Fabrication of Bragg Gratings in Flat Silica Substrates Using the Femtoprint Device and Use for Sensing

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ABSTRACT

Femtosecond laser-based 3D printing has strongly improved the field of photonics, enabling the fabrication of complex optical components. In this study, we present the development and characterization of a bulk Bragg grating sensor created using the Femtoprint system, which integrates a femtosecond laser for high-precision structuring. The latter enables the direct writing of waveguides with Bragg gratings within a transparent substrate. This unique manufacturing process grants control over the waveguide's geometry, grating period, and refractive index modulation, resulting in sensor capable of extraordinary sensitivity. We conducted a characterization of the waveguide with a Bragg grating sensor to assess its performance. Our results demonstrate remarkable sensitivity to environmental parameters, with a temperature sensitivity of 10.51 pm/°C and a mechanical strain sensitivity of 1.22 pm/με. These characteristics make the sensor ideal for a wide range of applications, including temperature monitoring and structural health assessment. The innovative combination of femtosecond laser printing and Bragg grating technology offers a new dimension to the design and application of optical sensors. Our research not only highlights the unique capabilities of these sensors but also opens up exciting prospects for future developments and interdisciplinary collaborations.

Keywords: Waveguide, Femtosecond, Femtoprint, Sensors, Bragg grating, Fused Silica glass

1. INTRODUCTION

Femtosecond lasers pulse [1] have emerged as powerful tools in the field of optics and material science [2], offering precision and control in the creation of different structures [3] at the nanoscale. One application of femtosecond laser technology is the fabrication of optical structures within silica glass substrates [4]. This process involves using ultrashort pulses of laser light, typically in the femtosecond range (10^{-15} seconds), to induce nonlinear absorption and photochemical effects within the material. In this context, the creation of optical structures within glass presents a remarkable spectrum of properties and functionalities. These structures exhibit unique characteristics that can be characterized in terms of temperature response (10.51 pm/°C) [5] and flexural behavior (1.22 pm/με) [6]. Understanding and characterizing these features are essential for optimizing the performance and reliability of devices and systems using such laser-fabricated structures. The ability to generate optical structures in glass with femtosecond lasers opens doors to diverse applications, including waveguides, microfluidic channels, and photonic devices. The thermal and flexural characteristics of these structures play a crucial role in determining their stability and functionality under various operating conditions. In this exploration, we search into the fabrication process of optical structures in glass using femtosecond lasers and the subsequent characterization of these structures concerning their response to temperature variations and flexural stress. By comprehensively studying these aspects, we aim to uncover insights that contribute to the advancement of precision optics and the development of robust and versatile optical devices.

2. FEMTOSECOND PULSES LASER ENGINEERING PROCESS

The femtosecond laser functions based on the principle of multiphoton absorption [7] , as illustrated in Fig 1a. This process involves exciting a photon through multiple energy levels to reach its highest state. While this mechanism provides access to higher energy levels, it also introduces challenges due to the high energy associated with the laser. The intense photon flux generated by the femtosecond laser can significantly alter the nature of resulting modifications, raising concerns for its applications.

As noted earlier, ultrafast femtosecond lasers can induce diverse modifications in silica glass depending on various parameters. The energy deposition [8] process is influenced by adjustable parameters such as repetition rate (Ω), pulse energy, writing speed, and non-linear beam waist [9]. Repetition rate, indicating the number of pulses delivered per second, directly affects the energy deposited. Pulse energy (E_p), representing the amount of energy in each pulse, also impacts the substrate's deposited energy (Φ_d). Writing speed (υ), or the speed at which the laser beam traverses the sample surface, affects the dwell time and, consequently, the total energy deposited. The non-linear beam waist (w_{nl}), an adjustable parameter dependent on the objective used, plays a crucial role

$$\Phi_d = \frac{4E_p}{\pi w_{nl}}\left(\frac{\Omega}{\upsilon}\right)$$

FEMTOprint [10] machines offer three objective types, each with different numerical apertures, voxels sizes and lengths, as depicted in Fig. 1b. The numerical aperture [11,12] influences the resolution and depth of field, with a higher numerical aperture resulting in a smaller beam waist and higher energy density. In addition to adjustable and non-adjustable parameters, material properties of the substrate and laser parameters, such as wavelength, also impact the energy deposition process. All these parameters must be considered when fabricating micro/nanostructures using femtosecond laser micro/nanofabrication. Notably, the energy pulse is a key parameter influencing induced modifications. The femtosecond laser has demonstrated the creation of various modifications in silica glass, such as increased refractive index (Fig. 1c) [13,14], the formation of nano gratings (Fig. 1d) [15], and ablation. The specific modification induced by the femtosecond laser depends on the duration, power, and shape of the energy pulse used. Therefore, meticulous selection of laser parameters is essential to ensure precise control over the modifications induced by the femtosecond laser. Femtosecond laser micro/nanofabrication stands out as a versatile and rapidly advancing technology for generating complex micro/nanostructures.

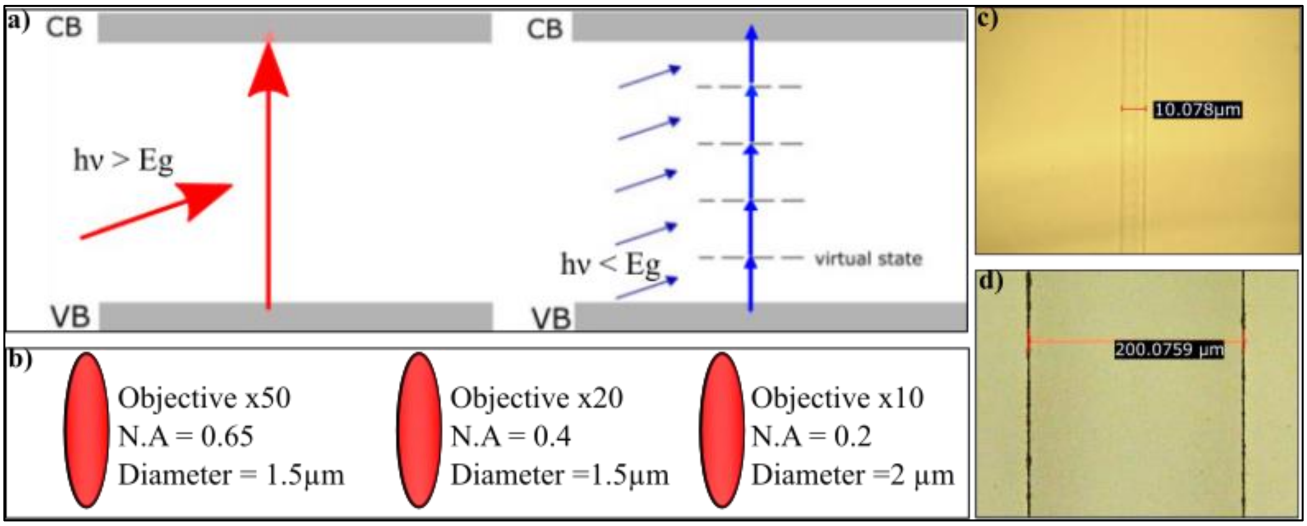

Fig. 1: a) Schematic representation depicting single-photon absorption and multi-photon absorption. b) Scheme displaying the variety of laser objectives, their respective diameters, and distinct numerical apertures. c) Microscopic image capturing a waveguide produced using a femtosecond laser in a silica glass plate. d) Microscopic image showing a nanograting formed on the surface of a silica glass plate using a femtosecond laser.

The femtosecond laser proves versatile in creating diverse structures, with an essential consideration being the increase in refractive index, particularly crucial for crafting optical elements like waveguides or Bragg gratings. Simultaneously, the nanograting provides the opportunity for wet etching on the glass plate, a common and well-established process in femtosecond laser applications. In this wet etching process, the glass plate exposed to the femtosecond laser is immersed in an etching agent, such as potassium hydroxide (KOH, 12M) [16,17]. Subsequently, the temperature of the etching agent is elevated to 85°C, initiating its action on the regions of the glass previously exposed to the femtosecond laser. This process facilitates the controlled alteration of the glass structure, enabling the creation of intricate and customized features. Among the various optical structures, our attention is directed towards the Bragg grating and the waveguide. The waveguide involves a densification of the plate structure, leading to a global increase in refractive index [18,19]. On the other hand, the Bragg grating is characterized by a periodic deformation inducing an optical response, observable in both reflection and transmission modes. Further details on these phenomena are elaborated in Fig. 2.

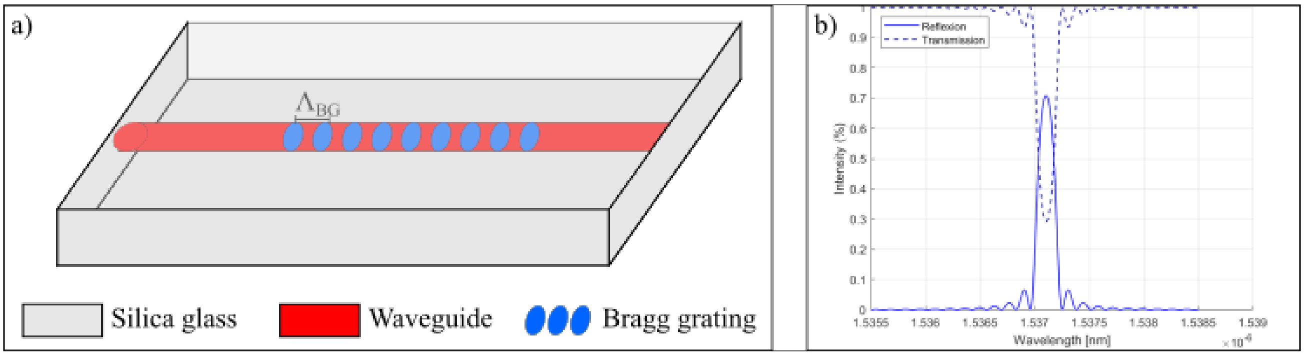

Fig. 2: **a)** Schematic representation of the Bragg grating into a planar silica glass plate. **b)** Spectrum representation of the Bragg grating in reflection and in transmission.

The Bragg grating, as illustrated in Fig 2, exhibits sensitivity to various parameters, with a distinctive responsiveness to changes in surrounding temperature and mechanical strain. According to the literature [e.g. 20], we can estimate its sensitivity to temperature to be approximately 10 pm/°C and 1.24 pm/με for mechanical strain.

3. MATERIALS & METHODS

To generate the examined structures, we utilized a standard silica glass material from Siegert Wafer with the FEMTOprint device. This device includes a femtosecond laser, high numerical aperture microscope objectives, and precision translation stages. The FEMTOprint device facilitates accurate sample alignment, with the Ti:Sapphire laser emitting 300 femtosecond pulses at a 1030 nm wavelength. The laser's repetition rate and pulse energy can be adjusted between 1 kHz to 2 MHz and 60 nJ to 700 nJ, respectively. These parameters are programmed into the Alphacam computer-aided design software, which provides options for creating various mechanical and optical structures within a silica glass plate. To manufacture diverse structures using the FEMTOprint machine, several crucial steps are outlined in Fig. 3 . The Solidworks design is essential for establishing sample dimensions. The resulting structure can significantly vary based on the chosen laser paths, making the initialization of these paths crucial to anticipate any tilt of the silica glass plate. Careful consideration is given to chemical etching, as prolonged exposure of the structure to KOH can result in optical destruction due to its high concentration (12M). The KOH exhibits heterogeneous spreading, with a notable contrast between the exposed (130 µm/h) and non-exposed (0.7 µm/h) areas affected by the femtosecond laser. This variation in etching speed creates a selectivity in the etching process, distinguishing between regions based on their exposure to the femtosecond laser.

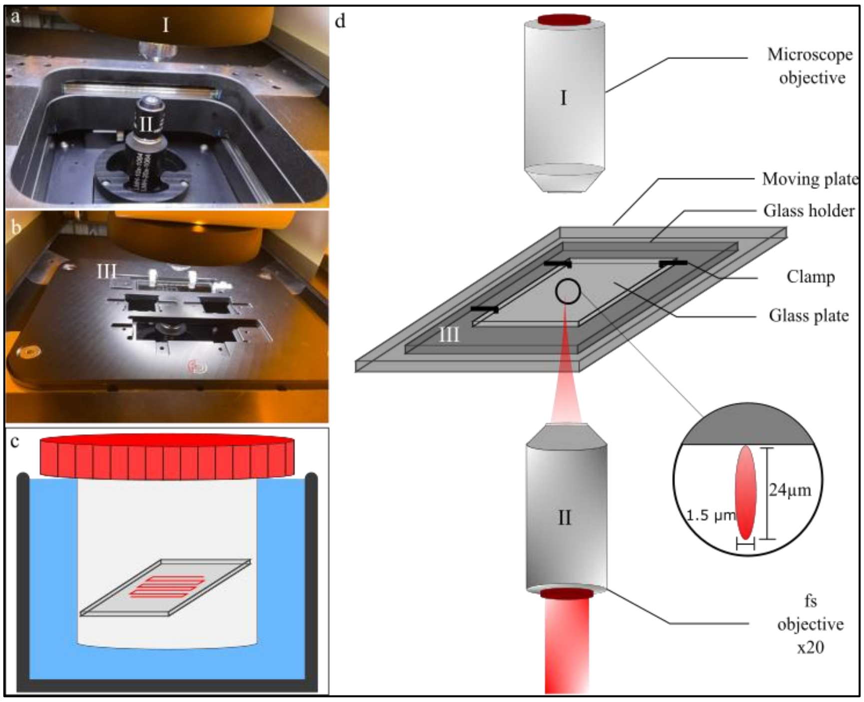

Fig. 3: a) Picture of the Inside of the Femtoprint machine with the microscope objective. (I) and the objective of the femtosecond laser (II) b) Picture of the Femtoprint with the glass holder setup for the inscription (III). c) Schematic representation of the wet etching of the silica glass plate d) Schematic representation of the setup of the Femtoprint machine.

The main objective of the study is to follow the evolution of the Bragg grating as a function of its surrounding environment and more specifically the impact of the temperature and the impact of the mechanical flexures on the signal of the Bragg grating. To do so we have put in place different experiments that aim to follow in the best possible way the evolution of the Bragg peak through the experiment. In terms of characterization, a combination of devices was employed to analyze the manufactured structures. Optical characterization was carried out using two microscopes: the VK-X200 3D laser scanning microscope from Keyence and the Axio imager from Zeiss. These microscopes facilitated the observation of surface roughness and measurement of the dimensions of the flexible structures. For spectral quality analysis of the optical structures, experimental setups were implemented. The reflected amplitude spectra were measured using a broadband optical source and an Optical Spectrum Analyzer (OSA) from Yokogawa (Model AQ6370D). For precise temperature and axial strain characterizations, a dedicated interrogator designed for fiber Bragg gratings was utilized. This interrogator (Fibersensing FS2200 industrial Braggmeter) offers a wavelength resolution of 1 pm and a repetition rate of 1 Hz.

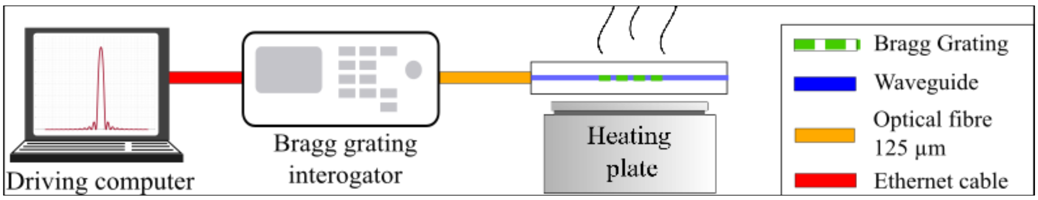

Fig. 4: Scheme representing the setup for the characterization of the evolution of the Bragg peak with the temperature.

Regarding the mechanical flexures, three types of deformation were introduced: vertical traction, three-point flexure, and a cantilevered beam. Despite these varied deformations, the sensitivity to the applied mechanical deformation remains consistent at approximately 1.24 pm/µε. However, due to the distinct characteristics of each deformation, several setups were created, each specifically designed for the characterization of the corresponding piece. This approach ensures accurate and tailored characterization for each type of mechanical flexure. The different setup for the different characterization are represented in Fig. 5.

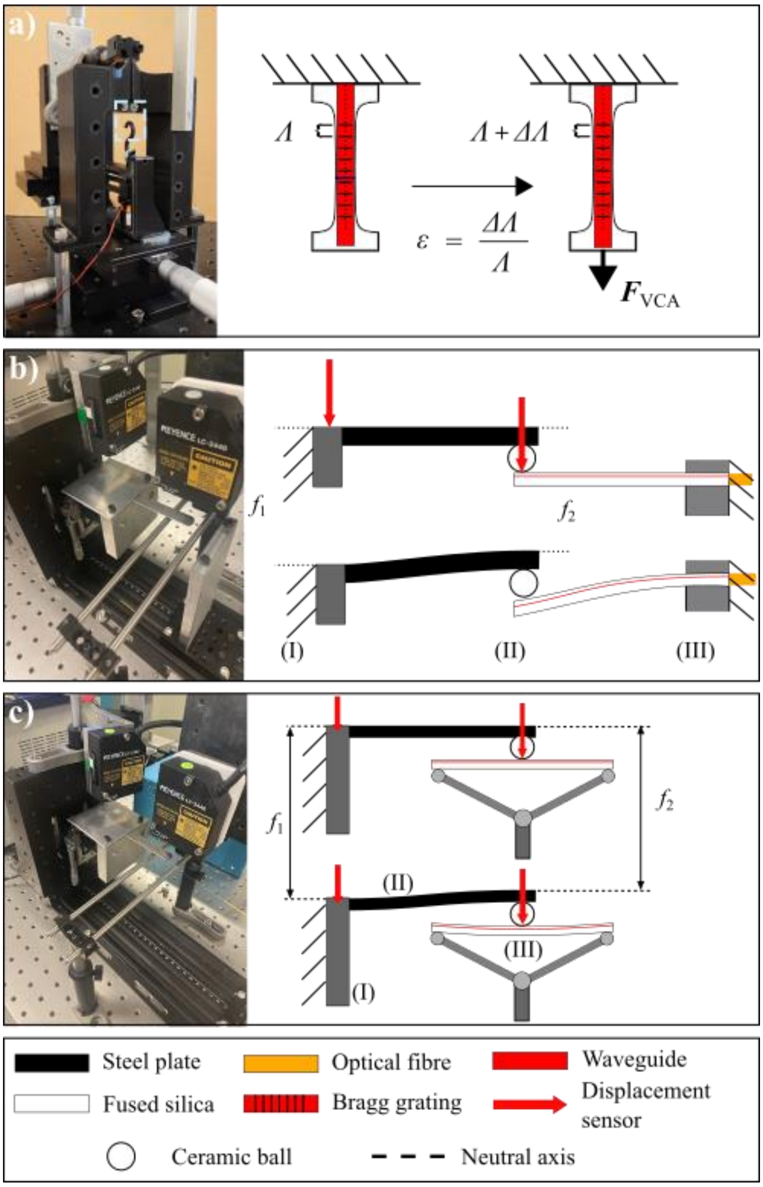

Fig. 5: **a)** Picture and schematic representation of the traction setup **b)** Picture and schematic representation of the Cantilever-beam setup **c)** Picture and schematic representation of the three-points setup

4. RESULTS & DISCUSSION

The temperature characterization presented in Fig. 6 illustrates the shift in Bragg wavelength concerning an increase in temperature ranging from 0 to 90 °C, starting from an ambient temperature of 20 °C. To demonstrate the repeatability of the experiments, six characterizations were conducted on the same sample. The average value and corresponding standard deviation were then calculated for each measurement. By subjecting the raw data to linear regression analysis, a temperature sensitivity of 10.51 pm/°C was determined. This value aligns with both theoretical predictions and measurements obtained from silica optical fibers, validating the consistency and accuracy of the experimental results.

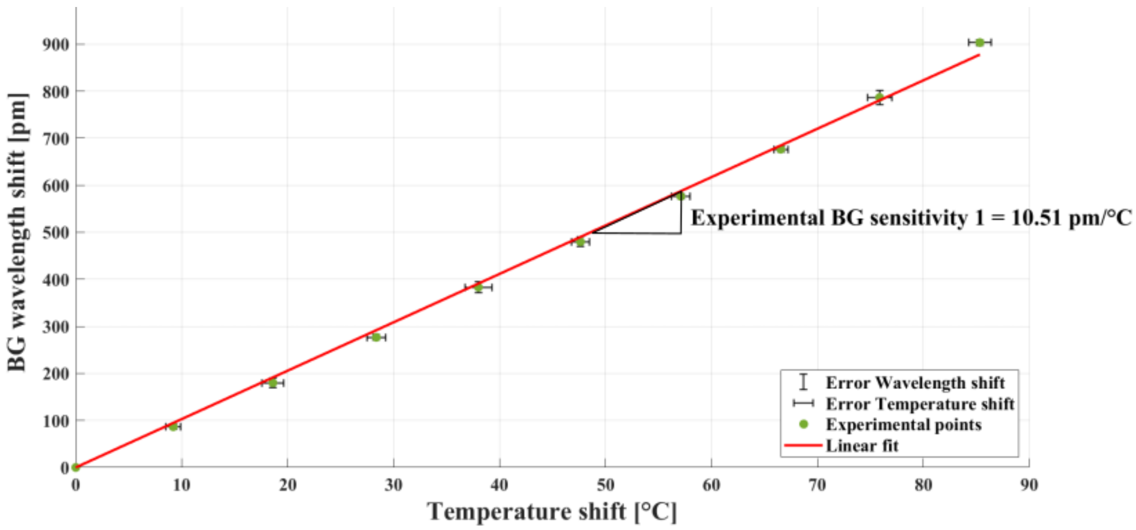

Fig. 6: The graph illustrates the variation in Bragg wavelength concerning temperature. Three measurements were conducted on the same sample. The error bars depict the average standard deviation for the respective batch.

For strain characterization, we employed the experimental setup depicted in Fig. 5. The wavelength shift was determined as the difference between the strained and unstrained specimens. To mitigate potential impacts of air fluctuations during the experiment, the setups were placed in confined spaces. Characterization was conducted for three types of mechanical deformation, with linear regression performed on each. The sensitivity characterization experiments of the Bragg grating for our different setups are depicted in Figure 4. The strain testing range varied depending on the experiment, with each range selected to minimize the probability of breakage. The characterized sensitivities of the Bragg grating for the three designs align well with the theoretical sensitivity (1.22 pm/με). Consequently, the validation of sensor manufacturing has been achieved, and further tests can be arranged in different configurations and environments based on specific applications.

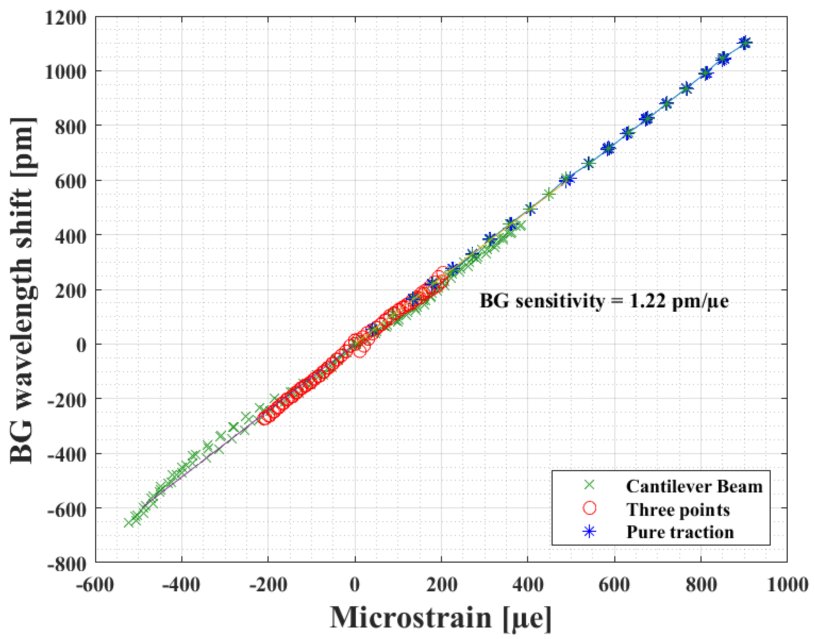

Fig. 7: Results of the characterized Bragg grating sensitivity to strain for the three specimen designs that are detailed in Figure 5. Each experiment has been performed 4 times. The standard deviation of the experiments from the linear fit is 10 με.

5. CONCLUSION

In summary, our study reveals that femtosecond laser inscription technology emerges as a potent means for crafting precise and enduring optical waveguides and gratings within silica glass substrates. The direct inscription of these structures using femtosecond laser pulses affords exceptional control over final device geometry, achieving micro-level accuracy. Moreover, the resulting waveguides and gratings demonstrate admirable stability, rendering them well-suited for integration into sophisticated optical devices and systems. Our investigation further underscores the temperature sensitivity (10.51pm/°C) and strain sensitivity (1.22 pm/με) inherent in these structures. We showcase the adaptability of this fabrication method, extendable beyond silica glass to various transparent materials. This versatility positions it as a promising avenue for producing a diverse array of optical devices, including sensors. In essence, our findings underscore the potential of femtosecond laser inscription technology in advancing optical device development, heralding new avenues for research in this domain.

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