Composite Modal Interferometer for Simultaneous Triple-Parameter Measurement Based on Cascaded No-Cladding Fiber and Thin-Core Fiber Structure

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Abstract In this paper, an in-fiber composite modal interferometer (CMI) is proposed and experimentally demonstrated based on cascaded no-cladding fiber (NCF) and thin-core fiber (TCF) structure, which respectively corresponds to multimode interferometer (MMI) and Mach-Zehnder interferometer (MZI). The self-image effect of MMI is deeply analyzed and the interference fringes distribution of CMI is accurately designed by the selective the length of NCF and TCF. The comprehensive tests are then conducted and the experimental results show that interference fringes present similar temperature response but the apparent differences in strain and refractive index (RI) tests owing to the asymmetrical structure. MMI has a near-zero intensity sensitivity of strain and red-shifts with the increased RI. But MZI has the sensitivity of \(-19.3\text{nm/RIU}\) and a 4.94 dB increment in the range of 300–1100 \(\mu\varepsilon\). Thus high-discrimination simultaneous triple-parameter measurement is achieved by means of joint wavelength and intensity demodulation. The proposed CMI has the merits of high sensitivity, low cost and ease of fabrication, and is very promising and potential for the engineering monitoring and sensing applications.

Index Terms Fiber optic sensor, composite modal interference, cascaded structure, no-cladding fiber, thin-core fiber.

I. INTRODUCTION

Recently, in-line modal interferometers (MIs) have received much attention and presented the promising and potential in the applications of engineering ranging [1], environment monitoring [2], health care and bio-chemistry sensing [3]–[6], due to the merits of high sensitivity, small size, light weight and immunity to electromagnetic interference. By means of ease of fabrication (e.g., etching, polishing, arc-discharge and flame brush), lots of MI-based configurations, such as multimode interferometers, in-fiber Mach-Zehnder/ Michelson interferometers, microfiber and micro-cavity [7]–[11], have been developed and utilized in the measurements of temperature, refractive index (RI), strain/curvature, torsion, liquid level and magnetic field [12]–[21]. As the enhancement of sensitivity, the functional and integrated fiber-optic sensors for simultaneous multi-parameter measurement with low cross-talk have become one of the hot topics.

So far, the dual-parameter measurements with high discrimination proficiency have been widely studied and typically the crosstalk from ambient temperature can be effectively eliminated by embedding a fiber Bragg grating, but with a sensitivity of \(\sim 10\text{ pm/}^\circ\text{C}\) [22]–[25]. In order to overcome this limitation, a thin-core fiber (TCF) based MI with suitable core offset is presented and differential temperature compensation is adopted due to ultra-high consistence of temperature response [26]. Furthermore, Yu reported a Fourier analysis method base on intensity-modulation to reduce the measuring error from temperature cross-sensitivity [27].
In addition, multimode fiber (MMF) based hybrid modal interferometers are reported in [28]–[30] and dual-parameter measurement is achieved by the inversion matrix method.

In this paper, a novel composite modal interferometer (CMI) is proposed and experimentally demonstrated based on a cascaded no-cladding-fiber (NCF) and thin-core-fiber (TCF) structure, which corresponds to multimode interferometer (MMI) and Mach-Zehnder interferometer (MZI), respectively. The mode coupling feature of CMI is characterized by beam propagation method and the comprehensive tests are then conducted in terms of temperature, RI and strain. The experimental results show that, because of the asymmetric structure, the obvious differences of wavelength and intensity are presented in RI and strain tests. Through joint wavelength and intensity demodulation, the proposed CMI achieves high sensitivity simultaneous triple-parameter measurement with high discrimination.

![FIGURE 1. Schematic diagram of composite modal interferometer, SMF: single-mode fiber, NCF: no-cladding fiber, TCF: thin-core fiber, MMF: multimode fiber.](image)

### II. PRINCIPLE AND FABRICATION

Fig. 1 shows the schematic structure of CMI, which is mainly made of two sections of NCF and TCF. Similar to SMS, in the first section (i.e., single-mode-no-cladding-thin-core fiber structure), multiple high-order modes will be excited and the multimode interference will generate when the incident light enters NCF from lead-in SMF. Further, in the second section (i.e., no-cladding-thin-core-multimode fiber structure), owing to the mismatched fiber core, the residual power of light will be split into the core and cladding of TCF and combined by MMF. Consequently, the Mach-Zehnder interference will be formed due to the effective RI difference between the core and cladding modes.

From [26], in MMI, the phase difference of high-order modes can be expressed by

\[
\varphi_1 = \frac{\pi}{4} \left( m - n \right) \left( m + n - \frac{1}{2} \right) \lambda L_N
\]

where \(m\) and \(n\) are the orders of mode \((m, n = 1, 2, 3 \ldots)\), \(L_N\) is the length of NCF, \(\lambda\) is the incident wavelength, \(r\) and \(n_{co}\) are the radius and effective refractive index of NCF, respectively. When the phase matching condition \(\varphi_1 = (2k + 1)\pi\) \((k = 1, 2, 3 \ldots)\) is satisfied, MMI will be generated and the resonance wavelength can be expressed as

\[
\lambda_1 = \frac{8r^2n_{co}(2k + 1)}{(m - n)(2m + 2n - 1)L_N}
\]

Further, according to [9], [27], the transmitted intensity of a two-beam MZI can be expressed as

\[
I = I_{co} + I_{cl} + 2\sqrt{I_{co}I_{cl}}\cos\varphi_2
\]

where \(I_{co}\) and \(I_{cl}\) are the light intensities of the fiber-core mode and fiber-cladding modes, respectively. \(\varphi_2\) is the phase difference between the fiber-core mode and fiber-cladding modes, which can be expressed as

\[
\varphi_2 = \frac{2\pi \Delta n_{eff} L_T}{\lambda}
\]

where \(L_T\) is the length of the TCF and \(\Delta n_{eff}\) is the effective refractive index difference between the fiber-core and the fiber-cladding. Similarly, when the phase matching condition \(\varphi_2 = (2m + 1)\pi\) \((m = 1, 2, 3 \ldots)\) is satisfied, the resonance wavelength of MZI can be expressed as

\[
\lambda_2 = \frac{2\Delta n_{eff} L_T}{2m + 1}
\]

In order to ensure that the CMI effectively generates MMI and MZI, the length of NCF is very crucial. From [21], the interference length of MMI is directly related to the self-imaging points and can be expressed as

\[
L_S = \frac{4n_{co}r^2P}{\lambda_1}
\]

where \(L_S\) is the length of self-imaging period, \(P\) is an integer and denotes the number of self-imaging point. Then the beam propagation method is used to observe the light field distribution in the proposed CMI. The main simulation parameters are given in Table 1. It is worth noting that the shorter TCF (e.g., \(L_T = 10\) mm) is chosen to get a large free spectral range and guarantee an obvious fringe-isolation between the MMI and MZI. Moreover, the background refractive index is set to 1.0 and the incident wavelength is 1550 nm.

The optical field distribution of CMI is shown in Fig. 2 along the axial direction. It is clear that, the light intensity in NCF shows a significant periodic distribution and the light intensity reaches maximum when \(P = 3\). In theory, a MMI can be generated at each self-imaging point but must with enough light intensity. Thus the MMI is generally formed at the point with the maximum light intensity. From (6),

**TABLE 1. The main simulation parameters.**

| Fiber | \(n_{co}/n_{cl}\) | radius(μm) | Length(μm) |
|-------|--------------------|-------------|------------|
| SMF   | 1.4501/1.4447      | 4/62.5      | 1000       |
| NCF   | 1.444              | 62.5        | 45000      |
| TCF   | 1.4587/1.444       | 2/62.5      | 10000      |
| MMF   | 1.479/1.445        | 52.5/62.5   | 2000       |
$L_S = 43.6$ mm when $P = 3$ and the corresponding high-order modes for MMI are LP08 and LP09 when the diameter of NCF is equal to 125 $\mu$m. It is worth noting that the distribution of modes is directly dependent on the diameter of fiber core and higher (lower) order modes can be excited by enlarging (reducing) the diameter of NCF when the power of incident light is enough [31]. Furthermore, in the MZI, LP02 mode is mainly excited in the cladding of TCF and interferes with fiber-core mode (i.e., LP01 mode) when it arrives at the MMF.

On account of the above results, the proposed structure is fabricated by the commercial fusion splicer (KL-280). The adopted NCF (YOFC, CL-1010-A), TCF (Nufern, TCF-980-HP) and MMF (Nufern, MM-S105/125-22A) are spliced in sequence and their lengths are 43.85, 10.5 and 1.8 mm, respectively. The sensor head is then connected to a flat broadband light source (BBS, KF-GFF-AES, with the range of 1525–1565 nm) and an optical spectrum analyzer (OSA, Agilent 86142B, with the resolution of 0.01 nm and 0.01 dB) by the lead-in and lead-out SMFs, respectively. As shown in Fig. 3, the wavelengths of fringes (denoted by Dip-1 and Dip-2, respectively) are located at 1543.35 and 1556.49 nm and the corresponding spatial frequencies are 0.076 and 0.156 $\text{nm}^{-1}$. It is worth noting that the Dip-1 belongs to MMI because the value of 1543.35 nm is very close to the calculated result by (6) when $L_S = 43.85$ mm. And the Dip-2 is resulted from MZI and has a smaller visibility due to the lower intensity of residual fiber core mode. It is noted that the value of $L_S$ can be minimized and the sensor head will be more compact if a smaller core radius is selected, such as 62.5 and 50 $\mu$m.

### III. EXPERIMENTS AND RESULTS

The temperature sensing characteristic of the composite modal interferometer is firstly tested by using the experimental setup shown in Fig. 4. The BBS current is adjusted to 60 mA. The sensor head is fixed on a heater (LICHEN, China) whose temperature range is 35-60$^\circ$C, and the spectrum is recorded by an OSA. Fig. 5 shows the transmission spectra of CMI with varied temperatures and similar temperature response for Dip-1 and Dip-2 are obtained.

With the rise of temperature, the dips red-shift and their wavelength shifts are 0.80 and 1.37 nm, respectively. By calculation, the corresponding wavelength sensitivity are 31.89 pm/$^\circ$C and 40.4 pm/$^\circ$C with the linearity of $>0.99$. It is noted that the thermo-optic coefficient of silica is greater than its thermal expansion coefficient. Thus the contribution of fiber length on temperature response is generally ignored, and the above wavelength sensitivities are mainly caused by the thermo-optic effect of fibers [32]. Moreover, it is noticed that the intensity (visibilities) of fringes is positive (negative) proportional to the variation of temperature. The calculated sensitivities of Dip-1 and Dip-2 are $-0.349$ dB/$^\circ$C and $-0.506$ dB/$^\circ$C, respectively. According to the 0.01-dB resolution of OSA, the detection resolution of temperature (Dip-2) is 0.02 $^\circ$C.

Then the RI sensing characteristic of CMI is tested. The sensing head is first fixed on a slide glass. Five sucrose solutions were prepared and the rise of RI from 1.34 to 1.38. The sucrose solution is dropped on the sensing head and the stable spectrum is recorded. The sensing structure is thoroughly cleaned with anhydrous ethanol before dropping the new test agent. Fig. 6 shows the transmission spectra of CMI with the varied RI. From Fig. 6, Dip-1 caused by MMI is red-shifted because of a positive RI change [33]. While, similar to most of in-line MZIs, the wavelength of Dip-2 exhibits a significant blue shift.

The corresponding RI wavelength sensitivity of Dip-1 and Dip-2 are 29.53 nm/RIU and $-19.3$ nm/RIU, respectively. According to [29], the effective diameter of NCF increases with the rise of surrounding RI, and the effective RI of the
NCF also increases as more energy of evanescent wave enters the liquid. From (6), the wavelength of self-image will drift into the long-wave direction. Because of the opposite RI response, the sensitivity can be improved by the differential method. The wavelength shifts of Dip-1 and Dip-2 are defined as $\lambda_1$ and $\lambda_2$, respectively. The differential sensitivity $S$ can be expressed as $S = (\lambda_1 - \lambda_2)/\Delta n$, where $\Delta n$ is the change of external RI. The calculated RI sensitivity reaches 48.83 nm/RIU, which is nearly twice as high as the original sensitivity. This differential method can provide a new solution for increasing the RI response of sensors. The calculated detecting resolution reaches 2.04 × 10^{-4} RIU.

Further, the characteristic of strain sensing is tested. The two ends of sensing head are respectively fixed on two horizontal displacement platforms, and the distance of two fixed points is 103 mm. During the strain test, one of the platforms moves along the axial direction of the fiber, which is controlled by the micro-motion controller, and the other platform remains stationary. The strain range in test is from 0 to 1100 $\mu$e, the transmission spectra are recorded by every 100 $\mu$e and are shown in Fig. 7.

The transmission spectra exhibit a significant blue-shift as the applied strain increases. And the wavelengths of Dip-1 and Dip-2 drift by 2.0 and 1.49 nm, respectively. By linearly fitting, the strain sensitivities of Dip-1 and Dip-2 are 1.82 and 1.36 pm/$\mu$e with high linearity of 0.99. According to [30], an asymmetric structure will be subjected to the uneven force and a turning point of strain will be generated. In Fig. 7(b), when a smaller strain is applied (less than 300 $\mu$e), the energy of core and cladding modes is well constrained. The extinction ratio (ER) of Dip-2 is almost unchanged and only the wavelength is blue-shifted due to the photo-elastic effect of fiber. However, as the applied strain increases, due to the fact that the light intensity of cladding mode may be leaked at the splicing point between NCF and TCF, the ER of Dip-2 is continuously reduced $\sim 4.94$ dB and the calculated sensitivity is about 0.00618 dB/$\mu$e.

Comparatively, in the range of 0–1100 $\mu$e, the intensity of Dip-1 merely has a fluctuation of $\pm 0.63$ dB, which is resulted from the power drift of light source in general [34]. Consequently, with the OSA resolution of 0.01 dB, the detecting resolution of strain is 1.62 $\mu$e. According to the above results, it is found that the resonant peaks of MMI and MZI have different linear sensitivities with respects to temperature, RI and strain. Therefore, from [24], the triple-parameter variations can be discriminated effectively, which is calculated using sensitivity matrix as

$$
\begin{bmatrix}
\Delta T \\
\Delta n \\
\Delta \varepsilon
\end{bmatrix} =
\begin{bmatrix}
k_{T,1} & k_{n,1} & k_{\varepsilon,1} \\
k_{T,2} & k_{n,2} & k_{\varepsilon,2} \\
k_{T,I} & k_{n,I} & k_{\varepsilon,I}
\end{bmatrix}^{-1}
\begin{bmatrix}
\Delta \lambda_1 \\
\Delta \lambda_2 \\
\Delta I_1
\end{bmatrix} \tag{7}
$$
where $\Delta \lambda_1$ and $\Delta \lambda_2$ are the wavelength shifts of Dip-1 and Dip-2. $\Delta I_1$ is the intensity change of Dip-1. $\Delta T$, $\Delta n$ and $\Delta \varepsilon$ denote the changes of temperature, RI and strain, respectively. Additionally, $k_{T,\lambda_1}$, $k_{n,\lambda_1}$ and $k_{\varepsilon,\lambda_1}$ are the temperature, RI and strain wavelength sensitivities of Dip-1. $k_{T,\lambda_2}$, $k_{n,\lambda_2}$ and $k_{\varepsilon,\lambda_2}$ are the temperature, RI and strain wavelength sensitivities of Dip-2. And $k_{T, I_1}$, $k_{n, I_1}$ and $k_{\varepsilon, I_1}$ are the temperature, RI and strain intensity sensitivities of Dip-1, respectively. By substituting the linear fitting data into (7), simultaneous measurement of temperature, RI and strain can be achieved, as shown in (8).

$$
\begin{bmatrix}
\Delta T \\
\Delta n \\
\Delta \varepsilon
\end{bmatrix} =
\begin{bmatrix}
0.03189 & 29.53 & -0.00182 \\
0.0404 & -19.3 & 0.00136 \\
-0.349 & 144.48 & 0
\end{bmatrix}^{-1}
\begin{bmatrix}
\Delta \lambda_1 \\
\Delta \lambda_2 \\
\Delta I_1
\end{bmatrix}
$$

(8)

By means of this matrix, the variations of temperature, strain and RI can be calculated after measuring the wavelength and intensity shifts of MMI and MZI. Furthermore, because the intensity-sensitivity of Dip-1 in term of strain is approximately equal to 0-dB/µε, the discrimination of multi-parameter measurement is effectively improved. Therefore, our sensor achieves simultaneous triple-parameter measurement with high discrimination and the corresponding detection resolutions with respects to temperature, RI and strain are $0.02 ^\circ C$, $2 \times 10^{-4}$ RIU and 1.62 µε, respectively. It is worth noting that our structure is flexible and can be more compact (by using a fiber with smaller core radius in MMI) and sensitive (by using a tapered fiber in MZI), which is significantly promising in multiple functional engineering applications.

IV. CONCLUSION

In this paper, the self-imaging effect of multimode interference is extensively studied and the interference fringes can be accurately positioned and distributed by means of the selective length of NCF and TCF. Further, a composite modal interferometer consisting of MMI and MZI is completed and fabricated by core-mismatch splicing technique. The experimental results show the apparent response differences in terms of wavelength and intensity owing to the cascaded and asymmetric structure. Hence our sensor achieves simultaneous triple-parameter measurement with high discrimination and the corresponding detection resolutions with respects to temperature, RI and strain are $0.02 ^\circ C$, $2 \times 10^{-4}$ RIU and 1.62 µε, respectively.

ACKNOWLEDGMENT

The authors thank Ms. Kehuan Liu for the original experimental design of the structure.
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