transfer modelling of fabrication process using COMSOL multiphysics software which determines the time dependent temperature profiles of CO_2 laser while interaction with glass and PMMA.

1.6 Contribution of Study

In this research an improved method of micro grating fabrication and microchannelling has been developed. The proposed technique is successful in enabling the fabrication of microchannels and micro gratings using CO_2 laser. This technique is able to develop the plastic microfluidic chips on polymethyl methacrylate PMMA. This study unfolds the understanding of CO_2 laser system for the micromachining of microfluidic devices. Specifically it focuses on the investigation of optical crown glass BK-7, quartz and polymethyl methacrylate PMMA. The outcome of this research will be a prototype used in microfluidic devices and laboratory applications. Carbon dioxide laser fabrication for such microfluidic devices and micro gratings is a promising technique which is competent with other methods available for fabrication. Some points of major contributions of this research are described as follows:

1- The development of micromachining system utilising CO_2 laser.
2- The design and development of such process which is dynamic especially in micromachining of non-metallic materials.
3- Careful consideration of important input parameters including laser power, scanning speed of translational xy-stage.
4- This research identifies the factors that affect the laser micromachining process while using low power CO_2 laser system.
5- This technique will help to improve the current study for the production of microfluidic devices on polymethyl methacrylate PMMA.
6- The successful results show the production capabilities of the CO_2 laser system which was a challenge in the past.

In the particular area of laser micromachining, direct laser writing method is carrying significance where either the laser or the workpiece is moving. In such cases there have been novel application extensions to the fundamental idea (Sugioka, 2010).

1.7 Organization of the Thesis

Chapter 1 describes the outline of thesis. This chapter starts with the introduction of the specific problem under consideration. This chapter describes the objectives of the research, justification, and contribution of the study. This chapter acts as a brief summary to the whole thesis.

Chapter 2 presents the literature review of the techniques for inscribing the microchannels and gratings. This chapter briefly explains how different researchers have look to the problem that we are trying to tackle. The literature survey also helps in the formalising the problem statement and also give ways to introduce the new method which will help to define the boundaries of the current research.

Chapter 3 explains the theory behind the laser material interaction. Different models explaining the theory of laser mater interaction has been mentioned in this chapter. This chapter further elaborates the physics involved in the formation of microstructures with the help of existing contributions.

Chapter 4 provides the detailed methodology involved in the micro-fabrication system. This chapter described the apparatus for experimentation. This chapter discusses the detailed methods and techniques that are involved to generate micro gratings and microchannelling on non-metallic materials. Low power CO_2 laser system is used to inscribe periodic structures. The analysis has been carried out by Scanning electron microscope SEM, Optical microscope and Taicaan surface profiler.

Chapter 5 consists of two parts. First part presents the data collection and experimental analysis of laser induced periodic structures using glass, optical crown glass BK-7 and Quartz. The second part of this chapter represents the experimental analysis of laser induced microchannelling for microfluidic devices and laboratory applications. The results are critically analysed using surface morphology techniques such as surface profiler, SEM and optical microscope.

Chapter 6 enlightens the theoretical analysis of laser induced periodic structures and laser induced microchannelling. COMSOL multiphysics have been used for modelling. In this chapter the experimental results have been theoretically analysed. The heat transfer in laser material interaction has been simulated along the laser path. The temperature distribution for gaussian distribution has been calculated by simulation.

Chapter 7 concludes the whole thesis with summary of all the study carried out in the formation of periodic structure. The recommendations for future work are also stated in this chapter. Finally the thesis ends up with references and appendices as well as list of publications and presentations.

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