Microdisplacement sensor based on a processed optical fiber by an ultrafast laser-assisted etching method

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ABSTRACT

In this work, a fabrication technique for microchannel-based reflectors used as an optical fiber sensor is demonstrated by using a processed optical fiber by an ultrafast laser-assisted etching method. This microdisplacement sensor was experimentally demonstrated to have an outstanding resolution of 5.9 rad/μm in the measurement range from 0 to 80 microns, by using the fast Fourier transform (FFT) measuring method.

Keywords: Chemical etching, femtosecond laser, microdisplacement sensor.

1. INTRODUCTION

Precision displacement measurements plays an important role in the fields of structural health monitoring, bioengineering or industrial or high-radiation environments among others [1]. Optical fiber microdisplacement sensors based on optical fibers offer exceptional advantages for applications requiring precise and reliable measurements [2], [3]. Their compact size and flexible design allow them to be integrated into confined spaces or complex systems where they can function under extreme conditions, including high temperatures, corrosive atmospheres, or high-pressure settings.

In this work, the experimental analysis of single-mode optical fibers (SMF) to which a series of transverse through-hole microchannels have been inscribed by means of a femtosecond laser and ultrafast laser-assisted etching is presented. The fabrication of high aspect ratio microchannels without the use of adaptive optics is shown. The focusing approach utilized in this work involves the prior creation of a fused silica plate with channels of the diameter of the optical fiber to be inscribed, so, the wavefront comes across a flat refractive index change (RIC) in the silica plate. The second experimental step is related with the in-fiber microchannel fabrication. Finally, this structure has been experimentally analyzed as micro-displaced sensor units as it will be here exposed. The achieved results for micro-displacements (<80 μm) demonstrates the suitability of the new sensing system fabrication technique.

2. HIGH RI CONTRAST BACKSCATTER STRUCTURE

The microdisplacement sensor consists of a standard single-mode optical fiber to which a series of transverse through-hole microchannels have been incorporated. By providing a high contrast in the refractive index, the backscatter reflection is significantly higher, making it possible to reduce, for example, the length of a laser cavity.

Manufacturing in-fiber microchannels is not a novel concept. In fact, creating artificial microchannels is the most straightforward method for constructing lab-in-fiber (LIF) devices [4]. Numerous studies in the literature employ ultrafast lasers through direct inscription (drill) [5], or in combination with wet hydrofluoric acid (HF) etching for their production [6]. However, it was not until a few years ago that adaptive optics were used to compensate for optical aberrations caused during inscription, such as the astigmatism generated by the cylindrical geometry of the fiber [7]. Without proper wavefront shaping of the ultrafast laser beam, achieving high aspect ratio (length to diameter ratio) channels in a 125 μm SMF is really challenging. This work introduces the fabrication of high aspect ratio microchannels without the use of adaptive optics, thereby simplifying the experimental setup. To achieve this, a two-step procedure is proposed: (1) multi-channel plate manufacturing, and (2) in-fiber microchannel fabrication. Both processes are detailed below.

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A. Ultrafast laser setup: All inscriptions were conducted using a fiber laser-based chirped pulse amplification (FLCPA) system from CALMAR. Operating at a wavelength of 1030 nm and a pulse duration of 370 fs. This laser allows for pulse repetition rates (PRRs) of up to 480 kHz. It also enables complete control of the polarization state of the laser beam. The laser pulses are precisely focused into the glass sample through a 0.4 numerical aperture (NA) aspheric lens (A110TM-B, Thorlabs). The sample is positioned on a nano-resolution XYZ motor stage from Aerotech. Finally, a CCD camera (DMK 31AG03 Imaging Source) is utilized to visualize the focused beam on the sample.

B. Multi-channel fused silica plate: To avoid astigmatism generated during fiber focusing without using adaptive optics (e.g., spatial light modulators) or oil-immersion lenses, various alternatives exist. One notable approach involves positioning the fiber between glass slides, surrounded by index-matching oil [8]. This configuration limits astigmatism in focusing since the interface where the refractive index changes (RICs) is flat. However, this technique proves less effective when focusing the beam in areas close to the surrounding of the cladding, as required for creating microchannels, as it spatially disrupts the fluid and, consequently, the beam focus. The focusing approach utilized in this work involves the prior creation of a fused silica plate with channels of the diameter of the optical fiber to be inscribed, i.e., 125 µm. To minimize the microspaces of air that may exist between the plate and the inserted fiber, a drop of index-matching oil is deposited on the tip of the fiber before placing it inside. This results in near-perfect transparency in the central section of the channel, allowing the fibers to blend seamlessly with the plate. The astigmatism while focusing the beam is thus negligible. Figure 1 shows an image of this multi-channel fused silica plate during the insertion of single-mode fibers. In this way, the wavefront encounters a flat RIC in the silica plate. The bare section of each fiber is carefully inserted into its respective channel until it reaches the remaining acrylate coating (in blue).

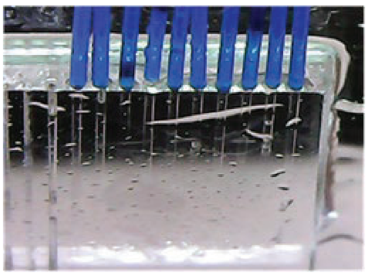

Fig. 1. Image of the multi-channel fused silica plate during the insertion of SMFs.

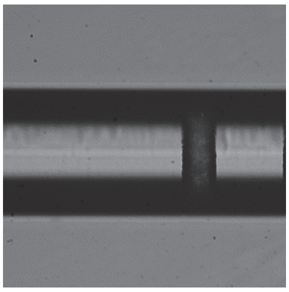

Fig. 2. Microscope image of the microchannel based reflector.

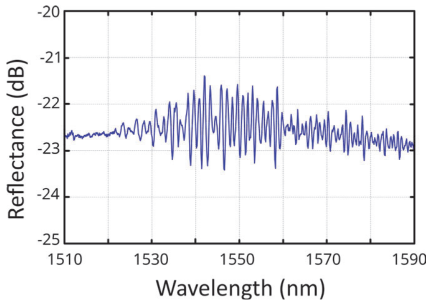

Fig. 3. Reflectance of the inscribed fiber in the C-band.

For the creation of these channels, ultrafast laser-assisted etching (ULAE) is employed. This technique involves a two-step process: initially, the sample undergoes irradiation with focused femtosecond laser pulses, followed by wet chemical etching of the laser-modified zone. Traditionally, HF has been used for this second step. However, more recently, the use of bases such as potassium hydroxide (KOH) or sodium hydroxide (NaOH) has gained prominence [9]. Not only does this reduce the risk for the operator during handling, but it also significantly decreases the environmental impact, as they are used at low concentrations [9]. The laser irradiation escalates the etching rate by up to three orders of magnitude compared to the pristine etching rate, paving the way for the manufacture of high-aspect ratio channels and the formation of 3D geometrical devices in glass substrates. The channels were inscribed on fused silica plates with dimensions of 10×10×1 mm (Spectrosil®2000 from UQG Optics). A total of 23 channels were written on the plate, spaced 400 µm apart (center-to-center). Each channel was inscribed with its center at a depth of 150 µm from the surface. The designed diameter of each channel is 125 µm, considering that the etching rate in pristine material (~0.5 µm/h in NaOH) will slightly increase the diameter to accommodate the fiber diameter tolerance. Each channel is formed from 225 single scans that make up the circumference of the channel. Each single scan covers the entire length of the sample (10 mm), starting / ending a sufficient distance away from the edges (150 µm on each side) to avoid any undesirable acceleration/deceleration ramps of the stage.

In manufacturing, a pulse energy of 250 nJ, a PRR of 120 kHz, and a speed of 12 mm/s were employed. Consequently, 10 pulses/µm are deposited. As demonstrated by Ochoa et al. in 2023, this few-pulse regime allows for maintaining high etching rates regardless of the polarization used in inscription [9]. In this case, circular polarization is set. Following the inscription, the edges of the sample were polished and subjected to an 18-hour etching process in a 5 wt% NaOH solution at 85±2 °C. Subsequently, the samples were thoroughly rinsed with isopropyl alcohol and distilled water to allow the glass cylinders of the channel to be extracted from the plate.

C. In-fiber microchannel fabrication: Using the multi-channel fused silica plate as a holder, several single-mode fibers (G652 of Draka Comteq) were inserted into each channel. As previously mentioned, index-matching oil was added during the insertion process to fill the air gap between the fiber and the channel. After securing the fiber's distal end and removing the residual matching oil with acetone, the holder with the fibers was placed into the XYZ motor stage from Aerotech, aligning the fibers' main direction with the Y-axis. After placing the plate into the motor stage, confocal illumination was employed to properly align each fiber. Since the fibers were not visible due to the index-matching oil, each fiber was centered using the edges as a reference, with the inscription made in the middle of the plate, offset by 5 mm from each edge. For the creation of each through-hole in SMF, a single-pass helical scan was implemented using the motor stage, with the axis of the helix aligned to the Z-axis. Using a fixed diameter of 40 µm, a 150 µm long helix was inscribed at the center of the channel, with a pitch of 4 µm. A pulse energy of 300 nJ, a PRR of 120 kHz, and a speed of 12 mm/s were employed. Consequently, 10 pulses/µm were deposited, operating in the few-pulse regime [9]. Following the inscription, all fibers were subjected to a 30-minute etching process in a 5 wt% NaOH solution at 85±2 °C.

Figure 2 shows a microscope image of this microchannel based reflector with one transversally inscribed microchannel. The obtained reflectance of the inscribed fiber measured using an optical spectrum analyzer (OSA) can be observed in Figure 3 where, as expected, a low reflectance level was measured along the C-band.

3. RESULTS AND DISCUSSION

The microchannel-based reflector used as an optical fiber sensor had a single transverse inscription of 40 microns in diameter in order to evaluate the sensitivity of this type of SMF with transverse through-hole microchannels as microdisplacement sensors (see Figure 2). The structure was evaluated as a sensor for uniaxial microdeformation or transverse microdisplacement. For this purpose, the reflector was interrogated according to the configuration illustrated in Figure 4, being illuminated by a wide white light source (WLS), and its reflectance recovered using an OSA.

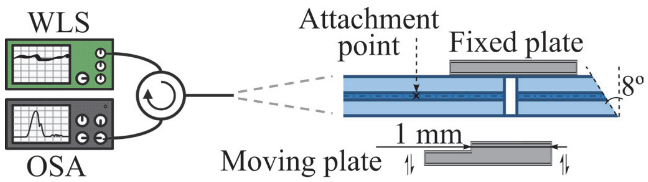

Fig. 4. Experimental setup employed during the microdisplacement sensor characterization.

To induce microdeformation on the sensor, the engraved section of the fiber was placed between two flat machined and polished pieces, facing each other, whose separation was controlled by a motorized stage with a spatial resolution of 17 nm. Subsequently, these flat surfaces were brought close to the contact threshold with the inscription, and subsequent cycles of deformation and relaxation were applied to the fiber at a rate of 204 nm per step and increasing maximum deformation values. At each step, the reflectance was recorded for analysis.

Given the interference pattern visible in Figure 3, the reflectance evolution under deformation was analyzed in the transformed domain instead of directly on the spectrum, following the methodology described in [10]. For this purpose, the FFT algorithm was applied to each measurement, identifying the common and constant existence of a single significant spatial frequency component, $f = 0.8\ nm^{-1}$, associated with the 1.25 nm period observed in Figure 3. For this component, its phase was monitored with each motor position, the result of which is shown in Figure 5 (a). As illustrated, the phase of this spatial frequency component faithfully followed the changes of fiber eccentricity over the etched section during the first deformation-relaxation cycle up to 60 microns, quickly losing elasticity and sensitivity after the ascending ramp during the next cycle of 90 microns, up to the rupture around 110 microns.

Focusing on this first cycle, Figure 5 (b) shows the strong linear trend between spatial phase and deformation during both the deformation and relaxation halves of the cycle, with a coefficient of determination $R^2 > 0.9984$ in every case, as well as slightly different sensitivities of 5.9 rad/µm and 6.5 rad/µm, respectively. Compared to previously developed micro-displacement sensors [11], the actuation system was simplified while preserving linearity and improving the detection threshold by an order of magnitude. Therefore, the viability of the structure as a sensor for microdeformation or transverse microdisplacement is demonstrated, opening the possibility of using it as a point pressure sensor both for its sensitivity to eccentricity variations and for presenting microchannels that pierce to the core.

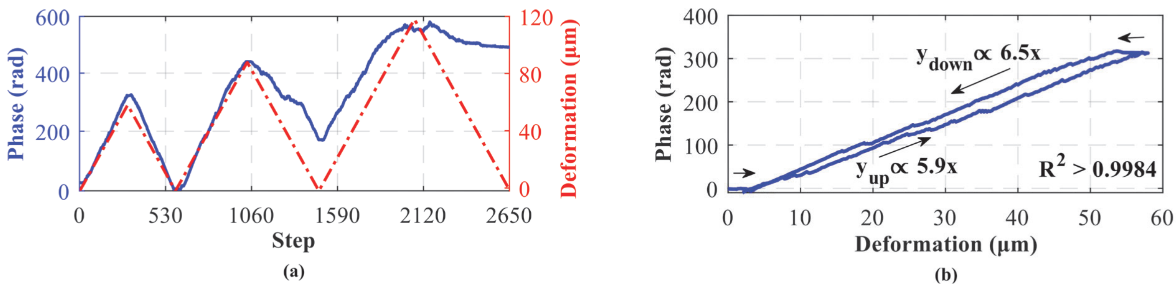

Fig. 5. (a) Evolution of the phase with exerted uniaxial transverse deformation, (b) resulting hysteresis for the deformation-relaxation cycle of 60 μm.

4. CONCLUSIONS

A new fabrication technique for the development of compact microdisplacement sensors using a processed optical fiber by an ultrafast laser-assisted etching method is experimentally demonstrated. This technique uses a series of transverse through-hole microchannels that have been inscribed by means of a femtosecond laser and ultrafast laser-assisted etching. So, the fabrication of high aspect ratio microchannels without the use of adaptive optics was presented. These structures are used as distributed mirrors of a laser sensing system. This developed structure is used for microdisplacement sensing, showing an outstanding resolution of 5.9 rad/μm in the measurement range from 0 to 80 microns, by using the FFT measuring method.

ACKNOWLEDGEMENTS

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