Fig. 3 *Power consumption against operational frequency at 1.1 and 1.5 V power supply*

P_a is analogue part of power consumption, P_d is digital part of power consumption
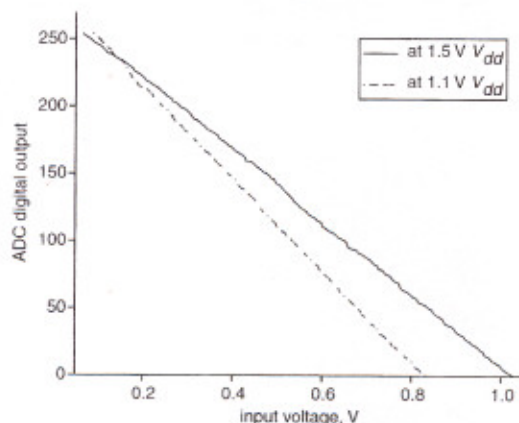

Fig. 4 *Transfer function curve between analogue input and digital output at 1.1 and 1.5 V power supply*

The analogue-to-digital converter operates from 22 kHz to 4.5 MHz clock rate, which corresponds to a sampling rate from 2 to 409 kS/s. Fig. 4 shows the transfer function curve of the ADC with a 1.1 and 1.5 V power supply. The data is collected at a clock frequency of 89 kHz corresponding to a sampling frequency of 8.9 kS/s. The input range was measured as 0.97 V for 1.5 V and 0.84 V for 1.1 V. The analogue-to-digital converter performed with an average 0.70 LSB differential nonlinearity (DNL) and an average of 1.02 LSB integral nonlinearity (INL) at 1.5 V power supply and 0.67 LSB DNL and an average of 0.9 LSB INL at 1.1 V power supply. Because of this ADCs extremely low power property, it is well suited for wireless sensors powered by energy scavenging systems and systems that require moderate precision but long duration of operations.

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References

1 *Proc. IEEE*, Special Issue on Sensor Networks, August 2003
2 Lal, A., Duggirala, R., and Li, H.: 'Pervasive power: a radioisotope-powered piezoelectric generator', *Pervasive Computing*, 2005, **4**, January–March, pp. 53–60
3 Scott, M.D., Boser, B.E., and Pister, K.S.J.: 'An ultralow-energy ADC for smart dust', *IEEE J. Solid-State Circuits*, **36**, (7), 2003, pp. 1123–1129
4 Fu, Z., and Culurciello, E.: 'An ultra-low power silicon-on-sapphire adc for energy-scavenging sensors'. Proc. of IEEE Symp. on Circuits and Systems, May 2006
5 Sauerbrey, J., Schmitt-Landsiedel, D., and Thewes, R.: 'A 0.5 V 1 μW successive approximation ADC', *IEEE J. Solid-State Circuits*, **38**, (7), 2003, pp. 1261–1265
6 Vittoz, E.A.: 'Low-power design: ways to approach the limits'. IEEE Int. Solid-State Circuits Conf., San Francisco, CA, USA, 1994, pp. 14–18
7 0.5 μm FC design manual, Peregrine Semiconductor Inc., San Diego, CA, 52/0005 edition, March 2005
8 Enz, C.C., and Temes, G.C.: 'Circuits techniques for reducing the effect of op-amp imperfections: autozeroing, correlated double-sampling, and chopper stabilization', *Proc. IEEE*, 1996, **84**, (11), pp. 969–982

Compact and efficient fibre-to-waveguide grating couplers in InP-membrane

F. Van Laere, M. Ayre, D. Taillaert, D. Van Thourhout, T.F. Krauss and R. Baets

The design and fabrication of compact grating couplers in InP-membrane waveguides for coupling to standard singlemode fibre is presented. A wafer bonding technique is applied to achieve a high vertical index contrast. Coupling efficiencies of 30% were measured on first fabricated couplers.

Introduction: Miniaturisation and integration of optical functions on a chip are key drivers for optical communications components at an acceptable price. When optical components are made in high index contrast material, they can be made much smaller. One major problem, compromising a large breakthrough of optical communication, is the coupling of the chip with the outside world (optical fibre). The large deviation in dimensions between a waveguide on chip and optical fibre causes high coupling losses and high packaging cost. Making components smaller makes the situation even worse. Several taper-based solutions have been proposed to solve the problem [1, 2]. We propose the use of grating couplers for coupling between fibre and nanophotonic waveguides. This approach has major advantages over classical coupling methods. Light is coupled out of plane from fibre to waveguide, allowing in- and outcoupling everywhere on the chip, and not only at the edges of the chip (no need to cleave or polish devices). This opens the prospect of wafer-scale testing. Grating couplers have already been studied extensively [3, 4]. However, traditional couplers often use weak gratings and are therefore rather long (several hundreds of μm). In [5], strong and compact (10 μm) gratings in silicon-on-insulator (SOI) are used, with coupling efficiencies from standard singlemode fibre to waveguide of 33%. In this high vertical index-contrast material system, the mode is very well confined, allowing for very compact components. However, SOI is not suited for active functions (e.g. lasers). InP and related materials can be used for both active and passive functions, but the vertical index contrast is typically modest, inhibiting the easy transfer of existing designs optimised for SOI. In this Letter, we describe the design and the successful fabrication of efficient grating couplers (30% coupling efficiency) in InP, based on benzocyclobutene (BCB) wafer bonding [6]. This technique has high potential for adding a bottom mirror to the structure, which will increase coupling efficiency substantially.

Principle and design: A sketch of the device is shown in Fig. 1a. The light in a fibre, positioned above the grating, is diffracted into a 10 μm-wide waveguide. A conventional taper performs the horizontal spot-size conversion. A practical realisation of a grating coupler is shown in the SEM picture of Fig. 1b. The grating is etched into a 300 nm thin InP-membrane layer on BCB. In our approach, the grating is at the bottom side. The 1D grating couplers are designed with CAMFR, an eigenmode expansion tool, for TE-polarisation. The three-dimensional problem can be reduced to a two-dimensional one, since the width of the waveguide is much larger than the height. The fibre coupling efficiency is calculated by multiplying the outcoupled power with the overlap integral between the outcoupled field distribution and the fibre

mode (beam diameter 10.4 μm). This value (the coupling efficiency of the 2D problem) is then multiplied by a correction factor to take into account the lateral direction. To avoid reflection back into the waveguide, the fibre is tilted to an angle of 10°. The parameters to be optimised are the period, filling factor, etch depth and BCB thickness. We consider the coupling from waveguide to fibre (the coupling from fibre to waveguide is the same, since we consider coupling from one mode to another mode). The optimised parameters are: period = 660 nm, filling factor = 0.5, etch depth = 120 nm, BCB thickness = 1.18 μm. The calculated coupling efficiency for this structure is 34%. The ratio between the power coupled upwards and downwards can be increased by applying a surface AR-coating. We use an Al_2O_3 layer ($n = 1.58$), with an optimal thickness of 260 nm. The maximum coupling efficiency is increased to 54% and the 1 dB bandwidth is around 50 nm. The field profile for an optimised structure is shown in Fig. 2. By adding a bottom mirror to the structure, radiation to the substrate can be avoided, and the theoretical coupling efficiency is further enhanced to 74%.
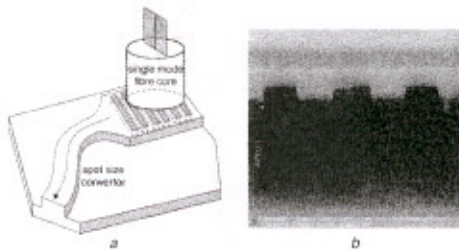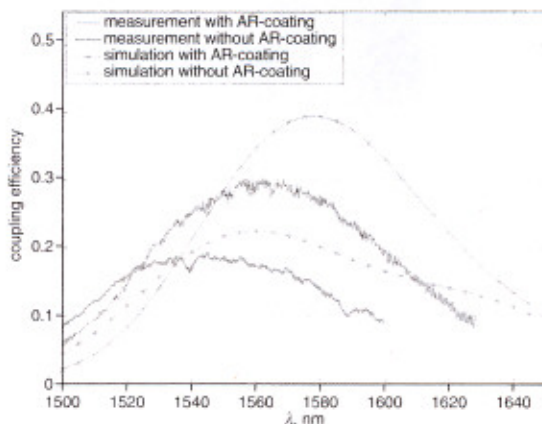

Fig. 1 *Sketch of grating coupler and cross-section of fabricated structure (with AR-coating)*

a Sketch of grating coupler
b Cross-section of fabricated structure (with AR-coating)

air
Al_2O_3
InP
BCB
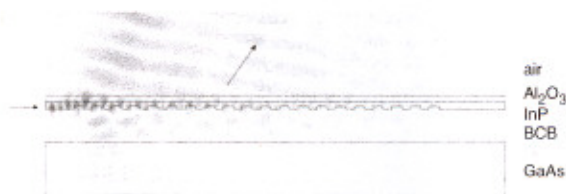
GaAs

Fig. 2 *Field profile of 1D-grating coupler*

Fig. 3 *Comparison between experiment and simulation for real fabricated structure*

Fabrication scheme: The layer structure used for the devices consists of an InP-substrate, an InGaAsP etch-stop layer and a 300 nm InP-layer, serving as the membrane layer. First, gratings and waveguides are defined by e-beam lithography using polymethylmethacrylate (PMMA). The waveguides are 10 μm wide and bounded by 5 μm-wide trenches. The pattern is then transferred into a Fox-14 (flowable oxide) hard mask by reactive ion etching (RIE) using CHF_3 (trifluoromethane). Finally, the structures are etched into the epistructure by RIE using CH_4/H_2 (methane/hydrogen) and the Fox-14 layer is removed with HF (hydrogen fluoride). This structure is then bonded onto a host substrate by means of BCB (a low refractive index

polymer), with the grating at the bottom side. After curing of the BCB for 1 h at 250°C in a nitrogen environment, the substrate is removed by mechanical polishing and wet etching. Finally, the etch stop layer is removed by wet etching.

Results and discussion: We fabricated a first sample of 1D grating couplers on InP-membrane (Fig. 1b). The performance of these couplers is determined from a fibre-to-fibre measurement. A fibre, connected to a tunable laser, is positioned above the grating, tilted at 10°. Another fibre is positioned (also at 10°) above the output grating and connected to a power detector. We assume that the input and output coupler are identical and neglect waveguide losses since they are 10 μm wide. From a transmission measurement we can thus estimate the coupling efficiency of a single coupler. First, measurements are carried out without AR-coating. The measured coupling efficiency is 19% per coupler (Fig. 3, thick line). The simulated coupling efficiency for the fabricated structure, with the grating parameters (etch depth, BCB thickness, ...) deduced from an SEM image, is 22% (Fig. 3, stars line). After applying a 240 nm (target is 260 nm) top Al_2O_3 layer, serving as an AR-coating, the measured coupling efficiency is enhanced to 30% (Fig. 3, thin line). Using the actual parameters of the fabricated structure, the simulated coupling efficiency is 39% (Fig. 3, x line).

The measurement results are comparable with previous results on SOI-grating couplers. However, as discussed above, the maximal theoretical coupling efficiency is 34% without AR-coating and 54% with AR-coating. The relatively large discrepancy between the maximum achievable coupling efficiency and the experimental values is explained by a deviation between the fabricated structure and the targeted structure. Part of the discrepancy can be explained by a deviation in BCB thickness. The simulated optimal BCB thickness is 1.18 μm, while the actual BCB thickness is 1.3 μm. Another important factor is the deviation in refractive index of the AR-coating. The actual refractive index at a wavelength of 1550 nm is around 1.47, while the theoretical value is 1.58. The optimal thickness of the AR-coating layer depends on its refractive index. In our case, the AR-coating thickness is optimised for the theoretical value, and is not optimal for the real fabricated structure. The final part of the discrepancy in coupling efficiency can be attributed to roughness induced through the etching and imperfectness of the bonding interface (included air bubbles or small dust particles) and the AR-coating layer.

Conclusion: First experimental results on bonded InP-membrane grating couplers are reported. The measured coupling efficiency to singlemode fibre was 30%. This value is comparable to the best results obtained on SOI so far. The fabricated structures showed some deviations from the design, accounting for the difference with the value predicted from simulations (54%). Improving the fabrication and including a bottom mirror (to avoid radiation to the host-substrate) will substantially increase coupling efficiency to a simulated value of 74%.

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References

1   Shoji, T., Tsuchizawa, T., Watanabe, T., Yamada, K., and Morita, H.: 'Low loss mode size converter from 0.3 μm square Si wire waveguides to singlemode fibres', *Electron. Lett.*, 2002, **38**, (25), pp. 1669–1670

2 Yan, X., Masanovic, M., Skogen, E., Hu, Z., Blumenthal, D., and Coldren, L.: 'Optical mode converter integration with InP-InGaAsP active and passive waveguides using a single regrowth process', *IEEE Photonics Technol. Lett.*, 2002, **14**, (9), pp. 1249–1251

3 Ang, T.W., Reed, G.T., Vonsovici, A., Evans, A.G.R., Routley, P.R., and Josey, M.R.: 'Effects of grating heights on highly efficient unibond SOI waveguide grating couplers', *IEEE Photonics Technol. Lett.*, 2000, **12**, (1), pp. 59–61

4 Orobtchouk, R., Layadi, A., Gualous, H., Pascal, D., Koster, A., and Laval, S.: 'High-efficiency light coupling in a submicrometric silicon-on-insulator waveguide', *Appl. Opt.*, 2000, **39**, (31), pp. 5773–5777

5 Taillaert, D., Baets, R., Dumon, P., Bogaerts, W., Van Thourhout, D., Luyssaert, B., Wiaux, V., Beckx, S., and Wouters, J.: 'Silicon-on-insulator platform for integrated wavelength-selective components'. Proc. of 2005 IEEE/LEOS Workshop on Fibres and Optical Passive Components, pp. 115–120

6 Christiaens, I., Roelkens, G., De Mesel, K., and Van Thourhout, D.: 'Thin film devices fabricated with BCB waferbonding', *J. Lightwave Technol.*, 2005, **23**, (2), pp. 517–523

Etch slope compensation for planar silica waveguide lens pair

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A silica lens pair has been designed to facilitate the free-space optical propagation between opposing planar waveguides. Each lens consists of a graded refractive index slab with a convexly shaped front face. A technique for compensating for the non-vertical etch of the front face curvature is described and shown to result in a significant reduction of optical loss.

A lens pair which allows the low loss transmission of light between two opposing waveguides has been described previously [1]. Of particular importance to the fabrication of the device is the ability to etch the front face of the lens curvature vertically. In practice, the actual etched surface can deviate somewhat from the vertical. This causes refraction of the optical beam and optical misalignment. This Letter shows how the deviation from the vertical can be compensated for.

The lens pair is illustrated in Fig. 1. Each lens pair consists of a graded index slab lens to focus light in the vertical direction, with a convexly shaped front face to focus light in the horizontal direction. The lens pair can be fabricated using standard PECVD and RIE techniques. A theoretical analysis and design procedure is described in [1].
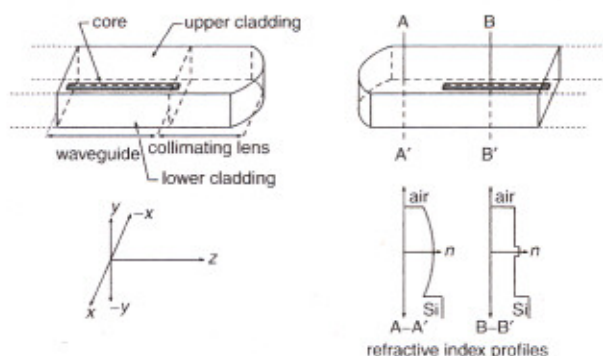

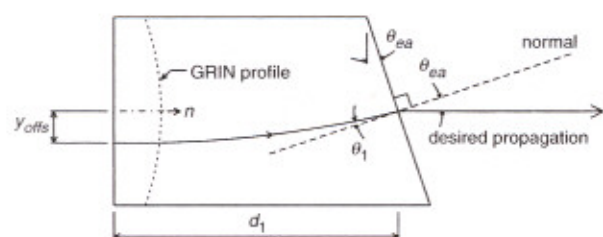**Fig. 1** *Silica waveguide lens pair detail*

Fig. 2 *Compensation for non-vertical lens front face curvature*

In practice, when the front face of the lens is etched using RIE it can be expected that there will be some angular deviation from the vertical. This causes refraction of the beam and the beam will no longer emerge from and re-enter the opposing lenses horizontally causing optical misalignment. However, so long as this deviation from the vertical is constant and reproducible, it can be compensated for by vertically offsetting the waveguide cores from the centre of the refractive index profile. The vertical offset compensation is illustrated in Fig. 2 which shows the side view of one lens. The lens has length d_1 and the front face deviates from the vertical with angle θ_{ea}. The waveguide cores are offset from the centre of the parabolic profile by distance y_{offs}. The parabolic profile of the graded index lens can be described by [2]:

$$n^2(y) = n_0^2 - n_0 n_2 y^2$$

The vertical offset y_{offs} is found by considering the slope of an optical beam as it propagates through a material with parabolic refractive index profile. The slope is given by [2]:

$$y'(z) = -\sqrt{\frac{n_2}{n_0}} \sin\left(\sqrt{\frac{n_2}{n_0}}z\right) y_0 + \cos\left(\sqrt{\frac{n_2}{n_0}}z\right) y_0'$$

where y' is the slope of the optical beam, y_0 is the initial vertical position (from the centre of the parabolic profile), and z is the distance in the direction of propagation.

Snell's law is used to find the angle θ_1 which will allow horizontal propagation in the free-space region. It can then be shown that the resulting compensation offset is given by:

$$y_{offs} = \theta_{ea} \frac{1 - (1/n_0)}{\sqrt{n_2/n_0} \sin(\sqrt{n_2/n_0}d_1)}$$

Fig. 3 demonstrates the effectiveness of this etch compensation technique by showing the results of 3D BPM simulation for etch angular deviations below $10°$. The lens design parameters are as described in [1]. The apparent slight loss of effectiveness of the technique at large angles is due to the BPM algorithm having reduced accuracy when modelling propagation through the sloped interface. BPM simulations indicate that for a front face etch angle of $4°$, the uncompensated optical loss is approximately 4.7 dB. By applying the vertical offset compensation, the optical loss is reduced to approximately 0.04 dB.
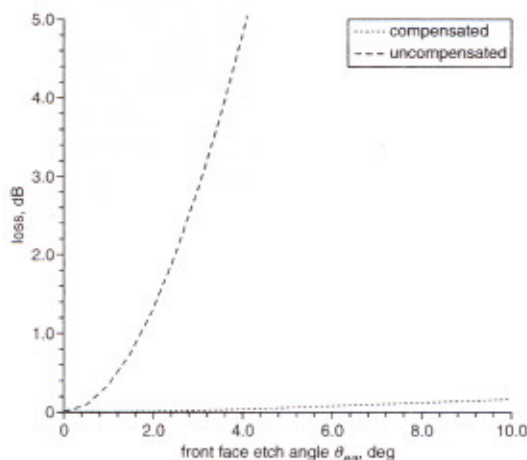

Fig. 3 *BPM simulation of optical loss for etch angular deviations below $10°$*

In summary, the non-vertical silica etch of the planar silica waveguide lens pair causes optical misalignment. However, if the angular deviation from the vertical is constant and reproducible, it can be compensated for by simply offsetting the planar waveguide cores from the centre of the parabolic profile.