Three-Dimensional Integrated Optical Neural Network

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ABSTRACT

Three-dimensional Optical Neural Networks (ONN) are a promising solution to the energy, time, and area yearning Artificial Intelligence (AI) hardware. The 3D additive manufacturing technique with Two-Photon Polymerization (TPP) can be used to build the 3D dense ONN. In our work, we designed and fabricated the hybrid waveguide circuit which fuses the polymer and air clad waveguides, an important interconnect for the ONN. The polymer-cladded waveguide can support single mode and evanescent coupling while the air-cladded can support tight bend for dense integration.

Keywords: Optical Neural Networks, Optical Computing, 3D additive manufacturing, 3D Micro-Optics & Photonics.

1. INTRODUCTION

Optical Neural Networks (ONNs) are propitious solutions to energy and time yearning AI hardware. Optical interconnects are faster and potentially more energy efficient for communication and computing compared to their electronics counterparts [1]. Yet, the area of ONNs fabricated with CMOS technology or with lithography techniques scales quadratic with the number of neurons, while this scaling reduces to linear in 3D circuits realized with additive manufacturing [2]. Additive manufacturing is a technology to build 3D objects from Computer-aided design (CAD). The 3D structure is built layer by layer unlike subtractive manufacturing processes like etching, milling, machining, etc. In the last two decades, Direct Laser Writing (DLW) and TPP are commonly used tools for 3D microfabrication with polymers.

Two-photon polymerization

TPP is a laser-writing technique to build 3D micro-structure in the range of sub-microns. A highly focused femto-second laser beam is maneuvered in a 3-dimenisonal space to polymerize the liquid monomer resin. The unpolymerized resin is then washed away to devise a desired 3D structure [3]. The degree of polymerization can be controlled by the laser power, which allows to shape optical structures with different refractive indexes [4]. The author has presented the step-index and graded-index optical waveguides with (3+1)D photonic integration [4]. The power of femto-second laser was varied to generate the slow varying core of the graded-index waveguide.

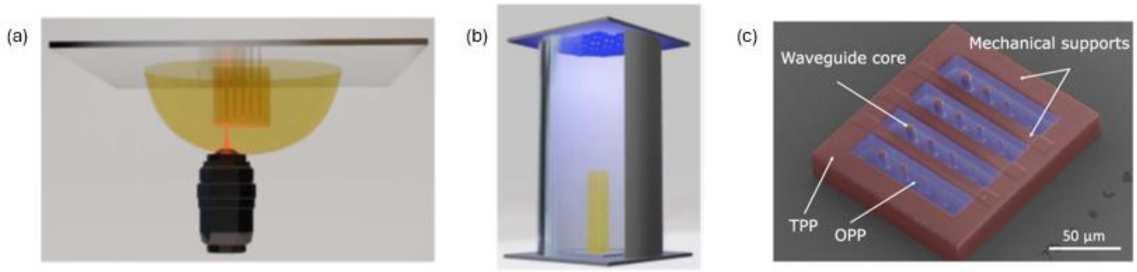

Figure 1. (a) Schematic of TPP: Femto-second laser from objective is focused on the resin to create the structure. (b) Schematic of OPP: The sample is placed in a UV chamber blanket to polymerize the unpolymerized resin. (c) 3D printed waveguides in a cage built with flash-TPP [5].

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Flash-TPP

In Flash-TPP, the author combines the one-photon and two-photon polymerization technology for optical waveguides for the first time to boost the fabrication speed and to increase the optical confinement [5]. The core was fabricated with TPP while the cladding was done with one-photon polymerization (OPP). OPP was done by exposing the sample UV chamber to induce one-photon polymerization (see Figure 1).

2. HYBRID WAVEGUIDE CIRCUITS

The 3D ONN requires a compact optical circuit capable of controlled mapping of input power to the output. To achieve this, we need an interconnect that combines air and polymer clad waveguide (see Figure 2). The air clad waveguide with core refractive index of ~1.5 (limited by the polymer resin IP-S from Nanoscribe) is single mode till a diameter of 0.4μm. Fabricating structure of 0.4μm with the technology limit of 0.1μm (form Nanoscribe) can cause high scattering losses due to high sidewall roughness. The high confinement of air clad waveguide makes it fragile for evanescent coupling. While the polymer clad can support single mode manipulation in the technology limit and the low confinement also makes it suitable for evanescent coupling. But the polymer clad waveguide requires large bend radius due to its beat length which can be achieved with air clad waveguide. The hybrid waveguide circuit can integrate best of both.

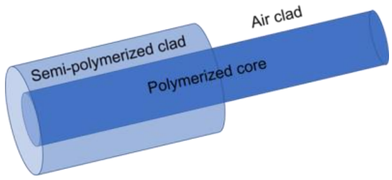

Figure 2. The schematic of polymer-clad and air-clad waveguide amalgamated together.

3. MODE MATCHING

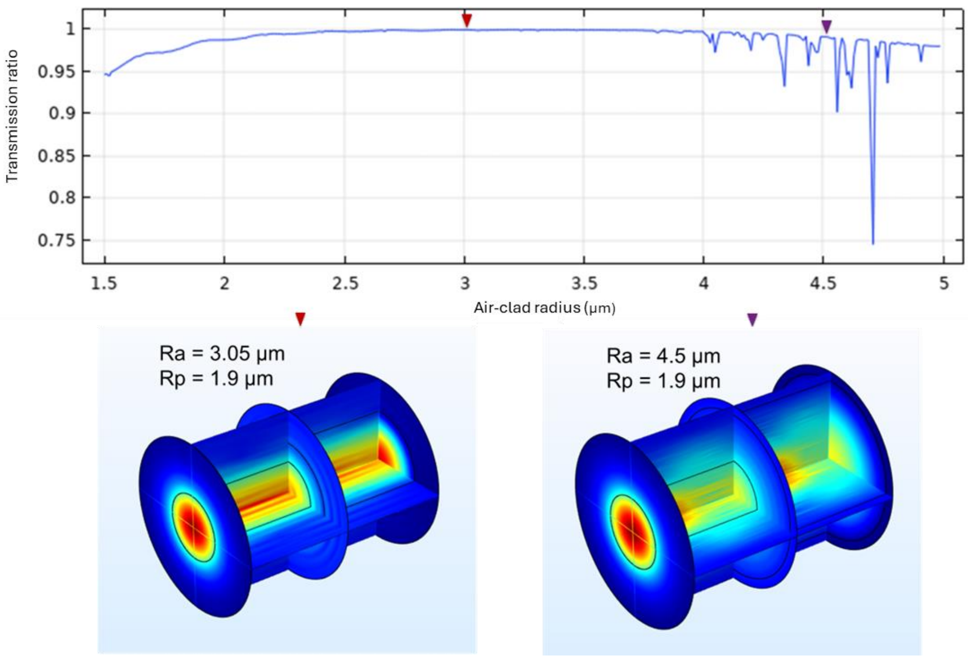

Figure 3. The plot for Transmission ratio of output power by input power at radius of 1.9μm of polymer-clad vs. sweep of air-clad radius. The bottom plots are the electric field profile for air-clad radius at 3.05μm (mode matched) and 4.5μm respectively.

The hybrid waveguide circuits need to match the fundamental modes of waveguiding concept. The wait of the gaussian beam of the fundamental mode of the waveguides need to match for smooth transmission of the mode. This can be done by finding a perfect match of radius of both the waveguides where the mode confinement matches. We started with the simulation by fixing the radius of polymer clad waveguide to the maximum it supports single mode (1.9µm) and then did the parametric sweep of the radius of the air clad waveguide to find the radius where we have mode matching. The results show that at a radius of 3.1µm for air clad waveguide the power transmission is maximum, and the electric field profile clearly shows the smooth transmission of fundamental mode (see Figure 3).

4. EXPERIMENTAL RESULTS

The designed hybrid waveguide is fabricated with flash-TPP (see Figure 4). The polymer clad waveguide is created inside the cage and air-clad waveguide below it with TPP and then the resin inside the cage is polymerized with one-photon after the development. The optical characterization is done at 660nm. The transmission ratio is normalized with polymer reference of the same length. The transmission plot showed at 2.4µm of air clad waveguide we get the minimum losses of ~0.5db and for the radius above 2.4µm we excite the higher order modes. Hence radius of 2.4µm for the air clad and 1.9µm of polymer clad gives the best result for the hybrid waveguides.

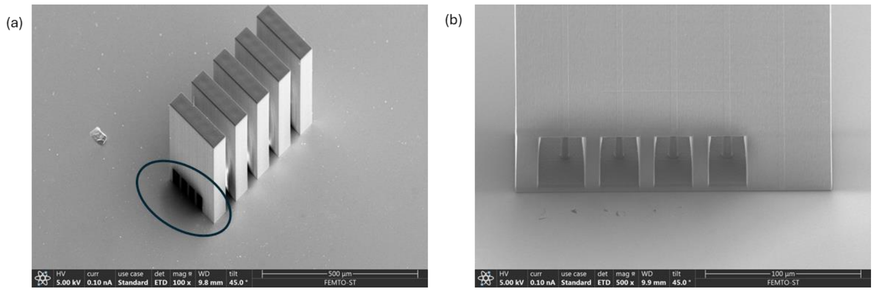

Figure 4. (a) SEM of polymer-clad at top inside the polymer filled cube and air-clad at bottom. (b) Inset of (a): Air-clad waveguide.

5. SUMMARY AND OUTLOOK

In summary, the hybrid waveguide was carefully designed to have single mode transmission with minimum losses to combines and leverages the best of both worlds: single mode manipulation, evanescent coupling from polymer clad waveguides, tight bends, and compact coupling from air-clad waveguides without the use of tappers. This strongly increases circuit density and aids scaling in future implementations.

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