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Regular Articles

Investigation on the impact of irregular fringe patterns of a single-fiber Mach-Zehnder interferometer on its sensing capabilities

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ABSTRACT

A novel single-mode single-fiber (SMSF) MZI formed by cascading of two non-adiabatic fiber tapers, with stable and repeatable spectrum, has been found to be useful in sensing applications in recent times. A multimode interference based novel simulation approach is proposed to predict the sensing characteristics of SMSF-MZI and is validated with experimental observation. The proposed method includes solving of simultaneous non-homogenous equations for determining the amplitudes of the interfering modes excited in the tapered section of the interferometer. The simulated fringe pattern and the experimental spectral response converge to some important comprehension reported for the first time. A linear shift in output spectral response, of SMSF-MZI, due to change in optical path length induced by temperature/strain etc., is likely to be characterized by three modes interference occurring in the interference region of the interferometer. Whereas if the spectral shift starts saturating at moderately higher temperature/strain, then the formation of interference fringes are possibly governed by two modes interference. Further, it was also explained that a SMSF-MZI with variable fringe widths in its spectral pattern exhibits higher sensitivity than that of the SMSF-MZI having wavelength spectrum with uniform free spectral range. These findings are useful in selecting and predicting the sensitivity of a given SMSF-MZI, based on its spectrum, for sensing applications.

1. Introduction

Recently, an interesting cascaded tapered fiber based configuration [1–7], single-mode single-fiber Mach-Zehnder interferometer (SMSF-MZI), has been reported for sensing various physical and chemical parameters, such as strain [1], temperature [2,3], refractive index [4], current [5,6], angle [7] etc. The sensing parameters directly affect the optical path length (by inducing change in effective refractive index and interference length) traversed by core and cladding modes propagating through the fiber arm resulting in proportional variations in its wavelength response observed on optical spectrum analyzer (OSA). The major advantages of this configuration are its stable wavelength spectrum, ease of fabrication, high sensitivity, environmental ruggedness and better mechanical strength in comparison to single fiber micro/nano-wires [8,9] and coupler based MZI. Zhaobing et al. [1] investigated MZI strain sensor based on two in-line abrupt single-mode fiber tapers having a linear wavelength shift of 2000 nm/ε to the different applied strains. Jasim et al. [2] reported a microfiber- MZI (MMZI) based inline high temperature measurement sensor of a length of 40 mm, and the sensitivity was found to be linear 13.4 pm/°C for temperature measurement up to 800 °C. Wang et al. [4] proposed a refractive index (RI) sensor based on MZI, formed by cascading of two fiber tapers and the sensitivity of refractive index measurement was reported to be 158.40 nm/RIU for the surrounding RI ranged from 1.33 to 1.3792. Ramachandran et al. [5] proposed micro-MZI (MMZI) based current sensor, fabricated by concatenation of tapered fibers, the current sensitivity of the sensor was found to be 1.76 nm/A^2. Recently, Zhao et al. [7] proposed a highly sensitive angle sensor, based on two cascading abrupt-tapers modal interferometer in single mode fiber, the angle measurement sensitivity of the sensor reached up to 601.80 nm/° in the measurement range of 0.0575° and 0.075°.

In all the above mentioned recent reports, the researchers relied on the shifts in fringe width, in the optical spectral response (OSR) of the SMSF-MZI, with change in the sensing parameter and determined the sensitivity of the sensor. The most of the authors explained the formation of fringe pattern, obtained from SMSF-MZI, on the basis of interference between LP_{01} and LP_{02} without providing much detail and plotted the variations in wavelength shift with sensing parameters i.e. temperature, pressure, current, strain etc. However, in real practice, it can be observed that separation between the notches/peaks in the output experimental spectrum of SMSF MZI, also known as free spectral range (FSR), observed on the OSA, seems to vary with wavelength in an

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unsystematic way. Further, the heights of the peaks and depths of the notches, also appears to increase and decrease with wavelength in an arbitrary manner. These two observations (i.e. irregularity in fringe widths and heights/depths of peaks/notches) induce one to suspect that a multimode interference taking place in the interference region of SMSF may be the cause of such deviations (in FSR) from an orderly spectrum. It may be recollected that two modes interference should provide a uniform value of FSR/fringe width with decreasing heights of peaks on both sides of central maxima. Though, even in two modes interference, there may be some deviations in FSR due to dispersion and other non-idealities etc. yet these digressions are expected to be of small magnitude and not pronounced as discerned in the experimental response of SMSF-MZI. Previous studies did not touch upon the issues related to the sensitivity and range of measurements and their qualitative correlation with fluctuations in FSR etc. of the MZI.

Ramachandran et al. [5] are probably the first to accept the occurrence of multimode interference in formation of the fringes and tried to explain the variations in the FSR through insertion of perturbation term in the analysis. They reported the experimental spectrum of three different samples, but did not offer any explanation for different sensitivity of each sample and its correlation with the corresponding spectrum of each SMSF-MZI. One of the three samples exhibited saturation in variations in wavelength shift with increase in current/temperature at moderate/high temperature. This saturation effect highlights that all SMSF-MZIs, do not necessarily always give linear fringe shifts with change in sensing parameters. Does there exist any simple mechanism predicting the qualitative comparative sensitivity of different SMSFs after looking at their OSR on OSA? These are the some of the questions, which may need to be investigated further for development of more clear understanding of the process of interference and spectral response and their qualitative connection with sensitivity of the sensor. In the present manuscript, the wavelength spectrum of a fabricated SMSF-MZI is simulated by employing the interference between two modes and also among three modes, for comprehending the variations in the fringe pattern with change in temperature of interference region of the sensor and there upon its comparison with the experimental results. The proposed study explains the saturation in wavelength shift, in some cases, while linear changes for some other cases at higher temperature. Based on the comprehension developed from the previously reported works, the inference and qualitative understanding in the light of present investigation is also presented.

2. Working principle

An all-fiber SMSF-MZI [4,5] is constituted of two cascaded abrupt bi-conical tapers separated by a distance of few centimeters of unjacketed fiber. The un-tapered and unjacketed fiber length between the two tapered sections, also known as interference region (or optical path length), acts as the sensing arm of the interferometer. Fig. 1 depicts the schematics of the experimental set up and structure of all fiber SMSF MZI. The input light emanating from erbium doped fiber was injected in the SMSF MZI placed in the vicinity of the power resistor and the output was observed on OSA. By systematically increasing the current flowing through power resistor and controlling the Joule's dissipated heat, temperature of the interference length of the MZI was increased in a deliberate manner.

The core and cladding modes excited en-route the first tapered fiber starts interfering among each other while propagating through the sensing arm. Once the V number of the transition region of the down tapered section of the first non-adiabatic fiber taper becomes less than 0.84 [10], the excited higher order modes get predominantly guided by the cladding (as core) and air (as cladding) under the finite cladding approximation. Under these operating conditions, LP_{01}, LP_{02} and other higher order LP_{0m} modes excited en-route the first taper; the maximum amount of power initially contained in LP_{01} mode gets coupled with LP_{02} and LP_{03} modes (instead of only with mode LP_{02}), and the fraction of power possessed by other higher order modes is negligible small. The beating among the core and cladding modes propagating through the interference region (unjacketed region) with different propagation constants before combining at the entrance of second tapered section of fiber, and gives rise to the interference pattern at the output end of all-fiber SMSF-MZI. A typical OSR of the fabricated all-fiber SMSF-MZI sensing arm observed on OSA is depicted in Fig. 2. The un-orderly variations in the height/depth of the peaks/notches and also the FSR with wavelength, in the spectrum, may be attributed to a multimode interference taking place in the region between two fiber tapers. Usually, two modes/beam interference patterns are recognized with orderly fringe widths and uniformly increasing or decreasing the heights/depths of the peaks/notches. In order to buttress the point, the variations in FSR with wavelength, found to be unsystematic or disorderly, of the fabricated SMSF-MZI are shown in Fig. 3 and the maximum variation of about 2 nm, over a range of 70 nm in the spectrum, can be discerned.

A careful examination of the spectrum of SMSF-MZI, investigated in previous reports, may also result in observance of variations in FSR with wavelength but those digressions were not discussed earlier and regarded as aberrations even though these changes might carry useful information on range of measurements and sensitivity of the MZI based sensor. Generally, the spectral pattern similar to that of shown in Figs. 2 and 3 can be obtained from multimode/multi-beam interference. Thus, it may be concluded that the wavelength response of all SMSF-MZI, fabricated by concatenation non adiabatic bi-conical fiber tapers, may not always be governed by two modes interference approach and a three modes approach may also be developed to get more insights.

3. Simulation methodology

Considering the interference taking place among the two/three modes, the output power emanating from the all-fiber SMSF-MZI structure at a specific wavelength can be expressed through the

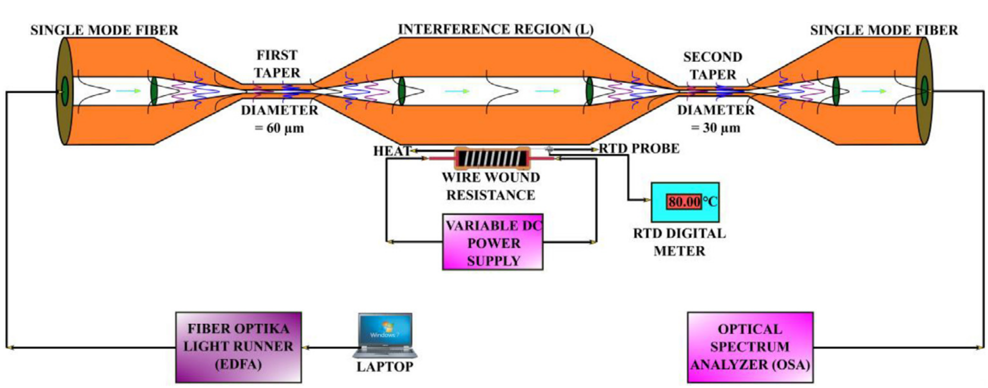

Fig. 1. Schematics of the experimental set up and structure of all fiber SMSF MZI.