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Discussion

A sensitivity enhanced temperature sensor based on highly Germania-doped few-mode fiber

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ABSTRACT

An all-fiber high-sensitivity temperature sensor based on highly Germania-doped few-mode fiber (HGFMF) is presented. The sensor employs Mach–Zenhder interferometer configuration and fiber mode LP_{01} and LP_{11} are excited in HGFMF. Temperature sensitivity higher than 97 pm/°C is demonstrated in experiment.

1. Introduction

Fiber-optic sensors have attracted a lot of attentions in many military and industrial applications because of their many unique advantages such as small size, cost-effective, immunity to electromagnetic interference, and resistance to harsh environment [1]. In the past few years, fiber temperature sensors have been intensively studied and various configurations have been proposed, such as long-period fiber gratings (LPFGs) [2,3], fiber Bragg gratings (FBGs) [4,5], and fiber interferometer-based sensors [6–9]. Generally speaking, sensors based on LPGs and FBGs possess the advantages such as absolute response parameters, large dynamic ranges. However, FBGs fabricated with a standard communication fiber has a low temperature sensitivity of ~11 pm/°C. LPFGs-based temperature sensors exhibit undesirable changes of the spectral response due to their high bending sensitivity [10]. Fiber-based Fabry-Perot cavities are also used for temperature sensing with compact configuration [11–14]. However, there still exist the disadvantages of requiring expensive equipments for cavity fabrication or needing special fibers (e. g. hollow core PCF) or using chemical reagents [15]. Comparing with those above-mentioned techniques, fiber interferometer-based sensors have also been widely used because of their high sensitivity, cost effective and simple fabrication process.

To meet the requirements of modern industry, the temperature sensitivity of the fiber temperature sensors must be further enhanced. Various methods have been reported to increase temperature sensitivity. Sensitivity of 58.5 pm/°C was obtained by employing mode interference in graded-index multimode fibers [16]. The Mach-Zehnder interferometer (MZI) built by two fiber tapers present temperature sensitivity of 71 pm/°C [17], however the taper based devices are very fragile due to a poor mechanical strength of the small taper waist. Another MZI based on microcavities can achieve 109 pm/°C for high temperature sensing, but the sensitivity is quite low in the range of 25 °C to 200 °C [18]. Benefit from polymer cladding and proper packaging, a MZI sensor with sensitivity as high as -3.9 nm/°C is demonstrated in [19], but the linearity of the sensing performance still needs improving. Recently, a temperature sensor formed by polarization maintaining fiber spliced between two sections of SMF demonstrated sensitivity of 115 pm/°C, however this scheme is polarization-dependent hence polarizer and polarization controller are needed in the experiment [20].

As we know, the temperature sensitivity is significantly affected by the thermal-optical coefficient which is typical 1.06×10^{-5}/°C for fused silica and this coefficient will increase with higher

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concentration of GeO_2 doping [21]. Therefore, in order to further enhancing the sensitivity of a fiber based temperature sensor, a potential method is to increase the doping concentration of GeO_2 so as to increase thermal-optical coefficient of the fiber core. Though, FBG fabricated in highly-Germania fiber has been reported in [22], but the temperature sensitivity is still quite low. One possible solution is to use the interferometer structure to further enhance the sensitivity.

In this paper, we propose and experimentally demonstrate a simple high sensitivity fiber temperature sensor using a fiber-based MZI formed by offset splicing a length of high GeO_2-doped few-mode fiber (HGFMF) with two sections of SMFs. This interferometer incorporates an intermodal interference between two core modes and exhibits high sensitivity as a temperature senor due to a relative high thermal-optical coefficient of the fiber core.

2. Principle

The SMF–HGFMF–SMF interferometer configuration is shown in Fig. 1. A section of HGFMF is offset spliced with two sections of SMF. The HGFMF is of a core diameter of 10 μm and a maximum index contrast of 3.3% between core and cladding corresponding to a GeO_2 doping concentration of 20 mol%. The measured index difference is shown in Fig. 2(a). This fiber can guide core mode LP_{01} and LP_{11} at 1.55 μm wavelength whose mode profiles are demonstrated in Fig. 2(b) and (c). Since the LP_{01} mode is axially symmetric while the LP_{11} mode is axially asymmetric, the first section of SMF (SMF1) is offset spliced with the HGFMF in order to excite both the LP_{01} mode and the LP_{11} mode in HGFMF. The coupling ratio from the LP_{01} mode in SMF_1 to each mode in the HGFMF can be controlled by the offset distance. As a result of propagation constant difference, a phase difference between these two modes accumulates over the HGFMF. At the output of the HGFWM, the second offset splicing point functions as a mode filter for the two modes to the core and cladding modes of SMF_2. However, only core mode can be supported and propagate though SMF_2, while the power of the cladding mode is absorbed by the coating. Since a part of the power from the two modes is recoupled into the core mode of SMF_2, inter-modal interference can happen. For a given wavelength, the intensity at the output of SMF_2 can be expressed as

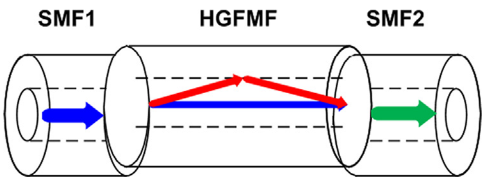

Fig. 1. Schematic illustration of the SMF–HGFMF–SMF interferometer utilizing offset splicing.

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left(\frac{2\pi\Delta nL}{\lambda}\right) \tag{1}$$

where I_1 and I_2 are the power coupled from mode LP_{01} and LP_{11}, respectively, λ is the wavelength of the propagating wave, L is the length of HGFWF, and Δn is the effect index difference of the two guided modes.

According to Eq. (1), in order to achieve maximum extinction ratio, $I_1 = I_2$ should be fulfilled and the transmission dip appears at the wavelength where the phase term of Eq. (1) equals to be $(2N-1)\pi$ ($N=1, 2, 3,\ldots$). I_1 and I_2 are determined by the coupling ratio of the two offset splicing points and can be controlled by the offset distance [23]. The Nth order interference dip is at the wavelength

$$\lambda_N = 2\Delta nL/(2N-1) \tag{2}$$

The wavelength spacing $\Delta\lambda$ of the interfering spectrum can be given by

$$\Delta\lambda \approx \frac{\lambda_N^2}{\Delta nL} \tag{3}$$

When the temperature of the HGFMF varies, the effective mode indices and the fiber length will change, as a result shifting the wavelength of transmission dip. The wavelength shift can be expressed as

$$\partial\lambda_{N,T} = \lambda_{N,T+\partial T} - \lambda_{N,T} = 2(\Delta n + \partial n_T)(L + \partial L)/(2N-1) - 2\Delta nL/(2N-1) \tag{4}$$

where ∂n_T and ∂L is the effective index and fiber length difference changed with∂T, respectively. ∂n_T is mainly determined by the thermal-optic coefficient while ∂L is related to the thermal-expansion coefficient. Because $\partial L/L$ is apparently small (5.5×10^{-7}/°C), if the thermal expansion is neglected, Eq. (4) can be simplified to be.

$$\partial\lambda_{N,T} = \frac{\partial n_T}{\Delta n}\lambda_N \tag{5}$$

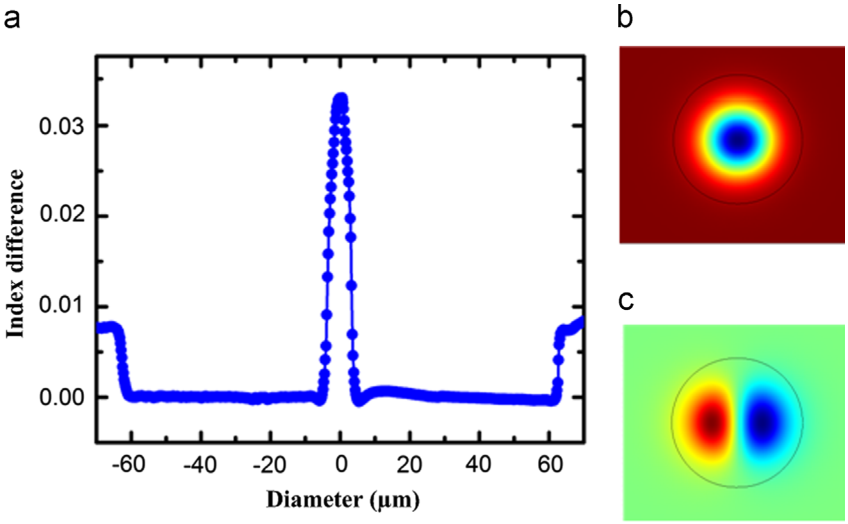

Fig. 2. (a) Index different profile of the HGFMF, (b) mode profile of LP_{01}, and (c) mode profile of LP_{11} in HGFMF at 1550 nm.