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Simultaneous measurement of displacement and temperature based on thin-core fiber modal interferometer

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ABSTRACT

An optical-fiber sensor based on a thin core fiber (TCF) has been proposed and experimentally demonstrated for simultaneous measurement of displacement and temperature. This in-line sensor consists of a segment of TCF between two segments of single-mode fibers (SMFs), and the interference between the core mode and the cladding mode of the TCF occurs. The transmission spectral responses to displacement as well as environmental temperature have been investigated. Experimental results show that the displacement sensitivities of −0.01028 nm/μm and −0.01535 nm/μm for a displacement range of 0–650 μm have been achieved, and the corresponding temperature sensitivities reach about 0.00942 nm/°C and 0.00493 nm/°C within a large temperature range of 20–90 °C, respectively. The proposed sensor exhibits such advantages as simple structure, compact size, ease of fabrication, high sensitivity, etc. Therefore, it has potential applications in accurate multi-parameter measurements.

1. Introduction

Displacement measurement is very important not only for devices but also for some industrial applications. Nowadays, due to their merits such as small size, fast response, immunity to electromagnetic noise, and capability in harsh environment, optical fiber sensors have attracted considerable research interests [1–5]. So far, different types of optical-fiber displacement sensors have been demonstrated by employing long-period gratings (LPGs) [6], fiber Fabry–Pérot interferometers [7,8], fiber Bragg gratings (FBGs) [9–12], Mach–Zehnder interferometer [13], and Sagnac interferometer [14]. These sensors exhibit good performances for displacement measurement applications. However, temperature monitoring is of great importance for accurate displacement measurement due to the issue of temperature cross sensitivity. It is necessary to improve the measurement precision through simultaneous measurement of displacement and temperature. Displacement and temperature are significant parameters for various applications, ranging from movement monitoring to industrial manufacture. They are important physical parameters that should be monitored in various applications, especially in the fields of machinery manufacturing and civil engineering [6,15].

Compared with the FBGs based on complicated fabrication procedure, LPGs in combination with various kinds of fibers with temperature cross sensitivity and modal interference possess several excellent characteristics, including temperature stability, simultaneous multi-parameter measurement, simple structure, and low transmission loss in the infrared wavelength region, and capability of compensating for the insufficient properties. Due to the core diameter of the TCF is smaller than the standard SMF, the confinement ability of the guided-mode light in the TCF is much weaker than the SMF, while the mode field diameter of the TCF is larger than the SMF. It provides a necessary prerequisite for effective mode excitation and modal interference. More recently, a thin core fiber modal interferometer has been extensively studied for measurement of refractive index [16], relative humidity [17], or pH [18], exhibiting its stable temperature sensitivity, the structure simplicity, and remote sensing capability. It also demonstrates that the thin core fiber has the great potential in simultaneous measurement of displacement and temperature.

In this paper, we have presented a fiber-optical sensor for simultaneous measurement of displacement and temperature based on a thin core fiber. The proposed device is fabricated by employing two segments of SMFs with the TCF in between. Since the

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interference dips have different responses to the external displacement and temperature perturbations, it is possible to achieve simultaneous measurement of displacement and temperature.

2. Experimental setup and operation theory

The schematic diagram of the proposed TCF-based fiber-optical sensor for displacement and temperature measurement is shown in Fig. 1(a).

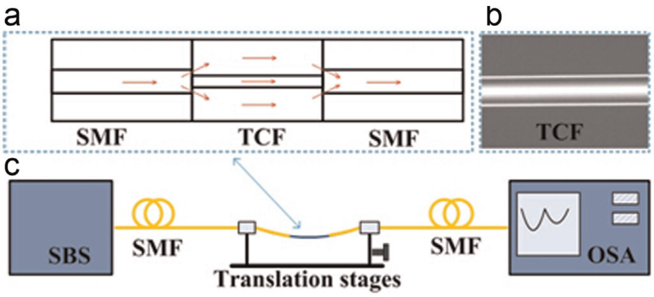

Fig. 1. (a) Schematic diagram of the TCF modal interferometer, (b) microscopic image of the TCF and (c) experimental setup of the proposed sensor.

When the input light propagates through the first splicing joint, multitude of cladding modes will be excited in the TCF due to the mode field mismatch. And both of the LP_{01} core mode and the LP_{mn} cladding modes will propagate along the TCF, and the cladding modes will interfere with the core modes when the light is re-coupled back to the output SMF. For the TCF modal interferometer, the transmission spectral intensity I can be written as [19]

$$I = I_{co} + I_{cl,m} + 2\sqrt{I_{co}I_{cl,m}}\cos\left[\frac{2\pi(n_{co} - n_{cl,m})L}{\lambda}\right] \tag{1}$$

where I_{co} and $I_{cl,m}$ are the intensities of the core and cladding modes propagating along the TCF, respectively, λ is the optical wavelength, L is the length of the TCF, and n_{co} and $n_{cl,m}$ are the effective refractive indices of the core and mth cladding mode, respectively. When the phase difference between the core and cladding mode satisfies $2\pi(n_{co}-n_{cl,m})L/\lambda=(2p+1)\pi$, where p is a positive integer, the interference light intensity will reach its minima and the notch wavelength can be expressed as [19]

$$\lambda_m = \frac{2(n_{co} - n_{cl,m})L}{2m + 1} \tag{2}$$

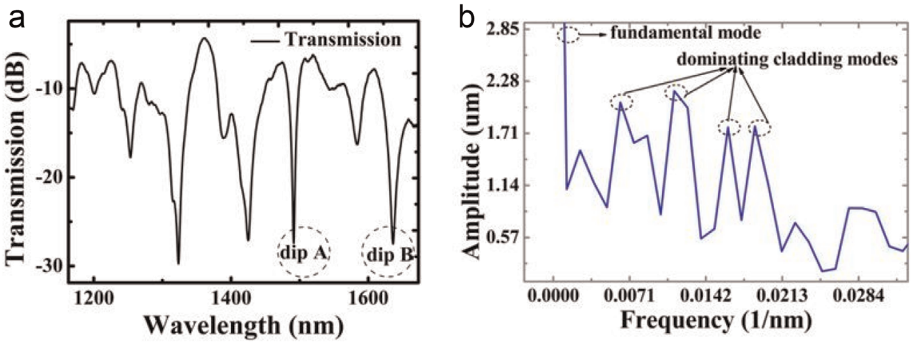

Fig. 2. (a) Transmission spectrum of the TCF modal interference and (b) spatial frequency spectrum showing the modal interference.

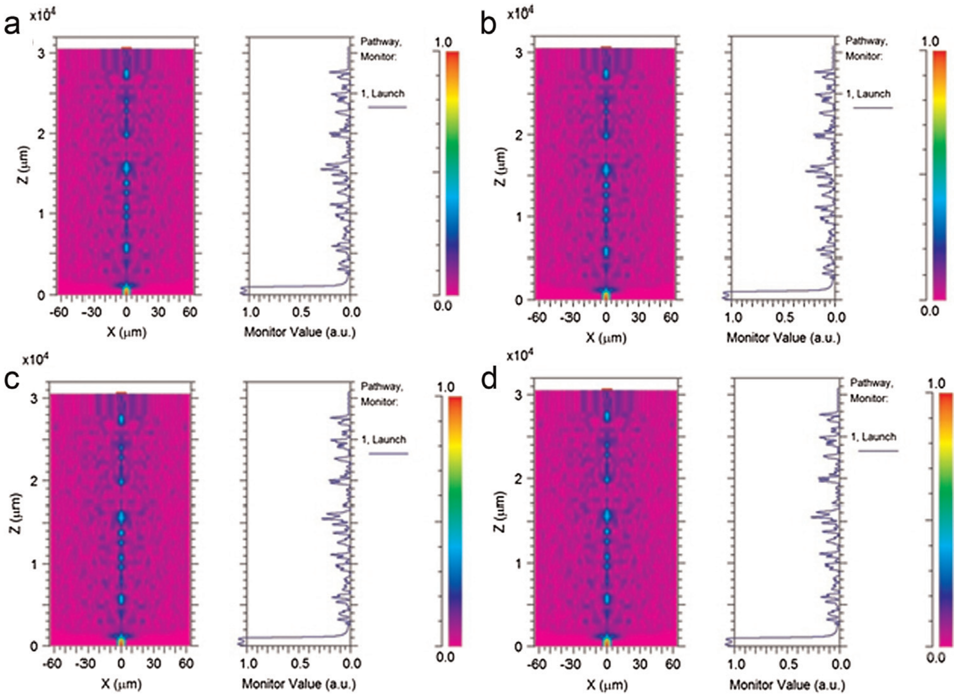

Fig. 3. Simulated light beam propagation along the SMF and TCF for different displacements: (a) 0 μm; (b) 200 μm; (c) 400 μm; and (d) 600 μm.