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Fabrication of Fiber Gratings with Different Bragg Wavelengths Using a Single Phase Mask

Kiyoshi NAKAGAWA*, Yutaka TAKEMURA[1], Ryou KUNIMOTO[1], Yasuo MIZUTANI[1], Susumu KIMURA[1], Yoshiyuki FUKUYAMA[1], Yoshifumi SUZAKI[2] and Seiki EJIMA[2]

Department of Reliability-Based Information Systems Engineering, Faculty of Engineering, Kagawa University, 2217-20 Hayashimachi, Takamatsu 761-0396, Japan
[1]*Shinko Electric Wire Co., Ltd., 1298-12 Shido, Sanuki 769-2101, Japan*
[2]*Department of Advanced Material Science, Faculty of Engineering, Kagawa University, 2217-20 Hayashimachi, Takamatsu 761-0396, Japan*

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We present a method of fabricating multichannel fiber Bragg gratings using a single mask under control of the applied tension to the optical fiber. The Bragg wavelength of fiber Bragg gratings is investigated as a function of the amount of tension applied to an optical fiber during the photoimprinting process. The Bragg wavelength changes linearly with the amount of tension applied to the optical fiber. Using the linear relation, an optical wavelength filter consisting of five fiber Bragg gratings with five different wavelengths is fabricated successfully using one phase mask. [DOI: 10.1143/JJAP.41.L599]

KEYWORDS: fiber Bragg grating, Bragg wavelength, optical fiber filter, optical fiber sensor

Fiber Bragg gratings (FBGs) are known as important components of fiber optics owing to the large number of devices functions in which they can be used.[1)] Wavelength-division multiplexed systems (WDMs), fiber lasers, and fiber sensors all use fiber gratings.[2–4)] In order to use the functions of FBGs in these optical communications or sensing systems, functions of FBGs should be precisely controlled during fabrication. Particularly, it is necessary that the Bragg wavelength of FBG is accurately adjusted to the desired wavelength for optical filtering or the wavelength of the light source be used. Precise tuning of Bragg wavelength is carried out during the fiber grating fabrication process.

Currently, fiber grating fabrication techniques have two different categories: the holographic and the phase mask approaches.[5,6)] The phase-mask technique is popular and attractive because it is highly reproducible, it offers easy alignment of the fabrication system, it requires low coherence light for photoimprinting the phase mask, and it makes per unit grating fabrication cost low. One drawback of the phase-mask technique is that the period of the phase mask imposes too strong a restriction on the grating wavelength. In short, a separate phase mask is required for each Bragg wavelength. To compensate this drawback, an approach has been recently reported.[7)] Another compensation technique for this drawback is to apply tension to the optical fiber. It is experimentally known that applying tension to the optical fiber during the photoimprinting process enables us to tune the Bragg wavelength of FBG.[1)]

In this letter, the Bragg wavelength of FBGs has been investigated as a function of the amount of the tension applied to the optical fiber during the fabrication process. It is shown that the Bragg wavelength of FBG can be tuned by changing the tension applied to the fiber. Using the tension dependence of the Bragg wavelength, an optical wavelength filter based on FBG, which exhibits multichannel filtering, is fabricated using one phase mask.

The FBGs fabrication setup is shown in Fig. 1. FBGs were fabricated using a zero-order nulled diffraction phase mask. The optical fiber was placed almost in contact with the periodic grating corrugation of the phase mask. Both ends of the optical fiber were fastened to two translation stages. One of the stages was fixed and the other was movable. The movable stage was pulled by a constant force owing to a weight, to apply constant tension to the optical fiber during the photoimprinting process. Coated resin of the optical fiber was removed between the two stages prior to ultraviolet light exposure.

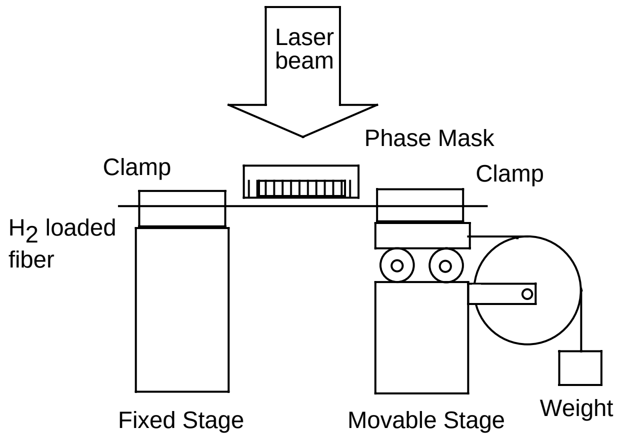

Fig. 1. Optical setup for drawing the grating structure with a phase mask. The amount of applied tension is controlled by the weight.

Ultraviolet light normal to the phase mask passes through and is diffracted by the periodic corrugations of the phase mask. The two diffracted ± 1 order beams interfere with each other to produce a periodic pattern that photoimprints a corresponding grating in the optical fiber. When the period of the phase mask grating is Λ_{mask}, the period of the photoimprinted index grating is $\Lambda_{\mathrm{mask}}/2$. The Bragg wavelength λ_{B} is given by

$$\lambda_{\mathrm{B}} = 2n_{\mathrm{eff}}(\Lambda_{\mathrm{mask}}/2), \tag{1}$$

where n_{eff} is the effective diffraction index of the optical fiber. The Bragg wavelength is fundamentally determined by the pitch of the phase mask used. However, any change in fiber properties, such as strain, temperature, or polarization, which changes the diffraction index or grating pitch, will also

*E-mail address: nakagawa@eng.kagawa-u.ac.jp

change the Bragg wavelength of the FBG.

We used a pulsed KrF excimer laser as the ultraviolet light source. The fluence of the laser beam at the optical fiber surface was around 60 mJ/cm^2 with a repetition rate of 20 Hz and the pulse duration was 30 ns. Exposure time was fixed to 1 min in this experiment. We used only a single phase mask in this experiment. The pitch of the phase mask was 1073.1 nm, and the diffraction efficiency in the zero order was minimized ($< 3\%$) at a wavelength of 248 nm. FBGs with center wavelength of around 1553 nm were fabricated in a standard single-mode fiber (Corning SMF-28 fiber), which was loaded with hydrogen (12 MPa, 373 K, 8 days) to enhance its photosensitivity.

The transmission spectrum of each FBG was monitored *in situ* during and after the laser exposure with an unpolarized broadband light and an optical spectrum analyzer set at 0.1 nm resolution. In this letter, Bragg wavelength was measured by the center wavelength at which the transmission spectrum of the FBG exhibited maximum attenuation.

The Bragg wavelengths of FBGs, which were fabricated under different amounts of applied tension during photoimprinting process, were measured individually. Measurement results of the relationship between the Bragg wavelength of FBGs and the amount of the applied tension during the photoimprinting process are shown in Fig. 2. The Bragg wavelength of each FBG was measured under a tension-free condition. The amount of tension during the ultraviolet light exposure is also shown in the figure. The amount of the tension was calculated for the optical fiber clad diameter of 250 μm. The Bragg wavelength linearly decreases with the applied weight, that is, the tension. The rate of the change in the Bragg wavelength per unit weight was 15.7 pm/g. It is known that this property is due to the residual stress in the optical fiber. From this relationship, when the amount of tension from 0 g to 250 g is applied to the optical fiber, we can fabricate FBGs, whose Bragg wavelengths are from 1553.2 nm to 1549 nm using a single phase mask of $\Lambda_{\text{mask}} = 1073.1$ nm only. Strictly speaking, these Bragg wavelengths also depend on the amount of the ultraviolet light exposure.

Using the tension dependence of the Bragg grating, a multichannel optical wavelength filter was successfully fabricated using a single phase mask. First, an FBG with a Bragg wavelength of 1549.6 nm was fabricated in an H_2-loaded optical fiber under the condition that tension corresponding to a weight of 250 g was applied to the optical fiber. After this fabrication, the weight was changed to 200 g. Under this condition, the next FBG with a Bragg wavelength of 1550.3 nm was fabricated at a different position in the same optical fiber. Subsequently, the weight was changed to 150, 100 and 50 g, and FBGs were respectively fabricated with different Bragg wavelengths at different positions under each condition of the applied tension. As a result, each FBG was fabricated as a cascade in the optical fiber. The length of each FBG was 15 mm and the separation between any two FBGs was 5 mm. Therefore, the total length of five FBGs was 100 mm. The transmission and reflection spectra of the multichannel optical fiber filter with FBGs are shown in Fig. 3. Excellent reflection spectrum properties at each desired wavelength are visible in the figure. This result shows that this multichannel optical wavelength filter can be utilized in dense wavelength-division multiplexed optical communication systems (DWDMs) in the near future, and these fabrication techniques are useful to precisely control the Bragg wavelength of FBGs.

Finally, we fabricated many single channel FBGs using a single phase mask under different amount of applied tension. Then, we measured the Bragg wavelength of each FBG as a function of the amount of applied tension, for the purpose of using these FBGs for a strain sensor. It is well known that FBG is useful sensor for strain measurement.[8] Recently, several techniques have been investigated for multiplexing FBG sensors together in a serial array, in order to measure strain distribution.[9] In these techniques, it is necessary to fabricate many FBGs with a number of Bragg wavelengths, which are elements of a sensor array. In this case, the Bragg wavelength of each FBG is also exactly controlled.

The measurement results are shown in Fig. 4. In this figure, the change in Bragg wavelength versus the amount of applied tension is shown, because the FBGs used here exhibit dif-

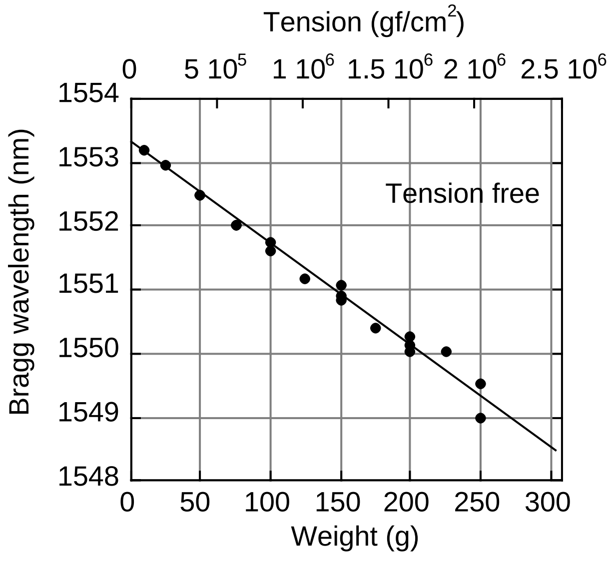

Fig. 2. Relationship between the center wavelength of FBGs and the amount of applied tension during the photoimprinting process. The center wavelength under tension and no tension are shown.

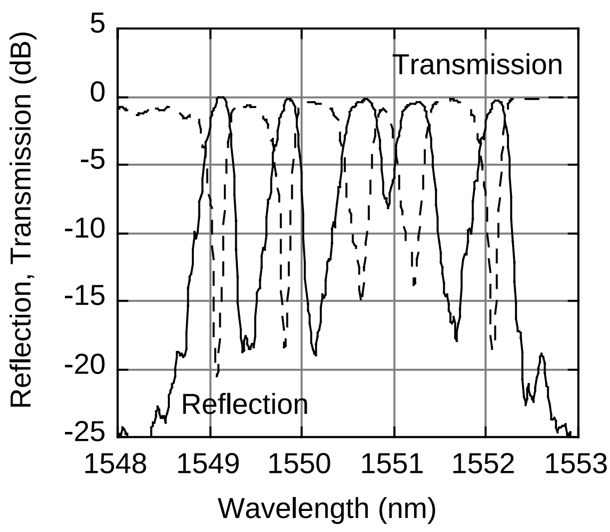

Fig. 3. Transmission (a dotted line) and reflection (a solid line) spectra of a multichannel optical fiber filter with FBGs used a single phase mask.

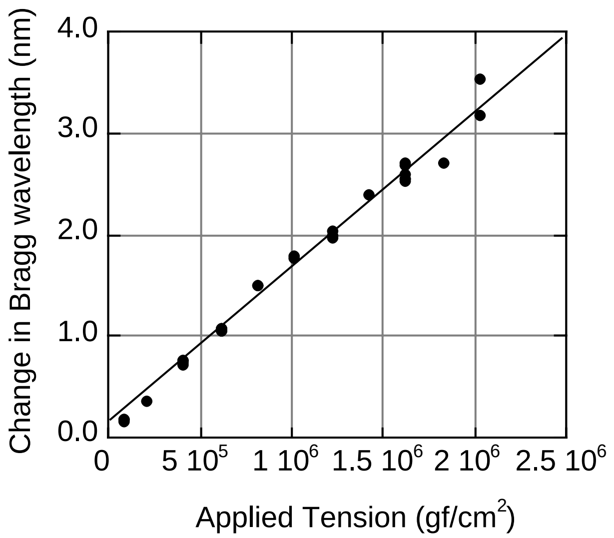

Fig. 4. Change in center wavelength of five FBGs with different center wavelengths, which were fabricated using a single phase mask under different amounts of applied tension.

ferent Bragg wavelengths owing to the different tensions applied during the photoimprinting process. In these measurements, 11 kinds of FBGs were used and 45 plots are drawn on this graph. Although the Bragg wavelength was different for each FBG due to the effect of the different tensions applied during the photoimprinting process, the change of the Bragg wavelength varies linearly with the amount of the applied tension and the behavior is all same for all FBGs. The rate of the change in Bragg wavelength per unit applied tension was 1.57×10^{-6} nm/(gf/cm^2). The variation of the change in Bragg wavelength is due to atmospheric temperature variation. FBGs, which exhibit different Bragg wavelengths, show the same tension dependence of the change in Bragg wavelength. Thus, these results show that the applied tension technique enables us to tune the Bragg wavelength of FBGs for an optical fiber strain sensor. We believe that this technique is useful for fabricating FBGs for sensor arrays in strain distribution sensing, because the Bragg wavelength of each FBG element should be controlled to obtain the spatial resolution of the distributed strain.

In conclusion, it is shown that the Bragg wavelength changes linearly with the amount of tension applied to the optical fiber during the photoimprinting process. Using the relationship between Bragg wavelength and applied tension, Bragg wavelength, which is fundamentally determined from the pitch of the phase mask, can be tuned. Multichannel optical wavelength filters of FBGs can be fabricated with one phase mask. FBGs with different Bragg wavelengths show the same tension dependence of the change in Bragg wavelength, although these FBGs were fabricated under different amounts of applied tension. We believe that these results are useful for fabricating FBGs for optical communication systems or optical fiber sensing systems.

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