

Simultaneous measurement of strain and temperature by employing fiber Mach-Zehnder interferometer

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Abstract: We demonstrated a novel fiber in-line Mach-Zehnder interferometer (MZI) with a large fringe visibility of up to 17 dB, which was fabricated by misaligned splicing a short section of thin core fiber between two sections of standard single-mode fiber. Such a MZI could be used to realize simultaneous measurement of tensile strain and temperature. Tensile strain was measured with an ultrahigh sensitivity of -0.023 dB/ $\mu\epsilon$ via the intensity modulation of interference fringes, and temperature was measured with a high sensitivity of 51 pm/ $^{\circ}\text{C}$ via the wavelength modulation of interference fringe. That is, the MZI-based sensor overcomes the cross-sensitivity problem between tensile strain and temperature by means of different demodulation methods. Moreover, this proposed sensor exhibits the advantages of low-cost, extremely simple structure, compact size (only about 10 mm), and good repeatability.

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1. Introduction

Optical fiber sensors based on Mach-Zehnder interferometers (MZI) have attracted great research interests and been widely used to monitor the health of smart engineering structures due to their unique advantages of compact size, low cost, high sensitivity, and immunity to electromagnetic interference [1–4]. So far, a few types of fiber MZI configurations have been demonstrated via long period fiber gratings (LPGs) [5,6], microfiber-based structures [7,8], photonic crystal fibers (PCFs) [9–11], and air-hole formed by femtosecond laser [12]. Besides these structure of costly fiber and complex technology, some low-cost MZI based on single-mode fiber were presented such as single-mode-multimode-single-mode (SMS) fiber structure [13, 14], mode field mismatch fusion [15], two core offset structure [16], fiber waist-deformed fiber taper [17], peanut-shape structure [18]. These configurations exhibit good performance in the applications of sensing temperature, strain and surrounding refractive index. However, the cross sensitivity between strain, RI and temperature is one of the most serious problem, resulting in poor measurement precision, of these MZI-based sensors [19–21].

In this paper, we demonstrated a novel fiber in-line MZI which was fabricated by splicing a section of thin core fiber (TCF) between two sections of standard single-mode fibers (SMFs) with one misaligned spliced joint. Such a MZI can be used to develop a promising smart sensor for realizing simultaneous measurement of strain and temperature and overcoming their cross-sensitivity problem. This MZI-based sensor exhibits show an ultrahigh strain sensitivity of $-0.023 \text{ dB}/\mu\epsilon$ (one order higher than that, e.g. $-0.0032 \text{ dB}/\mu\epsilon$, reported in references [22, 23]) and a high temperature sensitivity of up to $51 \text{ pm}/^\circ\text{C}$.

2. Basic principle of the MZI

Figure 1 illustrates a 3-D schematic diagram of the proposed fiber in-line MZI structure, in which a section of TCF is spliced between two sections of standard SMFs, i.e. so-called the lead-in SMF and the lead-out SMF. A core offset is created at the spliced joint between the lead-in SMF and the TCF. At the spliced joint with a core offset, light propagating in the lead-in SMF core is divided into two parts: a fraction of light will propagate into the core of the TCF as a core mode and majority of light will propagate into the cladding of the TCF as a cladding mode. After propagating through the TCF, the two parts of light will meet and recombine in the lead-out SMF, resulting in an interference pattern depending on the difference between the distances they travel.

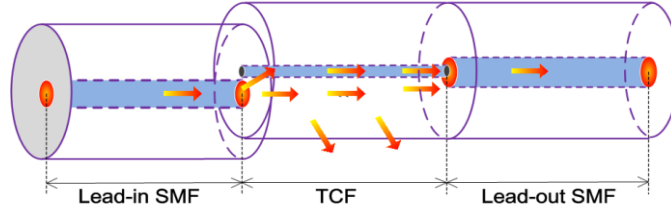


Fig. 1. Schematic diagram of the proposed fiber in-line MZI and the propagating light distribution in this structure.

Assuming that the amplitude of electrical field launched into the lead-in SMF is E_0 , the output intensity of the MZI could be expressed as [24]:

$$I_{out} = (E_0\gamma\beta)^2 + [E_0(1-\gamma)]^2 + 2E_0^2\gamma(1-\gamma)\beta\cos\varphi \quad (1)$$

where γ is the ratio of light emitted into the core and the cladding of the TCF at the lead-in spliced joint, β is the propagation loss of the cladding modes because of the propagating condition of the TCF cladding, and φ is the phase difference between the two modes. The visibility of fringe pattern can be given as:

$$V = 2\beta(\beta^2 \frac{\gamma}{1-\gamma} + \frac{1-\gamma}{\gamma})^{-1} \quad (2)$$

It can be easily found from Eq. (2) that the fringe visibility is critically determined by the splitting ratio γ , which can be carefully adjusted by changing the value of the core offset at the left spliced joint.

The accumulated phase difference φ between the two modes can be approximated as:

$$\varphi = \frac{2\pi \cdot \Delta n_{eff} \cdot L}{\lambda} \quad (3)$$

where Δn_{eff} is effective refractive index difference between the core mode and the cladding mode in the TCF, L is the length of the TCF and λ is the wavelength of light in vacuum. When the phase term satisfies the condition: $\varphi = (2k+1)\pi$, where k is the order of the modes, an intensity dip appears at the wavelength:

$$\lambda_{dip} = \frac{2\Delta n_{eff} \cdot L}{2m+1} \quad (4)$$

Equations (1) and (4) indicate that the length increase of the TCF will only shift linearly the wavelength of fringe dips but not impact the fringe visibility. And the shift of fringe dips can be impacted by the MZI length and the effective refractive index difference between the core and the cladding. Thus the strain-induced shift of fringe dips can be expressed as [15]:

$$\delta\lambda_{dip,\varepsilon} = \frac{2(\Delta n_{eff,\varepsilon} - \delta n_{eff,\varepsilon})(L + \delta L)}{2m+1} - \frac{2\Delta n_{eff,\varepsilon} \cdot L}{2m+1} \approx 2 \frac{\Delta n_{eff,\varepsilon} \cdot \delta L - \delta n_{eff,\varepsilon} \cdot L}{2m+1} \quad (5)$$

where $\Delta n_{eff,\varepsilon}$ is effective refractive index difference between the core more and the cladding mode at the tensile strain of ε , $\delta n_{eff,\varepsilon}$ is the strain-induced change of $\Delta n_{eff,\varepsilon}$ and δL is the strain-induced change of the TCF length.

And the temperature-induced shift of fringe dips can be expressed as [17]:

$$\delta\lambda_{dip,T} = \frac{2(\Delta n_{eff,T} + \delta n_{eff,T})L}{2m+1} - \frac{2\Delta n_{eff,T} \cdot L}{2m+1} = \frac{2\delta n_{eff,T} \cdot L}{2m+1} \quad (6)$$

where $\Delta n_{\text{eff},T}$ is effective refractive index difference between the core and the cladding modes at the temperature of T , $\delta n_{\text{eff},T}$ is the temperature-induced change of $\Delta n_{\text{eff},T}$.

3. Fabrication and experiments of MZI

3.1 Fabrication of MZI

As we can see in Fig. 2, a standard SMF (Corning SMF-28) with a core diameter of about $8\ \mu\text{m}$ and a TCF (Nufern UHNA-3) with a core diameter about $4\ \mu\text{m}$ were employed in our experiments. As shown in Fig. 2(a), a section of TCF was spliced between two sections of SMFs. And a core offset was created at the spliced joint between the lead-in SMF and the TCF. Figures 2(b) and 2(c) show microscope images of the two spliced joints with/without a core offset, respectively.

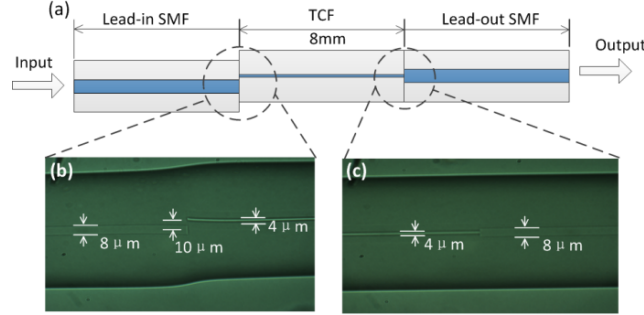


Fig. 2. (a) Fiber in-line MZI structure; Optical microscope image of (b) the lead-in spliced joints with a core offset and (c) the lead-out spliced joints without a core offset.

Fabrication process of the MZI structure is described as follow. Firstly, a section of TCF (Nufern UHNA-3) with a length of 8 mm was spliced with a standard SMF (Corning SMF-28), i.e. the lead-out SMF, without a core offset by use of a commercial splicer (Fujikura FSM-60s), as illustrated in Fig. 2(c). Secondly, another end of the TCF and the end of another standard SMF (Corning SMF-28), i.e. the lead-in SMF, were fixed via the left and right fiber holders, respectively, in the splicer. Meanwhile, a broadband light source and an optical spectrum analyzer were connected with the lead-in and lead-out SMFs, respectively, to monitor interference spectrum. The core offset between the lead-in SMF and the TCF was carefully adjusted via the hand mode of the splicer until good fringe visibility was observed.

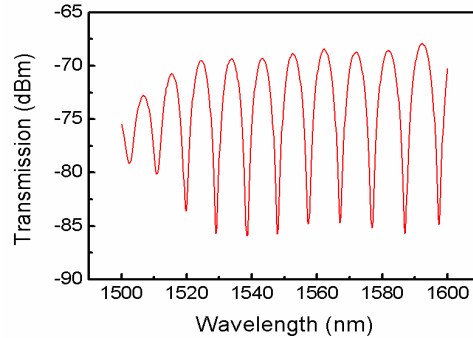


Fig. 3. Interference fringe pattern of the achieved MZI with a core offset of about $10\ \mu\text{m}$.

Consequently, a lead-in spliced joint with a core offset of about $10\ \mu\text{m}$ was created, as illustrated in Fig. 2(b), where the core of TCF was curved upward slightly caused by more splice overlap induced. So an in-fiber MZI with a core offset was successfully achieved and a good fringe pattern with a visibility of up to 17dB near the wavelength of 1550 nm was observed, as shown in Fig. 3.

3.2 Strain response

To investigate the response of the MZI structure to tensile strain, the lead-in SMF of the structure was fixed, and the lead-out SMF was stretched along the fiber axis to induce a tensile strain from 0 to 1500 $\mu\epsilon$ by use of a translation stage with a resolution of 10 μm . The length of the stretched fibers, including the lead-in and lead-out SMFs and the TCF, is 200 mm. Typical interference fringe patterns of the MZI with different tensile strains are illustrated in Fig. 4(a), where the tensile strain increases from 0 to 500 $\mu\epsilon$ with a step of 50 $\mu\epsilon$ and from 500 to 1500 $\mu\epsilon$ with a step of 200 $\mu\epsilon$.

As shown in Fig. 4(a), the dip wavelength hardly changed with an increased tensile strain from 0 to 500 $\mu\epsilon$, but the fringe visibility was enhanced. In contrast, while the tensile strain was increased beyond 500 $\mu\epsilon$, the fringe visibility hardly changed but the interference fringe exhibited a blue shift.

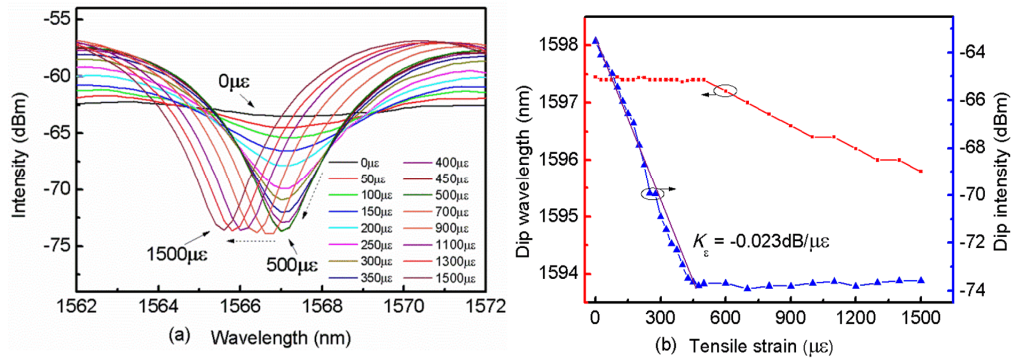


Fig. 4. (a) Interference fringe patterns of the MZI with different strain; (b) Dip wavelength and intensity versus tensile strain.

As shown in Fig. 4(b), the minimum intensity of interference fringe, i.e. dip intensity, linearly decreased with an ultrahigh sensitivity of $-0.023 \text{ dB}/\mu\epsilon$ while the applied tensile strain was increased from 0 to 500 $\mu\epsilon$, but the dip wavelength hardly changed. To the best of our knowledge, this strain sensitivity is about one order of magnitude higher than that reported in references [22, 23], in which a highly birefringent photonic crystal fiber loop mirror was employed to achieve a strain sensor with a sensitivity of $-0.0032 \text{ dB}/\mu\epsilon$. In contrast, the dip wavelength linearly shifted toward a shorter wavelength with an increased tensile strain of beyond 500 $\mu\epsilon$, but the change of the dip intensity was negligible. Furthermore, the above strain experiment of the MZI sample were done five times, and good repeatability was achieved owe to the simple and compact MZI structure, the strong strength of the lead-in spliced joint, and the power stability of the broadband light source employed.

In case the tensile strain was less than 500 $\mu\epsilon$, the applied tensile strain induced a significant physical deformation, i.e. the change of the core offset between the lead-in SMF and the TCF and the slightly curved core of TCF at the misalignment-spliced region, which changed the ratio, γ , of light emitted into the core and the cladding of the TCF. According to Eq. (1), the fringe visibility was effectively modulated with a strain sensitivity of $-0.023 \text{ dB}/\mu\epsilon$, as a result. In case the tensile strain was increased over a threshold of 500 $\mu\epsilon$, further physical deformation induced by the increased tensile strain at the misalignment-spliced joint is very weak due to the limit of the core offset so that the splitting ratio of light was hardly affected. And the increased tensile strain mainly resulted in an extension of the MZI cavity length. Hence, the dip intensity was insensitive to the applied strain of more than 500, whereas the dip wavelength shifted toward a shorter wavelength, as shown in Fig. 4(b). The threshold of the tensile strain depends strongly on the fabrication parameters such as the type of the fiber employed, the core offset, the fiber overlap at the splicing joint, and arc discharge parameters. Our experiments shows that, providing the fabrication parameters are not

changed, a few MZI samples has a similar strain threshold of about $500\mu\epsilon$. In other words, a repeatable results could be achieved for different MZI samples created by use of the same fabrication parameters. According to Eq. (5), the reason of above is that, the increase of the MZI cavity length, $\Delta n_{eff,\epsilon} \cdot \delta L$, has a weaker impact on the dip wavelength than the decrease of the effective refractive index difference, $-\delta n_{eff,\epsilon} \cdot L$, so that the dip wavelength ‘blue’ shifts while the tensile strain increases over $500\mu\epsilon$ [15].

3.3 Temperature response

Temperature response of the MZI was also investigated by means of placing it into a tube furnace with a temperature range from room temperature to 100°C (with a stability of $\pm 0.2^\circ\text{C}$). If the extinction ratio of the measured interference dip is not enough large, the measurement precision of the dip wavelength is very poor. So another interference dip with a large extinction ratio at the wavelength of 1538.36 nm was measured to investigate the temperature response of the dip wavelength. Temperature in the furnace rose gradually from 30 to 100°C with a step of 10°C , and then maintained about 30 min during each temperature rise.

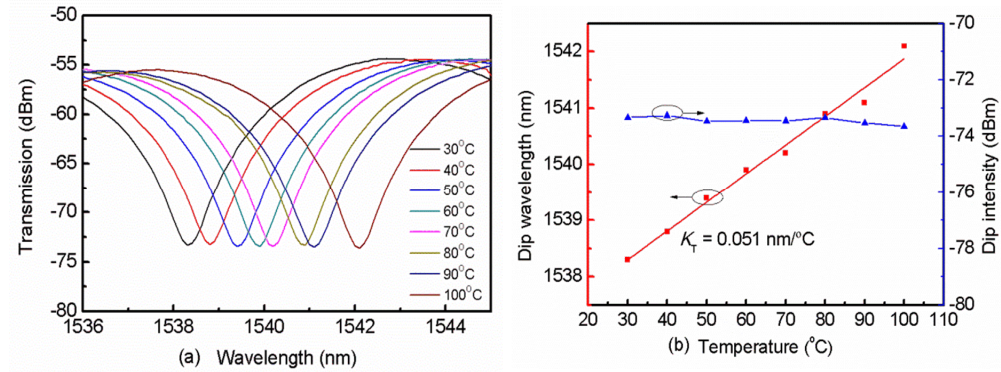


Fig. 5. (a) Interference fringe of the MZI with different temperature; (b) Dip wavelength and dip intensity versus temperature.

As shown in Fig. 5(a), interference fringes of the MZI shifted toward a longer wavelength with temperature rise. It can be easily found from Fig. 5(b) that the dip wavelength of the MZI ‘red’ shifted linearly with a sensitivity of $51\text{ pm}/^\circ\text{C}$, but the dip intensity hardly changed. Temperature-induced ‘red’ shift of the dip wavelength could be explained below. Since thermo-optic coefficient of the Ge-doped silica core is higher than that of the cladding consisting of fused silica [17], effective refractive index difference between the core and the cladding modes will increase with temperature rise. Consequently, according to Eq. (6), the dip wavelength shifts toward a longer wavelength due to the temperature-induced of $\delta n_{eff,T}$ while environmental temperature rises.

4. Discussions

Owing to the induced core offset between the lead-in SMF and the TCF and the slightly curved core of TCF at the misalignment-spliced region, the increase of tensile strain would change the splitting ratio, which result in the change of fringe visibility. And owing to the induced core offset, the cladding mode propagating in the cladding of TCF would be change by temperature, which result in wavelength shift of fringe dip.

According to Figs. 4(b) and 5(b), the dip intensity of the MZI decreases linearly with the increase of tensile strain within $500\mu\epsilon$ and is insensitive to temperature rise. In contrast, the dip wavelength of the MZI shifts linearly toward a longer wavelength with temperature rise and is insensitive to a tensile strain of less than $500\mu\epsilon$. Hence, the MZI can be used to

develop a promising sensor that can measure simultaneously tensile strain and temperature, which is an excellent advantage of overcoming the cross-sensitivity problem between tensile strain and temperature in practical sensing applications of smart engineering structures. In other words, tensile strain can be measured via intensity modulation of interference fringe with a high sensitivity of $-0.023 \text{ dB}/\mu\epsilon$ and a measurement range of up to $500 \mu\epsilon$. And temperature can be measured via wavelength modulation of interference fringe with a very high sensitivity of $51 \text{ pm}/^\circ\text{C}$. Therefore, our MZI-based sensor can realize simultaneous measurement of tensile strain and temperature.

It can be found from Figs. 4(b) and 5(b) that the fluctuation of the dip wavelength is less than 0.04 nm while tensile strain is less than $500 \mu\epsilon$ and the fluctuation of the dip intensity is less than 0.028 dBm during temperature rise. As a result, the strain-caused error of the dip wavelength and the temperature-caused error of the dip intensity are less than 0.8°C and less than $1.2 \mu\epsilon$, respectively, during simultaneous measurement of tensile strain and temperature, which can meet the sensing applications in smart engineering structures.

5. Conclusion

In conclusion, a novel fiber in-line MZI with a misalignment-spliced joint was demonstrated to develop a promising sensor that can realize simultaneous measurement of tensile strain and temperature. The strain and temperature sensitivities of the proposed sensor are $-0.023 \text{ dB}/\mu\epsilon$ and $51 \text{ pm}/^\circ\text{C}$, respectively. Such a sensor overcomes the cross-sensitivity problem between tensile strain and temperature. Furthermore, our MZI-based sensor exhibits the merits of compact size (only about 8 mm), high sensitivities, intensity-modulated for strain, good repeatability and mechanical reliability so that it is a good candidate of next-generation sensors in smart engineering structures.

Acknowledgments

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