A Mach-Zehnder interferometer by combining a microtaper with a long period grating in an all solid photonic bandgap fiber and its temperature sensing characteristic

Wu, Zhifang; Jiang, Meng; Liu, Yan-Ge; Wang, Zhi; Shum, Perry Ping; Dinh, Xuan Quyen

2012

Wu, Z., Jiang, M., Liu, Y. G., Wang, Z., Shum, P. P., & Dinh, X. Q. (2012). A Mach-Zehnder Interferometer by Combining a Microtaper with a Long Period Grating in an All Solid Photonic Bandgap Fiber and Its Temperature Sensing Characteristic. Proceedings of SPIE-OFS2012 22nd International Conference on Optical Fiber Sensors, 8421.

<https://hdl.handle.net/10356/79916>

<https://doi.org/10.1117/12.975192>

© 2012 Society of Photo-Optical Instrumentation Engineers (SPIE). This paper was published in Proceedings of SPIE-OFS2012 22nd International Conference on Optical Fiber Sensors and is made available as an electronic reprint (preprint) with permission of Society of Photo-Optical Instrumentation Engineers (SPIE). The paper can be found at the following official DOI: [<http://dx.doi.org/10.1117/12.975192>]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

A Mach-Zehnder Interferometer by Combining a Microtaper with a Long Period Grating in an All Solid Photonic Bandgap Fiber and Its Temperature Sensing Characteristic

Zhifang Wu^{a,b}, Meng Jiang^{b,c}, Yan-ge Liu^{*a}, Zhi Wang^a, Perry Ping Shum^{b,c}, Xuan Quyen Dinh^{c,d}

^a Key laboratory of Optical Information Science and Technology, Ministry of Education, Institute of Modern Optics, Nankai University, Tianjin 300071, China

^b OPTIMUS, School of Electrical and Electronics Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 637553

^c CINTRA CNRS/NTU/THALES, UMI 3288, Research Techno Plaza, 50 Nanyang Drive, Border X Block, Level 6, Singapore 637553

^d Thales Solutions Asia Pte Ltd, R&T Department, 28 Changi North Rise, Singapore 498755

ABSTRACT

We demonstrate a new type of Mach-Zehnder interferometer by combining a nonadiabatic microtaper with a long period grating in the same stage of all solid photonic bandgap fibers. Meanwhile, the mode-coupling caused by the microtaper is indirectly verified by the interference with the long period grating, which is designed for the resonance between the fundamental core mode and LP₀₁ cladding supermodes. Finally, the temperature response is also reported.

Keywords: taper, long period grating, photonic bandgap fiber, Mach-Zehnder interferometer

1. INTRODUCTION

Most of in-line Mach-Zehnder interferometers (MZIs) have been reported by using core-offset [1], long period grating (LPG) pair [2], single taper [3], two tapers [4], and so on. They are widely applied to fabricate sensors, filters and other devices. O. Frazão *et al.* has demonstrated a MZI by combining a LPG with a fused taper in single mode fibers (SMF) [5], and the extinction ratio of their MZI is no more than 1 dB. However, the MZI based on the combination of a taper and a LPG in photonic crystal fibers (PCFs) is still not reported. One of main challenges for this type of MZI is that LPGs are only effective for the coupling between particular modes but the taper is not in most cases. It is hard to generate the exact mode-coupling that matches the resonant condition for LPGs through tapering.

On the other hand, a lot of attention has been attracted to taper PCFs for functional devices. So far, most of these devices are based on index-guiding PCFs, while very few work concerned on tapered photonic bandgap fibers (PBGFs) are reported. Different from index-guiding PCFs, low-loss bands of PBGFs are highly sensitive to tapering [6]. In Ref [7], Aydogan Ozcan *et al.* demonstrate that the loss of core mode will exceed 10 dB if the taper ratio, defined by $(D_i - D_w)/D_i$ (where D_i is the initial diameter of the fiber and D_w is the diameter of the waist of taper), is over ~12% for air-core PBGFs. A MZI based on two slight tapers in air-core PBGFs is proposed by Jian Ju [4]. However, it is still suffering from high loss caused by tapers.

In this paper, we demonstrate a new type of MZI that consists of a microtaper and a LPG in a length of ~15.9 mm all solid photonic bandgap fiber (ASPBGF). The microtaper with the length of ~350 μm and the taper ratio of ~24% is fabricated by using ordinary CO₂ laser irradiation. And the loss induced by the microtaper is about 3 dB, which is much smaller than those of air-core PBGFs reported in Ref [4-7]. Moreover, the mode-coupling caused by the microtaper is indirectly verified by the interference with the LPG, whose pitch is designed for the resonance between the fundamental core mode and LP₀₁ cladding supermodes [8]. Finally, the temperature response of our MZI is also presented.

* ygliu@nankai.edu.cn; phone 86 22 23509849

2. CONFIGURATION AND FABRICATION

2.1 Configuration and Principle

The configuration of this MZI is shown in Figure 1. It consists of a microtaper and a LPG in the same stage ASPBGF, which is sandwiched between two SMFs.

Figure 1. The configuration of the MZI

For photonic bandgap fibers, the low-loss transmission bands depend closely on the scale of the structure [6]. And the bands will shift to the shorter wavelength as the diameter of PBGFs is decreased. If a part of PBGF is tapered, the low-loss band of the whole fiber is determined by the intersection of all parts of fiber with different diameters. In another word, these bands will be shrunk with the decreasing of the diameter, resulting in the mode-coupling from the core mode to one or several of cladding modes. For the ASPBGF, the LP_{01} supermode band is adjacent to the long-wavelength edge of the band I. Therefore, the fundamental core mode is most likely coupled into one or some of the LP_{01} supermodes when the ASPBGF is slightly tapered. Since the LP_{01} supermodes are the guided modes of the ASPBGF, the propagating loss of these modes is quite low. And then, partial light will be recoupled from the LP_{01} supermodes to the fundamental core mode when it propagates through a LPG with a special design pitch. Finally, the recoupled light will interfere with the other part of light that keeps transmitting in the core.

2.2 Fabrication

The ASPBGF in our experiments is fabricated by Yangtze Optical Fiber and Cable Corporation and its cross-section is shown in Figure 2(a). Thanks to the special design of a high-index germanium-doped rod surrounded by an additional index-depressed layer [9], it has very low transmission loss and bending loss. The diameter of the outer cladding and the core are respectively $125\ \mu\text{m}$ and $9.3\ \mu\text{m}$. The pitch between adjacent rods Λ is about $9.26\ \mu\text{m}$. The normalized radii of the high-index rod and the index-depressed layer are respectively 0.189Λ and 0.3786Λ . The average refractive index differences of the high-index rod and the index-depressed layer are respectively 0.0278 and -0.008 .

Figure 2. (a) The cross-section of the ASPBGF; (b) The spectra of different stages of the fabrication

Firstly, a length of $\sim 15.9\ \text{mm}$ ASPBGF is sandwiched between two SMFs. To minimize the coupling loss and the intermodal interferences, the alignment of the cores of the ASPBGF and SMFs is adjust as accurately as possible. The transmission spectrum of the spliced ASPBGF is shown as the black curve in Figure 3(b). As can be seen, the insertion loss is only around 2 dB, including the loss induced by connections.

Since the resonance caused by LPG only happens at a particular wavelength range, we choose that the microtaper fabrication is preceded by the LPG inscription to track the formation of the MZI more conveniently. We use the similar setup and method (mentioned in Ref [10]) to fabricate a LPG with the pitch of $160\ \mu\text{m}$ and the length of $6.4\ \text{mm}$ in the

ASPBGF. As demonstrated in Ref [8], this pitch is corresponding to the mode-coupling between the fundamental core mode and LP_{01} supermodes in ASPBGFs. A LPG with a ~ 20 dB resonant dip located at 1567 nm, as shown as the red curve in Figure 3(b), is fabricated after several scanning cycles of CO_2 laser irradiation. Another ~ 3 dB dip at 1549.1 nm is also generated as an accompaniment. The additional loss caused by the LPG fabrication is less than 0.5 dB, even when the outer cladding of the ASPBGF is seriously ablated on one side by CO_2 laser irradiation.

Then, the CO_2 laser beam is moved ~ 5 mm away from the LPG to make a microtaper in ASPBGF. The heating region is about 500 μm . Since the diameter of focused CO_2 laser beam in our system is about 100 μm , it is very hard to ensure that the whole fiber is heated uniformly. Moreover, it is also at high risk of severe loss caused by shearing stresses, which are more serious for smaller size of the laser spot. In order to avoid these problems, a defocused CO_2 laser is employed to the microtaper fabrication by increasing the height of the marking head of CO_2 laser. After several scanning cycles, an obvious interference is generated near the resonant dips, as shown as the blue curve in Figure 3(b). The insertion loss of the whole interferometer is about 5 dB. And the additional loss caused by the microtaper is about 3 dB. The extinction ratios are from 2 dB to 8.4 dB, which are much bigger than that in Ref [5].

Figure 3 The side view of the tapered ASPBGF

The tapered ASPBGF, as shown in Figure 3, is measured by a microscopy. The diameter of the waist is about 95 μm and the length of the tapered region is about 350 μm . The dimensions of other sections are marked in Figure 1.

3. SENSING CHARACTERISTICS

The temperature response of the interferometer is measured by monitoring the shift of the dips P1~P6.

Figure 4. Temperature response of the MZI

As shown in Figure 4, all the dips undergo a similar red-shift with increasing temperature from room temperature to 75.5 $^{\circ}C$. And the sensitivities of these dips are respectively 38.54 pm/ $^{\circ}C$, 38.42 pm/ $^{\circ}C$, 40.27 pm/ $^{\circ}C$, 33.91 pm/ $^{\circ}C$, 48.52 pm/ $^{\circ}C$ and 55.76 pm/ $^{\circ}C$. They are comparable with the performance of the LPG in ASPBGFs as reported in Ref [8]. Moreover, in general, the dips at the longer wavelength are more sensitive to temperature.

For a modal interferometer, its temperature sensitivity of the interference fringe can be approximately expressed by [11]

$$\frac{d\lambda_i}{dT} \approx \lambda_i \left(\frac{1}{\Delta n_{eff}} \frac{\partial \Delta n_{eff}}{\partial T} + \alpha_T \right) \quad (1)$$

where λ_f is the interference fringe wavelength, Δn_{eff} is the effective refractive index difference between the modes involved in the interference, α_T is the thermal expansion coefficient, which is independent of the wavelength. Since Δn_{eff} between the fundamental core mode and LP₀₁ cladding supermodes of the ASPBGF decreases monotonically when the wavelength increases, the temperature sensitivity of the interference fringe will rise with the increase of wavelength. This tendency basically agrees with the experimental results.

4. CONCLUSIONS

A new type of MZI is presented by integrating the slight taper and the LPG in the same stage of ASPBGF. The bandgap shifting caused by tapering and the LPG resonance are simultaneously employed to achieve the same mode-coupling between the fundamental mode and LP₀₁ cladding supermodes. Comparing with the previous works about interferometers based on tapered PBGFs, this MZI has some merits, such as low insertion loss, relatively high extinction ratio, and so on. And it also shows potential application in temperature sensing.

ACKNOWLEDGMENTS

This work was supported by the National Key Basic Research and Development Program of China under grant 2010CB327605, the National Natural Science Foundation of China under grants 11174154 and 11174155, the Tianjin Natural Science Foundation under Grant No. 12JCZDJC20600, Program for New Century Excellent Talents in University (NCET-09-0483).

REFERENCES

- [1] Dong, B., Zhou, D., Wei, L., Liu, W., and Lit, J. W. Y., "Temperature- and phase-independent lateral force sensor based on a core-offset multimode fiber interferometer," *Optics Express* **16**(23), 19291-19296 (2008).
- [2] Lim, J. H., Jang, H. S., Lee, K. S., Kim, J. C., and Lee, B. H., "Mach-Zehnder interferometer formed in a photonic crystal fiber based on a pair of long-period fiber gratings," *Optics Letters* **29**(4), 346-348 (2004).
- [3] Minkovich, V., Villatoro, J., Monzón-Hernández, D., Calixto, S., Sotsky, A., and Sotskaya, L., "Holey fiber tapers with resonance transmission for high-resolution refractive index sensing," *Optics Express* **13**(19), 7609-7614 (2005).
- [4] Ju, J., Ma, L., Jin, W., and Hu, Y., "Photonic bandgap fiber tapers and in-fiber interferometric sensors," *Optics Letters* **34**(12), 1861-1863 (2009).
- [5] Frazão, O., Falate, R., Fabris, J. L., Santos, J. L., Ferreira, L. A., and Araújo, F. M., "Optical inclinometer based on a single long-period fiber grating combined with a fused taper," *Optics Letters* **31**(20), 2960-2962 (2006).
- [6] Birks, T. A., "Photonic crystal fibre tapers and devices," presented at the Lasers and Electro-Optics, 2007. CLEO 2007. Conference on, 2007.
- [7] Ozcan, A., Tewary, A., Digonnet, M. J. F., and Kino, G. S., "Observation of mode coupling in bitapered air-core photonic bandgap fibers," *Optics Communications* **271**(2), 391-395 (2007).
- [8] Tai, B., Wang, Z., Liu, Y., Xu, J., Liu, B., Wei, H., and Tong, W., "High order resonances between core mode and cladding supermodes in long period fiber gratings inscribed in photonic bandgap fibers," *Optics Express* **18**(15), 15361-15370 (2010).
- [9] Guobin, R., Ping, S., Liren, Z., Xia, Y., Weijun, T., and Jie, L., "Low-loss all-solid photonic bandgap fiber," *Optics Letters* **32**(9)(2007).
- [10] Wu, Z., Wang, Z., Liu, Y., Han, T., Li, S., and Wei, H., "Mechanism and characteristics of long period fiber gratings in simplified hollow-core photonic crystal fibers," *Optics Express* **19**(18), 17344-17349 (2011).
- [11] Geng, Y., Li, X., Tan, X., Deng, Y., and Yu, Y., "Sensitivity-enhanced high-temperature sensing using all-solid photonic bandgap fiber modal interference," *Applied Optics* **50**(4), 468-472 (2011).