Vertical InP/InGaAsP tapers for low-loss optical fibre-waveguide coupling

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VERTICAL InP/InGaAsP TAPERS FOR LOW-LOSS OPTICAL FIBRE-WAVEGUIDE COUPLING

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Indexing terms: Integrated optics, Fibre-waveguide coupling, Waveguide tapers

We have realised vertically tapered and antireflection-coated waveguides in InP/InGaAsP with 1.7 dB coupling loss and relaxed alignment tolerances to lensed single-mode fibres with spot diameters of 3.8 μm . The waveguide tapers are fabricated by a dip-etch process that is well suited for integration with optical waveguide circuits.

Introduction: Modern communication systems require efficient coupling from integrated-optic semiconductor waveguide devices to single-mode fibres. The elliptically shaped optical modes of typical optical waveguide switches and modulators on semiconductors have to be matched to the larger and circular modes guided by the fibres. Several authors have reported spot-size transformations for low-loss coupling to cleaved fibres: Koch *et al.* [1] applied quasiadiabatic vertically tapered laser structures fabricated using ultrathin stop-etch layers to obtain coupling losses as low as 4.2 dB. Mueller *et al.* [2] used a vertically tapered waveguide with a 10 μm -high stack of layers realised by a shadow mask technique to achieve fibre-chip coupling losses of 4.9 dB. Zengerle *et al.* [3] realised waveguides with tapers in the vertical and horizontal direction by using a structure in which the main waveguide is located on top of a very thin waveguiding layer. They achieved coupling losses as low as 2.7 dB.

In this Letter we report on antireflection-coated vertical waveguide tapers having coupling losses of 1.7 dB and relaxed alignment tolerances to lensed fibres with spot diameters of

3.8 μm ($1/e^2$). Using these tapers the waveguide devices, optimised for switches and modulators, are affected only near the facets for coupling improvement. Conventional process techniques can be applied for the fabrication.

Taper concept and design: To increase the coupling efficiency between optical waveguide devices and single-mode fibres we propose vertical taper ridge-type waveguide structures (see Fig. 1). To realise such adiabatic waveguide tapers, the waveguide structures of optical switches and modulators [4, 5] were slightly modified by including a 20 nm InP stop-etch layer that divides the 600 nm InGaAsP waveguide core into a thick 530 nm and a thin 70 nm layer. This modification of the waveguide structure has only a minimal effect on the optimised operation of the waveguide switches and modulators. In the taper section, however, this structure allows the thick waveguide layer to be removed gradually by a dip-etch technique while keeping the thinner waveguide layer for coupling to the fibres. The adiabatic transformation from the conventional waveguide modes in the device section with elliptical mode shape to the modes with almost circular shape in the thin waveguide is achieved with vertical tapers. Optical shapes of the adiabatic tapers were determined by means of beam propagation analysis [6]. This analysis predicts that vertical tapers longer than 400 μm should exhibit conversion losses of less than 0.3 dB. The coupling from the thin waveguides with cores of 70 nm to lensed fibres with spot diameters of 3.8 μm is from overlapping the mode profiles, predicted to as low as 0.75 dB for TE polarisation and 0.65 dB for TM polarisation, respectively. The almost circular modes of the waveguide structures also relax vertical alignment tolerances.

Fig. 1 Longitudinal cross-section of integrated optical waveguide chip with central device section, adiabatically tapered waveguide section and coupling section

Taper section adapts waveguides which are optimised for device operation to waveguides which are optimised for fibre coupling. Intensity profiles of guided modes are indicated qualitatively

Taper fabrication: To demonstrate the above taper concept the following structure (Fig. 1) was grown in a first growth step on to an *n*-type InP substrate with MOVPE (metal-organic vapour phase epitaxy): a 1 μm InP buffer layer, a thin 70 nm InGaAsP ($\lambda_g = 1.3 \mu\text{m}$) waveguiding layer, a 20 nm InP stop-etch layer, a thick 530 nm InGaAsP ($\lambda_g = 1.3 \mu\text{m}$) waveguiding layer and a 20 nm InP top cladding layer. After covering the device section with photoresist, the tapers were etched by dipping the chip into a sulphuric acid solution. The dipping speed was chosen so as to taper the 530 nm InGaAsP layer linearly to zero within 400 μm . Similar tapers were formed at both ends of the chip. Then the photoresist was removed and the entire structure overgrown with an upper cladding of 1.5 μm InP. From this point on the wafers can be processed in regular fashion to form optically active or passive guided-wave components. To evaluate the coupling losses we fabricated waveguide devices consisting of ribs with widths varying from 2 μm to 4 μm . After etching and cleaving the chips, antireflection coatings were deposited on both waveguide facets.

Experimental results: Fig. 2 shows fibre-chip power transmission measurements against ridge width. Laser light with a wavelength 1.53 μm was coupled from a lensed fibre with 3.8 μm spot diameter through the entire waveguide taper and device structure to a second identical fibre which was con-

nected to a photodiode. For comparison purposes we have measured coupling combinations between cleaved or lensed fibres on one side and conventional or tapered waveguides on the other side. From these measurements the waveguide devices to fibre coupling loss was deduced.

Fig. 2 Measured fibre-chip coupling efficiency against width of ridge waveguide

- tapered waveguides to lensed fibres
- tapered waveguides to cleaved fibres
- conventional waveguides to lensed fibres
- conventional waveguides to cleaved fibres

Optical coupling losses as low as 1.7 dB were obtained for the coupling of tapered waveguides with ridge widths of 4 μm. The difference in coupling loss of 1 dB as compared to the predicted 0.65 dB (TE polarisation) and 0.75 dB (TM-polarisation) is believed to be caused by imperfections in the fibre lens, rest reflections at the fibre and chip facets, as well as by scattering losses in the taper section.

The tapered waveguides show a 2 dB improvement in coupling loss over the nontapered waveguides. When a conventional cleaved fibre with 10 μm spot diameter is used the tapered waveguide structure improves the coupling efficiency by about 3 dB in comparison to a conventional waveguide structure.

The difference between tapered and nontapered waveguide structures indicates scattering losses in the taper sections to be below 0.5 dB. Polarisation sensitivity is below 0.1 dB. Finally, we have measured the alignment tolerances that occur between lensed fibres and both tapered and nontapered waveguides. The results are depicted in Fig. 3. The tapered waveguide structure shows nearly identical tolerances for both the horizontal and the vertical misalignments. This indicates circular symmetry of the mode. This is in contrast to the conventional waveguide structures which are, because of their ellipticity, much more sensitive to vertical misalignments.

Fig. 3 Measured alignment tolerances of waveguides to lensed fibres

- Tapered waveguides:
 - horizontal
 - vertical displacement
- Conventional waveguides:
 - horizontal
 - vertical displacement

Conclusion: We have demonstrated a vertically tapered coupler in InP/InGaAsP with coupling losses to lensed fibres with 3.8 μm spot diameter as low as 1.7 dB and relaxed alignment tolerances. The dip-etch fabrication process for the

tapered waveguides is rather tolerant to variations. Changes in dipping speed or etch rate of the sulphuric acid solution will only result in changes of the tapers which have little effect for tapers longer than 400 μm. The structure is suitable for integration with optoelectronic waveguide devices.

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OPTICAL GAIN IN PROTON-EXCHANGED Cr: LiNbO₃ WAVEGUIDES

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Indexing terms: Integrated optics, Optical waveguides

We report on a study of optical gain in chromium-doped LiNbO₃ waveguides formed by the proton-exchange process. Optical gain in proton-exchanged Cr: LiNbO₃ channel waveguides has been measured for the first time. These waveguides show potential for diode-laser pumping of an integrated, broadband tunable laser in the 750-1150 nm spectral range.

Introduction: The recent demonstration of CW diode-laser-pumped laser action in Cr-doped materials (see, for example, Reference 1) has renewed interest in Cr-doped vibronic solid-state lasers as candidates for the applications requiring compact and efficient tunable lasers. Since the electro-optic, acousto-optic and nonlinear optical properties of LiNbO₃ crystals doped with laser ions offer interesting possibilities in various laser applications, the investigation of waveguides in Cr: LiNbO₃ is of interest for integrated optical applications, in particular for applications requiring a wavelength agile laser. By creating single-mode waveguides within doped laser crystals it is possible to obtain a very high gain and low laser threshold, as has already been shown in Nd: MgO: LiNbO₃ waveguide lasers and amplifiers at 1.084 μm [2], as well as in Er-doped LiNbO₃ waveguide lasers at 1.532 μm [3]. In this Letter we report the observation of broad-bandwidth optical