Optical Fiber Tip wth Integrated Mach-Zehnder Interferometer for Sensor Applications

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Abstract. *In this paper, we present design and preparation of novel Mach-Zehnder Interferometer (MZI) based structure for sensing applications. We present integration of this structure at the end of a single-mode optical fiber. Direct laser writing technology was used to prepare MZI-based structure with a hoop for tight connection to optical fiber facet. Details of the design, preparation process and connectorizing process are described and finally, transmission spectral characteristic of the prepared structure was measured using optical spectral analyzer.*

Keywords

Fiber facet structure, laser lithography, Mach-Zehnder interferometer, sensor, two photon polymerization.

1. Introduction

Originally it was assumed that the most significant advantage of the Lab on Chip (LoC) applications would be progress in diagnostics associated with decreasing dimensions. Further developments unveiled other significant benefits such as small amount of analyzed liquid sample, which opened up the opportunity to process individual cells. A small amount of reagent and sample size causes the reaction and analysis time to be much shorter [1].

Optical detection systems for LoC still remain very actual region with possibility to bring novel solutions [2]. Light propagation differs in various materials. Detection methods of most of the optical sensors for medical applications are based on the measurement of refractive index changes of the biological sample.

Integrated MZIs are often employed as sensing elements in portable testing devices for diagnostics [3]. Principle is based on the interference of split polarized input beams that propagate in reference and sensing arms [4]. The reference arm should be isolated from the investigated sample and only sensor arm is in interaction with the sample [4]. Each change in the refraction index of sample shifts the phase of the optical wave in sensing arm towards the phase of reference arm according to equation

$$\Delta\varphi = \frac{2\Pi L}{\lambda}(n_{eff,S} - n_{eff,R}), \tag{1}$$

where L is detection length, λ is the source wavelength and n_{eff} is an effective refractive index of sensing and reference arm.

In general, the use of a change in the optical refractive index is a promising principle in many applications, as well as in the future detection of diabetes by optical measurement of sugar concentration in human urine or blood. Quantification of sugar concentration in blood helps to reveal diabetes disease.

In this paper, we focused on design and preparation of 3D Mach-Zehnder Interferometer (MZI) applicable for sensing the refractive index changes of different biological samples. For the manufacture of this structure, we used 3D microprinting technology named Nanoscribe Professional GT. Nanoscribe works on principle of Two-Photon Polymerization (TPP) and provides preparation of polymer parts with resolution of hundreds of nanometers and in range up to several centimeters [5], [6] and [7]. Nowadays, Direct Laser Writing (DLW) has already become a fully-fledged tool in a wide range of scientific research such as biomimetics, biomedical engineering, microfluidics, microoptics, photonics and other, and even in art. Nanoscribe Professional GT is versatile system. It offers own glass substrate to prepare structures, but if required, there is a possibility to create structures on different surfaces (e.g. semiconductors for photovoltaic solar cells [8] or optical fiber facets [7] and [9]).

The preparation of optical structures on the facet of the fiber is not a novelty. In various fields of application such as remote optical sensing [10], [11] and [12], beam shaping [13], [14], [15] and [16], and optical manipulation [17] and [18], excellent devices applied on the fiber facets have been designed and realized. Long ago before DLW technology, the language was enriched by new idiom: "Lab on Fiber" [12] and [19].

The previously-mentioned findings have been implemented by a variety of technologies [20] and many not mentioned concepts were only considered but not realized, because they did not know the suitable technology at that time. Thanks to the 3D DLW technology, we can reasonably foresee: "Lab on Fiber" concept is only at the beginning and the realization of more outstanding microoptical structures not only on optical fiber facets can be considered [9].

2. Technology

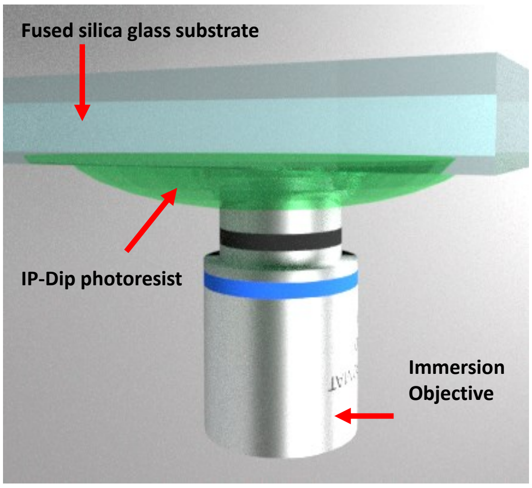


Fig. 1: DiLL configuration, the liquid Dip photoresist is dropped on substrate and turned upside down, objective is immersed in photoresist during DLW process [6].

The DLW by itself is carried out by focusing the writing laser into the photoresist. The photoresist is designed such that single photons from the writing laser cannot be absorbed, but a two-photon absorption can induce polymerization. Since nonlinear processes scale with intensity, the polymerization occurs where the intensity is the highest, i.e., in the focal volume of the objective. This volume is called voxel. Also, the resolution is limited by voxel size. In our setup, voxel was ellipsoid with a lateral diameter of about 250 nm and an axial diameter of about 600 nm. IP-Dip is the specially designed photoresist for Nanoscribe's Dip in Laser Lithography (DiLL) technology (Fig. 1) [5] and [6]. IP-Dip serves as immersion and photosensitive material at the same time by dipping the microscope objective into this liquid photoresist. Due to its refractive index matched to the focusing optics IP-Dip guarantees ideal focusing and hence highest resolution for DiLL [5] and [6].

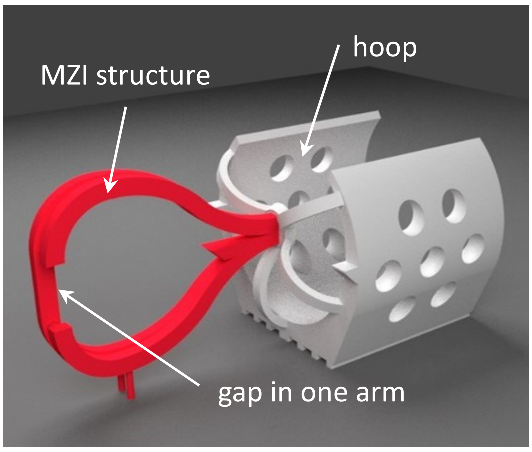
In DiLL configuration, a fused silica glass slide as substrate is used. One small drop of IP-Dip photoresist is applied to it. Substrate with photoresist is situated in holder and during writing process, it is turned upside down. DLW system Nanoscribe allows preparing on one substrate matrix of structures with different parameters (e.g. laser power or scan speed). After writing process, the sample was removed from the sample holder and remains of liquid unexposed photoresist were removed in Propylene Glycol Methyl Ether Acetate (PGMAE). Increasing developing time in PGMAE caused increasing shrinkage of the prepared structure. Because our structure does not contain the small holes and the hollow parts, 10 minutes is sufficient time for development. Finally, the sample is washed in isopropanol and dried by a nitrogen gun.

3. Structure Design

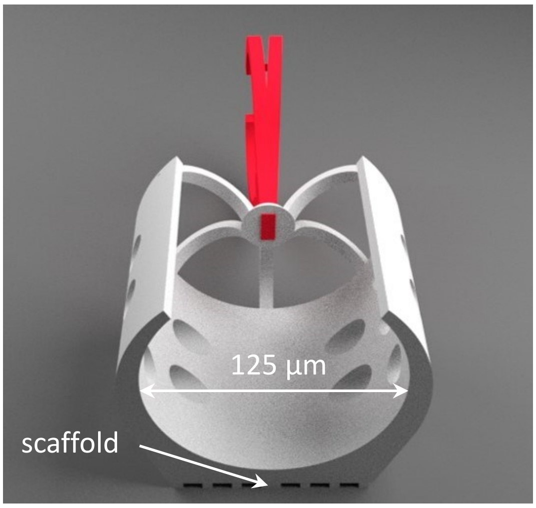
The polymer prepared by polymerization using DLW is very flexible material, optically transparent with a refractive index close to that of glass (circa $n = 1,54$ [5]). Consider these facts we designed MZI in the following design.

The entire structure is shown in Fig. 2(a) and consists of two logical parts: a hoop and an MZI. The inner diameter of the hoop is adapted for conventional telecommunication optical fiber and is equal to 125 μm. It is used to attach the structure to the optical fiber. The hoop contains 270 degrees of fiber perimeter and allows a firm connection with the optical fiber (Fig. 2(b)). The thickness of the hoop walls increases from 5 μm to 30 μm in the coarsest part. The hoop length is 120 μm. The front part consists of 5 arched arms with a 60 degree spacing. The arms maintain a structure centered on the core of the optical fiber. In Fig. 2(b), we can see also the scaffold in the structure for mechanical support of the MZI and also the hoop. This scaffold also enables better separation of all the structure from the glass substrate.

Second part is sensory part. The prepared structure works on the principle of MZI and consists of two parallel arms. One arm is called the reference, the second is sensing arm. The cross-section of the optical waveguides is 9×9 μm^2. The sensing arm contains interruption in length 36 μm. Depending on refractive index of measured liquid sample, the optical path length will be changed. This change can be observed by Optical Spec-



(a)



(b)

Fig. 2: Design of a) MZI-based sensor and b) detail to hoop for attaching the structure to the optical fiber.

tral Analyzer (OSA), as interference dip in frequency spectrum of interfering signals from both arms. Optical signal is coupled into/from the MZI structure via the waveguide. To suppress back signal refection, the end facet of the waveguide is not perpendicular but is sloped in 8 degrees angle as it is well known in APC connectors.

4. Experimental Results

The designed 3D MZI-based structure was prepared in IP-Dip polymer using laser lithography system. The final prepared structure was analyzed using Scanning Electron Microscope (SEM) as can be seen in Fig. 3. This inspection shows very good quality of the structure, especially 3D arrangement of waveguide structures.

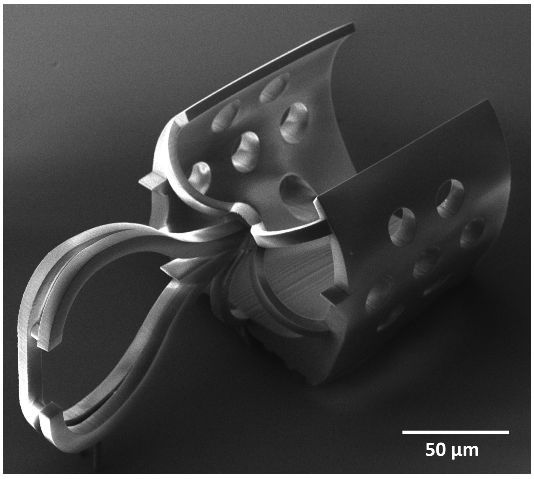


Fig. 3: SEM image of the prepared 3D MZI-based structure on fused silica substrate.

To attach the optical fiber to the structure, the 3D stage was used and the process was monitored by the camera. The camera scans the prepared structure from the bottom through the glass substrate. It was focused on the top of the belt. Optical fiber was placed over the belt using a 3D stage. Applying the outer force to the fiber causes the ring to expand and the fiber to slip into the belt. Once the force has been removed, the thread returns to its original position by its structure.

The final prepared structure attached to the end of the optical fiber can be seen in Fig. 4. Thanks to the high strength and elasticity of IP-Dip material, structure and fiber are strongly attached together. The elastic properties of prepared IP-Dip structure were demonstrated by simple pressing of this structure on the glass substrate as is shown in optical microscope image in Fig. 5. After the release, the structure has reached its original position without any deformations.

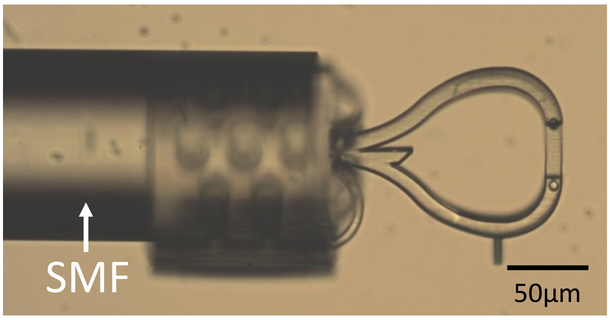


Fig. 4: Optical microscope image of final connection of the Single Mode optical Fiber (SMF) with prepared structures separated from the substrate.

Eventually, we arranged simple experimental setup for basic optical characterization of MZI. We coupled light from single-mode optical fiber which was coupled to the LED source with central emitting wavelength of

1550 nm to input waveguide part (Fig. 6). Transmitted light from MZI was registered by optical spectral analyzer Anritsu and optical circulator.

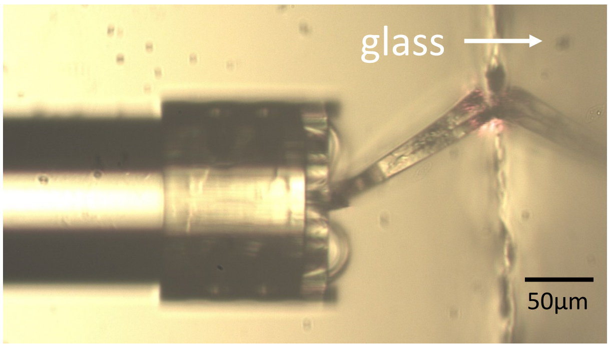


Fig. 5: Optical microscope image of depressed structure applied on the optical fiber.

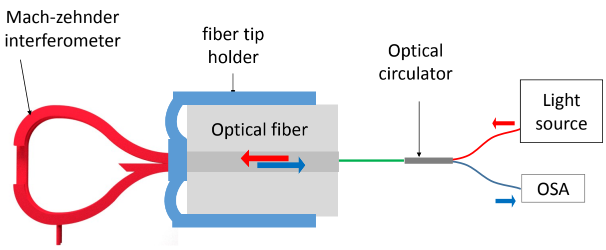


Fig. 6: Measurement setup for optical characterization of the prepared devices on fiber tip.

The transmitted spectrum from MZI is shown in Fig. 7. In this measurement, we observed interference dip in spectrum which was measured in air surroundings. Our structure shows considerable interference effect, which will be studied in forthcoming measurements for application as refractive index change sensor.

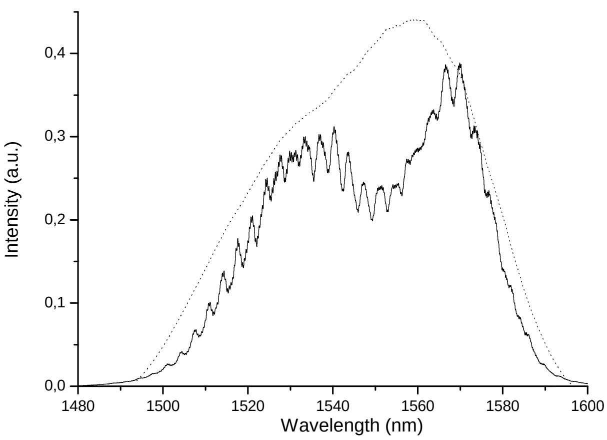


Fig. 7: Transmission spectral characteristic of the prepared Mach-Zehnder interferometer device and reference spectrum of the used light source (dotted line).

5. Conclusion

A preparation and functionality of MZI-based structure located at the end of a single-mode optical fiber are presented. Nowadays, very popular direct laser writing technology was used to print MZI-based structure with a hoop for tight connection to optical fiber facet. Details of the design and preparation process were described and after successful connectorizing process transmission spectral characteristic of the prepared structure was measured. We consider this device promising in forthcoming detailed measurements based on varying sugar concentrations.

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