Nanotaper for compact mode conversion

Vilson R. Almeida, Roberto R. Panepucci, and Michal Lipson

School of Electrical and Computer Engineering, Cornell University, 411 Phillips Hall, Ithaca, New York 14853

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We propose and demonstrate an efficient coupler for compact mode conversion between a fiber and a submicrometer waveguide. The coupler is composed of high-index-contrast materials and is based on a short taper with a nanometer-sized tip. We show that the micrometer-long silicon-on-insulator-based nanotaper coupler is able to efficiently convert both the mode field profile and the effective index, with a total length as short as 40 μm. We measure an enhancement of the coupling efficiency between an optical fiber and a waveguide by 1 order of magnitude due to the coupler. © 2003 Optical Society of America

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High-refractive-index materials allow for the fabrication of submicrometer-sized structures, such as waveguides and photonic crystals. Coupling to and from these devices usually involves high losses resulting from mode-size and effective-index mismatch between the optical fiber and the waveguide structure, which induces coupling to radiation modes and backreflection. To date, most of the on-chip structures suggested to alleviate this coupling problem[1–9] have suffered from at least one of the following drawbacks: they are very long (hundreds of micrometers), are difficult to fabricate, have strong backreflection, or have low coupling efficiency. Tapers from the waveguide dimensions to the fiber dimensions for improving coupling efficiency between optical-fiber and waveguide modes have been suggested.[4] However, to avoid excessive coupling to radiation modes in the taper, the required typical taper length must be of the order of millimeters. In addition, these tapers suffer from strong backreflections at the facet of the coupler. Manolatou and Haus[2] suggest a taper based on high-refractive-index materials in order to decrease the length to ~5.5 μm. Quarter-wavelength plates are embedded at the curved facet of the coupler to prevent backreflections, whereas layered structures with a graded index variation are introduced in the vertical direction. However, fabrication of such a structure requires several steps, and the theoretical coupling losses were estimated to be ~1 dB. Inverse tapers, from the waveguide dimensions to the dimensions of a small tip, have been proposed for coupling laser diodes to optical fibers.[4–6] These structures rely on the evanescent field at the tip to increase the mode size of the waveguide to that of the fiber. However, these structures are hundreds of micrometers long, and their coupling losses are fundamentally limited to ~1.3 dB. This is mostly a result of a high-effective-index mismatch between the optical fiber and the waveguide, which leads to relatively strong backreflections. Taillaert *et al.*[7] suggested a grating coupler with a relatively complex structure, presenting a theoretical coupling efficiency of 74% (insertion losses of 1.3 dB), but the experimental value was found to be only 19% (insertion losses of 7.2 dB). In this Letter we propose and demonstrate a micrometer-long nanotaper coupler that converts both the mode size and the effective index of the waveguide to that of the optical fiber.

The nanotaper coupler consists of a waveguide laterally tapered to a nanometer-sized tip at the facet in contact with the fiber (Fig. 1). Silicon-on-insulator (SOI) technology was chosen as the platform for the nanotaper and waveguides because it provides high-index contrast, includes a SiO_2 layer as an optical buffer, and permits compatibility with integrated electronic circuits.[10,11] The nanotaper is composed of the same high-refractive-index material (Si in this case) as the waveguide. At the tip the mode field profile becomes delocalized from the waveguide core. This delocalization of the mode field profile increases the mode overlap with the optical fiber mode. In addition, most of the mode field resides in the SiO_2 cladding region at the tip, causing the effective index to be close to that of the fiber, which results in negligible backreflections.

Simulations were performed with the beam propagation method and the finite-difference time domain (FDTD) method. All simulations were performed at $\lambda = 1.55$ μm. As an input mode reference, a single-mode optical fiber was used, with an effective index of $n_{\mathrm{eff}} = 1.468$ and a mode field diameter of MFD = 4.9 μm, which corresponds to the MFD of a typical erbium-doped optical fiber.[12,13] The waveguide core and cladding materials were Si ($n_{\mathrm{Si}} = 3.48$) and SiO_2 ($n_{\mathrm{Si}} = 1.46$), respectively. The waveguide height and width were taken as $h = 250$ nm and $w_w = 450$ nm, respectively, in order to achieve single-mode operation.[14–16] The power overlap and thus the mode mismatch loss depend on the tip width (Fig. 2) for both TE- and TM-like modes. Considering the TE-like mode in particular, the maximum power

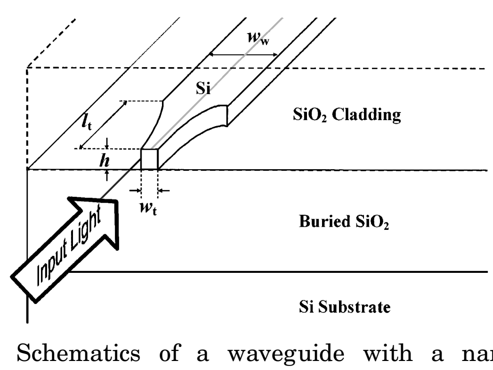

Fig. 1. Schematics of a waveguide with a nanotaper coupler.

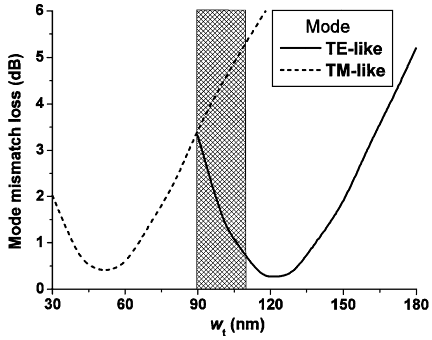

Fig. 2. Mode mismatch loss dependence on nanotaper tip width. The crosshatched region represents the range of experimental values of w_t.

overlap between the optical-fiber and tip modes was ~94%, obtained for $w_t = 120$ nm. This corresponds to a mode mismatch loss of 0.26 dB. In Fig. 2 one can see that a variation of 26 nm of the tip width in the fabrication process causes the mode mismatch loss to increase by only 0.5 dB with respect to the optimum performance. For all values of w_t shown in Fig. 2 the effective index of the mode at the tip stays below 1.48, leading to optical backreflections smaller than −48 dB at the facet. To convert the low-confined local mode at the nanotaper tip into the high-confined waveguide mode, a short tapered transition was employed by gradually varying both sidewalls in a symmetric parabolic transition toward the final waveguide width, where the parabola vertex is located at the nanotaper tip. The taper length necessary to convert the mode depends on the width of the nanotaper tip. Using two-dimensional (2D) FDTD, we estimated less than 0.25 dB of mode conversion loss for a TE-like mode for $l_t \geq 40$ μm and $w_t \geq 120$ nm.[6] This indicates that the taper can effectively convert both mode size and effective index in a very short length. Therefore the coupler losses are ultimately governed by the mode mismatch loss at the nanotaper tip facet.

The coupler was fabricated on a SOI wafer with a 3-μm buried oxide layer by e-beam lithography, followed by inductively coupled plasma etching (see Fig. 3) and the deposition of a 3-μm-thick SiO_2 cladding by plasma-enhanced chemical-vapor deposition. The average nanotaper and waveguide dimensions measured by scanning electron microscopy were $l_t = 40$ μm, $w_w = 470 \pm 20$ nm, $h = 270 \pm 10$ nm, and $w_t = 100 \pm 10$ nm. The sidewall angle was measured to be 82° for the nanotaper tip and 84° for the waveguide. The chips were singulated and polished. The distance from the nanotaper tip to the chip edge was ~3 μm.

We measured the transmittivity for light from a tapered-lensed fiber, with nominal MFD $= 5 \pm 0.5$ μm, coupled through air to a 13-mm-long Si waveguide terminating in nanotapers at each end (see Fig. 1). Two 90° bends with a radius of 50 μm introduced 3-mm input–output lateral shift in order to facilitate measurements. To determine the effect of the coupler quantitatively, we measured the transmittivity through the same waveguide after cutting back the input coupler and polishing the facet. The ratio between the transmittivity with (T_c) and without (T_w) the input nanotaper coupler is defined as the coupling efficiency enhancement (ξ), which is equal to the ratio between the correspondent coupling efficiencies, c_c and c_w, respectively. Therefore $\xi = T_c/T_w = c_c/c_w$. With the experimental values for T_c and T_w over the 1520–1620-nm wavelength range, the coupling efficiency enhancement ξ was found to be 7.0 ± 0.4 and 8.2 ± 0.5 for TM- and TE-like modes, respectively.

The insertion losses of the nanotaper coupler at $\lambda_0 = 1550$ nm were determined as follows. First, using the measured dimensions of the waveguide (w_w and h), we performed three-dimensional (3D) FDTD simulations to determine the theoretical coupling efficiency between the fiber and the waveguide (c_{wt}). Second, we estimated the coupling efficiency between the fiber and the nanotaper coupler by employing the expression $c_c = \xi c_{wt}$. Finally, we determined the insertion losses of the nanotaper coupler, $L_c = -10 \log_{10}(c_c)$, to be 3.3 ± 0.3 and 6.0 ± 0.4 dB for TM- and TE-like modes, respectively, at $\lambda_0 = 1550$ nm. Considering the TM-like mode, the estimated nanotaper insertion losses are consistent with the experimental value of 12% for the total optical transmittivity (insertion losses of 9.2 dB) of the waveguide with nanotapers on both ends. This conclusion takes into account the intrinsic losses of the waveguide (5 ± 2 dB/cm) obtained by employing the Fabry–Perot method.[16]

The measured nanotaper insertion losses for the two polarization modes originate from the mode mismatch losses between the optical fiber and tip facet modes and from mode conversion of the low-confined mode at the tip facet into the high-confined mode in the waveguide. The TE-like mode field profile for such a small tip width ($w_t = 100 \pm 10$ nm) is very delocalized from the tip core, and the 40-μm-long taper is not sufficient to completely convert this delocalized mode into the high-confined waveguide mode. As a result, the nanotaper insertion losses of 6.0 ± 0.4 dB also constitute a substantial contribution from the mode conversion loss. Using 2D FDTD, we estimated 1.5 dB of mode conversion losses for TE-like mode with $l_t = 40$ μm

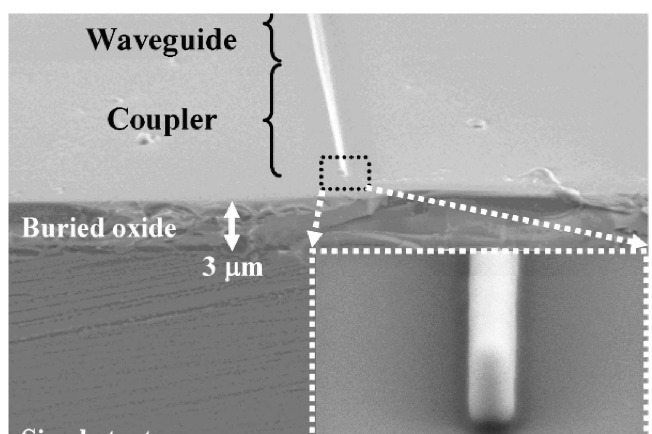

Fig. 3. Scanning electron microscopy pictures of a typical nanotaper coupler, showing an enlarged view of the tip.

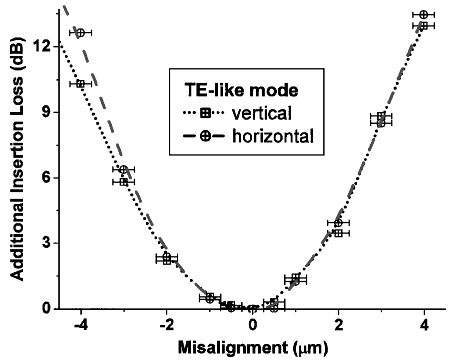

Fig. 4. Additional insertion loss of the nanotaper caused by fiber-coupler transverse misalignment for a TE-like mode at $\lambda_0 = 1550$ nm.

and $w_t = 100$ nm.[6] To obtain a coupling efficiency of 0.5 dB for the TE-like mode for $l_t = 40$ μm, a larger tip width of $w_t = 120$ nm is required (see Fig. 2). On the other hand, the TM-like mode is more localized at the nanotaper tip. In this case the taper does efficiently convert the mode, and the nanotaper insertion losses of 3.3 $\pm$ 0.3 dB arise mostly from the mode mismatch at the tip (see Fig. 2). To obtain optimal coupling efficiency for the TM-like mode (i.e., mode mismatch loss of 0.4 dB), a 50-nm tip width is required.

Figure 4 shows the experimental nanotaper additional insertion loss as a function of the lateral misalignment between the fiber and the nanotaper. One can see that the misalignment tolerance is relatively large, with only 1 dB of additional insertion loss for ± 1.2-μm misalignment in both the x and y directions. This is mainly a result of the large field dimensions at the tip.

Coupling between a fiber and a high-index-contrast waveguide has been a long-standing challenge in the field of integrated optics. Here we have demonstrated efficient coupling between a fiber and a submicrometer waveguide by using a nanotaper. The nanotaper corresponds to the shortest SOI-based mode converter with high coupling efficiency for bridging between optical structures across size scales.

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