Optics Communications 426 (2018) 506–510

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Simultaneous measurement of refractive index and temperature based on down-taper and thin-core fiber

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ARTICLE INFO

Keywords:
Mach–Zehnder interferometer
Down-taper
Thin-core fiber
Refractive index
Temperature

ABSTRACT

A Mach–Zehnder interferometer (MZI) based on the cascaded structure of a single-mode fiber (SMF) down-taper and thin-core fiber (TCF) is proposed and experimentally demonstrated. The down-taper acts as mode coupler to excite cladding modes. The extinction ratio of the transmission spectra can reach up to 20dB. By monitoring the wavelength shifts of interference dip1 and dip2, simultaneous measurement of refractive index (RI) and temperature can be achieved. The experimental results show that the wavelengths at interference dip1and dip2 have blue shifts with the increase of RI and red shifts with the increase of temperature. The RI sensitivities at interference dip1 and dip2 are -30.290 nm/RIU and -79.335nm/RIU, respectively. The temperature sensitivities at interference dip1 and dip2 are 0.065 nm/°C and 0.053 nm/°C, respectively. The proposed MZI exhibits the advantages of easy fabrication, high extinction ratio, low cost, and simultaneous measurement of RI and temperature, which will make a significant contribution to RI measurement.

1. Introduction

Fiber-optic sensors have been widely applied in physical and chemical sensing fields owing to their excellent characteristics, such as high sensitivity, compact size, corrosion resistance, immunity to electromagnetic interference [1,2]. RI and temperature are two fundamental parameters in sensing fields [3,4]. Therefore, optical fiber RI and temperature sensors have been intensively researched. In the past few decades, optical fiber sensors based on MZI have been widely studied, including TCF-based MZIs [5,6], taper-based MZIs [7,8], grating-based MZIs [9,10], photonic crystal fiber (PCF)-based MZIs [11,12], etc. For instance, in 2010, Zhu et al. [5] presented a MZI realized by welding a section of TCF between two SMFs for temperature sensing application, and the temperature sensitivity is 18.3 pm/°C. In 2011, Wu et al. [7] proposed a three-taper SMF-MZI by cascading a third taper between two normal tapers with a RI sensitivity of 28.6 nm/RIU. In 2014, Yao et al. [10] put forward a sensor based on a core-offset MZI combined with a fiber Bragg grating, and the RI and temperature sensitivities are 13.7592 nm/RIU and 0.0462 nm/°C, respectively. In 2016, Zhao et al. [11] designed a tapered PCF based MZI, and the RI sensitivity is 281.6 nm/RIU. However, the gratings usually need a long and complicated manufacturing process, and the PCFs are expensive. So compared with the grating-based and PCF-based MZIs, the TCF-based and taper-based MZIs are more simple and cost-effective.

In this study, a MZI based on the cascaded structure of a SMF down-taper and TCF is proposed and experimentally demonstrated. Only involving splicing, the fabrication of the proposed MZI is very simple. The proposed MZI can measure temperature and RI simultaneously and eliminate the cross-sensitivity. The proposed MZI has advantages of simple configuration, easy fabrication and low cost.

2. Design and principle

Fig. 1(a) shows the schematic structure of the proposed MZI. The MZI is composed of the following components: lead-in SMF, down-taper structure, middle section SMF, TCF and lead-out SMF, in which the length of the middle section SMF is L_1, and the length of the TCF is L_2. The core (cladding) diameter of the SMF is 8.2 (125) μm, and the core (cladding) diameter of the TCF is 3.6 (80) μm. The micrograph of the down-taper is shown in Fig. 1(b), with taper length Z (637 μm) and the waist diameter D (42 μm). Fig. 1(c) shows the micrograph of the splicing region between the SMF and TCF.

The proposed MZI fabrication involves only manual splicing. In the first step, a section of TCF is welded between the lead-in SMF and the lead-out SMF using one manual splicing program of a fusion splicer (FITEL, S178c). The discharge intensity and time of the manual splicing program are 90 bit and 1300 ms, respectively. Then a down-taper on the

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https://doi.org/10.1016/j.optcom.2018.06.004
Received 12 April 2018; Received in revised form 16 May 2018; Accepted 1 June 2018

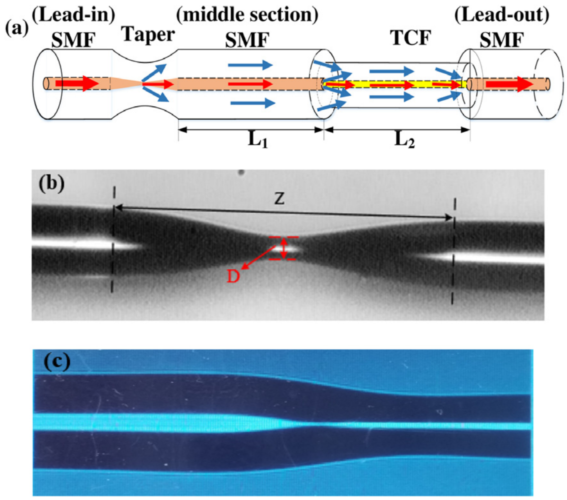

Fig. 1. (a) Schematic structure of the proposed MZI. (b) Micrograph of down-taper. (c) Micrograph of the splicing region between the SMF and TCF.

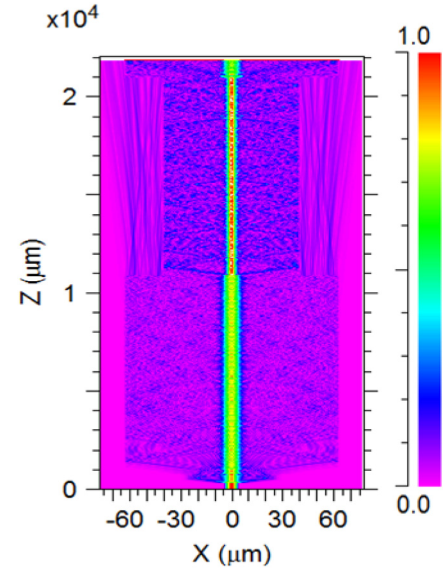

Fig. 2. Optical field distribution of the proposed MZI with $L_1 = L_2 = 1$ cm.

lead-in SMF is made using the other manual splicing program, in which the discharge intensity and time are 50 bit and 500 ms, respectively, and the program is used 3 times cumulatively.

In this MZI, the down-taper acts as a mode coupler, and the middle section SMF and TCF act as the sensing section. The optical field distribution of the proposed MZI with $L_1 = L_2 = 1$ cm is numerically simulated by beam propagation method (BPM), as shown in Fig. 2. In the simulation, the input optical wavelength is set as 1550 nm. It can be found from Fig. 2 that when the light is transmitted from the lead-in SMF to the down-taper structure, due to the splitting light effect of the down-taper, one part of the light will be transmitted along the core of the SMF, and the other part will enter the cladding of middle section SMF to excite the cladding modes. At the fusion point of middle section SMF and TCF, since the cladding diameter of TCF is smaller than that of SMF, one part of the light in the middle section SMF leaks to the external environment, and the other is transmitted in the core and cladding of TCF. It is worth noting that the light transmitted along the core of TCF comes from the interference between the core mode and the cladding modes in the middle section SMF. At the fusion point between TCF and lead-out SMF, the core and cladding modes satisfying the phase matching condition generate interference phenomenon.

The output light intensity of the proposed MZI, represented by I, can be expressed as [13]

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left[\frac{2\pi\left(n_{co}^{T} - n_{cl}^{T,n}\right)L_2}{\lambda}\right] \tag{1}$$

where, I_1 and I_2 refer to the light intensity of the core mode and n-order cladding mode of TCF, respectively, and n is an integer. n_{co}^{T} and $n_{cl}^{T,n}$ are the effective RI of core mode and n-order cladding mode of TCF, respectively. λ is the wavelength of the input light. However, the light entering into the core of TCF is the output from the interference between the core mode and cladding modes in the middle section SMF. Therefore, I_1 can be expressed as

$$I_1 = I_1' + I_2' + 2\sqrt{I_1' I_2'}\cos\left[\frac{2\pi\left(n_{co}^{S} - n_{cl}^{S,m}\right)L_1}{\lambda}\right] \tag{2}$$

where, I_1' and I_2' refer to the light intensity of the core mode and m-order cladding mode of the middle section SMF, respectively, and m is an integer. n_{co}^{S} and $n_{cl}^{S,m}$ are the effective RI of core mode and m-order cladding mode of the middle section SMF, respectively.

In terms of the interference that occurs at the fusion point of the middle section SMF and TCF, when $2\pi\left(n_{co}^{S} - n_{cl}^{S,m}\right)L_1/\lambda = (2k+1)\pi$, where k is an integer, the wavelength of interference dip can be expressed as

$$\lambda_s = \frac{2(n_{co}^{S} - n_{cl}^{S,m})L_1}{2k+1}. \tag{3}$$

As we all know, $n_{co}^{S}, n_{cl}^{S,m}$ and L_1 are related with the change of surrounding environment, so the wavelength of interference dip will shift with the change of surrounding environment. When temperature and RI change, the variation of λ_s caused by changes of temperature and RI, represented by $\Delta\lambda_s$, can be expressed as

$$\Delta\lambda_s = \lambda_s\left[(\alpha_s + \frac{\xi_{co}^{S} n_{co}^{S} - \xi_{cl}^{S} n_{cl}^{S}}{n_{co}^{S} - n_{cl}^{S}})\Delta T - \frac{\rho_s n_{cl}^{S}\Delta RI}{n_{co}^{S} - n_{cl}^{S}} - \frac{\alpha_s\rho_s n_{cl}^{S}\Delta T\Delta RI}{n_{co}^{S} - n_{cl}^{S}}\right] \tag{4}$$

where, α_s is the thermal expansion coefficient of SMF; ρ_s is the effective coefficient of the variation of n_{cl}^{S} with the change of RI; ξ_{co}^{S} and ξ_{cl}^{S} are the thermo-optic coefficient of core mode and cladding modes of SMF, respectively.

In terms of the interference that occurs at the fusion point of TCF and lead-out SMF, when$2\pi\left(n_{co}^{T} - n_{cl}^{T,n}\right)L_2/\lambda = (2i+1)\pi$, where i is an integer, the wavelength of interference dip can be expressed as

$$\lambda_T = \frac{2(n_{co}^{T} - n_{cl}^{T,n})L_2}{2i+1}. \tag{5}$$

When temperature and RI change, the variation of λ_T caused by changes of temperature and RI, represented by $\Delta\lambda_T$, can be expressed as

$$\Delta\lambda_T = \lambda_T\left[(\alpha_T + \frac{\xi_{co}^{T} n_{co}^{T} - \xi_{cl}^{T} n_{cl}^{T}}{n_{co}^{T} - n_{cl}^{T}})\Delta T - \frac{\rho_T n_{cl}^{T}\Delta RI}{n_{co}^{T} - n_{cl}^{T}} - \frac{\alpha_T\rho_T n_{cl}^{T}\Delta T\Delta RI}{n_{co}^{T} - n_{cl}^{T}}\right] \tag{6}$$

where, α_T is the thermal expansion coefficient of TCF; ρ_T is the effective coefficient of the variation of n_{cl}^{T} with the change of RI; ξ_{co}^{T} and ξ_{cl}^{T} are the thermo-optic coefficient of core mode and cladding modes of TCF, respectively.

The transmission spectra of the proposed MZI with different L_1 and L_2 are simulated by BPM in RSoft, as shown in Fig. 3. As can be seen from Fig. 3, the free spectrum range (FSR) becomes smaller as L_1 (L_2) increases when L_2 (L_1) remains unchanged, which is confirmed in the following experiments.

If there are two different interference dips (dip1 and dip2) that have different sensitivities towards RI and temperature, the variations