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# Hybrid Mach-Zehnder Interferometer manufactured by femtosecond laser multiscan technique

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## ABSTRACT

In this paper, a 6 mm hybrid Mach-Zehnder Interferometer (MZI) has been manufactured within a standard optical fiber using multiscan inscription with femtosecond laser. This technique allows the employ of cladding waveguides (CWG) as sensing arms for the interferometer. Refracted Near Field (RNF) profilometry and Quantitative Phase Microscopy (QPM) consistently suggest that CWG exhibit a smooth Type I refractive index change (RIC) that increases with the number of scans. This makes the scan number a potential way to control the coupling and Free Spectral Range (FSR) of the manufactured MZI. Its combination with a fiber Bragg grating (FBG) inscribed in the core makes possible to discriminate between different parameters.

**Keywords:** Femtosecond laser, Microstructure fabrication, Mach-Zehnder, Waveguide, Fiber Bragg grating.

## 1. INTRODUCTION

The use of femtosecond lasers as a means of direct inscription of components through three-dimensional structures inside the bulk volume of transparent materials has been a great opportunity in terms of simplicity and flexibility for the micromachining of materials [1]. It has a special interest in the design of optical fiber sensors (OFS) for its potential application in multiple scenarios.

In recent years, the design and manufacture of in-fiber devices based on cladding waveguides has increased significantly [2], as a result of its extreme sensitivity in external effects to the fiber itself and a higher control of propagation mode in comparison to cladding mode employment. Due to its simple design, the use of interferometers, especially the MZI, has traditionally been done using air cavities, fiber tapers, long-period fiber gratings (LPGs) or waveguides formed by fs laser-based RI changes [3]. In this work, it is proposed a hybrid MZI (combines a FBG in the core) through the manufacture of waveguides formed by multiple inscriptions, using the above-mentioned RI changes by fs laser. This multiscan technique allows to have control over the shape of the optical structures [2], for a better light guidance due to the smooth positive isotropic RIC generated. The FBG in the core has been manufactured by means of the point-by-point ($PbP$) inscription method. The use of this method has evolved to a well-known and flexible tool for the FBG inscription [1, 2]. The simplicity that this method presents compared to other techniques that require a longer inscription time or specific optics makes it useful for the development of applications that require simple implementations.

## 2. WAVEGUIDE INSCRIPTION

### 2.1 Multiscan technique

There are multiple techniques to control the cross-section of femtosecond laser inscribed waveguides. However, most of them consist in modifying somehow the conformation of the laser beam, either through active optics, spatio-temporal focussing techniques or slit-beam shaping [1].

Unlike these, waveguides inscribed in this work have been made using the multiscan technique, by which the waveguide cross-section is constructed by scanning the substrate through the focus of the laser beam many times, combining the lines of modified material induced by each scan, and thus correcting the waveguide asymmetry of a single inscription [1, 2]. Regarding manufacturing process, after each scan, the sample position moves slightly on the perpendicular axis to both the laser beam propagation axis and waveguide longitudinal axis (Figure 1b).

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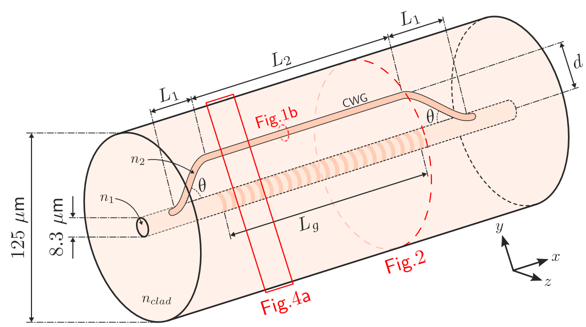
## 2.2 Sensor design

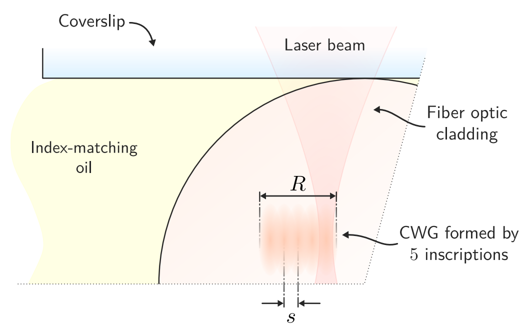
In an optical fiber, Mach-Zehnder Interferometers are based on the optical path difference (OPD) that arises when the light is divided into two different optical paths: one is set as reference (core) and the other acts as the sensor element (CWG). In the schematic depicted in Figure 1a, using a single-mode optical fiber (SMF), the fundamental mode is decoupled (by an S-Bend structure of length $L_1$) to a secondary mode propagated by a cladding waveguide of length $L_2$, before being coupled back to the core [3].

A series of MZIs were performed to investigate the optimal conditions. Consequently, lengths of S-Bend ($L_1$) and cladding section ($L_2$) of 1 mm and 4 mm have been established, respectively. On the other hand, the radial distance ($d$) between the cladding section and the core has been set at 40 $\mu$m, thus presenting a high sensitivity to the refractive index of the external medium. This value originates a core-CWG separation angle $\theta = 2.29^{o}$, adequate value to limit the waveguide losses. Additionally, the waveguide that forms the MZI has been made from a series of 5 inscriptions‡ radially separated $s = 0.2$ $\mu$m between them ("inscribe and step" process), originating a waveguide width of $R =\sim 4.5$ $\mu$m, as shown in Figure 1b.

Parallel to the MZI cladding section, a FBG with length $L_g = 4$ mm has been inscribed in the core using the point-by-point ($PbP$) inscription method with a grating period $\Lambda = 1.051$ $\mu$m, which originates a Bragg wavelength in the 3rd telecommunications window (2nd FBG order).



(a)



(b)

Figure 1. (a) Dimensions of the all-in-fiber 6 mm component formed by the MZI and the FBG located in the core, with references to the figures containing the CWG-FBG inscription result, the CWG cross-section, (b) and the multiple inscriptions used in the manufacture of the CWG (cladding section of the MZI).

Within the characteristics of an interferometer it is important to attend to the FSR, defined as the spectral distance between two successive transmitted optical intensity maxima or minima for a given wavelength $\lambda_0$ [3]. For a MZI, its FSR will be expressed by the well known equation

$$FSR \approx \frac{\lambda_0^2}{\Delta n \cdot L}, \tag{1}$$

where $\Delta n = |n_2 - n_1|$ is the effective mode index difference between fundamental and secondary modes and $L \approx 2 \cdot L_1 + L_2$ is the path length.

# 3. EXPERIMENTAL RESULTS

## 3.1 Inscription parameters

The inscriptions made, both for the manufacture of the MZI and the FBG, have been carried out using a femtosecond commercial Fiber Laser Chirp Pulse Amplifier (FLCPA) from `CALMAR` lasers, operating at 1030 nm, with a 370 fs pulse duration and a variable Pulse Repetition Rate (PRR) from 1 Hz to 120 kHz. The laser beam is focused through to NA = 0.5 objective lens from `Mitutoyo`. In order to eliminate the spherical aberration of the fiber itself, this is placed between a slide and a coverslip, depositing an index-matching oil between both [4]. The slide is placed on a platform located on a nanoresolution XYZ motor stage from Aerotech. The observation of the microstructures is obtained from a CCD camera and a white light source that illuminates the fiber.

‡Waveguides formed between 1 and 10 scans have been investigated, as discussed in section 3.

The MZI has been manufactured using a pulse energy of 0.19 $\mu$J, a PRR of 60 kHz and 800 pulses/$\mu$m (writing speed is $v = 75$ $\mu$m/s). However, the inscription of the FBG has used a pulse energy of 0.47 $\mu$J, a PRR of 10 Hz and a grating period $\Lambda = 1.051$ $\mu$m, which originates $v = 10.51$ $\mu$m/s.

### 3.2 Cladding waveguide

The produced waveguide (formed by 5 scans) can be seen in Figure 2a, with the two light spots: core and CWG, obtained by illuminating the opposite end-face with a white light. It is remarkable the circular symmetry obtained by the multiscan technique. As shown in the 3D profile of Figure 2b, the cross-section exhibits different refractive index regions. For this, RNF profilometry was applied by `Sira Electro-Optics` optical fiber refractive index profiler [3]. As shown in Figure 2c, the waveguide RI change is $\Delta n = 1.51 \cdot 10^{-3}$, positive RI in the focal volume, since adaptive optics has been used in the inscription process.

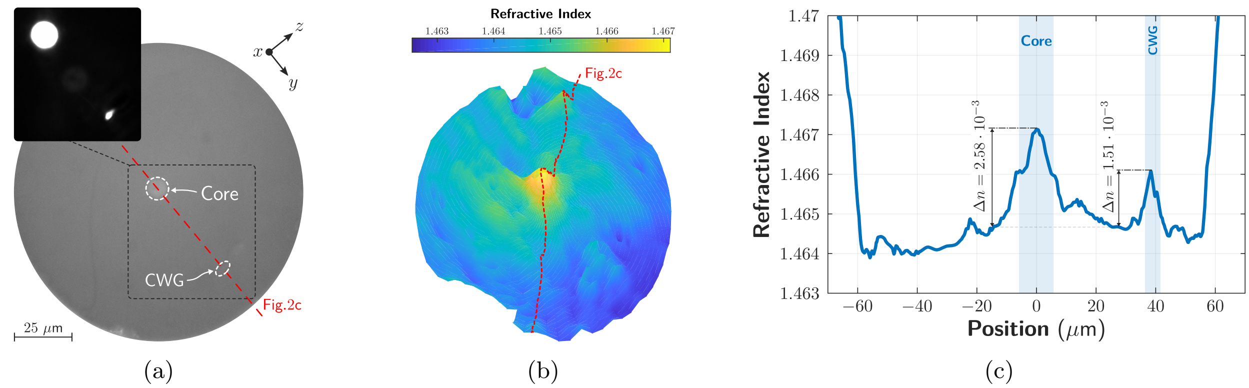



Figure 2. (a) SMF end-face of the inscribed waveguide captured with a CCD camera, along with the output light obtained when a white light source is connected to the distal end of the fiber sample. (b) 3D RI profile measured with a Refractive Index Profiler. (c) Core and CWG RI profile.

On the other hand, through the QPM technique[§] [5], the phase change associated with cladding waveguides formed by scans between 1 and 10 was characterized. The experimental results determine that the lines of modified material induced by each scan cause an increment in the phase change ($\Delta\phi \propto \Delta n$) of the waveguide, until reaching a point at which said change tends to stabilize (10 scans). The results are depicted in Figure 3. A CWG formed by 5 scans has been chosen, presenting a phase change similar to that of the core[¶].

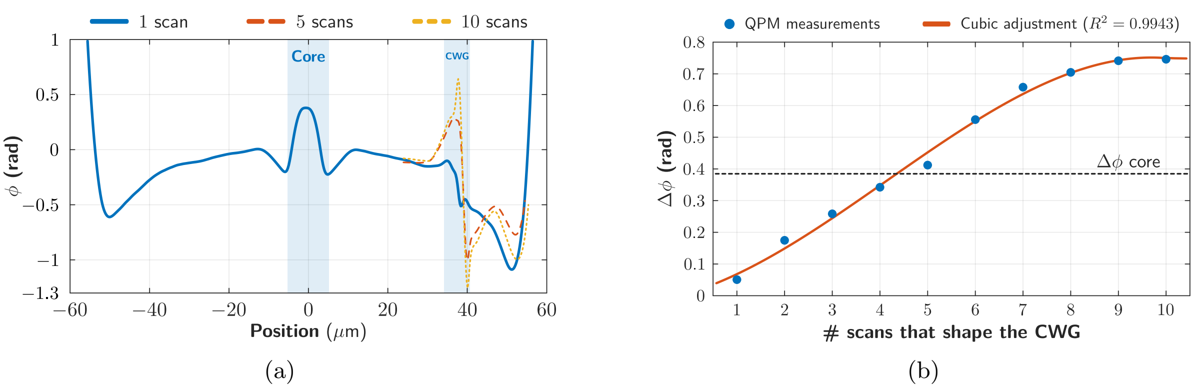



Figure 3. (a) Phase profile measured with QPM for waveguides inscribed by 1, 5 and 10 scans, (b) and the CWG-cladding phase change based on the number of scans that form the waveguide.

[§]Microscopy method that quantify the phase shift that occurs when light pass through a optically dense sample.

[¶]The CWG inscription of Figure 2 was stopped $\sim 5$ $\mu$m before the cleaved end of the fiber, which is why RNF indicates a lower RI change in the CWG than in the core, while QPM indicates a higher phase change in the waveguide than in the core (for 5 scans) (Figure 3b). However, the trend is identical.

### 3.3 MZI and FBG

In Figure 4b, using a broadband light source (`HP 83437A`) and an Optical Spectrum Analyzer (`Anritsu MS9740A`) in a transmission configuration, the MZI is characterized during multiscan inscription. As a result of the increase in the refractive index of the CWG and the expression shown in Equation 1, it can be seen that the FSR decreases as the number of scans increases. Finally, by adding the FBG in the core with the specifics detailed in subsection 3.1, a 2nd-order Bragg wavelength of $\lambda_B = 1516.9$ nm is generated, as it is depicted in Figure 4c. In this way, it is possible to solve the problems associated with the cross-sensitivity, allowing sensing different parameters (e.g., RI with MZI and temperature with FBG) with a 6 mm component in a standard fiber SMF.

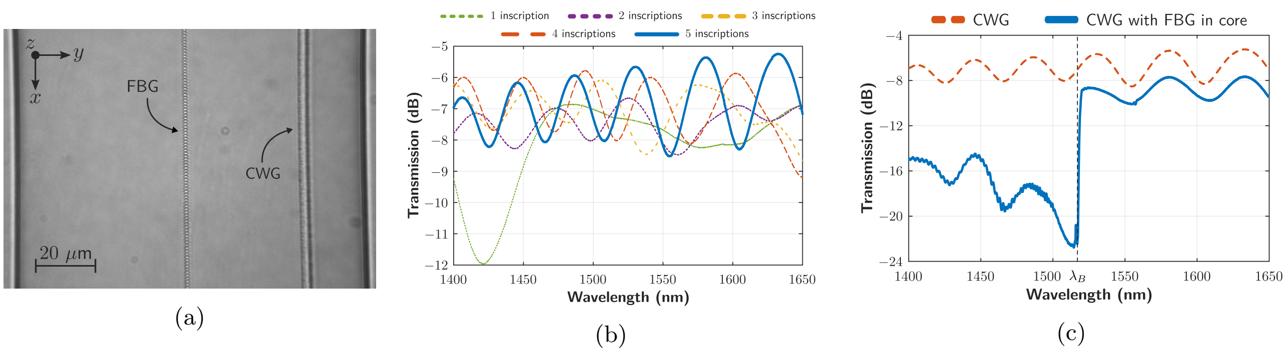



Figure 4. Manufacturing result. (a) Longitudinal view of the MZI cladding section together with the FBG inscription in the core. (b) MZI transmission spectra for waveguides formed between 1 and 5 scans, (c) and a comparison of the transmission spectra of the complete MZI (5 scans) without and with the FBG in the core.

## 4. CONCLUSIONS

An in-fiber hybrid Mach-Zehnder Interferometer based on multiscan waveguide inscription with femtosecond laser is presented. Using the QPM technique, the cladding waveguides have been characterized according to the number of scans inscribed, observing that an increase of them implies an increment in the phase (and refractive index) change until reaching a point where it occurs a saturation in the changes induced in the material. In this way, by means of a 6 mm compact component that combines an MZI (with a RI change similar to the core) and an FBG, it is possible to determine together with a high sensitivity changes in the RI of the external medium together with other parameters such as temperature, curvature or strain, with a high degree of spectral properties control. It should be noted that as it is a structure made with adaptive optics generating a Type I RIC, its behaviour at high temperature is relatively stable. Experimental measurements will be carried out to achieve an exhaustive characterization of the sensor.

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