Femtosecond Laser Micro/Nano-Machining of Silica Glass Planar Substrates for the Production of Bragg Gratings

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ABSTRACT

Femtosecond laser pulses are increasingly utilized for the micro/nano-machining of a wide range of materials. They have been effectively employed in the production of fiber Bragg gratings (FBGs) through the implementation of point-by-point, line-by-line, and plane-by-plane processes. This study reports on the use of such lasers for the manufacture of Bragg gratings in pure fused silica planar substrates. In particular, the commercial system known as FEMTOprint was employed. This machine enabled the efficient production of Bragg gratings from bulk silica through several steps. Initially, a waveguide was engraved into the glass substrate through precise control of laser pulses and paths. Subsequently, an access point was created at one edge of the substrate to facilitate the easy connection of a standard optical fiber for light injection and collection. This was accomplished through the use of femtosecond laser pulses, followed by an etching process utilizing KOH to selectively ablate some material and create the necessary open spaces in the substrate. Finally, a third femtosecond laser process was utilized to inscribe a Bragg grating within the waveguide. The reflected amplitude spectrum of the grating was characterized with an FBG interrogator, and the obtained experimental results will be presented in this paper.

INTRODUCTION

Femtosecond pulses lasers emit extremely short pulses of light, with a duration of approximately 10^{-15} seconds. These ultra-short pulses have a wide range of applications in various fields, including material processing, medical processes, or the creation of optical structures in optical fibers. In the context of our work, we rely on two specific aspects of the femtosecond laser technology: wet etching inscription and the direct inscription of optical structures. There are three main types of defects that can be created by a femtosecond laser: modification of the refractive index[1] (Fig 1.a), creation of nano-gratings [2] (Fig 1.b), and direct ablation. For femtosecond laser-assisted etching, the most important defect is the creation of nano-grating to guide the structures that will be etched in a strong base bath (in this specific case, KOH). For the creation of optical structures, the focus is on the modification of the refractive index. This modification will induce the creation of optical structures. Depending on the used shape, an optical waveguide or a Bragg grating can be produced. A waveguide is a structure that guides light along a specific path, typically in its core region. There are different types of waveguides, such as optical fibers, planar waveguides, and rib waveguides. The core of the waveguide is typically made of a material with a higher refractive index than the surrounding cladding, and the light is confined into the core by total internal reflections. Waveguides are used in a variety of applications, including telecommunications, sensing, and laser technology. A Bragg grating is a periodic variation of the refractive index of a material, typically created by a process called holographic inscription. The periodicity of the grating causes a specific wavelength of light, known as the Bragg wavelength, to be reflected while other wavelengths pass through. In our work, a waveguide is created by the modification of the refractive index of the material, while a Bragg grating is a regular deformation of the refractive index which is observed in reflection or in transmission, with the appearance of a peak.

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FEMTOSECOND THEORETICAL BACKGROUND

In order to create these different types of defects, a process known as multiphoton absorption was utilized. The energy of the laser pulse [3] is a crucial factor in determining the type of defect that will be created. In the current situation, a pulse energy of 130 nJ is typically sufficient to induce densification of the material, leading to an increase in the refractive index. On the other hand, a pulse energy of 230 nJ is typically required to create a nano-grating. The impact of these parameters on the efficient production of wanted structures was previously established through studies performed during the early stages of our research.

The creation of waveguides and Bragg gratings shares a common theoretical foundation in terms of material processing. On the one hand, a waveguide is characterized by a global increase in the refractive index ($\Delta n = 10^{-3}$) relative to the surrounding environment, so as to guide light along a specific path. On the other hand, a Bragg grating is characterized by a regular deformation of the refractive index within the core of the silica glass plate, as explained in Fig 1.c. There are three main types of Bragg gratings that can be created through femtosecond laser inscription. The plane-by-plane[4] inscription involves the simultaneous inscription of multiple planes of the grating, while line-by-line[5] inscription involves the inscription of a single line of the grating at a time. Point-by-point[6] inscription involves the inscription of individual points of the grating, one at a time. In this work, we used the FEMTOprint[7] device to inscribe a plane-by-plane Bragg grating within the optical structures.

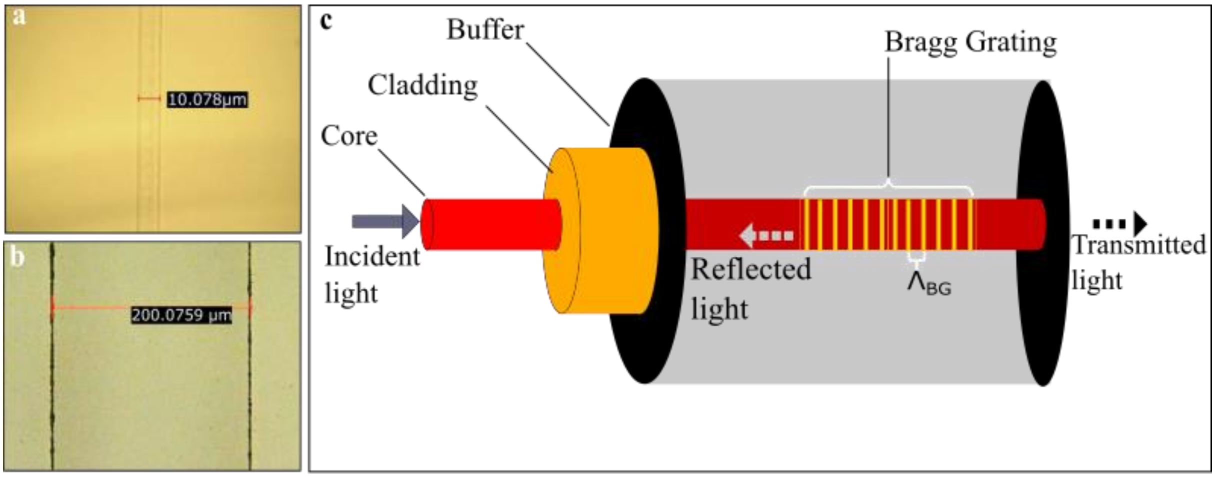

Figure 1: **a** Microscope picture of a modification of refractive index realised with femtosecond laser pulses on silica glass. **b** Microscope picture of a nanograting realised with femtosecond laser pulses on silica glass. **c** Schematic representation of the effect of the Bragg grating and its effect on the different optical answers.

MATERIAL & METHODS

In order to create the various structures under study, we utilize a standard silica glass from Siegert Wafer and the FEMTOprint device (Fig 2). The FEMTOprint device comprises a femtosecond laser, high numerical aperture microscope objectives, and high precision translation stages, which enable precise alignment of the sample under examination. The laser used in this device is a Ti:Sapphire laser which emits pulses of 300 femtoseconds at a wavelength of 1030 nm. The laser's repetition rate and pulse energy are adjustable, with a range of 1 kHz to 2 MHz and 60 nJ to 700 nJ, respectively. These parameters can be easily adjusted and are linked to computer-aided design software (Alphacam) for precise control and manipulation. In order to fully characterize the structures created through femtosecond laser inscription, a variety of different devices and equipment were employed. A microscope was utilized to obtain visual images of the various waveguides and Bragg gratings created. Furthermore, a system comprising an Optical Spectrum Analyzer (OSA) and a Bragg interrogator was employed to analyze and characterize the different Bragg gratings. This combination of devices and equipment allowed for a comprehensive understanding and characterization of the structures created through femtosecond laser inscription.

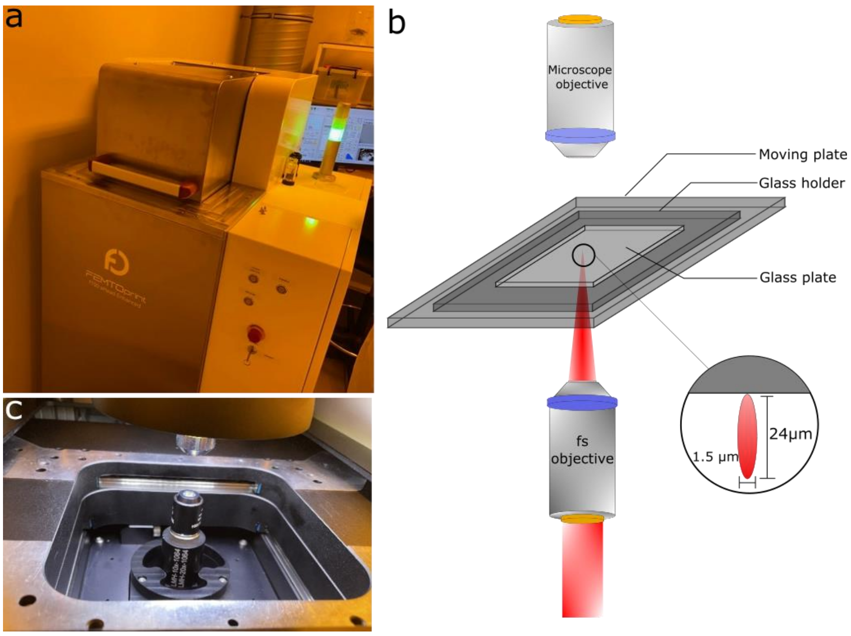

Figure 2: **a.** Picture of the FEMTOprint machine from the outside; **b.** Scheme of the global functioning of the FEMTOprint machine. Note that the glass substrate is fixed on a holder placed above the laser objective; **C.** Picture of the femtosecond laser objective located at the bottom and the observation objective located at the top.

EXPERIMENTAL CHARACTERIZATION

The initial result pertains to the demonstration of the efficiency of signal transmission. During the course of our study, a significant issue arose in regards to the quality of the waveguide utilized. In order to evaluate the transmission quality of the signal, a Bragg grating was incorporated into an optical fiber and subsequently characterized in transmission. Then, the same Bragg grating was characterized in transmission, however, in this instance, the optical waveguide that had been conceptualized was also incorporated into the transmission path. This resulted in a difference in transmission intensity, as depicted in previous work[8]. During the next part of our study, a primary challenge emerged in terms of alignment between the waveguide and the optical structure within the silica glass plate. To address this issue, a decision was made to construct a structure that would securely hold the optical fiber and ensure precise alignment with the optical waveguide.

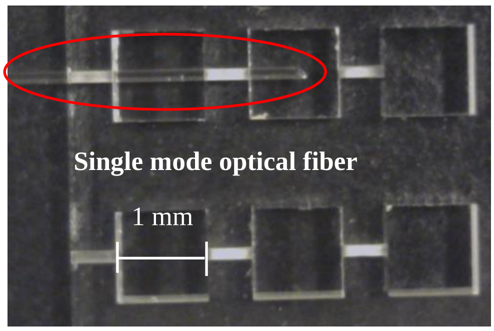

Figure 3: Picture of the optical fiber going through the silica glass plate within the etched structures.

The next step was to add a Bragg grating within the core of the waveguide. To create this Bragg grating we decided to adjust the parameters and increase the energy of the pulse (150 nJ) and lower the speed (15mm/min) to increase the difference in refractive index between the waveguide and the Bragg grating, resulting in the reflected amplitude spectrum shown in Fig. 4 for a 5 mm long FBG.

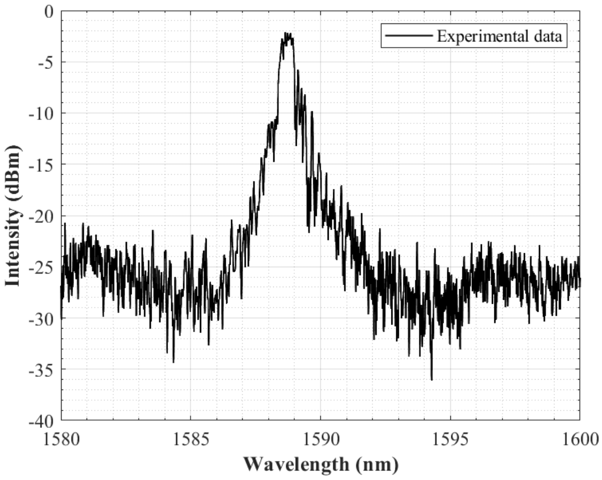

Figure 4: Reflected amplitude spectrum obtained from a uniform Bragg grating in the optical waveguide within silica glass.

The incorporation of a Bragg grating directly into an optical waveguide is depicted in Fig 4. Despite the challenges and difficulties encountered during the alignment process, success was observed. In this particular instance, a plane-by-plane Bragg grating was inscribed directly into the planar silica glass waveguide. This is a significant achievement as it will enable the use of this Bragg grating for future temperature and strain sensing. This is important as it allows for a deeper understanding of the behavior of the Bragg grating under different conditions, which can be used for various applications and improve the overall performance of the waveguide.

CONCLUSION

In conclusion, our study has successfully demonstrated the potential of femtosecond laser inscription technology for the fabrication of precise and stable optical waveguides and gratings in silica glass substrates. Our research has shown that by utilizing femtosecond laser pulses, it is possible to directly inscribe waveguides and Bragg gratings in silica glass with a high level of precision and stability. The results of this study have opened up new opportunities for the development of more advanced and efficient optical devices and systems. The fabrication method we used is highly versatile and can be applied to different types of transparent materials, for optical device fabrication.

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