throughputs of the 8 waveguides of the remapper were between 70 and 73% (see Fig. 6c), which constitutes a major improvement over the device reported by *Charles et al.* The remaining losses are mainly attributed to bulk absorption in the 30 mm long Eagle2000 block that contributed 20% (highlighted by a red box in Fig. 6) to the loss and two 6% losses (per facet) due to the mode-mismatch between the fibers and the waveguide mode at each end of the device. Indeed, when the 8 remapper throughputs were normalized with respect to the straight guides (dashed red line), the throughputs ranged between 96 and 100%. This indicates that there were negligible bend losses as is expected for 30 mm long waveguides with bend radii between 23 and 35 mm from Fig. 5. As the bend losses have now been minimized, it now becomes possible to redesign a remapper which has a smaller footprint (which will have shorter tracks and hence lower absorption losses), by increasing the minimum bend radius from the 23 mm used in the device discussed here towards 17 mm which sits at the edge of the throughput curve in Fig. 5. There is a limit to this as well and we estimate that a gain of 5-8% improvement in throughput can be made this way.

The vastly improved and equalized throughputs of the remapper will significantly increase the fringe contrast of an interferometer based on this chip and allow for very precise determination of the complex coherence of the incident radiation field which is key to high fidelity astronomical imaging (with specific application to high contrast detection of faint exoplanets against the glare of their host stars). However, measurements of the precision of such an interferometer are deferred to future work. This illustrates a successful real-world application of this technique.

5. Conclusions

In conclusion, we have identified different thermal stability regions in the direct-written waveguides and have utilized a differential thermal annealing process to significantly decrease the bend losses of waveguides written in the cumulative heating regime. The thermal annealing process exploits the different thermal stability of different regions within the induced refractive index profile. The heat treatment erases the outer ring, but leaves a very high index contrast (8.4×10^{-3}), Gaussian-like profile core behind. As a result, the waveguides show dramatically superior bend loss characteristics as compared to non-annealed waveguides. Indeed, we have demonstrated that this method has enabled the realization of an efficient 8 waveguide 3D, pupil-remapping chip. This performance improvement will have far reaching implications allowing rapid prototyping with MHz repetition rates (fabrication speeds in the range of 500-2000 mm/minute), while retaining the ability to fabricate complex, multi-element 3D photonic circuits.

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