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Design, Simulation and Technological Realization of Polymer Based 3D 1x4 Splitter

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Abstract. We demonstrate possibilities of three-dimensional printing technology based on two-photon polymerization applying polymer polydimethylsiloxane (PDMS). This silicone compound is meant for fabrication of photonic integrated circuits using 3D dip-in direct laser writing (DLW). First, a 3D Y-branch splitter was designed for TM-polarized light, working in the telecom operating wavelength region of 1550 nm. For the splitter design, a channel type 3D waveguide structure was applied. The simulations were performed in BeamPROP simulation engine of RSoft photonic tool. The splitter was optimized according to the optical properties and the manufacturable dimensions of the structure. Consequently, based on the design results, the 3D Y-branch splitter was fabricated using the 3D dip-in DLW optical lithography.

INTRODUCTION

3D printing technology based on two-photon polymerization (TPP) provides a number of advantages for additive manufacturing of polymer parts with dimensions ranging from few microns up to the millimeter scale [1]. Nowadays, TPP has become a functional tool in plenty of areas, such as micro/nanophotonics, microelectronics, bioengineering, microfluidics and others. PDMS polymer is highly transparent, operates at room temperature and has good dielectric properties [2]. Nanoscribe Professional GT system, in the dip-in configuration, enables to create 3D structures on various surfaces, from semiconductors, through glass substrates to optical fiber facets [3].

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 [4, 5], beam shaping [6-8], and optical manipulation [9], excellent optical fiber-based devices have been designed and realized, like a "Lab on Fiber" [10]. The previously mentioned discoveries have been implemented by a variety of technologies. Many not mentioned were only considered but could not be implemented. Each of these fields of application is broad and requires in-depth investigations to tap the full potential of such devices. With the 3D printing technology realization of more elaborate photonic structures on optical fibers can be envisaged.

In this paper, we present design, simulation and technological realization of Sylgard™ 184 PDMS silicone polymer based 3D 1x4 splitter and its optical parameters.

DESIGN AND SIMULATION OF 3D 1X4 SPLITTER

At first, the waveguide was designed and simulated in BeamPROP simulation engine of RSoft photonic tool. Figure 1 shows the graphical representation of its cross-section (a) together with an optical field simulated in the final waveguide structure in the x-axis (b), being in a good correspondence with the dimensions in the designed waveguide structure. As can be seen from the Figure 1 (a), the waveguide has a channel structure, i.e. a core that is

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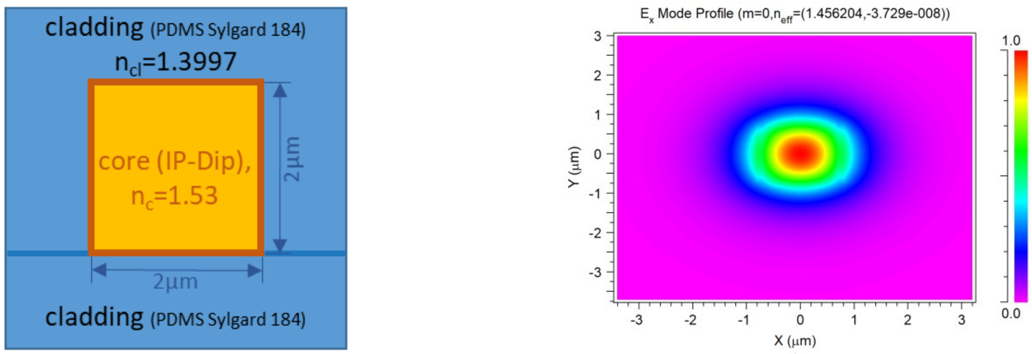
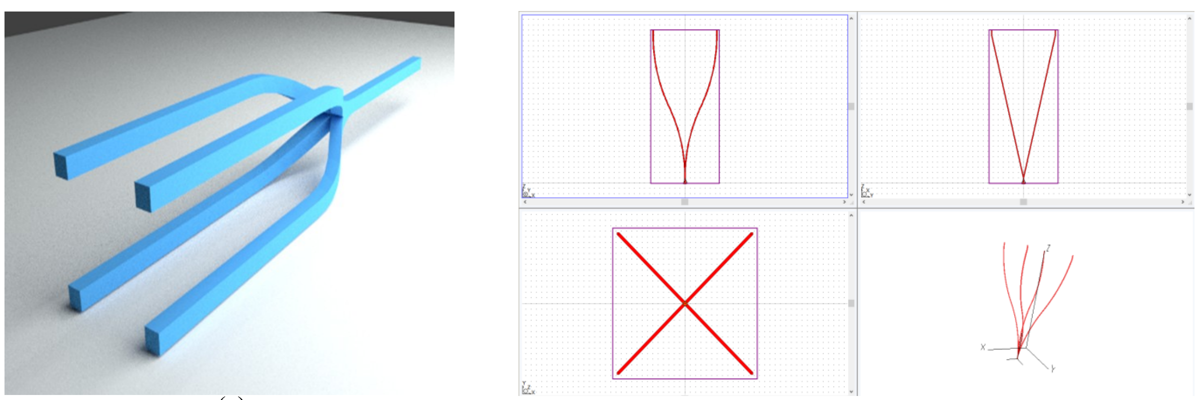
surrounded by a cladding. The refractive index of the core is n_c = 1.53 and of the cladding n_{cl} = 1.3997. The size and the structure of the waveguide was designed to support the single mode only (2x2 μm^2), propagating at 1550 nm. The normalized E_x mode profile from the Figure 1 (b) was used for the Y-branch splitter design.



(a) (b)

FIGURE 1. (a) Cross-section of the designed waveguide structure with basic design parameters, (b) optical field in the waveguide, simulated in x-axis for TM polarization.

This waveguide structure was used to create the desired 3D 1x4 Y-branch optical splitter based on the model depicted in Figure 2 (a). The border dimensions, limited by writing technology specifications, are 300μm for the total length of the splitter and 126μm for the pitch between the branches of the waveguides. The behavior of the splitter was simulated in 3D environment of BeamPROP simulation tool of RSoft CAD Layout. Its graphical representation in views of all axes combinations is shown in Figure 2 (b).



(a) (b)

FIGURE 2. (a) Graphical representation of the 3D splitter; (b) layout of its simulation in BeamPROP simulation engine of the RSoft photonic tool with the views of all axes combinations.

OPTIMIZATION OF THE SIZE OF 3D 1X4 SPLITTER

To keep the length of the splitter as short as possible, also the length of its branches needs to be obtained the shortest possible, with low losses. To this purpose, the length of the branches was scanned in a range between 0 and 300 μm, taking into account the technological possibilities in laboratories where the fabrication of the splitter was realized. The output of this simulation is presented in Figure 3. As expected, when the branch is too short, the optical power is damped. This is caused by the scattering of the light at the steep curvature of the waveguides. At approximately 270μm (dashed green line) scattering losses are significantly reduced. Therefore, and being in good agreement with technological possibilities, the length of the branches in the designed 3D splitter was set to L = 270 μm. The overall layout of the simulation of the proposed 3D splitter is in Figure 4, together with the optical power for the TM polarization simulated in each output waveguide (represented in the figure as first to fourth power). As can be seen, there is a high uniformity in distribution of the split optical power over the output waveguides, ranging from 0.17153 for the output waveguide in one branch to 0.17132 for the output waveguide in the fourth branch, with values for the remaining two output waveguides lying in-between.

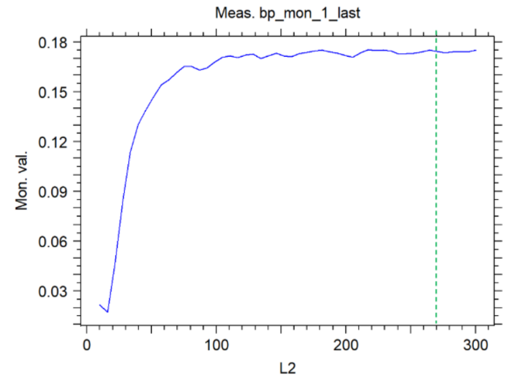
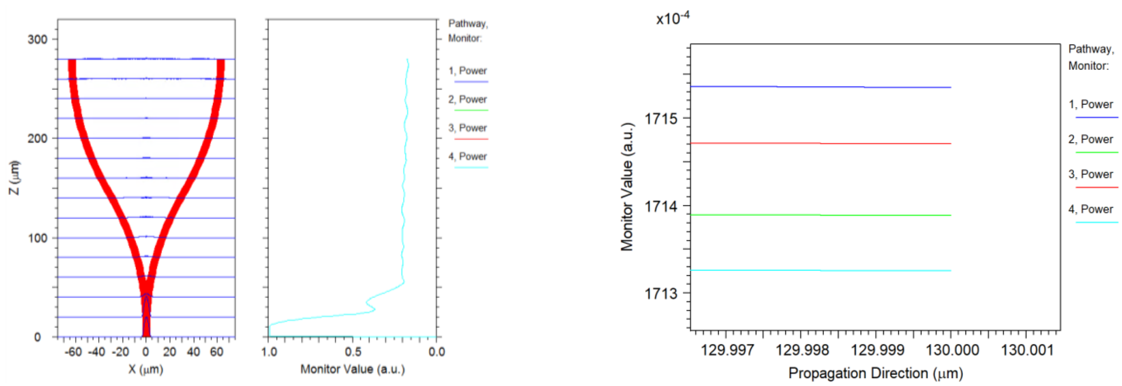


FIGURE 3. Scanning of the length of the splitter's branches in order to find minimum scattering losses.



(a) (b)

FIGURE 4. (a) Layout of one of the two identical branches creating the 3D Y-branch splitter, together with the simulated optical power; (b) scanning of the length of this branch with regards to optical power calculated in the waveguides.

Table 1 summarizes the optical power from each output waveguide and calculated insertion losses (*IL*) for TM polarization. Subsequently, the insertion uniformity loss (*ILu*) is calculated, as the difference between the lowest (*min IL*) and the highest (*max IL*) loss.

TABLE 1. Summary of simulated and calculated parameters for the polymer-based 3D 1x4 Y-branch splitter.

Output waveguide	Output power [a.u.]	Insertion losses, *IL* [dB]
1	0.171535	7.6564
2	0.171388	7.6602
3	0.171470	7.6581
4	0.171325	7.6618
min IL		*7.6564*
max IL		*7.6618*
ILu		***0,0054***

TECHNOLOGICAL REALIZATION OF 3D 1X4 SPLITTER

Complex free-form 3D structures can be produced by a relative movement of a voxel and a substrate. IP-Dip photoresist after polymerization is very elastic. It allows easy application of the prepared structure on a fiber tip. The DLW itself is carried out by focusing the writing laser beam into the photoresist. In IP-Dip photoresist, the single photons from the laser beam 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, the voxel. So it is voxel size what limits the resolution of technology. Voxel size is controlled by output laser power. Lower powers lead to desired smaller voxel sizes. However, to start the polymerization at a specific point, the minimum threshold has to be overcome. On the other hand, if the density in the focal point is too high, inner explosions in the resist are obtained [6].

The structure on Figure 5, representing the core of the waveguides in splitter, was fabricated on a glass substrate using commercially available laser lithography system (Photonic Professional, Nanoscribe GmbH). Tightly focused 780 nm femtosecond laser beam triggers polymerization inside a droplet of liquid UV-curable resin optimized for the NanoScribe devices (IP-Dip, Nanoscribe GmbH) via TPP polymerization, occurring only in a defined volume of the laser focus – the voxel.

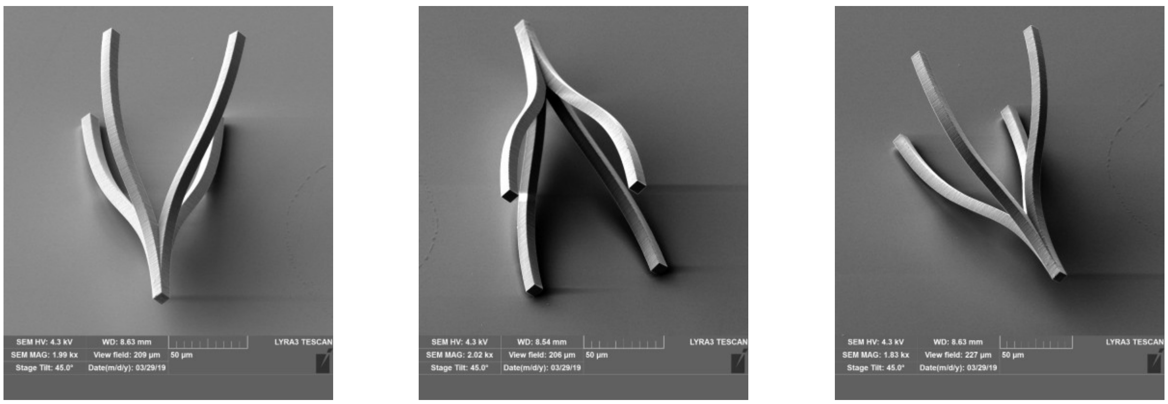


FIGURE 5. SEM images of the core of the polymeric device, a 3D 1x4 Y-branch splitter, prepared from IP-Dip photoresist.

CONCLUSIONS

We designed, simulated and technologically realized a 3D 1x4 Y-branch splitter based on polymer material platform. The structure of the splitter was based on technological possibilities and according to these optimized to reach the shortest possible length. Optical splitter was simulated and the results confirm rather low losses and high uniformity of the split optical power over the output waveguides. Insertion loss uniformity, *ILu*, reached 0.0054 dB. Well-handled technology with an appropriate photoresist enabled the realization of the functional prototype.

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