Integrated Graded-Index Luneburg Lens for Robust Fiber-to-Chip Coupling

CNF Project Number: 980-01
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Abstract:

We demonstrate a high contrast, low loss, graded-index lens for robust fiber-to-chip coupling of silicon waveguides. We experimentally show increased alignment tolerance in comparison to a conventional inverse taper.

Summary of Research:

Graded-index (GRIN) photonics has received a lot of attention in recent years [1, 2]. The ability to control the flow of light brought about by advances in transformation optics, metamaterials, and fabrication techniques is changing the way we design optical devices, enabling features once unimaginable. Nonetheless, although many such devices have already been demonstrated, most are limited by scattering losses resulting from the discrete structures that compose their effective graded material. In this work, we employ a low loss platform for high contrast GRIN devices to fabricate a compact Luneburg lens [3, 4] with a 30 µm diameter that is integrated with conventional silicon waveguides to improve their alignment tolerance in fiber-to-waveguide coupling.

Similarly to a conventional lens, the Luneburg focuses light at a position determined by the angle of incidence of the beam. On the other hand, this spherical GRIN lens does not suffer from aberration or coma, which on a conventional lens change the focusing spot depending on the distance of the light beam to the optical axis. Additionally, due to its index profile \( n(\rho) = n_0 \left( 2 - \rho^2 \right) \), where \( \rho \) is the normalized radius, the index at the edge of the lens \( n(1) = n_0 \) can be designed to match the surrounding environment, rendering this lens reflectionless over a wide wavelength range.

Combined, these properties make the Luneburg lens a great candidate for coupling large delocalized fiber modes into highly confined silicon waveguides with tolerance for the exact incoming position of the fiber beam, a fundamental aspect for future optical networks. As illustrated in Figure 1A, the integrated Luneburg lens, present in the same substrate of our waveguides and inverse tapers [5], effectively plays the role of gathering the signal coming from the fiber and delivering it to the taper even if the former is slightly misaligned to the latter. We thus expect increased coupling robustness along the chip edge direction, while, as our results show, introducing no changes in the out-of-plane direction.

To produce the required profile for the Luneburg lens (with index variation of 41% from edge to center) we used a tapered slab waveguide [6, 7] in a compact size (15 µm radius), suitable for integration. On an SOI wafer with 250 nm device layer the waveguides and tapers were defined by electron beam lithography and anisotropic plasma etching. Then the Luneburg lenses were patterned via focused ion beam milling. Finally, the samples were cladded with 2 µm of SiO\(_2\). An optical microscope image of the cladded device is shown in Figure 1A, as well as an atomic force microscope (AFM) scan of the silicon slab height compared with the designed lens profile (Figure 1B), which matches quite well the fabricated device.
We measured the coupling misalignment loss for two Luneburg couplers and two conventional inverse tapers. The results, seen in Figure 2A, show the normalized collected power when the input fiber is scanned across the devices via a piezoelectric stage in both horizontal (along the edge) and vertical (out-of-plane) directions. We can observe that the Luneburg couplers improve the overall alignment robustness of the system in the horizontal direction as expected. In Figure 2B cross-sections of the maps are shown for the four devices along the horizontal direction. We can see, for example, 6 dBm less penalty for the Luneburg couplers than for the tapers at 4 µm misalignment. Additionally, a similar analysis shows that the presence of the lens does not hinder the sensitivity in the vertical direction. Simulations performed with COMSOL Multiphysics closely agree with the experimental results.

GRIN photonics holds the promise of new capabilities for future and existing optical systems. This work demonstrates the use of one of these devices, a compact aberration-free Luneburg lens, to improve the alignment sensitivity of fiber-to-waveguide coupling for future optical networks.

References: