Efficient Planar Single-Mode Fiber-to-Chip Coupler based on Two-Stage Adiabatic Evolution

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Abstract: A novel planar two-stage adiabatic single-mode fiber-to-chip coupler design is presented. The combination of rib and inverse tapers allows to make it 2-2.5 times shorter than state-of-the art inverse taper-based couplers with similar conversion efficiency.
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OCIS codes: (130.3120) Integrated optics devices, (250.3140) Integrated optoelectronic circuits

Microphotonic circuits using strongly-confined waveguides promise dense integration of optical components on a chip and complex, high-performance signal processing devices [1]. However, the miniaturization of photonic devices, achievable with silicon-on-insulator technology, makes it challenging to couple light between optical fibers and sub-micron Si waveguides because of mode area mismatch of up to 3 orders of magnitude. Several approaches to this problem have been proposed, such as couplers based on inverse tapers [2-4] and waveguide gratings [5]. In couplers based on inverse tapers, the light from the fiber is first coupled into a low-index waveguide with a mode size matching that of the fiber. A silicon waveguide is then introduced into the low-index waveguide. The Si-waveguide is very narrow in the beginning and is gradually widening up, so that the mode of the structure becomes more and more confined in silicon. Inverse tapers allowed to demonstrate coupling losses as impressive as 0.5dB [3, 4]. This result was achieved using specialty fibers with small core size (mode field diameter of about 2µm in [4] and 4.3µm in [3]) and coupler lengths were 150µm in [4] and more than 200µm in [3]. However, it is desirable to use fibers with larger core sizes in order to reduce mode conversion losses in the fiber (e.g. in a lensed fiber) and to improve misalignment sensitivity. Our calculations show that the inverse taper length required for efficient mode conversion increases rapidly with the fiber core size, so that the coupler footprint on a chip can become too large for applications which require dense on-chip integration. We propose a novel coupler design which achieves the same mode conversion efficiency as the inverse taper in less than half the length. The proposed coupler can also be used with fibers with cores larger than possible with inverse taper-based couplers of the same length. The coupler is single-mode throughout its length and is compatible with planar fabrication technology.

The layout of the proposed two-stage coupler is shown in Fig. 1(a) [6]. The fiber mode is coupled into a low-index (e.g. polymer) waveguide. In stage I of the coupler, the mode size is reduced vertically by introducing a rib and adiabatically narrowing it down until most of the light is transferred into the wider bottom section of the guide (the mode evolution is illustrated in Fig 1(b)). In stage II, an inverse taper is used to transfer light into the Si waveguide. This design thus combines the idea of a rib taper [7] and inverse taper [2-4] in a single device to achieve improved efficiency. Unlike in our previous work [6, 8], we would like the coupler to be single-mode along all its length to avoid potential multi-mode effects which might take place because of fabrication imperfections.

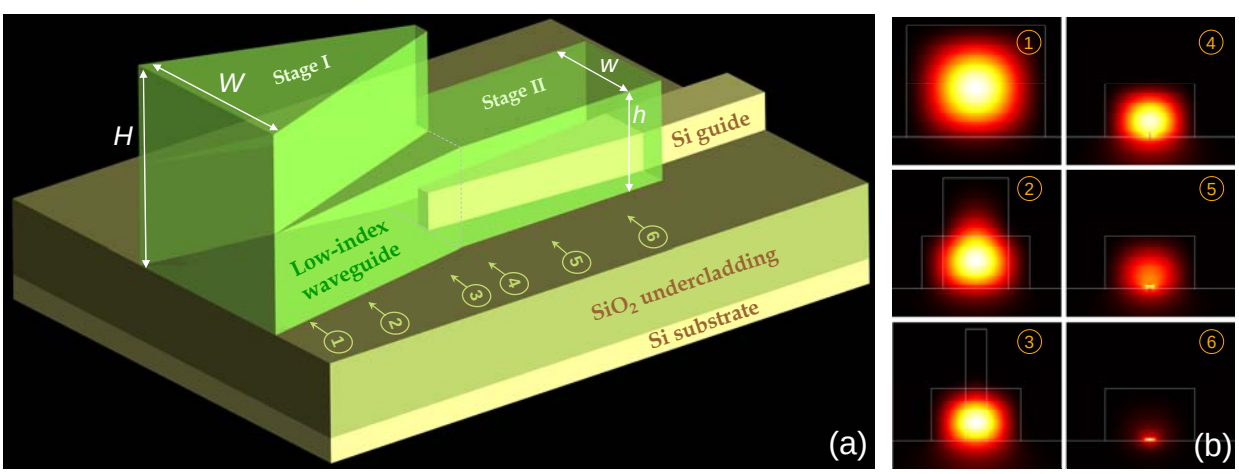

Fig. 1. (a) The layout of the proposed two-stage adiabatic coupler (not drawn to scale) and (b) an example of mode evolution along the coupler.

We now briefly describe the procedure of optimization of coupler parameters and consider 3 examples of input low-index waveguide cross-sections: (A) 4x4µm, (B) 5x5µm, and (C) 6x6µm, corresponding to full widths at $1/e^2$ of roughly 3.5µm, 4.3µm, and 5.3µm, respectively. We do not consider larger spot sizes because in this case it is hard to achieve low-loss single-mode operation due to leakage into SiO_2 undercladding. For a given cross-section, the refractive index of the low-index material should be chosen as high as possible provided that the 2nd mode is cut off. For our three examples, the refractive indices were chosen to be (A) 1.497, (B) 1.481, and (C) 1.468. The thickness of the SiO_2 undercladding (refractive index=1.45) was assumed to be 3µm.

Let us denote the height and width of the low-index waveguide at the input of stage I as H and W, the height and width of the low-index waveguide at stage II as h and w, and $\alpha=H/h$ as the height ratio (see Fig. 1). Apart from reducing the waveguide height from H to h in section I we would also like to reduce its width from W to w. However, if w is made too small, the fundamental mode will experience losses due to leakage through the undercladding into Si substrate. We selected w from the condition that the leakage loss is $\leq$10dB/cm, corresponding to a power loss of 0.1-0.2dB over a 100-200um region. The values of h and w found from this condition are shown in Fig. 2(a). We see that as the height ratio $\alpha=H/h$ increases, the section II width w needs to increase as well, eventually exceeding the input width W for large values of α.

To select the height ratio α, one can note that the total length of the coupler is the sum of the lengths of the rib taper and the inverse taper. For a given mode conversion efficiency, the former term increases and the latter term decreases with α. Therefore we can expect that there exists an optimum value of α which minimizes the overall coupler length required for a given conversion efficiency. Fig. 2(b) shows the coupler lengths required for 5% mode conversion loss as a function of height ratio α. At each point of this plot, the relative lengths of the two sections where optimized to minimize the overall length. We can see that considerable reduction in coupler length is possible for α~2 compared to inverse taper-based couplers (α=1). Fig. 2(c) compares the lengths of the inverse taper-based coupler and the proposed two-stage coupler required for 5% mode conversion loss. We see that the two-stage coupler allows to achieve 2-2.5 times reduction in device length with equal mode conversion efficiency. In our simulations, 600x105nm Si waveguide cross-section, 50nm Si tip width, and 1550nm wavelength were assumed. The width of the rib at the point where it is terminated was (A) 0.6µm, (B) 0.7µm, and (C) 0.8µm. The designs were optimized for TE-polarized light only, which is not a limitation for many important applications such as intra- and inter-chip communications. Note that in addition to mode conversion loss, the total coupler loss also includes end-facet mode mismatch loss (~0.25dB for optimized cross-sections) and leakage loss (~0.1dB). The total loss corresponding to Fig. 2(c) is thus about 0.6dB.

In conclusion, we propose an efficient fiber-to-chip coupler design which uses rib taper and inverse taper to achieve high mode conversion efficiency. This design allows to achieve 2-2.5 times length reduction compared to state-of-the-art couplers based on inverse tapers. The proposed coupler is adiabatic and single-mode, which improves its tolerance to possible fabrication errors.

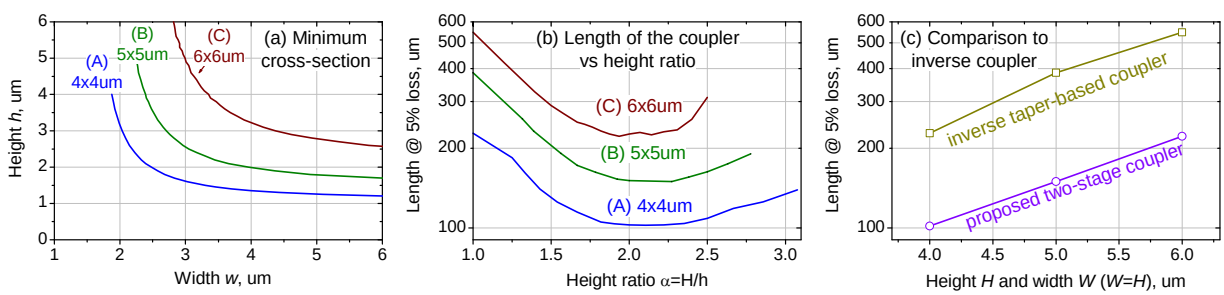

Fig. 2. (a) Minimum height h and width w of section II for designs (A-C), as found from 10dB/cm leakage loss of the TE mode; (b) Coupler length required for 5% mode conversion loss as a function of height ratio $\alpha=H/h$ for designs (A-C); (c) Lengths of the inverse taper-based coupler and optimized two-stage coupler required for 5% mode conversion loss vs. width and height of the input waveguide (assuming $W=H$).

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