Optical Fiber Technology 40 (2018) 13–17

Contents lists available at ScienceDirect

Optical Fiber Technology

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

A PDMS microfiber Mach-Zehnder interferometer and determination of nanometer displacements

Ivan Martincek, Daniel Kacik*

Department of Physics, Faculty of Electrical Engineering, University of Žilina, Univerzitná 1, 01026 Žilina, Slovakia

ARTICLE INFO

Keywords:
Microfiber
Polydimethylsiloxane
Mach-Zehnder interferometer
Displacement sensor

ABSTRACT

A polydimethylsiloxane (PDMS) microfiber Mach-Zehnder interferometer (MZI), integrated between single-mode optical fibers (SMFs), is proposed and demonstrated experimentally. One arm of the interferometer consists of a microfiber of diameter 7 µm and length 270 µm; the second is an air arm. Due to the good elastic properties of PDMS microfiber, the length of the air arm of MZI can be changed by changing the distance between SMFs. The change in length of the air arm results in a change in the transmission characteristics of the MZI; thus, the relative displacement can be measured in the range 10–250 nm. By measuring the peak-to-peak amplitude of the difference in transmission powers (in dB), the smallest displacement by prepared MZI was determined as being on the order of a few nm for a ratio of intensities of 0.135. For a higher ratio of intensities of transmission functions, the smallest displacement could be determined on the order of subnanometers.

1. Introduction

Due to their very high sensitivities and compactness, optical fiber interferometers are used in sensor technology for the precise determination of various physical quantities such as refractive index [1–4], temperature [3,4], axial strain [4], pressure [5] etc.

Microfibers and nanofibers (MNFs) are of particular interest in the miniaturization of optical fiber interferometers for phase-sensitive optical measurements [3,6–8]. One advantage of using MNFs in the construction of interferometers is their small bending losses, due to the large refractive index contrast between the microfiber material and air [9].

In recent years, several Mach-Zehnder interferometers (MZIs) using MNFs as their arms have been proposed. In 2005, Lou et al. proposed a nanofiber MZI structure for a miniaturized optical sensor which was characterized by high sensitivity [10]. In 2008, Li et al. experimentally demonstrated a similar structure assembled from silica and tellurite glass microfibers, where the diameter of the microfibers used was reduced to 1.2 µm and their length to less than 500 µm [11]. In 2014, Yu et al. proposed a similar MZI structure placed on an MgF_2-coated glass substrate of flexible poly(trimethylene terephthalate) microfibers, where the diameter was 700 nm and the length of the structure about 110 µm, for highly sensitive measurements of refractive index [12]. In the same year, Li et al. demonstrated the same MZI structure but made of polymethylmethacrylate, with microfibers of diameter approximately 2 µm [13]. In 2011, Yang et al. proposed a single S-tapered fiber MZI sensor of length 600 µm, with the smallest taper diameter 65 µm, for measurements of refractive index and axial strain [14]. Wo et al. reported a refractive index sensor in 2012 which was based on a microfiber MZI, using a microfiber with diameter 2 µm as the sensing arm [15].

All the above mentioned MNFs interferometers have a common feature, in that it is not possible to change the length of arms (or this is possible only to very small extent). This is due to their solid state. This drawback can be eliminated by recently published MZI using 9 µm single tapered silica optical microfiber [16]. Nevertheless, it is solid state, the change of length path difference is done by bending of microfibers. Another possibility is using a form of interferometer with an adjustable air optical line in one arm and a microfiber in the second. A microfiber Mach-Zehnder interferometer of this type is proposed in this paper. These interferometers may be useful in applications where the measurands will only affect the properties of the microfiber (for example, in the sensing of volatile organic compounds).

In this paper, we describe the preparation and characterization of a polydimethylsiloxane (PDMS) microfiber MZI which was directly integrated between single-mode optical fibers. One arm of the interferometer consists of PDMS microfiber, and the second is formed from an air optical line. The length of the prepared MZI was about 270 µm and the smallest diameter PDMS microfiber was 7 µm. We measured the transmission characteristics of the prepared interferometer as a function of the length of the air optical line. The use of the interferometer as a sensor of very small displacement was validated.

* Corresponding author.
E-mail addresses: Ivan.martincek@fel.uniza.sk (I. Martincek), daniel.kacik@fel.uniza.sk (D. Kacik).

http://dx.doi.org/10.1016/j.yofte.2017.10.006
Received 11 May 2017; Received in revised form 7 September 2017; Accepted 31 October 2017

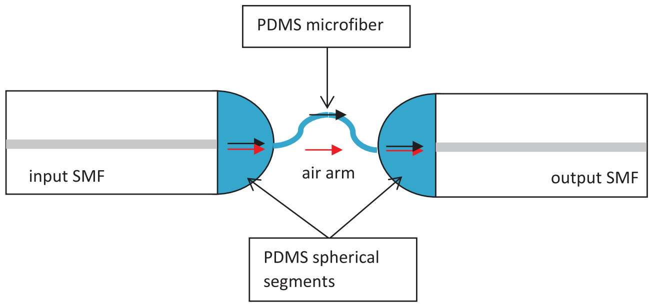

Fig. 1. Schematic illustration of the prepared PDMS microfiber MZI integrated with the SMFs.

2. Fabrication of PDMS microfiber MZI

For the preparation of the PDMS microfiber, we used liquid silicone Sylgard 184 (Dow Corning), supplied as two-part liquid component kits. The prepolymer (part A) and curing agent (part B) were mixed in the ratio 10: 1. After 30 min of air degassing, the mixture was applied to the ends of stripped conventional single-mode fibers (SMFs) placed on differential micrometer stages. Then, the ends of the SMFs covered by the mixture were connected. A PDMS microfiber was subsequently developed between two SMFs using the technique of drawing the partially cured PDMS [17,18].

The prepared PDMS microfiber had a diameter of 7 µm and a length of 270 µm. This microfiber was formed on the PDMS spherical segments with a height of about 50 µm, situated on the end faces of the SMFs. The spherical segment served to split the light beam transmitted through the core of the input SMF into two beams: one beam was transmitted through the PDMS microfiber and the second was transmitted through the air optical line. These beams were recombined at the second spherical element into a single beam propagating through the core of the output SMF. That meant that the prepared structure had the properties of an MZI (Fig. 1). Measured insertion loss of prepared MZI is about 18 dB and depends on actual setting of MZI.

If the microfiber between the SMFs is straight, the light is “trapped” in the microfiber, so that no interference between the beams propagated through the air arm and the microfiber is observed. In order to split the beam emitted from the spherical segment, it is necessary to bend the microfiber so that the straight line between the SMFs can form the air arm of the MZI. Since the PDMS microfiber has good elastic properties, the bending of microfiber is carried out by decreasing the distance between ends of the SMFs. By decreasing the distance between the ends of the SMFs, the length of the air arm of the MZI is changed, while the length of the microfiber changes only minimally due to bending. By decreasing the distance between the SMF fibers, it is thus possible to vary the optical path length difference between the beam transmitted through the microfiber and the beam spread by the air arm. The prepared PDMS microfiber MZI is shown in Fig. 2.

3. Transmission characteristics of the PDMS microfiber MZI

A broadband light source (SLED Safibra OFLS-6) with central wavelength at 1550 nm and spectral width 100 nm was used in the investigation of the properties of the prepared microfiber MZI; this was connected to the input SMF. The output SMF was connected to the optical spectrum analyzer (Anritsu MS9710B) with a resolution of

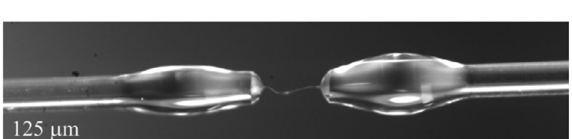

Fig. 2. Prepared PDMS microfiber MZI, integrated with the SMFs.

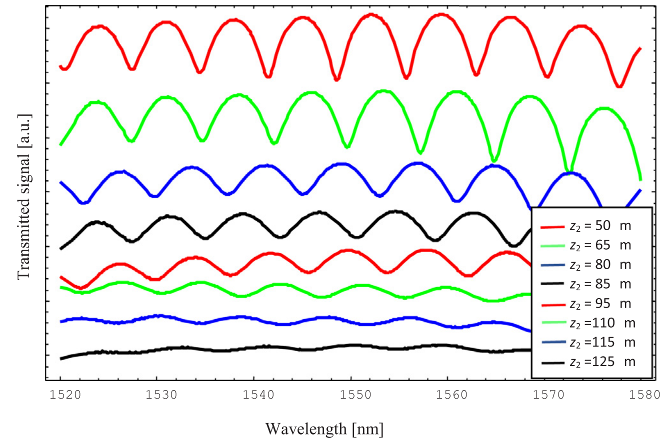

Fig. 3. Vertically shifted transmission spectra of the MZI for different measured air arm lengths z_2 from 50to 125 µm.

0.07 nm. The positions of the ends of the SMFs with the PDMS microfiber were adjusted by differential micrometer stages. The MZI was placed in air chamber with stabilized temperature, pressure and humidity.

The transmission spectrum of the prepared MZI in a range of wavelengths from 1520 nm to 1580 nm for different lengths of the air arm of between 50 m and 125 m is shown in Fig. 3. From the figure, it can be observed that the amplitude of the signal oscillations for a particular length of the air arm varies a small amount within the range of the measured wavelengths. These small variations in amplitude are probably due to the spectral dependence of the signal amplitude in the bent microfiber and the spectral dependence of light emitted from the spherical segment to the air arm. With an increase in the length of the air arm of the MZI, the amplitude of oscillation of the signal decreases, due to a decrease in the optical signal intensity which is coupled to the core of the output SMF from the air arm of the MZI.

Free spectral range (FSR) which determined the distance between two adjacent maximal (minimal) values at interference pattern depends on actual setting of interferometer. For measured length of air arm 50 µm the FSR is 6.8 nm and for length of air arm 125 µm the FSR is changed to 8.8 nm.

Since the interference pattern in our microfiber MZI is mainly formed from two beams, one of which is guided by the microfiber and other by air, the transmission spectrum of MZI can be expressed as

$$I_a(\lambda) = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left(\beta(d,n_1,n_2,\lambda)z_1 - \frac{2\pi n_2}{\lambda}z_2\right), \quad (1)$$

where I_1 and I_2 are the intensities of the light coupled to the core of the output SMF from the microfiber and from the air arm, respectively; β is the phase constant of the mode guided through the microfiber; z_1 is the length of the microfiber; z_2 is length of the air arm; n_1 is the refractive index of the PDMS fiber; n_2 is the refractive index of the air; d is the microfiber diameter; and λ is the wavelength of the propagating light in a vacuum. If we assume that only the fundamental mode HE_{11} is guided through the microfiber, β is the phase propagation constant of this mode for a step-index optical fiber with PDMS core and air cladding.

Fig. 4 shows the measured and calculated transmission spectra for the microfiber MZI. The MZI parameters used for simulation (obtained from experiment) were as follows: the measured length and diameter of microfiber were $z_1 = 270$ µm and $d = 7$ µm, respectively; the refractive index of PDMS was $n_1 = 1.3997$, obtained from [19], and the refractive index of air $n_2 = 1$. The phase constant β of the HE_{11} mode for the step-index PDMS optical microfiber was calculated numerically using the values d, n_1 and n_2. The ratio $I_2/I_1 = 0.34$ and the length of an air optical line $z_2 = 44.90$ µm were obtained from a comparison of the measured and calculated transmission spectra. Then, the length of the