Next generation of 3D printed photonic circuits for scalability and high-performance hybrid integration

Adrià Grabulosa[1], Johnny Moughames[1], Xavier Porte[1] and Daniel Brunner[1]
1. Institut FEMTO-ST, Université Franche-Comté, CNRS UMR6174, Besançon, France.

Summary.
Using additive and CMOS compatible one- and two-photon polymerization, i.e. flash-TPP printing, we create air- and polymer-cladded 3D photonic waveguides and single-mode splitters for scalable, dense and parallel interconnects. Our 3D technology represents a breakthrough towards the highly-interconnection required in optical neural networks, which removes the high energy dissipation of electronics and where 3D integration enables scalability that is challenging to realize in 2D.

1 Introduction

In electronics, when realizing a direct connection of multiple channels, the capacity of long and dense electronic wires results in high energy dissipation and bandwidth limitations. Optical routing is advantageous in terms of speed, latency and energy dissipation, since the energy associated with charging the capacity of the electronic wires is removed. Likewise, combining the strength of multiple photonic and electronics concepts in one hybrid and multi-chip platform is a promising solution for the diversification of chips for specific computing tasks to boost performance [1]. We have demonstrated a new routing strategy for integrating photonic neural networks via additive 3D fabrication, showing parallel and large-scale interconnection of 225 in- and 529 output channels [2], see Fig. 1 (a). We further demonstrated *flash*-TPP [3], a novel CMOS compatible lithographic methodology that enables ultra-fast fabrication of high-performance 3D photonic circuits based on additive fabrication via one- (OPP) and two-photon polymerization (TPP) combined with direct-laser writing (DLW), see Fig. 1 (b).

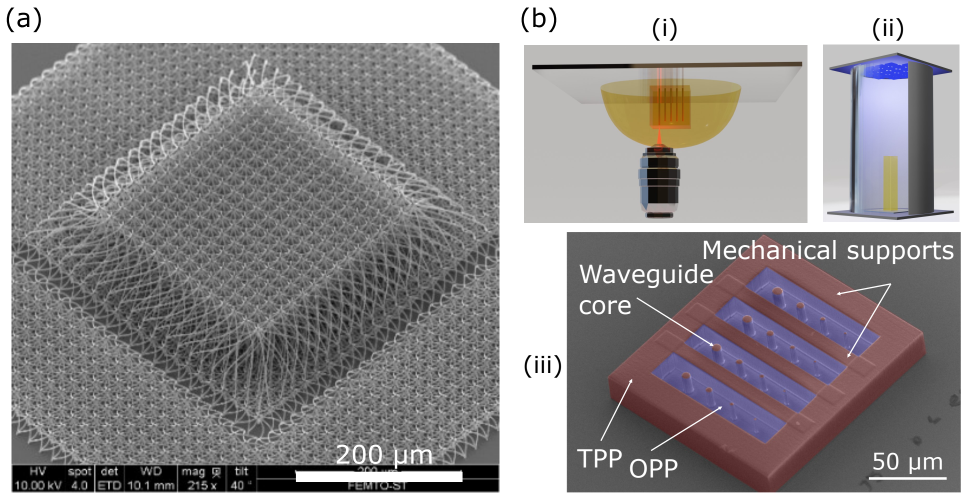

Figure 1: 3D printed photonic circuits. (a) SEM micrograph depicting a 3D printed array of optical splitters interconnecting in parallel 225 in- and 529 output waveguides. (b) *Flash*-TPP concept for photonic integration: (i) the waveguides cores (mechanical supports) are printed with high(low)-resolution via DLW-TPP; (ii) the cladding is polymerized under UV blanket exposure via OPP. (iii) SEM micrograph of a cross-section where the red (blue) region represents the sections polymerized via TPP (OPP).

2 Experimental results

Using DLW-TPP additive fabrication, we demonstrated multi-mode optical splitters based on air-cladded waveguides with a 1 to 4, 1 to 9 and 1 to 16 configuration [4] as well as efficient scalability of optical interconnects by cascading a double-layer of 1 to 9 splitters, resulting in 81 outputs, see Fig. 1 (a-b). For large-scale networks, we fabricated 3D parallel interconnects by spatially multiplexing 1 to 9 splitters, resulting in an array of 3x3 input waveguides with 25 outputs, see Fig. 1 (c).

Via *flash*-TPP, we fabricated polymer-cladded waveguides with a refractive index contrast between core and cladding in the order of $\Delta n \approx 5 \times 10^{-3}$, enabling single-mode propagation over large (6 mm) distances, and with only 1.3 dB/mm (0.26 dB) propagation (injection) losses. We further showed a general tapering strategy of single-mode optical splitters leveraging adiabatic transfer from one input to up to 4 outputs in a single component.

In a last investigation, we showed the concept's CMOS compatibility by successfully printing a cascaded 1 to 16 splitters on top of GaAs quantum dot micropillar laser array [5], as shown in the SEM micrograph from Fig. 2 (d). Preliminary optical characterization of photonic waveguides printed on top of such semiconductor device showed good performance in terms of optical losses and stability over time.

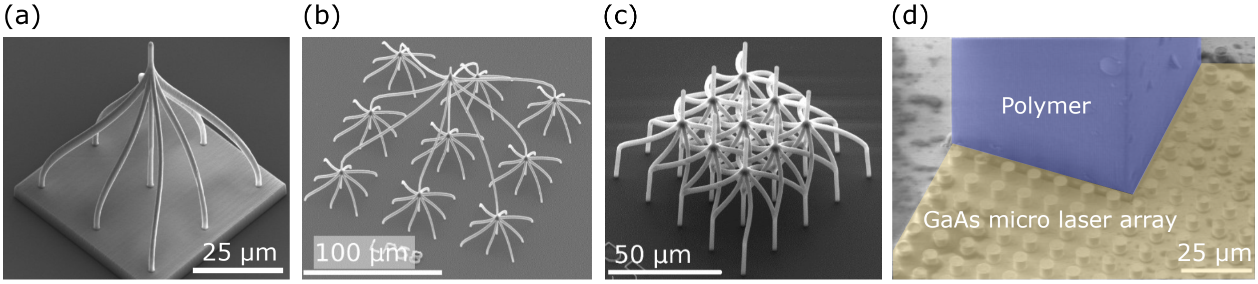

Figure 2: 3D printed optical splitter and CMOS compatibility. (a) SEM micrographs depicting 3D printed air-cladded 1 to 4 optical splitter, (b) Double layer of 1 to 9 splitters resulting in 81 optical outputs, and (c) 3x3 input array of large-scale interconnects after spatially multiplexing 1 to 9 splitters. (d) SEM micrograph of a 3D cuboid integrating a 1 to 16 adiabatic coupler printed on top of a GaAs quantum dot micropillar laser array [5].

3 Conclusions

We have demonstrated the 3D additive fabrication of multi-mode and air-cladded optical splitters with 1 to 4, 1 to 9 and 1 to 16 optical outputs [4] as well as highly-connected photonic circuits with 225 in- and 529 output waveguides that only occupies 460x460x300 μm^3 [2]. These architectures are prime candidate for highly-dense photonic packaging, specially towards photonic neural networks schemes. We further developed *flash*-TPP [3], a simple lithographic configuration that combines DLW-TPP and OPP for the ultra-fast fabrication of polymer-cladded single-mode photonic waveguides and adiabatic splitters. Finally, we have demonstrated the reliability of *flash*-TPP with CMOS technology by printing a cascaded 1 to 16 adiabatic couplers on top of micro-laser arrays [5]. With this, we lay a promising foundation for scalable integration of hybrid photonic and electronic platforms [1]. Such scalability is essential for efficient parallel communication throughout a densely-connected network, which is challenging in 2D.

References

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