Sensors and Actuators A 252 (2016) 180–184

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Birefringence manipulation in tapered polarization-maintaining photonic crystal fiber Mach-Zehnder interferometer for refractive index sensing

Dyandeo Pawar, S.N. Kale*

Department of Applied Physics, Defence Institute of Advanced Technology (DU), Girinagar, Pune 411 025, Maharashtra, India

ARTICLE INFO

Article history:
Received 9 June 2016
Received in revised form 3 October 2016
Accepted 23 October 2016
Available online 24 October 2016

Keywords:
Refractive index sensor
Mach-Zehnder interferometer
Polarization maintaining fibers
Birefringence

ABSTRACT

A temperature insensitive, compact and high resolution refractive index measurement system using tapered polarization maintaining photonic crystal fiber (PM-PCF) Mach-Zehnder interferometer (MZI) is proposed. The sensor exhibits sensitivity of 20.53 nm/RIU with very high refractive index resolution of 1.2175×10^{-5} RIU and 252.6906 dBm/RIU within the refractive index range from 1.33 to 1.37. The birefringence value varied from 1.90619×10^{-5} to 1.86978×10^{-5} with the corresponding change in refractive index. The core and clad having different propagation constant and the changes in the optical path length and hence a change in interference pattern is correlated with the minute changes in refractive index of the subjected sample.

1. Introduction

Polarization maintaining Photonic crystal fiber (PM-PCF) has attracted much interest in recent times due its exquisite properties such as nonlinearity and large birefringence [1]. Optical fibers, in general, are an interesting proposition for various miniaturized sensors due to its small size and EMI-free properties. In the recent past, many PM-PCF based fiber sensors have been developed for various sensing applications such as magnetic field detection [2], stress-strain [3] and multi-photon imaging [4]. Among the different sensors, refractive index sensing is always a topic on anvil. This is because, the conventional techniques such as spectroscopic ellipsometry, are quite complex and not rapid. Refractive index measurements (and moreover, minute change in refractive index) is required in various fields such as in chemical industries, textile industries, bio sensing for monitoring molecular binding, packaging industries and food/confectionary industries and so on [5].

To date, various optical fiber based interferometers are developed for various parameter sensing. Among the various interferometric approaches, the Mach-Zehnder interferometer (MZI) is one of the approaches for refractive index and temperature sensing. The MZI sensors have the many advantages over the other interferometers due to its simple construction [6]. Research has also been done using either the tapered or normal fiber in MZI mode for simultaneous measurement of refractive index and temperature. Jasim et al. [7] used a MZI tapered plastic optical fiber, while Yao et al. reported on MZI Fiber Bragg Grating [8]. Lu et al. [9] has also studied similar system for refractive index measurement [10–12]. The results have shown the sensitivity in similar range, however, their other indirect impacts such as temperature effects may alter the data, which hinders its sensing property.

On the other hand, among the various speciality fibers, PM-PCF based interferometric structures and designs have been sparsely studied in this context, though it shows very high linearity and sensitivity in sensing applications. As this fiber is made up with only silica, it can be expected that parameters such temperature will have less hindering effect. Among other speciality fibers, Wang et al. developed a PCF based MZI for refractive index measurement and observed a resolution of 1.62×10^{-4} RIU in the refractive index range of 1.333–1.422 [13]. Milenko et al. developed PCF tip interferometer for refractive index sensing in the range of 1.33–1.40 [14]. In 2012, Kim fabricated in-line Mach-Zehnder polarization maintaining fiber for refractive index measurement [15]. The half tapered PCF interferometer demonstrated for refractive index sensing within the range of 1.33-1.38 with resolvable index change of 2.56×10^{-4} by Wang et al. [16]. In-fiber PCF MZI based on double cladding fibers have been developed for refractive index sensing by Pang et al. [17]. Chen et al. [18] used the PCF for refractive index measurement from 1.33 to 1.42 with sensitivity and detec-

---

* Corresponding author.
E-mail addresses: sangeetakale2004@gmail.com, sangeetakale@diat.ac.in (S.N. Kale).

http://dx.doi.org/10.1016/j.sna.2016.10.032
0924-4247/

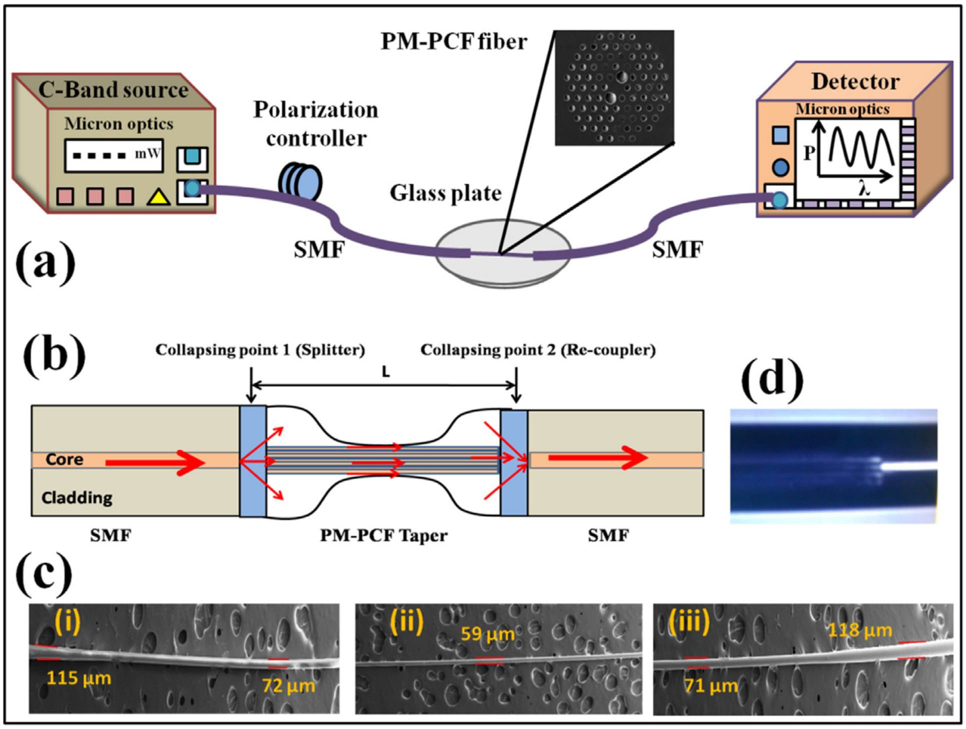

Fig. 1. The experimental setup is shown in (a). (b) shows schematic of tapered PM-PCF fiber used in Mach-Zehnder interferometer mode for refractive index sensing. (c) and (d) are the FE-SEM images of tapered PM-PCF fiber in different regions and optical microscope image of spliced PM-PCF with SMF region, respectively.

tion limit of 12 nm/RIU and 5×10^{-4} RIU. Complex fabrications and designs are also implemented, such as Graphene coated PCF MZI, which was demonstrated for refractive index sensing [19]. The MZI tapered PCF based sensor has been developed by a group [20], which observed that the tapered PCF fiber shows much higher sensitivity than tapered SMF fiber.

In this work the MZI PM-PCF fiber structure is fabricated by etching the cladding part of the fiber. The sensor fabricated this way exhibits sensitivity of 20.53 nm/RIU within refractive index range of 1.33–1.37, with resolution of 1.2175×10^{-5} RIU. The results are correlated to the high birefringence values and fringe visibility, which is the novelty as compared to the documented earlier literature reports. The temperature effects are studied to handle cross-sensitivity issues.

2. Experimental

The sensor was fabricated by splicing a 4-cm length PM-PCF (PM-1550-01, Crystal Fiber A/S Denmark) fiber in two single mode fiber pieces as shown in Fig. 1(a). The broad C- band laser source with 20 nm bandwidth (Micron optics optical sensing analyzer Si720, 1510 nm- 1590 nm, wavelength resolution of 0.25 pm) transmitted the light from one end of the SMF- PM-PCF- SMF fiber setup and the other end was connected to the detector. We used the PM-PCF and SMF-28 fibers due to their lower fusion loss and were spliced with the help of fusion splicer (T35 Orientek) with total fusion loss of 0.02 dB. These regions are explicitly shown in Fig. 1(c) and (d). As shown in the schematic of Fig. 1(b), at the collapsing points, the air holes of PM-PCF were partially collapsed in to the SMF fiber up to the length of around 200 µm. The interference created via the interaction of evanescent waves and the core modes lead to high birefringence values accompanied by the change in the power of the signal. These results are discussed in subsequent paragraphs. After that, the polymer coating of the PCF was stripped off by using fiber stripper (Sumitomo Electric Lightwave). The sensing region was drawn into a taper by dipping the fiber in hydrofluoric acid with concentration of 95% and it was washed with ethanol several times before to use it for sensing purpose. The FE-SEM images (a seen in Fig. 1, in regions (a), (b) and (c)) showed the tapered diameter and tapered fiber length of 59 µm and around 2 cm, respectively. The laser source of input power 1 mW was used for the detection purpose. The sensing region (which is also the tapered region, shown by a circularly marked region in Fig. 1) was immersed in the test solutions, which had different refractive indices. Variation in refractive index was achieved by using standard NaCl solutions of various molarities (1 M–5 M, changing refractive index from 1.3333 to 1.3744.) [21]. The polarization controller was used for better fringe visibility. All data were measured atleast 4 times and were found to be repeatable. The average data is discussed below.

3. Theory and discussion

The principles of the inline MZI is expressed in terms of two-beam optical interference equation. The total intensity of interference between core and clad modes of the MZI in terms of I_{core}, I_{clad}, and phase difference ∅ is given by the equation [6,7,20]-

$$I = I_{\mathrm{core}} + I_{\mathrm{clad}} + 2\sqrt{I_{\mathrm{core}} I_{\mathrm{clad}}} \cos(\phi) \tag{1}$$

Where, the phase difference between core and clad modes of an MZI is expressed by the equation-

$$\phi = \frac{2\pi \Delta n_{eff} L}{\lambda} \tag{2}$$

The input light which travels in inline MZI, partially diffracts in core (guided modes) and cladding modes (unguided modes) at the collapsing point 1 (as shown in Fig. 1 (b)). The core modes continue to travel in the core region of fiber, while cladding modes travel in the nearby cladding-air interface. Thus, cladding modes are allowed to interact with the surrounding medium. At second collapsing point 2, the core and clad modes are recombined giving rise to an interference signal of an interferometer.