Fabrication and Analysis of Chirped Fiber Bragg Gratings by Thermal Diffusion

Seung-Hyun Cho, Jaedong Park, Byoungwhi Kim, and Min-Ho Kang

ABSTRACT—We propose and demonstrate a fabrication method of chirped fiber gratings by a thermal diffusion process. The method could suggest a direction for a simple and cost-effective implementation of chirped fiber grating-based devices.

Keywords—Chirped fiber Bragg grating, thermal diffusion, core dopants.

I. Introduction

Fiber Bragg gratings represent key elements in both the conventional and emerging fields of optical communications and optical fiber sensors [1], [2]. There are various types of fiber Bragg grating structures including the common Bragg reflector, the blazed Bragg grating, and the chirped Bragg grating [3], [4]. Generally, chirped fiber gratings are fabricated by using a non-periodic phase mask and a UV light source. In this paper, we propose another direction for the fabrication of a chirped fiber grating. The basic idea of this technique is to change the effective index for the guided mode in the fiber by the thermal diffusion of dopants (such as germanium and boron) in the core region into the cladding region. The grating is then written with a periodic phase mask using a UV-exposure technique on the intended region, where the effective index for the guided mode is modulated.

II. Principle of the Method

Chirped fiber gratings can be realized by axially varying either the period of the grating, Λ, or the effective index of refraction. From the first order Bragg condition, the Bragg wavelength is given by

$$\lambda_B(z) = 2n_{eff}(z)\Lambda(z). \tag{1}$$

In contrast to the conventional method of chirping, we only change the effective index, $n_{eff}(z)$, to produce the chirping effect by thermal diffusion where dopants in the core diffuse into the cladding. Grating period Λ is constant because the gratings are written after the diffusion in this method. The proposed method and its key principle can be easily understood by observing the changes of the index profile and effective index distribution along the fiber length, as schematically illustrated in Fig. 1.

III. Fabrication and Performance Analysis

We installed a photosensitive optical fiber with the jacket stripped into the mount of a coupler manufacturing system. For the thermal diffusion, we heated the fiber by oxy-hydrogen flame. We observed an increase in the mode field diameter (MFD) from the initial value of 8.42 μm to 14.74 μm after five minutes of heating. After the diffusion process, a UV light from a KrF excimer laser producing a 248-nm radiation at a fluence of 130 mJ/cm^2/pulse was exposed to the diffused region of the fiber through a 10-mm long phase mask with a 1060-nm period. The UV exposing time was about 40 minutes. We monitored the grating spectrum using a super-luminescent light emitting diode and optical spectrum analyzer.

The chirping effects of the grating depend on the change of the effective index of refraction by the thermal diffusion process. In other words, the change of the effective index related to the decrease of core index n_{core} determines the Bragg wavelength and reflection bandwidth of the fiber gratings. Therefore, we have examined the relation between the normalized MFD

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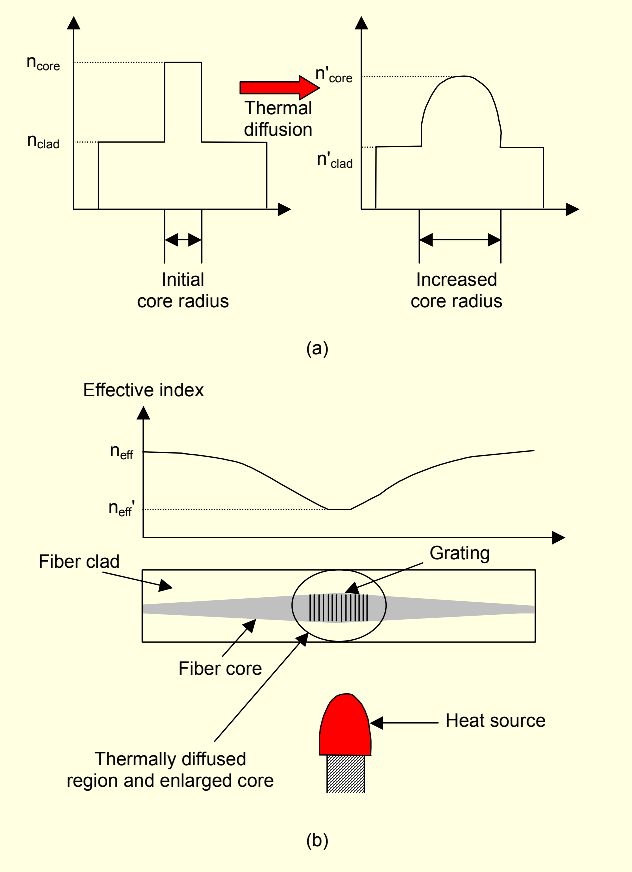

Fig. 1. (a) The index profile of the fiber before and after the thermal diffusion process and (b) the effective index distribution along the fiber length after the thermal diffusion process.

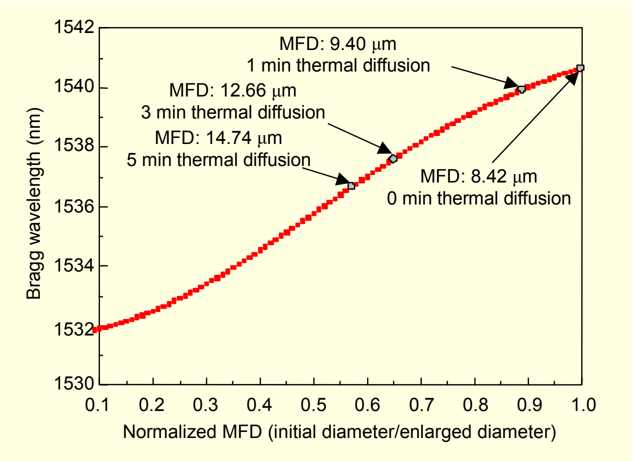

Fig. 2. The relation between the Bragg wavelength and the normalized MFD. Experimental data is also shown.

and reflection (Bragg) wavelength. The normalized MFD expresses the degree of thermal diffusion instead of n_{core} because it can be easily measured and analyzed. For a fiber with a step index profile, the effective index is calculated using the power fractions of the guided mode in the fiber core region, P_{core}, the relative refractive index difference, Δ, and the clad index, n_{clad}, as

$$n_{eff} = (1 + P_{core} \cdot \frac{\Delta}{1-\Delta}) \cdot n_{clad}, \qquad (2)$$

$$P_{core} = 1 - \exp\left(-2M^2\right), \qquad (3)$$

$$\Delta = \frac{1}{2} \cdot \left(\frac{2.405\lambda_c}{2\pi a n_{clad}} \right)^2, \qquad (4)$$

where M is the normalized MFD, λ_c is the cutoff wavelength of the fiber, and *a* is the fiber core radius. The Bragg wavelength is then predicted by (1) and (2). Figure 2 shows the calculated results between the Bragg wavelength and the normalized MFD. It is clear from this figure that the reflection wavelength gets shorter as the normalized MFD decreases. We expected that a chirped grating with a reflection bandwidth of 5 nm can be fabricated by reducing the normalized MFD from 1 to 0.5.

The reflection and transmission spectra of the chirped grating are shown in Fig. 3. In the transmission spectra, shown in Fig. 3(a), the center wavelength shifts from 1540.78 nm to the shorter wavelength of 1535.78 nm with an increase in the thermal diffusion time as a consequence of the decrease in the effective index, n_{eff}. We saw that the calculated and experimental results showed a similar behavior. We observed that the rejection ratio decreases for longer thermal diffusion times. This indicates that the photo-refractive index change in the diffused region is smaller than that in the non-diffused region for the same UV exposing conditions. This can be explained by the reduction of the germanium concentration in the diffused fiber core, as the photo-refractive index change is proportional to the germanium concentration in the fiber core [3]. The fabricated chirped fiber gratings have losses at a wavelength shorter than the main transmission dips due to out-coupling by the Bragg grating [4]. This loss can be further reduced by increasing the grating-mode overlap using several methods [5].

Figure 3(b) represents the reflection spectra for different diffusion times, indicating clearly the spectral broadening effect and center wavelength shift. The full-width at half maximum (FWHM) of the main peak in the reflection spectra is increased to 4.1 nm while that of the fiber grating without diffusion process is less than 1 nm. Also, the changes of the center wavelengths in the reflection spectra are the same as in the transmission spectra. Although the thermal diffusion processing time is different for each chirped fiber grating sample, we obtained the relatively high rejection ratio of about 25 dB.

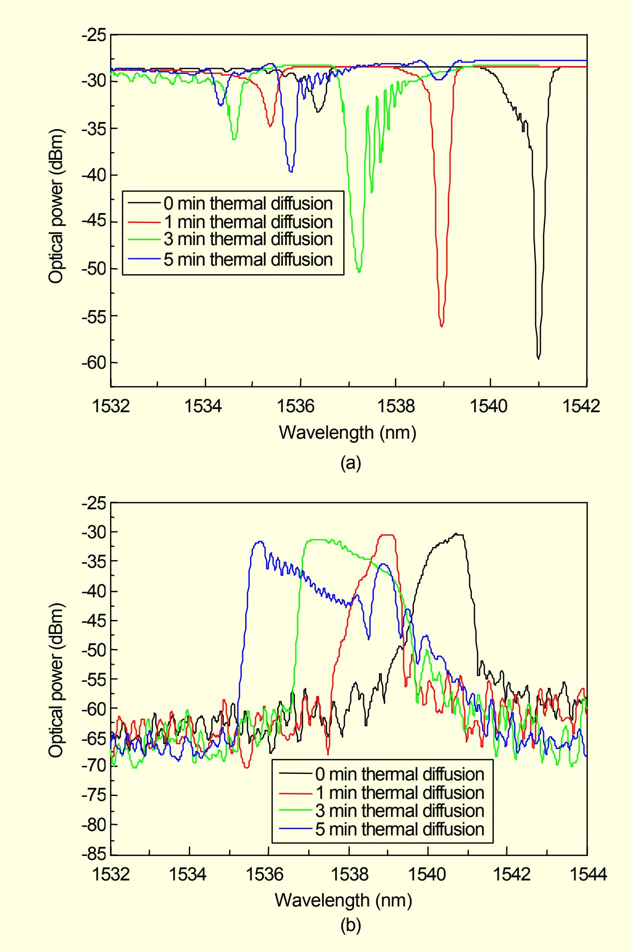

Fig. 3. (a) Transmission and (b) reflection spectra of the fabricated chirped fiber grating.

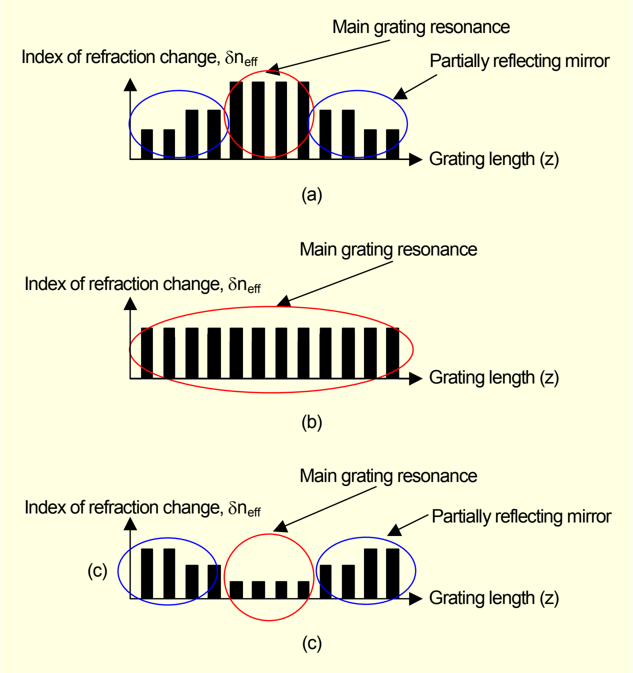

Fig. 4. (a) Schematic diagrams of the non-uniform dc index of refraction in the non-diffusion sample, (b) in the 1-min diffused sample, and (c) in the 3- and 5-min diffused samples.

In the case of a non-diffused sample, there is a significant periodic structure on the shorter wavelength side near the main peak, as shown in Figs. 3(a) and (b). This phenomenon can be physically understood as a kind of Fabry-Perot effect [5]. There is a frequency region near the short wavelength side of the grating resonance where the edges of the grating are near their local Bragg resonances but the center of the grating is not. Qualitatively, the edges of the grating behave as partially reflecting mirrors and the center as a transparent region [5]. In addition, the main peak at a longer wavelength of the spectra is due to the increase in the space-averaged index of the refraction because the refractive index change in the center of the grating is higher than that in the edges. After all, this is a result from the non-uniform dc index of the refraction change along the grating, which is schematically shown in Fig. 4(a) [5], [6].

In the case of the 3- and 5-minute diffused samples, there are many ripples at a longer wavelength from the main peak, which is also explained by Fabry-Perot as mentioned above. As shown in Fig. 4(c), the effective index at the center of the grating becomes low relative to the edge of the grating due to the thermal diffusion, which gives longer wavelength ripples from (1). We consider these effects because there exists a pair of reflection points which has the same reflection wavelength around the edge of the thermally diffused region, and this yields unwanted ripples at the longer wavelength side in the reflection and transmission spectra.

On the other hand, the sample with a one-minute diffusion time does not show ripples. This result can be explained by the geometrical distribution change in n_{eff}. Diffusion occurs mostly around the center of the flame. As shown in Fig. 4(b), the initial shape of the larger n_{eff} around the center becomes flat, and the value of the effective index in the center region is similar to that in the two sides of the gratings. The result indicates that the diffusion process invites a kind of apodization, as can be seen from the one-minute diffusion sample without the degradation ripples [3], [6]. In this case, thermal treatment gives us useful apodization methods.

IV. Conclusions

We have proposed a new method for the fabrication of the chirped fiber gratings using the thermal diffusion of core dopants, which brings variation in the effective index of the guided mode. Using our suggested method, the center wavelength shifts of the fiber gratings from 1540.78 nm to the shorter wavelength of 1535.78 nm with an increase in the thermal diffusion time were obtained and chirped fiber grating samples with bandwidths from 1.0 to 4.1 nm have been fabricated. We achieved relatively high rejection ratios of about 25 dB for all the samples. The experimental results indicate that the diffusion process invites a kind of apodization as well as the chirping. This may suggest that the technique can be used for many applications in optical communications and fiber sensors.

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