Sensors and Actuators A 250 (2016) 237–242

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Packaged in-line Mach–Zehnder interferometer for highly sensitive curvature and flexural strain sensing

H.S. Lin [a,b,*], Y.M. Raji [a], J.H. Lim [b], S.K. Lim [b], M.R. Mokhtar [a], Z. Yusoff [a]

[a] Faculty of Engineering, Multimedia University, Persiaran Multimedia, 63100 Cyberjaya, Selangor, Malaysia
[b] Lee Kong Chian Faculty of Engineering & Science, Universiti Tunku Abdul Rahman, Jalan Sungai Long, Bandar Sungai Long, Cheras, 43000 Kajang, Selangor, Malaysia

ARTICLE INFO

Article history:
Received 26 February 2016
Received in revised form 8 July 2016
Accepted 2 September 2016
Available online 24 September 2016

Keywords:
Fiber-optic sensors
Mach–Zehnder interferometer
Curvature sensor
Abrupt taper

ABSTRACT

The paper presents an innovative packaging approach to allow highly sensitive in-line Mach–Zehnder interferometer (IMZI) sensor to be used for accurate measurement of curvature and flexural strain specifically in civil engineering. The sensor which consists of two tapers is protected within a polypropylene package to survive in harsh, in-the-field conditions. The package design employs cost effective materials without compromising the curvature and flexural strain sensitivity which are 85.2 dB m^{-1} and 0.0148 dB/$\mu\epsilon$. The accuracy of measurement results is further verified by obtaining the flexural modulus for the steel which is in good agreement with theoretical value.

1. Introduction

The fiber based Mach–Zender interferometric effect has been observed and studied in the abrupt biconical fiber taper since the late 1980s [1]. In the following years, the IMZI was fabricated based on long period grating pairs [2], two-taper structure [3], mode-mismatch structure [4] and core-offset structure [5]. The fabrication process of the two-taper structure is the simplest and fastest yet has the comparable sensing performance among the mentioned structures. The IMZI has been extensively used for fiber sensor applications such as refractive index (RI) sensing [5–7], strain sensing [8–14], temperature sensing [9–13,15–21] and curvature sensing [16–29]. Generally, most researches characterized the curvature sensitivity of IMZI based on the wavelength shift-curvature relation [16–20,22–27], but only a few have been reported on intensity–curvature relation [21,25–29]. It is worth noting that fiber optics sensor that responds to wavelength signature has grown tremendously since 1980s with the development of fiber Bragg grating sensor [30]. For the in-field application, the wavelength interrogation system is developed to demodulate wavelength and multiplex multiple sensors. However, the implementation cost of the system is comparably higher. Nevertheless, for the in-field application, the optical sensing system based on intensity–curvature relation is practical and the advantages are: low cost, simplicity of implementation, and possibility of being multiplexed. Although, intensity interrogation technique might suffer from fluctuations of optical power or other external disturbances. However, these types of errors can be prevented by calibrating the sensors before use.

The process of fabricating the IMZI from the optical fiber has compromised the optical fiber's rigidity, and its fragile nature poses a limitation for its field sensing applications. Some form of packaging is required to ensure the rigidity of the fiber taper and guarantee its durability. Teflon coating, has been proposed [25], which promised to maintain the overall performance of the fiber taper. Although this is a very rigid and flexible material, the coating cost and its non-adhesive characteristic make it difficult to be deployed for curvature sensing application. Besides that, polymer tube [31] and perspex packaging [32] have been reported in appropriately packaging the fiber taper. The encapsulating adhesive method in the polymer tube is only applicable to adiabatic fiber taper, whereas the perspex sheet packaging design is too bulky and rigid that the small bending effect could not be effectively coupled to the IMZI.

In this research paper, an innovative and cost effective packaging of IMZI based curvature and flexural strain sensor which is generally applicable to various IMZI structure designs is demonstrated. The new packaging method ensures that the IMZI is able to survive real field sensing applications without compromising its sensitivity. Furthermore, the characterization of intensity–curvature relation is proposed in the curvature sensing application due to the fact

---

[*] Corresponding author at: Faculty of Engineering, Multimedia University, Persiaran Multimedia, 63100 Cyberjaya, Selangor, Malaysia
E-mail address: linhs@utar.edu.my (H.S. Lin).

http://dx.doi.org/10.1016/j.sna.2016.09.006
0924-4247/

that cladding mode of the proposed packaged IMZI is drastically suppressed corresponding to the bending effect.

2. Fabrication of packaged IMZI

2.1. IMZI fabrication

The IMZI sensor was fabricated on a single mode fiber by using an in-house designed arc discharge fabrication system [33,34]. The customized arc discharge system has the flexibility to control the arc power and the exposure time. In addition, by using the customized rig, the profile of the tapers and the distance between them can be precisely controlled using motorized stages. A digital microscope is integrated to capture the microscopic view of fiber taper as shown in Fig. 1. In the fabrication of IMZI, a section of fiber was stripped and the two abrupt tapers were fabricated by using aforementioned arc-discharge fabrication system. The tapers were kept at the distance of approximately $L = 50$ mm apart along the stripped fiber. After the fabrication process, the sample was then transferred to a customized high magnification power microscope stages to profile the diameter along the axial axis with step size of 1 μm. The profile of the first (Taper 1) and second (Taper 2) fiber tapers are shown in Fig. 2. The diameters of the first and second taper are 26.2 μm and 34.2 μm, respectively. The diameter profiles of the tapers were further analyzed based on the delineation criterion which was reported by Love et al. [35]. Referring to Fig. 3, both Taper 1 and Taper 2 are verified to be the abrupt tapers as both tapering ratios fall above the delineation curve (in the non-adiabatic region). Therefore, the optical power from the fundamental mode is significantly coupled to the cladding mode. From the delineation criterion, at both tapers, the non-adiabatically mode coupling occurs along the operating wavelength of the IMZI sensor which is from 1520 nm to 1560 nm.

2.2. Packaging material and design justification

Prior to designing the package of IMZI sensor, an experiment was carried out to characterize the surrounding refractive index (SRI) response of the IMZI for the RI which is less than and greater than that of the cladding, respectively. Each end of the unstripped fiber was held straight using a fiber holder to ensure the fiber remained in place throughout the experiment. A stage was placed directly below the IMZI sensor, where a piece of standard microscope slide was placed upon. A tunable laser source was set to sweep across a bandwidth from 1520 nm to 1560 nm at a resolution of 128 pm. While the optical light was fed into the IMZI, the spectral response was synchronically detected by an optical component tester.

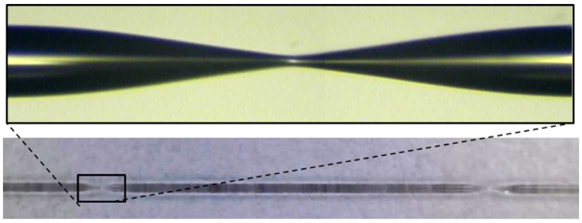

Fig. 1. Microscopic view of IMZI interferometer with zoom-in fiber taper.

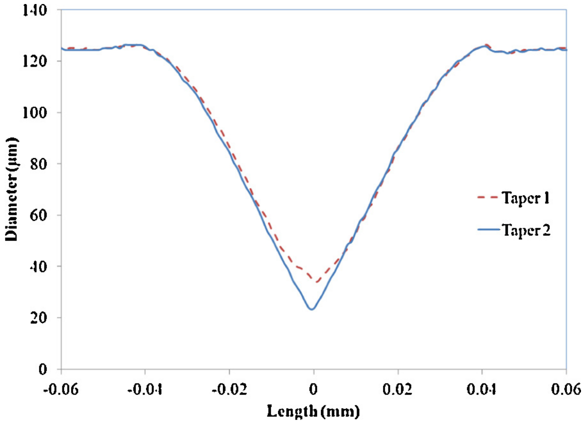

Fig. 2. Diameter profile of Taper 1 and Taper 2 that form the IMZI sensor.

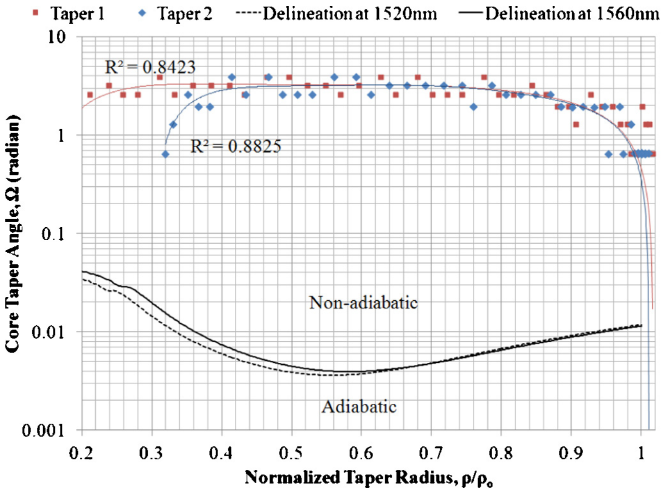

Fig. 3. The taper angle profile of the fabricated tapers and the delineation criterion at wavelength, λ of 1520 nm and 1560 nm.

In the experiment, Cargille oil was applied in between the tapers without immersing the tapers with the intention of observing the effect of SRI along the interferometer length only. In order to prevent tapers from immersing into the Cargille oil, the fiber was positioned along the width of the microscope slide which is 25 mm shorter than the interferometer length as shown in Fig. 4(a). Cargille oil with different RI values at room temperature of 24 °C was tested.

The Fourier transform of the output spectrum (inset of Fig. 4(b)) gives the spatial frequency spectrum. The spatial frequency, ξ is expressed as $\xi = \Delta n_{eff} L/\lambda_o^2$ where $\Delta n_{eff} L$ is the optical path length difference between the fundamental mode and the higher order cladding modes, whereas λ_o^2 is center wavelength expanded from first order Taylor series [8]. Fig. 4(b) shows the spatial frequency dominant peak at around 0.1 nm^{-1}, which corresponds to the mentioned interferometer length, $L = 50$ mm. While the IMZI is immersed into the SRI that is less than that of the cladding, there are multiple spatial frequency peaks that correspond to different order of cladding modes. As the stripped fiber between tapers is immersed into the SRI that is greater than that of the cladding, the multiple spatial frequency peak is eliminated and the dominant spatial frequency is suppressed. In other words, as long as the SRI is greater than that of the cladding, the Cargille oil acts as an absorption layer that allows single cladding mode to be weakly guided in the IMZI structure. In this condition, when the fiber is slightly bent, the surviving cladding mode significantly penetrates through the absorption layer. As a result, the fringe visibility, $K = 2\sqrt{I_1 I_2}/(I_1 + I_2)$ decreases accordingly. This shows that the absorption layer coated IMZI is highly sensitive to the curvature sensing.

Apparently, the coating of standard single mode fiber (SMF28) has the required nature where the RI of inner coating and outer coating is 1.4786 and 1.5294, respectively, at 1550 nm [36]. Therefore, in the design of IMZI packaging, the interferometer length remains unstripped during the tapering process. Besides that, cyanoarcylate is well suited to act as an adhesive epoxy in