Demonstration of an Ultra-Wide Wavelength Tunable Band Rejection Filter Implemented with Photonic Crystal Fiber

Jinchae KIM†, Gyeong-Jun KONG†, Un-Chul PAEK†, Kyung Shik LEE††, and Byeong Ha LEE†
a), Nonmembers

SUMMARY Press-induced long-period fiber gratings exhibiting strong core-to-cladding mode coupling were formed in photonic crystal fiber. Only one resonance peak was observed over a 600 nm spectral range and the resonant wavelength was tuned over the whole range by tilting a groove plate before pressing the fiber. The resonant wavelength decreased with increasing periodicity of the grating, which was opposite to the trend of the step-index conventional optical fiber. Meanwhile, the resonant wavelength increased with increasing the ambient refractive index, which was also opposite to that of the conventional optical fiber.

key words: photonic crystal fiber, long-period fiber grating, mode coupling, band-rejection filter

1. Introduction

Photonic crystal fiber (PCF) [1], [2] is composed of a single material with many air holes surrounding a defect located at the center of the fiber. The light guiding mechanisms of PCF can be understood by the modified total internal reflection [3] and photonic bandgap effect [4]. The modified total internal reflection can explain the wave guiding properties of the PCF having a solid defect. PCF has attracted much attention of optical community because of its peculiar and unique optical properties such as a single mode operation over a wide wavelength range [1] and wide flattened group velocity dispersion [5]. PCF has also been studied for device applications such as dispersion compensators [6] and couplers [7]. As filter devices, PCF has been utilized in flexible acoustic wave filter, permanently deformed long-period grating [8], fiber Bragg grating [9], core-to-core mode coupling grating [10]. Especially, the long-period fiber grating (LPG) has been attractive to the gain flattening filters for fiber amplifiers [11], spectral shaping device of light sources for optical coherence tomography [12], and sensitive sensor elements for measuring bend, compression, twist, and temperature [13].

In this paper, we report a tunable filter implemented with PCF by inducing periodic mechanical pressure [14]. The novel features of the grating formed on the PCF is reported. The resonant wavelength and the band rejection strength of the LPG could be adjusted. Unlike the LPG with the conventional fibers [15], over a 600 nm spectral range only one resonant peak was observed and its wavelength could be tuned over that whole range. By analyzing the resonant wavelength variation against the period, the effective index difference between the core and the cladding modes of the in-house PCF could be measured and compared with that of a conventional step-index single-mode fiber. Interestingly, we observed that the resonant wavelength decreased when the period increased and increased with index matching oil on the cladding surface. These are rarely observed phenomena with conventional single mode fibers.

Section 2 describes the experimental setup and the procedure to corrugate the optical fiber and the tuning mechanism of the grating periodicity. Section 3 shows the experimental results and summary is in Sect. 4.

2. Experimental Setup

The PCF was fabricated by the stack-and-draw method [16]. It consisted of 54 air holes in 4 layers with hexagonal shape as shown with Fig. 1. The diameters of the air holes and the distance between them were about 2.5–3.6 µm and 9.8±0.2 µm, respectively. The diameters of the air holes in each layer were gradually decreased and the holes in the last 4th layer were almost closed. The outer diameter of the PCF was about 120±2 µm and the shape of the fiber was hexagonal as shown in Fig. 1.

Periodic mechanical pressing was induced along the PCF by pressing a flat metal plate against a grooved plate. The fiber was loaded between the plates, and a load sen-

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†The authors are with the Department of Information and Communications, Gwangju Institute of Science and Technology, 1 Oryong-dong, Buk-gu, Gwangju, 500-712, Korea.
††The author is with the School of Information and Communication Engineering, SungKyunKwan University, Suwon 400-746, Korea.
a) E-mail: leehb@gist.ac.kr
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Fig. 1 Scanning electron microscope (SEM) image of the cleaved end facet of the in-house PCF.

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Fig. 2 Schematic of the experimental setup: MM (micrometer), P/LS (metal plate/load sensor), GP (grooved plate), RS (rotating stage), CH (chuck holder), S (1300 nm, 1550 nm LED), and OSA (optical spectrum analyzer).

Fig. 3 Schematic of the mechanism for tuning the grating periodicity.

Fig. 4 Transmission spectra of the LPGs formed with different pressures. At first, the resonant depth increased as increasing the load (a) and then decreased after a critical pressure marked by (III) (b).

Fig. 5 Transmission spectra of the LPGs with different periodicities. The period was adjusted by tilting a grooved plate having a 600 µm periodicity. The tilting angles from right to left were 27°, 33°, 38.3°, 42.2°, and 47°, respectively.

Fig. 6 Transmission spectra...
resonant wavelength is observed to increase with the grating period [17]. This reverse movement of the resonant wavelength might be explained with the dispersion property of the PCF. From the result of Fig. 6, we can say the cladding mode of the PCF was more dispersive than the core mode. However, for the detail analysis of the spectral behaviors of the LPG in PCF, we should develop the tool that can handle the cladding mode of the photonic crystal fiber.

From the measured resonant wavelength of the LPG, the difference in the effective indices of the core and the cladding modes was obtained. The mode coupling in an LPG occurs when the wavelength $\lambda$ satisfies the well-known phase matching condition

$$\left(n_{\text{eff}}^{\text{co}}(\lambda) - n_{\text{eff}}^{\text{clad}}(\lambda)\right)\Lambda_{\text{eff}} = \lambda,$$  \hspace{1cm} (2)

where $n_{\text{eff}}^{\text{co}}$ and $n_{\text{eff}}^{\text{clad}}$ are the effective indices of the core mode and the cladding mode, respectively. Therefore, from the measurements of Fig. 6, the difference in the effective indices of the core and the cladding modes, or differential effective index of the PCF could be obtained as a function of the wavelength. As can be seen with the closed squares in Fig. 7, the differential effective index of the PCF increased with the wavelength. The same measurement was done with a conventional single mode fiber (SMF) using the same apparatus. Interestingly, the differential effective index decreased with wavelength as shown with the open circles in the figure.

The increment phenomenon of the differential effective index of the PCF with wavelength is consistent with the appearance of the endless single mode in PCF [1]. Meanwhile, the numerical aperture of the PCF increased as increasing the wavelength to maintain the single mode operation over a wide wavelength range. Here, the numerical aperture is related to the difference between the modal indices of the core and the fundamental space filling modes, whose wavelength dependence is similar to that of the cladding mode(s) in the realistic PCFs having a finite cross-section and air holes.

To see the orientation dependency of the LPG made in PCF, the transmission spectrum was measured with two different orientations of the PCF. For the experiment, the acrylate coating on the PCF was removed and then, keeping the same grating making condition, only the PCF was rotated along its axial axis. As shown in Fig. 1, the PCF had a hexagonal shape.

The experiments were performed with several angles as shown in Fig. 8 and it was observed that the peak P2 was very sensitive to the orientation and the other peak P1 was fairly insensitive. Its resonant wavelength remained within $\pm3$ nm variation. This orientation dependent resonant phenomenon can not find its counterpart with a conventional single mode fiber. However, it is believed to be related with the polarization effects, the stress distribution and the geometry of the fiber. As was mentioned, a detail analysis of the cladding mode of PCF should be supported for further understanding.

As the last experiment, the effect of the ambient re-
fractive index on the resonant wavelength of PCF-LPG was measured. A series of index matching oils (Cargille Laboratory®) were applied on the surface of the PCF-LPG region. Astonishingly, the resonant wavelength was increased with the oil index as shown with Fig. 9. This behavior is opposite to what is generally observed with the LPGs made in a standard SMF [18]. However, the wavelength shift was appreciably small compared to the SMF case [18]. From this measurement, we can say that the cladding mode, which is coupled from the core mode, is confined near the central parts of the fiber rather than near the outer air boundary of the fiber.

4. Conclusion and Discussion

We have presented the behaviors of the long-period fiber gratings fabricated in PCFs. The gratings were formed by applying a periodic pressure on the side of the PCF. A strong core-to-cladding mode coupling was maintained over a 600 nm wavelength range, which was limited by the shortage of the measurement devices such as a source and a spectrum analyzer. The resonant wavelength of the grating decreased with increasing the period, which was in good harmony with the well-known phenomenon of endless single-mode operation in the PCF. The oil-induced resonant wavelength shift was opposite to what was observed with the LPGs made in a standard SMF. It was also observed that the resonant peak was related with the angular orientation of the PCF having a hexagonal symmetry. However, for thorough understanding of the resonant coupling in the PCF, further investigation on the cladding mode of the PCF and its polarization properties is required.

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References

Jinchae Kim received his bachelor’s degree in physics from Chungnam National University in Korea in 1998. He earned his master’s degree in information and communications from Gwangju Institute of Science and Technology (GIST) in 2000, and is currently pursuing his doctorate degree in information and communications from the same institute. His research interests are the fabrication of the novel optical waveguides (such as photonic crystal fiber) and devices as well as their numerical modeling and designs.

Gyeong-Jun Kong was born in Jeonnam province, Korea. He received the B.S. degree from Information and Communication Engineering, Suncheon National University, Korea, in 2003. He is now a M.S. candidate in Department of Information and Communications, Gwangju Institute of Science and Technology (GIST). His main research areas are the design of photonic crystal fiber and optical interconnection for optical communications.

Un-Chul Paek was born in Korea. He received the B.S. degree from Korea Merchant Marine Academy, Pusan, Korea in 1957. 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, Gwangju Institute of Science and Technology, Gwangju, 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 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 GIST (Gwangju Institute of Science and Technology), Korea. His interests are in the field of fiber optics, fiber gratings, photonic crystal fiber, especially fiber optic devices for WDM communications and smart sensor systems. He is also trying to apply fiber optic devices for Optical Coherence Tomography.

Kyung-Shik Lee Photograph and biography are not available.