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Refractive index sensor based on lateral-offset of coreless silica interferometer

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ABSTRACT

A compact, cost-effective and high sensitivity fiber interferometer refractive index (RI) sensor based on symmetrical offset coreless silica fiber (CSF) configuration is proposed, optimized and demonstrated. The sensor is formed by splicing a section of CSF between two CSF sections in an offset manner. Thus, two distinct optical paths are created with large index difference, the first path through the connecting CSF sections and the second path is outside the CSF through the surrounding media. RI sensing is established from direct interaction of light with surrounding media, hence high sensitivity can be achieved with a relatively compact sensor length. In the experimental work, a 1.5 mm sensor demonstrates RI sensitivity of 750 nm/RIU for RI range between 1.33 and 1.345. With the main attributes of high sensitivity and compact size, the proposed sensor can be further developed for related applications including blood diagnosis, water quality control and food industries.

1. Introduction

Optical fiber sensors have been continuously researched to satisfy the ever growing challenges in real applications. Optical fiber based sensor is desirable for many applications due to its compactness, and high design flexibility. There are different types of fiber based sensing techniques which may categorized into fiber laser [1], fiber Bragg grating [2] and fiber interferometer [3–17]. Fiber interferometers such as Fabry-Perot interferometer (FPI) [3], Michelson interferometer (MI) [4] and Mach-Zehnder interferometers (MZI) [5–17] are typically realized from combination of different segments of optical fibers jointed by fusion splicing process. The sensors can be optimized for single or multi-parameters sensing to detect measurands such as temperature, refractive index (RI), bending, displacement and vibration. In order to realize a MZI i.e. with light split and recombine mechanisms, few methods have been proposed which include fiber tapers [5,6], fiber core mismatched [7], partially ablated fiber using femtosecond laser [8–10], peanut-shape structure [11], collapsed region in photonic crystal fiber (PCF) [12,13], lateral-offset [14–17]. Fiber tapers technique has been demonstrated to achieve high sensitivity in refractive index sensing with reported result of 1656.35 nm/RIU for a tapered SMF [5] and 2210.85 nm/RIU for tapers incorporated in a thinned SMF [6]. Ultra-compact partially ablated fiber technique using femtosecond laser has shown further enhancement of performance with achieved sensitivity as high as ∼10,000 nm/RIU [8]. The use of PCF for refractive index sensing also has gained promising result of 1600 nm/RIU with relatively low temperature dependency of 8.49 pm/°C [13]. However, all of the previously mentioned techniques require the use of special equipment or fiber which inevitably will increase overall fabrication cost.

Meanwhile, lateral-offset technique is relatively simpler in terms of process and equipment used compared with the aforementioned techniques. There are several noteworthy works related to lateral-offset fiber interferometer have been demonstrated which can be categorized into two major types. The first type requires a small lateral offset of the sensing fiber such that light from a lead-in fiber will be spread into core and cladding of the sensing fiber, and hence detection is established from the interaction between the cladding modes with the surrounding material [14–16]. The second type of the technique requires large offset of sensing fiber such that light from the lead-in fiber will be spread into the surrounding (e.g. air and liquid) as well as the cladding of a fiber [17], which creates two distinct interferometer arms with large RI difference. RI sensitivity of the latter technique is significantly higher than the former, which can be achieved with relatively much shorter sensor length attributed from direct interaction with the surrounding material. For example, the sensitivity achieved by large offset sensor has been reported as high as 3402 nm/RIU with arm length ∼0.41 mm [17]. This sensitivity is much higher compared to the short offset sensor, for example, a

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small offset evanescent field type sensor with the length of 66 mm has achieved sensitivity of −26.22 nm/RIU [14]. A subsequent work in core-offset evanescent type sensor with tapered MZI arm has shown improvement with reported sensitivity of 78.7 nm/RIU with relatively shorter sensor length of 30 mm [16].

As stated previously, a large offset technique with direct interaction mechanism has demonstrated high sensitivity (in the range of thousands of nm/RIU) with relatively short sensor length. However, the use of single mode fiber as the sensing element and lead in/out fiber in direct interaction scheme [17] is subjected to high tolerance requirement as the core diameter of single mode fiber is typically around 9 μm. This suggests that slight misalignment in the range of few micrometers could lead to an unworkable sensor. To mitigate this problem, we propose the use of core-offset structure based on coreless silica fiber (CSF) in MZI configuration. The use of CSF allows lower tolerance requirement due to the large diameter of the lead in/out cladding of 125 μm, hence easier fabrication while retaining high sensitivity of the scheme. In this work, the sensor structure is simulated in BeamProp software to obtain the optimum offset value for maximum fringe for a particular arm length. The optimized designs are then fabricated using customized fusion splicing recipe. A CSF based MZI sensor with length of 1.5 mm demonstrates RI sensitivity of 750 nm/RIU for the range between 1.33 and 1.345. Temperature dependence of the sensor is also studied to understand the extent of temperature effect. Temperature sensitivity manifested by the sensor is 27.21 pm/°C for the range between 30 and 100 °C. The main advantages of this sensor are that, high sensitivity has been achieved with relatively very short sensor length of 1.5 mm and the lower tolerance in term of the accuracy requirement of offset distance that reduce the complexity during fabrication process.

2. Working principle and optimization

The proposed MZI structure consists of three sections of CSFs (FG125LA, Thorlabs) sandwiched between two lead in/out SMFs as shown in Fig. 1. All the fiber sections are aligned centrally in the y-direction. Meanwhile, in the x-direction, section B is offset by a certain distance, *d* relative to the position of the top of sections A and C. This creates a symmetrical structure of the sensor which aimed to simplify the optimization process by only varying the offset distance at particular sensor length (section B length). The second optical path is created in a gap between section A and C from the offset process, allowing light to be directly interact with surrounding refractive index. As can be seen, reflected light from Section A and Section C of the CSF may recombine to form a Fabry-Perot structure. However, the weak reflection from Section C in current setup prevents the desired interference effect from occur. The core/cladding diameters of SMF used in simulation and experiment are 9 μm/125 μm, while the cladding diameter of CSFs is 125 μm. Section A, B and C lengths are 0.5 mm, 1.5 mm and 0.5 mm, respectively. The use of a 125 μm diameter of the CSF which is identical to the SMF is to avoid unnecessary complexity in splicing process.

As illustrated in Fig. 1, the incoming light is spread throughout the CSF diameter of the section A. Due to the offset, the light is split into the surrounding and into section B, and then recombined at section C. A large portion of light in section C is further transmitted to the cladding of the lead-out fiber. The cladding mode in SMF will be eventually diminished due to high scattering loss of the cladding and leakage loss. Leakage loss occurs if the cladding surface is covered by material with refractive index higher than that of the cladding such as acrylic residue [18]. Due to small overlap of surface area, a small portion of the light in section C is transferred to core of the lead-out SMF. The working principle of the proposed structure is identical to a MZI. Hence, the intensity of the light detected at the receiving photo detector can be expressed as:

$$I(\lambda) = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\emptyset \quad (1)$$

I_1 and I_2 are the light intensities of the CSF modes and the gap modes, respectively. While $\emptyset$ is the phase difference between these two modes which can be written as:

$$\emptyset = \left(\frac{2\pi(n_{cl} - n_{eff})L_0}{\lambda}\right) \quad (2)$$

where λ is center wavelength of light source, L_o is the MZI arm length, n_{cl} and n_{eff} are the effective refractive indices of CSF cladding and surrounding material in the gap, respectively. Any change of the surrounding RI will drastically change the interference spectrum due to direct interaction of the light with the surrounding. According to this equation, it is crucial to have $I_1 = I_2$ in order to get maximum fringe visibility of the interference spectra [19]. The dip and peak of the interference spectra occur when the $\emptyset$ is multiple of $(2N+1)\pi$ and $2N\pi$, respectively, where N is an integer. Under this

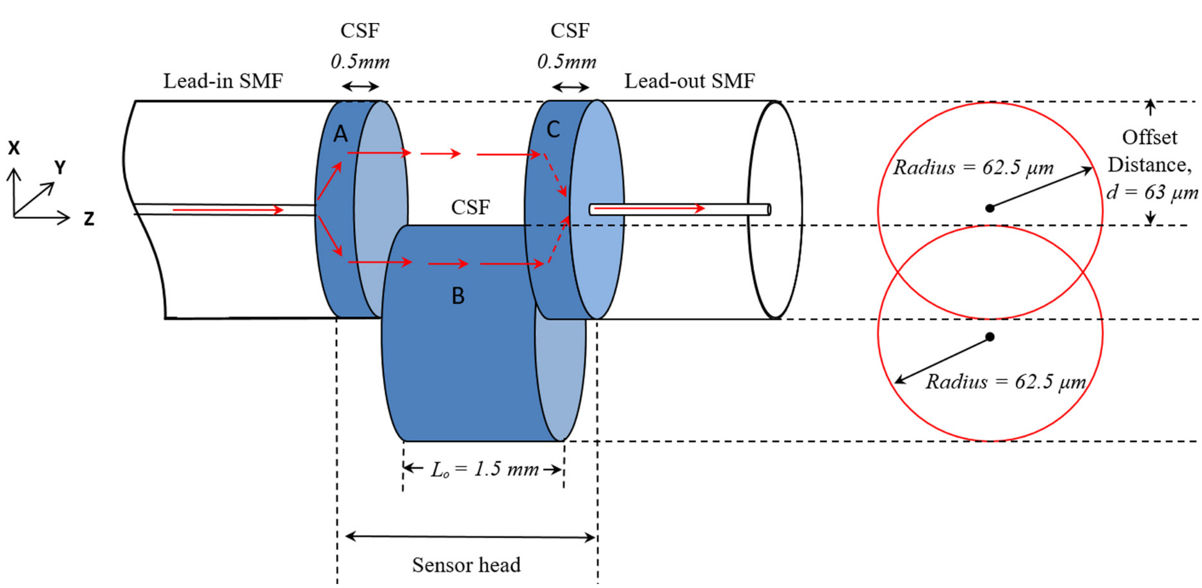

Fig. 1. Schematic of the core-offset CSF based MZI sensor.