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Cost effective refractive index sensor based on optical fiber micro cavities produced by the catastrophic fuse effect

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ABSTRACT

We propose a refractive index optical fiber sensor based on the micro cavities generated through the fiber catastrophic fuse effect. This sensor was tested in the measurement of solutions with refractive indices ranging from 1.3320 to 1.4280. The linear dependence of the reflection spectra modulation period as function of the surrounding environment refractive index leads to a resolution of 3×10^{-4} RIU. The proposed sensor is an innovative solution based on optical fiber damaged by the fuse effect, resulting in a cost effective solution.

1. Introduction

The refractive index (RI) measurement is a relevant procedure for research and industrial fields such as biology, chemistry, medicine, structural monitoring or oil industry being used to monitor the evolution of chemical reactions or the presence of specific substances, the control of food quality, among other solicitations [1–3]. Refractive index is usually determined using optical refractometers, mostly based in the Abbe configuration [4], achieving resolution values up to 10^{-5}. However, this solution has severe restrictions in terms of remote sensing or miniaturization. To overcome such limitations, new types of optical fiber based refractometers have been the focus of extensive research over the last years. Several optical fiber refractometers based on Bragg gratings in etched optical fibers [5], long period gratings [6], tilted Bragg gratings [7] and surface plasmon resonance [8] have been reported.

Recently, the use of Fabry–Perot Interferometer (FPI) micro cavities became attractive due to their reduced dimension, linear response and high sensitivity [9,10]. These devices are composed by two separated reflecting surfaces where the optical signals can be partially reflected. Regarding the optical fiber intrinsic FPI, the sensing element is a short section of a micro machined fiber with two parallel mirror surfaces. When a hollow micro cavity is produced in an optical fiber, its behavior is similar to the one observed in intrinsic FPIs, allowing the production of high sensitivity devices [11]. Nevertheless, the production of FPI-based sensors requires expensive and complex techniques, since the micro cavities are usually shaped with a femtosecond pulsed laser [10]. Recently, some of us have proposed the use of recycled optical fibers, destroyed by the catastrophic fuse effect, to produce

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optical spherical micro cavities that were used as strain sensors [12].

In this letter, we demonstrate the use of micro cavities, produced by the catastrophic fuse effect in optical fibers, to develop a low cost refractive index optical fiber sensor.

2. Production of optical fiber sensing cavities

The fiber fuse effect was first witnessed in 1987 [13] and it is characterized by the optical fiber continuous self-destruction. To ignite the fiber fuse it is required an initial optical power density of 1.8 MW cm^{-2} [14]. This irreversible destructive phenomenon creates a plasma (~3000 K) fuse region that moves continuously towards the optical source, vaporizing the fiber core and creating periodic voids structures as a result of the silica fiber core vaporization [15,16].

Fig. 1(a) shows one image of the optical fiber core (model *SMF28E*, from *Corning*) destroyed by the fiber fuse effect ignited with an optical power of 3.0 W, revealing the presence of a periodic hollow damage train string (voids) with a 14 µm period, similarly to that reported for this type of fibers [17,18].

In order to produce the RI sensor head, the damaged fiber was cleaved along the voids cross-section and spliced to a standard SMF fiber, using a splice machine (model *FSM-60S*, from *Fujikura*). The fibers were previously aligned through the cladding overlap optimization, using a 2000 ms discharge time and an arc current of 20 bits. This procedure allows the production of a larger cavity than the initial voids. The control of the cavity size is essential to shape the optical cavity transfer function and, therefore, the sensitivity of the sensor. The critical stage during the sensors production is the void cleavage; for a manual production process, we estimate a usefulness rate of around 20% for this process. However, considering the fiber cost this value is acceptable. The final optical cavity is shown in Fig. 1(b). When placed in contact with an aqueous solution, the liquid meniscus inside the fiber tip results in the change of the cavity effective refractive index. The produced sensor has a cavity length of 170 ± 2 µm, a maximum width of 83 ± 2 µm and a width in the fiber tip of 24.8 ± 1.3 µm.

To describe this micro cavity working principle, we can consider that the reflection transfer function is periodic in the frequency domain (or in the wavelength domain for a limited bandwidth), with a period that depends on the surrounding environment refractive index, Eq. (1). This equation describes the relation between the modulation period, Γ, the signal wavelength, λ_0, the cavity effective refractive index, n_{eff}, and the cavity length, L:

$$\Gamma = \frac{\lambda_0^2}{2n_{eff}L} \tag{1}$$

The modulation period has an inverse dependence with the refractive index, with a sensitivity given by:

$$\frac{d\Gamma}{dn_{eff}} = -\frac{\lambda_0^2}{2n_{eff}^2L} \tag{2}$$

Assuming $n_{eff} = 1.38$, the typical values attained from these equations for the modulation period and modulation period sensitivity are 5.13 nm and −3.71 nm/RIU, respectively.

3. Sensor characterization

To investigate the RI sensing performance, the sensor was tested using aqueous solutions with different saccharose concentrations, ranging from 0.0 to 1.1 g/mL, which provide a RI variation between 1.3320 and 1.4281. The refractive indices were initially measured at 22 °C, using an 8° tilted fiber Bragg grating based refractometer [7]. In order to guarantee a constant cavity length (L), the experimental tests were performed in a controlled environment of constant pressure and temperature.

The manufactured FPI sensor sensitivity to RI changes was estimated by immersing the optical fiber end tip in the saccharose solutions, Fig. 2. A fiber support allows to control the depth at which the sensor head is immersed in the aqueous solutions. The reflected spectra were monitored using an optical sensing interrogator (model *sm125*, from *Micron Optics*), with 1 pm resolution.

Fig. 3 shows the sensor reflection spectra under immersion, presenting a notorious period decrease in the spectral modulation as the solution RI increases. This behavior is in agreement with that predicted by Eq. (1). It was also observed an increased in the modulation depth of the amplitude fringes as the refractive index growths, which is also consistent with the behavior of an optical cavity with the rising of the feedback reflection. The increase of the aqueous solution refractive index rises the refractive contrast (to the cavity medium refractive index ≈ 1),

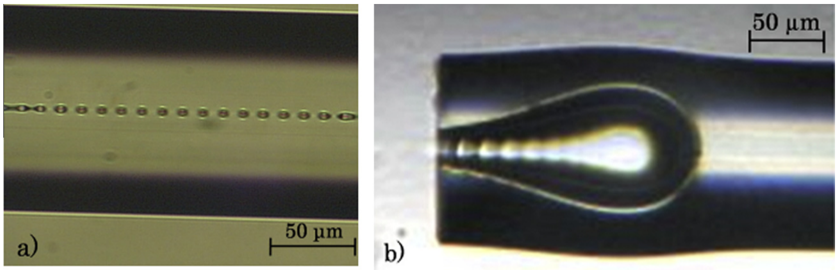

Fig. 1. Optical microscopy images of (a) an optical fiber destroyed by the fuse effect ignited with an optical power of 3.0 W and (b) sensor head, displaying the micro cavity.