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Original research article

Simultaneous measurement of current and temperature by using an all-fiber interferometric cost-effective and non-destructive sensing scheme

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A B S T R A C T

A single-mode single fiber Mach-Zehnder interferometer is fabricated and employed for simultaneous measurement of temperature and direct current flowing through the resistor without disturbing the electronic circuit. The all-fiber interferometric sensing scheme is completely non-destructive, cost-effective and relies on change in heat induced fringe pattern of the Mach-Zehnder interferometer placed near the direct current carrying power resistor. The values of the sum of the modal thermo-optic coefficient and thermal expansion coefficient and other thermal properties of the optical fiber are also estimated. The optical and electrical methods proposed herein are found to be repeatable and provides stable results. The scheme predicts reasonable accurate values of the temperature and direct current with the root mean square errors of 0.45 and 0.00084, respectively.

1. Introduction

Optical fiber sensors seem to have overwhelming advantages, such as high sensitivity, compactness, light weight, immunity to electromagnetic interference, remote sensing and multiplexing capability over conventional sensors. These sensors have been successfully realized for a wide range of applications including the measurement of temperature [1–3], pressure [3,4], current [5,6], refractive index [3], strain [4,7], magnetic field [8], angle [9], hydraulic pressure, humidity [10], heart rate detection [11], and so on. In recent times, simultaneous measurements of multi-parameter all-fiber sensors have been reported [1,3,4]. Many all-fiber interferometric sensing techniques, for instance, long period fiber grating (LPFG) [12], fiber Bragg grating (FBG) [12], Mach-Zhender interferometer [7–10], have been reported for estimation and measurement of diverse physical parameters. Similarly, cascaded interferometer structure based on Mach-Zehnder interferometer (MZI) and Sagnac interferometer has been also proposed for simultaneous sensing of strain and stress [4]. Despite many advantages, all-fiber interferometers suffer from high degree of random variations in their output response/fringe pattern necessitating the use for employment of special packaging techniques [13].

Further, in order to reduce the Joule's heat losses in the high tension power transmission lines, there has been a proposal for replacing the existing AC (alternate current) transmission by employment of DC (direct current) transmission lines. The Joule's heat dissipation (in DC transmission lines even though less than that of AC transmission lines) leads to axial elongation of the transmission electric wires. Such problem necessitates the estimation/measurement of the current flowing through the long distance power transmission line in real time [5]. The Faraday effect based (non-fiber based) current sensors are costly and bulky in nature.

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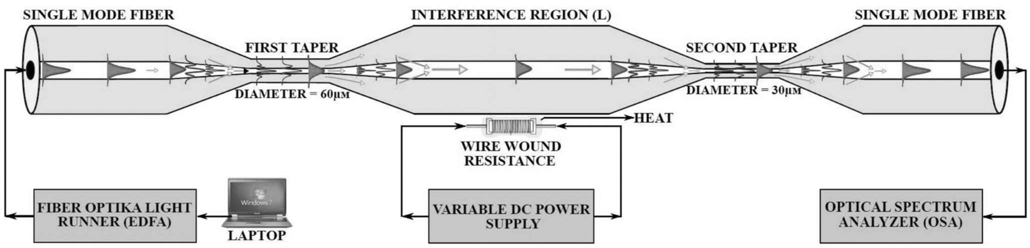

Fig. 1. Schematic of the optical experimental setup.

Generally, all-fiber current sensor exploits the change in state of polarization (SoP) of the light traveling through the optical fiber due to the Faraday's effect [6]. However, the polarization based all-fiber technique requires the employment of long fiber length, and extensive and complicated electronic circuitry arrangement. Recently, an interesting tapered fiber based configuration has been reported for sensing direct current [5,6]. The major advantage of this configuration is its stable wavelength spectrum and non-destructive nature. The cascaded taper based configuration forms a single-mode single fiber (SMSF)-MZI, which is easier to fabricate, and capable of sensing multiple parameters [3]. In the present paper, all-fiber SMSF-MZI is fabricated and placed near a current carrying power resistor. The dissipated Joule's heat (by power resistor) induces changes in output wavelength response of all-fiber SMSF-MZI, which are optically and electrically measured on optical spectrum analyzer (OSA) and photo-detector interfaced LAB-VIEW system, respectively. A LABVIEW interfaced all-fiber sensing system, reported herein, is more user friendly and economically viable solution over the OSA based fiber optic sensors. By comparing the theoretical formulation with those of experimental observations, the values of the thermal properties of the optical fiber, ambient temperature and direct current flowing through the resistor are determined and found to be reasonably accurate and stable. The shift in the fringe width at various wavelengths in the yield range of the fabricated interferometer is shown at the first time and the resonant wavelength with maximum sensitivity and linear dependence is also distinguished.

2. Operational mechanism of SMSF-MZI

An all-fiber SMSF-MZI sensing arm is constituted of two cascaded abrupt bi-conical tapers separated by an un-tapered and un-jacketed fiber having length of few centimeters, while the input and output ends remains as a single mode fiber. The un-tapered fiber, between the two tapered sections, acts as an interference region, and its length is called as the interference length (L) and its schematic representation is depicted in Fig. 1.

The higher order cladding modes get excited as the input light propagates through the first non-adiabatic tapered fiber. Under weakly guiding approximation, considerable amount of power initially possess by LP_{01} mode gets coupled with LP_{02}, LP_{03} and other higher cladding modes. However, fraction of the optical power coupled to other higher order cladding modes is negligible small and the most of the power is retained by LP_{01}, LP_{02} and LP_{03} modes. As these three modes enter the un-tapered and un-jacketed fiber length L, the beating among these modes, before combining at the entrance of second fiber taper, would lead to occurrence of interference pattern. The wavelength spectrum confirming the beating process can be observed on an OSA connected to the output port of the second fiber taper of SMSF-MZI. Since the interferometer is realized by employing a single-mode single fiber, it is called as SMSF-MZI. As all the interfering modes propagate through a single arm, the fringe pattern provided by this configuration is more stable in comparison to two/multi-arms all-fiber interferometers. Most of the earlier investigations on SMSF-MZI considered the interference between LP_{01} and LP_{02} modes and the free spectral range (FSR i.e. $\Delta\lambda$) of the output spectrum was expressed as [7]:

$$\Delta\lambda = \frac{\lambda^2}{\Delta n_{eff} L} \tag{1}$$

where $\Delta n_{eff} L$ is the optical path difference for the LP_{01} and LP_{02} modes, with effective indices n_{eff_1} and n_{eff_2} respectively, propagating through the interference length (L).

The variations in FSR of the wavelength spectrum with change in temperature and other environment random variations can be illustrated through:

$$\frac{1}{\Delta\lambda}\frac{\partial\Delta\lambda}{\partial T} = \left(\frac{1}{\Delta n_{eff}}\frac{\partial\Delta n_{eff}}{\partial T} + \frac{1}{L}\frac{\partial L}{\partial T}\right)$$

$$\frac{1}{\Delta\lambda}\frac{\partial\Delta\lambda}{\partial T} = \frac{1}{\lambda}\frac{\partial\lambda}{\partial T} = (\alpha + \beta) \tag{2}$$

where $\alpha = \frac{1}{\Delta n_{eff}}\frac{\partial\Delta n_{eff}}{\partial T}$ and $\beta = \frac{1}{L}\frac{\partial L}{\partial T}$; are modal thermo-optic and thermal expansion coefficient of the silica fiber, respectively. Eq. (2) has been derived from Eq. (1) with assumption $\frac{1}{\Delta\lambda}\frac{\partial\Delta\lambda}{\partial T} = \frac{1}{\lambda}\frac{\partial\lambda}{\partial T}$ [1,14].

It may be noticed that conditions (1) and (2) holds for the case when the interference between only two modes (LP_{01} and LP_{02}) has been considered, while traveling the length L. However, in actual practice, it has been seen that higher order cladding modes also propagate through the interference region and getting coupled with LP_{01} and LP_{02} modes and among themselves. This coupling of