Manufacturing Technology of Long-Gauge FBG Array for Distributed Sensing

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Fiber Bragg grating (FBG), which is written in the core of an optical fiber using ultraviolet laser light, has attracted considerable attention in the field of optical fiber sensing. We developed optical fibers that enable writing gratings through a coating, and applied the writing method to produce a long-gauge FBG array that is suitable for distributed sensing. Sufficiently high reflection signal level without ghost signal was obtained by stepwise changing the wavelength of each unit FBG. Furthermore, the high precision laser scanning position and fiber feed mechanism enable stable FBG connection with small gaps.

1. Introduction

Fiber Bragg grating (FBG) is an optical component with a diffraction grating which has periodic refractive index change formed by irradiating ultraviolet (UV) laser light from the lateral side of an optical fiber. FBG sensing technology was proposed in the late 1980s [1)] and has since been employed in a range of applications, such as structural health monitoring and shape sensing. It is expected that this technology will be applied in a variety of fields due to its advantageous characteristics, including high sensing accuracy, immunity to electromagnetic interference, high flexibility, and a compact size [2)3)]. For instance, FBG-based distributed sensing is attracting interest due to its various potential applications, as it enables the measurement of multiple points along the longitudinal direction using only a single optical fiber.

We have developed a manufacturing technology for long-gauge FBG arrays suitable for distributed measurement, which can be used for shape sensing. This report outlines the features of the developed optical fiber that Bragg grating can be written through the coating, the reel-to-reel FBG manufacturing equipment, and the long-gauge FBG array.

2. Distributed Sensing Using FBG

FBG based optical fiber sensing could be classified into two categories: point sensing and distributed sensing. In point sensing, multiple FBGs are written discontinuously in an optical fiber, and the resulting Bragg wavelengths are used to measure strain at each longitudinal position. On the other hand, distributed sensing enables the continuous measurement of strain through the employment of a continuous FBG array written along an optical fiber. The reflection spectral characteristics are measured along the entire length of the FBG array using optical frequency domain reflectometry (OFDR), which has a spatial resolution of tens of micrometers and a continuous measurement length of tens of meters. One of the most remarkable applications of distributed sensing is the shape sensing using a multi-core FBG sensor in which FBG array is written in each core of multi-core fiber [4)]. The three-dimensional shape of the multi-core FBG can be reconstructed with high accuracy by measuring the change in Bragg wavelength of the FBG array and analyzing the difference in strain between the inner and outer cores introduced by bending of the fiber [5)]. Furthermore, the combination of a high signal-to-noise ratio for the FBG sensor and a high spatial resolution for the OFDR enables real time and high accuracy measurement on distributed sensing.

3. FBG Writing Method

3.1 FBG Writing Through the Coating

FBGs generally use germanium-doped silica glass, whose refractive index is changed easily by UV irradiation, as a core of optical fiber and is fabricated commonly by either the two-beam interferometry method or the phase mask method. The two-beam interference method enables for wavelength adjustment over a broad range by modifying the angle of the two beams separated by the splitter with the use of a mirror. Since this process is a time-consuming process and it is difficult to stabilize the optical axis of the optical system, it is unsuitable for the mass production of FBGs. The phase mask method avoids the necessity for high-precision adjustment of complex optical systems, and it is possible to write stable FBGs on optical fibers because the interference fringes can be produced with high reproducibility by passing the irradiation light through a mask. Consequently, we selected the phase mask method as shown schematically in

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Abbreviations, Acronyms, and Terms.

FBG—Fiber Bragg Grating
A device comprising a structure with a periodically varying refractive index within an optical fiber, which reflects light of a specific wavelength.

WTC—Writing Through Coating
A technology for the writing of FBGs by means of irradiating a ultraviolet beam onto an optical fiber that has been coated with a material that is permeable to ultraviolet light.

OFDR—Optical Frequency Domain Reflectometry
A measurement method that can measure the position, intensity and frequency information of light reflected within optical fibers with high spatial resolution.

Rayleigh scattering level—Rayleigh scattering level
Rayleigh scattering is defined as the scattering of light by particles that are smaller than the wavelength of the light in question. In the case of optical fibers, the scattering that occurs due to structural heterogeneity is referred to as Rayleigh scattering. The signal level is defined as the Rayleigh scattering level.

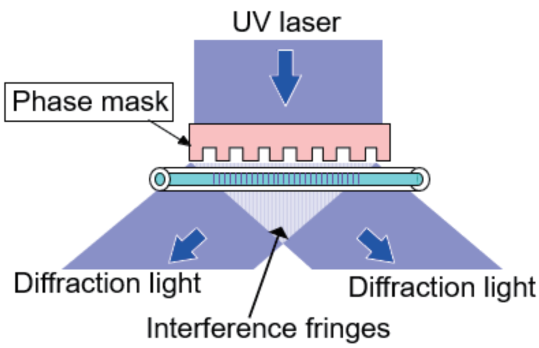

Fig. 1. Phase mask method.

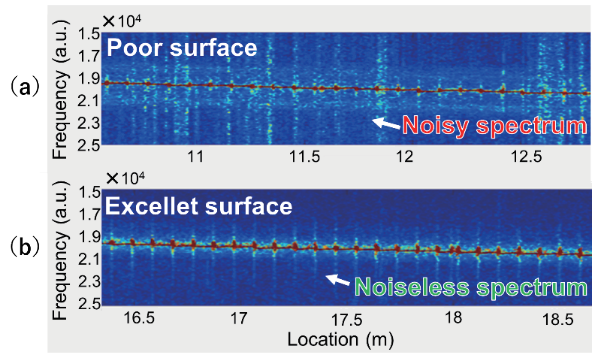

Fig. 2. Spectrum of manufactured FBG array (a) with poor surface smoothness and (b) with excellent surface smoothness of coating of optical fibers.

Fig. 1. Since the conventional coating of optical fiber does not transmit UV light, an FBG is written by irradiation from the lateral side of the cladding after removing the coating, and then recoated over the bare cladding for protection. This method requires a complex manufacturing process, giving rise to concerns about tiny scratches on the cladding surface during the fabrication process which may degrade the mechanical strength of the optical fiber. Consequently, the coating removal process and the writing of long and continuous FBG array may increase a risk of optical fiber breakage due to a decrease in strength.

It has been proposed that silicone-based coating can be utilized for FBG writing through the coating (WTC) due to its UV transparency and thermal stability [4)6)]. However, it is difficult to keep the soft and sticky surface of silicone coating clean and smooth over an entire length due to touching on the tooling used for FBG writing. Such degraded surface smoothness of coating causes unnecessary refraction and scattering of UV laser light, thereby causing an irregular change in the refractive index of FBG. We investigated coating material with excellent surface smoothness to ensure the FBG with stable refractive index change.

Figure 2 shows the difference of the spectrum of FBGs written using optical fibers with different levels of surface smoothness of coating. The reflection spectrum of the FBG written in an optical fiber with poor surface smoothness of silicone-based coating exhibited a considerable amount of noise, as shown in Fig. 2(a). In distributed sensing, it is difficult to determine the position accurately from the disrupted reflected wavelengths of the FBG on OFDR measurement. On the other hand, Fig. 2(b) shows the spectrum of FBG with excellent surface smoothness. By enabling the UV light to reach the cores without scattering at the coating surface, a constant interference fringe was obtained, thereby producing a low-noise FBG. The surface smoothness of the coating plays a decisive role to obtain a high-quality FBG in the WTC method. We developed successfully a simple but sophisticated process for producing better performance of FBG by using an optical fiber with smooth coating suitable for WTC.

3.2 Reel-to-Reel FBG Writing Equipment

Figure 3 shows an overview of the Reel-to-Reel FBG

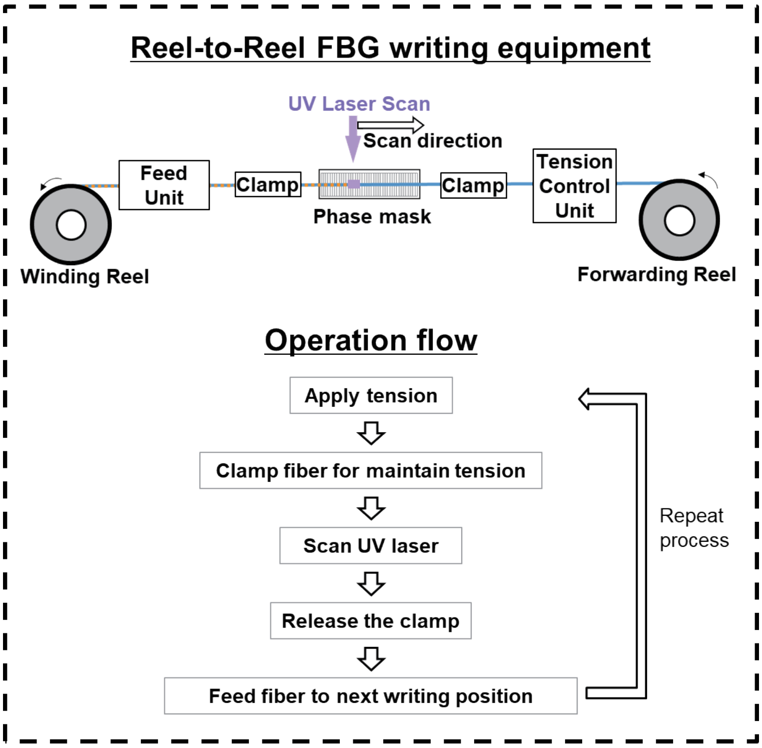

Fig. 3. Overview of Reel-to-Reel FBG writing equipment and its process flow.

writing equipment developed as a proprietary technology and its process flow [7]. During the process of rewinding an optical fiber from a reel to another reel under pre-determined tension, UV laser light is scanned from one end of the phase mask to the other and irradiating onto the coating surface through the mask. After the scan is completed to obtain one unit of FBG, the optical fiber is forwarded to the position where the next FBG will be written. Repeating this cycle enables to manufacture FBG array continuously along the entire length of the optical fiber. It is possible to change slightly the Bragg wavelength of each FBG unit by adjusting the tension between UV laser light scans through a tension control unit, as described in section 4.1.

A scanning stage equipped with a linear encoder enables precise connection between the FBG units and precise control of the feed rate of the optical fibers to obtain long-gauge FBG array.

4. FBG Characteristics

4.1 Long-Gauge FBG Array for Distributed Sensing

A long-gauge FBG array with a single Bragg wavelength often shows multiple reflections to generate ghost signals in OFDR measurement. These ghost signals obscure the accurate detection of the reflection position, which overlaps and obscures the reflection signals. Furthermore, the intensity of reflection signal increases as the entire gauge length of the FBG array increases and makes the detector susceptible to saturation. Nevertheless, if the signal level of the FBG is diminished with the intention of suppressing this saturation, it becomes difficult to obtain the sufficient FBG signal-to-noise ratio necessary for the detection of the signal.

In order to avoid these issues, we developed a manufacturing technique for FBG array that can achieve higher signal levels by varying Bragg wavelengths with each FBG unit. Figure 4 shows the OFDR measurement result for an FBG array written under a sequential stepwise

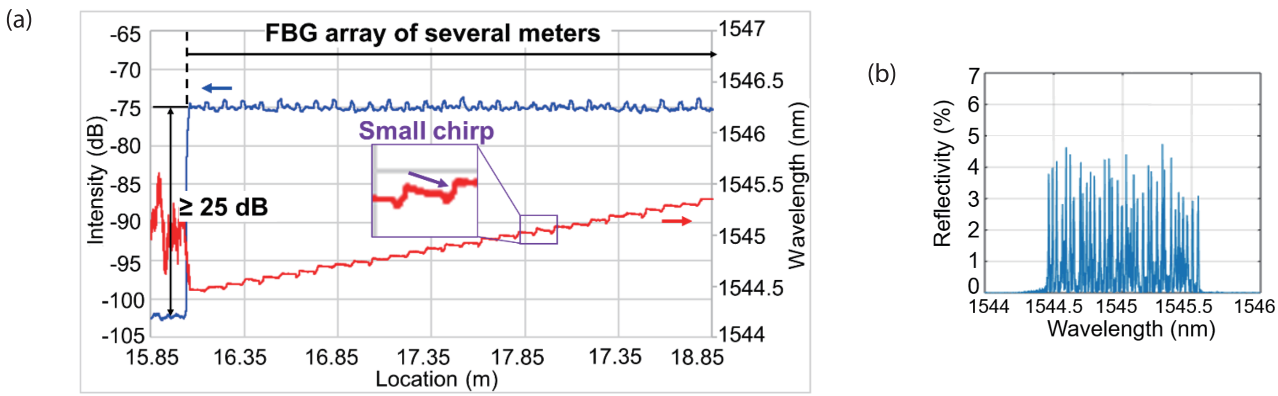

Fig. 4. (a) Reflection signal and reflected wavelength for each FBG array position. (b) Reflectivity spectrum of the FBG array.

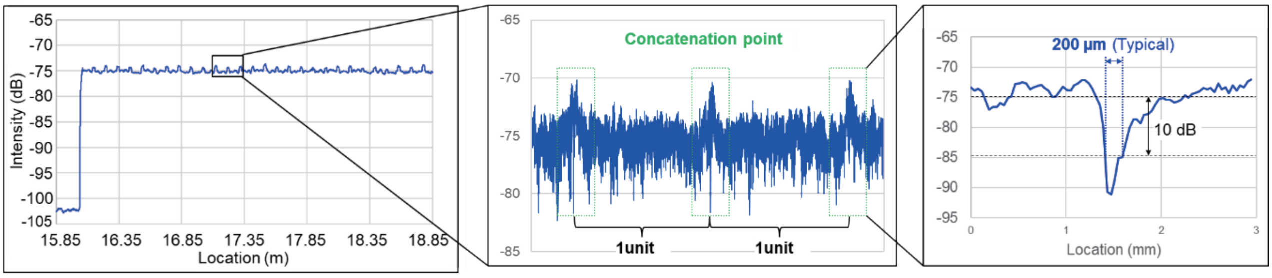

Fig. 5. Reflection signal at concatenation point of FBG array.

change of applied tension on the Reel-to-Reel FBG writing equipment. Figure 4(a) shows a uniform signal level of FBG array over a length of 3 m. Since the ratio of the signal level to the Rayleigh scattering level of the optical fiber exceeded 25 dB, the FBG signal of entire gauge length could be detected without ghost noise. The phenomenon of multiple reflections can be mitigated by modifying the Bragg wavelength in 30 pm increments for each FBG unit, achieved by the control of tension during the FBG writing process. Furthermore, the overlap of Bragg wavelengths within each FBG unit can be reduced by thermally assisted small chirps due to the thermal expansion of the optical fiber on the absorption of UV laser light by the coating resin during FBG writing. Figure 4(b) shows the FBG reflectivity of each unit by wavelength. The distribution of the stepwise change in Bragg wavelength between the FBG units and the small chirp within the FBG unit effectively suppressed reflectance to less than 5% across the entire range of wavelength, thereby preventing saturation of the detector during OFDR measurement. We established an FBG array with stable signal level and suppressed multiple reflections by stepwise changing the reflected wavelength through precise tension control of the FBG writing process.

4.2 The Accuracy of FBG Concatenation

In distributed sensing applications, there is a possibility that Bragg wavelength information may be lacking, if there is a large gap in the connection of neighboring FBG units. It is therefore imperative to ensure the precise concatenation of all FBG units to achieve accurate distributed measurements.

In order to obtain the stable continuity at the connections between FBG units in the Reel-to-Reel FBG writing process, it is essential to control the scanning position of the UV laser light and forward the fiber precisely. Figure 5 shows a magnified view of the signal level, and the right panel shows that the reduction of 10 dB in signal level at a connection point between FBG units was constrained to a maximum of 200 μm which is sufficiently small considering the spatial resolution in OFDR measurement. Because there is no lack of information on the Bragg wavelength, it is possible to perform distributed sensing over the entire length of the longitudinal direction. The absence of gaps at the connection points ensures seamless information on the Bragg wavelength, enabling distributed sensing along the entire longitudinal length of the FBG array. We established precision control method of laser scanning position to perform highly accurate concatenation of FBG array.

5. Conclusion

We developed a fiber that enables FBG to be written through the coating, and manufacturing method of FBG arrays with ghost-free reflection signal level and small gap concatenation points. Such FBG array will contribute to precise and real-time distributed sensing that can be used in wide variety of application.

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