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Physical measurement with in-line fiber Mach-Zehnder interferometer using differential phase white light interferometry

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ABSTRACT

In this letter, the sensitivity to strain, curvature, and temperature of a sensor based on in-line fiber Mach-Zahnder interferometer (IFMZI) is studied and experimentally demonstrated. The sensing structure is simply a section of single mode fiber sandwiched between two abrupt tapers to achieve a compact IFMZI. The phase of interferometer changes with the measurand interaction, which is the basis for considering this structure for sensing. The physical parameter sensitivity of IFMZI sensor has been evaluated using differential white light interferometry (DWLI) technique as a phase read-out system. The differential configuration of the IFMZI sensor is used to achieve a high phase resolving power of ± 0.062° for read-out interferometer by means of omission of phase noise of environment perturbations. The sensitivity of the sensor to the strain, curvature, and temperature has been measured 0.0199 *degree/με*, 757.00 *degree/m*$^{-1}$, and 3.25 *degree/°C*, respectively.

1. Introduction

In-line fiber interferometer sensors based on modal interference have been extensively investigated in recent years for the advantages of simplicity of structure, easily and low cost constructing, no couplers required, reduced susceptibility to ambient conditions which make devices more compact and simple in the applications of refractive index [1,2], pH [3], temperature [4,5], strain [6], flow meter [7], and curvature sensor [7–9]. In-line fiber Mach-Zehnder interferometers (IFMZI) as a usual modal interferometers consists of an optical fiber placed between two internal optical mode couplers. Various IFMZI structure with different mode coupler designs have been proposed and constructed, for instance, mismatched core diameter [9,10], long period grating pairs [11], lateral-offset and up-taper [12], abrupt taper pairs [1,6,8,13].

To characterize the IFMZI output, the channel spectrum of the sensor using a commercial spectrum analyzer usually is analyzed. The wavelength shift of spectrum and/or fringe visibility change was concerned as a function of physical measurand changes. The other practical and most attractive interferometric interrogation system is based on white light interferometry system. In this read-out system, the interferometric phase was achieved combining white light addressing with pseudo-heterodyne or phase generated carrier signal processing [2,10,14].

The differential white light interferometry (DWLI) method has been developed to eliminate the disturbances induced by thermal drifts, or vibrations in the read-out interferometric system. Meanwhile, the DWLI technique has been employed to measure differential temperature [15], refractive index [2,16], Humidity [17] and for fuel conformity analysis [18]. To our knowledge, A.D. Kersey and et al. [15], have demonstrated experimentally a differential temperature fiber Bragg sensor based on DWLI technique for the first time. Y.L. Lo and et al. [16] used two Fabry-Perot interferometers, one as sensing head and the other as reference sensor and then using two parallel Fabry-Perot cavities as two path-matching cavity, the differential phase has been measured. C. Gouveia and et al. [2] have interrogated two similar non-adiabatic tapered optical fiber sensor in a differential scheme using a Mach-Zehnder white light interferometry. They have demonstrated the performance of the design to detect the refractive index change of $\Delta n \approx 1.46 \times 10^{-6}$. S.M. Murtry and et al. [17] have been shown the performance of a humidity sensor based upon the measurement of the refractive index of air using low coherence differential interferometry. J.H. Osorio and et al. [18] have been developed a high sensitivity fiber fuel conformity analysis sensor. The sensor is in-line Mach-Zehnder interferometer using mechanically induced long period grating and tapered fiber and the sensor has been interrogated using the DWLI technique.

In this work, a simple structure of IFMZI based on two abrupt tapers over a short length of single mode fiber (SMF) to couple partial core mode into cladding modes and vice versa has been fabricated. Since the core and cladding modes exhibit different responses to various physical parameters, the phase of interferometer changes with the measurand interaction, which is the basis for considering this structure for sensing. The physical parameter sensitivity of IFMZI sensor has been evaluated

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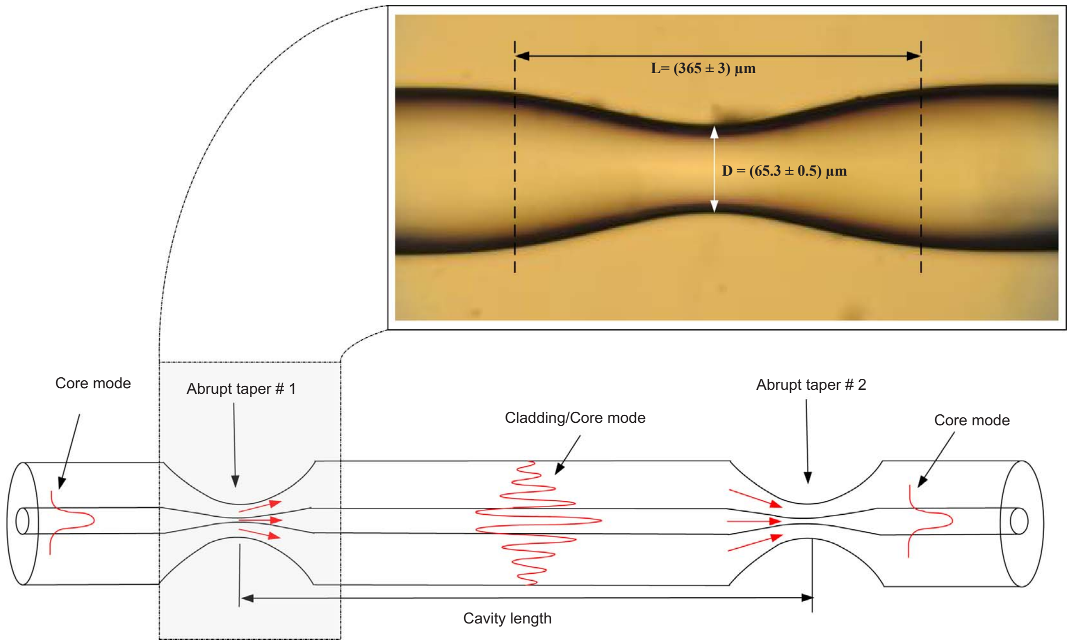

Fig. 1. Schematic configuration of IFMZI structure. The inset shows the optical microscope image of a fabricated abrupt taper.

using DWLI technique. The differential configuration of the sensor is used to compensate the phase noise of environment perturbations. The IFMZI experimentally is characterized for strain, curvature and temperature.

2. Sensing principle and experimental setup

2.1. IFMZI sensor and fabrication process

The IFMZI used in this work consists of a section of SMF placed between two abrupt tapers as the optical mode couplers. According to [1,6,8,13], abrupt taper, which is defined as axisymmetric short taper fiber with an adequate taper angle, can be used to excite the cladding mode and hence, so this two tapers leads to form a compact IFMZI interferometer. Fig. 1 shows the schematically the IFMZI structure. For the simplified case, assumed that the interference only occurs between core and a special cladding mode. The transmission intensity of IFMZI can be expressed by

$$I= I_1 + I_2 + 2\sqrt{I_1 I_2}\cos[2\pi\Delta n_{eff}\, d/\lambda] \quad (1)$$

where I_1 and I_2 are the intensity of the core and cladding modes, d and λ are the distance between two tapers and wavelength of light, respectively. Also, $\Delta n_{eff} = n_{co}^{eff} - n_{cl}^{eff}$ is the effective refractive index difference of the core and cladding mode and n_{co}^{eff} and n_{cl}^{eff} are effective refractive index of the core and cladding mode, respectively. Because the core mode and the cladding modes have different propagation constants, the optical path difference (OPD) between them leads to interferences in the transmission spectra of IFMZI sensor. Since, the core and cladding modes exhibit different responses to various physical parameters, such as temperature, strain, and curvature, then, a phase shift occurs when the OPD between the core and cladding modes i.e. $\Delta n_{eff}\, d$ is altered.

A commercial fusion splicer machine was used to fabricate the IFMZI sensor employing manual splicing mode. Firstly, a section of SMF is cleaved and put into the fiber fusion splicer to fabricate an abrupt taper. By tuning the proper parameters in manual splicing mode, the SMF fiber is spliced to other cleaved fiber while an abrupt taper is fabricated at this section. Then, a proper length of this fiber was cleaved and fiber coating of this section was stripped off and then the second abrupt taper with the same pervious conditions was made. During the fabrication process, a laser lunched to the input of fiber and the power output is monitored with a power meter. The fusion parameters has been adjusted to produce an abrupt taper with 3 dB insertion loss. An optical microscope image of a fabricated abrupt taper has been shown in inset of Fig. 1. The length of the tapered region was measured L= $(365 \pm 3)\mu$m, while the waist was D= $(65 \pm 0.5)\mu$m.

When IFMZI is subjected to external bending, the inner part of fiber is compressed while the outer part is stretched. Therefore, the OPD will change, resulting in phase shift between core and cladding mode. The asymmetric of index profile, derived from external bending, will induce the changes in the symmetry of the cladding modes, while the profile of the core mode can be considered constant because the diameter of fiber core is much smaller than that of fiber cladding. According to [9,19] for some cladding modes such as LP_{04}, LP_{12}, $LP_{21,}$ the effective index of mode decreases with curvature while the other modes like LP_{02} and LP_{03} behave contrary. Therefore, the sign of phase shift depends on which group of cladding modes is dominant in interfere with core mode.

A geometry of curved IFMZI sensor along Y-axis direction is shown in Fig. 2. The effective refractive index difference of the core and cladding mode due to optical fiber bending can be expressed by [8,9]:

$$\delta(\Delta n_{eff}\, d) = \eta^{cl}.\ C \quad (2)$$

Where η^{cl} is the sensitivity of OPD to the curvature variation and depends on cladding mode number and strain refractive index coefficient of cladding mode and $C = 1/R$ is defined as the curvature parameter versus m^{-1} for fiber bending radius of R. According to Fig. 2, the translation stage movement distance x can be converted to fiber curvature C and so C can be approximately expressed by [8]

$$C = \frac{1}{R} = \sqrt{24x/L_0^3} \quad (3)$$

where R is the radius of the bent fiber and the L_0 is the initial length of the bent fiber segment.

Moreover, when the strain ε and the temperature variation ΔT is applied to the IFMZI, corresponding phase shift can be expressed by [4,13]

$$\delta(\Delta n_{eff}\, d) \approx (\Delta n_{eff}\, d)[(1 + \Gamma_{strain})\varepsilon + (\alpha + \Gamma_{temp})\Delta T] \quad (4)$$

where Γ_{strain} is the efficient elesto-optic coefficient, α is thermal expansion coefficient of fiber, and Γ_{temp} is efficient thermo-optic