Bandpass filter with adjustable bandwidth based on a press-induced long-period twisted holey-fiber grating

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A bandpass filter with adjustable bandwidth based on a press-induced long-period grating in a twisted holey fiber is presented. By twisting the holey fiber prior to the application of periodic pressure, each rejection band of the nontwisted induced long-period grating is split into two shifted rejection bands that move further apart as the twist ratio increases. This feature results in a wide bandpass filter with controllable bandwidth. A bandpass filter at 1523 nm with adjustable bandwidth from 15 to 65 nm with near-linear response and insertion loss lower than 0.7 dB is demonstrated. Additionally, the bandpass filter can be tuned over 100 nm. © 2007 Optical Society of America

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All-fiber bandpass filters are devices required in applications for spectral equalization or shaping [1,2]. So far, two typical configurations have been demonstrated to obtain bandpass filters based on long-period fiber gratings (LPFGs). One approach uses a pair of LPFGs in cascade with a core blocker between them; the first LPFG couples the light from the core to the cladding, and the second couples light back to the core; meanwhile, the core blocker intercepts the core mode transmission and ensures that the core signal after the cascade comes totally from the recoupled cladding modes [2–4]. The other option is the π-phase method, in which a π-phase shift is introduced during the LPFG periodicity inscription so that the destructive mode coupling is converted into constructive mode coupling and a bandpass filter is obtained [5]. The main limitation of the first proposal is the relative high insertion loss (>1 dB); meanwhile, the other one has simple fabrication but shows poor flexibility in the bandpass filter parameters. To obtain flexible bandpass filters based on LPFGs it is important to explore and propose other novel configurations.

In this Letter, we demonstrate that the introduction of twist in a press-induced long-period holey fiber grating (LPHFG) can be used to split any resonance peak into two shifted peaks to obtain a bandpass filter with controllable bandwidth. With this method, a bandpass filter at 1523 nm with adjustable transmission bandwidth from 15 to 65 nm and insertion loss lower than 0.7 dB is demonstrated. Additionally, the bandpass filter can be tuned to a range of 100 nm. A schematic diagram of the bandpass filter based on the press-induced long-period twisted holey-fiber (HF) grating is shown in Fig. 1. In the experimental setup, two identical metallic corrugated plates of $70\ \mathrm{mm} \times 25\ \mathrm{mm} \times 10\ \mathrm{mm}$ (length × width × thickness) with a grooved pattern were used to generate the periodic index modulation over the twisted HF by pressure (P). The grooved pattern has a period of $\Lambda = 460 \pm 10\ \mu\mathrm{m}$, a duty circle of 48%, and a depth of $400 \pm 10\ \mu\mathrm{m}$. The period of the grating may be adjusted by the rotary stage (RS) according to the expression $\Lambda = (460 \pm 10)/\cos\phi$, where ϕ is the rotational angle of the grooved plates with respect to the fiber, while the length of the grating is determined by the interaction length of the plates. The HF under test was fixed to one side by a fixed fiber fastener (FFF), and the other fiber side was fixed to a rotational fiber fastener (RFF) with a separation length (L_τ), of 22 cm, where the HF can be twisted by turning the RFF. The inset in Fig. 1 shows a photograph of the transversal structure of the HF used in the experiment. This HF presents a lattice pitch of 11 μm, air-hole diameter of 5 μm, and core/cladding diameters of 10/125 μm. To measure the transmission spectrum of the press-induced LPHFG under controlled twist, a white light source (WLS) and an optical spectral analyzer (OSA) were used.

At first, the HF was placed between the plates and fixed with the fiber fasteners, and then a 485 μm period was selected and the pressure between the metallic plates was adjusted until a rejection band filter

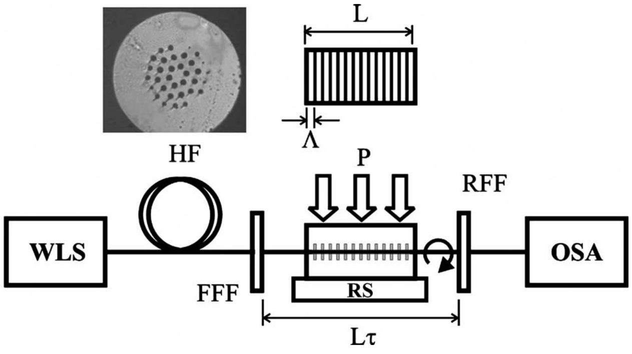

Fig. 1. Schematic of the press-induced LPHFG under twist. Abbreviations defined in text.

at 1523 nm, with 15 dB notch depth and a bandwidth of 9 nm, was obtained (dotted curve in Fig. 2). Then, without applied pressure the HF was twisted 4 turns clockwise, and pressure was gently applied again. Afterwards, the normal rejection band filter was split into two symmetrically shifted rejection bands, which results in a bandpass filter with an insertion loss of 1.8 dB (solid curve in Fig. 2). It is worth mentioning that for a twist ratio of <3 turns, the separation between the shifted rejection bands was not enough to obtain a bandpass filter with insertion loss lower than 3 dB. This proof was repeated for a twist of 4 turns counterclockwise, and negligible differences in the split of the rejection band and wavelength separation of the shifted rejection bands were observed. In the same way, the other rejection band simultaneously obtained at 1118 nm exhibited similar splitting behavior as described above.

Figure 3 shows the evolution of the transmission spectrum of the bandpass filter when the twist ratio increases from 4 to 12 turns. The bandpass filter shows a broadening of the bandwidth and a reduction of the insertion loss as the twist ratio increases. The inset in Fig. 3 shows a plot of the bandwidth broadening of the transmission bandpass as a function of the twist ratio, where we can observe a near-linear dependence. The bandwidth of the bandpass filter rises from 15 nm at 4 turns to 65 nm at 12 turns; meanwhile, the insertion loss decreases from 1.8 to 0.7 dB after 6 turns. For more than 12 turns the HF was regularly broken, and we cannot increase the bandwidth more than 65 nm. Moreover, the bandpass filter can be tuned by changing the period of the index modulation over the twisted HF, as is shown in Fig. 4, where the bandpass filter is tuned from 1565 to 1465 nm. Also, the transmission amplitude of the bandpass filter shown in Fig. 5 can be controlled by adjusting the broadening of the shifted resonance bands by means of the interaction length of the grooved plates over the twisted HF. Figure 5 shows the attenuation of the transmission amplitude of the bandpass filter when the interaction length decreases from 70 to 43 mm. The amplitude of the bandpass filter can be adjusted by this method; meanwhile, the bandwidth of the bandpass filter stays lower than two times the bandwith of the split rejection bands. The inset in Fig. 5 shows the transmission amplitude as a function of the length of the plates over the HF.

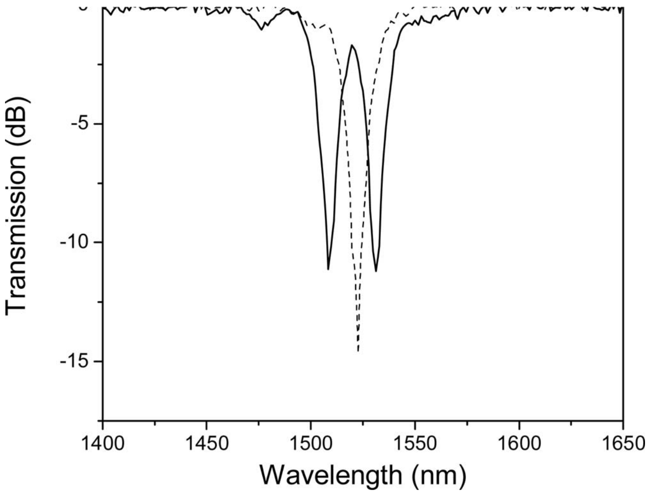

Fig. 2. Transmission spectrum of the rejection filter and the bandpass filter.

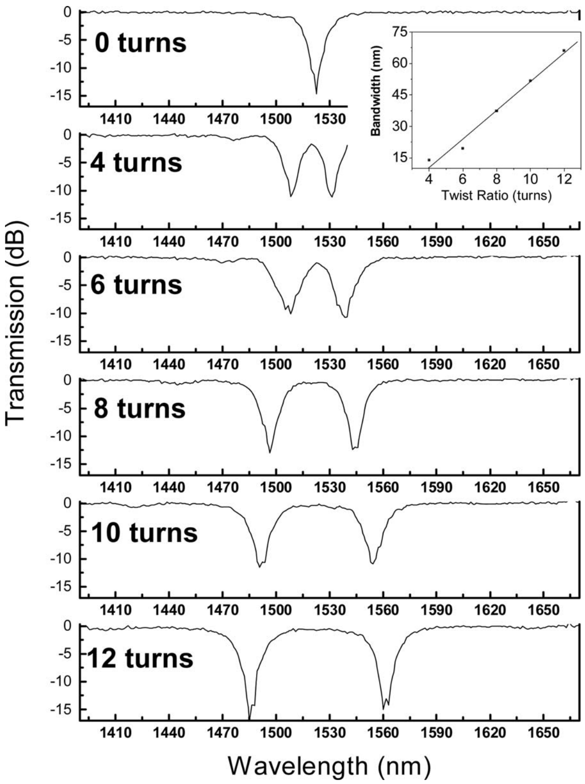

Fig. 3. Spectral evolution of the bandpass filter for different twist ratios.

Experimental reports on corrugated and CO_2-impressed long-period gratings (LPGs) in standard fiber under slight twist (<0.2 rad/cm) have shown that their cladding mode resonances shift linearly to shorter or longer wavelengths depending of the twist direction [6,7]. Recently, unexpected effects have been observed when the mechanically induced LPGs are under twist. The simultaneous application of lateral press and twist results in the shift of the

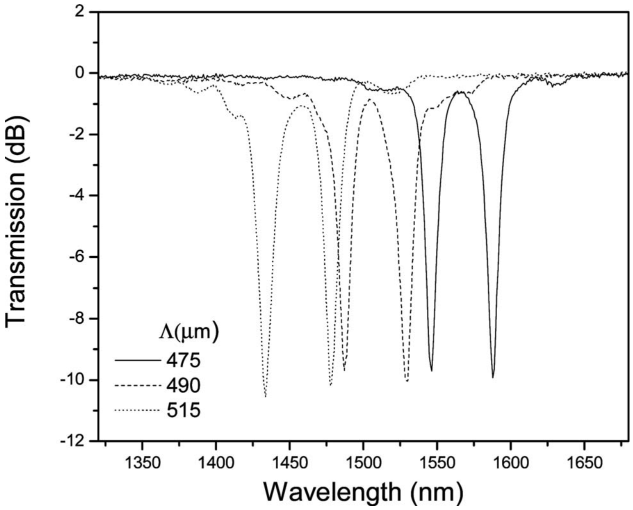

Fig. 4. Wide tuning range of the bandpass filter.

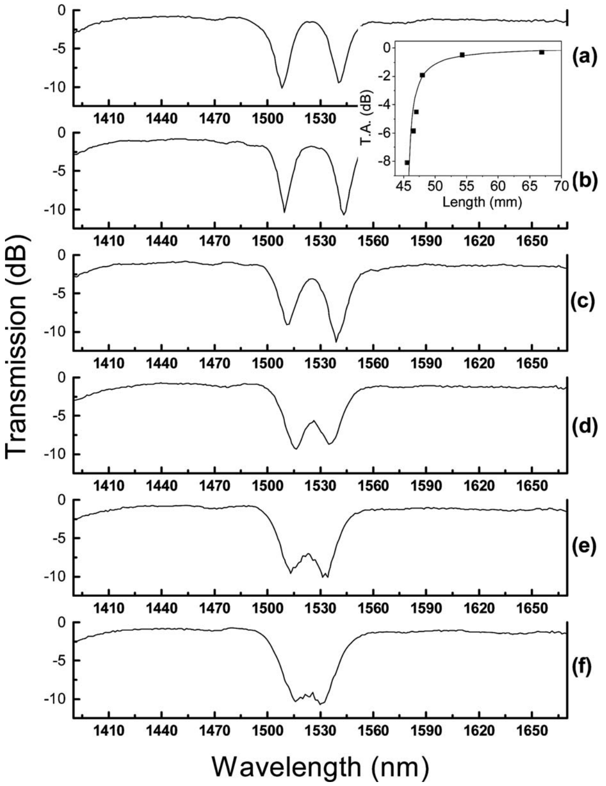

Fig. 5. Transmission amplitude as a function of the interaction length of the press-induced LPHFG: (a) 63.5, (b) 51.5, (c) 45.5, (d) 44.5, (e) 44, (f) 43 mm.

cladding mode resonances to shorter wavelengths and after a certain level of twist (>5 rad/cm) a split of the cladding mode resonances is observed [8]. In contrast, we have found that mechanically induced LPGs in the HF under twist exhibit a split of the cladding mode resonances for twist ratios <2 rad/cm, where the value of the split has a near-linear dependence on the twist ratio applied to the HF.

Based on the coupling mode theory, Ivanov [9] demonstrated that the twist applied in LPGs in standard fiber removes the degeneracy of the hybrid modes of the long-period modes in the cladding, and consequently splitting of the cladding mode resonances is observed. For antisymmetric LPFGs, the value of the splitting is determined by $\delta\beta = \tau p_{44} \varepsilon_{cl}$, where τ is the twist per unit of length, p_{44} is the photoelastic constant, and $\delta\beta$ is the change of propagation constant during the transition from the core mode to a cladding mode. The calculated and experimental split sensitivities to twist for standard single mode fiber are of the order of 1–2 nm/(rad/cm) [8,9], while in our case the split sensitivity is ~18 nm/(rad/cm), i.e., ~10 times larger than in standard fiber. This significant difference is expected since the cladding modes have a smaller diameter in the microstructured fiber, as predicted by Ivanov [9], and the magnitudes of the effective index changes in the core and the air–silica microstructured cladding are different. In the case of LPGs based on standard fiber, under slight twist, the index changes of the core and the cladding are approximately similar, and it is not enough to break the degeneracy of the hybrid mode of the corresponding cladding mode resonances so that only the wavelength shift is observed. Hence, the standard fiber requires a larger twist ratio to break the hybrid mode degeneracy and bring about the onset of mode splitting. In addition, the HF presents irregularities in the photonic crystal structure that contribute to reduction of the degeneracy of the hybrid modes. Another important parameter in the splitting is the longitudinal electric field component of the hybrid modes in core fiber. This parameter may be larger in HF than standard fibers, and it plays an import role in the coupling strength coefficients in resonance wavelengths in the LPGs in twisted fibers.

In summary, we present a novel bandpass filter with adjustable bandwidth based on the split of a rejection band of a press-induced LPG over holey fiber when the fiber is subjected to controlled twist. We have demonstrated a bandpass filter with insertion loss less than 0.7 dB and adjustable transmission bandwidth from 15 to 65 nm that is tunable in a range of 100 nm. An important advantage of the proposed bandpass filter compared with other methods is the flexibility to independently adjust the bandwidth, the tunable range, and the transmission amplitude with relative low insertion loss.

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