

waveguide is multi-mode, in which case the fabrication quality must be high enough to avoid power exchange between the modes propagating along the coupler.

To achieve high efficiency in a two-stage coupler, one needs to optimize the cross-section of the fiber-matched waveguide, the lengths of the rib and inverse tapers, the height ratio α , as well as some other parameters. The optimization procedure is described in Sec. 4. For our two examples with MFD = 4.0 μm and 8.0 μm , the optimal values of α were between 2 and 3. It was found that the performance of the coupler is close to optimal within a quite wide range of α so that the precise value of α is not very important. For low refractive indices, care must be taken to avoid optical loss due to leakage of the fundamental mode through the oxide undercladding. The leakage loss can be reduced by limiting α and widening the low-index waveguide in the inverse taper section.

The increased conversion efficiency offered by the two-stage coupler means that the footprint of the coupler on a chip can be reduced. Importantly, this also means that for a given footprint, the two-stage design can work with fibers with increased mode size. The increased fiber mode size leads to improved misalignment tolerances and simplified chip packaging. In addition, if a lensed fiber is used to bring light to the chip, a larger focal spot size usually means lower insertion loss because the lensed fiber losses are strongly spot size-dependent.

It is necessary to note that while in this work we were mostly discussing the mode conversion loss, there may be also other sources of loss in the coupler, such as the loss due to mode mismatch with the fiber (0.2-0.3dB). Therefore, whenever it is mentioned that a coupler has a mode conversion loss of 5% (0.22dB), it is necessary to keep in mind that the total loss of such a coupler is approximately 0.5dB. Additional losses at locations where the rib taper ends, inverse taper starts, and the low-index waveguide overlaying the inverse taper is terminated can be avoided with proper design.

Another source of loss is the scattering loss induced by the sidewall roughness of the inverse Si taper. For given roughness, scattering losses increase as the waveguide becomes narrower [36], therefore the roughness-induced loss in the inverse taper will be higher than in a full-width Si waveguide of the same length. We did not consider the scattering-induced loss because it is determined by the fabrication quality and can in principle be reduced to a very low value as fabrication techniques are being improved. Even if this loss is high, e.g. 20dB/cm, the total loss in the inverse taper of the two-stage coupler is only around 0.1dB for MFD = 4.0 μm and 0.5dB for MFD = 8.0 μm for the designs of Fig. 7. Note that compared to pure inverse taper-based couplers, the scattering loss in two-stage couplers is lower because their length is shorter and because the inverse taper occupies only a part of this length.

Although all optimizations in this work were carried out for TE-polarized light, we predict that the two-stage coupler concept is efficient for TE and TM polarizations simultaneously. This was confirmed with FDTD simulations for one example of a coupler design. In this example a Si waveguide with thicker core – 220nm rather than 105nm as in the rest of the paper – has been assumed. Efficient operation of the two-stage coupler in this case illustrates that the two-stage design can be efficient for different Si waveguide geometries.

The couplers in this paper were designed assuming linear taper shapes in the two stages. Initial results on optimized taper shapes show that switching from a linear to an optimized taper shape allows to gain a factor of 2-3 in length, which is in addition to the gain achieved by switching from the conventional inverse taper-based design to the two-stage design. This additional improvement in coupler efficiency should make it possible to practically couple light directly from standard single-mode fibers with 10 μm mode field diameter. This subject requires further investigation.

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