Silicon Nitride Waveguides and Spot Size Converters with < 1.76 dB Loss Over Broad Wavelength Range from 1010 nm to 1110 nm for OCT Applications

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ABSTRACT

In this work the first spot size converters for edge coupling into the silicon nitride waveguide platform with coupling loss lower than 1.76 dB in the wavelength range from 1010 nm to 1110 nm are presented. The spot size converters consist of a SU-8 waveguide matching the mode field diameter of a single mode fiber. High quality end facets of SU-8 are prepared by carefully dicing through the SU-8 waveguides without edge polishing. The SU-8 waveguide mode is converted to the Si_3N_4 waveguide mode by an inverse taper. The Si_3N_4 taper tips are narrower than 200 nm, which is required to avoid reflections. They are fabricated using cost efficient i-line projection lithography with a nominal resolution of 500 nm. The Si_3N_4 waveguide propagation losses are as low as 0.4 dB/cm. Such low loss broadband photonic platform can find use in e.g. retinal optical coherence tomography. The measured coupling loss is comparable to the best available devices for longer wavelengths.

Keywords: silicon nitride, integrated photonics, spot size converters, edge coupling

1. INTRODUCTION

The silicon nitride waveguide platform is especially interesting for applications at visible and near infrared wavelengths such as optical coherence tomography (OCT) [1, 2], which requires broadband low loss photonic integrated circuits (PICs). Grating couplers, which are often used to couple light into PICs, are not well suited for broadband applications as their principle of operation is intrinsically wavelength dependent. The best grating couplers have been shown to reach a 3-dB bandwidth of 76 nm, and required bottom distributed Bragg reflectors, which are challenging and costly to fabricate [3]. A better performance in terms of bandwidth and loss can be achieved using edge coupling, which can also be less technically demanding. The height of Si_3N_4 waveguides is typically lower than 400 nm, meaning that matching the mode field to that of the single mode fibers (SMF) of several microns in diameter requires fabricating complicated 3D structures as spot-size converters. Finally, spot-size converters often make use of inverse tapers with narrow tips in order to avoid reflections. Since the waveguide dimensions are proportional to the wavelength, this is becoming more and more challenging as the wavelength of interest gets shorter and higher resolution lithography is required. Moreover, the optical quality of the facets has to be high, which often makes it necessary to polish the PICs after dicing them into separate chips.

Here, we present first spot size converters for a broad wavelength range from 1010 to 1110 nm, which is especially interesting for OCT applications such as retinal OCT [4]. Thanks to the use of SU-8 for matching to the SMF modes, our devices are efficient and straightforward in fabrication. Furthermore, we achieve sub-200 nm tip widths of Si_3N4 inverse tapers exclusively using i-line stepper lithography, which makes our devices low loss and cost-effective at the same time.

2. DESIGN

The spot size converters consist of SU-8 waveguides, which efficiently couple light from an SMF (mode field diameter of 6.5 µm), and a taper section converting the large SU-8 mode to the much smaller Si_3N_4 waveguide mode (Figure 1a). To maximize the efficiency of light coupling to the SU-8 its core dimensions are set to 7 µm × 7 µm, which matches well the mode of the SMF. The Si_3N_4 waveguide is 200 nm high and 700 nm wide and supports a single TE mode in the wavelength range of interest from 1010 nm to 1110 nm. The tip of the inverse Si_3N_4 taper is narrower than 200 nm in order to avoid reflections and maximize the converters efficiency. Since the refractive index contrast of Si_3N_4 ($n = 2$) and SU-8 ($n = 1.56$) is relatively low the taper has to be long to efficiently convert the modes. If only the Si_3N_4 waveguide is tapered the maximum conversion efficiency reaches only 83 % even for tapers as long as 3.5 mm. In order to improve the conversion efficiency, the SU-8 is also tapered, enhancing efficiency to 85 % with a shorter taper of 2 mm (Figure 1b). Elongating the taper further results in a less significant increase of efficiency. Reaching lossless conversion would require at least a 4 mm long taper, which is impractical for the PIC design. Therefore, 2 mm was chosen as a tradeoff for the final devices.

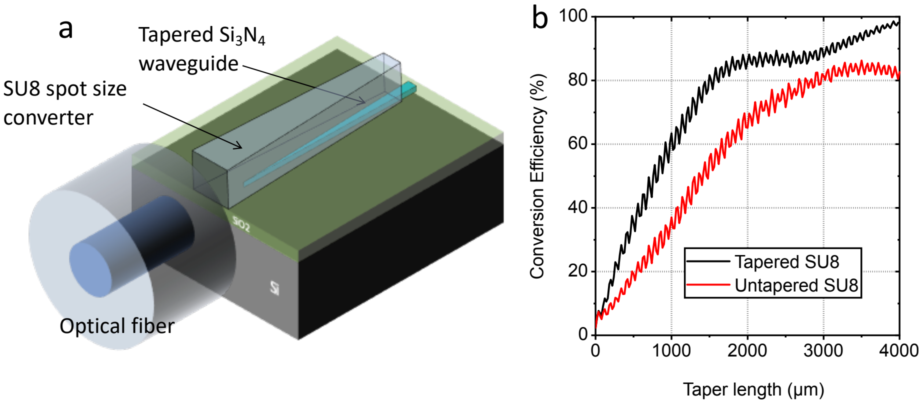

Figure 1 a) A schematic of the SU-8 spot size converter b) Simulated mode conversion efficiency from the SU-8 spot size converter to the Si_3N_4 waveguide vs the Si_3N_4 taper length for tapered SU-8 (black) and untapered SU-8 (red).

3. FABRICATION

PICs have been fabricated on 6" silicon substrates with 2.3 µm of thermally grown SiO_2. Then, 200 nm of Si_3N_4 has been deposited by low-pressure chemical vapor deposition (LPCVD) and the waveguides have been patterned using projection lithography (Canon FPA 3000 i5r i-line Stepper with 0.5 µm resolution) and dry etching. Si_3N_4 taper tips narrower than 200 nm have thus been obtained. Next, 1 µm of LTO cladding (low temperature oxide) has been deposited in an LPCVD furnace. In order to achieve a direct contact of SU-8 with Si_3N_4, cavities have been etched into the SiO_2 cladding using exactly the same layout as that of the SU-8 tapered waveguides. A combination of wet and dry etching lead to Si_3N_4 waveguides that were completely uncovered without damaging the Si_3N_4 surface (Figure 2a). Next, SU-8 waveguides have been fabricated from a 7 µm thick layer of SU-8 by i-line stepper lithography. This has been followed by dicing the wafers into individual chips. During this step, the SU-8 waveguides were also cut to reveal the facets of the spot size converters (Figure 2b). As the surface of the SU-8 facet was smooth directly after dicing, no extra polishing step was required.

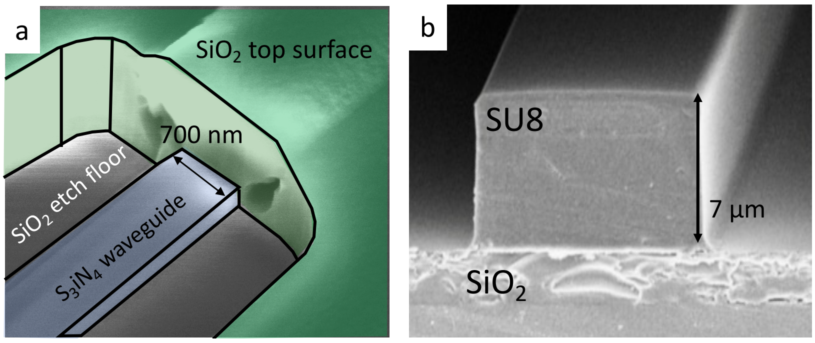

Figure 2 a) SEM micrograph taken at a 35-degree angle of a cavity in SiO_2 etched to uncover the Si_3N_4 waveguide before SU-8 deposition. b) Diced SU-8 facet of a finished spot size converter.

4. CHARACTERIZATION

The spot size converters and waveguides have been characterized with a continuously tunable laser (Toptica CTL) with a wavelength tuning range from $\lambda = 1010$ nm to 1110 nm and a Newport 1918-IR power meter. Two cleaved single mode polarization maintaining SMF fibers (OptoSigma PM980) have been aligned with the spot size converters using X-Y-Z manual stages. In addition, an index matching liquid (Norland) has been used to reduce reflections from the end facets of both fibers and the SU-8 waveguides. Waveguide propagation and coupling losses have been measured using the cutback method [5] (Figure 3a). The slope of the linear fit of the transmission loss versus the Si_3N_4 waveguide length indicates the waveguide propagation loss, while the intercept with the Y-axis indicates the combined coupling loss of input and output spot size converters. A propagation loss of only 0.3 - 0.4 dB/cm was observed. The measured coupling losses were lowest at λ = 1010 nm with a value of only 1.42 dB per coupler and were lower than 1.76 dB over the entire wavelength range, which is marked with a straight red line in Fig. 3b. The transmission spectrum of a spot size converter with 2 mm long taper shows oscillations with a free spectral range of approximately 6 nm and an amplitude of 0.5 dB (Figure 3b). In order to identify the source of these oscillations, spot-size converters with various lengths have been measured. They show a clear dependency of the free spectral range on the taper length. This indicates that the mode conversion is incomplete and that reflections from the end of the SU-8 taper are causing the oscillations. This indicates that losses can be further reduced by optimizing the design of the taper section of the device.

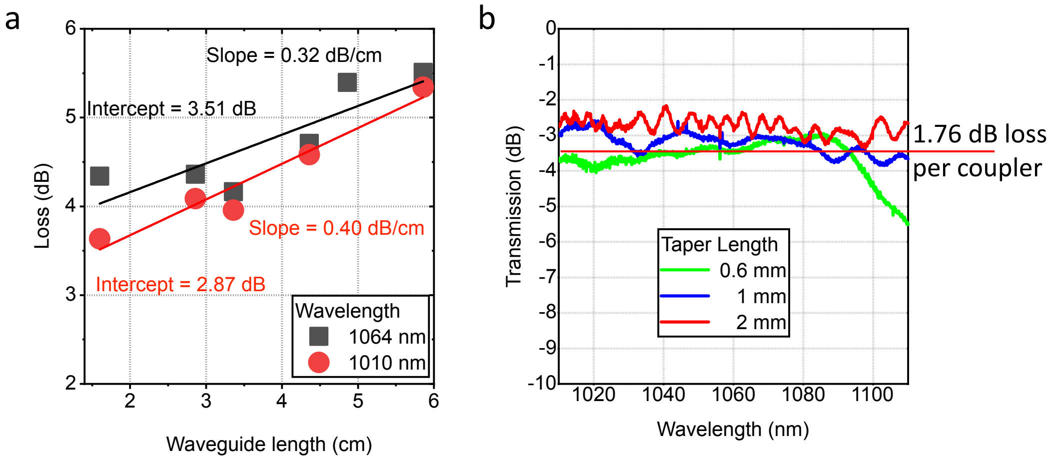

Figure 3 a) Coupling loss and waveguide propagation loss measured by the cutback method. b) Transmission spectra through a pair of spot size converters. The waveguide loss of 0.175 dB of 5.5 mm long Si_3N_4 waveguide has been subtracted and the curves depict only the combined loss of input and output spot size converters.

5. CONCLUSIONS

The presented spot size converters are the first devices of this kind for the wavelength range from λ = 1010 to 1110 nm. Their coupling loss of 1.76 dB is comparable with the best devices available for longer wavelengths (1.5 dB [6]). SU-8 has several advantages over inorganic materials: high quality facets obtained with simple dicing, ease of fabrication and the possibility of further improvements by utilizing multilayer SU-8 structures. All devices were fabricated exclusively using a conventional i-line stepper with a relatively low resolution of 500 nm, which eliminates the need for expensive deep UV or electron beam lithography. Hence, our broad band spot size converters complement the low loss silicon nitride waveguide platform, making it extremely useful for applications such as OCT or on chip spectroscopy.

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