Characterization of Femtosecond Written Mach-Zehnder Interferometers Based on Titanium Dioxide Coated Long Period Fiber Gratings

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Abstract: Optical fiber Mach-Zehnder interferometers were fabricated by combining two TiO_2 coated LPFGs fabricated by femtosecond laser direct writing. Results of its refractometric characterization are presented and compared with the single LPFGs sensors. Wavelength sensitivity of 1175 nm/RIU at 1.38 and spectral resolution of $2.2x10^{-5}$ was achieved.

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1. Introduction

Optical fiber sensors (OFS) based on long period fiber gratings (LPFGs) have been extensively studied due to their well-known advantages [1] from the coupling of radiation between the core and co-propagating cladding modes [2]. The period, the refractive index (RI) modulation, and the surrounding refractive index (SRI) modify the coupling conditions causing variations in the output spectrum [3], thus making LPFGs sensitivity to different parameters [4].

LPFGs for sensing water-based solutions require its sensitivity to be enhanced for optimal operation. Sensitivity in the vicinity of water refractive index can be improved , for example, coating with a material that has a RI higher than the cladding refractive index (CRI) [5], such as titanium dioxide (TiO_2) [6, 7].

Several methods have been developed for LPFGs fabrication in a variety of fibers using several techniques [8], such as exposure to UV or CO_2 laser radiation, electric arc discharge, ion beam irradiation, chemical etching, and infrared femtosecond laser radiation [2].

The femtosecond laser induces localized RI changes and leads to thermally stable LPFGs over a broader temperature range, compared to UV induced gratings. The laser beam is focused with high resolution in a small section inside the fiber core. Femtosecond LPFGs have a far greater polarization dependent response and the ability to couple to higher order sets of cladding modes. The technique is suitable for the automated fabrication of a large number of devices as well as to the production of hybrid devices, such as fiber Bragg gratings in tandem with LPFGs [9].

An OFS based on a Mach-Zehnder interferometer (MZI) composed of a pair of 3 dB LPFGs has been reported, where the sensitivity of the cladding mode to the SRI was utilized while improving the RI resolution [9].

In this work, a femtosecond laser direct writing system was developed to fabricate MZIs composed by two LPFGs in silica fibers. Both were coated with a TiO_2 thin film, and the spectral behavior to variations of the SRI greater and lesser than the CRI was characterized and reported.

2. Materials and Methods

The MZI were written in standard single mode fiber (SMF28, Corning, Inc.). The device consists of two identical inline LPFGs and a section of a bare optical fiber in between, whose length was set to 1.375 cm, as shown in Fig. 1. The LPFGs were produced by the femtosecond laser direct writing, using previously reported methodologies [10]. The period of each LPFG was 380 µm, yielding a resonance wavelength at ~1.5 µm, related to the $LP_{1,6}$ asymmetric cladding mode. Bare and TiO_2 coated MZI were produced.

The visibility of bare interferometers was optimized by setting the attenuation of each LPFG to 3 dB which was reached for 16.000 mm length. The two LPFGs were written in a single run to avoid rotations that can induce a spectral mismatch. Titanium dioxide films 30, 40, and 50 nm thick were produced around the MZIs by thermal evaporation of pure titanium in a controlled oxygen atmosphere using an electron beam evaporator Auto 306 (Edwards Ltd, U. K.) following the procedure described in [7]. In addition, single LPFGs, bare and coated with 50 nm of TiO_2, were fabricated for comparison of characteristics and performance.

Both OFS, MZI, and LPFGs, were characterized in transmission mode with a broadband light source (BBS) and an optical spectrum analyzer (OSA) model ANDO AQ 6315B, as illustrated in Fig. 1. One end of each OFS was clamped with a magnet while at the other end, a 5 g magnetic weight kept the fiber stretched at a constant tension.

The spectral response to the SRI was achieved by immersing the OFS in RI calibrated oils (Cargille-Sacher Laboratories Inc., U.S.A.), from 1.3000 to 1.6400, using a glass V groove and wrapping the entire OFS.

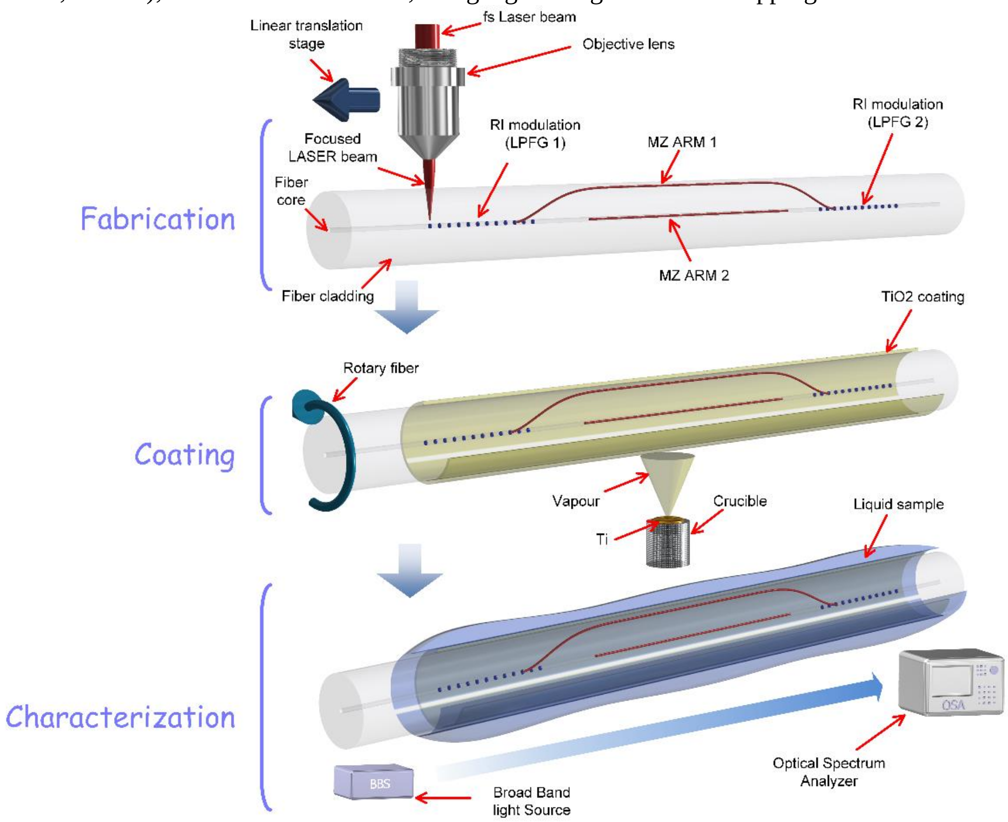

Fig. 1. Illustration of the fabrication, coating, and characterization processes concerning the study of Mach-Zehnder interferometers and long period fiber gratings.

The spectral resolution of a refractometric OFS is an essential feature. To access the stability and repeatability of the different sensing scheme, the same sensor was used to obtain several acquisitions. The RI spectral resolution, R_{RI}, can be estimated considering the values obtained from two measurements linked with two different values of the SRI [11]: $R_{RI} = \sigma/S_{RI} = (\Delta n/\Delta\lambda)\sigma$, where the Δn is the RI difference, S_{RI} is the sensitivity to RI variations, $\Delta\lambda$ is the difference in the wavelength of the resonant dip and, σ is the highest standard deviation associated with the sensor output variation associated to a step variation of the external RI.

3. Experimental Results and Discussion

Optimization of the MZIs visibility depends on the optical power transmitted to the cladding mode. After coating, the attenuation band of the LPFG suffers a blue shift and a decrease of amplitude [6]. Therefore, the coated MZIs were created with LPFGs whose attenuation band was set to ~4.5dB. The measured transmission spectra corresponding to the interference of the $LP_{1,6}$ cladding mode with the fundamental core mode, are presented in Fig. 2 (a) and (b), for the uncoated and coated (30 nm of TiO_2) MZI, respectively, for SRI from 1.30 up to values lower than the CRI. For a cavity length of 1.375 cm between LPFGs, all MZIs analyzed presented two leading bands. The normalized wavelength shift was calculated using these bands, named Band A and Band B, and is presented in Fig. 3 (a) and (b) for MZIs uncoated and coated with 30, 40, and 50 nm of TiO_2. The sensitivity of the sensors was determined by calculating the 1st order derivative of these curves and is presented in Fig. 3 (c) and (d), for SRI lower and higher than the CRI, respectively. The sensitivity of the single LPFGs is also shown for comparison.

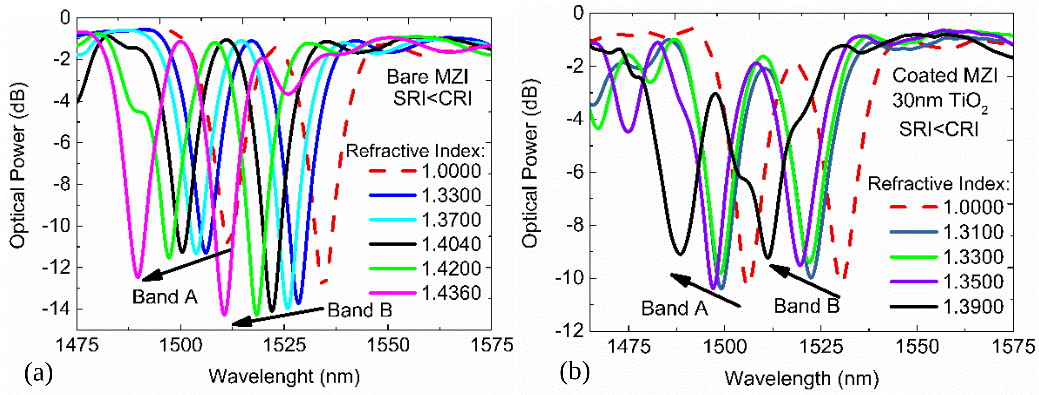

Fig. 2. Transmission spectra of an MZI, (a) uncoated and (b) coated with 30 nm thick TiO_2 film, for several values of the surrounding refractive index (SRI).

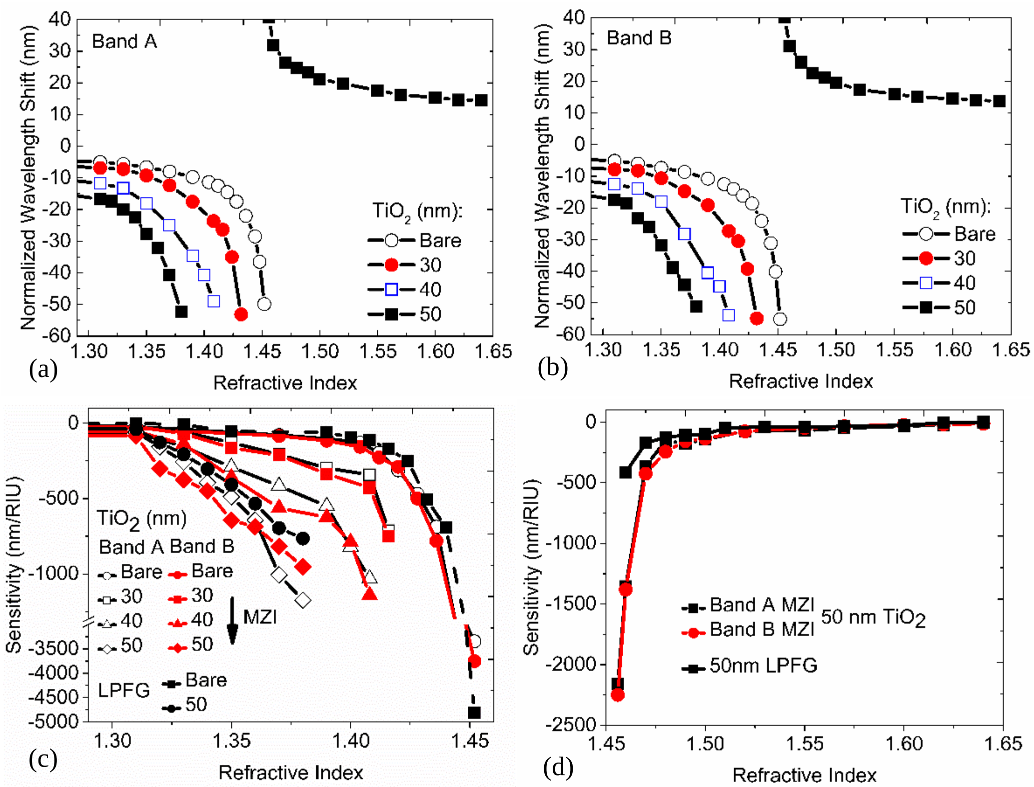

Fig. 3. Normalized wavelength shift as a function of the SRI for MZI with a cavity of 1.375 cm, uncoated and coated with 30, 40 and 50 nm of TiO_2: (a) Band A, (b) Band B. Wavelength sensitivity of the MZIs and the LPFGs for SRI; (c) lower and (d) higher than the CRI.

The wavelength shift is higher for coated MZIs and increases with the thickness of the TiO_2 film, for both interferometric bands. This observation agrees with the results presented in [6] for TiO_2 coated LPFGs. However, it must be noticed that the calculated sensitivity presented in Fig. 3 (c) and (d) is higher than the determined for the single LPFGs, either bare or coated. As shown in Fig. 3 (c) and (d), no substantial difference in sensitivity between bands A and B was found, within the experimental error. The spectral resolution can be estimated using the procedure outlined above and equation (1) considering the values obtained from two measurements linked with several different values of the SRI. Figure 4 shows data concerning two of these steps, from which a spectral resolution better than $1.1x10^{-5}$ and $2.1x10^{-5}$ was estimated for the bare MZI, and for band A and B, respectively; for the 50 nm coated MZI a spectral resolution better than $2.2x10^{-5}$ and $1.3x10^{-5}$ was calculated, for band A and B, respectively. It must be noticed that for single LPFGs the calculated resolution is $3.1x10^{-4}$ and $4.6x10^{-4}$, for the uncoated and the 50 nm coated, respectively. The broad attenuation band characteristic of the LPFG compared with the much narrower bands of the interference spectrum contributes to a better spectral resolution.

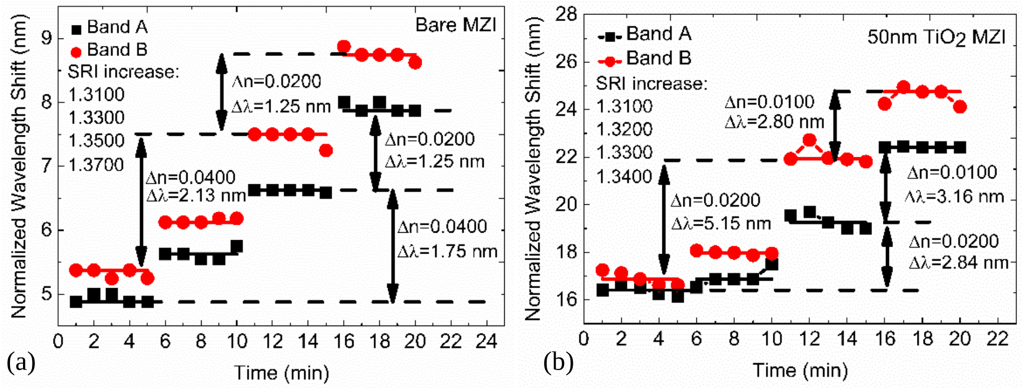

Fig. 4. The normalized wavelength shift of the interferometric bands of MZI when the surrounding medium undertakes step variations: (a) bare and (b) 50 nm TiO_2 coated.

4. Conclusions

A preliminary study on the development of femtosecond written Mach-Zehnder interferometers based on TiO_2 coated LPFGs was presented. The structure benefits from the increased wavelength sensitivity of the TiO_2 coated LPFGs and of the improvement of the spectral resolution given by the interferometric structure.

Higher sensitivity and resolution were obtained with MZI in comparison with the single LPFGs. For the parameters here tested, a TiO_2 coated MZI presents a enhances wavelength sensitivity and one order of magnitude higher spectral resolution. It is expected that by optimization of the TiO_2 thickness and cavity length, an increased sensitivity may be obtained while maintaining the resolution.

5. Acknowledgments and funding

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