Design and performance optimization of waveguide tapers for fiber to chip coupling

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A methodology for optimizing the length of an adiabatic waveguide taper with a given loss performance target is proposed. The method builds a non-linear taper and replace the linear one based on mode overlap calculations, which is verified by 3D-BPM simulations. It is applied to design a 110 nm thick Si_3N_4/SiO_2 taper with a starting width of 2.5 μm and an ending width of 0.6 μm. The length of the optimized taper is 65% shorter than the linear one but still achieves a similar transmission (94%). Furthermore, the tolerance of the design has been studied.

Introduction

The design of waveguide tapers has great importance in research because they are crucial means to achieve a high coupling efficiency between two waveguides [1]. Adiabatic waveguide tapers have low loss themselves because of their slowly geometric variation along the propagation direction, and can achieve this target. The compactness of the tapers is significant in order to achieve high-density integration and reduce fabrication costs. However, the long length of adiabatic tapers limits the achievement of these targets. Different techniques for optimizing adiabatic tapers have been already proposed in the literature [2,3]. In this paper, we present a methodology to build nonlinear tapers on small footprint that operates adiabatically and achieve a coupling efficiency as high as linear adiabatic tapers.

Theory and design

The target of our methodology is to reduce the length of the taper and keep the adiabatic condition with overall low loss. To reach our target we replaced the linear structure with a nonlinear one. Comparing our structure to broadly used linear structures we can much better reduce the used area, saving space and achieving high density integration. The taper structure allows us to change the shape of the optical mode aiming high coupling efficiency between waveguides with different cross sections. We want to keep adiabatic condition: this means that the taper angle is small enough to guarantee that there is a negligible loss of power from the fundamental mode as it propagates along the length of the tapering structure.

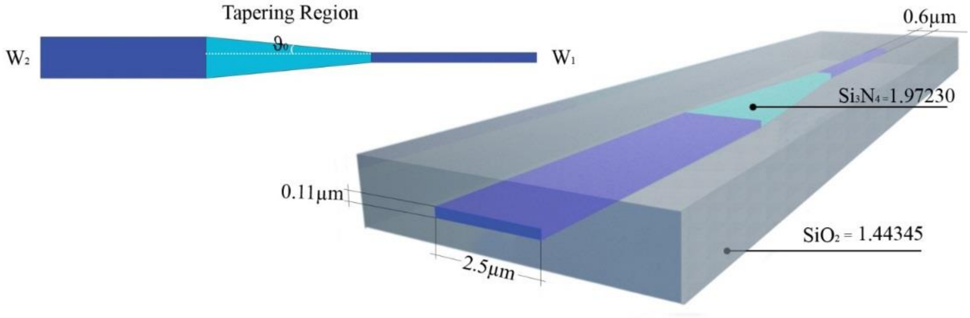

Fig. 1: Top view and 3D representation of the linear structure.

Figure 1 describes the top view of a linear taper, Si_3N_4 buried in SiO_2, and a three dimensional drawing of the structure. The working wavelength is 1.55 µm while the refractive indices are N_{SiO_2}=1.44345 and $N_{Si_3N_4}$= 1.97230. The thickness of silicon nitride is 110 nm.
The taper links a thick and a thin waveguide, each one 10 µm long. In this case talking about mode overlap we mean the power transferred between the two waveguides. So after building the cross section, with Film Mode Matching (FMM) solver method the mode overlap values were calculated [6].

Optimization procedures

First of all, we built a 3D linear structure and then performed a convergence test simulating the increased lengths using the 3D-BPM [5] simulations. This is a semi-vectorial beam propagation method, more accurate than 2D simulations but with the disadvantage of being really time consuming. In this way it was possible to choose a value of proposed length (PrL) where the transmission converges and adiabaticity (>92%) is satisfied, more precisely high transmission and the difference between two near measurements is less than a fixed (1%) threshold. The adiabatic angle is then determined as:

$$\theta_0 = \left[\frac{(|W_2 - W_1|)/2}{ProposedL}\right]$$

To build the optimized structure of the linear adiabatic taper with small tapering angle, we first calculated the mode overlap between section i and $i+1$ ($O_{i,i+1}$) by the FMM simulations. The tapering angle has a relation of the section number N and $O_{i,i+1}$ [4]:

$$\theta_i \propto \arctan\left[\frac{|W_2 - W_1|}{-20log10(\mathrm{O_{i,i+1}}) \cdot N}\right]$$

We used W_2= 2.5 µm and W_1 = 0.6 µm as the input and output widths of our tapering region. In order to figure out the changing trend of tapering angle at different regions along the propagation direction, we normalized the angle to its maximum value, i.e. $\theta_{i,norm} = \theta_i/\theta_{i,max}$.
Next step is to numerically fit a function $f(W)$ for $\theta_{i,norm}$ regarding to the width W. The $\theta_{i,norm}$ shows how sensitive is the i-th section. The more sensitive is the section , the smaller θ_i should be used.The optimized taper angle $\theta_{i,optimized}$ is calculated based on th enormalized function $f(W)$.

$$\theta_{i,optimized} = a \cdot f(w) + \theta_0$$

Varying the coefficient a it is possible to find $\theta_{i,optimized}$, and the length of each slice D_i. Adding all lengths of the sections the total length L of the optimized taper can be obtained.
The selection of the parameter is done at some point of the inflection of the L versus a curve.

$$D_i = \frac{\Delta W/2}{\tan(\theta_{i,real})}, L = \sum_{i=1}^{N} D_i$$

To build the optimized taper structure for a fixed a we took the corresponding values of D_i and created an array decreasing $\Delta W = (|W_2 - W_1|)/N$ at each step to update the width.

Results

After the convergence test with 1% as a fixed threshold value, we chose 900 μm as proposed length because for that specific value the transmission was above 94%, so our adiabaticity condition was satisfied Figure [2(a)]. The corresponding adiabatic angle is $\theta_0 = 0.0604789°$.

Figure [2(b)] shows the results for the optimized nonlinear taper structure from the 3D-BPM simulations. The optimized taper is only 320 μm long with a similar transmission efficiency as the linear taper which is around 94%.The optimized structure built with our method saves more than 65% in length. Furthermore, a comparison between transmission curves built with different proposed lengths is shown in Figure [2(c)]. The curves all converge to the one we chose as reference (ie. $PrL = 900$ μm).

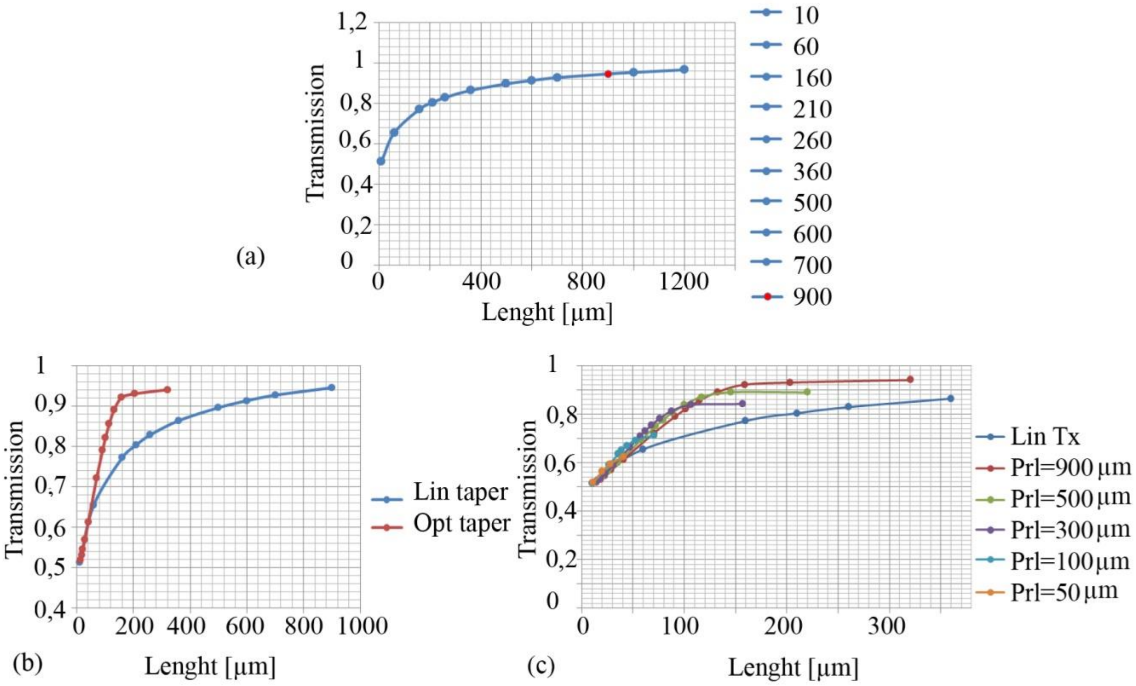

Fig 2: (a) Convergence test for linear taper in case of 2.5 μm to 0.6 μm widths; (b) Comparison of transmission values between optimized and linear structure; (c) Comparison of transmission values between several proposed lengths.

Some tolerance tests for the designed and for the linear structure have been done varying thickness (± 10 nm) and widths (± 0.2 μm). For widths from 2.3 μm to 0.4 μm there is no mode because we are under cut off frequency at the tip of 0.4 μm. Both structures respond with the same trend to the variation of the width and thickness.

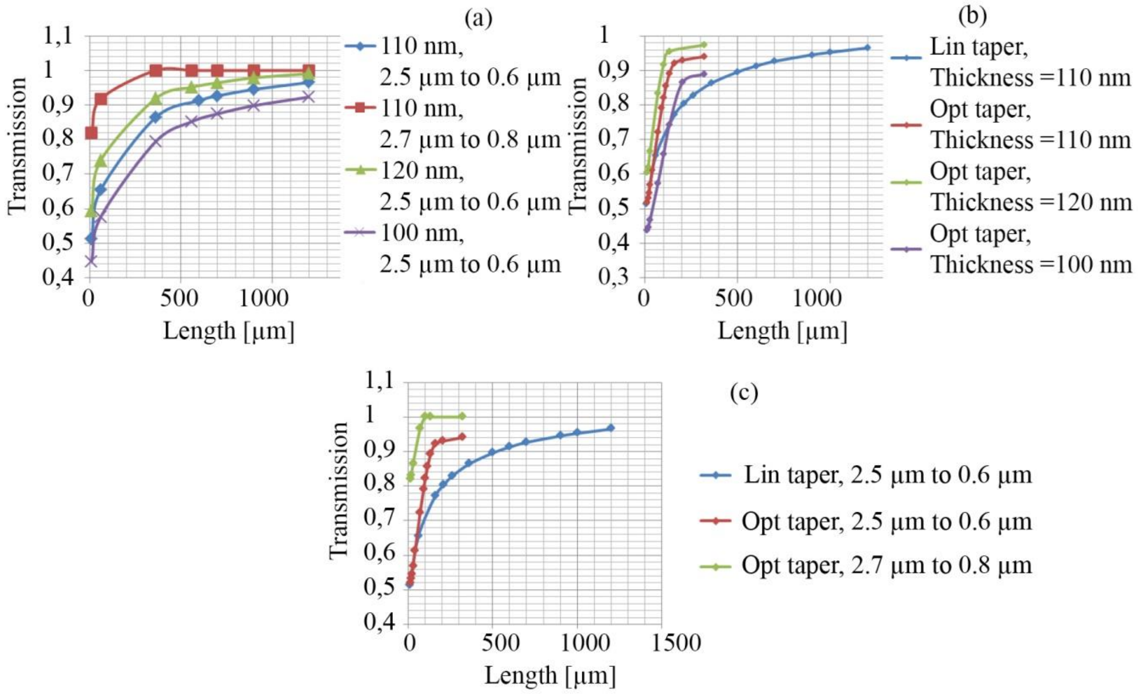

Fig 3: (a) Linear taper, tolerance tests; (b) Optimized Taper with proposed length= 900 µm: tolerance tests for thickness (± 10 nm); (c) Optimized taper with proposed length= 900 µm: tolerance tests for widths;

Conclusions

We present a numerical method for optimizing the length of adiabatic tapers. The tapering angle of different region along the propagation direction is optimized based on the mode overlap calculations using FMM method. The optimized tapers are verified by 3D-BPM simulations and with a comparison of the corresponding linear taper. This method is applied to design an optimized 110 nm thick Si_3N_4 taper with starting width of 2.5 µm and ending width of 0.6 µm. The optimized taper has about 65% shorter in the length than the linear ones while stay the same coupling efficiency (94%).

References

[1] A. R. Nelson, “Coupling optical waveguides by tapers,” Appl.Opt. 14, 3012–3015 (1975).

[2] Y.Fu, T.Ye, W.Tang, T.Chu “Efficient adiabatic silicon-on-insulator waveguide taper”, Photon. Res. 2 No.3, A41 (2014)

[3] C. Lee, M.-L. Wu, *et. al.*, "Design and analysis of completely adiabatic tapered waveguides by conformal mapping", J. Lightwave Technol. 15, 403-410 (1997).

[4] J. Mu, M. A. Sefunc, S. M. Garcia-Blanco, “Design and length optimization of an adiabatic coupler for on-chip vertical integration of rare-earth-doped double tungstate waveguide amplifiers”, in Transparent Optical Networks, 2014 16th International Conference on (2014).

[5] J. VanRoey, J. van derDonk, and P. E. Lagasse, "Beam-propagation method: analysis and assessment", J. Opt. Soc. Am. A **71,** 803-810 (1981).

[6] A. S. Sudbo, "Film mode matching: a versatile numerical method for vector mode field calculations in dielectric waveguides", Pure Appl. Opt. 2, 211-233 (1993).