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Femtosecond laser direct writing of Fiber Bragg Grating with high-speed and high-resolution scanning technique

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A R T I C L E I N F O

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A B S T R A C T

We employed two fabrication methods, a laser scanning system and a phase mask, to produce Fiber Bragg Gratings (FBGs). A micro-scanning adapter was used to enable high-speed and high-resolution laser focusing inside the optical fiber via a scanner and an objective lens. By continuously moving the fiber-fixed stage while adjusting the scanner repetition speed, micropatterns with various periods were generated. This approach allowed for the detection of FBG signals at multiple wavelengths. Laser direct writing, utilizing a high-speed and high-resolution laser scanning system, facilitated FBG production without the need to remove the fiber coating. This method provided a straightforward way to control the FBG wavelength, signal intensity, and bandwidth by adjusting the scanner and stage movement speeds. The use of femtosecond lasers for FBG fabrication offers the additional advantage of reduced material dependence, enabling FBG production in various optical fibers without requiring additional processing steps compared to conventional methods.

1. Introduction

Fiber Bragg Gratings (FBGs) are widely utilized in various fields such as optical communication, fiber lasers, and sensors [1–3]. Recently, the demand for FBGs has increased due to specific environmental applications [4], ultra-high-speed optical transmission, distributed sensors for real-time measurements, and resonators for narrow-bandwidth, high-power laser cavities used in wavelength or coherent beam combining [5]. Additionally, FBGs are essential for gravitational wave detection and single-frequency fiber lasers with linearly polarized light for coherent LIDAR applications [6,7]. As a result, significant research and development efforts have been directed toward fabricating various types of FBGs to meet these emerging requirements.

Conventional FBG fabrication methods often rely on ultraviolet (UV) light sources and phase masks [8,9]. These methods typically use optical fibers containing germanium (Ge), which reacts with UV light. The fabrication process involves removing the cladding coating on the fiber surface and performing additional steps such as hydrogen loading and recoating. However, these approaches are primarily suitable for producing single-wavelength FBGs. To fabricate FBGs with multiple wavelengths, several phase masks with

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different periods corresponding to the desired FBG wavelengths are required. This poses challenges as phase masks are expensive and time-consuming to produce. Furthermore, the use of Ge-based optical fibers can limit the applicability of FBGs as sensors in certain environments.

To address these limitations, researchers have explored FBG fabrication using alternative laser sources instead of conventional UV light [10–21]. Previous studies have investigated femtosecond laser-based FBG fabrication or alternative methods to replace UV light sources. Additionally, efforts have been made to fabricate FBGs by directly inscribing patterns on optical fibers using femtosecond lasers without relying on phase masks. However, challenges such as slow processing speeds have hindered the widespread adoption of these approaches.

This study employed a direct writing approach using highly focused laser light through an objective lens, as illustrated in Fig. 1 [22–38]. The optical system combined a scanner and an objective lens to continuously move the optical fiber, enabling the creation of fine line patterns. The direct writing method utilized high-density laser energy focused through the objective lens to produce various shapes or patterns. Unlike other lasers, femtosecond lasers can penetrate transparent materials and selectively alter the refractive index of the material at the focal point. This capability allows femtosecond lasers to create micropatterns within optical fibers, forming the FBG. FBG signals were detected through the fabricated micropatterns, and their signal intensity and reflection wavelength were controlled by varying the laser processing system's parameters.

2. Experimental details and results

Existing laser processing systems are broadly categorized into two methods: the stage-based approach using an objective lens and the scanner-based method employing a scanner. The objective lens method is advantageous due to its ability to focus laser light with high resolution, making it suitable for very fine processing. However, it is hindered by slow processing speeds due to the use of mechanical stages. On the other hand, the scanner method utilizes two-axis galvanometer mirrors mounted on precision motors, which allow for rapid processing without moving the processed object. Despite the advantage of fast processing, this method cannot achieve the same high-resolution focus of laser light as the objective lens method.

To fabricate FBGs using the laser direct writing method, both high-resolution laser beams and high-speed scanning technology are essential. To address this, we employed a laser optical system that combined an objective lens with the scanner methods from traditional processing systems, effectively integrating the high-speed scanning capabilities with the advantages of the objective lens. This integration successfully met the requirements for high-resolution focusing and rapid scanning necessary for FBG fabrication.

We employed a laser micro-scanning adapter (IBSolution Co., Ltd., μ-SA), a device that combines the high-speed processing capabilities of a scanner with the ability to focus laser light at high resolution through an objective lens.

Fig. 2 presents a schematic of the high-speed and high-resolution laser scanning system used in the experiments. Fig. 2(a) shows a system capable of high-speed processing using the scanner device, while Fig. 2(b) illustrates the conceptual diagram of a system enabling high-resolution processing using an objective lens. Fig. 2(c) presents a conceptual diagram of the high-speed and high-resolution laser scanning system with a micro-scanning adapter, which combines the advantages of both the scanner and the objective lens.

The use of a 50 × objective lens in the micro-scanning adapter enables scanning of an area measuring 1 × 1 mm. The scanning area per iteration varies depending on the magnification of the applied objective lens: with 5 × magnification, the scanning area is 7 × 7 mm; with 10 × magnification, it is 4 × 4 mm; and with 20 × magnification, it is 2 × 2 mm. Additionally, the system is applicable to laser wavelengths in the range of 800–1100 nm.

This optical scanning system combined a scanner and an objective lens. The laser light, directed by two mirrors attached to the scanner, entered the objective lens at a fixed position through the optical system. The incident laser light was then focused by the objective lens, and the high-resolution laser light rapidly moved along the direction of the scanner mirrors.

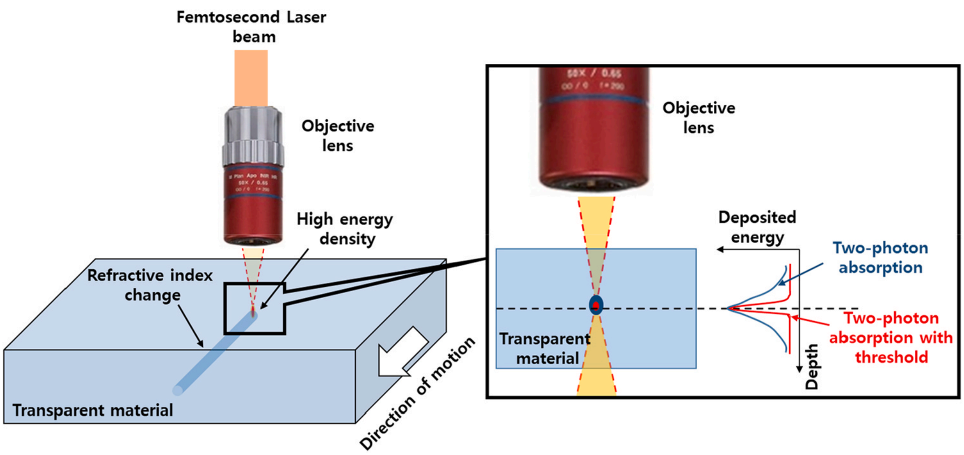


Fig. 1. Schematic of femtosecond laser direct writing inside transparent material [39].

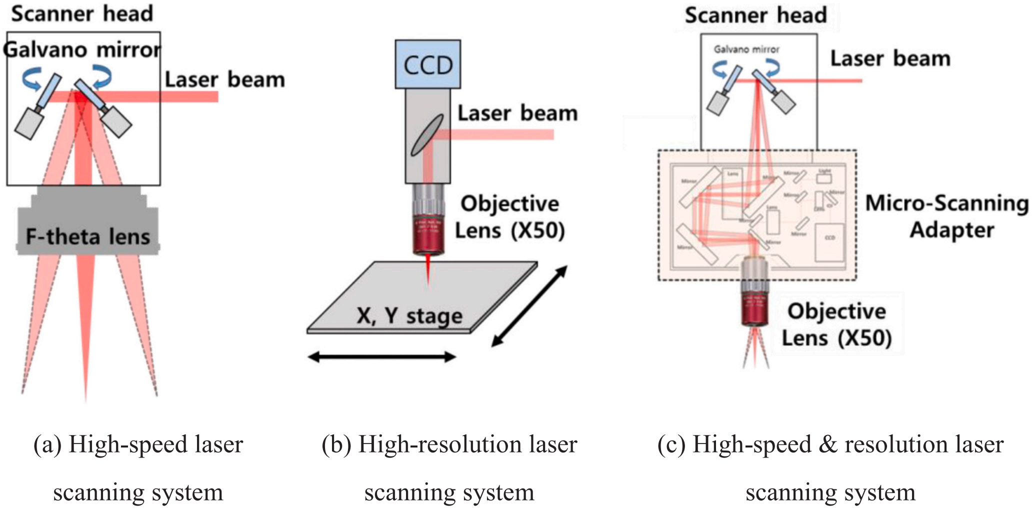


Fig. 2. Schematic of high-speed and resolution laser scanning system.

Using this system, we created precise micropatterns inside an optical fiber using a high-speed and high-resolution laser source, achieving a consistent periodic pattern. The femtosecond laser used in this experiment had a central wavelength of 800 nm, a pulse repetition rate of 1 kHz, a pulse width of 25 fs, and a maximum output power of 1 W. The FBGs were fabricated using both the laser light investigation with a phase mask and the laser direct writing method with a high-speed and high-resolution laser scanning system.

A micron-optics SM125 Interrogator was employed to measure the FBG signals generated by the micropatterns created inside the optical fiber using the laser. The optical fiber for micropattern fabrication was fixed in the laser processing system, with one end connected to the interrogator. Real-time monitoring of the FBG signals generated by the laser processing was performed during the experiment. The signals measured by the interrogator detected the wavelength signals reflected by the micropatterns, which were inscribed with a consistent periodic pattern inside the optical fiber.

Fig. 3 shows a conceptual diagram of the laser direct writing method for creating a micropattern inside an optical fiber. Additionally, an image of a high-speed and high-resolution laser scanning system that integrates a micro-scanning adapter and a stage processing method is also presented.

The procedural sequence for creating micropatterns inside an optical fiber using the direct laser writing technique is as follows. The optical fiber used in FBG fabrication was a commonly employed communication-grade optical fiber (Corning, SMF-28), featuring a cladding diameter of 125 μm and a core size of 8 μm for single-mode optical fiber. Since the laser direct-writing method was employed to create micropatterns inside the optical fiber, the micropatterns could be fabricated without removing the coating material covering the outer layer of the optical fiber.

During the fabrication of the micropatterns inside the optical fiber, a stage was used to move the optical fiber along the x-axis at a

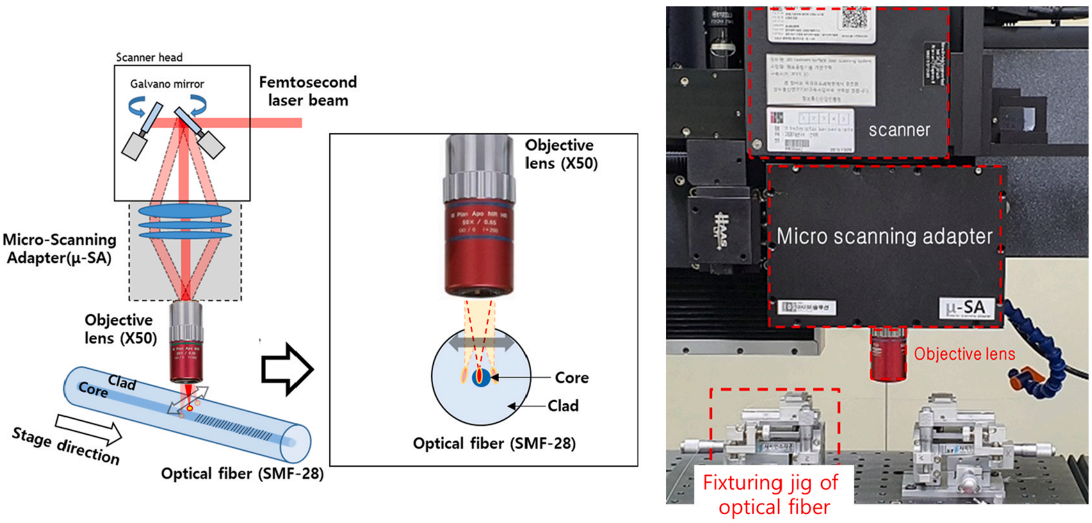


Fig. 3. Schematic and device image of femtosecond laser direct writing of optical fiber utilizing high-speed and resolution laser scanning system.

constant speed. The scanner was synchronized to perform repeated processing along the y-axis, allowing concurrent laser processing. In addition, experiments were conducted to compare the laser direct-writing method with a method involving laser light and a phase mask for FBG fabrication.

For FBG fabrication using a femtosecond laser and phase mask, the cylindrical lens and phase mask were aligned on the same axis, and the experiments were conducted by adjusting the laser irradiation time and output. A phase mask (Ibsen) with a pattern period of 2132 nm was used in the experiment.

We confirmed the internal processing using direct laser writing with a high-speed and high-resolution laser scanning system. Using a 50 × magnification objective lens, the laser focus was positioned at a 50 μm point inside the silica, and the experiment was conducted with an 8-mW laser output. The processing followed a concept similar to the method used to create micropatterns inside an optical fiber. While the scanner repetitively moved along the y-axis direction at a speed of 20 mm/s, the stage, with the optical fiber fixed, moved along the x-axis direction at a speed of 0.05 mm/s to achieve internal processing of silica.

Fig. 4 shows the experiment conducted to assess the precision and fine processing capabilities of the laser system before the FBG experiment. This experiment aimed to determine whether the device could precisely and finely process materials internally before conducting FBG experiments. Measurements were performed under 500 × magnification using a microscope. Due to the high-resolution laser light inside the silica, the refractive index of the material was observed to change, resulting in the creation of a finely shaped pattern with a pattern line width and period of 1.3 μm and 3.7 μm, respectively.

We fabricated FBGs using two methods: direct writing with a high-speed and high-resolution laser scanning system and a method employing a phase mask with a femtosecond laser. Subsequently, we conducted a characterization analysis.

Fig. 5(a) and (b) show microscopic images captured at 500 × magnification of the micropatterns written using each method, respectively. As shown in Fig. 5(a), the laser direct writing method involved repetitive scanning along the y-axis through the scanner, resulting in evenly spaced, line-shaped processed regions across the entire optical fiber. In contrast, Fig. 5(b) illustrates the phase mask method, where precise micropatterns were created in localized areas using the line beam from a cylindrical lens.

The fabrication process shown in Fig. 5(a) was carried out with a laser output of 3 mW, and a 50 × objective lens focused the laser inside the optical fiber core. The scanner speed was set to 20 mm/s, and the stage movement speed was set to 0.024 mm/s. Using the stage, a distance of 3 mm was moved along the x-axis, and it took 120 s to fabricate a single FBG.

As shown in Fig. 5(b), the phase mask method employed a cylindrical lens with a focal length of 19 mm and a phase mask with a line pattern of 2132 nm. The laser output was set to 800 mW, and the laser was applied for 20 s. When comparing the shapes of the micropatterns created inside the optical fiber, the direct writing method resulted in micropatterns throughout the fiber, whereas the phase mask method created micropatterns only in the core of the fiber.

In addition, there was a significant difference in the laser output required for the fabrication of the micropatterns. In the direct writing method, the high-resolution focus of the laser facilitated micropattern fabrication within the optical fiber with a very low laser output. Increasing the laser output in this method could affect the coating surrounding the optical fiber. In contrast, the phase mask method required a high laser output due to the cylindrical lens, and a low laser output could result in failure to fabricate the micropatterns within the optical fiber. The laser output was configured differently for each processing method.

Fig. 6(a) and (b) show the measured results of the FBG signals produced by the two methods using an interrogator. The interrogator detected the signals reflected by the micropatterns inside the fiber, displaying only the intensity of the reflected wavelength. Both methods exhibited high signal strength at a similar wavelength of 1542 nm, owing to their comparable pattern periodicity and line width. However, the laser direct-writing method produced a slightly lower signal than the phase-mask method.

This discrepancy could be attributed to a subtle shift in the laser focus position, possibly due to the absence of fiber coating removal. Alternatively, processing the entire fiber may have caused a specific loss, leading to lower detection of FBG signals.

By employing the Bragg wavelength formula, the wavelength of the FBG and the periodicity of the micropatterns inside the fiber were determined. Using this formula, the wavelength of the FBG created by the laser was used to calculate the periodicity of the micropatterns inside the optical fiber.

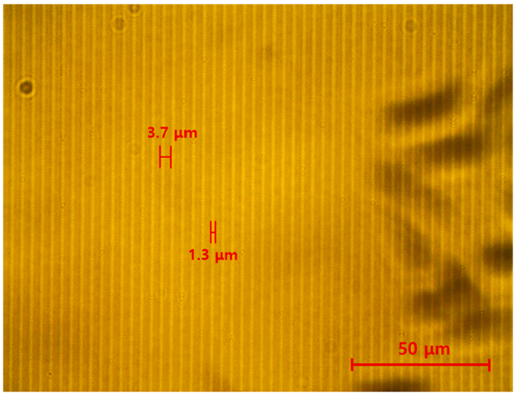
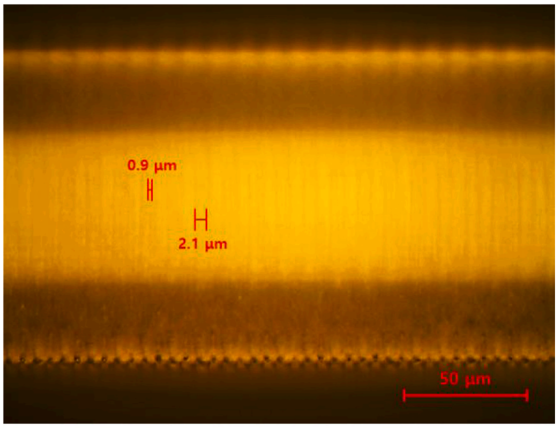
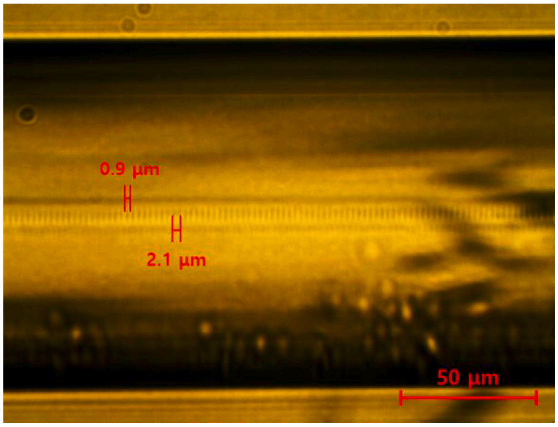


Fig. 4. Optical microscope image of a micro pattern written via a femtosecond laser inside fused silica using high-speed and resolution laser scanning system.



(a) Micro pattern written via a femtosecond laser inside an optical fiber using laser direct writing with a high-speed and resolution laser scanning system



(b) Micro pattern written via a femtosecond laser inside an optical fiber using phase mask and laser exposure

Fig. 5. Optical microscope image of a micro pattern written via a femtosecond laser inside an optical fiber.

$$\text{Bragg wavelength}: \quad n\lambda = 2n_{eff}\Lambda$$

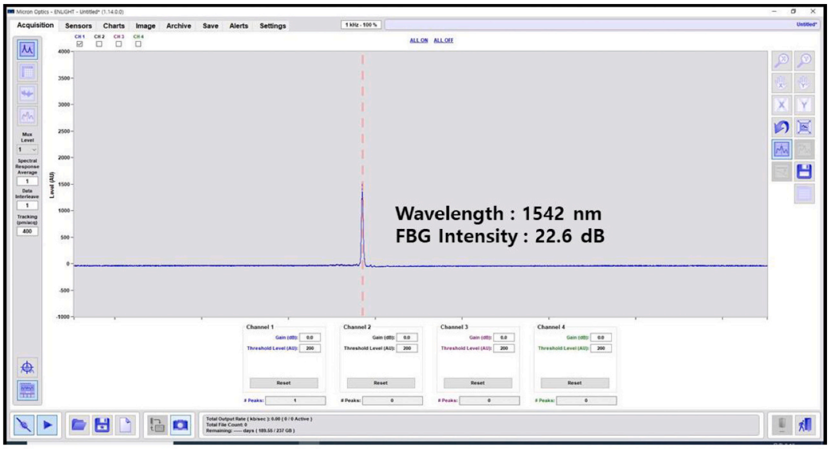
n_{eff} = effective refractive index of the propagating core mode at wavelength λ.
Λ = period of the FBG.

The measured results in Fig. 6(a) and (b) show the FBG signals detected at wavelengths of 1542 nm and 1542.68 nm, respectively. Using the Bragg wavelength formula, the calculated periodicities of the micropatterns were 2131 nm and 2132 nm, respectively, with the effective refractive index of the optical fiber being 1.447. The FBG created using the phase mask conformed to the specifications of the mask. However, in the case of the direct laser writing method, slight differences were observed compared to the micropatterns created by the phase mask. These differences were influenced by the scanner repetition speed and stage movement speed.

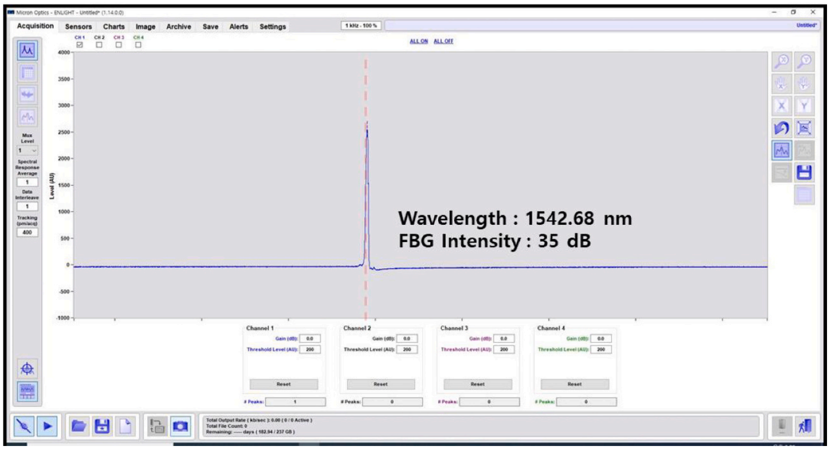
Using a high-speed and resolution laser scanning system with the direct writing method, the total length of the micropatterns fabricated inside the optical fiber was 3 mm. Considering the periodicity of the patterns, approximately 1408 patterns were inscribed. For the phase mask method, a single exposure resulted in a 3 mm pattern length inside the optical fiber, with approximately 1408 patterns inscribed.

The ability to adjust the scanner repetition speed and stage movement speed demonstrated the feasibility of creating FBGs with various wavelengths. This indicated the potential to produce FBGs with different wavelengths by altering the laser processing conditions. Additionally, experiments were conducted using other phase masks with different pattern periodicities to fabricate FBGs with different wavelengths for comparison.

Fig. 7(a) and (b) show the wavelength control of the FBGs fabricated using the laser direct writing and phase-mask methods. The laser direct writing method for processing was employed to control the wavelength of the FBG by adjusting the speed of the scanner and stage used in FBG fabrication, thereby altering the periodicity of the micropatterns. In contrast, the phase-mask method utilized



(a) Reflection spectrum of FBGs written via a femtosecond laser inside an optical fiber using a high-speed and resolution laser scanning system



(b) Reflection spectrum of FBGs written via a femtosecond laser inside an optical fiber using a phase mask

Fig. 6. Reflection spectrum of FBGs written via a femtosecond laser inside an optical fiber, employing two different methods.

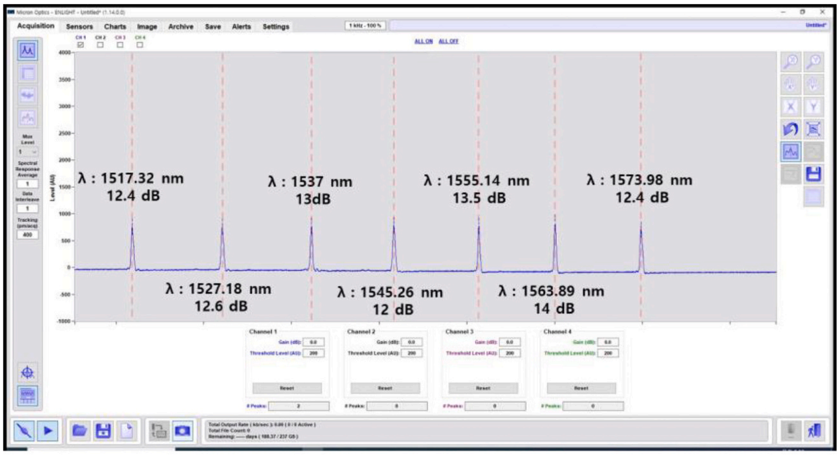
masks corresponding to each wavelength for FBG fabrication.

In Fig. 7(a), the scanner repetition speed was adjusted to 18–23 mm/s, and the stage movement speed was set at 0.019–0.025 mm/s. Multiple micropatterns were created on a single fiber at regular intervals, allowing the observation of signals corresponding to various FBG wavelengths on the interrogator. Using the Bragg wavelength formula, the calculated periods for each wavelength were determined to be 2097, 2110, 2124, 2135, 2149, 2161, and 2175 nm. As the wavelength of the FBG signal increased, the period spacing also increased. However, the small size of the period variation, in the order of several nanometers, made the visual measurement of the changed period challenging. Nevertheless, variations in the period were distinguishable using the interrogator's FBG wavelength signals.

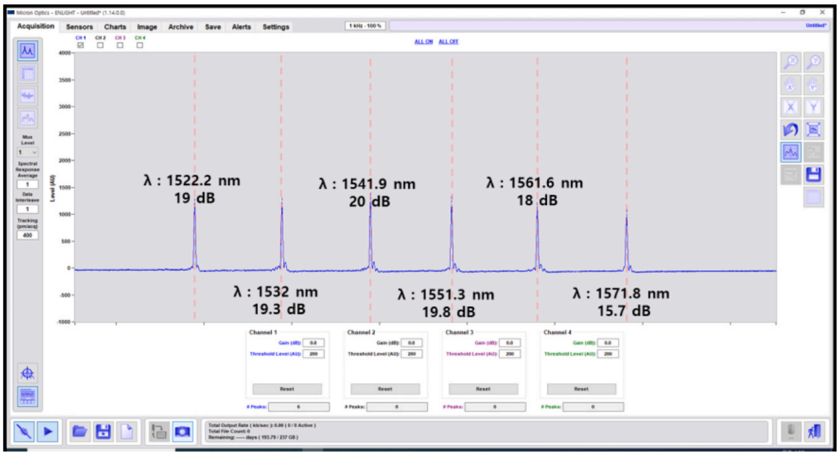
As shown in Fig. 7(b), the FBG was fabricated using the laser exposure method with a phase mask and a laser exposure time of 15 s. Six masks with periods of 2104, 2118, 2132, 2145, 2159, and 2173 nm were used. Correspondingly, FBGs with signals at 1522, 1532, 1542, 1552, 1562, and 1572 nm were generated on the interrogator.

Similar to the previous experiment, the phase mask experiment was conducted by spacing multiple FBGs at certain intervals along a single strand of optical fiber. The interrogator measured the FBG signals at various wavelengths. This experiment demonstrated that the laser direct writing method does not require multiple phase masks and that wavelength control can be achieved by adjusting the repetition speed of the scanner and the speed of the stage.

To investigate the intensity control of the FBG signals, experiments were conducted using both processing methods. The laser direct



(a) Reflection spectrum depicting varying period of patterns, written via a femtosecond laser i nside an optical fiber using a high-speed and resolution laser scanning system (Λ = 2097, 21 10, 2124, 2135, 2149, 2161, and 2175 nm)



(b) Reflection spectrum depicting varying period of patterns, written via a femtosecond laser i nside an optical fiber using phase mask (Λ = 2104, 2118, 2132, 2145, 2159, and 2173 nm)

Fig. 7. Reflection spectrum depicting variations in the period of patterns written via a femtosecond laser inside an optical fiber using two different methods.

writing method involves adjusting the grating length fabricated inside the optical fiber, while the phase mask method involves adjusting the laser exposure time.

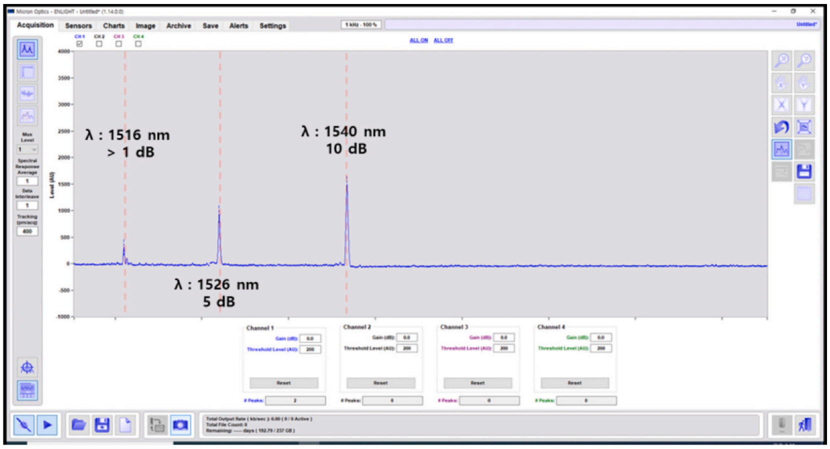
Fig. 8(a) and (b) present the modulation of the FBG signal intensity by adjusting the length and exposure time of the micropatterns inside the optical fiber, respectively.

Fig. 8(a) shows the FBGs produced using the laser direct writing method, where the FBGs were fabricated on a single strand of optical fiber to compare the FBG intensity based on the variation in grating length. The intensity of the FBG signal was controllable by adjusting the grating length engraved inside the optical fiber. Grating lengths of 0.5, 1.0, and 1.3 mm were created, with an observed increase in intensity corresponding to the respective increase in grating length.

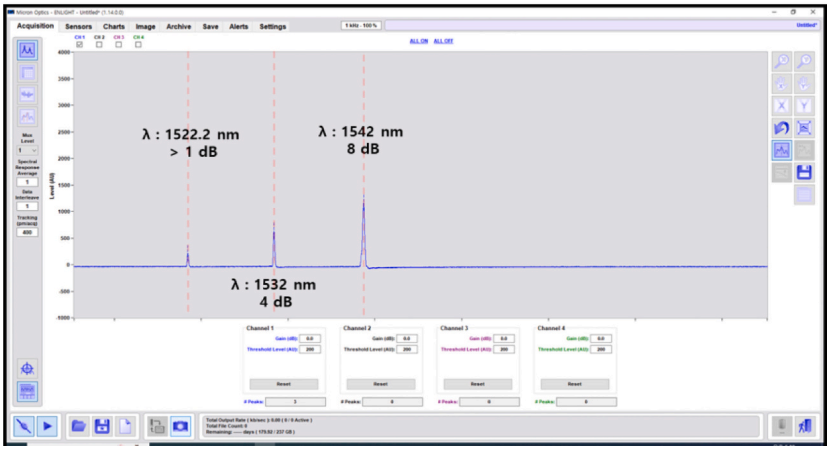
Fig. 8(b) illustrates the phase mask method, where the intensity of the FBG signal increased with longer exposure times. In this method, the laser was irradiated for 1, 3, and 10 s. By engraving different grating lengths inside the optical fiber and varying the exposure time using the phase mask, the changing FBG signal intensity was measured and graphically represented.

Figs. 9(a) and 9(b) present a comparison of the intensities of the FBG signals for different grating lengths and laser exposure times.

The signal strength of the FBG increased with both the grating length and exposure time. However, when the grating length



(a) Reflection spectrum depicting varying grating lengths, written via a femtosecond laser inside an optical fiber using a high-speed and resolution laser scanning system (grating length = 0.5, 1.0, and 1.3 mm)



(b) Reflection spectrum depicting varying laser exposure times, written via a femtosecond laser inside an optical fiber using a phase mask (exposure time = 1, 3, and 10 s)

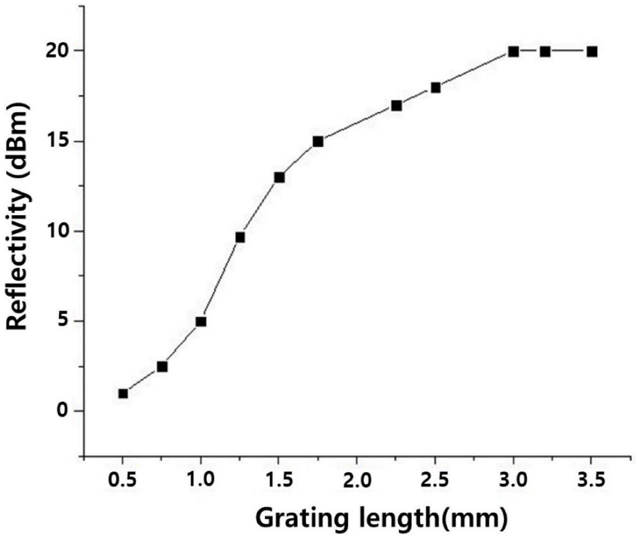
Fig. 8. Reflection spectrum depicting variations in grating length or laser exposure time, written via a femtosecond laser inside an optical fiber using two different methods.

exceeded 3 mm or the exposure time exceeded 20 s, the FBG signal intensity decreased.

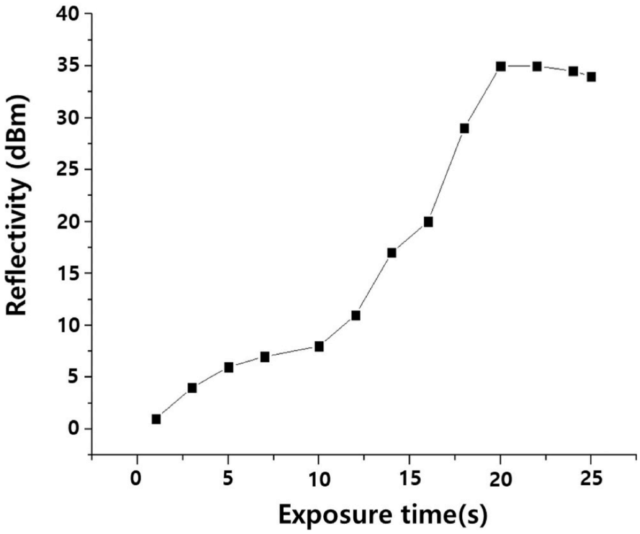
In the case of laser direct writing, an increase in the number of patterns inside the optical fiber resulted in an increase in the reflected intensity of the light source, leading to a higher FBG signal and a narrower pulse width of the signal. However, excessive patterns caused scattering or loss of reflected light, resulting in a decreased intensity. In the case of the phase mask, the decrease in signal intensity with prolonged exposure time was attributed to reduced reflection due to internal damage within the optical fiber.

3. Conclusion

This study explores the fabrication of Fiber Bragg Gratings (FBGs) using two distinct methods: the Direct Writing approach, which employs a femtosecond laser to directly inscribe micro-gratings inside the optical fiber, and the Phase Mask method, which utilizes laser irradiation through a phase mask. Unlike conventional methods that use UV light sources and phase masks, this research focuses on these alternative techniques and compares the characteristics of FBGs fabricated using both approaches to analyze their efficiency and applicability.



(a) Intensity variation with different grating lengths observed using a high-speed and resolutio n laser scanning system



(b) Intensity variation with laser exposure time using a phase mask, with a fixed grating leng th of 3 mm

Fig. 9. Intensity variation with different grating lengths and laser exposure times, written via a femtosecond laser inside an optical fiber using two different methods.

In the Direct Writing method, high-speed and high-resolution scanning technology was applied to directly process high-precision micro-gratings inside the optical fiber. This method demonstrated advantages such as simplified processes and significant reductions in fabrication time. In contrast, the Phase Mask method involved forming gratings within the optical fiber using a phase mask, without utilizing high-speed scanning technology. The results highlight that high-speed and high-resolution scanning technology is particularly effective in the Direct Writing approach, significantly simplifying the FBG fabrication process and contributing to time savings, establishing it as a critical advancement in the field.

For the laser direct writing process inside the optical fiber, a micro-scanning adapter was used to exploit the scanner's high-speed and high-resolution laser focus via the objective lens. A laser microscanning adapter rapidly repeated the high-resolution laser beam along the y-axis, while the optical fiber, fixed on a stage, was moved along the x-axis at a constant speed, enabling the rapid fabrication of a micropattern inside the optical fiber. Furthermore, the FBGs were produced using both a femtosecond laser and a phase mask. A cylindrical lens with a focal distance of 19 mm, a phase mask, and an optical fiber were aligned along the same axis for the FBG fabrication.

Both methods successfully produced micropatterns inside the optical fiber, as confirmed by the detection of the FBG signals through an interrogator.

To produce FBGs at various wavelengths, the periodicity of the micropatterns inside the optical fibers must be adjusted. The phase-mask method requires the use of different masks for each desired wavelength, which is costly and time-consuming due to the alignment of optical components during each fabrication. In contrast, the laser direct writing method allowed the adjustment of the micropattern periodicity by controlling the scanner repetition speed and stage movement speed in the processing software. This flexibility facilitated the straightforward production of FBGs at various wavelengths.

Furthermore, synchronization between the scanner and stage facilitated precise control of the grating length inside the optical fiber. This capability demonstrates that adjusting the length and repetition rate of the grating facilitates control over the FBG signal intensity and width.

In conventional Direct Writing or Phase Mask methods for fabricating Fiber Bragg Gratings (FBGs), the fiber coating must be removed, and additional processes such as hydrogen loading or annealing are required. However, with the application of high-speed and high-resolution scanning technology, the fiber coating does not need to be removed, and hydrogen loading or annealing processes are unnecessary. This simplification of the fabrication process significantly reduces the time required for FBG production.

In high-speed and high-resolution scanning technology, the fabrication time is determined by the stage movement speed of the fixed optical fiber. It takes approximately 1–5 min to produce a single low-reflection or high-reflection FBG. This technique directly forms micro-gratings inside the optical fiber through high-speed scanning, allowing for the adjustment of grating spacing based on the stage speed, which in turn determines the wavelength of the FBG. When comparing the wavelengths of the fabricated FBGs, a resolution of approximately 0.2 nm was achieved.

The use of a femtosecond laser as a light source enables FBG fabrication in optical fibers composed of various materials, reducing the material dependency inherent in conventional fabrication methods.

In conclusion, the laser direct writing process and the phase mask method present potential advantages by addressing the limitations of traditional FBG fabrication techniques. The ability to control FBG characteristics, particularly in terms of wavelength and signal intensity, demonstrates the versatility of these methods. Additionally, the use of femtosecond lasers in direct writing processing and phase-mask exposure holds promise for applications in diverse fields where traditional FBG fabrication faces challenges. We anticipate that these advancements will lead to further research and the development of new technologies.

CRediT authorship contribution statement

Young-Chul Noh: Validation. **Ik-Bu Sohn:** Writing – review & editing. **Bong-Ahn Yu:** Formal analysis. **Yeung Lak Lee:** Methodology. **hun-kook choi:** Writing – original draft. **Young-Jun Jung:** Data curation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ik-bu sohn reports financial support was provided by Gwangju Institute of Science and Technology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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