Design, Fabrication and Characterization of Inverse Adiabatic Fiber-To-Chip Couplers

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ABSTRACT

An inverse-taper coupler between a fiber and a SiN_x-waveguide overclad with silicon oxide was fabricated. 1.0 dB loss was measured for a 750 µm-long device with a low-index multimode waveguide designed to match a 4.0 µm fiber.

Keywords: coupler, waveguide, integrated optics

1 INTRODUCTION

In silicon photonics, light sources are typically located off-chip and connected to the chip with optical fibers. The problem of efficient coupling between the fiber and a submicron waveguide is challenging because the mode areas of the fiber and the waveguide can differ by up to three orders of magnitude. The problem of coupling is also important because coupling loss can dominate the overall loss in a practical system, and packaging cost can dominate the overall cost.

Two primary ways to achieve efficient coupling are to use inverse tapers [1-6], where the fiber is aligned with the plane of the chip, and grating couplers [8-10], where the fiber is at some angle to the chip normal. We chose the former type because they promise easier packaging and lower insertion loss. Couplers based on inverse tapers have demonstrated coupling loss as low as 0.5-1.0 dB between sub-micron Si waveguides and fibers with mode field diameters (MFDs) of 2-4 µm [2-5]. Specifically, 0.5 dB loss was reported between a fiber with 4.3 µm mode field diameter and a 0.3 × 0.3µm Si waveguide using a 200 µm-long inverse taper [3]. Note that the mode size of the fiber used was several times smaller than that of a standard single-mode fiber (mode field diameter ~10 µm), which is typical of inverse coupler studies. For comparison, in the same work, much higher coupling loss, 2.5dB, was measured for a standard fiber with 9.0 µm mode. In another work [5], 0.5dB coupling loss has been reported between a microlensed fiber with 2.1 µm spot diameter and a 0.45 × 0.22µm Si waveguide using a 150 µm-long inverse taper length. The loss was measured with 0.4 dB uncertainty. A record-short 40µm inverse taper with parabolic width profile has been proposed in [6] with theoretical coupling loss of about 0.5dB for the TE mode. The experimental coupling loss for a fiber with ~5 µm mode field diameter was 3.3 dB for TE and 6.0 dB for TM modes.

While the works mentioned above relied on e-beam lithography, in [4] and [7] the coupler was fabricated with CMOS tools using 248 nm deep UV lithography. In [4], 1.9 dB loss has been demonstrated between a lensed fiber and a sub-micron silicon waveguide with 3 µm × 3 µm low-index waveguide. In [7], a coupling loss of less than 1 dB has been reported between a 4.5µm × 4.5µm low-index waveguide and a 0.4µm × 0.7µm high-index waveguide with 350 µm inverse taper.

In this work we are applying the inverse taper concept to couple light from a fiber to a SiN_x waveguide with 2 µm-thick overcladding. We demonstrate that the lower-index fiber-matched waveguide does not have to be single-mode, but a multimode waveguide can be used as well. The fact that multi-mode waveguides can be used means that materials with higher refractive indices can be used for the fiber-matched waveguide, which significantly increases the range of materials which can be used for coupler fabrication.

2 DESIGN

The layout of the coupler is shown in Fig. 1(a). Light from the fiber is coupled into a low-index polymer waveguide and transferred into a SiN_x (n=2.2) waveguide with an inverse taper [1-6]. The SiN_x waveguide is very narrow at the beginning of the taper so that the fundamental mode of the structure is confined not in the SiN_x waveguide but in the polymer waveguide, as shown in the top of Fig. 1(b). As the SiN_x width increases, the light becomes more and more confined in the SiN core, as illustrated in Fig 1(b). In our coupler, the material of the low-index waveguide was bisbenzocyclobutene (BCB), sold under the name cyclotene^{tm}. It's refractive index was 1.53 and its cross-section was 5.2µm × 4.3µm (width × height), designed for optimum mode overlap with a fiber with 4.0 µm mode field diameter.

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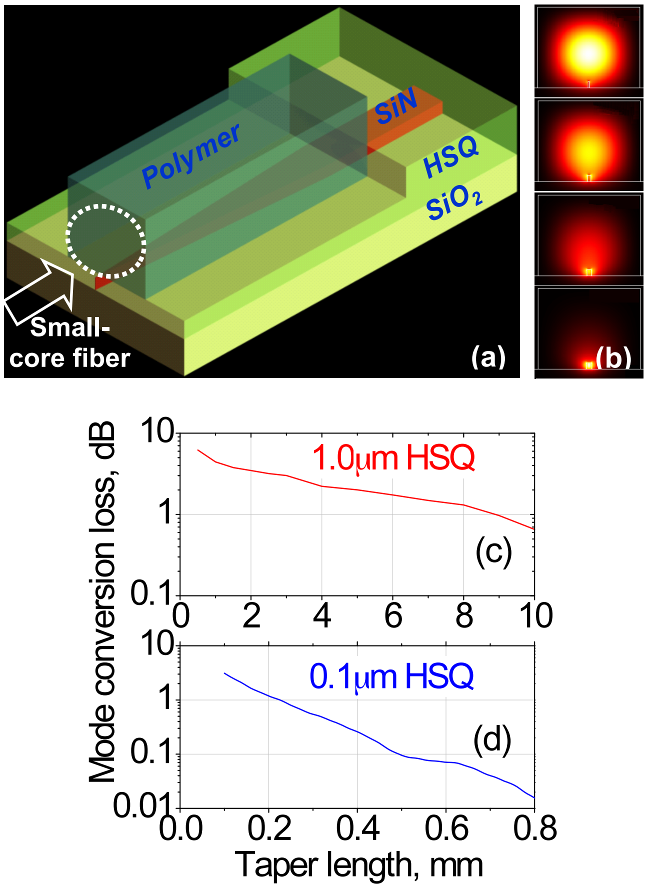

Figure 1: (a) Layout of the coupler, (b) mode evolution along the inverse taper, (c) calculated mode conversion loss as a function of inverse taper length with 1μm-thick HSQ layer, (d) with HSQ thinned down to 100nm.

The coupler was designed to be a part of a chip carrying an integrated photonic analog-to-digital converter [11]. This chip included, among other components, microring-resonator filters with metal heaters on top of the rings. The heaters were separated from the rings by 2.0 μm overcladding to prevent optical losses due to contact wth metal. The overcladding was annealed spin-on-glass hydrogensilsesquioxane (HSQ), which is a dielectric with the chemical composition of $SiHO_{3/2}$. The refractive index of the annealed HSQ overcladding was 1.44, which was lower than the index of the polymer (1.53) carrying the light. Therefore, the mode field only penetrates evanescently from the polymer into the HSQ. This leads to poor mode overlap with the SiN_x waveguide and therefore to poor coupling efficiency. Fig. 1(c) shows the calculated coupling loss as a function of inverse taper length for 1.0 μm overcladding. Calculations were performed with a eigenmode expansion method, as implemented in Fimmwave/Fimmprop software [12]. The length of the taper required for efficient mode conversion is above 1 cm, which is too long for a practical coupler. In reality, the overcladding is 2.0 μm-thick, and the evanescent penetration into the overcladding is even smaller, leading to unacceptable coupler lengths. To overcome this problem, the HSQ overcladding layer was thinned down to 100 nm in the coupler region of the chip. This dramatically reduces the required coupler length. This can be seen from Fig. 1(d), which shows the mode conversion loss as a function of coupler length in case of 100 nm overcladding. One can see that coupling loss as low as 0.5dB can be achieved with 500 μm-long taper.

3 FABRICATION

The fabrication process consists of three major steps: fabrication of SiN_x tapers, coating and patterning HSQ, and coating, curing, and patterning of the high-index BCB waveguide.

In the first step, silicon nitride is first deposited using low-pressure chemical-vapor-deposition (LPCVD). Then 200 nm of PMMA, a positive e-beam resist, is coated and baked on top of the SiN_x layer.

Next, 40 nm of AquaSave, a water-soluble conductive polymer, is spun on the sample to prevent charging during scanning electron beam lithography (SEBL). Using a Raith 150 SEBL system operating at 30 KeV, the SiN_x pattern is written in the PMMA. The AquaSave is then removed and the PMMA developed. Using electron-beam evaporation and a lift-off step a 50 nm nickel hard mask is formed. Then, using the Ni hard-mask, SiN_x is etched with a 16 to 3 ratio of CHF_3 and O_2, in a reactive-ion-etching (RIE) chamber. The Ni hard-mask is then removed.

In the second step, the overcladding layer is formed by spin-coating the sample with HSQ and annealing. As described in the previous section there should be an insulator between the waveguides and filters with very low optical absorption and stable at high temperatures.

Silicon oxide could be a good candidate for this layer, but it has problems with filling high-aspect-ratio gaps, since it is usually deposited by CVD [13]. As a cheaper and more reliable alternative hydrogen silsesquioxane (HSQ) is used in this project, which has excellent gap filling property [13]. It is found that by rapid thermal annealing HSQ at temperatures above 1000 C for 30 s in an oxygen atmosphere it is possible to remove both the Si-H bonds and the tensile stress from HSQ film [13].

With the removed tensile stress, we can have multiple layers of HSQ to get to higher thickness and a more uniform surface over the silicon nitride waveguides/tapers. It is worth mentioning that silicon nitride waveguides have a thickness of 400 nm, thus the coated HSQ cannot be uniform and fabrication tests have shown that we will have a step of 140 nm +/- 10nm over the nitride waveguide parts. Thus, in order to get a uniform surface before having filters or polymer waveguide on top of the HSQ layer, we need to have another layer coated and annealed on top of the first layer, which reduces the height of this step to below 30 nm. We can almost eliminate this nonuniformity by doing another step of coating and annealing.

For the HSQ thinning, we fabricated a Ni hard mask using photolithography and a lift-off method. CF_4 is used in the RIE chamber to etch down HSQ in the coupler region. Finally, BCB is coated, cured and patterned using a silicon oxide hard mask. The BCB is etched in the RIE chamber using a 1 to 3 ratio of CF_4 and O_2. SEM images of the SiN_x and polymer waveguides are shown in Fig. 2.

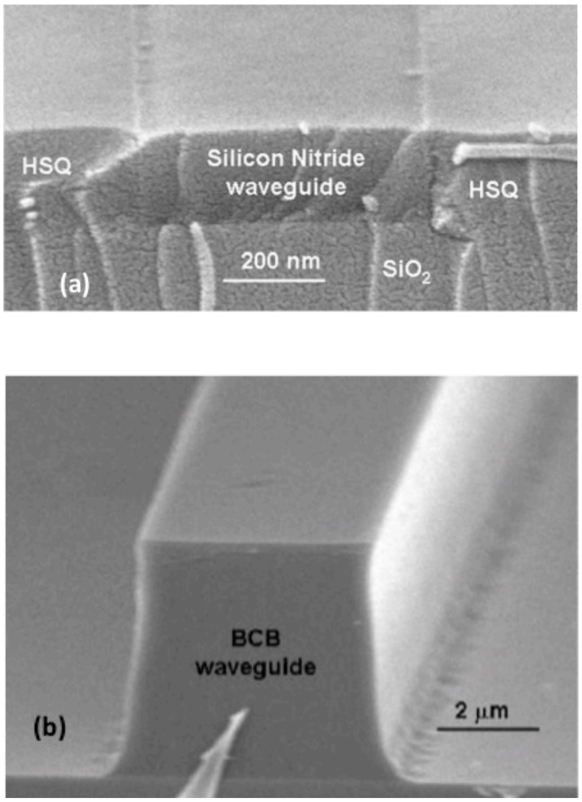

Figure 2: (a) Scanning electron micrograph (SEM) image of silicon nitride waveguide embedded in HSQ. Silicon nitride waveguide and taper structure is fabricated using electron beam lithography with PMMA (b) SEM image of a BCB waveguide fabricated using an oxide hard-mask and a 33% CF_4 plasma reactive ion etch.

4 MEASUREMENT RESULTS

Coupling loss of a good coupler is small, which makes it challenging to be measured accurately. One problem is that the experiment measures total coupling loss, which includes, apart from coupling loss, also waveguide losses, losses in the fibers and when applicable, losses at the air-waveguide interface. To find the coupling loss, one needs to subtract all these losses from the total loss. This approach can yield poor accuracy when two large magnitudes are subtracted to find a small magnitude. Another problem with accurate loss measurement comes from variations of end facet quality due to imperfect cleaving.

To impove the accuracy of coupling loss measurements, several test structures has been fabricated. These strucures contain varying numbers of concatenated tapers and are otherwise identical. To find the mode conversion loss, the difference in loss between the structures is found and divided by the difference in the number of tapers.

Fig. 3(a) shows the measured output powers as a function of wavelength for structures with 8 and 14 tapers. The difference between these powers corresponds to a loss of about 2 dB per taper (see Fig. 3(b)). This number includes not only the mode conversion loss but also the propagation loss in the SiN_x waveguide. This loss turned out to be higher than anticipated and was independently measured to be about 40 dB/cm by looking at the Q-factors of weakly coupled ring resonators. When waveguide losses are taken out, the mode-conversion loss becomes about 0.7 dB. Note that this method of loss measurement does not include the loss due to fiber-waveguide mode mismatch, which was calculated to be about 0.3 dB. It is assumed that there is no air gap between the fiber and the input facet of the coupler, which should be the case for a properly packaged chip. Therefore, the total coupling loss of the fabricated coupler is estimated to be 1.0 dB (0.7dB measured mode conversion loss plus 0.3dB calculated mode mismatch loss).

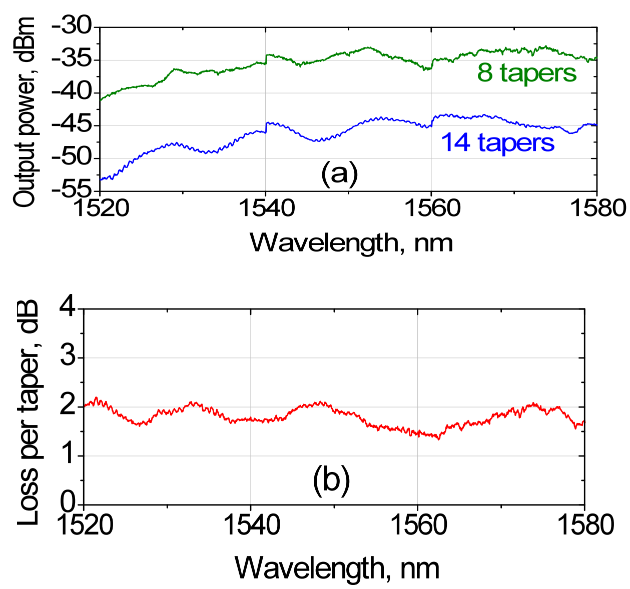

Figure 3: (a) Measured optical spectra at the output of test structures with 8 and 14 concatenated inverse tapers; (b) loss per taper, including waveguide propagation loss.

The transmission of the tapers as a function of wavelength exhibit some oscillations, as it can be seen from Fig. 3(a). These oscillations can be attributed to multi-mode effects happening in the structure. Specifically, sidewall roughness of polymer waveguide leads to wavelength-dependent energy exchange between the fundamental and

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higher-order modes during propagation along the polymer waveguides. Only the fundamental mode gets coupled into the SiN waveguide and the power in all higher-order modes is lost. The coupling efficiency therefore becomes a function of wavelength, as can be seen in Fig. 3. More severe oscillations were observed in structures where light propagates over longer sections of the polymer waveguide. Therefore, although the multi-mode approach worked reasonably well for our coupler (see Fig. 3), care must be taken to minimize roughness of polymer waveguides, and to avoid light propagation in multi-mode polymer waveguides over long distances.

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