Femtosecond laser inscription of diffraction gratings in CYTOP fibers for optical fiber sensing

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ABSTRACT:

The use of the new CYTOP fibers for the inscription of optical structures and the sensing of different parameters has started to gain importance in the last decade. This work presents the design and manufacture of a CYTOP fiber-based optical structure intended for later use as a refractive index sensor. The structure is based on a diffraction grating inscribed in an area of the fiber with a specific curvature, and previously polished.

Key words: polymer optical fiber, perfluorinated fiber, CYTOP, femtosecond laser.

1.- Introduction

A great attention and research effort have been drawn to the transducing properties of optical fibers, which has made possible a great advance in the last 50 years with regard to optical fiber sensors (OFSs) [1], whether in glass fiber or plastic optical fiber (POF). Its electrical immunity, small transmission loss, remote sensing, and high sensitivity, outperform other more traditional schemes.

All this, together with the discovery of new materials in the fibers [2], which improve their optical properties, allow their application in increasingly varied fields, whether in the scope of engineering, industry, medicine, or biochemistry, among others.

In this work, an optical structure based on a perfluorinated POF is designed and manufactured using a femtosecond laser. Taking advantage of its transmission in the near-infrared, it is intended to be used in the future as a refractive index sensor. To do this, a diffraction grating is inscribed in an area of the fiber previously polished, in order to favor modal interaction with the surrounding medium.

2.- CYTOP fibers

With regard to plastic fibers, poly(methyl methacrylate) (PMMA) has traditionally been used. The first fibers based on PMMA cores emerged in the 1960s, and their growth has been extraordinary to this day, as can be seen in Figure 1. In contrast to glass fibers, POF stands out for its ease of handling, flexibility, and reduced price [3]. Likewise, the improvement of the manufacturing process has considerably limited their attenuation, and they can be used for short-haul communications or optical fiber sensors [4].

However, in the late 1990s Asahi Glass Co developed a special type of POF, based on an amorphous fluorinated polymer called CYTOP (Cyclized Transparent Optical Polymer) [2]. It is poly(perfluoro-butenylvinyl ether). Characterized by a refractive index of 1.34 and an Abbe number of 90 [5], it stands out for its very low attenuation in the near infrared (~10 dB/km), providing a higher transmission bandwidth up to 1300 nm. Since it is a graded-index polymer optical fiber (GI-POF), it supports bandwidths that are 100 times larger than those provided by PMMA POFs, due to its lower modal noise and material dispersion [3]. The use of CYTOP fibers began to gain important relevance in the 2010s (see Figure 1), so it is a field with a great future projection. In recent years, the inscription of optical structures using femtosecond lasers in the fiber for the development of optical fiber sensors stands out [6–9].

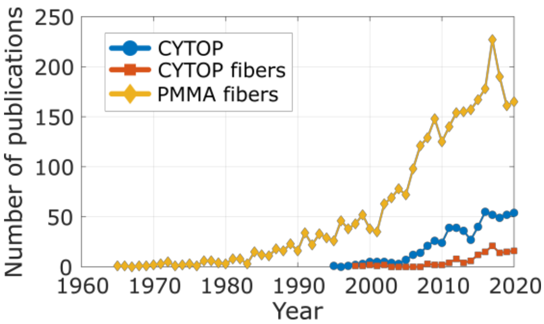

Fig. 1: Number of publications per year as a result of the search in the Scopus database (Elsevier). The search was restricted to titles, abstracts and keywords of the publications. Queries for each line were: TITLE-ABS-KEY (cytop) blue line; TITLE-ABS-KEY (cytop fiber) orange line; and TITLE-ABS-KEY (pmma fiber) yellow line.

3.- Structure design

The designed optical structure is the one depicted in Figure 2. It is based on a perfluorinated GI-POF, also known as CYTOP fiber, with core (d_{core}) and cladding (d_{clad}) diameters of 120 and 500 µm, respectively. The fiber, which is measured in transmission, has to be placed with a curvature defined by a radius of curvature (ROC) R, which takes a value of 5 mm in this work. To fix this ROC, two PMMA bulks are manufactured with the groove where the fiber will be placed, and the fiber is placed in the middle, closing the sandwich-structure with epoxy resin.

Subsequently, the part of the bulk corresponding to the curvature of the fiber begins to be polished. At the moment in which the outer interface of the fiber is reached, $\epsilon = 0$. If polishing continues ($\epsilon > 0$), the polished part of the fiber begins to generate an elliptical shape in the XY plane, as depicted in Figure 3c. To determine the depth of polishing of the fiber, the dimensions of the ellipse generated must be considered, specifically its minor and major axes. The geometric and trigonometric relationships that relate the different design parameters are presented in Figures 3a (for the major axis) and 3b (minor axis) [10].

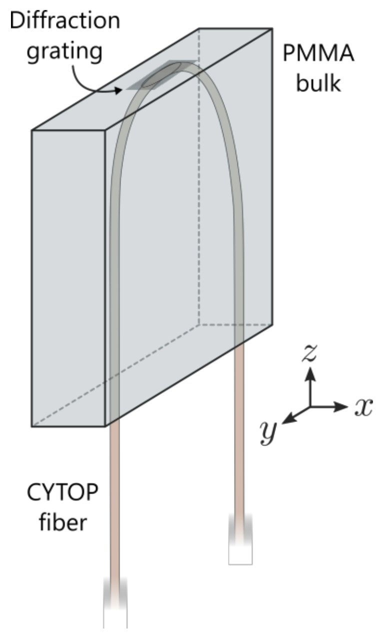

Fig. 2: Diagram of the manufactured CYTOP-based optical structure.

For Figure 3a, the following is derived:

$$\sin\theta = \frac{y}{R + \frac{d_{clad}}{2}}, \cos\theta = \frac{R + \frac{d_{clad}}{2} - \epsilon}{R + \frac{d_{clad}}{2}},$$

$$\frac{\sin\theta}{\cos\theta} = \frac{y}{R + \frac{d_{clad}}{2} - \epsilon},$$

$$y^2 + \left(R + \frac{d_{clad}}{2} - \epsilon\right)^2 = \left(R + \frac{d_{clad}}{2}\right)^2. \quad (1)$$

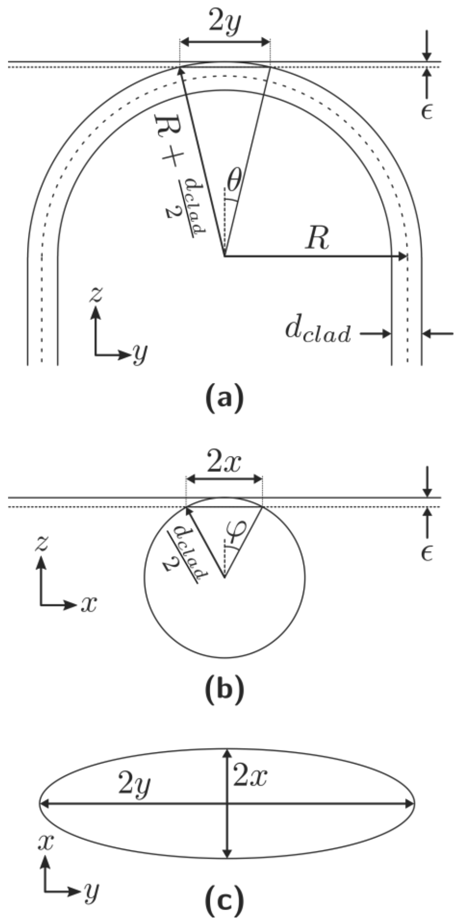

Fig. 3: (a) Geometric relationships that define the major axis of the ellipse generated in the XY plane. (b) Geometric relationships that define the minor axis of the ellipse generated in the XY plane. (c) Ellipse generated in the XY plane.

On the other hand, Figure 3b gives rise to:

$$\sin\varphi = \frac{x}{\frac{d_{clad}}{2}}, \cos\varphi = \frac{\frac{d_{clad}}{2} - \epsilon}{\frac{d_{clad}}{2}},$$

$$\frac{\sin\varphi}{\cos\varphi} = \frac{x}{\frac{d_{clad}}{2} - \epsilon},$$

$$x^2 + \left(\frac{d_{clad}}{2} - \epsilon\right)^2 = \left(\frac{d_{clad}}{2}\right)^2. \quad (2)$$

Typically, it is a structure whose applicability as a sensor is based on the interaction of the different propagated modes with the external mode. Being a graded-index fiber, the light is more confined in the longitudinal axis of the fiber, being more robust against bends in the fiber. Hence, in order to increase the interaction with the medium, the polishing of the fiber must reach the core $\left(\epsilon \geq \frac{d_{clad}-d_{core}}{2}\right)$, or at least stay as close as possible.

Once the fiber is polished, a diffraction grating is inscribed as depicted in Figure 1. In a possible application as a sensor for the external refractive index (n_o), it should be noted that $n_o = f(\lambda)$, and the lower attenuation of CYTOP fiber in a spectral width up to 1300 nm allows determining the spatial variability of the diffraction orders with wavelength:

$$n_o \sin\theta_d = n_i \sin\theta_i \pm \frac{m\lambda}{\Lambda}. \quad (3)$$

n_o is the refractive index of the surrounding medium, n_i the refractive index of the incident medium (considering that $n_{core} = 1.352$ and $n_{clad} = 1.34$ [11]), θ_i the incident angle, θ_d the diffracted angle, λ the light wavelength, Λ the grating period, and m the diffraction order.

4.- Experimental results

4.1.- Experimental setup

The inscription of the diffraction grating was carried out using a commercial femtosecond fiber laser chirped pulse amplifier (FLCPA) from CALMAR lasers. Its wavelength is 1030 nm, the pulse duration 370 fs, and it allows a maximum pulse repetition rate (PRR) of 120 kHz. The pulses were tightly focused with an infinity corrected NA=0.5 objective lens from Mitutoyo. The sample is placed on a nano-resolution XYZ motor stage from Aerotech, and the vision is achieved with a CCD camera.

4.2.- Results and discussion

The fiber is polished until it is located 25 µm from the axial axis of the fiber, that is, $\epsilon = 225$ µm. The polishing depth, as previously stated, is controlled from the dimensions of the ellipse axes. According to Equations (1) and (2), this ϵ value has related major and minor axes of the ellipse of 3.04 mm and 497 µm, respectively. This ellipse can be seen under a microscopic image in Figure 4c, and on a real scale with PMMA bulk in Figure 4b.

The diffraction grating has been inscribed using a pulse energy of 60 nJ, and a PRR of 300 Hz, with 10 pulses/µm. The grating has a length of 3 mm, with 550 µm lines perpendicular to the major axis of the ellipse, and a period of $\Lambda = 3$ µm. The inscription depth of each line is 2 µm. Figure 4a shows the result of a zone of the diffraction grating.

As a future application of the manufactured optical structure, its use as an external refractive index sensor is envisaged.

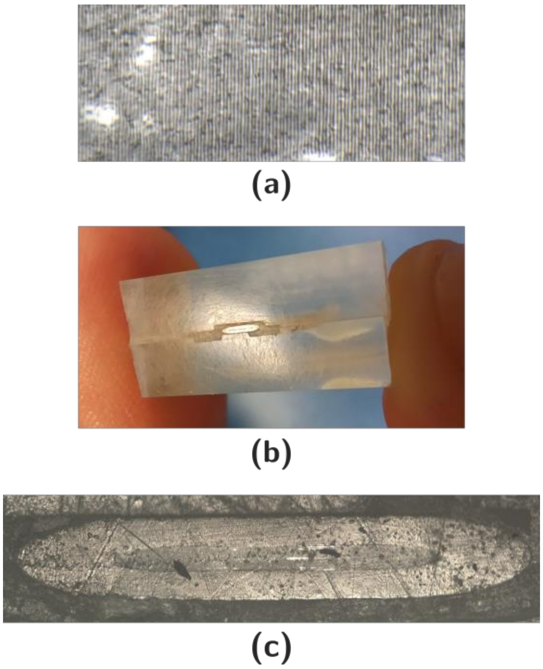

Fig. 4: (a) ×100 microscope image of the $\Lambda = 3$ µm diffraction grating inscribed. (b) Image of the upper area of the manufactured structure, showing the ellipse corresponding to the polishing of the fiber in the central part. (c) ×5 microscope image of the ellipse generated due to polishing.

5.- Conclusion

A CYTOP fiber-based structure has been demonstrated. Designed to interact with the surrounding medium, and to sense the refractive index, it uses a diffraction grating inscribed by means of a femtosecond laser in a previously polished area. The detailed geometric analysis of the structure for its manufacture has been carried out.

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