Scalable Free-standing 3D Optical Circuit Design using Direct Laser Writing

(Student paper)

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We present a design for 3D optical circuits using a DLW (direct laser writing) technique. The design uses polymer stand-offs to create air-clad waveguides to enhance modal confinement to enhance waveguide properties. The 3D geometry offers a compact design with a lot of flexibility for functionalisation, making it attractive for scientific and commercial use. The design is also manufacturable by UV lithography making it more scalable.

Keywords: *Direct laser writing, 3D optical circuits, polimer photonics, refractive index contrast, waveguide properties, waveguide interference, UV lithography.*

INTRODUCTION

The field of photonics has undergone a significant transformation with the advent of Direct Laser Writing (DLW) technology[1,2]. This technique offers the ability to create three-dimensional (3D) polymer structures with complex geometries, thereby enhancing the potential for photonic applications. However, the current state of the art for integrated optical circuit nanofabrication relies heavily on ultraviolet (UV) lithography[3,4], which is capable of scaling to industrial standards but restricts the platform to two-dimensional patterning mostly. We here present a simple and very flexible design for 3D optical circuits with high refractive-index contrast. Although the project is currently limited to a conceptual stage, it demonstrates the potential of the platform.

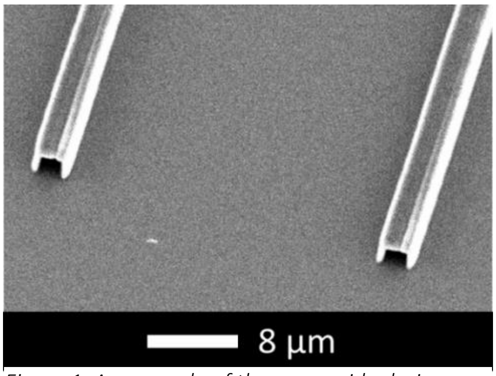

Figure 1: An example of the waveguide design fabricated with DLW. The image was recorded with the use of a scanning electron microscope. The waveguide core width is 2µm.

The proposed waveguide design is based on photonic fiber cores that use supporting stand offs ("leg" structures), as depicted **in Figure 1,** to keep the substrate at a distance. As a consequence, the full index of refraction contrast from the polymer to air is available, allowing small bending radii of the optical waveguide**.** This air-clad waveguide design offers the potential for increasing the density of optical waveguiding structures not only in 2D but also in 3D by adjusting the height of the polymer stand-off, thereby creating platforms of scientific and commercial value.

Furthermore, the design enables higher refractive-index contrast connectivity, enabling the creation of ring resonators on a micrometer scale, thereby increasing the compactness of optical circuits and reducing the required printing surface. This, in turn, increases the chances of commercial application, even in the context of fast prototyping fabrication. The design's simplicity also makes it manufacturable by UV lithography, potentially expanding its reach and impact.

RESULTS

Supported optical modes: We utilized the electromagnetic modal vector-wave equation and a finite-element method (COMSOL Multiphysics) to determine the optical modes that the waveguide designs can support. An example of the calculation can be seen in **Figure 2**. The first three modes of the waveguide design are displayed. The wavelength being considered is 800 nm, the core's width is 1 µm, and its height is 820 nm. The fundamental and second modes have a similar overlap with the waveguide's core, but the fundamental mode is more confined within the core compared to the second mode. The third mode shows a nodal line in the light distribution, with some field extending onto the support structure. This mode is therefore expected to experience higher losses, as most of its profile is attached to the interface of the structure, where fabrication roughness will have a significant impact. The stand offs have no effect on the mode profile of the fundamental and first-order modes and they

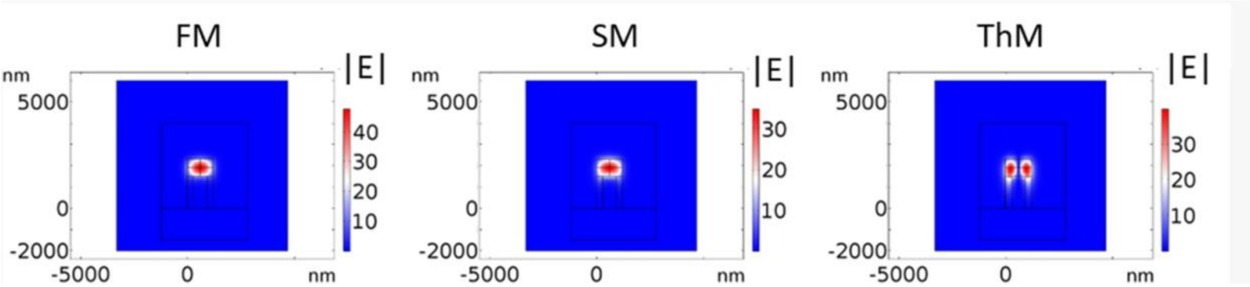

Figure 2: First three modes of the legged waveguide design. The wavelength is 800 nm and the core's width and height are 1 µm and 820 nm, respectively. The fundamental mode (FM) and the second mode (SM) have orthogonal polarisation, but similar field profiles, with the FM being slightly better confined within the core. The third mode (TM) demonstrates is the first mode with a nodal line and is expected to have higher losses due to its attachment to the support structure interface where fabrication roughness is pronounced.

behave similar to an air-clad waveguide. Higher-order modes are affected by the presence of stand-offs. Furthermore, the effective refractive indices of the fundamental and second modes must differ from that of the third mode to prevent coupling to the more lossy mode. By plotting the effective refractive index values for each wavelength against the waveguide's geometrical cross-section, the design can be optimized for specific values and requirements. It is observed that longer wavelengths have reduced effective refractive indices due to decreased confinement within the core. However, this fabrication parameter can be optimized based on the refractive index of the resist used to fabricate the structure. **Figure 3** provides a deeper insight into the waveguide geometry. We compare the effective refractive index values of the first three supported modes with COMSOL. There are configurations where the first and second modes, which both travel mainly within the core, have the same effective

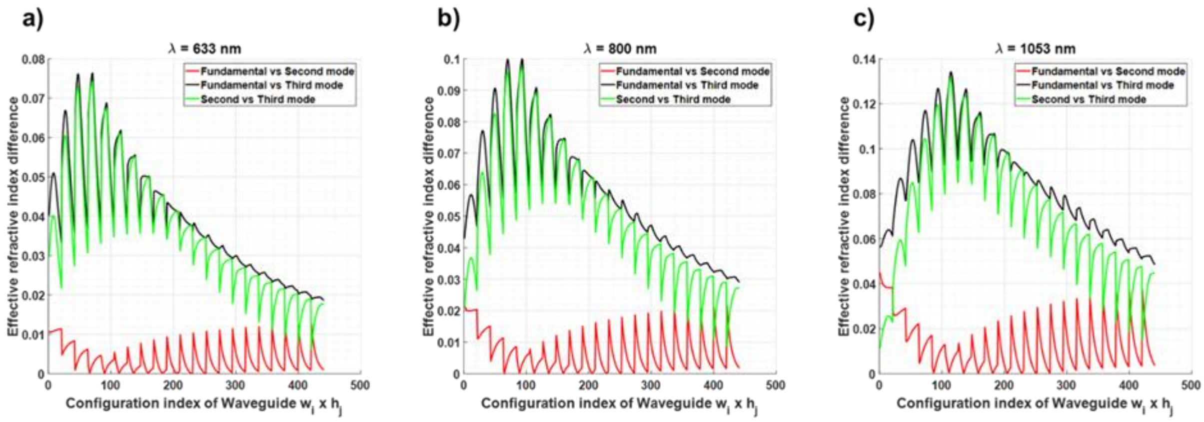

Figure 3: Difference of effective refractive index values between pairs of the three modes of the waveguide geometry computed with COMSOL for three wavelengths. The first and second modes are matched for certain configurations, both traveling within the core at the same effective index. However, there is no match between the third and the fundamental or second modes, indicating independent mode operation.

index. However, there is no effective index overlap for any configuration between the third and the fundamental or second modes.

Experimental validation: Although the fabrication is still in an early stage, the pilot tests on our waveguide designs showed that the optical circuits functioned as waveguides and showed light transmission despite the fabrication errors. The goal was to measure waveguide losses per µm, but couplers that help couple light into the waveguide result in additional losses. We used a 3D curved input-output coupler for the measurements, as it was expected to align with the focus spot, but the coupler and final geometry were not optimized. As shown in Fig. 4, two geometries were created to optimize the optical transmission. The "hippodrome" geometry **(Fig.4 a,c)** measures the combined losses of the waveguide and coupler, including curvature losses. The "staircase" geometry (**Fig.4 b and d**) measures waveguide losses per length, including losses between the waveguide and coupler. Preliminary data show propagation losses of not more than 5 dB/cm.

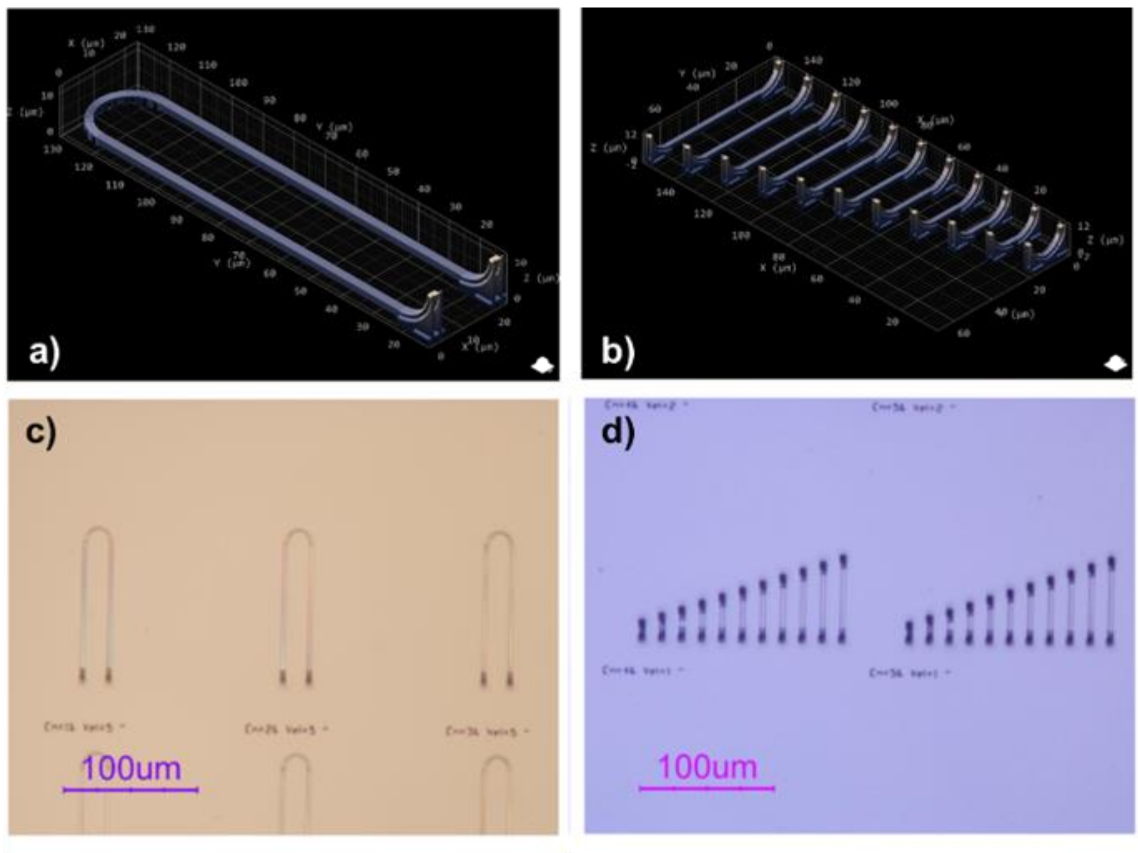

Figure 4: Comparison of waveguide loss measurements using different geometries. (a) and (c) show the "hippodrome" geometry, measuring combined losses of the waveguide and curved coupler. (b) and (d) show the "staircase" geometry, measuring waveguide losses per length, including losses between the waveguide and coupler. The pilot tests on our waveguide designs display functionality and transmission despite the fabrication errors, however, the coupler and final geometry have not been optimized.

DISCUSSION

In conclusion, the proposed design for 3D optical circuits using DLW technology offers a promising solution for advancing photonic applications. With its 3D geometry and high refractive-index contrast, the design has the potential to make circuits with a high density of waveguide components in a compact footprint, making it attractive for both scientific and commercial applications. The pilot test results demonstrate the optical circuits' functionality and optical transmission of the waveguides. The design's simplicity could be leveraged to fabricate similar structures using industrial UV lithography, thereby making it a valuable addition to the field of photonics. In the future further optimization and improvement in the design are needed to fully realize its potential for rapid prototyping and ad-hock polymer waveguiding structures on surfaces.

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