Length optimization of planar waveguide taper

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Tapered structures have been widely used in integrated optics in applications such as mode converters and adiabatic couplers. Tapers with short lengths are significantly beneficial to photonic integration. A length optimization methodology of planar waveguide tapers by replacing a linear taper with an arbitrary optimized curvilinear shape was studied. Both types of tapers, linear and optimized, were fabricated using SU-8 as core material on a glass substrate. We experimentally demonstrate the feasibility of the optimization approach by comparing the losses of the optimized tapers with the corresponding linear tapers.

Introduction

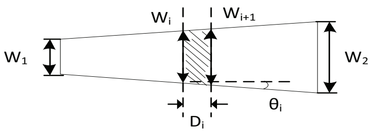
With the recent developments in large scale optical interconnects, waveguide tapers are extensively utilized to realize efficient coupling between different optical sections on silicon-on-insulator (SOI) platforms. Photonic wire waveguides fabricated on SOI exhibit high refractive index contrast and low loss figures for light transmission [1]. However, fiber-to-chip and chip-to-chip coupling might have high losses due to the high refractive index contrast, low tolerance to misalignment and mode beating. Adiabatic waveguide tapers can overcome these issues [2]. Nevertheless, the long length of adiabatic tapers challenges those designs with severe size constraints. Different techniques have been proposed to optimize the length of adiabatic tapers, ranging from multi-sections tapers [3], to approaches based on numerical analysis [4]. They either lack quantitative analysis of each section or are too complicated to be implemented efficiently. In this paper, we present a novel methodology of length optimization based on mode overlap calculations and demonstrate its validity in preliminary experiments.

Methodology

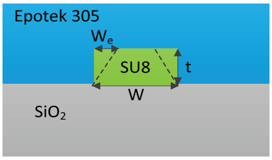
The detailed theory of the methodology was introduced in [5]. The taper region is divided uniformly in a sufficiently large number of sections *N*. The objective of the proposed approach is to calculate the maximum angle for each taper section that will keep the propagation loss below a certain required value. Assuming that the taper is composed of many sections [Fig. 1 (a)], its total propagation loss L can also be estimated using mode overlap ($O_{i,i+1}$) when the changes on the cross section are small enough. The maximum tapering angle can be derived as:

$$\theta_{i,max} = arctan\left(\frac{l|W_1 - W_2|}{-20\, log_{10}(O_{i,i+1})\, N}\right) \tag{1}$$

where W_1 and W_2 are the widths at the beginning and at the end of the whole taper, $\theta_{i,max}$ is maximum taper angle of the i-th section that keeps the propagation losses induced by the taper below the desired value l, N is the number of taper sections, and l is the maximum acceptable propagation loss in the taper region in dB per unit length.



(a)



(b)

Fig 1: (a) Top view of linear taper; (b) Cross section profile. The green rectangle was the intended shape while the dotted lines show the actual shape of the experimental waveguides.

In the proposed methodology, the widths of the two sides of each section are kept fixed. Its length (D_i) can be calculated by simple geometrical relations when the tapering angle for that section is set to the maximum allowed value $\theta_{i,max}$. Therefore, the optimization of each section leads to a substantial length reduction of the whole taper structure.

Device design

The negative tone epoxy SU-8 has a good transmission (>95%) above a wavelength of 400 nm, especially at the visible wavelength of 632.8 nm, and telecommunication bands such as original band (O-band) and conventional band (C-band). Therefore, SU-8 2000.5 was selected as the material of waveguide core for the experimental demonstration of the taper length optimization. The waveguide core cross section is shown in Fig. 1 (b). The refractive indices of SU-8 2000.5 measured using Metricon 2010 prism coupler system are 1.575 ± 0.001 and 1.573 ± 0.001 at the wavelengths of 1.3 µm and 1.55 µm, respectively. To achieve single mode operation for telecommunication wavelengths propagating inside the SU-8 waveguide, optical epoxy Epotek-305 is utilized as top cladding material to reduce the refractive index contrast between the core and cladding. Epotek-305 has refractive indices of 1.498±0.002 at both wavelengths of 1.3 µm and 1.55 µm.

The total propagation loss of the taper region is a combination of the propagation loss due to the absorption of the core material and the propagation loss introduced by the taper, l. In the methodology of the present work, l can be selected by the designer depending on the requirements of a particular application. The polymer materials utilized here, SU-8 and Epotek-305, are reported to have a propagation loss due to absorption ranging from 0.08 to 1.5 *dB/cm* at wavelengths in the range between 0.63 to 1.55 µm [6]. In this design, $l = 0.1\ dB/cm$ was selected to ensure that the losses introduced by the taper are negligible. Furthermore, the number of sections in which the taper section is divided into, N, was determined by convergence test. Following a similar approach to the one proposed for Si_3N_4 waveguide tapers in [5], $N = 50$ is set for SU-8 waveguide tapers in this study.

The target waveguide taper was designed for the wavelength of 1 55 µm. Fig 2 illustrates the maximum angles calculated for all 50 sections of the waveguide taper with $W_1 = 1.6\ \mu m$ and $W_2 = 4.8\ \mu m$. The less confined mode at the beginning of the taper (i.e., close to the W_1 end) requires smaller angles to obtain propagation with loss below the pre-determined threshold, l. Thus, the lengths of the sections at that taper end are longer. Nevertheless, the whole taper length, which integrates the length of each section, still presents a significant reduction. For example, the linear taper with a taper angle of 0.1° has a length of 917 µm while the taper optimized by this approach is only about 170 µm long.

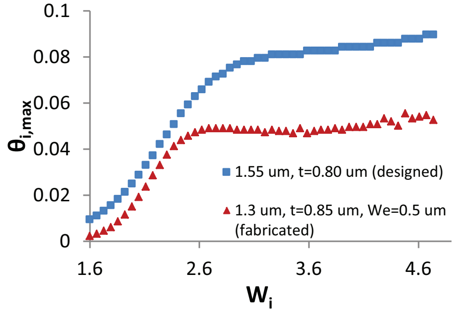


Fig 2: The maximum tapering angle calculated at the wavelength of 1.3 µm (red) and 1.55 µm (blue).

Fabrication and characterization

The steps of fabrication process of SU-8 waveguide taper are as follows: wafer cleaning, dehydration bake, spin coating of SU8-2000.5 film (750 rpm), soft bake, ultraviolet (UV) lithography, post-exposure bake and development. After the development, Epotek-305 is applied on the top of the waveguides as cladding. The whole chip is cured at 65 °C for 2 hours. Thickness of the core measured by Dektak 8 surface profiler is about 50 nm higher than the designed one (eg., 0.85 instead of 0.8 µm). Furthermore, the scanning electron microscope (SEM) image in Fig 3 shows the profile of the SU-8 cross section, which is etched with a width (W_e) of 0.5 µm [see also Fig. 1 (b)]. The fabricated etched width results in the cut-off of the 1.55 µm wavelength. The maximum tapering angles of all sections were calculated for the fabricated cross section for 1.3 µm wavelength. The result is shown by the red triangles in Fig 2. The trend is close to the one at the wavelength of 1.55 µm but the value of $\theta_{i,max}$ is smaller. Therefore, it is expected that the fabricated tapers will exhibit higher losses at the wavelength of 1.3 µm.

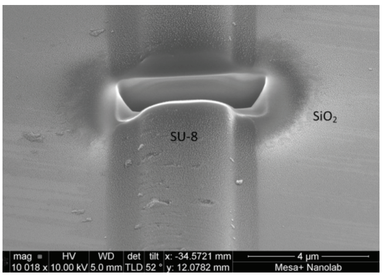


Fig 3: SEM image of the cross section profile.

Figure 4 (a) shows that the calculated losses at 1.3 µm wavelength for both linear and optimized tapers at different values of W_e simulated using 3D beam propagation method (BPM) are very small for small W_e. At $W_e = 0.5\,\mu m$ (i.e., result of our first round of fabricated devices) the linear taper has 0.30 dB while the optimized one has 0.45 dB. The measured losses, Fig. 4 (b), are 0.25 dB for the linear taper and 0.6 dB for the optimized taper, respectively. Although the expected errors are quite large due to the limited dataset and variations on the quality of the end facets, the measurements seem to be in good agreement with the simulations at the wavelength of 1.3 µm. It is important to remark that, even for a perfect cross section (i.e., $W_e = 0$), the losses of the optimized taper are larger than for the linear taper. This is due to the fact that the current taper shape was optimized for 1.55 µm wavelength. Work is currently underway towards the improvement of the fabrication process that will permit demonstrating the taper design at 1.55 µm wavelength.

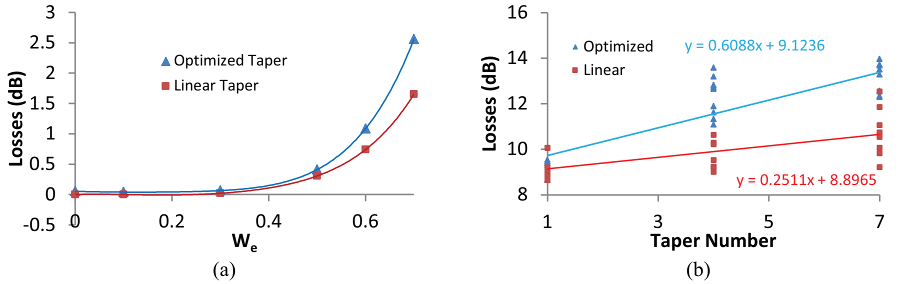


Fig 4: (a) Simulated taper losses as a function of etched width W_e, and (b) measured total losses as a function of number of tapers. The slope of the linear fits represents the total losses per taper. Both simulation and measurement were realized at the wavelength of 1.3 µm wavelength.

Conclusion

A methodology for optimizing the length of waveguide tapers based on mode overlap calculations is presented. Preliminary measurements on structures with non-ideal cross section and at 1.3 µm wavelength agree well with the values expected from simulations: the linear taper with a length of 917 µm has a loss of 0.25 dB whereas the optimized taper with a length of 170 µm has a loss of 0.6 dB. The good match between simulation and preliminary experimental results indicates that the approach works.

Acknowledgements

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