Communication

Fiber-Optic Axial-Strain Sensor with Sensitivity Enhancement and Temperature Compensation

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Abstract: In this paper, we report a tapered thin-core fiber based in-line Mach-Zehnder interferometer to improve the response of axial-strain. With the varied diameters of taper waist, the light field distributions are studied by beam propagation method, and the structures are fabricated by arc-discharged lateral offset splicing and tapering techniques. The comprehensive tests are then conducted and compared in terms of axial-strain and temperature. The experimental results show that, by reducing the diameter of taper waist, more than 400% enhancement of wavelength sensitivity can be gained, and the maximum reaches 4.07 pm/με with the measured error of 3.6%. Moreover, owing to high consistency of temperature response, the near-zero crosstalk is presented by differential compensation method. Furthermore, owing to the merit of high repeatability and stability, our sensor is very practical and promising in the high-precision measurement and engineering monitoring.

Keywords: fiber-optic sensor; axial-strain; thin-core fiber; taper; crosstalk

1. Introduction

Fiber-optic axial-strain sensors have been widely used in precision measurement, aerospace engineering and structural health monitoring of buildings, owing to their compactness, light weight, anti-electromagnetic interference, and good repeatability [1–4]. Typically, the wavelength response is merely ~1 pm/με for a silica fiber-based strain sensor, such as fiber Bragg gratings (FBGs) [5,6], long period fiber gratings (LPGs) [7,8], photonic crystal fibers (PCFs) [9,10], and model interferometers (MIs) [11–13]. According to the theory of Young’s modulus, the smaller cross-sectional area of the fiber can bring an enlarged axial strain [14–16]. Aiming to improve sensitivity, the schemes based on a reduced diameter of fiber have been frequently proposed and investigated, which is fabricated by etching, polishing, arc-discharge, flame and laser machining [17–20]. Wherein, the techniques of flame brush and arc-discharge were widely used in the fabrication of taper fiber due to the merits of timesaving, cost-efficiency and ease of operation [21–24]. Zhang et al. proved that the precise wavelength sensitivity of strain can be gained by accurately controlling the diameter of microfiber [25]. In addition, an ultra-high sensitivity of ~83 pm/με was demonstrated in a microfiber coupler-based scheme with the diameter of ~2.5 μm [26]. Nevertheless, the practicality is heavily constrained by the <0.2 μm tolerance error of fabrication.

Comparatively, the arc-discharged tapering technique has higher stability and repeatability of fabrication, although the diameter of taper is usually not smaller than 30 μm [27]. The tapered schemes based on multimode fiber (MMF), PCF and twin-core fiber had been studied and the ~6 pm/με sensitivity can be gained in the range of 0–400 με [28–30]. More recently, Liu et al. sandwiched a tapered SMF into the open-cavity and over ~45 pm/με sensitivity is presented, but merely in the range of 0–110 με [31]. To improve prac-
ticality, it is necessary to acquire the trade-off between the sensitivity and linear measurement range. Furthermore, it is worth noting that the temperature-induced error usually lowers the accuracy measurement. To alleviate this error, FBGs have been frequently used to monitor the variation of ambient temperature [32–34]. Moreover, the schemes based on intensity modulation and difference compensation were also investigated to eliminate the effect of temperature crosstalk [35–37].

In this paper, an in-line Mach-Zehnder interferometer based on the tapered thin-core fiber (t-TCF) structure is proposed to improve the response of axial strain. With varied diameters of taper waist, the light field distributions of t-TCF are studied and the comprehensive tests are conducted. The results show the reduced diameter of taper waist obviously enhances the wavelength sensitivity of axial-strain, and the maximum reaches 4.07 pm/με, with low measured error and high repeatability. Moreover, the proposed scheme presents high consistency of temperature response and the near-zero crosstalk is obtained by differential compensation.

2. Principle

The schematic of t-TCF structure is illustrated in Figure 1, which mainly consists of the lead-in/lead-out single-mode fibers (SMF) and a piece of tapered TCF, connected by the lateral offset (denoted by a) splicing technique. Therefore, the incident light from lead-in SMF is split at the offset point and transmits along the core and the cladding of TCF, respectively. Owing to the difference of refractive index (RI) between the fiber core and fiber cladding, the optical path difference occurs and a Mach-Zehnder interference will be formed when the two beams arrive at the lead-out SMF.

![Schematic diagram of t-TCF structure. (a) Cross-sectional view (b) side-view.](Image)

According to the principle of dual-beam interference, the intensity of in-line MZI can be expressed as [35],

\[
I = I_{co} + I_{cl} + 2\sqrt{I_{co}I_{cl}}\cos\Delta\phi,
\]

where \(I_{co}\) and \(I_{cl}\) are the light intensities of the core and cladding of TCF, respectively. \(\Delta\phi = 2\pi\Delta n_{eff}L_{TCF}/\lambda\) is the phase difference between the modes of cladding and core, and where \(\lambda\) is the wavelength of incident light, \(L_{TCF}\) is the length of TCF, and \(\Delta n_{eff} = n_{co} - n_{cl}\) is the difference in effective RI between the core and the cladding. When \(\Delta\phi = (2m+1)\pi\) \((m = 0, 1, 2, 3...\), the resonance wavelength can be written by,

\[
\lambda_m = \frac{2\Delta n_{eff}L_{TCF}}{2m+1},
\]

The free spectral range (FSR) can be expressed as,

\[
FSR = \lambda_m - \lambda_{m-1} = \frac{\lambda_m^2}{\Delta n_{eff}L_{TCF}}
\]

It is known that both \(L_{TCF}\) and \(\Delta n_{eff}\) will be changed when the axial strain is applied, which surely brings a phase difference and the shift of fringes. Assume that the total length of fiber is \(L_s\) and equal to the sum of \(L_{TCF}\) and the length of SMF (denoted by \(L_{SMF}\)), and \(\Delta L_s\) is the change of \(L_s\), the wavelength shift caused by axial strain can be written as

\[
\Delta\lambda_s = (1 + \rho_s)\lambda_m S,
\]
where \( P_b = (L_3/\Delta n_{d0})\partial(\Delta n_{d0})/\partial L_3 \) is the elastic optical coefficient, \( S = \Delta L_3/L_3 \) is the applied strain. From [31], the strain applied to a silica fiber is unevenly and directly negatively proportional to the diameter of fiber. Thus, the applied axial-strain of the \( t \)-TCF structure can be approximately written as,

\[
S_{t-TCF} = \frac{L_3}{L_{t-TCF} + L_{SMF}d^2/D^2} S,
\]

where \( d \) is the diameter of taper waist and \( D \) is the diameter of SMF. Next, for the \( t \)-TCF structure, Equation (4) is changed as,

\[
\Delta \lambda_{S,t-TCF} = (1 + P_b) \left( \frac{L_3}{L_{t-TCF} + L_{SMF}d^2/D^2} \right) \lambda_m S,
\]

Clearly, Equation (6) indicates the smaller \( d \) can bring the larger axial-strain response, but maybe with the price of a worsened mechanical strength. In addition, according to the principle of evanescent wave, this reduced diameter of taper will lead an energy loss of cladding mode in taper area. From [25], the normalized extinction ratio (ER) of fringes can be written as,

\[
ER = \frac{2\sqrt{\lambda_m c_0}}{L_{t-TCF} + L_{SMF}},
\]

Therefore, the reduced \( L_3 \) may bring a significant intensity variation. Furthermore, with the variation of the ambient temperature, the transmission spectrum is also changed, and the corresponding wavelength sensitivity can be expressed by,

\[
\frac{\Delta \lambda}{\Delta T} = \lambda \left( \gamma + \frac{k_{oa} n_{oa} - k_{od} n_{od}}{n_{oa} - n_{od}} \right),
\]

where \( \gamma \) is the thermal expansion coefficient of fiber, \( k_{oa} \) and \( k_{od} \) are the effective thermal-optical coefficients of core and cladding, respectively, and \( \Delta T \) is the varied ambient temperature. Clearly, because \( n_{oa} > n_{od} \), the transmission spectrum will be red-shifted with the rise of temperature. During the test of axial-strain, such wavelength shift resulted from the possible temperature variation must lead the obvious measure error.

3. Simulation and Fabrication

In order to optimize the parameters of fabrication, the light field distribution of \( t \)-TCF structure is simulated by beam propagation method. The center wavelength of incident light is 1550 nm, the background RI is 1.0. The core and cladding diameters of TCF are 3.6 \( \mu m \) and 125 \( \mu m \), the RIs of core and cladding are 1.46 and 1.445. For simplicity, the transition length of taper is kept constant and the whole length of taper is 800 \( \mu m \). Specially, the offset value is set equal to 12 \( \mu m \) in order to obtain high ER and uniform FSR, and the LP\( \omega \) and LP\( \alpha \) are the main modes for interference [13]. As shown in Figure 2a, the deduction of diameter of taper waist (denoted by \( d \)) from 80 \( \mu m \) to 40 \( \mu m \) (the blue parts) leads a clear loss of cladding energy in the region of taper waist. From Figure 2b, the intensity of light is continuously but non-linearly decreased with the reduced \( d \). A turning point of the leaked intensity occurs when \( d < 50 \mu m \), which means the intensity modulated scheme may be realized by the structure with smaller diameter.

The fabrication flow chart of \( t \)-TCF is shown in Figure 3a. Firstly, let \( a = 12 \mu m \) and the TCF is spliced with the lead-in and lead-out SMFs under the state of offset splicing mode, respectively. Next, two SMF-TCF structures are spliced and tapered through the two-step arc-discharged fusion technique. Here, the length of TCF is set equal to ~5 cm to avoid the large increase of cladding mode [38]. The key parameters are that the pre-discharge intensity and time are 40 bit and 180 ms, the main discharge intensity and time are 70 bit and 2200 ms, the splicing waiting time is 1200 ms and the splicing speed is in the range of 0.08–0.17 \( \mu m/\text{ms} \). Figure 3b shows that the diameter of waist is linearly decreased with the increase of splicing speed. On account of the precision of 0.01 \( \mu m/\text{ms} \), the fabrication error of the diameter of taper waist is about \( \pm 1.5 \mu m \). Figure 4a shows the images
of t-TCF structure with the varied \( d \) from 79.32 µm to 30.13 µm, and the corresponding transmission and spatial frequency spectra are given in Figure 4b,c, respectively.

![Figure 2](image-url)

**Figure 2.** (a) The light field distributions and (b) the normalized energy with the varied \( d \).

![Figure 3](image-url)

**Figure 3.** (a) The fabrication flow of t-TCF structure, (b) the relation between the fusion speed and the diameter of taper waist.

![Figure 4](image-url)

**Figure 4.** (a) The micro-images, (b) transmission and (c) spatial frequency spectra of t-TCF structures with the varied \( d \).

It is found that the ER of fringes is decreased with the deduction of diameter but can be maintained above 9 dB in the band of 1550 nm. Figure 4c shows that, for the given \( L_{TCF} \), the unique dominated peak located at 0.174 nm\(^{-1}\) occurs in the spatial frequency spectra, except for the case of \( d = 30.13 \) µm, which means the over smaller diameter of taper waist may worsen the transmission spectrum. Therefore, in order to guarantee the yield of fabrication, the minimum of taper waist should be not less than ~30 µm in our subsequent experiments. Furthermore, five new samples are fabricated and compared with the same parameters of \( L_{TCF} = 5 \pm 0.1 \) cm, \( \alpha = 12 \) µm and \( d = 30 \) µm. Figure 5 shows the average values of ER and FSR are 12.4 dB and 5.68 nm, respectively, with the maximum fluctuations of
±0.77 dB and ±0.14 nm. These results indicate the fabrication repeatability of the t-TCF structures reach 88.1% and 95.1% in terms of ER and FSR-uniformity.

![Figure 5](image)

**Figure 5.** The fabrication repeatability in terms of (a) ER and (b) spatial frequency of fringes.

4. Experiments and Results

The experimental setup for axial-strain sensing is shown in Figure 6, which includes a micro-motion controller (MMC, Newport, Model ESP-300, with a minimum accuracy of 0.1 μm), a broadband light source (BBS, CONNET VENUS, with the range of 1525–1565 nm) and an optical spectrum analyzer (OSA, Agilent 86142B, with a resolution of 0.06 nm/0.01 dB). The fabricated t-TCF structures are then placed horizontally on the platform of MMC and quickly fixed by UV glue. The distance between the two fixed points is 10.2 cm. During the axial-strain test, the stage-1 is fixed, and the stage-2 is moved for stretching with the interval of 50 με. Moreover, it is noted that the transmission spectra of the fixed t-TCF structures shown in Figures 7 and 8 are a little different from the original spectra demonstrated in Figure 4 because of the applied pre-axial-strain caused by the adhesive.

![Figure 6](image)

**Figure 6.** Experimental setup for axial-strain test.

From Figure 7a,b, the transmission spectra are flatly blue-shifted with the increased axial-strain. When the diameter is reduced from 79.32 μm to 58.96 μm, there is a slight improvement in sensitivity in the range of 0–3600 με, but the linearity becomes worse. The sensitivity of dips is increased from −0.82/−0.77 pm/με to −0.89/−1.16 pm/με, and the intensity fluctuation of fringes is constrained within ±1.2 dB. From Figure 6c, when d = 40.12 μm, the wavelength sensitivity is further improved and equal to −1.74/−1.88 pm/με but only in the range of 0–750 με. With the added strain, the wavelength response of dip1 is decreased ~39% in the range of 750–2650 με. Additionally, it is observed that the intensity variation, especially for dip2, is increased to ~7.14 dB, which corresponds the sensitivity of 0.003 dB/με in the range of 650–2650 με. Further, as shown in Figure 8a, when d = 30.13 μm, the sensitivity of dips reaches ~4.07/−3.74 pm/με, which is about 5-time higher than that of the structure with d = 79.32 μm. The corresponding linear range is further decreased to 0–600 με. In addition, for the intensity changes of dips, there is an obvious turning at the point of ~500 με. By calculation, the sensitivity of dip2 is ~0.09 dB/με in the range of 0–500 με. Such contradiction between wavelength sensitivity and linearity are
also presented in [28]. This indicates sensitivity enhancement of axial strain is usually with the price of linear-range deduction, because of the worsened mechanical strength of fiber.

**Figure 7.** Transmission spectra and the axial-strain responses when (a) \( d = 79.32 \ \mu m \) (b) \( d = 58.96 \ \mu m \), and (c) \( d = 40.12 \ \mu m \).

Next, to avoid the disturbance of external force, as shown in the inset of Figure 6, the structure with \( L_{cr} = 5 \ \text{cm} \) and \( d = 30.13 \ \mu m \) is packaged into a thin steel tube with the diameter of 200 \( \mu m \) and the length of 6 cm. Again, the strain response of the packaged sensor is tested, and the results are shown in Figure 8b. Comparatively, after packaging, the wavelength sensitivity of strain suffers a reduction of \(~45\%\) (about \(-2.24/-2.07 \ \mu m/\mu \varepsilon\)) due to the fact that more UV glue is used to fix the fiber structure in the steel tube. However, the linear range is greatly improved and reaches 1100 \( \mu \varepsilon \). Furthermore, more obvious intensity variation of dip2 is demonstrated, and the calculated sensitivity is \(-0.035 \ \text{dB/\mu\varepsilon}\) in the range of 0–400 \( \mu \varepsilon \). Figure 9 demonstrates the relation between the sensitivity and linear range with varied diameters of taper waist. There is an obvious reduction of linear range (>80\%) when \( d < 44 \ \mu m \), although the sensitivity is enhanced. Comparatively, after packaging, a trade-off is obtained between the sensitivity and linear range. The linear range of measurement reaches 1100 \( \mu \varepsilon \), and the sensitivity is still maintained above 2.2 \( \mu m/\mu \varepsilon \).
Furthermore, the structure with $d = 30.13 \, \mu m$ is selected for a temperature test, and the corresponding transmission spectrum is given in Figure 10a. The wavelengths of dips are red-shifted about 3.36 nm in the range of 25–85 °C. From Figure 10b, the sensitivities of dip1 and dip2 are 57.31 pm/°C and 56.78 pm/°C, respectively, with the linearity of >0.996. Such high sensitivity-consistency (~99.06%) provides the ability to eliminate the temperature crosstalk by the method of differential compensation [13,38–40]. In detail, the whole wavelength shift can be expressed as,

$$d\lambda = \frac{\partial \lambda}{\partial S} dS + \frac{\partial \lambda}{\partial T} dT,$$

where $\partial \lambda/\partial S$ and $\partial \lambda/\partial T$ are the sensitivities of strain and temperature, respectively, $dS$ and $dT$ are the change of strain and temperature. Since the crosstalk from ambient temperature can be easily eliminated through the simple differential operation, the difference of wavelength shifts between dip1 and dip2 is,

$$d(\lambda_1 - \lambda_2) = \left(\frac{\partial \lambda}{\partial S} - \frac{\partial \lambda}{\partial T}\right) dS,$$

By calculation, $d(\lambda_1 - \lambda_2) = 0.179$ nm. Therefore, the corresponding error of sensitivity (denoted by $\varepsilon$) is 0.162 pm/με, which is mainly resulted from the non-linear strain response of dip2. From [40], the corrected sensitivity (denoted by $\varepsilon$) can be gotten by the formula $\varepsilon = \varepsilon_0 + \varepsilon \varepsilon$ (where $\varepsilon_0$ is the measured sensitivity of strain). Thus, the calculated $\varepsilon$ is equal to ~2.232 pm/με with the measured error of 3.6%.
Figure 10. (a) Transmission spectra of t-TCF with varied temperature and (b) the relationship between wavelength response and temperature.

In addition, five samples with $\alpha = 12$ $\mu$m and $d = \sim 30$ $\mu$m are fabricated and their axial strain responses are tested and compared. According to Figure 11a, the average strain sensitivity is about 2.23 pm/$\mu$e, and the maximum deviation is constrained within $\pm 3.5\%$. Additionally, Figure 11b shows that the maximum wavelength drift is merely $\pm 10$ pm in a short-term test (40-min), possibly caused by the fluctuation of ambient temperature. Furthermore, the hysteresis test is performed, and the results are given in Figure 11c. It is found that, within two weeks, the wavelength sensitivities are continuously increased, and the maximum drift reaches 0.14 pm/$\mu$e, which indicates the error of hysteresis test is approximately equal to 6.33%.

Figure 11. (a) Repeatability, (b) the short-term and (c) long-term stabilities of axial-strain response.

5. Discussion

Table 1 compares the performance of fiber-optic axial-strain sensors in terms of sensitivity, linear range and temperature compensation. It is clear that the tapering is an effective method for improving the wavelength sensitivity of axial-strain. In addition, the thinner diameter leads the higher response, but maybe with the price of a decreased linear
range. From [31], the linear range of a tapered micro-cavity is merely 110 με, which is strongly limited the application of sensor, although the sensitivity of ~45 pm/με is obtained. Comparatively, to improve practicality, the t-TCF structure balances the sensitivity and linear range. The linear range of measurement reaches 1100 με when it is well packaged. Moreover, different from the FBG-based schemes, high temperature-sensitive consistency of our sensor can provide the ability of self-differential temperature compensation, and the near-zero crosstalk can be easily achieved.

Table 1. Performance comparisons of the reported fiber-optic strain sensors.

| Structures                        | Sensitivity | Linear Range | Temperature Compensation | Refs |
|-----------------------------------|-------------|--------------|--------------------------|------|
| FBG in four-core fiber            | −1.83 pm/με | 0–1000 με    | Yes                      | [5]  |
| LPG and microspheres              | 0.8 pm/με   | 0–1500 με    | No                       | [7]  |
| tapered hollow core fiber         | 2.7 pm/με   | 0–2100 με    | No                       | [10] |
| TCF-MZI                           | −1.92 pm/με | 0–800 με     | Yes                      | [13] |
| microfiber coupler                | 83 pm/με    | 0–400 με     | No                       | [25] |
| dual-tapered twin-core fiber      | 6.39 pm/με  | 0–500 με     | No                       | [29] |
| tapered micro-cavity              | 45 pm/με    | 0–110 με     | No                       | [31] |
| tapered TCF                       | −4.07 pm/με | 0–600 με     |                          |      |
|                                   | −2.23 pm/με | 0–1100 με    | Yes                      | Our work |

6. Conclusions

In this paper, a novel in-line MZI based on tapered TCF is proposed and the comprehensive tests are conducted and compared in term of axial strain. The experimental results show that the wavelength sensitivity of strain can be improved by reducing the diameter of taper waist. In addition, more than 400% enhancement is gained when the diameter of taper waist is reduced to ~30 μm. Moreover, the linear range of measurement is nearly doubled by a suitable package and the sensitivity is maintained above 2.2 pm/με. Furthermore, benefitting from high constancy of response, the temperature crosstalk is eliminated by differential compensation, and the measured error is constrained within 3.6%. Owing to high repeatability and stability, our sensor has the capability to achieve high-precision axial-strain related engineering measurement.

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