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COMMUNICATIONS

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# POLYMER BASED DEVICES FOR PHOTONICS ON THE CHIP

*In this paper we present promising technology for preparation of photonic devices based on polymer materials on the chip. We designed 2D and 3D structures in CAD (computer-aided design) software and we used two-photon polymerization mechanism for direct writing of these structures to IP-Dip photoresist material. This paper also deals with experimental procedures for preparation of polymer photonic devices on the chip and a new way of light coupling to devices on the chip. Morphological properties of prepared devices were investigated by scanning electron microscope (SEM). As a result, transmission spectrum characteristic was measured.*

***Keywords:*** *Waveguide, resonator, polymer, laser lithography.*

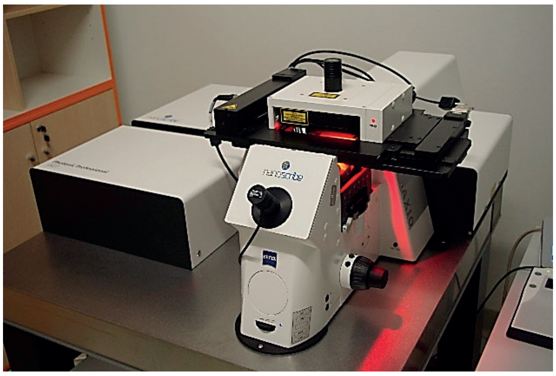
## 1. Introduction

Integrated optical structures are the fundamental building blocks for application in optical communications and optical sensing. They also offer interesting perspectives for integrated quantum optics on a chip. At present, however, they are mostly fabricated using essentially planar fabrication approaches like electron-beam lithography [1], UV lithography [2] or focused Ion beam (FIB) etching [3]. All stated processes are used to prepared 2D resp. 2.5D structures. Nowadays, 3D optical devices are very perspective for on-chip applications [4]. Preparation of 3D devices in nanoscale requires technological equipment with femtosecond laser for two-photon polymerization of photoresist master.

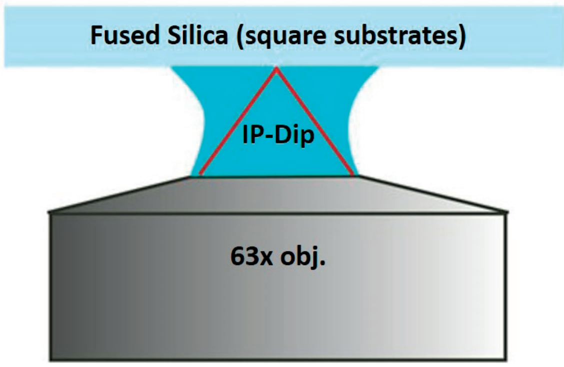
While the silicon photonics is a very widespread field, nowadays, polymer materials have become very attractive in photonics and micro optics because of very good material and optical properties. Various optical devices based on polymer materials were presented [5 - 8]. We focused on preparation of polymer devices using modern three-dimensional (3D) laser lithography system. Design, preparation and morphological inspection of photonic devices was performed in this paper.

## 2. Experimental

For fabrication of photonic devices based on polymer material, Photonic Professional GT system was used in our experiments (Fig. 1a). Principle of this DLW (direct laser writing)



*a)*




*b)*

*Fig. 1 a) Photonic Professional GT lithography system and b) arrangement of laser lithography system in DiLL (Dip-in Laser Lithography) configuration [10]*

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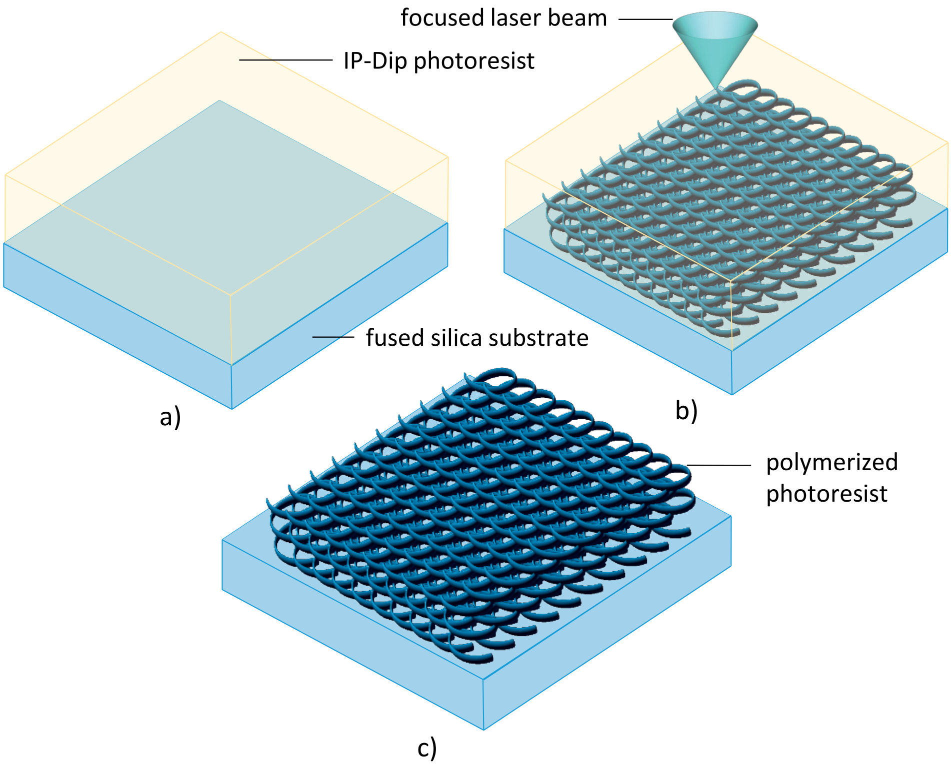


*Fig. 2 Illustration of a) IP-Dip photoresist layer deposition on fused silica glass substrate, b) exposition process using two-photon polymerization mechanism and c) final 3D photonic structure after developing process*

system is based on 3D scanning of focused laser beam in sample volume [9]. The system uses Er-doped femtosecond frequency-doubled fiber laser emitting pulses at 780 nm wavelength with approximately 100 MHz repetition rate and 150 fs pulse width [10, 11]. Laser beam is scanned in x and y plane by high resolution galvanometer mirror system. The movement in z-axis using motorized micro stage [11] allows preparation of complex micro 3D structures layer by layer directly inside the photosensitive medium. In our experiments, we used laser lithography system in configuration with 63 x immersion objective (Fig. 1b). 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 the highest resolution for DiLL (Dip-in Laser Lithography) [11, 12].

Technology of 3D structures preparation consists of several steps. First, we deposited IP-Dip photoresist drop on clean fused silica glass substrate (Fig. 2a) and the sample was turned upside down. In this position it remained during the whole DLW process. For photoresist exposure, we used ultrafast laser pulses which caused two-photon polymerization in photoresist volume (Fig. 2b). The writing process has to start on substrate surface in order to achieve the bond of the structure to the substrate. Otherwise, polymerized parts can be washed away from the substrate. Finally, the sample was developed in PGMA (Propylene glycol monomethyl ether acetate) developer for 20 min, rinsed in isopropyl alcohol and polymerized parts were bonded to the substrate (Fig. 2c).

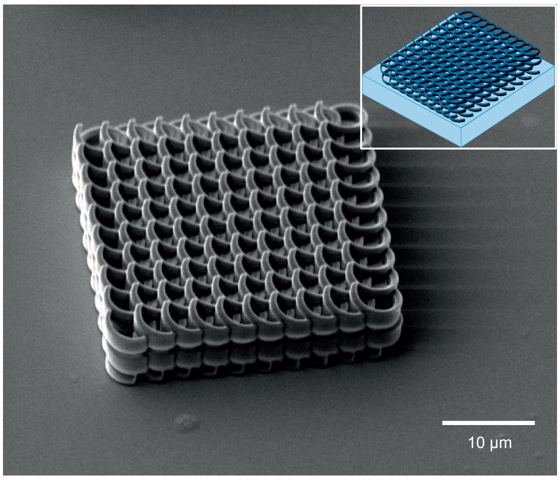


*Fig. 3 SEM image of prepared structure in IP-Dip photoresist with 3D CAD model of photonic crystal in helical design (inset)*

Precise piezo positioning stage can be used for moving the sample in a vertical dimension. This enabled us to prepare 3D structures using two-photon polymerization in the vertical dimension. As a demonstration, we designed helical photonic crystals with period of 3 μm and height of 8 μm. Final prepared helical photonic crystal with width of 700 nm with corresponding CAD model is shown in Fig. 3.

## 3. Results and discussion

DiLL configuration used in our experiment enables us to prepare structures in a large area in orders of several cm$^2$ with 200 nm resolution if the 63 x objective is used. For the preparation of structures in micrometric scale we used higher laser power and coarse hatching distance.

We designed a ring resonator structure in racetrack configuration with the radius of the curved (ring-like) portions of the racetrack resonator $R$ of 100 μm and the racetrack length $\Delta L$ of 750 μm. The length of the resonator has a great influence on transmission properties. From the light propagated in the waveguide only part whose wavelength is a divisor of $\Delta L$ is coupled into the ring. This coupled light forms a standing wave pattern in the ring resonator part where

$$\lambda_{resonant}^{(m)} = \frac{\Delta L n_{eff}}{m} \quad (1)$$

where $m$ is an integer and $n_{eff}$ is effective refractive index of the waveguide. Frequency separation between two successive resonances is expressed by free spectral range (FSR)

$$FSR \approx \frac{\lambda^2}{n_{eff}\left(2\pi R + L_C\right)} \quad (2)$$

where $\lambda$ is the wavelength of transmitted signal, $L_C$ is the coupling length between the resonator and the waveguide bus (which is zero for a point coupled ring). This coupling region between the waveguide bus and the ring resonator has a great influence on quality factor of ring resonator. The gap between the waveguides in coupling region was designed 200 nm.

The ring resonator consists of waveguides with an asymmetrical refractive index alignment. The refractive index of IP-Dip core is 1.54 and the bottom glass cladding has refractive index of 1.44. The waveguide is surrounded by air from above. Assuming these parameters and the transmission wavelength of 1550 nm we calculated a value of FSR = 2 nm.

CAD software was used to design our waveguide structures with following parameters. The waveguide height was designed to 3 μm, the width to 3.5 μm and 90$^o$ slope angle of the sidewalls. SEM (scanning electron microscope) image of prepared ring resonator in racetrack configuration in IP-Dip polymer with designed parameters is shown in Fig. 4. Very well stitching properties were achieved what is documented in this figure.

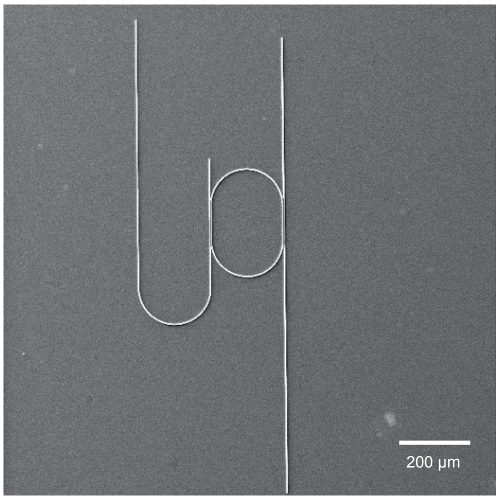


*Fig. 4 SEM image of ring resonator in racetrack configuration prepared in IP-Dip photoresist*

3D lithography allows us to use a non-conventional way how to couple light into the waveguide and out of the waveguide. The ends of the waveguide are not perpendicular walls but they were modified into 45° slope (Fig. 5). The light can be coupled from optical fiber into optical structure and vice-versa, from structure to detection fiber, due to total internal reflection on the interface between the waveguide and the air.

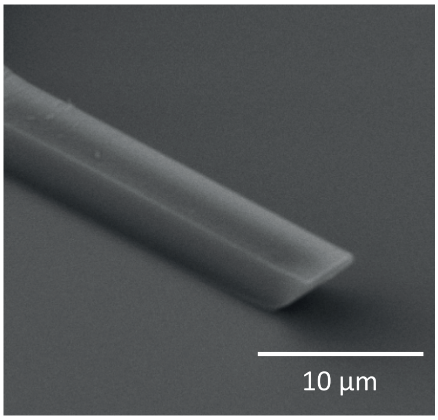


*Fig. 5 SEM image of modified end of the waveguide to 45° slope*

Finally, we investigated optical transmission properties of prepared racetrack resonator. We coupled light from LED source with central emitting wavelength of 1550 nm to single-mode fiber to the waveguide and we observed the output light using Optical Spectrum Analyzer (Fig. 6). Transmission spectral characteristic was measured from the same channel and is shown in Fig. 7. In this characteristic typical resonance dips were observed. The transmission spectrum corresponds to our calculations where 2 nm free spectral range was measured.

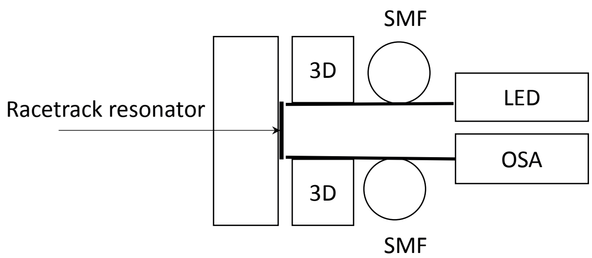


*Fig. 6 Experimental setup for the spectral characterization of waveguide structures, LED - light emitting diode, SMF - single-mode optical fiber, 3D - nanopositioning mechanical stage*

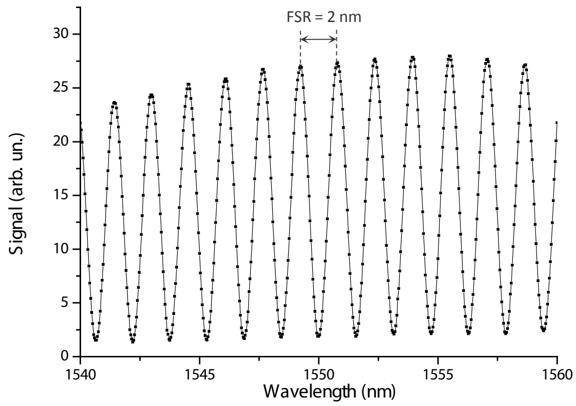


*Fig. 7 Measured transmission spectral characteristic of racetrack resonator within the wavelength range 1540-1560 nm*

## 4. Conclusion

In this paper, we highlighted promising technology for preparation of photonic devices based on polymer materials. We presented non-conventional way of light coupling to waveguide devices prepared on fused silica substrates what enables us to measure optical spectral characteristics of prepared devices. This also gives the possibility to integrate more devices on a chip with vertical inputs and outputs. For photoresist master preparation we used 3D laser lithography. We demonstrated the possibilities of this preparation technology on several 2D and 3D devices. The morphological inspection of our structures showed 90° slope angle of the sidewalls. The optical spectrum measurement of racetrack resonator showed typical resonance dips. Final devices are promising for lab on a chip and sensing applications due to unique optical, elastic and chemical properties.

## Acknowledgement

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