Addressing challenges in spatial division multiplexing domain with 3D-printed optical interconnects

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The increasing demand for high speed and high data rate transmission is driving technological advancements in the field of optical communication. Current technologies must evolve and adapt to keep pace with these developments. Single-core optical fibers have long been the backbone of our data transmission networks, but their capacity is gradually approaching a saturation point. In response to this challenge, the telecommunications and research communities are actively exploring spatial division multiplexing using multi-core optical fibers (MCFs) as a promising solution. By leveraging the spatial separation of multiple cores within a single optical fiber, this approach offers the potential to significantly boost data transmission capacity. However, this transition is not without its challenges. A significant obstacle lies in the limited number of existing specialized interconnection solutions, which are required to fully exploit the potential of MCFs. Fan-in and fan-out (FIFO) components are typically used first to connect the individual cores of MCFs with standard single-core fibers, since for the latter standard and low-cost components are readily available on the market. However, this results in rather voluminous, costly, and often sub-optimal solutions given the large number of fibers involved. Similar challenges arise when it comes to addressing MCF interconnection issues with photonic integrated circuits. The impact of MCFs could therefore be greatly enhanced if dedicated interfacing components for MCFs would be developed.

Additive micromanufacturing technologies may offer a route to obtain such components. Recent advances in the field of 2-photon polymerization-based direct laser writing (2PP-DLW) indeed allows for 3D-printing with sub-micrometer resolutions. Few-moded low-loss waveguide components have for example been fabricated [1], [2]. Among others, a unique property of 2PP-DLW is that it allows fabricating devices directly onto the end facet of optical fibers [3], [4].

Here we report on a series of building block elements that can be used to address the challenges in the field of MCF interconnects. We demonstrate waveguides that are mode matched with standard SMF-28 fibers, adiabatic tapers for mode conversion to smaller size waveguides, and S-bends with aspect ratio lower than 1 that offset the waveguide axis. All these components have been thoroughly modeled, optimized, and fabricated using 2PP-DLW for operation in telecommunication C- and L-bands (1530 nm – 1630 nm) featuring losses below 3 dB and low polarization dependent performance. We also report on our recent modeling and experimental results on multimode interference (MMI) couplers for applications in spatial division multiplexing, and a 1x3 splitter for MCFs that uses all of the above-mentioned components.

To fabricate our devices, we used a commercially available Nanoscribe Photonic Professional GT+ workstation that implements 2PP-DLW with line-by-line scanning and layer-by-layer printing in Nanoscribe's proprietary IP-DIP photoresist with a refractive index of 1.53 around 1550 nm upon polymerization. All the components reported below are designed for IP-DIP material with air as cladding and for operation in the wavelength range from 1530 nm to 1630 nm, which covers the C- and L- bands. For our numerical simulations we used Ansys Lumerical's MODE and FDTD software suites.

Figure 1(a) shows a 3D-printed component featuring square-shaped 14 × 14 μm^2 waveguides for SMF-28 fiber coupling, with parabolic taper sections on both sides. This component showcases our 3D-printing and transmission characterization approach for such components. Note also that V-grooves are 3D-printed on both sides of the component to facilitate alignment and free-space butt-coupling of the fibers with the polymer waveguides. Figure 1(b) provides a front view of the V-groove and polymer waveguide, while Figure 1(c) offers a top view of the taper to the 14 × 2 μm2 cross-section waveguide. Finally, Figure 1(d) and 1(e) present S-bends with Bezier-shaped cross-sections, designed to offset the waveguide axis by 50 μm in the lateral direction.

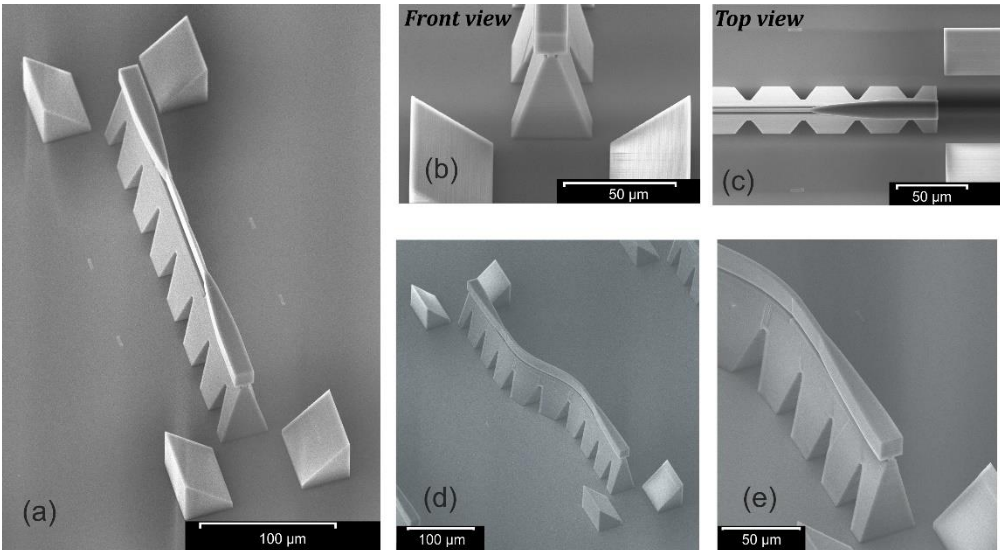

Fig. 1. Scanning Electron Microscope (SEM) images of a tapered waveguide providing for adiabatic transition from 14 x 14 μm^2 to 14 x 2 μm^2 cross-sections (a-c). SEM images of S-bends for a waveguide offset of 50 μm over a length of 170 μm, using a waveguide with a 14 × 4 μm^2 cross-section.

Building on these components we proceeded to designing a 1x3 splitter for MCFs based on multi-mode interferometer (MMI) coupler. The MMI uses a 14 × 2 μm^2 waveguide at the input and then splits an optical signal to 3 identical output waveguides. Figure 2 shows a finite-difference time-domain (FDTD) simulation of such an MMI with a 10 µm-wide multimode interference region. For the given waveguide width, a 33 µm-long MMI generates an interference pattern that addresses 3 output waveguides with identical 14 × 2 µm^2 cross-sections, with insertion losses below 0.5 dB per channel across the C- and L-bands and for both TE- and TM-polarizations.

Finally, we also fabricated a 1x3 splitter for MCF based on this MMI. The component that includes tapers, S-bends, and the MMI, with an overall length of 250 µm, was fabricated in approximately 20 minutes with all the supports and V-grooves. Initial characterization was done with SMF-28 fibers on both sides, and measurements were conducted for six components using various sets of V-grooves for different output waveguides. The initial transmission characterization of the components with a broadband unpolarized light source and SMF-28 fibers indicates that an average loss of about 3 dB per channel can already be achieved. Given that these are early results obtained with our first prototype components, we are confident that further optimization of the design and fabrication parameters will result in substantially lower loss values.

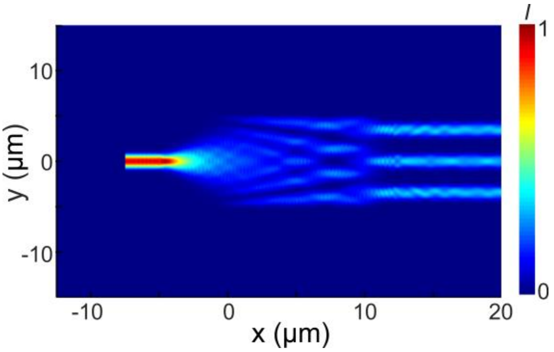

Fig. 2. FDTD modeling of an MMI 1x3 coupler consisting of input and output waveguides with a cross-section of 14 × 2 µm^2.

References

[1] H. Gao, G. F. R. Chen, P. Xing, J. W. Choi, H. Y. Low, and D. T. H. Tan, "High-Resolution 3D Printed Photonic Waveguide Devices," Adv. Opt. Mater., vol. 8, no. 18, p. 2000613, Sep. 2020.

[2] T. Baghdasaryan, K. Vanmol, H. Thienpont, F. Berghmans, T. Geernaert, and J. Van Erps, "Design and two-photon direct laser writing of low-loss waveguides, tapers and S-bends," JPhys Photonics, vol. 3, no. 4, 2021.

[3] K. Vanmol et al., "3D direct laser writing of microstructured optical fiber tapers on single-mode fibers for mode-field conversion," Opt. Express, vol. 28, no. 24, p. 36147, Nov. 2020.

[4] J. Van Erps, K. Vanmol, T. Baghdasaryan, A. Kyriazis, N. Vermeulen, and H. Thienpont, "Laser direct writing of interfacing structures for short-distance optical interconnections," in Advanced Fabrication Technologies for Micro/Nano Optics and Photonics XVI, Mar. 2023, vol. 1243303, no. March, p. 6.