Low-loss inverted taper edge coupler in silicon nitride

(Student paper)

Juan Fernández[1,2], Rocío Baños[1], David Doménech[1],
Carlos Domínguez[3] and Pascual Muñoz[2]

[1] *VLC Photonics S.L, c/ Camino de Vera s/n – 46022, Valencia – Spain – david.domenech@vlcphotonics.com*
[2] Universitat Politènica de València, c/ Camino de Vera s/n – 46022, Valencia – Spain – pascual.munoz@upv.es
[3] *Instituto de Microelectrónica de Barcelona (IMB-CNM), CSIC – Bellaterra 08193 - Spain*

ABSTRACT

An inverted lateral taper with one vertical discrete step was designed for a medium confinement silicon nitride waveguide platform in the C-band, as chip edge coupler, with predicted insertion loss of 0.58 dB. The design is supported by an extensive study to evaluate the impact of fabrication process variations in the performance of such coupler. The device was manufactured and measured, showing an insertion loss of 1.47 dB, which was traced back to fabrication process variations as cross-checked with simulations. To our knowledge, the reported edge coupler is the shortest and among the best performing found for silicon nitride platforms.

Keywords: Silicon nitride, photonic integrated circuits, fiber coupling, inverted taper

1. INTRODUCTION

Silicon Nitride based integration platforms are subject of attention due to the wide wavelength range over which the material is transparent (400-2400 nm) and inherently low-loss [1]. This waveguide technology is based on a combination of silicon nitride as waveguide layers, filled by and encapsulated with silica (SiO_2) as cladding layers grown on a silicon wafer. SiO_2 and Si_3N_4 layers are fabricated with CMOS-compatible industrial standard chemical vapour deposition (both low pressure, LPCVD, and plasma enhanced, PECVD) techniques, that enable cost-effective volume production [2]. Edge coupling to the chips can make use of spot-size converters (SSC) [3]-[4]. Inversely tapered waveguides, either lateral, vertical and combined (3D) [5], waveguides are one type of SSC providing some advantages: simple design, easy fabrication, broad transmission bandwidth, and high coupling efficiency. Silicon nitride SSCs have been previously reported, with 3.3 dB insertion loss, 500 µm length and tip height 100 nm [6] and others with 0.65 dB losses, length of 800 µm [7] 150 nm tip width, and 700 nm tip height. Other papers quote 0.5 dB loss for film heights of 100 nm [8]. In this paper, we report on the design and characterization of an inverted taper with 1.5 dB insertion loss and 150 µm length for a silicon nitride platform with guiding film height of 300 nm and taper tip height of 150 nm.

2. DEVICE DESIGN

The edge coupler proposed makes use of the already existing lithographic steps in our previously developed Si_3N_4 generic integration platforms [2]. That is, it does not resort to specialized additional process steps such as wet etching or more complex lithography approaches as the use of a shadow mask, but it rather markers the use of the different nitride etching levels of our platform. The mode transformer design is made up of two height levels of an adiabatic inverse lateral taper structure in silicon nitride shown in Fig.1.

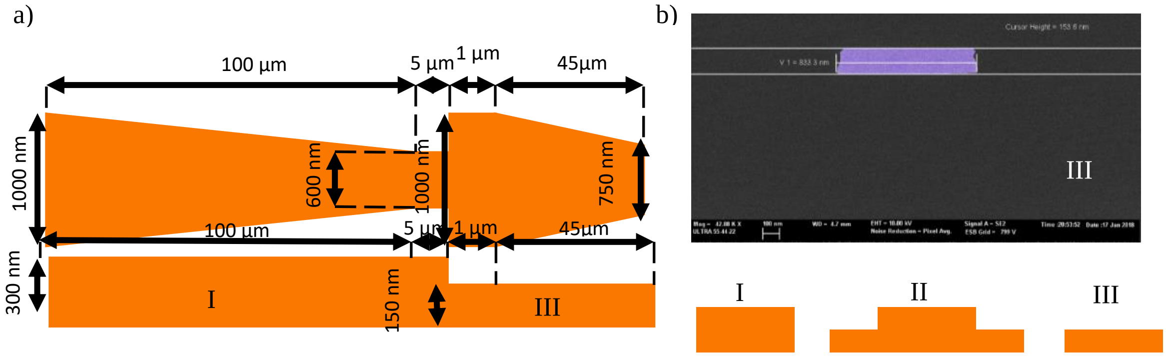

Figure 1. a) Top and side view of the inverted taper, b) platform waveguide cross-sections, I deep, II shallow and III mini-deep and SEM micrograph (in pseudo-color) of the facet tip for one of the measured inverted tapers (tip widths in 0.8-0.9 µm).

The designed device was fabricated in a Silicon Nitride photonics platform compatible with a standard CMOS pilot line Three different waveguide structures are defined by photo-lithography with a I-line stepper (minimum feature 600 nm) followed by a reactive ion etching (RIE) of the silicon nitride film. The 300 nm silicon nitride layer may be etched: completely to form a strip waveguide structure (deep), partially avoiding core obtaining a rib waveguide structure (shallow) or partially in the core and completely in the sides to form a strip waveguide of 150 nm thickness (mini-deep). To obtain the insertion loss of the device, the overlap integral [9] between different widths of the three possible cross-sections and a 2.5 µm Mode Field Diameter (MFD) that it is typical of lensed fiber has been performed. Firstly, the mini-deep waveguide is the best cross-section to couple power to 2.5 µm MFD as compare with deep or shallow cross-section. There is a local minimum for the power loss of 0.35 dB with a waveguide width of 750 nm. Secondly, to obtain a deep cross-section output of inverted taper, an overlap integral between deep cross-section and mini-deep cross-section must be studied.

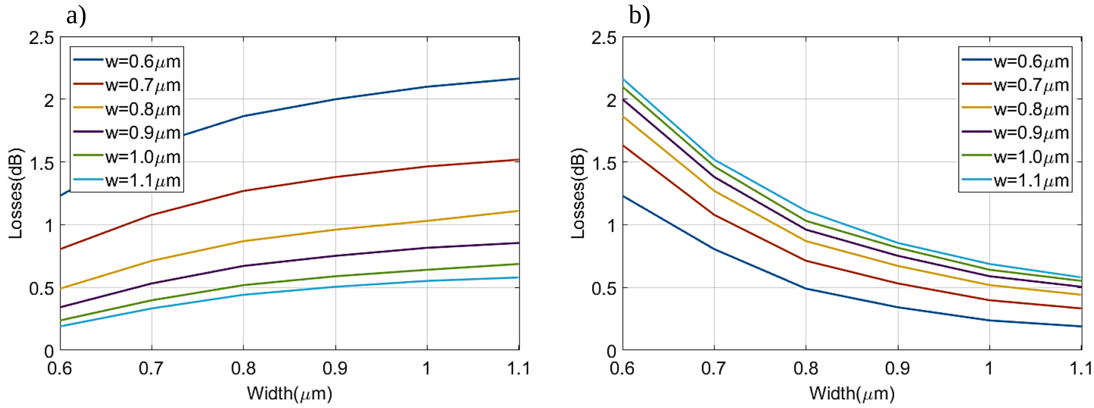

Figure 2. Overlap between deep waveguide and mini-deep waveguide. a) different deep widths vs mini-deep widths, b) different mini-deep widths vs deep widths.

As shown Fig. 2 a), the loss is reduced when the deep waveguide width is decreased and the mini-deep waveguide is decreased. From the graphs, the optimum point is for widths of 1 µm and 0.6 µm for the deep and mini-deep cross-sections respectively. These values ensure single mode operation as well. To optimize the excess loss of the overall device, the tapering losses must be minimized as well. Next, the beam propagation method (BPM) from the FIMMWAVE software package is employed to obtain the taper response and losses.

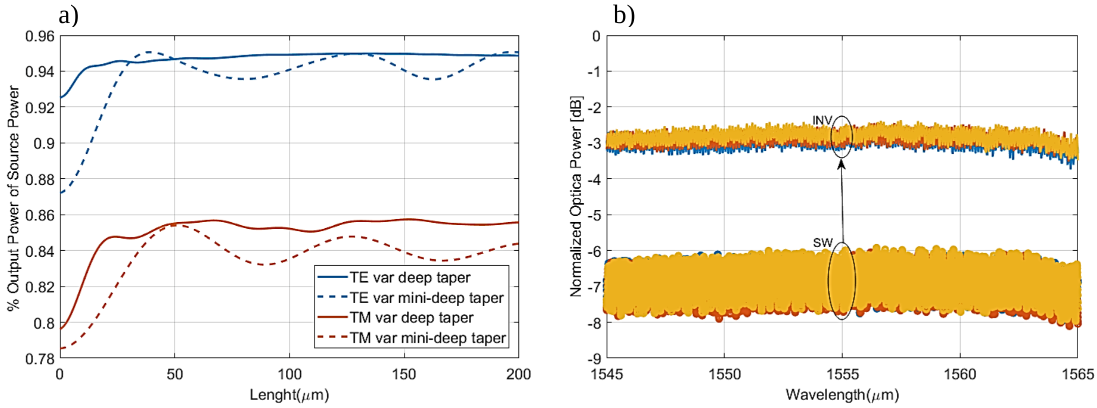

Figure 3. a) Total output power for different taper lengths for mini-deep and for deep cross-sections. b) fiber to fiber TE transmission measurements for test structures with (INV) and without (SW) inverted tapers.

The results are shown in Fig. 3 a), where shows the total power coupled, for different lengths of the first taper in the mini-deep cross-section, for fixed length (100 µm) of the deep cross-section taper. Complementary, Fig. 3 b) shows the results for fixed length (50 µm) of the mini-deep taper, and lengths of the deep section taper. From the graphs, Fig. 3 a) shows how the power coupling oscillates with the mini-deep taper length. At 45 µm taper length TE polarization shows a maximum. Thus, the taper lengths chosen according to all the above and to maximize coupled power are: 45 µm length for the mini-deep taper and 100 µm length for the deep taper. With this configuration, the simulation yields 0.23 dB excess losses with a 20 dB suppression of the higher order modes. Design tolerances were thoroughly analysed, but the mask misalignment between process steps was found to be the most relevant. Defining the deep and mini-deep cross-sections in lithography makes use of two different masks that are to be aligned in different steps. To explore the impact of possible misalignments, a straight deep section is introduced in between the two tapers, as shown in Fig. 1. The misalignment can only happen in the longitudinal direction, since the mini-deep is actually done with same deep mask, but without the shallow mask protection.

The mask alignment errors of 1 µm result into approximately 0.4 dB extra losses for the TE. This design was fabricated in a multi-project wafer run (MPW) offered by IMB-CNM [2] within a 5x5 mm^2 chip die. Instead of use DoE (Design of Experiments), only one design with optimum values is used since fabrication variations were expected, as later detailed, and with the aim of correlating experimental results to the design and simulation flow outcomes.

3. EXPERIMENTAL RESULTS

We used and end-fire measurement setup with microscope objectives with MFD 2.5 µm and with polarizers, in order to inject and collect TE polarization. The test structure is composed of two edge couplers, each at one side of the chip, and a straight deep waveguide of 1 µm width between them. To measure the response a ASE broadband source was employed, together with a OSA. All the measurements are normalized to the spectrum acquired without the chip, that is between the microscope objectives face to. All measurements are with the polarizers set to allow TE to go through to/from the microscope objectives. Fiber collimators are employed, so as to allow fiber connections from the ASE source and to the OSA. The results are shown in Fig. 3 b) both for a straight waveguide with two inverted tapers and without them as detailed. The fiber to fiber loss is 3.635 dB when inverted tapers are employed. The measured propagation loss for the 1 µm width deep straight waveguide is 1.41dB/cm [1]. Each edge coupler has 1.47 dB insertion loss for the TE polarization. This is significantly different from the 0.58 dB predicted by simulation (0.35 dB due to overlap and 0.23 dB due to the tapers, i.e. transition loss). The difference is attributed to the following. Firstly, the wafers were stealth diced 25 µm inside the die. Therefore, the mini-deep taper was no longer 45 µm long, but its length was reduced accordingly. Simulations for the new length and result width of 0.9 µm width in the mini-deep result into additional overlap coupling loss of 0.405 dB insertion losses for TE polarization. Furthermore, the new taper length increases the taper loss up to 0.351 dB. Next, the width variations in the lithographic processes are of the order of 100 nm, which in turn result from simulation into an 0.295 dB in total (overlap and transition). Mask and fabrication alignment errors could add 0.4-0.5 dB as mentioned in section D1 due to misalignment between masks that produce overlap losses. In summary, the overall losses in the worst case, including a width error, may reach 1.051 dB for TE, whereas losses due to mask alignment and fabrication may add an extra 0.4-0.5 dB. This could explain the experimental 1.47 dB vs the 0.58 dB predicted in the design stage.

4. CONCLUSION

A lateral inverted taper was designed for a Silicon Nitride platform, with theoretical insertion loss of 0.58. Experimental results yield 1.47 dB loss, and the difference was studied incorporating into the simulation the known manufacturing variations. This structure as edge coupler is the shortest reported in silicon nitride with a length of 150 µm, and among the ones with the lowest insertion loss in the literature.

REFERENCES

[1] P. Muñoz e.a., "*Silicon Nitride Photonic Integration Platforms for Visible, Near-Infrared and Mid-Infrared Applications*," Sensors, 17(9), 2088 (2017).

[2] Silicon nitride technology at IMB-CNM-CSIC. http://www.imb-cnm.csic.es/index.php/en/clean-room/silicon-nitride-technology

[3] T. Shoji e.a., "*Low loss mode size converter from 0.3 µm square Si wire waveguides to single mode fibres*," Electron. Lett. 38, 1669-1670 (2002).

[4] K. Shiraishi e.a., "*A silicon-based spot-size converter between single-mode fibers and Si-wire waveguides using cascaded tapers*," Appl. Phys. Lett. 91, 141120 (2007).

[5] Moerman, I., Van Daele, P. P., & Demeester, P. M. "*A review on fabrication technologies for the monolithic integration of tapers with III-V semiconductor devices*," IEEE Journal of Selected Topics in Quantum Electronics, 3(6), 1308-1320 (1998).

[6] Y. Shani e.a., "*Efficient coupling of a semiconductor laser to an optical fiber by means of a tapered waveguide on silicon,*" Applied physics letters, 55(23), 2389-2391 (1989)

[7] M.T. Doan e.a., "*Spot size mode converter for efficient coupling to SiN waveguides,*" In Proc. Photonics North International Society for Optics and Photonics, pp. 221-228, December 2004.

[8] L. Zhuang e.a., "*Low-loss, high-index-contrast Si_3N_4/SiO_2 optical waveguides for optical delay lines in microwave photonics signal processing*," Opt. Express 19, 23162-23170 (2011)

[9] H. Kobayashi e.a., "*Narrow-beam divergence 1.3- µm multiple-quantum-well laser diodes with monolithically integrated tapered thickness waveguide*," IEEE Journal of Selected Topics in Quantum Electronics, 1998, vol. 3, no 6, p. 1384-1391.