Optics & Laser Technology 63 (2014) 76–82

Contents lists available at ScienceDirect

Optics & Laser Technology

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

Review

A robust fiber inline interferometer sensor based on a core-offset attenuator and a microsphere-shaped splicing junction

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A R T I C L E I N F O

Article history:
Received 17 December 2013
Received in revised form
10 March 2014
Accepted 1 April 2014
Available online 23 April 2014

Keywords:
Mach–Zehnder interferometer
Refractive index sensors
Temperature sensor

A B S T R A C T

A robust inline fiber interferometer sensor based on concatenating a core-offset attenuator and a microsphere-shaped splicing junction is proposed, fabricated and applied for sensing applications. Its transmission spectrum shows multiple resonant dips due to the interference between core and cladding modes. While the interferometer sensor is utilized to test surrounding RI from 1.33 to 1.37, it exhibits a linear relationship between peak wavelength shift and RI change. A maximal sensitivity of −56.325 nm/RIU (refractive index unit) is obtained. For temperature sensing, the sensor presents a fair quadric relationship between peak wavelength shift and temperature from 25 to 650 °C, in which the variation rate of the effective RI difference between core and cladding modes with temperature is nonlinear. In addition, a coefficient matrix is constructed to simultaneously measure RI and temperature. The fiber interferometer sensor offers high potential in sensing applications due to its advantages of low cost, simplicity, and robustness.

Contents

1. Introduction

Various fiber sensors have been intensively studied to detect physical quantities including refractive index (RI), temperature, gas concentrations, and stress based on their unique advantages such as immunity to electromagnetic interference, compact size, low cost, and the possibility of distributed measurement over long distance [1,2]. Among many fiber-optic techniques, fiber-based interferometer sensors exhibit prominent merits of high sensitivity, high integration, simplicity, and compact inline measurements. Recently, large amounts of interferometer structures have been reported, including Mach–Zehnder interferometers (MZIs) [3–21], Fabry–Pérot interferometers (FPIs) [22–35], Michelson interferometers (MIs) [36–39], and various grating based interferometers [40–45]. MZIs and their applications have gained considerable attention recently. Various structures can form MZIs, including two core-offset attenuators on a single-mode fiber (SMF) [17], two abrupt tapers [3–5,21], a microcavity pair based interferometer [10], etc. FPIs structures require precise and small cavities in the beam path, which can be realized in several ways, such as drilling

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http://dx.doi.org/10.1016/j.optlastec.2014.04.002

vertical micro-channels in the fiber [24,32,33], simply splicing a section of endlessly single-mode photonic crystal fiber to a conventional single-mode fiber [26], and large lateral offset splicing [22]. MIs need a beam splitting structure and a reflection part, the reflection part is normally made by metal deposited fiber ends, and the beam splitter structure can be made using an abrupt taper [37,39] and a fiber-core mismatch [38]. Grating based interferometers shows large signal-to-noise ratio (SNR) and uniform interference fringes and many efforts are made to improve the sensor sensitivities [40,42,45], or extend the application range of normal gratings [41,43,44].

RI and temperature are two key parameters in chemical or food industries monitoring. The reported ultrahigh RI sensitivity is on the order of ~1000 nm/RIU [46,47] and the normal RI sensitivity is from tens to hundreds of nm per RIU due to low loss of evanescent field to outer medium [43,45,48,49]. RI of liquid is normally temperature sensitive, which causes a cross sensitivity problem, thus it demands the fiber sensor can still precisely work at different temperature. This study proposes a simple and robust MZI based on the interference between core and cladding modes. The sensor, consisting of a core-offset attenuator and a microsphere-shaped splicing junction, is fabricated by a commercial fusion splicer using a SMF and therefore is extremely cost effective compared with LPFG, FBG, and PCF type sensors. Just one core-offset attenuator design avoids the asymmetric problem of two core-offset attenuators. For RI sensing, it exhibit different sensitivities by using different peaks and it can reach a maximum sensitivity of −56.325 nm/RIU in the range of 1.346–1.369. As to temperature measurement, it offers a capability to measure a large temperature range up to 650 °C. Meanwhile, a coefficient matrix is constructed to measure RI and temperature simultaneously.

2. Principle

Fiber-based interferometric sensing requires a splitting of optical signals into two separate arms and their subsequent recombination for phase difference detection [39]. Fig. 1 illustrates the schematic structure of the interferometer sensor. By fusion splicing two coating stripped sections of SMF with a certain connector offset, light from the transmission fiber is split into two paths. A fraction of light remains in the fiber core, while the remainder is transferred to the cladding and subsequently propagates as higher order cladding modes. The excited cladding modes cannot propagate over long distance due to the attenuation at the cladding–ambient interface. However, if another recombination junction is introduced only several centimeters away from the core-offset attenuator, light in the cladding can be coupled back to the core. In this study, a microsphere-shaped splicing junction is introduced to recombine the light in cladding and core. Due to the difference of effective RI between core and cladding modes, there is a phase difference ϕ when the two arms of the light reach the recombination junction and it can be determined by the following equation:

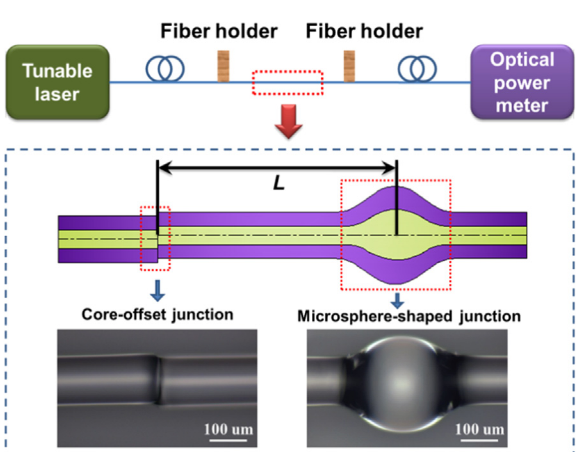

Fig. 1. Schematic structure of the interferometer and the optical microscope images of the core-offset and the microsphere-shaped junctions (L is the length between the two junctions).

$$\phi = \frac{2\pi(\delta n_{eff} L)}{\lambda} + \varphi_0 \tag{1}$$

where $\delta n_{eff} = n_{eff}^{core} - n_{eff}^{cladding}$ denotes the effective RI difference between core n_{eff}^{core} and cladding modes $n_{eff}^{cladding}$. L is the length between core-offset attenuator and microsphere-shaped splicing junction, λ is the wavelength of propagating light. The second term φ_0 accounts for the initial phase difference. While light emitted by a tunable laser propagates through the interferometer, the two arms of light propagating in the core and cladding will interference destructively if the following condition is satisfied.

$$\frac{2\pi(\delta n_{eff} L)}{\lambda_m} + \varphi_0 = (2m+1)\pi \tag{2}$$

where m is an integrator and λ_m is the peak wavelength of the mth order interference dip. By use of Taylor expanding, the fringe spacing of the mth interference dip $\lambda_m^{spacing}$ can be approximated to [8,50,51]

$$\lambda_m^{spacing} \approx \frac{\lambda_m^2}{\delta n_{eff} L} \tag{3}$$

If the RI of surrounding environment or ambient temperature changes, this will lead to a phase difference change $\Delta\phi$ and hence the peak wavelength will make a shift $\Delta\lambda$. Combining Eqs. (1) and (3), the relationship between $\Delta\phi$ and $\Delta\lambda$ can be approximately expressed as

$$\frac{\Delta\phi}{2\pi} \approx \frac{\Delta\lambda}{\lambda_m^{spacing}} \tag{4}$$

For the RI testing, the phase difference $\Delta\phi_m^{RI}$ is caused by the variation of the effective RI difference $\Delta(\delta n_{eff})$, depending on the surrounding RI. The peak wavelength shift $\Delta\lambda_m^{RI}$ can be described by

$$\Delta\lambda_m^{RI} = \lambda_m^{spacing} \frac{\Delta\phi_m^{RI}}{2\pi} = \frac{L \cdot \lambda_m^{spacing}}{\lambda_m} \cdot \Delta(\delta n_{eff}) \tag{5}$$

The cladding modes are guided by the cladding–ambient interface and directly exposed to the environment. The evanescent field of these modes extends beyond the cladding of the host fiber, and then the RI variation of the ambient can be detected [52–55]. If the surrounding RI increases, the effective RI of cladding modes will decrease, resulting in a blueshift of peak wavelength.

The change of the ambient temperature results in the phase difference variation of $\Delta\phi_m^T$ for the interferometer, which can be expressed as the equation below by making a mathematical differentiation of Eq. (1)

$$\Delta\phi_m^T = \frac{2\pi L}{\lambda}\left(\frac{\partial(\delta n_{eff})}{\partial T} + \delta n_{eff} \cdot \frac{1}{L}\frac{dL}{dT}\right) \cdot \Delta T \tag{6}$$

where $\partial(\delta n_{eff})/\partial T$ is the thermally induced variation of the effective RI difference, and the second term is attributed to the thermal expansion effect. Combining with Eq. (4), the peak wavelength shift corresponding to temperature altering can be described as [56,57]

$$\Delta\lambda_m^T = \frac{L \cdot \lambda_m^{spacing}}{\lambda_m}\left(\frac{\partial(\delta n_{eff})}{\partial T} + \delta n_{eff} \cdot \frac{1}{L}\frac{dL}{dT}\right) \cdot \Delta T \tag{7}$$