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Fabrication and Characterization of a Broadband Long-Period Grating on a Hollow Optical Fiber with Femtosecond Laser Pulses

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We have fabricated broadband long-period gratings (LPGs) on hollow optical fibers (HOFs) by 15 corrugating slots with various widths by point-by-point exposure of a Ti:sapphire femotosecond laser. The corrugated LPGs showed unique broadband rejection whose FWHM extended to 190 nm with a low insertion loss of less than 1 dB. The maximum coupling strength was 8.5 dB, which is a significant improvement in comparison with previous HOF acousto-optic tunable filters (AOTFs). The center wavelength and coupling strength of the resonant peak could be systematically controlled by modulating the width of the corrugation.

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I. INTRODUCTION

In order to accommodate flexible wavelength manipulation in wavelength-division multiplexing (WDM) optical communication systems, passive and dynamic channel selective filters are in great demand. In recent years, all-fiber band rejection filters have been investigated with various fabrication schemes [1,2]. In particular, band rejection filters with narrow bandwidth of less than 0.5 nm, as well as broad bandwidths over 50 nm, have been reported for various applications, such as wideband optical component in S, C, L and U bands [3–5], flexible filters for coarse-wavelength-division multiplexing (CWDM) in access networks [6] and characterization of these components and devices [7,8].

Recently, the authors have reported efficient and broadband mode conversion in a hollow optical fiber (HOF) by using acousto-optic tunable filters (AOTFs), where the spectral bandwidth rejection was tunable from 47 nm to 160 nm [9]. Broadband coupling has been attributed to unique mode-beating dispersion in HOF, which is composed of three unique layers: a central air hole, a ring-core and silica cladding [10]. The coupling strength, however, was limited to about 5 dB in the previous report due to weak acousto-optic interaction and subsequent refractive index modulation. In order to maintain a broad bandwidth and further improve the rejection strength, we have investigated writing of long period grating (LPG) on HOF and we found that a conventional photorefractive grating was not formed in HOFs in a routine manner.

In this paper, for the first time to the best knowledge of the authors, we report a corrugated HOF-LPG fabricated by using a novel femtosecond laser machining system to mechanically inscribe slots [11,12] over HOF cladding in order to obtain even stronger mode coupling and wide bandwidth. The detailed fabrication process is described and the transmission characteristics are thoroughly investigated.

II. EXPERIMENTS AND DISCUSSION

The proposed LPG structure is schematically illustrated in Figure 1. The HOF used in this experiment had a 6-μm air-hole diameter, a ring-core with a 2-μm

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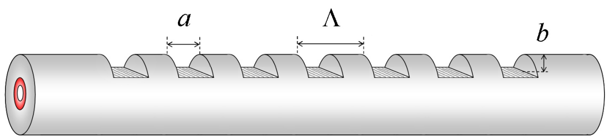

Fig. 1. Schematic diagram of the LPG on HOF.

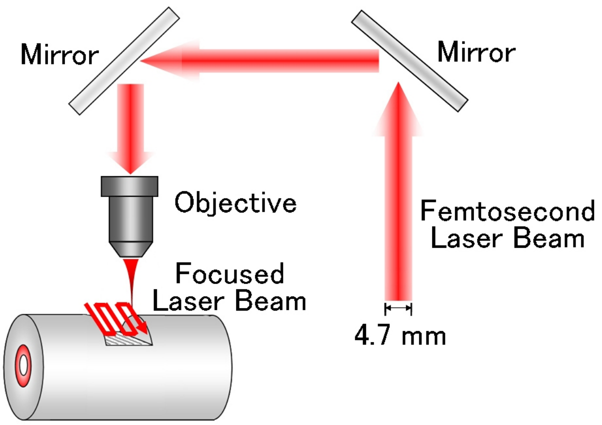

Fig. 2. Experimental setup and slot inscribing process.

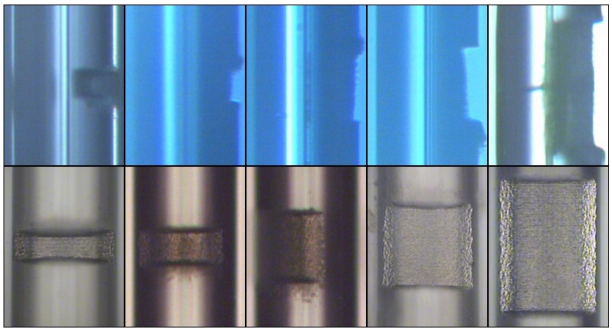

Fig. 3. Photographs of side- and top-views of actual corrugated HOFs in the order 30 μm, 40 μm, 80 μm, 90 μm and 150 μm from the left.

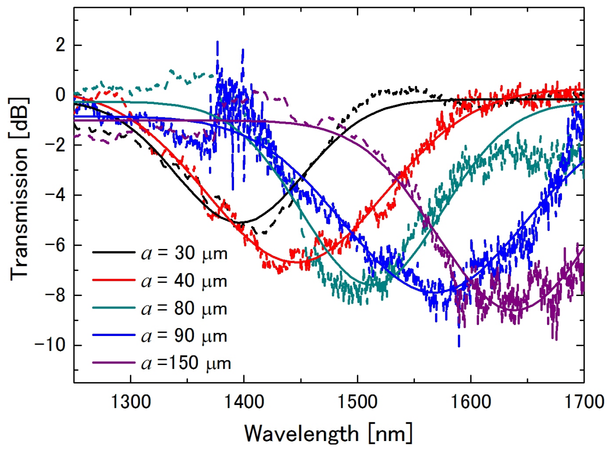

Fig. 4. Transmission spectra of band rejection as a function of wavelength. Dashed lines represent rejection of fibers themselves and solid curves mean their Gaussian fits.

thickness and a 125-μm cladding diameter [10]. The SiO_2 cladding of HOF was ablated by using femtosecond laser pulses in a systematic manner to produce periodic corrugations with appropriate dimensions. The characteristics of the Ti:sapphire laser used in this experiment are a center wavelength of 785.5 nm, a pulse duration of 184 fs, a 1-kHz repetition rate, an average power of 3.59 mW and a NA of 0.4 with a $\times$20 microscopic objective lens.

Near the center of a one-meter-long HOF, the corrugated HOF-LPGs with 15 slots were fabricated by using point-by-point exposure of the laser. The dimensions of the corrugations were controlled such that a pitch Λ of 550 μm and a depth b of 13 μm were fixed while the width a was given various values, 30 μm, 40 μm, 80 μm, 90 μm and 150 μm. It is noted that the depth of the corrugation in the HOF-LPGs was significantly shallower than those of conventional one-side corrugated SMF-LPGs, which could be attributed to the unique stress distribution in the HOF along with the air holes, in contrast to those of solid SMFs [13].

The experimental setup and the corrugation process are described in Figure 2. The focused laser had a beam diameter of 5 μm and the single scan of the laser beam ablated the SiO_2 silica cladding to a depth of 6.5 μm. Utilizing a motorized laser beam scanning system, linear corrugated LPGs were carved perpendicular to the fiber axis. The number of laser scans could precisely control the width of the slots.

Pictures of fabricated HOF-LPG are shown in Figure 3, where corrugated structures are clearly seen. It is noted that in each slot, there exists significant roughness on the surface due to non-flat top beam mode and relatively small beam area of the femtosecond laser. Further optimization of the laser parameters and the scanning mechanism will ensure reduced surface roughness and scattering loss.

For the fabricated HOF-LPGs, we have experimentally measured the output transmission as a function of wavelength with an unpolarized white light source and optical spectrum analyzer. Note that the HOF-LPG was held straight to avoid bending effects. The corrugated HOF-LPGs were observed to be highly sensitive to mechanical bends because the pristine HOF itself is already sensitive. The band rejection spectra of the fabricated HOF-LPGs were achieved by subtracting from the sample spectra the pristine HOF reference. The results are summarized in Figure 4 for various corrugation widths. The filters showed somewhat noisy spectral transmissions because of the rough corrugated surfaces. The spectral noise increased with larger a because the number of laser beam scans increased. The conventional SMF-LPG spectra were analyzed using a Gaussian fitting [14, 15] to evaluate the FWHM and the resonance peak wavelengths. In the case of the corrugated HOF, there are various contributions for periodic index change, such as mechanical stress around the core and cladding, which will con-

Table 1. FWHM as a function of a.

a (μm)	30	40	80	90	150	Average
FWHM (nm)	132.78	184.25	144.82	187.95	160.66	162.09

tribute to the low-pass filtering spectra. Therefore, we used a Gaussian fitting to analyze the spectra as in the case of conventional SMF-LPGs in order to represent the net effects of corrugation as an effective refractive index change. Using the Gaussian fitting, we estimated the FWHM and the resonance peak positions.

For the case $a = 90$ μm, the used HOF was different from other samples and it had a larger OH contents to result in larger noise near 1390 nm, where the OH absorption line is located. The fitting in this spectrum was carried out to minimize the error in the 1450 nm to 1700 nm range and the noise from OH peaks.

Prior SMF-LPGs showed band rejection in the spectral bandwidth from 10 nm to 20 nm. On the other hand, the central air hole and the ring-core of the HOF result in significantly different mode beating dispersion between the core and cladding modes. As experimentally observed in the case of AOTFs [9], the phase matching condition for the LP_{01}^{core}-LP_{1m}^{clad} anti-symmetric mode coupling occurs in a broad spectral range, so that HOF-AOTF can provide a much broader rejection band up to 160 nm. In this study of corrugated HOF-LPGs, we found that the FWHM of band rejection grew to 190 nm, which was very comparable or even wider than that of the HOF-AOTF. All corrugated HOF-LPGs showed a low insertion loss of less than 1 dB. Note that bandwidth is determined by the dispersion of coupled modes; that is to say, the shape of the core will decide the band rejection ranges, so the FWHM will not be affected significantly by the structure of the corrugation [10]. Actually, the FWHM shows irregular values, as listed in Table 1, whose average is around 160 nm.

Coupling strengths from 5 dB to 8.5 dB were observed in the rejection band peaks. Note that the maximum coupling efficiency of 8.5 dB in the corrugated HOF-LPG means more than a 3.5-dB enhancement compared with prior HOF-AOTFs [9].

There have been many attempts to control the resonance peak of the LPG [16–18]. These attempts, however, were made on SMF or a photonic crystal fiber and had serious risks that could damage samples by physical or chemical deformation. All of them showed narrow-band rejection spectra. Corrugated HOF-LPG showed a remarkable feature to control both the rejection efficiency and the spectral position of the peak simultaneously by changing a. The coupling efficiency monotonically increased for increasing a, as illustrated in Figure 5. The resonant peak wavelength also showed a monotonic increase, as in Figure 6. The stronger coupling efficiency could be attributed to increase in stress along the fiber core for larger a, which is in accordance with previous

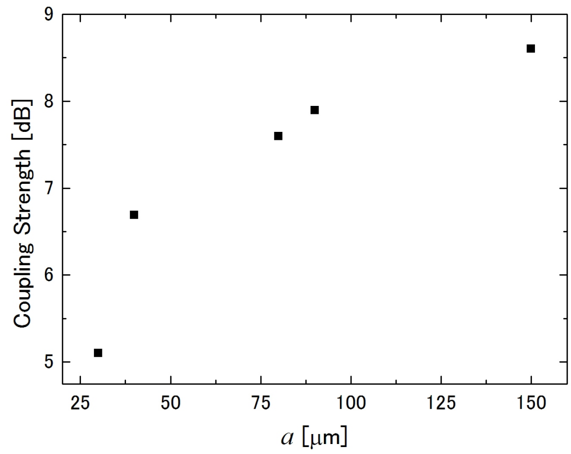

Fig. 5. Coupling strength as a function of a.

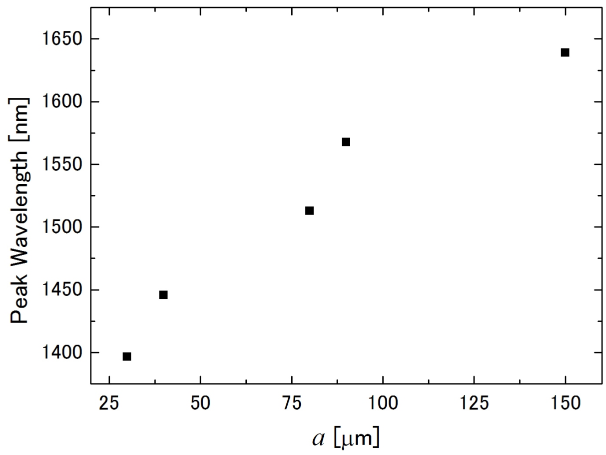

Fig. 6. Peak wavelength of the rejection as a function of a.

LPGs on conventional SMFs [19–21].

This stress-induced refractive index perturbation also leads to a peak wavelength shift. For a corrugated LPG with refractive index variations in the core δn_{core} and cladding δn_{clad}, it has been shown that the wavelength λ_{max} at which resonant coupling occurs can be written as [22]

$$\lambda_{max} \cong \lambda_{res}\left(1 + \frac{(\delta n_{core} - \delta n_{clad})\frac{d\lambda_{res}}{d\Lambda}}{(n_{core} - n_{clad})^2}\right), \quad (1)$$

where λ_{res} is the initial resonant wavelength, n_{core} is the effective index of the fundamental core mode, n_{clad} is the effective index of the resonant cladding mode and Λ is the period of the core refractive index modulation. Unless higher-order modes are coupled, the slope of the resonant shift, $d\lambda_{res}/d\Lambda$, is positive and keeps a constant value for a fixed Λ [23]. By broadening a in the corrugated structure, we can expect two effects: 1) increase in δn_{core} due to the enlarged stress-optic effect and 2) a reduction of δn_{clad} due to a larger amount of ablation of silica and inclusion of air in the cladding. The increase of a in the corrugated grating, therefore, will increase $\delta n_{core} - \delta n_{clad}$, in a collaborating manner, which subsequently results in a red shift of the resonant wavelength.

III. CONCLUSIONS

In conclusion, we successfully fabricated a broadband LPG on HOF by using femtosecond laser pulses to achieve a broad bandwidth and a strong band rejection efficiency. We could achieve an insertion loss of less than 1 dB, a FWHM of up to 190 nm and a maximum coupling strength of 8.5 dB. We were able to observe monotonic increases in the center wavelength and coupling strength as a was increased, which could be explained in terms of a stress-optic index perturbation. Therefore, the corrugated HOF-LPG, rather than HOF-AOTFs, can be used as a novel wide band rejection filter with stronger mode coupling in a rigid package. We expect the corrugated HOF-LPG to provide ample potential for wide-band rejection filter applications in communications due to their strong mode coupling with flexible control of the rejection range.

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