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Strain measurement at high temperature environment based on Fabry-Perot interferometer cascaded fiber regeneration grating

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ABSTRACT

In this paper, a Fabry-Perot interferometer structure (FPIS) cascaded with a regenerated grating (RG) is proposed for strain measurement in a high temperature environment. The FPIS is fabricated by splicing a section of simplified hollow-core fiber (HCF) between two single-mode fibers (SMFs). Simple splicing and cleaving techniques are used to optimize the interferometer in order to produce the FPIS with the properties of lower temperature sensitivity and high strain sensitivity. The optimized FPIS is cascaded with a seed grating and then subjected to a thermal annealing process in order to activate the RG. Experimental results indicate that the proposed sensor can be used for simultaneous measurement of strain and temperature over ranges of 0 $\mu\varepsilon$ to 600 $\mu\varepsilon$ and 19 °C to 600 °C, respectively, and consists of a matrix with a low condition number of 12.09.

1. Introduction

Since the last few decades, fiber optical based sensors are considered as a leading area of interest among many researchers and industries in several sensing applications due to their numerous advantages namely, light weight, low cost, and immunity to electromagnetic interference (EMI). The physical parametric sensing has a significant role for health monitoring in various structures, chemical, as well as the oil and gas industries. Among them, fiber optic sensors suitable for dual-parameter simultaneous monitoring have attracted the attention of many research groups. Simultaneous measurement of the strain and temperature is crucial for applications in the aviation industry, high temperature oil and gas pipelines, combustion engines, and nuclear reactors, etc. [1–4].

In this regard, many fiber optic based techniques have been reported for simultaneous measurement of strain and temperature in order to fulfill the requirements of modern industries. Two fiber Bragg gratings (FBG) with different wavelengths were inscribed on a single mode fiber (SMF) for simultaneous measurement of strain and temperature up to 60 °C and 600 $\mu\varepsilon$, respectively [5]. A long period grating (LPG) inscribed using CO_2 laser and packaged with a hybrid mechanism of elastic gauge attachment was used to measure large strain up to 15 $\mu\varepsilon$–200 $\mu\varepsilon$ until a temperature level of 700 °C [6]. Most recently, it has been reported that thermal regeneration in dual gratings with wavelengths of 1310 nm and 1550 nm has been helpful in achieving strain measurement at ultra-high temperatures up to 800 °C [7]. This dual FBGs technique was based on the wavelength dependence of the photo-elastic effect which was useful in achieving the two gratings with different temperature and strain sensitivities. To improve the strain sensitivity at ultra-high temperature environment, Wang et al. studied the strain response of cladding etched RG over a temperature range up to 800 °C. Experimental results show that the strain sensitivity enhances from 0.86 pm/$\mu\varepsilon$ to 4.5 pm/$\mu\varepsilon$ when the fiber diameter was etched from 125 μm to 60 μm [8]. The long-period fiber grating written using high-frequency CO_2 laser pulses was proposed for high-temperature measurement up to 650 °C while the micro extrinsic Fabry-Perot interferometer sensor fabricated using 157 nm F2 laser pulses, was used for strain measurement under high temperature [9]. A FBG combined with a segment of multimode fiber that acts

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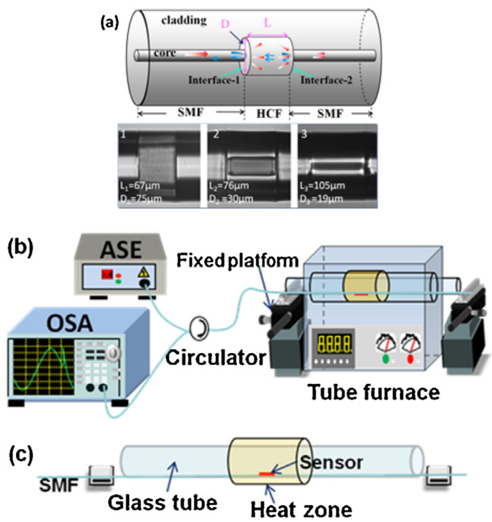

Fig. 1. (a)Schematic diagram and figure taken from splicer for FPIS structure using three different diameters of HCFs, (b)Experimental setup for strain and temperature measurement, (c)The state of fiber in tube furnace.

as a Mach–Zehnder interferometer was also used for strain and temperature measurement. Experimental results showed that the condition number was 44.96 [10]. Two long-period fiber gratings, inscribed on a segment of few-mode fiber and SMF respectively, were cascaded for strain and temperature measurement [11].

In this paper, a Fabry-Perot interferometer structure (FPIS) cascaded with a regenerated grating (RG) for strain measurement at high temperature up to 600 °C is proposed. The interferometer structure is formed with a hollow-core fiber (HCF) sandwiched by two SMFs and the performance is experimentally optimized to achieve low temperature and high strain sensitivities. The proposed sensor structure is calibrated and characterized and the experimental results are obtained using a sensitivity matrix. Experimental results indicate that the proposed technique can be adhered to potential applications in the chemical and space industries.

2. Sensing principle and fabrication

The schematic diagram of FPIS structure is shown in Fig. 1(a). In this structure, the refractive index difference between the core of SMF and HCF takes a large value which results in a partial Fresnel reflection at interface-1 and interface-2. The propagation light in SMF reaches the glass-air interface-1 and a portion of light reflects back into SMF, meanwhile, the remaining light that couples into HCF excites the high-order modes. In general, transmitted high-order cladding modes cannot propagate in the fiber core due to being absorbed by the surrounding high-index. However, once the coupling conditions, such as the fiber core mismatch or the refractive index change are satisfied, the fundamental mode is excited to high-order modes, and the reflected or transmitted high-order cladding modes are recoupled into the fiber core. They can propagate over a long distance with a transmission loss as low as that of the core mode. Thus, both the high-order modes and fundamental mode can be guided by HCF which subsequently propagates into the air-glass interface-2. Portions of them reflect at interface-2 and the residues pass through the interface and couple into the cladding and core of SMF. As such, an interference pattern is formed in the HCF, if the fundamental mode and high-order modes satisfy the phase matching condition, which is finally guided by lead-in SMF and detected by Optical Spectrum Analyzer (OSA).

The distribution of energy and the visibility of fringe pattern heavily rely on the ratio of the intensity of $I_{LP_{01}}$ and $I_{LP_{ij}}$ [13]. The optical interference pattern intensity can be expressed as,

$$I = I_{01} + \sum_{ij} I_{ij} + 2\sum_{ij}\sqrt{I_{01}I_{ij}}\cos(\Delta\phi_{ij}) \tag{1}$$

where, I_{01} is the intensity of fundamental mode, I_{ij} is the cladding mode, ϕ_{ij} is the corresponding phase difference between the core mode and ith cladding mode, here i ,j = 1, 2, 3... The optical path-length difference between the fundamental mode of$I_{LP_{01}}$ and a cladding mode of $I_{LP_{ij}}$ propagating through an interferometer of length L at operation wavelength λ leads to a phase difference of,

$$\Delta\phi_{ij} = \frac{2\pi\Delta n_{eff}^{ij} L}{\lambda_m} = (2m+1)\pi \tag{2}$$

From Eq. (1), it can be seen that the fringe pattern intensity is determined from the intensities of I_{01} and I_{ij}. Once the FPIS is treated for temperature and strain measurement the effective index of fiber cladding $n_{eff-cladding}$ and fiber core $n_{eff-core}$ experiences different values due to the three layered structure of optical fiber even though the fiber core and cladding share the same thermal optic coefficient α and stress-optic coefficient ζ, respectively. Besides, the FPIS cavity length L changes with the applied stress. From Eq. (2), it is understood that the phase difference varies with variation in all three parameters $n_{eff-cladding}$, $n_{eff-core}$ and L, which finally induces the change in the interference pattern.

Furthermore, the fundamental mode and cladding modes that pass through interface-1 and interface-2 will suffer from coupling loss due to the mismatch in the core diameter between SMF and HCF. In our observation, the splicing loss is the range of 0.3–0.5 dB at well-controlled splicing conditions. These intensity losses affect the interference pattern and therefore, the splicing has to be carefully implemented and well controlled to enhance the interference visibility. To avoid the Fresnel reflection, the end surface of the lead-out SMF was angle cleaved. Theoretical calculation in the work of [12] shown that the power of high-order modes reflected by the end surface of lead-out SMF is less than 0.1% which can be neglected to attribute the interference pattern.

A Fujikura arc fusion splicer (FSM-100P+) was used in the current experiment and the arc condition was manually controlled to avoid the air-core of HCF from being collapsed. Experimental setup for calibration of the sensor is shown in Fig. 1(b). Amplified spontaneous emission (ASE) from an Erbium doped fiber amplifier (EDFA) was used as a broad band light source, which was connected through a circulator to the sensor. The fiber sensor was freely passed through a glass tube furnace and formulated by thermal annealing process as shown in Fig. 1(c). The length of the heating zone in the tube furnace was ~200 mm, where the fiber sensor was placed at the central position of the glass tube in order to make sure it experienced a well-distributed ambient temperature. Reflection spectrum of the FPIS was measured using an OSA with a wavelength resolution of 0.02 nm. To characterize the response of the sensor with longitudinally applied strain, two sides of sensor were fixed using epoxy on the fixed platform, where one side was fastened on a micro-displacement stage with a displacement resolution of 0.01 mm. The fiber was then stretched by a calibrated micrometer and the measurements of both ΔL and L were taken. The initial tension was carefully fixed and the increment at each step was made using the micro- displacement linear stage. A displacement step of 0.1 mm was applied to 1.0 m fiber which is equal to a strain step of 100 $\mu\varepsilon$. Each increment length and the corresponding wavelength λ were recorded, respectively. This proposed sensor is compact and fabricated only with the usage of splicing and cleaving techniques. These advantages show that the proposed sensor will be poten-