Bragg grating manufacturing in planar silica substrates

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ABSTRACT

Femtosecond laser pulses are more and more spread for the micro/nano-machining of various materials. They were successfully used for the manufacturing of Bragg gratings in optical fibres through the implementation of the so-called point-by-point, line-by-line and plane-by-plane processes. In this work, we report the use of such laser for Bragg grating manufacturing in pure fused silica planar substrates. In particular, we rely on the commercial system called Femtoprint. This machine has efficiently produced Bragg gratings from bulk silica following several steps. First of all, a waveguide was imprinted in the glass substrate by tight control of the laser pulses and path. Then, an access point was created at one edge of the substrate so that a standard optical fibre can be easily connected with the engraved waveguide for light injection and collection. This was again done with femtosecond laser pulses and a subsequent etching with KOH was performed to create the required open spaces in the substrate. Finally, a Bragg grating was imprinted within the waveguide thanks to a third femtosecond laser process. The reflected amplitude spectrum of the grating was characterized using a dedicated interrogator and the obtained experimental results will be presented in this paper.

Keywords: Waveguide, Femtosecond laser, Bragg grating, Sensors, Silica glass

INTRODUCTION

Femtosecond lasers[1-5] are a class of ultrafast lasers that emit pulses with extremely short durations. Recently, femtosecond laser-assisted etching has emerged as a powerful technique for the high-precision manufacturing of complex, three-dimensional glass structures. This method can be used to create fully functional waveguides[6-8] inscribed with a Bragg grating[9-10] in the core of a silica glass plate. During the same operation, the monolithic structure and the periodical deformation of the Bragg grating can be manufactured, making it a highly efficient process. During the femtosecond laser-assisted etching process, several types of modifications can be created, depending on the various parameters involved. One type of modification is based on the densification of the glass, which results in an increase in the refractive index of the material[6-7]. This increase in refractive index can induce the creation of optical structures such as waveguides or Bragg gratings, which are useful in many applications. Another modification that can be induced by the femtosecond laser is the creation of the nanogratings[11]. Increasing the energy of the laser pulse can lead to the formation of these periodic structures, which are crucial for the femtosecond laser-assisted wet etching process. The nanogratings serve as a template for the different microstructures that are created, and they help to guide the etching process by spreading the KOH solution uniformly over the silica glass plate. Overall, femtosecond laser-assisted etching is a powerful and versatile technique for the high-precision manufacturing of complex glass structures. It offers the ability to create a wide range of modifications and structures, including waveguides, Bragg gratings, and nanogratings, and it has numerous potential applications in fields such as telecommunications, sensing, and microfluidic. Our work has focused on the fabrication of optical Bragg gratings using femtosecond laser technology. These gratings are widely used in the field of sensing with optical fibre due to the rich information they can provide and the high degree of precision with which they can be engineered. A Bragg grating is a periodic modification of the refractive index induced by increasing the energy of the femtosecond laser pulse. This regular modification allows us to obtain valuable information about the reflected and transmitted light. In our work, we have taken a novel approach by simultaneously inscribing the Bragg grating and the optical waveguide in the same operation.

This approach provides a highly efficient and streamlined process for the fabrication of complex optical structures. The resulting waveguide with integrated Bragg grating offers unique advantages, such as the ability to selectively filter specific wavelengths of light and the potential for highly sensitive sensing applications. Overall, our work has demonstrated the potential of femtosecond laser technology for the precise engineering of complex optical structures with broad applications in sensing and communication systems.

THEORETICAL BACKGROUND

The femtosecond laser operates on the principle of multiphoton absorption[12], explained in Fig 1a, which involves exciting a photon through multiple levels to reach its highest possible energy state. While this mechanism enables access to higher energy levels, it also presents challenges associated with the high energy involved in the laser. The intense photon flux generated by the femtosecond laser can significantly alter the nature of the resulting modifications, inducing concerns for the applications of the laser. As previously noted, the femtosecond laser is an ultrafast laser that can give access to diverse modifications in silica glass depending on various parameters. One of the most important parameters in femtosecond laser micro/nanofabrication is the energy deposited[13] on the substrate in Fig. 1b. The energy deposition process is influenced by several adjustable parameters such as repetition rate, pulse energy, writing speed, and non-linear beam waist. Repetition rate refers to the number of pulses delivered per second, and the energy deposited on the substrate is directly proportional to the repetition rate. Pulse energy, which of energy refers to the amount of energy in each pulse, also affects the amount deposited on the substrate. Writing speed, or the speed at which the laser beam moves across the sample surface, affects the dwell time of the laser at each point and hence the total energy deposited. The non-linear beam waist is another important parameter that affects the energy deposited on the substrate. It is a non-adjustable parameter that depends on the objective used. In FEMTOprint[14] machines, there are three types of objectives available represented in Fig. 1c, each with a different numerical aperture, size, and length. The numerical aperture determines the resolution and depth of field of the objective, and a higher numerical aperture results in a smaller beam waist and hence higher energy density. In addition to the adjustable and non-adjustable parameters, the material properties of the substrate and the laser parameters, such as the wavelength, also affect the energy deposition process. All these parameters must be taken into account when fabricating different micro/nanostructures using femtosecond laser micro/nanofabrication. Notably, the energy pulse constitutes a key parameter that influences the nature of the induced modifications. The femtosecond laser has been shown to create a wide range of modifications in silica glass, such as increased refractive index shown in Fig. 1d, the creation of nano gratings in Fig. 1e, and ablation. The specific modification induced by the femtosecond laser is largely dependent on the duration, power, and shape of the energy pulse used. Thus, careful selection of the laser parameters is crucial to ensure the precise control of the modifications induced by the femtosecond laser. Femtosecond laser micro/nanofabrication is a versatile and rapidly evolving technology used to create complex micro/nanostructures.

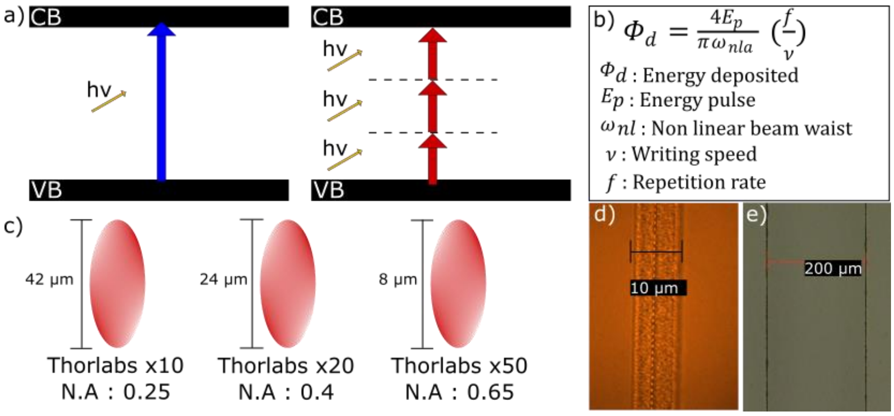

Fig 1: a) Schematic representation of the single photon absorption and the multi-photon absorption. b) Equation of the energy of deposition induced by the different printing parameters of a femtosecond laser. c) Schematic of the different laser objective available, their diameter and their different numerical aperture. d) Microscopic picture of a waveguide and a bragg grating realized with a femtosecond laser within silica glass plate. e) Microscopic picture of nanograting created with femtosecond laser at the surface of the silica glass plate.

The successful inscription of a Bragg grating within an optical waveguide embedded in silica glass is a key objective of various inscription techniques. This final objective has significant scientific and technological applications in the field of photonics, including communication systems and sensing technologies[15]. A Bragg grating is a periodic deformation, represented in Fig 2a that introduces a regular modulation of the refractive index in a waveguide. The result is the formation of a novel structure selectively transmitting and reflecting specific wavelengths of light, it's spectrum is shown in Fig 2c. The physical structure of a Bragg grating can be explained as a period of refractive index regions. In the literature, there are several types of Bragg gratings, differing in the type of deformation used to create them. Point, line, and plane deformations are the most common types of Bragg gratings[16-18] they are represented in Fig 2b. Additionally, the type of induced deformation can be elongated, irregular, or tilted[19]. These various types of Bragg gratings have unique properties and applications, making them essential in various fields of research. The ability to fabricate Bragg gratings in optical waveguides using silica glass is a significant advancement in the field of photonics. In sensing applications, Bragg gratings can be used to measure physical parameters such as temperature, pressure, and strain. They have also been used in biosensing, where they can detect biological molecules with high specificity and sensitivity. Overall, the inscription of Bragg gratings within optical waveguides embedded in silica glass is a critical objective in the field of photonics. The diverse range of Bragg gratings available, coupled with their unique properties and applications, makes them a valuable tool in research and technological advancements.

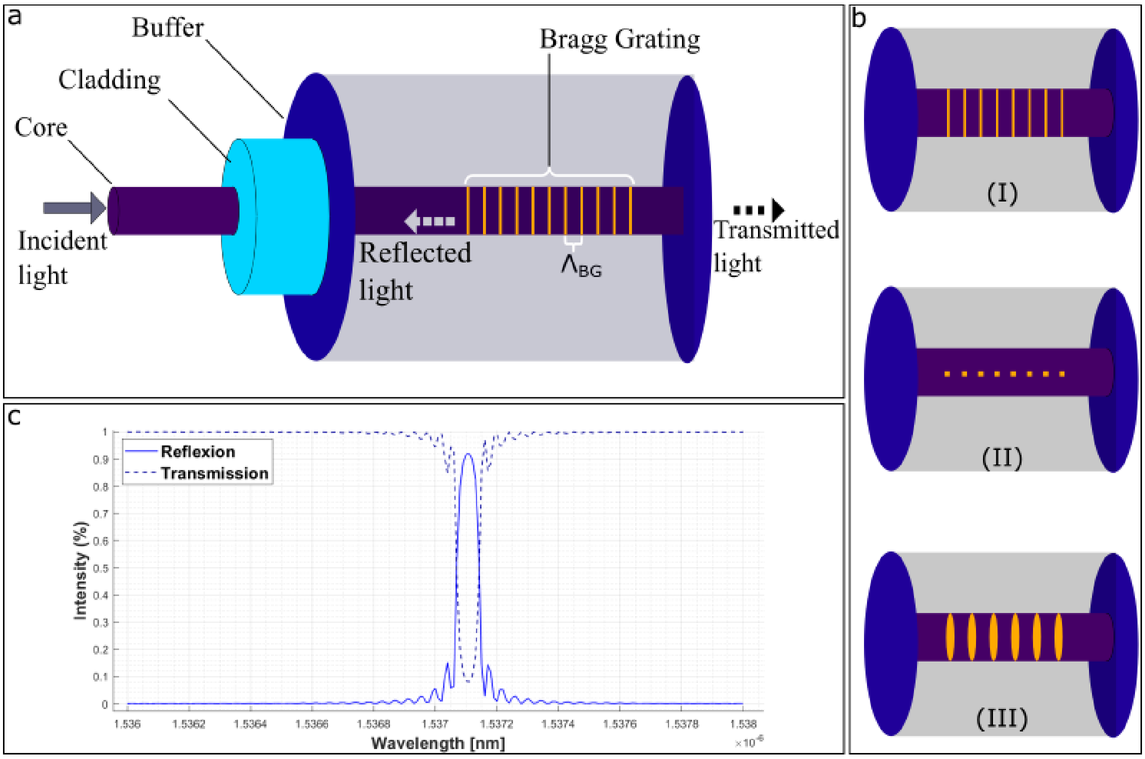

Fig. 2 : a) : Schematic representation of a Bragg grating in an optical fibre. b) Schematic representation of the different types of Bragg grating (I) line by line, (II) point by point, (III) Plane by plane. c) Spectrum simulation of a Bragg grating in Reflexion and in transmission.

MATERIALS & METHODS

In order to produce the structures under investigation, a standard silica glass material procured from Siegert Wafer was employed in conjunction with the FEMTOprint device, which comprises a femtosecond laser, high numerical aperture microscope objectives, and high precision translation stages. The FEMTOprint device enables precise sample alignment, while the Ti:Sapphire laser emits 300 femtosecond pulses at a wavelength of 1030 nm. The repetition rate and pulse energy of the laser can be modulated in the range of 1 kHz to 2 MHz and 60 nJ to 700 nJ, respectively. These parameters are programmed into the computer-aided design software (Alphacam), which offers several options for creating various mechanical and optical structures within a silica glass plate. To fabricate the diverse structures with the FEMTOprint machine, several critical steps need to be considered and summarized in Fig. 3. The design of Solidworks is critical to establish the dimensions of the sample. Depending on the chosen laser paths, the resulting structure can significantly vary. The initialization of the laser paths is pivotal to anticipate any tilt of the silica glass plate, while the chemical etching must be cautiously anticipated as prolonged exposure of the structure to KOH can lead to optical destruction due to its high concentration (12M).

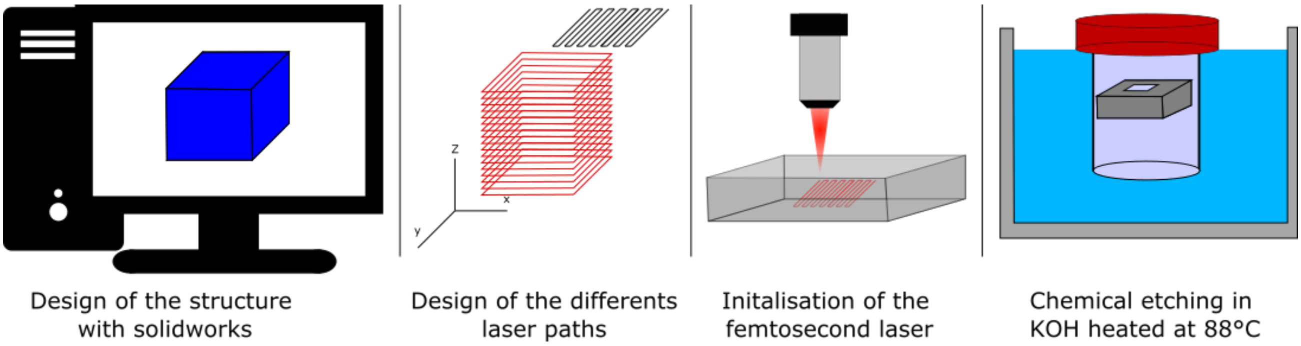

Fig 3 : Summary of the different step of the Femtoprint process.

To fully characterize the structures produced with the FEMTOprint machine, a variety of machines and equipment were utilized. Different types of microscopes were available for measurements and images, such as the VK-X200 3D laser scanning microscope from Keyence and the Axio imager from Zeiss. Optical characterization in reflection was carried out using a broadband optical source and an optical spectrum analyzer from Yokogawa (Model AQ6370D). Together, these tools enabled a comprehensive analysis of the produced structures.

RESULTS & DISCUSSION

In this article we present the different successes during the realisation of this optical structure within a silica glass plate made with the FEMTOprint machine. Several problems were encountered the first one is linked to the waveguide , the waveguide is created with the lowest energy pulse possible to induce densification of the silica glass plate and then an increase of the refractive index. These different test are summarized in the last SPIE event. The goal of the waveguide is to transmit the signal through the silica glass plate until it reaches the Bragg grating. One of the first problem we’ve encountered is the alignment because on a silica glass plate we are aiming at a 10 µm waveguide. So we needed to create that increase the precision of aiming the waveguide. So that is why we created a fibre older inside the silica glass plate that allows us to align the output of the optical fibre directly with the beginning of the waveguide. The design represented in Fig 4. a,b is separated in several part. The big holes are there for an easier spreading of the waveguide through the glass plate. These holes also have a role of cleaning in case the optical fibre breaks during the alignment. The second part are the small cavity/tunnel between the open cavities. These tunnel are there to guide the optical fibre through space until it reaches the side of the glass plate and then the entrance of the optical waveguide. These fibre holder are designed at the same moment as the inscription of the optical structures.

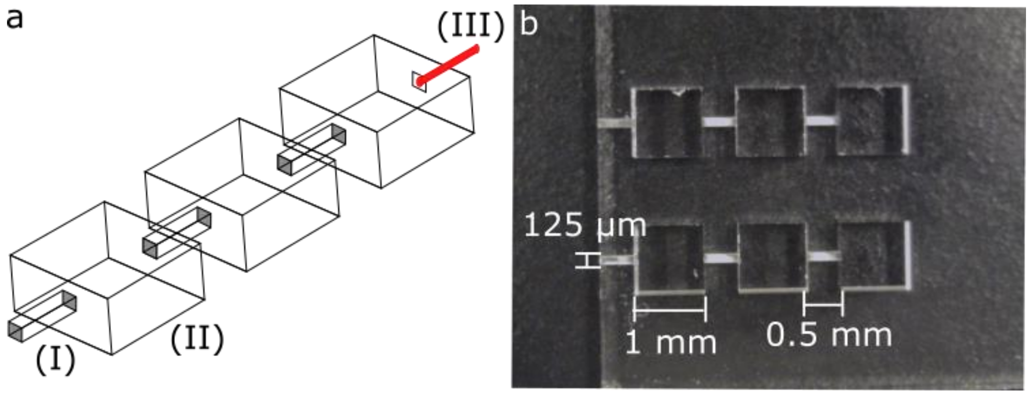

Fig 4 : **a)** Scheme of the fibre holder separated into three different parts.(I) Square-shaped insertion cavity for the insertion of different optical fibres. (II) Open cavity used for increasing the speed of spreading of the KOH. (III) Optical parts where the insertion takes place between the optical waveguide and the optical fibre. **b)** Picture of the fibre holder taken from above with the associated dimension.

Following the installation of the fibre holder it was necessary to optimize the waveguide signal and Bragg grating response. To accomplish this, several tests were conducted. The initial tests aimed to identify the first energy pulse that could cause slight densification of the silica glass plate. This was achieved through a comprehensive study in which we incrementally increased the energy of the silica glass pulse in 10-nJ intervals. By analyzing the response of the waveguide and Bragg grating to each pulse energy increment, we were able to identify the optimal energy level that achieved the desired level of densification.

Once the optimal energy level was identified, we proceeded to determine the optimal spacing between the different laser paths and the appropriate speed of inscription. The primary goal of these tests was to find the perfect balance between the lowest possible energy of the pulse, the ideal speed to ensure homogeneity throughout the entire waveguide, and the optimal spacing to avoid excessive accumulation caused by frequent overlap of the laser's voxel. Achieving this balance is critical to ensure optimal performance and reliability of the waveguide and associated Bragg grating. Overall, these tests allowed us to optimize the signal of the waveguide and the response of the Bragg grating, ensuring that the waveguide performs with the highest efficiency and reliability possible. The findings of this study have significant implications for the design and fabrication of waveguides, and can provide valuable insights for researchers and engineers in the field. All these results can be found and summarized with more detail[20].

After determining the efficiency of the waveguide, we decided to incorporate a plane-by-plane Bragg grating into the core of the silica glass waveguide. To achieve this, we utilized a slightly superior energy pulse, aimed at further increasing the refractive index. The Bragg grating, measuring 5 mm in length with a period of 2.1 µm, was successfully constructed. Following its completion, we observed the emergence of a Bragg peak, as depicted in Fig. 5 This peak is indicative of the Bragg grating's ability to reflect specific wavelengths of light within the waveguide.

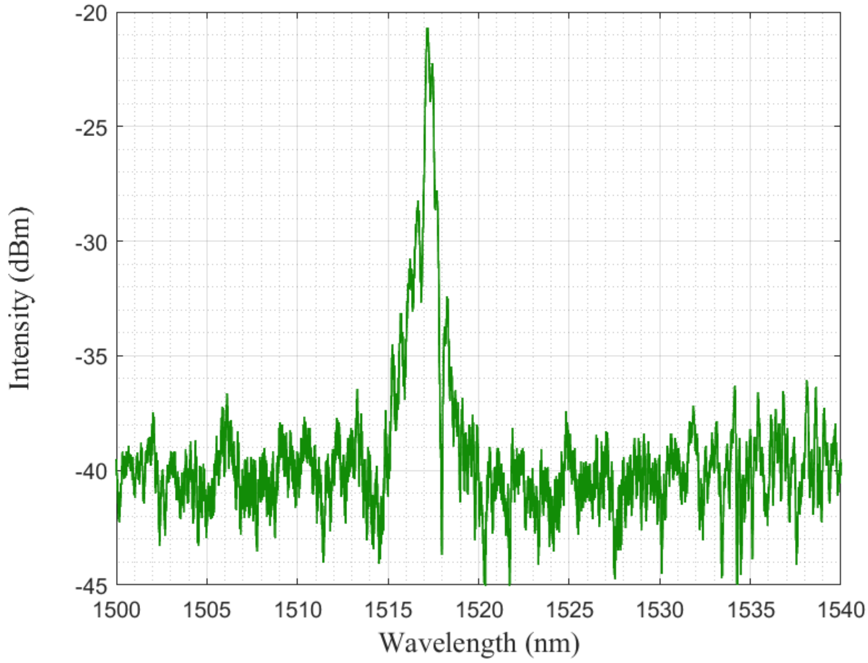

Fig. 5 : Reflected amplitude spectrum of a 5 mm long Bragg grating within a femtosecond pulses laser process silica glass plate.

CONCLUSION

In summary, our study has shown that femtosecond laser inscription technology is a powerful tool for the fabrication of precise and stable optical waveguides and gratings in silica glass substrates. The direct inscription of these structures using femtosecond laser pulses enables a high degree of control over the final device geometry, with a micron accuracy. Furthermore, the resulting waveguides and gratings exhibit good stability, making them ideal for use in advanced optical devices and systems. Our research has demonstrated the versatility of this fabrication method, which can be extended to other transparent materials beyond silica glass. This makes it a promising approach for the production of a wide range of optical devices such sensors. Overall, our study highlights the potential of femtosecond laser inscription technology for the development of advanced optical devices and systems, paving the way for future research in this field.

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