Mach–Zehnder Based on Large Knot Fiber Resonator for Refractive Index Measurement

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Abstract— A Mach–Zehnder sensor based on a large knot fiber resonator with a diameter of a few millimeters is designed using a single long taper. The long taper of some centimeters is fabricated with a CO_2 laser technique. In air, light cannot couple between adjacent sections in the knot, and no signal is observed. However, in liquid, light is less confined and there is coupling between adjacent sections of the knot, resulting in a phase difference and consequent interference. The Mach–Zehnder is formed by the two contact points in the knot. The refractive index sensing of liquid compounds is achieved by monitoring the wavelength shift of the spectra. A sensitivity of 642 ± 29 nm/refractive index unit (RIU) is achieved for refractive index sensing in the range of 1.3735–1.428 with a resolution of 0.009 RIU. For temperature sensing, a sensitivity of -42 ± 9 pm/°C is observed. A low influence of temperature in the refractive index change is observed: 6.5×10^{-5} RIU/°C.

Index Terms— Large knot fiber resonator, Mach-Zehnder, optical fiber sensor, refractive index sensor.

I. INTRODUCTION

RECENTLY, optical refractive index sensors or refractometers based on all-fiber interferometers [1] or resonators [2] have been studied and developed due to their high sensitivity, broad measurement range and compact size [2]. From these all-fiber based interferometric sensors, the all-fiber Mach-Zehnder interferometers (MZI) have received considerable attention [1], [4]–[7].

The MZI technique is used for measuring the refractive index of a medium due to the induced phase shift of the guided light created by the analyzed medium [3].

For this purpose, Tian *et al.* [1] presented a single-mode fiber (SMF)-based MZI by simply concatenating two fiber tapers separated by a short (24–55 mm) middle section, obtaining 17.1 nm/RIU (RIU – Refractive Index Unit) of sensitivity. Lu *et al.* [4] used a tapered fiber MZI created on single-mode fiber by simple fusion splicing for the simultaneous measurement of refractive index and temperature. They achieved sensitivities of −23.188 nm/RIU and 0.071 nm/°C for refractive index and temperature sensing, respectively. In 2012, an all-fiber in-line single mode-multimode-thinned single

mode (SM-MM-TSM) MZI fiber structure was developed, using only a splicing method, obtaining a sensitivity of −25.2935 nm/RIU for refractive index and 61.5 pm/°C for temperature sensing [7].

Other fiber sensors have been developed with this purpose. For example, a biconical fiber taper sensor proposed by Kieu and Mansuripur [8], which presents sensitivities of ∼650 nm/RIU and ∼10 pm/°C, was applied for refractive index and temperature sensing. Moreover, a MZI embedded in a taper was reported with a refractive index sensitivity of 2210.84 nm/RIU, good for low index variation sensing, and temperature sensitivity of −6.66 pm/°C [14].

There has also been a great interest in the past few years in microfiber resonators applied as sensing elements. To this class of devices belong the knot resonators, which are made tying a knot in an optical microfiber taper, creating a ring geometry with micrometer dimensions [9]. The taper in the knotted zone allows the evanescent field of light to couple between the adjacent sections of the taper creating a resonance [10]. This overlap of the fiber with itself does not require a precise alignment [9].

In the temperature sensing field, a comparison between a silica microfiber knot resonator (MKR) and a polymer MKR is presented by Wu *et al.* [11], reaching a sensitivity of 52 pm/°C with a 190 μm-diameter silica MKR, assembled using a 1.7 μm-diameter microfiber; and a sensitivity of −266 pm/°C with a 98 μm-diameter polymer MKR, assembled using a 2.1 μm polymer microfiber. For refractive index sensing, Lim *et al.* [12] proposed a MKR with a diameter of ∼0.5 mm in a Sagnac loop reflector, obtaining a RI sensitivity of 30.49 nm/RIU and a temperature sensitivity of 20.6 pm/°C. Yu *et al.* [13] reported a polymer MKR for refractive index sensing achieving a sensitivity of about 95.5 nm/RIU. In the last year, a cascaded MKR with a sensitivity of 6523 nm/RIU was presented, suitable for slight refractive index variations [15].

In this letter, a Mach-Zehnder based on a large knot fiber resonator (MZ-LKR) with a diameter of a few millimeters is presented for refractive index sensing of liquids. The knot is made on a taper with around 60 μm-diameter fabricated with a CO_2 laser.

II. EXPERIMENTAL SETUP AND RESULTS

Figure 1a) shows the experimental setup. It consists in a broadband source with a central wavelength of 1550 nm and a bandwidth of 100 nm connected to an optical fiber where the MK-LKR is located. The transmitted signal spectrum is
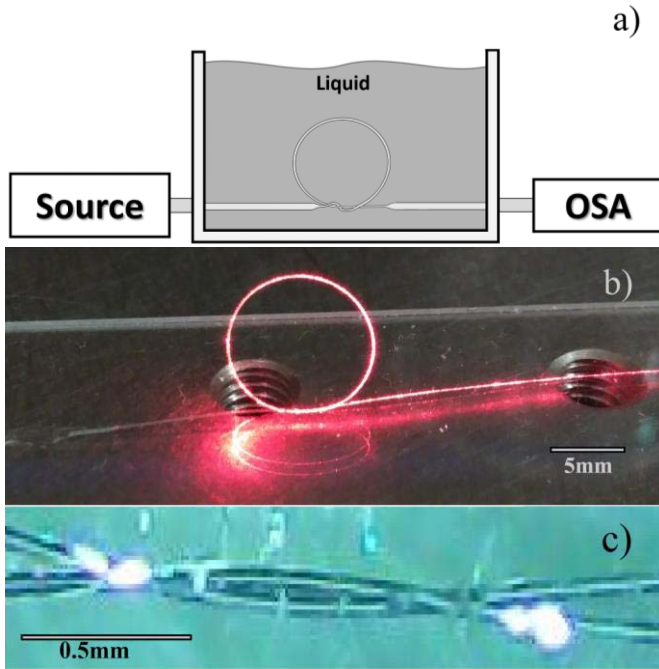
Fig. 1. a) Experimental setup. b) Mach-Zehnder large knot resonator in air, illuminated by a He-Ne laser. c) Photograph of a knot of a Mach-Zehnder large knot resonator with 3.5mm diameter.

observed in an optical spectrum analyzer (OSA) with a 1nm resolution. The sensor is immersed in liquid. This allows it to be studied under different liquids with different refractive indices. The setup also allows a gradual heating of the liquid. The sensor is made manually by tying a knot in a tapered single mode optical fiber (SMF28). The taper was fabricated using a CO_2 laser to reduce the fiber diameter to ~ 60 μm. The diameter of the ring is reduced until it reaches a value of ~ 3.5 mm. The knot is located near the transition zone between the untapered SMF and the tapered section.

In Figure 1b) a 1 cm-diameter MZ-LKR illuminated by a He-Ne laser is shown.

The transmitted signal spectrum of a 3.5 mm diameter MZ-LKR, in air and in liquid (ethylene glycol, $n = 1.426$), illuminated by a broadband source can be observed in Figure 2. The MZ-LKR interferometer is formed by the two contact points in the knot, visible in Figure 1c).

The mode of operation of the MZ-LKR is the following: in air, light travels in the ring and is lost in the loop and in the knot due to curvature losses. Around the two contact points in the knot, the presence of air does not allow light to be coupled between adjacent sections because of the high confinement of light due to large taper diameter dimensions. Hence, the light cannot pass directly to the output of the ring and a low power signal is observed. When the sensor is immersed in liquid, light in the contact points of the knot is now less confined and capable of coupling between adjacent fibers, with a certain phase difference, giving rise to an interference spectrum. This interference is visible in Figure 2. Part of the light is now capable of passing directly to the output of the ring, without losing itself in the loop, and a spectral signal with higher intensity is observed in the OSA.
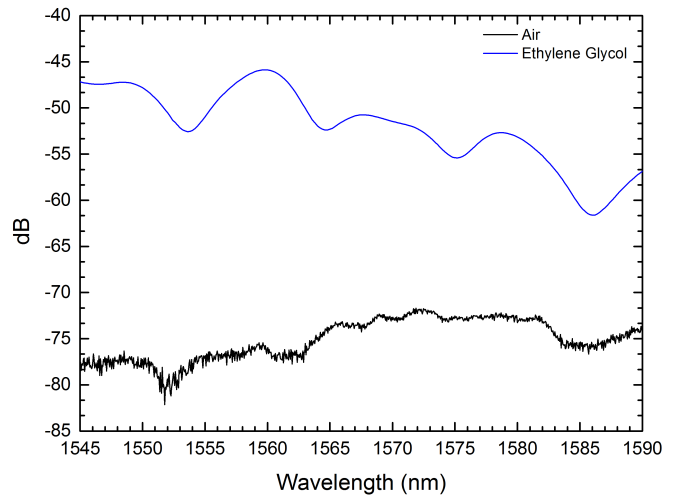

Fig. 2. Transmitted signal of the MZ-LKR when it is in air and when it is immersed in ethylene glycol ($n =$1.428). The free spectral range (FSR) in ethylene glycol is approximately 10.15 nm.
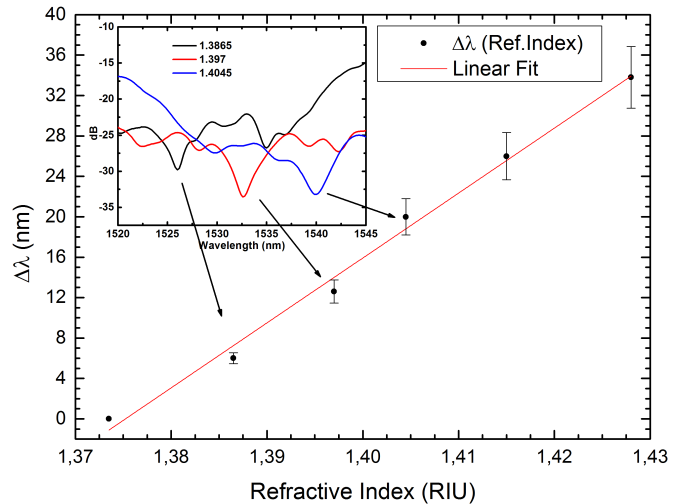

Fig. 3. Wavelength shift as function of refractive index. The inner plot shows the spectra of the transmitted signal for three different refractive index.

The peak shift of the transmitted signal spectrum from the sensor was studied by dipping the sensor in ethylene glycol mixtures with different refractive indices [16]. In Figure 3 the wavelength shift as function of the refractive index is presented. As the wavelength shift is directly proportional to the refractive index [3], a linear fit was applied. From this fit, a sensitivity of 642 ± 29 nm/RIU was obtained. The auxiliary graph in Figure 3 clearly shows the wavelength shift due to refractive index change.

The study of the wavelength shift as a function of temperature variations was also performed. The MZ-LKR was immersed in water whose temperature was progressively increased. The wavelength shift as a function of temperature is depicted in Figure 4. A linear fit was performed on the data. From this fit, a sensitivity of -42 ± 9 pm/°C was obtained. The negative sensitivity is related to the knot dimension, being the thermo-optical effect dominant in this case. Dividing both sensitivities, a value of 6.5×10^{-5} RIU/°C is reached,

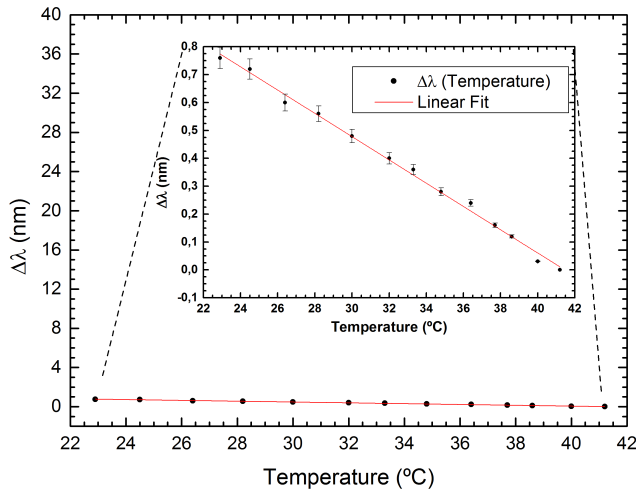Fig. 4.   Wavelength shift as a function of temperature.

TABLE I
COMPARISON BETWEEN DIFFERENT CONFIGURATIONS

Author	Type	Sensitivity
This work	Large Knot Resonator	**642nm/RIU**
[12]	MKR in Sagnac loop	30.49nm/RIU
[13]	Polymer MKR	95.5nm/RIU
[4]	Tapered Fiber MZI	-23.188 nm/RIU
[7]	SM-MM-TSM MZI	−25.2935nm/RIU
[1]	SMF based MZI	17.1 nm/RIU
[8]	Biconical fiber taper	∼ 650nm/RIU
[14]	MZI embedded in a taper	2210.84nm/RIU
[15]	Cascaded MKR	6523nm/RIU
This work	Large Knot Resonator	**–42pm/ºC**
[12]	MKR in Sagnac loop	20.6pm/ºC
[11]	Simple polymer MKR	-266pm/ºC
[4]	Tapered Fiber MZI	71 pm/ºC
[7]	SM-MM-TSM MZI	61.5pm/ºC
[8]	Biconical fiber taper	∼ 10pm/ºC
[14]	MZI embedded in a taper	-6.66pm/ºC

showing a low influence of temperature in the refractive index measurement.

III. CONCLUSION

The refractive index sensing of liquids was achieved with a MZ-LKR. For refractive index sensing, a sensitivity of 642 ± 29 nm/RIU was obtained in a refractive index range from 1.3735 to 1.428 with a resolution of 0.009 RIU. Comparing the sensitivity with previous published results and with other different configurations, as shown in Table 1, the MZ-LKR stands in a zone where most of the remaining configurations have less sensitivity, except the MZI embedded in a taper [14] and the cascaded MZI configuration [15]. This sensor presents a similar sensitivity to the biconical fiber taper [8].

For temperature sensing, a sensitivity of -42 pm/°C was observed. This sensitivity is of the same order as the already published MKR and MZI, except for the polymer MKR [11] which reveals a significant increase in the sensitivity due to the polymer. The size of the MZ-LKR allows it to be easily made and manageable. The sensor is more resistant due to its dimensions, revealing an advantage in relation to the micrometer size knot resonators. On the other hand, the MZ-LKR shows a higher sensitivity to refractive index variations than most of the other MKR and MZI.

Further studies should be performed to investigate the influence of the number of contact points in the knot in the signal spectrum, as well as to determine if there is any predominance of one contact point over the other in the interference spectrum.

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