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In-line Mach-Zehnder interferometer composed of microtaper and long-period grating in all-solid photonic bandgap fiber

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We report a compact in-line Mach-Zehnder interferometer combining a microtaper with a long-period grating (LPG) in a section of all-solid photonic bandgap fiber. Theoretical and experimental investigations reveal that the interferometer works from the interference between the fundamental core mode and the LP₀₁ cladding supermodes. The mechanism underlying the mode coupling caused by the microtaper can be attributed to a bandgap-shifting as the fiber diameter is abruptly scaled down. In addition, the interferometer designed to strengthen the coupling ratio of the long-period grating has a promising practical application in the simultaneous measurement of curvature and temperature. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4756894>]

All-fiber in-line Mach-Zehnder interferometers (MZIs) have attracted considerable attention for their wide range of applications in fiber sensors and communications. Most of the in-line MZIs are constructed by using, for example, core-offsetting,¹ long-period grating (LPG) pair,² single taper,³ and dual tapers.^{4,5} However, the MZIs based on a taper-LPG combination are seldom reported. One of the main challenges for this type of MZI is that LPGs are only effective in coupling between particular modes, whereas the taper is not in most cases. Generating the exact mode coupling that matches the resonant condition for LPGs through tapering is difficult. Although Frazão *et al.* demonstrated a MZI by combining a LPG with a fused taper in a single-mode fiber (SMF),⁶ its extinction ratio was no more than 1 dB.

As a powerful post-processing technique, tapering has been widely applied in all kinds of fibers, including SMFs, multimode fibers (MMFs), photonic crystal fibers (PCFs), and other special fibers. As for tapering PCFs, most reports have been devoted on achieving dispersion engineering, mode coupling, and high-sensitivity sensing by tapering index-guided PCFs.⁷ Also, a few reports have focused on tapered hollow-core photonic bandgap fibers (HCPBGFs), although these configurations are very prone to high losses through loss in structural integrity of HCPBGFs.^{8,9} However, little attention has been paid to tapered all-solid photonic bandgap fibers (ASPBGFs),¹⁰ another class of PBGFs. Compared with HCPBGFs, ASPBGFs can be more suited to investigate bandgap evolution and mode coupling in the tapering process with the elimination of hole collapse. Moreover, ASPBGFs bring not only the intrinsic properties of PBGFs but also the advantages of all-solid fibers, such as ease in fabrication and splicing, and potential for inscribing fiber grating or active doping.

In this letter, a compact MZI consisting of a microtaper and a LPG in a section of ASPBGF is proposed. The interference is demonstrated both theoretically and experimentally to occur between the fundamental core mode and the LP₀₁ cladding supermodes. The mode-coupling mechanisms of the microtaper and LPG can be attributed to the effect of bandgap-shifting with scaling down the fiber diameter and phase-matching, respectively. Compared with previous work,^{4,6,9} this kind of MZI has advantages from compact size, relatively high extinction ratio, and low loss. By purposefully strengthening the coupling ratio of the LPG, a single resonant dip of the LPG can be retained in the interference spectrum. As this LPG dip and the interference dips respond differently to curvature and temperature, this device finds a promising application in the simultaneous measurement of curvature and temperature.

The configuration of this MZI is shown in Fig. 1. A portion of light is first coupled from the fundamental core mode to one or several cladding supermodes by the microtaper. After propagating through a certain length of fiber, the light in the cladding is partly coupled back to the core by the LPG and then interferes with the rest of the light in the core due to the difference in the effective refractive index between the core mode and the cladding supermodes.

The ASPBGF in our experiments is produced by Yangtze Optical Fiber and Cable Corporation and its cross-section is shown in the inset (a) of Fig. 2. Owing to the special design of every high-index germanium-doped rod encased in an additional index-depressed layer,¹¹ the ASPBGF has very low transmission loss and bending loss. Its diameter is about

FIG. 1. Configuration of the MZI.

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FIG. 2. Spectra of the LPG and MZIs. Inset (a) is the cross-section of the ASPBGF; (b) is the side-view of the tapered ASPBGF.

125 μm ; the pitch between adjacent rods is about 9.26 μm . The normalized radii of every high-index rod and index-depressed layer are 0.181 Λ and 0.3786 Λ , respectively. Their respective average refractive index differences are about 0.028 and -0.008 relative to that of the pure silica background.

Fabrication of the MZI is described as follows. First, a ~ 15.9 mm long ASPBGF was sandwiched between two SMFs. The transmission spectrum of the spliced ASPBGF is shown as the black curve in Fig. 2. The insertion loss is around 2 dB, including the loss induced by all connections. Second, we used a CO₂ laser to fabricate within the ASPBGF a LPG with a pitch of 160 μm and a length of 6.40 mm. The LPG fabrication setup and method are the same as that mentioned in Ref. 12. The transmission spectrum with the LPG, shown as the red curve in Fig. 2, has a resonant dip located at 1568 nm of depth of over 20 dB. Another ~ 3 dB dip at 1549.1 nm is also generated. The additional loss caused by the LPG fabrication is less than 1 dB. Finally, the CO₂ laser beam was moved about 5 mm away from the LPG to make a microtaper in the ASPBGF. The axial length of the heated region was about 500 μm . As the diameter of the focused CO₂ laser beam in our system is about 100 μm , it is very hard to ensure that the whole fiber is heated uniformly. Moreover, there is a high risk of severe loss caused by shearing stresses that become more serious for a smaller-sized laser spot.¹³ To avoid these problems, a defocused CO₂ laser was employed in the microtaper fabrication by increasing the height of the marking head of the CO₂ laser. After several scanning cycles, an obvious interference is generated near the LPG resonant dips, shown as the blue curve in Fig. 2. The insertion loss of the whole interferometer is about 6 dB, indicating that the additional loss caused by the microtaper is about 3 dB. Compared with the results mentioned in Refs. 4 and 9, the loss in the tapered ASPBGF is reduced significantly, partially benefiting from the fact that the transmission loss of the LP₀₁ cladding supermodes in the ASPBGF is very low. The extinction ratios of the dips range from 2.0 dB to 8.4 dB, which are much higher than that obtained in Ref. 6. A side view of the tapered ASPBGF is shown in the inset (b) of Fig. 2. By using a microscope, the measured diameter of the waist and the

length of the tapered region were found to be about 94.5 μm and 350 μm , respectively. The physical length L of the MZI, from the center of the LPG to the center of the taper, was about 8.96 mm. The wavelengths of the dips are about 1547.4 nm (P₁), 1556.1 nm (P₂), 1567.1 nm (P₃), 1572.3 nm (P₄), 1580.9 nm (P₅), and 1589.5 nm (P₆), respectively. The average fringe spacing is about 8.42 nm. It is noteworthy that the fringe spacing between dips P₂ and P₃ is much wider than the average fringe spacing, whereas that between P₃ and P₄ is narrower than the average. Moreover, the wavelength of dip P₃ is very close to the main resonant dip of the LPG before tapering. Therefore, dip P₃ is still the LPG resonant dip rather than the interference dip, considering that the mode coupling caused by the LPG overwhelms that of the very slight microtaper in the center region of the main LPG dip.

As a comparison, another MZI with the same configuration but a different physical length for the interferometer ($L = 23.53$ mm) was fabricated by the same fabrication process. It contained a LPG with the same pitch and length as the first MZI. To enhance the extinction ratio of the interference, we fabricated the LPG for a relatively weak resonant dip (~ 15 dB) and a sharper microtaper. The diameter of the microtaper in the second MZI was about 75.0 μm . The corresponding transmission spectrum is shown as the magenta curve in Fig. 2. As can be seen, the extinction ratio of the interference ranges from 5 dB to 14 dB, which is much higher than that of the first MZI. The average fringe spacing is about 3.66 nm. However, the transmission loss of the second MZI is greatly increased because of the excessive tapering.

To investigate the mechanisms within the MZIs more systematically, we begin with the mode coupling of the LPG. According to theory, the mode coupling in a LPG only happens for those modes that satisfy the phase-matching condition. It is helpful to identify the modes involved in the interference. Based on previous work on LPGs in ASPBGFs,^{14,15} the mode coupling often occurs between the fundamental core mode and the LP₀₁ cladding supermodes when the LPG pitch is less than 200 μm . Using the plane-wave-expansion method and the structural parameters of the original ASPBGF ($D = 125$ μm) used in our experiments, the bandgap map of the ASPBGF was calculated (Fig. 3). The first bandgap is depicted as the orange region and the LP₀₁ cladding supermode band is bounded by two black curves, which are the effective refractive indices of the lowest- (upper black curve) and highest-order (lower black curve) LP₀₁ supermodes. Meanwhile, the effective refractive index curve of the fundamental core mode was calculated using the full-vector finite-element method (red line in Fig. 3). The resonant wavelength λ_{res} of the LPG can then be deduced from $\lambda_{\text{res}} = \Delta n_{\text{eff}} \cdot \Lambda_{\text{LPG}}$, where Δn_{eff} is the effective refractive index difference between the LP₀₁ supermodes and fundamental core mode, and Λ_{LPG} is the LPG pitch. We remark that we use the effective refractive index of the highest-order LP₀₁ supermode to calculate this pitch. The main reasons are as follows: (1) the effective refractive index difference among the LP₀₁ cladding supermodes of the original ASPBGF is relatively small; (2) usually, in practical experiments, several supermodes will interact with the fundamental core mode for the same pitch. The calculated pitch of the

FIG. 3. Bandgap map, effective refractive index curve of fundamental core mode, and shifting of the LP₀₁ cladding supermode band. The inset is the LPGA pitch and the group refractive index difference against wavelength.

LPGA against wavelength is plotted as the olive line in the inset of Fig. 3. As illustrated, the theoretical resonant wavelength is around 1620 nm for a pitch of 160 μm. This agrees well with the measured resonant wavelength of 1568 nm.

Based on the calculation of the effective refractive indices of modes participating in the interference, the theoretical interference fringe spacing can be obtained

$$\Delta\lambda_c = \frac{\lambda^2}{\Delta n_g \cdot L}, \quad (1)$$

where $\Delta\lambda_c$ is the calculated fringe spacing, L is the physical length of the interferometer, and Δn_g is the group refractive index difference. Δn_g can be computed using the dispersion relations expressed in the form

$$\Delta n_g = \Delta n_{eff} - \lambda \frac{d(\Delta n_{eff})}{d\lambda}. \quad (2)$$

The calculated Δn_g is represented by the magenta line in the inset of Fig. 3 and has a value of about 0.030 around 1570 nm. Thus, the calculated fringe spacings $\Delta\lambda_c$ of the two MZIs of length 8.96 mm and 23.53 mm are about 9.17 nm and 3.49 nm, respectively. Both match the experimental results.

As for the mechanism underlying the mode coupling caused by the microtaper, this can be inferred from bandgap-shifting as the ASPBGF diameter varies. According to the scaling law for photonic crystals,¹⁶ bandgaps will shift to shorter wavelengths as fiber diameter decreases. Correspondingly, the LP₀₁ cladding supermode band shifts to shorter wavelengths as well. As illustrated in Fig. 3, the LP₀₁ cladding supermode band shifts to the region bounded by the blue lines when the fiber diameter is scaled down to 94.5 μm. Thus, the effective refractive indices of the LP₀₁ cladding supermodes are decreasing. As the diameter of the ASPBGF is scaled further down to 75.0 μm, the LP₀₁ cladding supermode band shifts to the region bounded by the green lines. Accompanying the blue-shifting of the band, the width of the LP₀₁ cladding supermode band becomes much wider in the long-wavelength region, indicating that the

effective refractive index differences among these supermodes are increasing and the effective refractive indices of the higher-order LP₀₁ supermodes decline more rapidly. For the given wavelength range in Fig. 2, it is remarkable that the effective refractive indices of some supermodes are comparable to that of the fundamental mode of the original ASPBGF, when the diameter is under 94.5 μm. Therefore, it becomes quite possible to couple light from the fundamental core mode to one or several LP₀₁ cladding supermodes by abruptly tapering the fiber diameter from 125 μm to less than 94.5 μm.

In addition, the sensing responses to curvature and temperature of the first MZI ($L = 8.96$ mm) were measured. When the curvature increases from 0 to 1.295 m⁻¹ under room temperature, dip P₃ shifts slightly to a longer wavelength, whereas all the other dips shift to shorter wavelengths in varying degrees. Dip P₃ shows the lowest curvature sensitivity of 0.1868 nm/mm⁻¹, whereas the others (P₁, P₂, P₄, and P₅) are -0.5593, -0.8340, -0.8319, and -0.9607 nm/m⁻¹, respectively. Figure 4 illustrates the curvature-sensing performance of dips P₃ and P₅. Their spectral evolutions under different curvatures are also given as insets (a) and (b). The extraordinary sensitivity of dip P₃ to curvature may be attributed to the fact that dip P₃ originates from the LPGA rather than the interference. In contrast, the MZI shows a relatively high sensitivity to temperature. All the dips undergo comparable red-shifts as temperature increases from 26.1 °C to 75.5 °C. The temperature sensitivities of dips P₃ and P₅ are about 42.6 pm/°C and 48.0 pm/°C, respectively, as shown in Fig. 5. Since both P₃ and P₅ show linear and discriminating sensitivities to curvature and temperature, the MZI can be used to measure curvature and temperature simultaneously by using the following relation:^{5,17,18}

$$\begin{aligned} \begin{bmatrix} \Delta C \\ \Delta T \end{bmatrix} &= \begin{bmatrix} S_{C,P_3} & S_{T,P_3} \\ S_{C,P_5} & S_{T,P_5} \end{bmatrix}^{-1} \begin{bmatrix} \Delta\lambda_{P_3} \\ \Delta\lambda_{P_5} \end{bmatrix} \\ &= \begin{bmatrix} 0.1868 & 0.0426 \\ -0.9607 & 0.0480 \end{bmatrix}^{-1} \begin{bmatrix} \Delta\lambda_{P_3} \\ \Delta\lambda_{P_5} \end{bmatrix}, \end{aligned} \quad (3)$$

where ΔC and ΔT are the curvature and temperature variations, S_{C,P_3} , S_{T,P_3} , S_{C,P_5} , and S_{T,P_5} are the curvature and temperature sensitivities of dips P₃ and P₅, respectively.

FIG. 4. Curvature responses of dip P₃ (red) and P₅ (black) of the first MZI. Insets (a) and (b) are the respective spectral shifts for dips P₃ and P₅ with varying curvature.

FIG. 5. Temperature responses of dip P₃ (red) and P₅ (black) of the first MZI. Insets (a) and (b) are the respective spectral shifts for dips P₃ and P₅ with varying temperatures.

In conclusion, we have reported the fabrication and mechanisms of a compact in-line Mach-Zehnder interferometer, which is constructed of an abrupt microtaper and a LPG in a section of ASPBGF. Theoretical and experimental investigations demonstrate that the fundamental core mode and the LP₀₁ cladding supermodes are involved in the interference. The mode couplings generated by the microtaper and the LPG are due to bandgap-shifting with scaling down the fiber diameter and phase-matching, respectively. Taking advantage of the low propagating loss of the LP₀₁ cladding supermodes and large effective refractive index differences between the fundamental core mode and the LP₀₁ cladding supermodes, the interferometer has specific advantages, such as compact size, relative low loss, and high extinction ratio. In addition, by using a strong coupling LPG and a slight microtaper, the main resonant dip of the LPG remains in the interference spectrum and shows different sensitivities to curvature and temperature compared with those of the interference dips. A very promising application is the simultaneous measurement of curvature and temperature.

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