ME 323 Project Report
Photonic Crystal Fabrication using Femtosecond lasers

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Abstract

The project would include fabricating 1-dimensional photonic crystals composed of waveguides using infrared femtosecond lasers. The underlying phenomena responsible for this process is nonlinear absorption influenced by multiphoton absorption, tunnelling ionization, and avalanche ionization[1]. These phenomena cause a change in the refractive index of the material along the path of the waveguide. Light can then be guided along this path to achieve the desired destination. Complex paths can be generated using this technique. In this experiment, two kinds of paths were generated with varying process parameters, and the width and depth of the paths had been studied.

1. Introduction

1.1. Product description

A photonic crystal is an optical nanostructure in which the refractive index changes periodically in space [2]. Photonic crystals are made up of periodic arrangements of dielectric, metallo-dielectric, or even superconductor microstructures or nanostructures. These structures create regions with alternating high and low refractive indices, affecting how electromagnetic waves travel through them. Similar to how a semiconductor crystal's periodic potential affects the movement of electrons and defines their energy bands, photonic crystals define which light wavelengths can pass through and which are blocked. The wavelengths that can travel through the crystal in a particular direction are referred to as modes, while the range of these wavelengths is known as bands. On the other hand, wavelengths that cannot propagate form a photonic band gap. This selective propagation of light is a unique characteristic of photonic crystals, making them valuable in various optical applications.

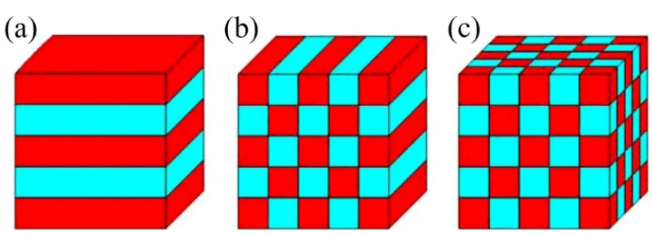

Fig 1: (a) 1-dimensional, 2-dimensional,
3-dimensional photonic crystal structures [3]

1.2. Applications

Photonic crystals, discovered about 30 years ago, are used in various everyday devices like light sources, lasers, and efficient solar cells. They also play a crucial role in trapping light in tiny spaces and processing optical information. Photonic crystals are extremely valuable as they allow precise control over light emission, making them ideal for cutting-edge uses like nonlinear processors in quantum computing and optical memories that store data as light [4].

They can be used wherever light needs to be manipulated. For example, one-dimensional dielectric mirrors can produce mirrors with extremely high reflectivity at specific wavelengths. Two-dimensional photonic crystals, like photonic-crystal fibers, are commonly used in fiber-optic communications. They are also used to create optical circuits, using waveguides to guide the path of light. Two-dimensional crystals are also used in biological and chemical sensors. Three-dimensional crystals also hold immense value as they are the cornerstone of optical computers and could lead to the development of more efficient solar cells [2].

1.3. Manufacturing Methods

Photonic crystals are fabricated by etching patterned nanopores into a substrate, typically a silicon wafer or soda glass, using lasers. The design of these patterns ensures that the crystal's refractive index changes periodically on a scale comparable to the wavelength of visible light. This periodic variation in refractive index generates a photonic "band gap," which controls the way photons move through the crystal. The band gap effectively dictates whether specific wavelengths of light are allowed to pass through or are blocked by the crystal.

Two-dimensional photonic crystals, such as optical waveguides, can be manufactured using femtosecond lasers. Two processes are generally used for this. The first process is the photophysical method in which the fs laser is used to ablate away parts of the material or change its properties. This causes changes in the optical behavior of the crystal. The second process is photochemical polymerization, which involves molecules of the material getting polymerized to change their optical properties in specific areas [3].

2. Objectives

The primary objective of this experiment is to fabricate photonic crystals using femtosecond lasers and analyse the propagation of light through the crystal. The two types of optical structures which are made in the experiment are: Straight waveguide and Optical beam splitter. Process parameters like laser scanning speed and laser power have been varied and the waveguides are characterised and studied.

3. Methodology

There are various methods that can be utilized for the fabrication of photonic crystals, such as chemical vapour deposition(CVD), biological template method, electron beam evaporation, spin coating, etc. However, one of the most precise and important micro-nano manufacturing technologies is Femtosecond laser multi-photon polymerization. The diffraction limit and spatial resolution that can be obtained through this technique are beyond any other conventional laser machining technology. There is also no requirement for any photomask [3].

3.1 Creating Parallel Channels

The incident light can be traversed across the width of the workpiece after focussing the photons to an appropriate depth, which has to be found out after some preliminary experiments. These parallel channels will be separated by a certain distance and it would create a 1-dimensional photonic crystal.

3.2 Creating an Optical Splitter

A Y-Junction splitter will diverge the beam into two parts having theoretically equal output powers, which is the half of the input port power.

Parameter	**Value**
Focal length	50 mm
Pulse width	206 fs
Beam diameter	9 mm
Wavelength	1030 nm
Beam waist diameter	7.3 micrometres

Table 1: Parameters of Yb laser to be used

4. Experimental Setup

The experimental setup comprises a Yb laser beam, which is responsible for the generation of photonic crystals. This is a femtosecond laser with Infrared beam radiations. After exiting the laser device, the beam is reflected by the mirrors and enters the beam expander. The beam then enters the galvoscanner, which is a device that uses a mirror and motor to deflect a laser beam in two dimensions. The detailed mechanism to control the laser path is shown in Figure 2. Galvoscanner's exit has an F-theta lens, which is able to realize tighter spot sizes, translating into higher resolution for scanning or printing, as well as higher and constant intensity in the image plane. The F-theta lens is designed to have a linear relationship between the input angle of the beam and the distance of the spot from the optical axis. It also ensures the spot remains focused across a wide, flat area. This is achieved by introducing distortions in the lens to create a flat field of focus. The focal length, beam diameter, and lens design are balanced to maintain uniform focus. The workpiece is placed over a moving stage, which can be translated into 3 dimensions using CNC. However, for the purpose of fabrication, the laser beam's spot size has been moved over the workpiece along its width after focussing it to the correct depth. The workpiece used is soda glass, that is, 70–75 wt% SiO_2, 12–16 wt% of Na_2O, and 10–15 wt% CaO.

4.1 M squared

The m-square value of the laser used is 1.06. The m-squared parameter, also called beam propagation ratio or beam quality factor is a measure of laser beam quality. If the beam has a perfect Gaussian profile(TEM_{00} mode), the m-square value is 1; otherwise, it is greater than 1. Experimentally, it is determined by studying the beam through beam profile meter, and fitting the curve with a gaussian distribution.

4.2 Beam spot size measurement

Thermal paper can be used to find the spot size of the beam. The procedure involved is single laser pulse ablation of the thermal paper, which generates a spot by changing its colour. The diameter of the spot generated is equal to the spot diameter. The thermal paper doesn’t have any non-linear effects or heat-affected zones, so we do not get an oversized spot. Theoretically, the beam spot size can be obtained by the incubation model.

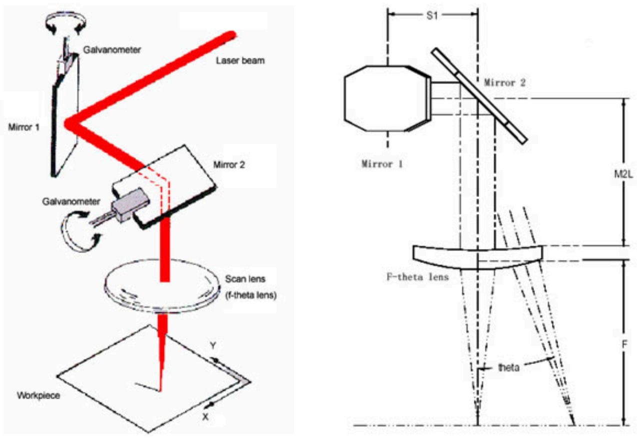

Fig 2: Galvanoscanner's motion mechanism controlled using two rotating mirrors[5]

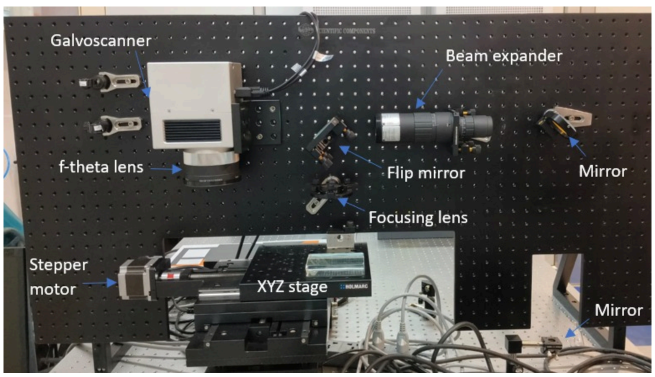

Fig 3: The optical setup mounted on a vertical optical bench

Fig 4: Yb IR Laser with wavelength 1030nm

5. Experimental Design

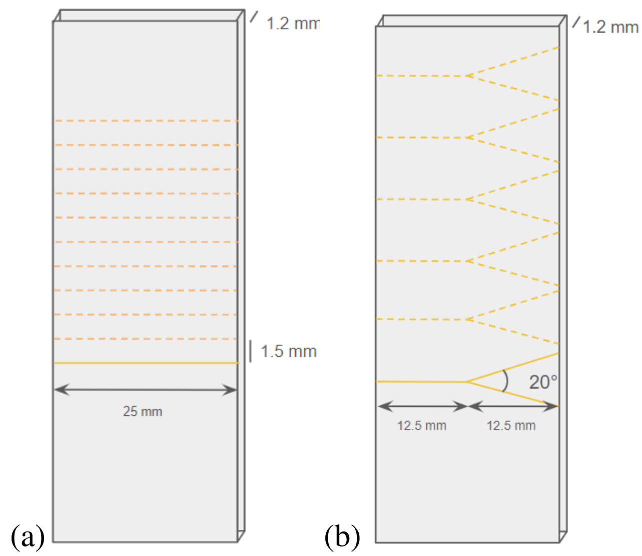

Fig 5 : (a) Straight optical waveguide (b) Optical beam splitter with angle of separation as 20° (Figure not drawn to scale)

The femtosecond laser pulse has to be focussed in the soda glass workpiece to an appropriate depth which would not damage the workpiece but modify the optical properties locally. This is done by changing the Z-position of the movable stage. Using a Pulse Repetition Rate(PRR) of 50 kHz, the optical passage have been created varying the following two set of parameters:

Laser scanning speed(mm/s)
10
100

Laser Power(W)
0.25
0.2
0.15
0.1
0.075

Table 2: Process parameters

Hence, 10 optical passages have been fabricated over the two workpieces. The straight optical passage (Fig5.a) is a 25mm channel built along the width of the workpiece separated by a distance of 1.5mm each. The optical splitter (Fig5.b) is a channel splitting midway 12.5 mm from the starting end into two passages diverging at an angle of 20°. The laser is an invisible IR laser but when it is focussed over the sample, it generates plasma which glows distinctly, and helps to detect the spot.

6. Characterization

It is necessary to evaluate the characteristics of waveguides during fabrication as it gives a feedback check to the design. The major characteristics may include refractive index, layer thickness, optical coupling, optical loss, and nonlinear properties[6]. Experimental evaluation and validation are necessary since these characteristics are rather difficult to determine theoretically.

The refractive index of a waveguide can be measured with techniques such as near-field coupling, prism coupling, evanescent-field imaging, M-Line spectroscopy, and Propagation mode near-field technique[7].

Furthermore, reflectance or transmittance spectrum can be calculated from the transfer matrix method (TMM) in a stratified medium together with the band structure, calculated based on the Bloch theorem[8].

However, due to the weak power of laser and more than optimum scanning speed, the waveguides of our sample are not fabricated distinctly. The boundaries of the waveguides are blurry because of only subtle change in the Refractive Index compared to the vicinity. Hence, the above-mentioned characterization cannot be carried out.

The width of the optical waveguide has been measured using Zeta™-20 Optical Profiler. The depth up to which the photons have been absorbed is also found using the same instrument, by measuring the change in focal point to make the path visible.

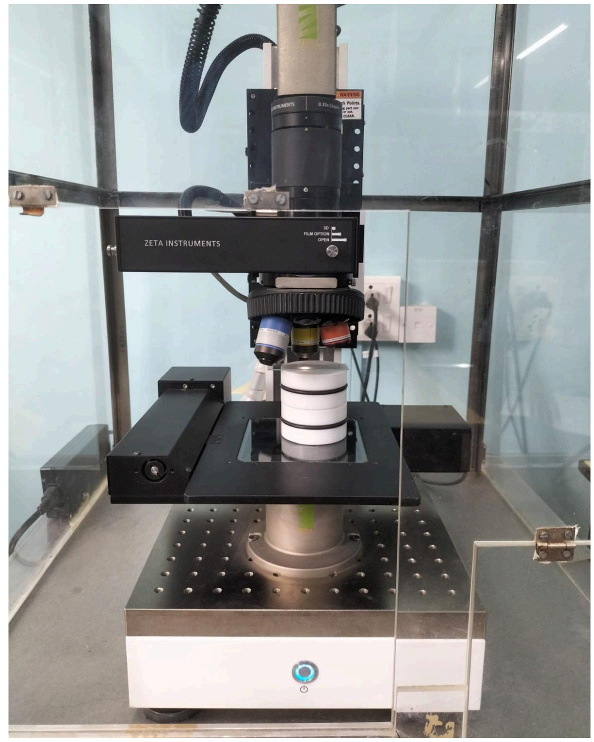

Fig 6: The Zeta™-20 Optical Profiler studying samples

Fig 7: Waveguide 4 image on PC scanned by Microscope

7. Results and Discussions

The width and depth of various straight waveguides have been measured by Zeta™-20 Optical Profiler. The path of the waveguides(WG-6 to WG-10) formed at high scanning speed (100 mm/s) are not visible by the optical microscope, so they couldn't be studied. The reason can be ineffective absorption of photons due to the elongated nature of Gaussian beam and the less time available to interact.

Also, path 4 has been formed partly on the surface due to the defocusing of the beam and uneven topology of the substrate's surface. Hence, no waveguide was fabricated, and the laser was used for ablation instead of absorption. The ablation depth came out to be 4.95µm.

Power (in W)	**Scanning speed (mm/s)**	**Width (µm)**	**Absorption depth(um)**
0.25	10	10.4	499.64
0.2	10	7.8	415.64
0.15	10	7	349.97
0.075	10	5.2	206.6

Table 3: Width and depth measurements

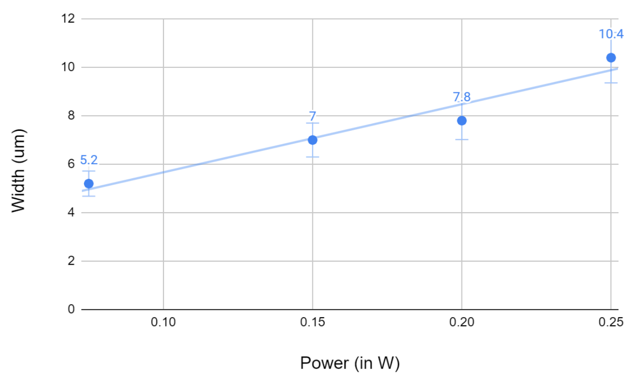

Fig 8: Variation of Waveguide width vs Power of laser

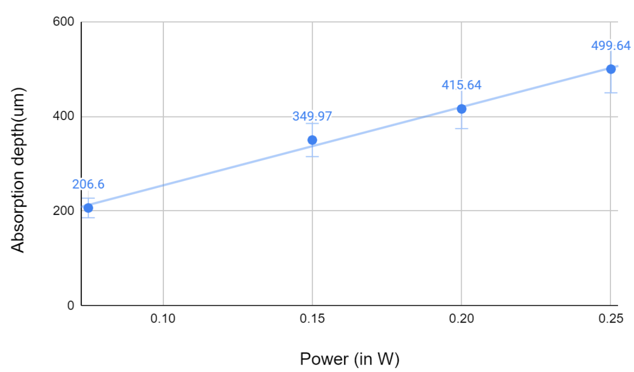

Fig 9: Variation of Absorption Depth vs Power of laser

The graphs show a direct correlation of Absorption depth and Waveguide width with the power of the laser, which is intuitively reasonable.

8. Conclusions

The experiment was carried out to find out the width and absorption depth of the fabricated waveguides. These values were showing a positive trend with the laser power used. The information can be further used to tune the laser parameters so the other waveguides have proper photon absorption and have a significant change in refractive index.

9. Future Scope of Project

Going forward, further characterization can be carried out for the waveguides using more precise instruments. We can get a more accurate measurement for width and depth with an optical profiler of higher magnification. We can also inspect the waveguide for defects such as jagged edges and scratches, which may cause scattering of light.

The refractive index can be determined using techniques such as reflectometry and ellipsometry. Reflectometry provides an approximation of the real part of the refractive index, while ellipsometry can be used to estimate both the real and complex components of the refractive index. Light waves consist of two perpendicular electric and magnetic fields. When the light is linearly polarized, these fields are in phase. A phase difference between the two fields is introduced if the light wave is reflected from a surface. In ellipsometry, a linearly polarized light wave is reflected from the sample surface, and the elliptically polarized reflected wave is analyzed. The phase difference obtained can give us the refractive index of the sample.

The power of the light wave decreases as it travels through the waveguide due to reasons such as absorption and scattering. This is known as optical loss. We can measure optical loss using the cutback method. In this method, first a long waveguide is fabricated. Light is passed through it, and the decrease in intensity is measured using an optical power meter. Then the waveguide is cut to a shorter length, and the same process is repeated. We know that intensity decays exponentially as the light passes through the waveguide.

$$I(x) = I_0 \exp(-\alpha x/10)$$

where I_0 is the initial power and α is the attenuation coefficient[6].

We can find the attenuation coefficient by using the data for two different lengths of the waveguide, keeping the other parameters the same[6].

10. References

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