Asymmetric Transmission Spectrum of a Long-Period Fiber Grating and Its Removal Using a Beam Scanning Method*

Tae-Jung EOM†, Young-Jae KIM†, Youngjoo CHUNG†, Won-Taek HAN†, Un-Chul PAEK†, and Byeong Ha LEE†, Nonmembers

SUMMARY In an ideal fiber grating having a uniform refractive index modulation, the reflection or the transmission spectrum is symmetric with equal amount of side lobes on both sides of the resonant wavelength of the fiber grating. It is observed that a long-period fiber grating made by a non-uniform UV laser beam through a uniform amplitude mask has an asymmetric transmission spectrum. The asymmetric characteristic is explained with Mach-Zehnder effect in the long-period fiber grating. The non-uniform UV laser beam makes also a non-uniform index modulation along the fiber core. Therefore, a beam coupled to a cladding mode at a section of the grating can be re-coupled to the core mode after passing a certain distance. The re-coupled beam makes Mach-Zehnder-like interference with the un-coupled core mode. However, it is presented that the asymmetric phenomenon can be overcome by scanning the UV laser beam along the fiber over the mask. The beam scanning method is able to suffer the same flucence of the UV laser beam on the fiber. Finally, a linearly chirped long-period fiber grating was made using the non-uniform UV laser beam. Due to the asymmetricity the chirping effect was not clearly observed. It is also presented that the beam scanning method could remove the asymmetric problem and recover the typical spectrum of the linearly chirped fiber grating.

key words: fiber grating, long-period fiber grating, chirped grating, band-rejection filter, WDM communication system

1. Introduction

A long-period fiber grating (LPG) has been widely studied as prominent devices for accurate sensor systems and optical communication systems [1]–[3]. The LPG is a comparatively simple device consisting of a periodically modulated core in a conventional fiber as shown with Fig. 1. The mode coupling from the fundamental core mode to a cladding mode occurs when the modulation of the core index satisfies the phase matching condition [3] of

$$K \equiv \frac{2\pi}{\Lambda},$$

with the periodicity $\Lambda$ of the grating, $\beta_{co}$ and $\beta_{cl}$ are the propagation constants of the core and the cladding modes, respectively, given as

$$\beta_{co} = k_o n_{co}^2 = k_o n_{co} \cos \theta,$$

$$\beta_{cl} = k_o n_{cl}^2 = k_o n_{cl} \cos \varphi,$$

where $n_{co}^2$ and $n_{cl}^2$ are the effective indices of the core and the cladding modes, respectively. Further, $n_{co}$ and $n_{cl}$ are the refractive index of the core and the cladding, respectively. The angle $\theta$ and $\varphi$ are the propagating angles of the core mode and the cladding mode, respectively, when the beam propagation in a fiber is represented with ray-optics. As shown with Fig. 2, the core mode propagating with an angle $\theta$ against the fiber direction is coupled to the cladding mode having the propagation angle $\varphi$ with the help of the grating that have the grating momentum $K$.

The LPG is generally fabricated by exposing a UV laser beam over an optical fiber through an amplitude mask. The UV exposure induces refractive index change in the core of the fiber [3]. The widely used KrF excimer laser (248 nm) has a one-inch long beam size. Therefore, a uniform LPG of the length shorter than the beam size has been made by simply exposing the laser beam through the amplitude mask having a

![Fig. 1 The schematic diagram of an LPG and the refractive index modulation at the core of the optical fiber.](image-url)
uniform periodicity. It is well known that a uniform LPG has a series of resonant peaks caused by coupling to several cladding modes. Each resonant peak is composed of a main peak centered at the phase matching wavelength and a series of side lobes on both sides of the main peak. In principle, a uniform LPG should have the side lobes in a symmetric pattern [3], [4]. However, the transmission spectra of the LPG appeared in the most of the published works did not give the symmetric characteristic [3], [5]. In our works also, most of the LPGs that were fabricated using a uniform amplitude mask had the asymmetric spectra. Usually, the side lobe at the shorter wavelength side was bigger than that of the longer wavelength side.

The similar phenomenon was observed with a FBG (fiber Bragg grating) and was explained with the Fabry-Perot effect [6]. However, the study on the asymmetric transmission spectrum of the LPG has not been widely studied. We present that the asymmetricity of an LPG can be explained with the Mach-Zehnder effect in the LPG. The beam coupled to a cladding mode at a section of a non-uniform LPG is re-coupled to the core mode when it meets the section where the grating period becomes the same. This Mach-Zehnder effect can be simply removed by scanning the UV beam over the whole length of the grating. In order to confirm the idea, we made two linearly chirped LPGs. One was made by using the conventional method and the other one was made by using the beam scanning method. By comparing the two spectra, the importance of the Mach-Zehnder effect in LPG will be presented.

2. Mach-Zehnder Effect

It is well known that the minimum transmissivity of a uniform LPG is [7],

$$T_{\text{min}} = 1 - \sin^2(\kappa d),$$  \hspace{1cm} (5)

where $d$ is the length of the grating and $\kappa$ is the coupling coefficient related with the modulation depth of the grating $\delta n_{ac}$, i.e.,

$$\kappa \propto \delta n_{ac},$$  \hspace{1cm} (6)

While the resonant wavelength is determined as,

$$\lambda_0 = (n_{\text{eff}}^0 + n_{\text{avg}}^0 - n_{\text{eff}}^d) \Lambda,$$  \hspace{1cm} (7)

where $n_{\text{avg}}^0$ is the average index variation of the fiber core induced by the UV illumination. During the LPG writing process, it is generally observed that not only the grating grows but also its center wavelength shifts toward the longer wavelength direction because the average index variation increases as the UV exposing time increases [8].

In the case of using a non-uniform UV laser beam with a uniform amplitude mask, the resonant wavelength varies along the grating length. The section of the grating where the UV intensity is higher will have the larger average index modulation $n_{\text{avg}}^0$. When the non-uniform UV laser beam has a Gaussian-like intensity profile as shown with Fig. 3, the resonant wavelength at the middle part of the grating (region B in Fig. 3) becomes longer than those in the beginning and the ending parts of the grating (region A and C in Fig. 3). For that case, the beam coupled to the cladding mode at the beginning part of the grating is recoupled to the core mode at the ending parts of the grating. The recoupled beam makes Mach-Zehnder-like interference with the un-coupled beam in the core [4]. However, the beam coupled at the middle parts of the grating does not induce interference because there is no available region where the recoupling to the core mode occurs. Thus, an interference structure in the shorter-wavelength region is expected.

Figure 4 is the transmission spectrum of the LPG made by illuminating a UV laser beam which was suspected to have a slightly Gaussian-like intensity profile. The amplitude mask had a 400 $\mu$m grating period and the grating length was 20 mm. The optical fiber was...
Fig. 4 The transmission spectrum of the LPG made by a Gaussian-like UV laser, experimental result (solid line) and numerical result (dotted line). The LPG has an asymmetric spectrum.

Fig. 5 The simulation result of the transmission spectrum of the LPG made by the UV laser beam which have an inverse Gaussian-like intensity profile through a uniform amplitude mask.

Fig. 6 The schematic configuration of the experimental setup for scanning the UV laser beam along the fiber. The setup is able to suffer the same fluence of the UV beam on each region of the fiber under the mask and make a uniform index modulation in the fiber core.

Fig. 7 The transmission spectrum of the LPG made by scanning a UV laser beam along the fiber, experimental result (solid line) and numerical result (dotted line). The asymmetry was removed.

3. Beam Scanning Method

In order to make an LPG having a uniform index modulation, the same experimental setup was used but the UV laser beam was scanned along the fiber as shown in Fig. 6. The reason for this setup was to suffer the same fluence of the UV beam along the whole length of the grating. The fiber and the amplitude mask were moved with a constant speed while exposing the UV laser beam at a position. Therefore, there was no difference in the exposed fluence of the UV beam at any position of the LPG. The result is shown with Fig. 7. The interference structure in the shorter wavelength region was almost completely disappeared and the spectrum became quite symmetric. The small peaks on both sides are typical side lobes of the transmission spectrum for a uniform index modulation. It confirms that the asymmetry of the LPG was mainly induced by the uniformity of the used laser beam's intensity.

We also applied the beam scanning method to a chirped LPG. The chirped LPG is one of the solutions to make a filter having a uniform rejection ratio in a wide bandwidth [9], [10]. The period of the chirped grating \( \Lambda(z) \) varies linearly along the length of the structure such as

\[
\Lambda(z) = \left(1 + \alpha \frac{z}{d}\right) \Lambda_0,
\]

where, the dimensionless parameter \( \alpha \) is a chirping ratio and \( \Lambda_0 \) is the grating period at the beginning of the gratings. The change of the refractive index can be
Fig. 8 Calculated transmission spectra of the chirped LPGs with various chirping ratios; $\alpha$ is 0.05, 0.075, 0.10, and 0.125. 

Presented by

$$\Delta n(z) \propto \cos \left( \frac{2\pi}{\Lambda(z)} z \right).$$

(9)

Figure 8 shows the calculated transmission spectrum of the chirped LPG with different chirping ratios but with the same coupling coefficient. As the chirping ratio $\alpha$ increases, the bandwidth of the transmission spectrum is broadened and its shape becomes flattened. For the numerical calculation, the coupling coefficient of $\kappa d = 0.25\pi$ was used. However, with the linear chirping, the broadened and flattened filter was not obtained. As the chirping ratio increased, both sides of the main peak were increased and the main peak itself was decreased, but real flatness was not obtained. In order to get the more effectively flattened spectrum, a phase inducing method was reported [9]. In addition to the linear chirping, certain amount of phase shift is intentionally applied at several positions along the grating. However, the detail is not in the scope of this work.

The transmission spectra of the chirped LPGs made without (a) and with (b) the beam scanning method are shown in Fig.9. The solid lines of the figures are experimentally measured spectra and the dotted lines are the simulated ones. The periodicity of the amplitude mask was linearly varied from 380 $\mu$m to 420 $\mu$m, and the optical fiber was the single-mode FiberCore fiber. The spectrum of the linearly chirped LPG made without using the scanning, Fig.9(a), shows strong asymmetric. It is not easy to distinguish the chirping-induced broadening from side lobes of a conventionally made uniform LPG.Whilst, when the beam scanning method was used, the spectrum became symmetric and similar to the simulated spectra of Fig.8. Up to 2-dB, widely broadened spectrum is clearly observed. The broadening is clearly distinguished from the side lobes of a conventional uniform LPG.

Fig. 9 (a) The transmission spectrum of the chirped LPG made without the beam scanning method, (b) The transmission spectrum of the chirped LPG with the beam scanning method. The grating period is linearly varied from 380 $\mu$m to 420 $\mu$m over the 20 mm grating length. The solid lines are the measured spectra and the dotted lines are simulated ones.

4. Conclusion

We have revealed that the transmission spectrum of the LPG made by illuminating a non-uniform UV laser beam through a uniform amplitude mask was asymmetric. The pulsed KrF excimer laser may have a non-uniform intensity profile. This characteristic led to a Mach-Zehnder-like interference, so that asymmetric transmission spectrum of the long-period fiber grating was resulted. To remove the asymmetricity, we have presented the beam scanning method. By scanning the UV laser beam over the uniform amplitude mask, each region of the fiber under the mask was made to suffer the same fluence of the UV beam. The spectrum of the LPG made by the scanning method showed highly symmetric transmission spectrum, which was well fitted with the curve calculated by numerical method. We also have presented that the uniformity problem was important for the case of chirped LPGs. The spectrum of the chirped LPG made by the conventional method could not give the effect of chirping, but the effect was clearly observed when the scanning method was used.
Our results are expected to be used in designing and implementing precise filter devices for sensor systems or WDM communication systems.

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References


Tae-Jung Eom was born in Pusan, Korea. He received the Diploma in electronics from Pusan National University, Korea, in 1998, the Master degree in information and communications engineering from the Kwangju Institute of Science and Technology (K-JIST), Korea, in 2000. He is now a Ph.D. candidate in K-JIST. His main research interests are in the areas of fiber optics, fiber gratings, design of special fiber for long-period fiber gratings and its application, especially fiber optic devices for WDM communications.

Young-Jae Kim was born in Seoul, Korea. He received the B.S. degree in physics from Sogang University, Seoul, Korea, in 1999, the Master degree in information and communications engineering from the Kwangju Institute of Science and Technology (K-JIST), Korea, in 2001. He is now a Ph.D. candidate in K-JIST. His main research interests are in the areas of fiber optics, fiber gratings, design of special fiber for long-period fiber gratings and its application.

Youngjoo Chung was born in Pusan, Korea. He received the B.S. degree in physics from Seoul National University, Seoul, Korea, in 1982, and M.S. and Ph.D. degrees from Princeton University in 1985 and 1989, respectively. He was with the Advanced Photon Source at Argonne National Laboratory between 1989 and 1996. He returned to Korea as an associate professor at Kwangju Institute of Science and Technology in 1996 and he is currently serving as the department chair. His research interests include fabrication and application of optical fiber gratings to optical communication, optical fiber sensors, and linear and nonlinear devices for optical signal processing.
Won-Taek Han received his B.S. and M.S. degrees from the Department of Metallurgical Engineering, Seoul National University, Korea in 1979 and 1981, respectively. From 1981 to 1983, he was with Dong-A University, Korea as a Full-time Instructor. After receiving the Ph.D. degree in glass science from Case Western Reserve University, Ohio, U.S.A. in 1988, he moved to the Center for Glass Science and Technology in Rensselaer Polytechnic Institute, New York and worked as a Research Fellow from 1988 to 1991. In 1991, he returned to Korea and worked as the Head of the Glasses and Photonics Laboratory of the Korea Institute of Industrial Technology. In 1998, he joined the faculty of the Department of Information and Communications, Kwangju Institute of Science and Technology, Korea and currently he is an Associate Professor. His research interests are in the field of high performance glasses and photonics materials, glass fibers, fiber gratings, nonlinear optical glasses and their applications for the optical switching devices, and glass processings.

Un-Chul Paek was born in Korea. He received the B.S. degree from Korea Merchant Marine Academy, Pusan, Korea in 1957. He received the M.S. and Ph.D. degrees from the University of California, Berkeley, in 1965 and 1969, respectively. From 1969 to 1991, he was with Bell Labs, Lucent (then AT&T), where he was a Member of the Technical Staff, a Distinguished Member of the Technical Staff and a Bell Labs Fellow. In 1991 he returned to Korea and became the Executive Vice President of Korea Academy of Industrial Technology. During 1994–2000, he had worked as a Professor of the Information and Communications Department, and the Director of the Research Center for Ultrafast Fiber-Optic Networks, Kwangju Institute of Science and Technology, Kwangju, Korea. After retirement in 2000, he continues research at the same institute as a Chaired Professor. His research interests are in the areas of optical communications, optical fiber technology, and fabrication of optical devices and components. Dr. Paek is a Fellow of the Optical Society of America, a Fellow of American Ceramic Society, and a member of Sigma Xi.

Byeong Ha Lee received his B.S. and M.S. degrees in Department of Physics of Seoul National University, Korea, in 1984 and 1989, respectively. In University of Colorado at Boulder of U.S.A., he received Ph.D. degree in Physics with the thesis title of "Absolute Strain Measurement Using Fiber Bragg Grating." He worked in Osaka National Research Institute of Japan as a STA fellow during 1997 to 1999. He is now working as an Assistant Professor in the Department of Information and Communications of K-JIST (Kwangju Institute of Science and Technology), Korea. His interests are in the field of fiber optics, fiber gratings, fiber property measurement using fiber gratings, especially fiber optic devices for WDM communications and smart sensor systems.