Combined long-period grating and micro-cavity in-line Mach-Zehnder interferometer for refractive index sensing

Monika Janik[a,*], Marcin Koba[b,c], Predrag Mikulic[a], Wojtek J. Bock[a], Mateusz Śmietana[b]

[a]Centre de recherche en photonique, Université du Québec en Outaouais, 101 rue Saint-Jean-Bosco, Gatineau, QC J8X 3X7, Canada; [b]Institute of Microelectronics and Optoelectronics, Warsaw University of Technology, Koszykowa 75, 00-662 Warsaw, Poland; [c]National Institute of Telecommunications, Szachowa 1, 04-894 Warsaw, Poland;

ABSTRACT

This work presents combined long-period grating (LPG) and a micro-cavity in-line Mach-Zehnder interferometer (µIMZI), both induced in the same single-mode optical fiber. In order to increase refractive index (RI) sensitivity of the LPG, it has been nanocoated with aluminum oxide (Al_2O_3). Next, the µIMZI has been fabricated as a cylindrical cavity (d = 60 µm) in the center of the LPG. In transmission measurements for various RI in the cavity and around the LPG we have observed two effects coming from two independently working sensors. There was no significant impact on one or the other in terms of their functional properties. Such a combination of sensorial effects can be applied for cross-reference measurements of the two different parameters at the same time or for discrimination of influence of other parameters on the RI measurements.

Keywords: Mach-Zehnder interferometer (MZI), long-period grating (LPG), optical fiber sensors, refractive index sensing, microstructure fabrication, femtosecond laser ablation, thin films

INTRODUCTION

Long-period gratings (LPGs) have been known and explored as a sensing structures for almost two decades [1]. The LPG is a periodic modulation of the refractive index along the length of a core in a single-mode optical fiber, which allows for coupling between the fundamental core mode and a series of cladding modes. This coupling results in the appearance of resonances in the LPG transmission spectrum. A number of sensors based on the LPGs have been proposed for many different applications, e.g., temperature [2], hydrostatic pressure [3], bending [4], and refractive index (RI) sensing [5]. In order to increase sensitivity of the LPG to external RI, a tuning of its operational point [6] or its coating with high RI thin films has been proposed [7].

A concept of Mach-Zehnder interferometer (MZI) is also well known. In the MZI the light beam splits into two parts propagating in two different paths, which after given distance interfere with each other [8]. There are many different ways for implementing MZI in an optical fiber, e.g., as a pair of LPGs [9], by core mismatch [10], implementing segments of different fibers [11] or air cavities micro-machined in the fiber [12]. The structure presented in this paper refers to the last-mentioned concept, in which the light splits into a reference and sensing path – both with different optical lengths, but in one optical fiber. Due to its micrometric dimensions, the process of fabrication of the cavity has to be accurate, repeatable and cause relatively small damages. Among many known methods of fabricating MZIs, the fs laser micro-machining can meet all these challenging demands. That is the reason why a fs laser system was recently used to fabricate various micro-cavity in-line MZI (µIMZI) structures [12,13].

Both aforementioned sensing concepts have already been used separately, but up till now they have never been combined. In this paper, we report results for RI sensing with combination of a highly sensitive LPG and a µIMZI as one device for RI sensing.

METHODOLOGY

2.1 LPG manufacturing

The commercially available germanium-doped and hydrogen-loaded Corning SMF-28 single-mode optical fiber was used. A set of LPGs was fabricated by UV irradiation of 5cm-long fiber section with a KrF excimer laser employing a chromium amplitude mask having a periodicity of Λ = 226.8 µm. After the UV-writing, the LPGs were annealed in 150 °C for 3 hours in order to release the hydrogen and thus to stabilize the properties of the gratings. After fabrication, the LPGs were coated with aluminum oxide thin film according to procedure raported in [14].

*monikaa.janik@gmail.com ** M.Smietana@elka.pw.edu.pl

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2.2 Manufacturing of the µIMZI structures

Structures in the form of cylindrical holes (micro-cavities) were fabricated in the middle of previously made LPG (Fig. 1). The micromachining process was performed using a Solstice Ti:Sapphire fs laser operating at λ = 795 nm. The fiber was irradiated by 82 fs pulses. The system was working with a repetition rate of 10 kHz. In order to make the micro-cavity, the laser beam was directed into a suitably designed micromachining setup based on the Newport µFab system. The system was equipped with a 20x lens, with NA = 0.30. The hole size equaled to 60 µm which was chosen for mechanical rubustnes and ease of liquid application. During fabrication fiber transmission was monitored with an NKT Photonics SuperK COMPACT supercontinuum white light source and a Yokogawa AQ6370C optical spectrum analyzer. The fabrication process was controlled with a software developed in-house.

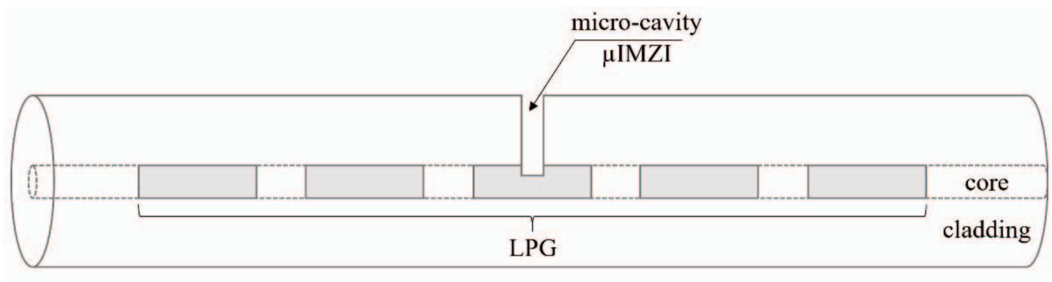

Figure 1. Schematic drawing of the LPG-µIMZI structure. Features are not to scale.

2.3 LPG and LPG-µIMZI analysis

First the spectral response of the LPGs was investigated in the wavelength range of 1100 to 1700 nm using a Yokogawa AQ6370C spectrum analyzer and an NKT Photonics SuperK COMPACT supercontinuum white light laser source. The RI sensitivity was measured by immersing the LPGs in a water-glycerin mixture with RI ranging from 1.3333 to 1.4000 RIU. The RI of the liquids was measured using a VEE GEE PDX-95 digital refractometer with a resolution of 10^{-4} RIU. Liquid samples were taken directly from the vicinity of the LPG. Between the immersions, the LPG was rinsed with deionized water. Temperature and strain were kept constant during all the RI measurements. Exactly the same measurement setup and same conditions were used for LPG-µIMZI structure analysis.

RESULTS

The measurement results of the spectral response of an LPG (without any modifications) immersed in liquids of various RI is shown in Fig. 2. An increase of the spectral distance between the resonances is observed when external RI is increased, which is very characteristic for this type of sensing structure working at the dispersion turning point (DTP) of higher order cladding modes [14]. The RI sensitivity for each resonance is close to 9000 nm/RIU.

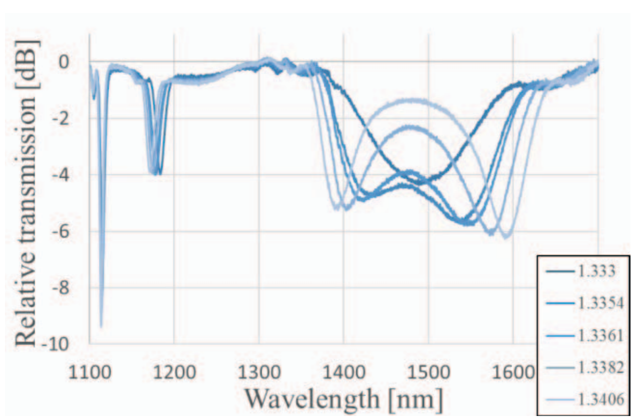

Figure 2. Spectral response of the investigated LPG to external changes in external RI.

The transmission spectra for the same grating, but after the micro-machining process, thus with the micro-cavity in the middle of the LPG, are shown for different external RI in Figs. 3(a) and 3(b).

a) b)

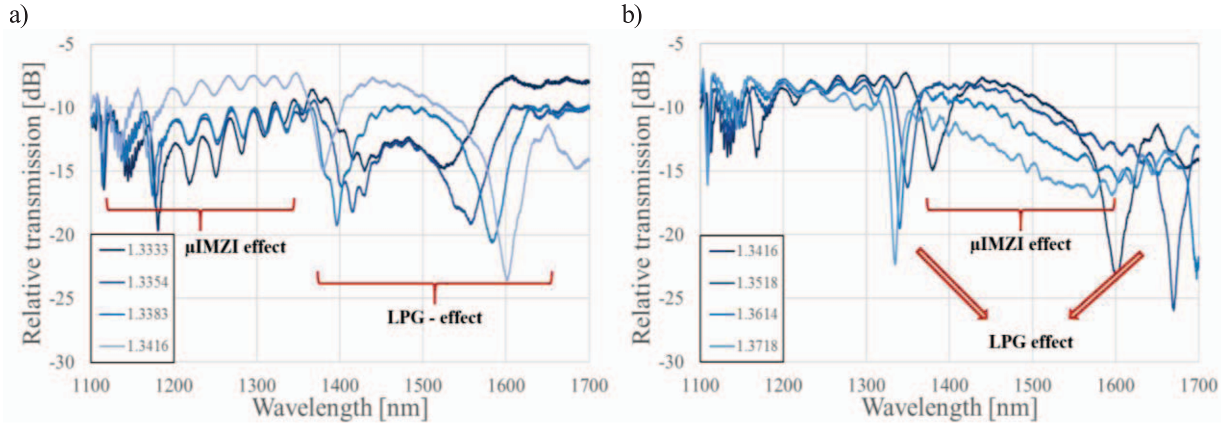

Figure 3. Spectral responses of the investigated LPG-µIMZI structure for varying external RI (a) in range RI from 1.3333 to 1.3416 RIU and (b) in range RI from 1.3416 to 1.3718 RIU, with indication of the LPG and the µIMZI related effects.

The first thing we can observe on the apperance of the spectrum after the micromachining process is the lower overall transmitted power. Relative transmission dropped to values between -7 and -11 dB. This effect is induced by the µIMZI, which by being fabricated in the fiber core causes parts of the light transmitted in the core as well as in the cladding to scatter and interfere with one another. The effect of scattered waves interference is manifested by the oscillatory character of the spectrum. Except of these observations, we can notice two significant effects, i.e., part of the spectrum above 1400 nm in wavelength looks very similarly to the one for LPG before micromachining. The other part (below 1400 nm) is dominated by the above mentioned periodic interference response - the effect of the micro-cavity in the fiber (Fig. 4 – an example of the µIMZI of the same diameter alone).

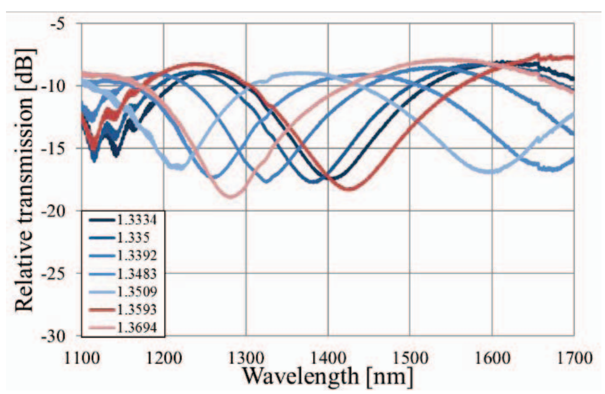

Figure 4. Spectral response of the µIMZI alone, with diameter d = 60 µm

As expected with the increase of the RI, the spectral distance between the LPG resonances increases. As opposed to the LPG with no micro-cavity, in the case of the LPG-µIMZI combination, a minimum moving toward shorter wavelength can be observed on the top of the LPG response, which is typical for µIMZI (Fig. 3b and 4). The effects overlap, but there is no visible disruption of the LPG resonant response induced by the interference. Despite a significant discontinuity in the fiber cladding, which is responsible for sustaining the cladding modes, the LPG-related effect remains valid. The two effects steming from the LPG and from the µIMZI seem to be absolutely independent. They are not affecting each other which can be of significant importance in terms of utilizing this platform for measurement of two different parameters at the same time. This is even more interesting when one realizes that in contrast to the LPG, the µIMZI is almost temperature insensitive [15].

CONCLUSIONS

The work presents first to the date presentation of the LPG-µIMZI combined sensor. The standard LPG coated with aluminum oxide thin-film has been modified to incorporate a cylindrically shaped hole reaching the fiber core. During the process a femtosecond laser has been used and the micro-cavity with diameter of d = 60 µm was fabricated in the middle of the 5 cm-long LPG. As a result, we have observed two independently working sensors, having no significant impact on each other's operation, although a manifestation of some interferometric effects can be observed in the analyzed spectral range. The independent operation at some values of RI leads to overlapping of the effects, which has to be taken into consideration. It is also worth noting that such sensor combines temperature sensitive and insensitive structures. Thus, this kind of sensor might be well suited for cross-reference measurements of the two different parameters at the same time.

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REFERENCES

[1] Vengsarkar A.M., Lemaire P.J., Judkins J.B., Bhatia V., Erdogan T., Sipe J.E. "Long-period fiber gratings as band-rejection filters." J. Light. Technol., 14, 58–65 (1996)

[2] Wolinski T. R., Czapla A., Ertman S., Tefelska M., Domanski A. W., Wojcik J., Nowinowski-Kruszelnicki E., Dabrowski R. "Photonic Liquid Crystal Fibers for Sensing Applications," IEEE Transactions on Instrumentation and Measurement, 57 (8), 1796-1802 (2008)

[3] Bock W.J., Chen J., Mikulic P., Eftimov T. "A novel fiber-optic tapered long-period grating sensor for pressure monitoring." IEEE Trans. Instrum. Meas. 56, 1176–1180 (2007)

[4] Szymańska M., Krogulski K., Mikulic P., Bock W.J., Śmietana M. „Sensitivity of long-period gratings modified by their bendig", Procedia Engineering 87, 1180-1183 (2014)

[5] Śmietana M., Brabant D., Bock W. J., Mikulic P., and Eftimov T., "Refractive-Index Sensing with Inline Core-Cladding Intermodal Interferometer Based on Silicon Nitride Nano-Coated Photonic Crystal Fiber," J. Lightwave Technol. 30, 1185-1189 (2012)

[6] Śmietana M., Koba M., Mikulic P., Bock W.J. „Combined Plasma-Based Fiber Etching and Diamond-Like Carbon Nano-overlay Deposition for Enhancing Sensitivity of Long-Period Gratings", Journal of Lightwave Technology, 34, 19, 4615-4619 (2016)

[7] Śmietana M, Myśliwiec M, Mikulic P, Witkowski BS, Bock WJ. „Capability for Fine Tuning of the Refractive Index Sensing Properties of Long-Period Gratings by Atomic Layer Deposited Al_2O_3 Overlays." Sensors (Basel, Switzerland). 13(12), 16372-16383 (2013)

[8] Dębowska A.K., Koba M., Janik M., Bock W.J., Śmietana M. „Increased sensitivity of femtosecond laser micro-machined in-fiber Mach-Zehnder Interferometer for small-scale refractive index sensing", Proc. SPIE 9916, 99160Q (2016)

[9] Jong H. Lim, Hyun S. Jang, Kyung S. Lee, Jin C. Kim, and Byeong H. Lee, "Mach–Zehnder interferometer formed in a photonic crystal fiber based on a pair of long-period fiber gratings," Opt. Lett. 29, 346-348 (2004)

[10] Ngyuen, L.V.; Hwang, D.; Moon, S.; Moon, D.S.; Chung, Y.J. "High temperature fiber sensor with high sensitivity based on core diameter mismatch" Opt. Express, 16, 11369-11375 (2008)

[11] Zhu, J.J; Zhang, A.P.; Xia, T.H.; He, S.; Xue, W. "Fiberoptic high-temperature sensor based on thin-core fiber modal interferometer" IEEE Sens. J., 10, 1415-1418 (2010)

[12] Jiang L., Zhao L., Wang S., Yang J., and Xiao H., "Femtosecond laser fabricated all-optical fiber sensors with ultrahigh refractive index sensitivity: modeling and experiment", Opt. Express 19 (18), 17591-17598 (2011)

[13] Sun, X. Dong, Y. Hu, H. Li, D. Chu, J. Zhou, C. Wang, and J. Duan, "Highly sensitive refractive index fiber inline Mach-Zehnder interferometer fabricated by femtosecond laser micromachining and chemical etching," Sensors Actuators A. Phys., 230,11–116 (2015)

[14] Śmietana M., Koba M., Mikulic P., and Bock W. J., "Towards refractive index sensitivity of long-period gratings at level of tens of µm per refractive index unit: fiber cladding etching and nano-coating deposition," Opt. Express 24, 11897-11904, 2016.

[15] T. Y. Hu and D. N. Wang, "Optical fiber in-line Mach–Zehnder interferometer based on dual internal mirrors formed by a hollow sphere pair," Opt. Lett. 38, 3036-3039 (2013)