

Extremely low-loss vertically-tapered spot size converter in InP-based waveguide structure

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Low-loss spot size converters (SSC) are important elements for coupling photonic integrated circuits to fibres. We have developed a Cl₂-based inductively-coupled-plasma process to etch non-selectively InP and photo-resist (PR). This process was then used to transfer a vertically-tapered PR pattern into an InP/InGaAsP structure. The tapered PR pattern was made using a standard optical lithography combined with sliding-mask technique. One, 2 and 3-mm long SSCs were fabricated and characterized. Excess losses between 0.5-2 dB were measured for all SSCs. We also fabricated lateral SSCs using the same epi-structure, however these SSCs showed higher losses (>4dB/SSC).

Introduction

Spot-Size Converters (SSCs) are key elements for reducing the coupling loss from the fibre to InP photonic waveguides. Generally, most devices on InP are designed and fabricated on a thin InGaAsP (Q) layer (usually between 400 and 700 nm) in order to obtain monomode behaviour in the vertical direction. However, this results in a small optical field in the vertical direction, thereby complicating the coupling of light from these waveguides into the fibres, which generally have a larger spot. SSCs are devices made to increase the spot size on the chip in order to minimise the in- and out-coupling loss.

Many different types of SSCs have been investigated [1]. Usually, they are fabricated in a material, which consists of two stacked layers (the regular Q film layer, and another thicker fibre-matched film). In the SSCs, the light is then adiabatically coupled from the thin Q layer to the fibre-matched film and vice versa. This is commonly done by slowly tapering the film layer into cut-off, thereby forcing the optical mode to couple from the regular thin-film waveguide into the fibre-matched waveguide. The regular waveguide is usually either tapered laterally in the width [2,3], or vertically in the thickness of the thin-film layer [4,5].

In this work, we report on the design, fabrication, and characterization of two distinct SSCs. One is based on the vertical tapering of the thin film layer (the vertically-tapered SSC), and the other one is based on the lateral tapering of the waveguide width (the laterally wet etched SSC).

Design

The epitaxial layer for both devices consists of a highly-doped InP substrate onto which a 5µm non-intentionally-doped (n.i.d.) InP fibre-matched film layer (layer no. 1 on figure 1a) has been grown, followed by a 600nm n.i.d. Q1.3 regular film layer (layer no. 2) and a 450nm n.i.d. InP cladding (layer no. 3). The vertical confinement of the light in the InP fibre-matched film layer with respect to the InP substrate is achieved through the carrier-induced refractive index change due to the doping [6]. Since the substrate is heavily

doped, it will have a slightly lower refractive index ($n \sim 3.15$) than the n.i.d. fibre-matched film layer ($n \sim 3.17$).

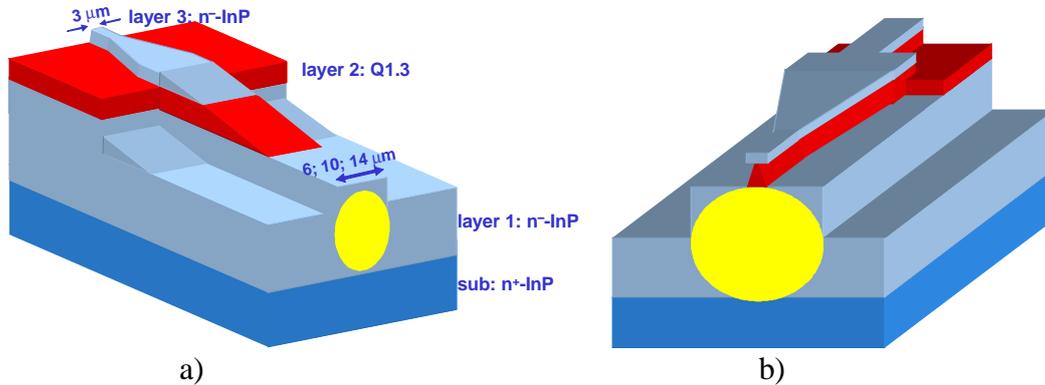


Figure 1- 3D-scheme of the vertically-tapered spot size converter a), and the laterally –wet etched spot size converter.

Figure 1a shows a picture of the vertically-tapered SSC. In this device, the regular $3\mu\text{m}$ -wide waveguide is first laterally tapered to the fibre-matched-waveguide width with a taper. And then, the mode in the thin-film Q1.3 layer is coupled into the fibre-matched layer via the vertical taper. For this design, 3 different vertical taper lengths have been investigated (1, 2, and 3mm). BPM simulations (2D) show that vertical tapers should be longer than 2mm for an adiabatic mode conversion. Three different widths of the fibre-matched waveguide have been studied: 6, 10, and $14\mu\text{m}$.

Figure 1b shows a picture of the laterally wet etched SSC. The concept of the device is basically to gradually taper down the width of the regular waveguide until cut-off. However, for a regular ridge-type waveguide, the mode is only cut-off for very narrow widths ($<500\text{nm}$), which are difficult to realize with standard lithography. That's why, the idea is to achieve these small dimensions via an underetch using a selective etch of the quaternary layer that etches very slowly in the etch-stop planes of the crystal. For this purpose, the waveguides have been fabricated along the V-groove direction of the wafer. The study of the behaviour of these devices require a 3D simulation program, and are quite cumbersome. Three different taper lengths have been investigated (0.5, 1, 1.5, and 2mm) for the same fibre-matched-waveguide widths as the vertically-tapered SSC.

Fabrication

The fabrication of the vertically-tapered SSC is very similar to the patented work reported in [7]. At first, a photoresist pattern with a vertical taper was fabricated by using a sliding mask technique. However, unlike reported in [7], the mask contains a raster (see step 2 on figure 2) with fixed spacing and a gradually increasing opening along the taper. The regions with the bigger openings in the raster will effectively be more exposed than the regions with the smaller openings, thereby creating a gradient in the exposure time along the taper. During the development, a vertical taper is then formed in the photoresist layer. The advantage of using a raster mask instead of a single sliding window is that with the raster, it is not necessary to slide the mask along the whole taper length. Our experiments have shown that sliding the mask roughly 57 times

the raster spacing ($57.3\mu\text{m}=170\mu\text{m}$) is sufficient to obtain a linear gradient in the exposure time.

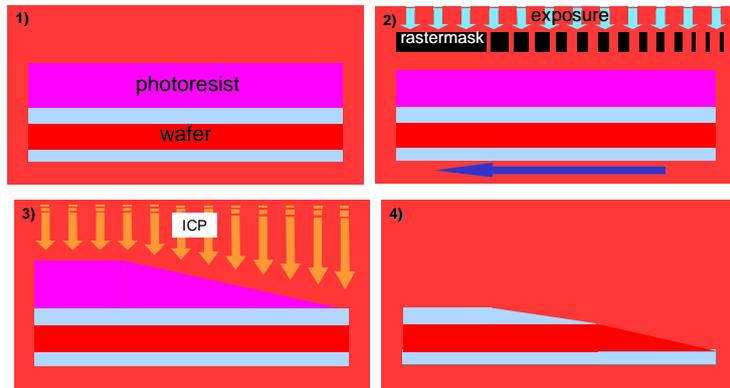


Figure 2- Fabrication process of the vertical tapers.

The vertical taper is then transferred into the InP substrate by using a non-selective Cl_2 -based inductively-coupled-plasma process, which has been optimised to etch photoresist and InP with a 1.2:1 ratio, while the Q layer is etched as fast as the photoresist. Then, a silicon-nitride layer is deposited on the chip and the waveguides are defined using standard lithography and reactive-ion etching (RIE). Finally, the regular thin-film-waveguide parts are covered with Ti in a lift-off process, and the fibre-matched waveguides are additionally etched to the required depth in a $\text{CH}_4\text{-H}_2$ RIE process. This last sequence of process steps is the standard double-etch process in our group, which makes the fabrication of these SSCs compatible with the processing of other devices.

The fabrication of the laterally-underetched SSC starts with the definition of the regular waveguides with standard lithography and RIE etching. Then, the fibre-matched waveguides are formed, in an identical way. And then, a silicon-nitride layer is deposited over the whole wafer, and the wet-etch regions are defined with lithography and wet etching in a buffered HF solution. Finally, the chip is dipped in a $\text{H}_2\text{O}_2\text{:H}_2\text{SO}_4\text{:H}_2\text{O}$ solution (which selectively etches InGaAsP and not InP) until the right underetch is achieved.

Results

The total coupling loss of a SSC consists of the internal losses in the SSC (due to radiation, and absorption), and of the overlap losses to the specific fibre used. The internal loss of the SSCs was first determined with Fabry-Pérot measurements. Then, transmission-loss measurements were performed in order to measure the overlap losses. A high-numerical-aperture (HNA) fibre with a reduced core and a beam waist of $3,6\mu\text{m}$ was used to couple light in- and out of the chip. This commercially available HNA fibre was spliced to a standard single-mode fibre (SSMF).

Figure 3 shows the best results that were obtained for the vertically tapered SSC. These results show a best total incoupling loss of 1.3dB to the HNA fibre. The laterally-wetetched SSCs showed poorer results ($>4\text{dB}$), and should be investigated further.

Conclusions

We have successfully developed a process to fabricate vertically tapered SSCs with a total incoupling loss of 1.3dB to a HNA fibre. This process is straightforward and

compatible with the processing of our photonic circuits containing Mach-Zehnder-interferometer switches and semiconductor optical amplifiers. The fabricated laterally wet etched SSC showed poorer results and will be investigated further in the future.

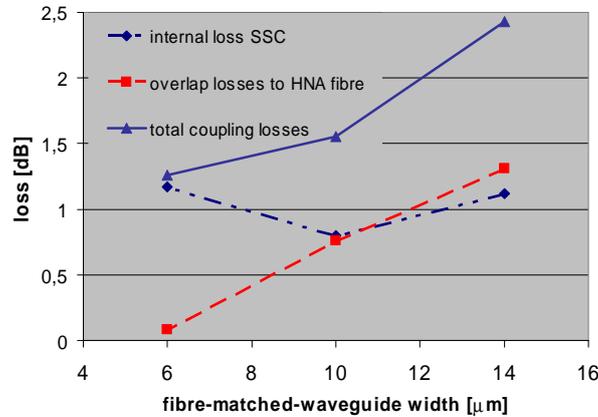


Figure 3- Measured best results for the vertically-tapered SSCs.

Acknowledgements

The authors are indebted to Anja van Langen-Suurling for fabricating the lithography masks, and to Chris Roeloffzen for having supplied the HNA fibres.

References

- [1] I. Moerman, P. P. van Daele, and P.M. Demeester, "A Review on Fabrication Technologies for the Monolithic Integration of Tapers with III-V Semiconductor Devices", *J. of Sel. Topics in Quantum Electron.*, vol. 3, no. 6, pp. 1308-1320, dec. 1997.
- [2] G. A. Vawter, R. E. Smith, H. Hou, and J. R. Wendt, "Semiconductor Laser with Tapered-Rib Adiabatic-Following Fiber Coupler for Expanded Output-Mode Diameter", *IEEE Photonics Technology Letters*, vol.9, no.4, pp. 425-427, apr. 1997.
- [3] M. Galarza, K. De Mesel, S. Verstuyft, C. Aramburu, I. Moerman, P. Van Daele, R. Baets, and M. López-Amo, "1.55 μm InP-InGaAsP Fabry-Pérot Lasers with Integrated Spot Size Converters using Antiresonant Reflecting Optical Waveguides", *IEEE Photonics Technology Letters*, vol.14, no.8, pp. 1043-1045, aug. 2002.
- [4] J. Stulemeijer, A. F. Bakker, I. Moerman, F. H. Groen, and M. K. Smit, "InP Based Spot-Size Converter for Integration with Switching Devices", *IEEE Photonics Technology Letters*, vol.11, no.1, pp. 81-83, jan. 1999.
- [5] Y. Suzaki, R. Iga, K. Kishi, Y. Kawaguchi, S. Matsumoto, M. Okamoto, and M. Yamamoto, "Temperature- and Polarization-Insensitive Responsivity of a 1.3- μm Optical Transceiver Diode with an Integrated Spot-Size Converter", *IEEE J. of Quantum Electron.*, vol. 34, no. 4, pp. 686-690, apr. 1998.
- [6] B. R. Bennett, R. A. Soref, and J. A. del Alamo, "Carrier-Induced Change in Refractive Index of InP, GaAs, and InGaAsP", *IEEE J. of Quantum Electron.*, vol. 26, no. 1, pp. 113-121, jan. 1990.
- [7] D. Trommer, R. Steingrüber, R. Löffler, and A. Umbach, "A Novel Flexible, Reliable and easy to use Technique for the Fabrication of Optical Spot Size Converters for Imp based PICs", 11th International Conference on Indium Phosphide and Related Materials (IPRM '99), 1999, Davos, Switzerland, postdeadline papers, pp. 12-13.