André D. Gomes, Ricardo M. Andréa, Stephen C. Warren-Smith, Jan Dellith, Martin Becker, Manfred Rothhardt, and Orlando Frazãoa

Combined microfiber knot resonator and focused ion beam-milled Mach-Zehnder interferometer for refractive index measurement

Proceedings of SPIE 25th International Conference on Optical Fiber Sensors, 2017 / vol.10323, pp.1032340-1-1032340-4

Combined Microfiber Knot Resonator and Focused Ion Beam-Milled Mach-Zehnder Interferometer for Refractive Index Measurement

André D. Gomes*[a,b], Ricardo M. André[a,b], Stephen C. Warren-Smith[b,c], Jan Dellith[b], Martin Becker[b], Manfred Rothhardt[b], and Orlando Frazão[a]

[a]INESC TEC and Department of Physics and Astronomy, Faculty of Sciences, University of Porto, Rua do Campo Alegre 687, 4150-179 Porto, Portugal;

[b]Leibniz Institute of Photonic Technology (IPHT Jena), Albert-Einstein-Straße 9, 07745 Jena, Germany;

[c]Currently with Institute for Photonics and Advanced Sensing (IPAS) and School of Physical Sciences, The University of Adelaide, Adelaide 5005, Australia.

ABSTRACT

A Mach-Zehnder interferometer was created from a cavity milled in the taper region next to a microfiber knot resonator. A focused ion beam was used to mill the cavity with 47.8 µm in length. The microfiber knot resonator was created from an 11 µm diameter taper, produced using a filament fusion splicer. After milling the cavity, the microfiber knot resonator spectrum is still visible. The final response of the presented sensor is a microfiber knot resonator spectrum modulated by the Mach-Zehnder interference spectrum. A preliminary result of -8935 ± 108 nm/RIU was obtained for the refractive index sensitivity of the cavity component in a refractive index range of n = 1.333 to 1.341. Simultaneous measurement of refractive index and temperature using this combined structure is a future goal.

Keywords: Focused ion beam, Mach-Zehnder interferometer, microfiber knot resonator, refractive index sensor.

1. INTRODUCTION

The Mach-Zehnder interferometer (MZI) has been vastly used, mainly as a refractive index sensor[1], but year after year new configurations have been developed to increase the scope of this sensor. Currently, new developments in this topic still occur, which now involve creating new configurations with enhanced sensitivity by combining different structures[2,3].

Microfiber knot resonators (MKR) had a significant impact, not only in the field of sensing, but also in other fields such as ultrafast optics, due to its high Q-factor. In terms of sensing, a wide variety of parameters have been measured with this device, such as: temperature[4–6], concentration of sodium chloride and refractive index,[6–8] and humidity[9]. More recently, materials such as graphene, palladium, or even polymers have been incorporated into the microfiber knot resonator in order to achieve devices with enhanced sensitivity to the measured parameters[10–12].

In this paper, a microfiber knot resonator is combined with a Mach-Zehnder interferometer with the objective of obtaining a new sensor with improved refractive index sensitivity. The Mach-Zehnder interferometer is based on a cavity created by milling the microfiber with a focused ion beam.

2. FABRICATION AND CHARACTERIZATION

A schematic of the proposed sensor is presented in figure 1. The sensor consists of a microfiber knot resonator (MKR) and an air cavity milled in the taper region next to the MKR structure. The output of the sensor should be the joint response of the cavity and the MKR. These two structures form a single and compact sensor.

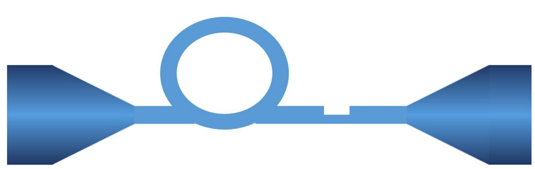

Figure 1. Schematic of the sensor: milling of an air cavity in the taper region next to the MKR.

25th International Conference on Optical Fiber Sensors, edited by Youngjoo Chung, Wei Jin, Byoungho Lee, John Canning, Kentaro Nakamura, Libo Yuan, Proc. of SPIE Vol. 10323, 1032340 · © 2017 SPIE · CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2265387

Initially, a taper was produced using a filament fiber processing unit (Vytran, GPX-3400), with an obtained taper waist of 11 µm. Using this taper, an MKR was created with a 700 µm-diameter. A scanning electron microscope (SEM) image of the MKR is depicted in figure 2(a).

The cavity was milled using a Tescan (Lyra XMU) FIB-SEM system (focused ion beam – scanning electron microscope). In order to use this technique, sample preparation is needed to eliminate charging effects. First, droplets of silver paint were used to fix the taper onto an aluminum holder, creating electric contacts. Then, the structure was masked except the taper region directly next to the MKR. A 50 nm thick tantalum film was deposited in the exposed area using a sputtering chamber.

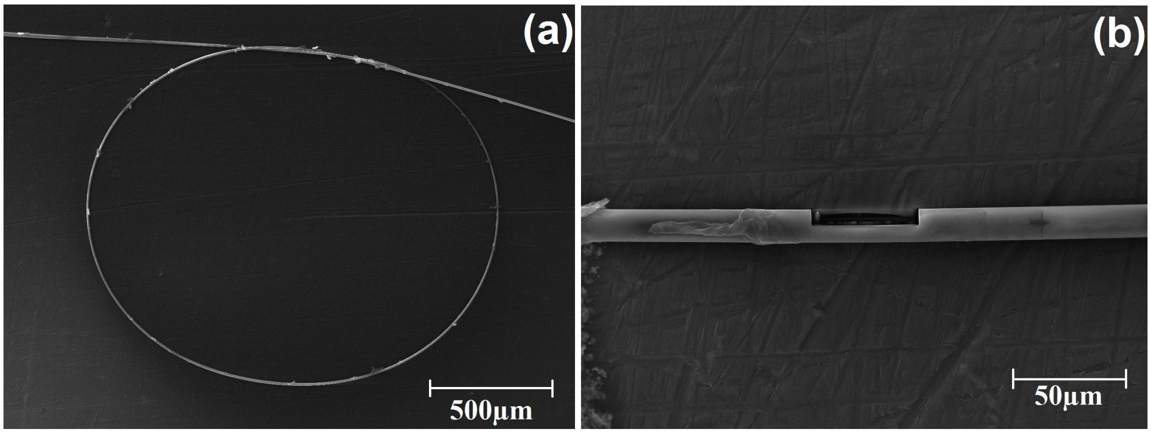

Figure 2. (a) SEM image of the MKR structure. (b) FIB image of the cavity. The cavity length is 48 µm

A 45 µm wide and 5 µm high cavity was milled in the coated taper region directly next to the MKR. The milling was performed using a current of 1000 pA. The three sides of the cavity were polished with the same current. The obtained final cavity length was 47.8 µm. A scanning electron microscope image of the cavity is presented in figure 2(b). Finally, the tantalum coating was removed using the FIB to minimize the losses. Figure 3(a) shows the MKR component of the transmission spectrum before and after the cavity milling. Before milling, the spectrum is the response of the MKR structure. After creating the cavity, the transmitted signal intensity dropped from an average of -39dB to -46dB at 1550 nm. This drop in the transmitted intensity is only due to light that is lost in the cavity. The MKR spectrum is still visible after the cavity milling. However, the diameter of the MKR structure is slightly different and this is detected through a small change in the free spectral range (FSR).

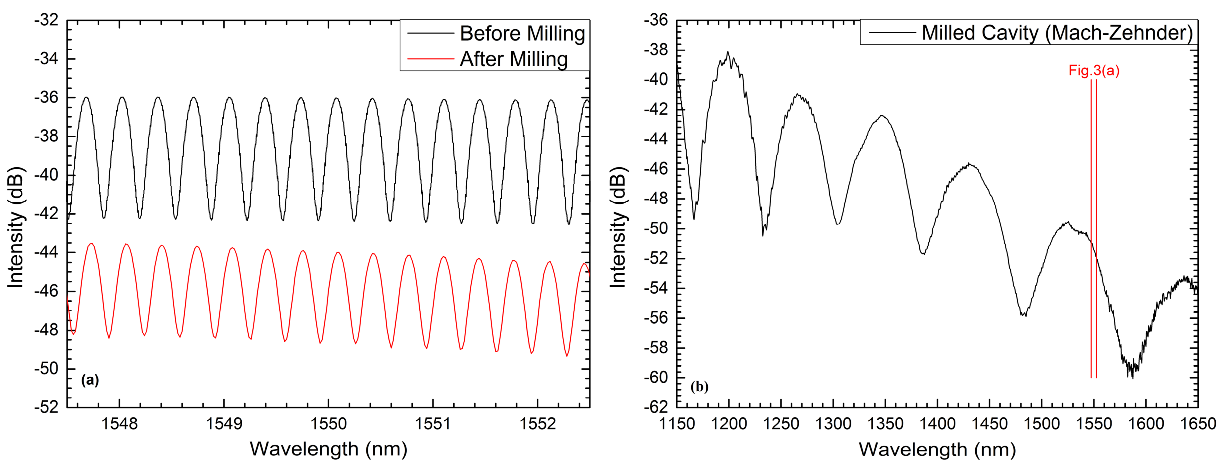

Figure 3. (a) Transmission spectrum of the sensor in air, before and after milling the cavity (MKR component). (b) Transmission spectrum of the sensor in air after milling (cavity component).

In order to observe the spectrum of the created cavity a wider range of wavelengths is necessary due to the significantly shorter optical path length and thus larger free spectral range. To do so, a supercontinuum source was used. The result is shown in figure 3(b). Note that the transmitted intensity in figure 3(b) is lower than in figure 3(a) due to dirt in the cavity. The measured FSR is 105 nm at 1550 nm. A deeper analysis on the result shows that the cavity interference spectrum matches with the response of a Mach-Zehnder interferometer (MZI), where part of the light travels through the air cavity and the other part through the silica fiber taper, as exemplified in figure 4. The phase difference between the two optical paths originates in the difference between the refractive index of silica and the cavity. This behavior is different from a Fabry-Perot cavity, where the phase difference is due to different physical path lengths of the light in the cavity.

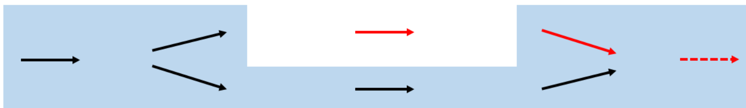

Figure 4. Illustration of the light path in the Mach-Zehnder interferometer.

The MZI cavity was dipped in different refractive index solutions in order to determine the refractive index sensitivity of the structure. The phase difference between the silica arm and the cavity arm of the interferometer will be affected by the refractive index of the cavity. The sensor was dipped in three sodium chloride solutions with refractive indices of 1.333, 1.337, and 1.341 at 1550 nm. The sensor spectra under these solutions is shown in figure 5. The wavelength shift near 900 nm was monitored as a function of the cavity refractive index. A preliminary result of -8935 ± 108 nm/RIU was obtained for the refractive index sensitivity.

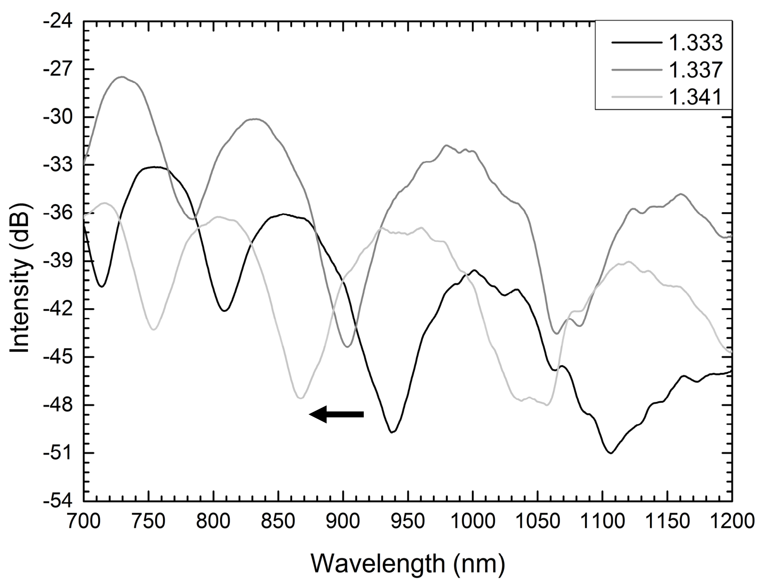

Figure 5. Transmission spectrum of the Mach-Zehnder interferometer under different refractive index solutions.

3. DISCUSSION

A Mach-Zehnder interferometer was created using FIB milling in the taper region next to a 700 μm diameter MKR. The created cavity was 47.8 μm-wide. The detected intensity decreased from -39 dB to -46 dB at 1550 nm, after milling, due to losses introduced by the cavity. The MKR interference spectrum was maintained, despite being slightly changed due to a small change in the diameter of the ring. The cavity behavior matches with a Mach-Zehnder interferometer. The full response of the sensor corresponds to a Mach-Zehnder interference pattern modulating the MKR response. A preliminary result of -8935 ± 108 nm/RIU at 900 nm was obtained for the refractive index sensitivity of this cavity by dipping the sensor in three sodium chloride solutions with refractive indices of 1.333, 1.337, and 1.341.

For the future, the cavity should be characterized in terms of temperature. Although MKRs have been extensively studied, it should be important to characterize the MKR in refractive index and temperature. After being fully characterized, the proposed sensor can be used for simultaneous measurement of refractive index and temperature. Both devices (the MKR and the cavity) have different sensitivities to these parameters, allowing the use of a matrix method to discriminate between refractive index and temperature. If the diameter of the MKR changes while dipping in liquids, a low index polymer coating of the structure can be used to increase the stability and resistance of the sensor, along with an increase in the temperature sensitivity.

ACKNOWLEDGEMENTS

André Gomes is funded by DAAD (German Academic Exchange Service) through the short-term grant 57214227/2016. Ricardo André is supported by Fundação para a Ciência e a Tecnologia through the grant SFRH/BD/84048/2012. Stephen Warren-Smith is funded by the European Commission through the Seventh Framework Programme (FP7), PIIF-GA-2013-623248. This work was financed by FCT – Fundação para a Ciência e Tecnologia (Portuguese Foundation for Science and Technology) and by ERDF (European Regional Development Fund) through: COMPETE Programme (Operational Programme for Competitiveness) within project FCOMP-01-0124-FEDER-037281; ON.2 – O Novo Norte (Northern Portugal Regional Operational Programme).

REFERENCES

[1] T. Schubert, N. Haase, and H. Kück, "Refractive-index measurements using an integrated Mach-Zehnder interferometer," Sensors Actuators A 60(100), 108–112 (1997).
[2] X. Ni et al., "A Hybrid Mach–Zehnder Interferometer for Refractive Index and Temperature Measurement," IEEE Photonics Technol. Lett. 28(17), 1850–1853 (2016).
[3] S. Dass and R. Jha, "Micrometer Wire Assisted Inline Mach-Zehnder Interferometric Curvature Sensor," IEEE Photonics Technol. Lett. 28(1), 31–34 (2016).
[4] X. Zeng et al., "A temperature sensor based on optical microfiber knot resonator," Opt. Commun. 282(18), 3817–3819 (2009).
[5] H. Yang et al., "Temperature Sensing in Seawater Based on Microfiber Knot Resonator," Sensors 14(3), 18515–18525 (2014).
[6] K.-S. Lim et al., "Integrated microfibre device for refractive index and temperature sensing," Sensors (Basel). 12(9), 11782–11789 (2012).
[7] Z. Xu et al., "Highly sensitive refractive index sensor based on two cascaded microfiber knots with vernier effect," Opt. Express 23(5), 6662–6672 (2015).
[8] H. Yu et al., "Solution concentration and refractive index sensing based on polymer microfiber knot resonator," Appl. Phys. Express 7(2), 3–7 (2014).
[9] M. A. Gouveia et al., "Analysis of immersed silica optical microfiber knot resonator and its application as a moisture sensor," Appl. Opt. 53(31), 7454–7461 (2014).
[10] C.-B. Yu et al., "Graphene oxide deposited microfiber knot resonator for gas sensing," Opt. Mater. Express 6(3), 727–733 (2016).
[11] X. Wu, F. Gu, and H. Zeng, "Palladium-Coated Silica Microfiber Knots for Enhanced Hydrogen Sensing," IEEE Photonics Technol. Lett. 27(11), 1228–1231 (2015).
[12] M. S. Yoon, S. K. Kim, and Y. G. Han, "Highly Sensitive Current Sensor Based on an Optical Microfiber Loop Resonator Incorporating Low Index Polymer Overlay," Journal of Lightwave Technology 33(12), 2386–2391 (2015).