Hybrid Spot Size Converter on Semi-Insulating InP Substrate at 1.55μm Wavelength

M. Nikoufard and R. Taheri

***Abstract*— This article describes the design of a hybrid spot size converter (SSC) on Semi Insulating (SI)-InP substrate, which utilizes two lateral and vertical tapers. It can be monolithically integrated with the active and the passive components such as photodetector, modulator, laser, Arrayed Waveguide Grating (AWG), and Mach-Zehnder Interferometer (MZI). The taper loss and mode-mismatch loss are about 1.8 and 0.8 dB, respectively, for a 1.5 mm long vertical and 0.15 mm long lateral tapers. The shallow input waveguide is with a width of 2 μm and the output waveguide is with a width and a thickness of 10 and 5 μm, respectively, which is suitable for coupling of the light between a standard single mode fiber and an optical chip.**

***Index Terms*— Integrated optic, semi-insulating InP substrate, spot-size converter, vertical and horizontal tapers.**

I. Introduction

THE rapid expansion of internet and data traffic has created a requirement to monolithically integrate the photonic devices to increase the capacity and to reduce the fabrication and packaging costs. The integration of the basic components of optical integrated circuits such as laser, photodetector, phase shifter and modulator is a significant challenge for researchers. Efficient coupling from a standard single-mode fiber (SSMF) into photonic integrated circuits (PICs) is difficult with high losses. The more reliable and the most commonly used way to couple an optical signal from a SSMF into a PIC or vice versa is the butt coupling method. The mode field diameter (MFD) of the InP-based waveguide is much smaller than the MFD of the SSMF mode which creates a high mode mismatch (>10 dB) [1]. Several techniques have been utilized to couple the light from the optical fibers to the optical chips. Using a tapered-fiber or a microlense increases the packaging cost and depends on the matching tolerance. Spot size converters (SSCs) change the MFD of a standard optical fiber (10 μm × 10 μm) to a very low MFD of the optical integrated chips [2].

Galarza [3] reported a SSC by using the anti-resonant reflecting optical waveguide (ARROW) concept for both the lateral and vertical optical confinement which is monolithically integrated with a quantum-well (QW) laser on highly-doped n-InP substrate. The thickness of total epitaxial layers between the QW active layers and substrate is about 6 μm including (from up to down): fiber matched waveguide (FMW) layer with a thickness of 3.5 μm, two layers of n^+-InGaAsP material with a bandgap wavelength of 1.3 μm (Q(1.3)) with a thickness of 320 and 320 nm and an n^+-InP layer with a thickness of 1.86 μm between the Q(1.3) layers. The laser and lateral taper are 750 and 520 μm long, respectively. The fabrication process requires a planar growth step and a single conventional etch process. The monolithic integrated device shows a coupling loss of 4 dB to standard single-mode fiber.

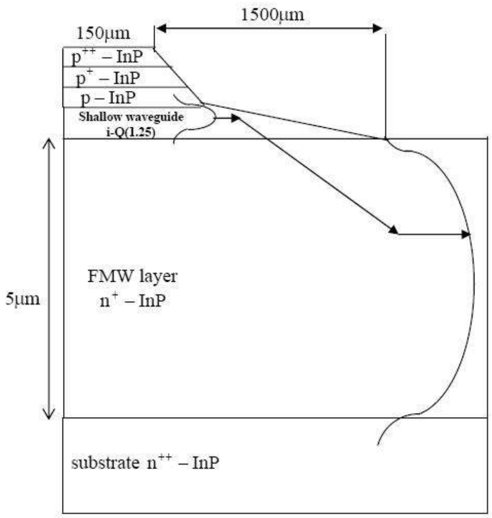
Soares [1] realized a hybrid SSC on a highly-doped n-InP substrate with a 0.8 dB taper loss and 2dB coupling loss for a 1.5 mm long vertical taper. The SSC is monolithically integrated with the four MZI switches. The SSC is also suitable to integrate with active and passive components such as modulators, photodetectors, phase shifters, and MZI which operate at frequencies up to a few GHz due to using highly n-doped InP substrate. The fabrication of the vertical taper is based on sliding-window technique by using a raster mask, standard lithography, and non-selective dry-etch to create the vertical taper in the InP/InGaAsP material. The monolithic integration of the SSC with the passive and active components requires epitaxial regrowth steps with the shallow and deep etching fabrication processes which are very complicated.

Galarza [4] simulated a monolithic integrated laser and a compact lateral taper by using an asymmetric twin-waveguide (ATG) vertical coupler concept on SI-InP substrate. The total length of the taper and coupler is about 25 μm for an InP separation layer thickness of 300 nm. The device exhibits a coupling loss of less than 0.1 dB which is lower than adiabatic types. It also requires single epitaxial growth and the fabrication process can avoid submicron photolithography. But, the length of the laser grown on top of the passive waveguide is restricted to the beat lengths of the vertical taper.

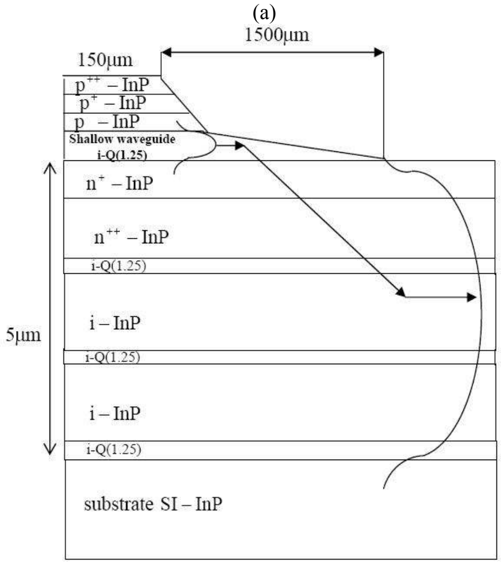
In this article, we present a hybrid SSC on the semi-insulating (SI)-InP substrate at a wavelength window around 1.55 μm based on layer stack used in the Opto-Electronic Device (OED) group at the Eindhoven University of Technology, Holland. It utilizes two lateral and vertical tapers and can be monolithically integrated with all active and passive components such as waveguide semiconductor optical amplifier (SOA), photodetectors [5], modulators [6], MZI,

M. Nikoufard is with the Department of Electrical Engineering, Faculty of Engineering, University of Kashan, Kashan, Iran (corresponding author phone: +98 361 5912491; e-mail: mnik@kashanu.ac.ir).

R. Taheri is with Department of Electrical Engineering, Zarin-Dasht Branch, Islamic Azad University, Zarin-Dasht, Iran (e-mail: taherireyhaneh@yahoo.com).



(a)



(b)

Fig. 1. 2-D longitudinal cross section of the hybrid SSC on a) highly-doped n-InP substrate (see ref. [1]) and b) SI-InP substrate.

and AWG [7] which operate at bit rates of up to 40 Gb/s. The main difference between the SSC realized in ref. [1] and the proposed SSC in current article is in utilizing the highly doped n-InP substrate and the semi-insulating (SI) substrate, respectively, which enforces to use ARROW concept as indicated in Fig. 1.

II. Spot-Size Converter Design

The MFD of a shallow etched waveguide converts to the MFD of a standard optical fiber by using a combined vertical and lateral taper. Fig. 1a shows a longitudinal cross section of a hybrid SSC on the highly doped n-InP substrate given in reference [1]. The optical field with a small MFD is coupled from the shallow waveguide of the quaternary InGaAsP material with a bandgap wavelength of 1.25 μm (Q(1.25)) and through an adiabatic vertical taper with a 1500 μm long to a fiber-matched (FM) waveguide with a larger MFD. Both the FM layer and the substrate are made using InP material, but the refractive index of the highly doped substrate is lower than the refractive index of the FM layer, because the doping level of the FMW layer is lower than the substrate. There are two drawbacks for using the highly n-doped substrate:

a) The doping concentration is between 1 and $4 \cdot 10^{+18}$ /cm^3. At this range, there is large dependence of the refractive index on the doping concentration, and the index contrast changes considerably which bring a significant mode-mismatch loss [1].

b) The highly doped substrate is not suitable for the high speed components such as modulators and photodetectors because a large part of signal and ground electrodes are placed on the highly-doped substrate which creates high microwave attenuation. So, using the SI-InP substrate is an alternative way [5].

High-speed photonic components such as SOA, laser, photodetectors, modulators, and phase shifters require a pin-doped layer stack on SI-InP substrate. The pin structure consists of three graded p-doped InP cladding layers with the thicknesses of 1000, 300, 200 nm and the doping levels of 1e18, 5e17, and 3e17 /cm^3, respectively, and a 500 nm thick non-intentionally doped InGaAsP layer with a bandgap cutoff wavelength of 1.25 μm (i-Q(1.25)) as shallow waveguide layer. The buffer layers are two graded n-InP layers with the thicknesses of 200 and 1300 nm and the doping levels of 5e17 and 1e18 /cm^3, respectively, which reduce the optical loss for the passive components and the electrical resistance for electron-hole carriers in the vicinity of the i-doped Q(1.25) layer for the active components. In the active components such as photodetector and SOA, a thin absorbing layer of i-Q(1.55) material is sandwiched in the center of i-Q(1.25) shallow guiding layer. However, the SI-InP substrate has a refractive index of 3.1693 which is more than the refractive index of n-InP buffer layers. So, n-InP buffer layers cannot behave as the FMW layers shown in Fig. 1a. To increase the refractive index of the FMW layers respect to the refractive index of the SI-InP substrate, a multi-layer ARROW is employed [8]. The Arrow layers comprises of three i-Q(1.25) layers sandwiched between the InP layers with a total thickness of 5μm. We use Q(1.25) material, which gives sufficient optical confinement and electo-optical effect and is sufficiently far from the band edge of Q(1.55). The thicknesses of the ARROW InP-layers are chosen 1.5, 2, and 1.5 μm. The total thickness is about half of the MFD of the standard optical fiber to reduce the cost of the epitaxial growth [1]. The thicknesses of the ARROW i-Q(1.25) layers are chosen 15, 20, and 15 nm based on equations available in references [3, 8]. Fig. 1b shows the SSC layer stack including FMW and pin-doped layers on the SI-InP substrate.

Fig. 2 shows a 3-D view of the hybrid SSC in which the modal field of the shallow etched waveguide is laterally enlarged by the lateral taper and then adiabatically tapered through a vertical taper to match the MFD of the optical field to an optical fiber. So, an optical field will be coupled from

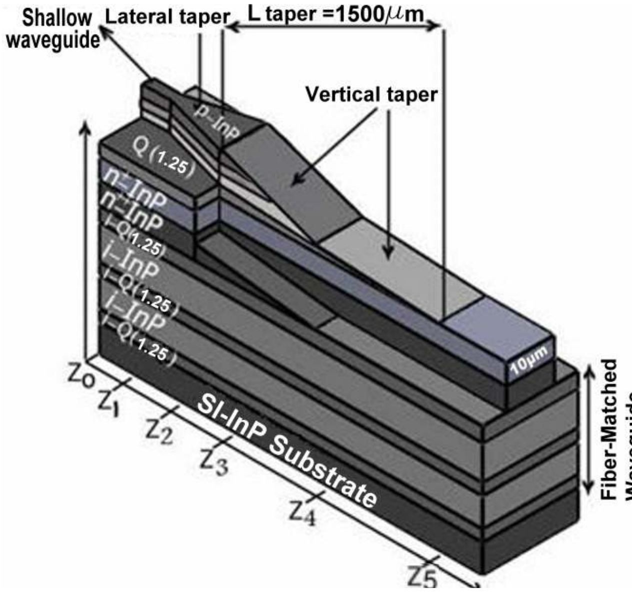


Fig. 2. 3-D representation of the hybrid SSC formed by two lateral and vertical tapers on top of the ARROW layers on the SI-InP substrate.

upper shallow waveguide with a width of 2 μm and a thickness of 500 nm to a 10 μm wide and a 5 μm thick fiber-matched optical waveguide. Taking into account the difference in etch rate between InP and InGaAsP (≈1.3:1), two different slopes in vertical taper can be seen.

III. Simulation Results

An accurate 3D-simulation of the SSC requires to a high-speed and high-capacity computer with a long execution time. Due to the limitations, the SSC is analysed to determine the transverse electric (TE) field distribution in the lateral and the longitudinal cross sections, separately, by using COMSOL and OPTIWAVE softwares. Fig. 3 shows the propagation of the TE mode in six different lateral cross-sections of the SSC (indicated by Z_0 to Z_5 in Fig. 2) by using COMSOL software which utilizes finite element method (FEM) by solving time-independent Maxwell's equation and then spatial-discretization on a Lagrangian triangular mesh. The effect of mesh refinement with a special focus on layer edges and boundaries has been taken into account to determine the number of elements which guarantee sufficiently accurate results within the lower computation time. The boundary condition is considered as perfect electric conductor. This simulation carried out on an Intel PC with 2.6 GHz processor and 4GB RAM memory. It can be seen that the TE polarization mode is transferred from the upper input shallow waveguide (Z_0 in Fig. 3) to the output facet of the FMW layers (Z_5 in Fig. 3).

Fig. 4 demonstrates the propagation of the TE mode through the longitudinal cross section of the SSC with a 1.5 mm long vertical taper which is carried out by OPTIWAVE software and using finite difference beam propagation method (FD-BPM) and using Gaussian excitation filed and perfectly matched layer (PML) boundary condition at 1.55μm wavelength. The loss of the SSC as a function of the vertical taper length from 0.5 to 3 mm and different index contrast (Δn) between the n^{++}-InP buffer layer and the SI-InP substrate is shown in Fig. 5. It shows that a minimum loss of about 1.8 dB can be achieved for a 1.5 mm long vertical taper. Moreover, by increasing the doping level of the buffer layers, the refractive index decreases and the index contrast (Δn) increases. It causes more light shifts toward FMW layers which have more refractive indices. In resultant, it creates less taper loss.

The amount of light coupled from the fiber to the waveguide is characterized by the mode-mismatch loss. The mode-mismatch loss is given [1]:

$$L_{\text{mismatch}} \approx -10\log\left\{4\frac{MFD_{\text{xwav}}\times MFD_{\text{ywav}}\times MFD_{\text{fiber}}^{2}}{\left(MFD_{\text{xwav}}^{2}+MFD_{\text{fiber}}^{2}\right)\times\left(MFDy_{\text{xwav}}^{2}+MFD_{\text{fibre}}^{2}\right)}\right\}$$

Where MFD_{fiber} is the MFD of the optical fiber and MFD_{xwav} and MFD_{ywav} are the horizontal and vertical MFD of the output FMW waveguide, respectively. The argument also is the overlap integral between the two modes of waveguide and optical fiber in which the optical fields are replaced with the Gaussian approximation.

The circular mode of an SSMF has an MFD of 10.2×10.2 $(\mu m)^2$. The optical fields of the FMW waveguide are determined for different FMW layer thicknesses and different doping levels of n^{++}-InP buffer layer in Z_5 cross-section. Then, the MFD of the optical field at two directions (MFD_{xwav} and MFD_{ywav}) are numerically computed. Fig. 6 shows the mode-mismatch losses for the different FMW-layer thickness and different index contrasts (Δn). The plot shows that the lowest and highest mode-mismatch losses are obtained for the FMW layer thickness of 3.25μm to 5μm at values range of 0.8 dB to 1.9 dB depending on the index contrast Δn. The plot exhibits a lower mismatch loss respect to the ref. [1] due to more concentration of the optical filed in the ARROW layers.

IV. Conclusion

We have designed a hybrid spot size converter on the SI-InP substrate which utilizes one lateral and one vertical tapers. It can be monolithically integrated with passive and active components. By using the lateral and vertical tapers with 150 and 1500 μm long, respectively, the taper loss of about 1.8 dB can be determined. Calculations show that the mismatch is in the range of 0.8-1.9 dB for various FMW layer thicknesses of 3.25μm to 5μm.

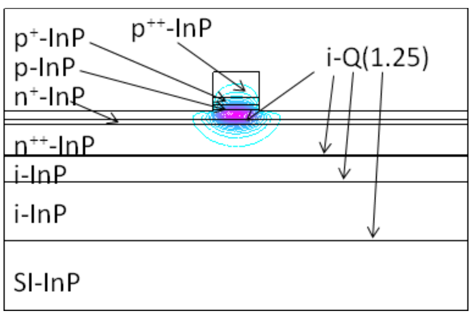
Acknowledgment

The authors are grateful to University of Kashan for supporting this work by Grant no. 3713/2.

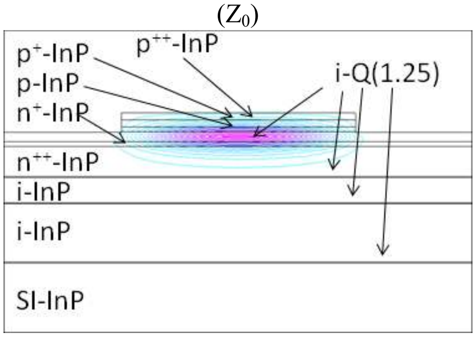
References

[1] F. M. Soares, "Photonic Integrated true-time-delay beamformers in InP technology," Ph.D. dissertation, Fac. Elect. Eng., Eindhoven University of Technology, Eindhoven, the Netherlands, 2006.

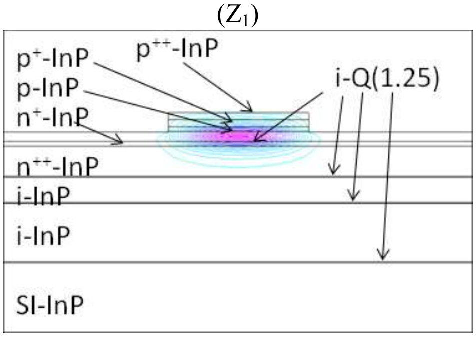
[2] K. De Mesel, “Spot size converters for photonic integrated circuits,” Ph.D. dissertation, Dep. Information Technology, Gent University, Gent, Belgium, 2002.
[3] M. Galarza, K. De Mesel, S. Verstuyft, C. Aramburu, M. Lopez-Amo, I. Moerman, P. Van Daele, and R. Baets, “A New Spot-Size Converter Concept Using Fiber-Matched Anti-resonant Reflecting Optical Waveguides,” *IEEE Journal of Lightwave Technology*, vol. 21, pp. 269-274, 2003.
[4] M. Galarza, D. Van Thourhout, R. Baets, and M. Lopez-Amo, “Compact and highly-efficient polarization independent vertical resonant couplers for active-passive monolithic integration,” *Optics Express*, vol. 16, pp. 8350-8355, 2008.
[5] L. Xu, M. Nikoufard, X. J. M. Leijtens, T. de Vries, E. Smalbrugge, R. Nötzel, Y. S. Oei, and M. K. Smit ,”High bandwidth waveguide photodetector based on an amplifier layer stack on an active-passive semi-insulating InP at 1.55μm,” *IEEE Photonics Technol. Lett.*, vol. 20, no. 23, 2008.
[6] W. Pascher, J. H. den Besten, D. Caprioli, R. van Dijk, X. J. M. Leijtens, and M. K. Smit ,"Modeling and characterization of a travelling-wave electro-optic modulator on InP", *Adv. Radio Sci.*, vol. 1, pp. 67-71, 2003.
[7] J. H. den Besten, , D. Caprioli, R. van Dijk, F. E. van Vliet, W. Pascher, J. J. M. Binsma, E. Smalbrugge, T. de Vries, R. G. Broeke, Y. S. Oei, E. A. J. M. Bente, X. J. M. Leijtens, and M. K. Smit, “Integration of MZI modulators and AWG-based multiwavelength lasers in InP,” in *Proc. Symp. IEEE/LEOS Benelux Chapter,* Ghent, pp.95-98, 2004.
[8] J. Kubica ,"Analysis of Arrows with thin cores," *Optical and Quantum Electronics*, vol. 34, pp. 737-745, 2002.



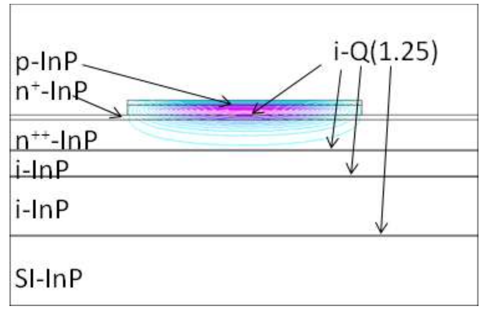
(Z_0)



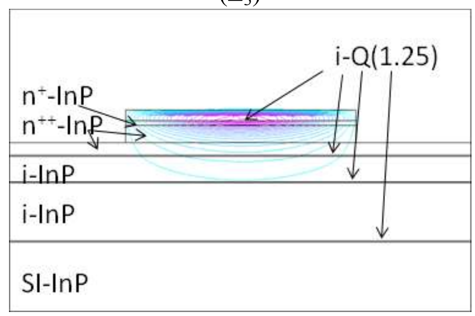
(Z_1)



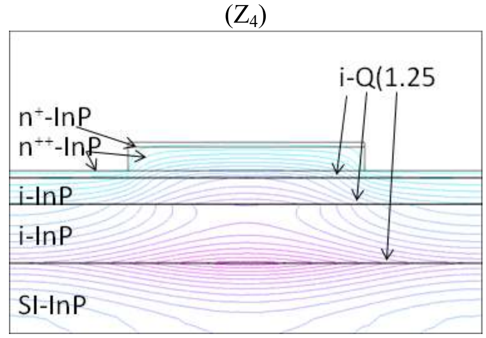
(Z_2)



(Z_3)



(Z_4)



(Z_5)

Fig. 3. Contour plot of TE polarization mode at different cross-section of the SSC along the propagation direction. Z_0 to Z_5 are indicated in Fig. 2.

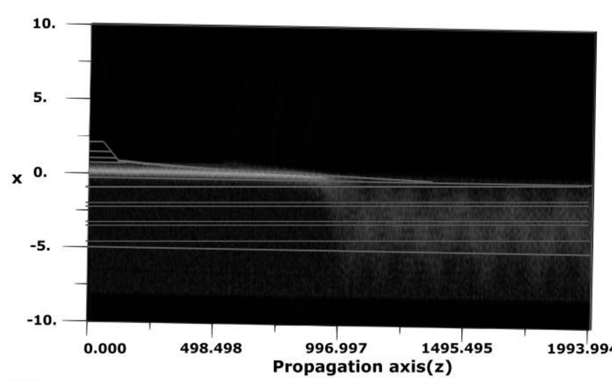


Fig. 4. Propagation of the TE field through the vertical taper.

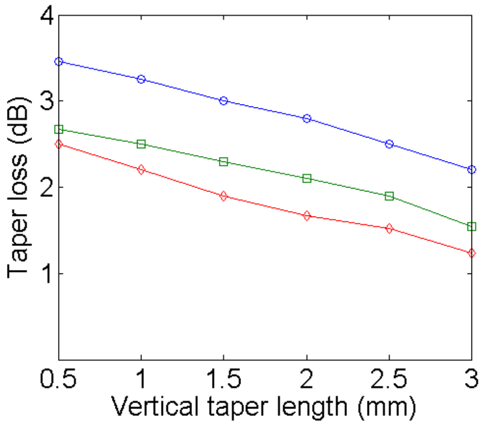


Fig. 5. SSC loss as a function of vertical taper length for different refractive index contrast (Δn) between the n^{++}-InP buffer layer and the SI-InP substrate for three values of Δn=0.005 (o), Δn=0.01 (□), and Δn=0.015 (◊).

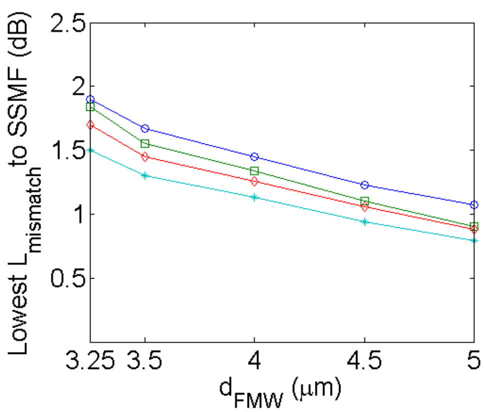


Fig. 6. Lowest mode-mismatch loss between an SSMF and a FMW-layer thickness and different index contrast (Δn) between the n^{++}-InP buffer layer and the SI-InP substrate for four values of Δn=0.005 (o), Δn=0.01 (□), Δn=0.015 (◊), and Δn=0.02 (∗).