Integration of Grating Couplers with Compact PhC Demux on InP Membrane

Tiziana Stomeo[1,*], Frederik Van Laere[2], Melanie Ayre[3], Cyril Cambournac[3], Henri Benisty[3], Dries Van Thourhout[2], Roel Baets[2] and Thomas F. Krauss[1]

[1]*School of Physics and Astronomy, University of St. Andrews, Fife, KY16 9SS, U.K.*

[2]*Department of Information Technology (INTEC) at Ghent University- IMEC, B-9000 Ghent, Belgium*

[3]*Laboratoire Charles Fabry de l'Institut d'Optique, CNRS, Univ Paris-Sud, Campus Polytechnique, RD 128, F-91127 Palaiseau, France*

[*]*Corresponding author: tiziana.stomeo@unile.it*

We demonstrate the integration of a 30% efficient grating coupler with a compact photonic crystal wavelength demultiplexer (DeMUX). The DeMUX has seven output channels that are 10 nm spaced apart and is aimed at coarse WDM applications. The integrated devices are realized on a high-index-contrast InP membrane using a simple BCB wafer bonding technique. Cross-talks of -10 to -12 dB for 4 channels 20nm apart are obtained without optimization. © 2008 Optical Society of America

OCIS codes: (integrated optics, spectrometer, photonic crystals, fiber coupling).

Compact integration of optical functions on a chip is a key driver to provide low-cost optoelectronic devices that are needed in metropolitan optical networks. High-refractive-index

contrast materials and planar photonic crystal (PhC) technology enable the large-scale integration of optical functions, since waveguides, bends and core integrated elements can be very compact. Many recent examples of exploiting a large refractive index contrast are provided by silicon-on-insulator (SOI) structures [1-3] and III-V materials in membrane configuration [4]. Regarding the SOI platform, it is very well suited for performing passive functionality, but it is still rather elusive to achieve active functionality on Silicon, due to its indirect bandgap. An emerging solution is to heterogeneously integrate III–V material (active functions) and SOI (passive functions) [5], placing high demands on both. Another solution is to use Indium Phosphide (InP) compounds, which have been a workhorse for implementing photonic devices with various active functions such as photodetection, tunability and carrier injection for gain and lasing. Since such an integration is especially relevant to frequency-selective devices, we use this approach, rather than silicon, as the platform for our investigation. Namely, we use a simple BCB wafer bonding technique [6] to realize InP membrane type devices. Using this approach, we present the integration of an efficient grating coupler with a very compact PhC wavelength demultiplexer that operates in the 1500-1560 nm wavelength range.

The one-dimensional (1-D) grating coupler (12x12 μm^2) implemented here on top of a gold mirror can achieve a coupling efficiency from standard single-mode fiber to membrane-based waveguides of around 56% [7,8] with relaxed alignment tolerances and relatively large bandwidth. The DeMUX is a membrane version of the device already described in [9-12] for conventional InP heterostructures. It exploits energy transfer caused by intermodal coupling at mini-stopbands (MSB) [13,14] of a multimode PhC waveguide. When polychromatic light impinges along the axis of such a waveguide, it essentially feeds the transverse fundamental mode at all frequencies. But, as it experiences propagation along the periodic PhC waveguide,

this fundamental mode is coupled to a higher-order mode only for the frequency range within the MSB. The generated signal, *i. e.* the WDM signal of interest, is then efficiently and directionally extracted by thinning one of the PhC walls to a few rows. The wavelength selectivity is introduced by varying the central frequency of the MSB, which, in practice, relies on tuning (stepwise or continuously) the PhC waveguide width along the guide.

A typical layout is shown in Fig. 1 a. The PhC waveguide is defined by removing five rows of holes ("W5") along the ΓK direction, with the PhC cladding on one side thinned down to two rows of holes in order to extract the higher-order mode. For each channel, a section of ~ 30 µm in length is sufficient for good extraction, which results in a compact device, that successfully compares to e.g. the approaches of refs [15-17]. The PhC period is 540 nm and the filling factor 41%.

Experimentally, we used a heterostructure consisting (from top to bottom) of 300 nm InP-membrane layer, 400 nm InGaAsP etch-stop layer, 300 nm InP etch-stop layer and 400 nm InGaAsP etch-stop layer on an InP substrate. All the etch-stop layers are sacrificial and are removed in the membraning/benzocyclobutene (BCB) bonding process. We used a heterostructure with multiple etch-stop layers, although simpler designs are possible. The essential part of the heterostructure is the 300 nm InP guide layer followed by a 400-600nm (in our case: 522 nm) thick InGaAs etch-stop layer. A noteworthy challenge is that the 1-D grating coupler requires shallow etching (~90 nm deep) whereas the wavelength-selective DeMUX has to be deeply etched (~300 nm completely through the membrane layer). In order to avoid alignment errors, both the coupler and the DeMUX are written in a single step using a Raith Elphy e-beam lithography tool. After e-beam writing in ZEP520-A positive resist and pattern transfer into the SiO_2 hard mask using reactive ion etching (RIE) with fluorine chemistry, a

window is opened by optical lithography in order to etch the DeMUX first completely through the InP membrane (300 nm). During the first InP etch, the grating coupler and the waveguide are covered with photoresist. The photoresist is then removed and the whole pattern is etched further to a depth of 90 nm. This means that the DeMux is etched slightly into the first InGaAsP etch-stop layer. Since this layer will be removed later, however this is of no consequence. SEM pictures of the sample prior to bonding are shown in Fig. 2. High quality grating coupler (period of 660 nm and duty-cycle of 50%) and PhC DeMUX (hole diameter of 362 nm) with well controlled sizes were achieved after the pattern transferred to the InP layer. In the next step, a BCB-buffer layer is spin-coated onto the InP die and gold is deposited opposite the grating couplers. The die is then bonded onto a GaAs host substrate (with an other BCB layer), aligning the cleaving planes of both substrates [6]. We chose GaAs as host substrate in the BCB bonding process to facilitate facet cleaving, although other substrates such as SOI or Silicon are equally suitable. After curing of the BCB, the InP substrate is removed using lapping and wet etching. Finally, all three etch-stop layers are wet etched, the BCB is removed from the holes by inductively coupled plasma (ICP) etching in order to obtain air holes and an output facet is cleaved (see optical image in Fig. 1.b).

In order to test the integrated device, a single-mode input fiber connected to a tunable laser is positioned at 10 degrees off the vertical axis above the grating in order to avoid reflections [7]. The 1-D grating couples the light into the membrane waveguide from where it feeds into the PhC demultiplexer. The optical signal in the 7 channels, ranging from 1500 nm to 1560 nm, is collected at the output facet using a microscope objective lens and measured with a detector. One channel is measured at time, while scanning the laser frequency. The demultiplexing operation of the PhC device can be clearly seen in Fig. 3.b. The Q-factor

obtained for the extracted signals as well as the uniform channel spacing of 10 nm are close to those designed. The output signals are normalized to the input grating coupler spectrum determined from a fibre-to-fibre reference measurement on the same sample (see Fig. 3. a). The cross-talk of the device is -8 to -12 dB for channels spaced by 20 nm. Between adjacent channels (10 nm spacing) it raises up to -4 dB instead of the theoretically predicted value of -7.5 dB. Improvement should result from engineering the transfer function of the MSB, *e.g.* through fine-tuning the size and number of holes of the PhC cladding through which the signal is extracted. Fig. 3.c shows the corresponding coupled-mode modeling [12], which reproduces very well all the spectral details related to the succession of shifted MSBs, for example the kinks and shoulders of the rightmost channel spectrum. The basis towards further optimization is thus clearly given, and hinges on modestly reducing losses and optimizing the section lengths for each channel.

In conclusion, we have demonstrated the integration of two very distinct passive structures on a bonded InP membrane. We combined a shallow-etched 1-D grating coupler with a deeply etched PhC demultiplexer for operation at 1500-1560 nm wavelength window. We achieved a good separation of 7 optical channels with a spectral resolution of 10 nm and -4 dB cross-talk, or 4 channels suitable for coarse WDM at 20 nm spacing with a cross-talk of -10/-12 dB. The typical -10/-12 dB cross-talk for the CWDM 20 nm spacing (every other channel here) can be further improved, all the more because the coupled-mode theory underlying the demultiplexing operation seems fully validated for this first implementation on a membrane. We thus demonstrate a remarkable combination of a nanophotonic strong-index contrast technology and of a design exploiting modes at such a mesoscopic scale, that applicability of a revisited coupled mode approach is granted. This extension of tools that have proven so benefitial to

5

traditional integrated optics in the past and today, in one of the most compact embodiments for demultiplexing [16-18], clearly fosters the perspectives of nanophotonic approaches towards devices of the real-world. Along this line, further extension of this work to include detectors and emitters is readily possible, given the InP based material used in our experiments.

References

1. M. Loncar, T. Doll, J. Vuckovic and A. Scherer, "Design and fabrication of silicon photonic crystal optical waveguide", IEEE J. Lightwave Technol**. 18**, 10, 1402-1411 (2000).

2. I. Marki, M. Salt, H. P. Herzig, R. Stanley, L. El Melhaoui, P. Lyan and J. M. Fedeli, "Optically tunable microcavity in a planar photonic crystal silicon waveguide buried in oxide," Opt. Lett. **31,** 4, 513-515 (2006).

3. Y. Akahane, T. Asano, B.S. Song and S. Noda, "Fine-tuned high-Q photonic-crystal nanocavity", Opt. Express, **13**, 4, 1202-1214 (2005).

4. A. Xing, M. Davanco, D. J. Blumenthal, E. L. Hu, "Fabrication of InP based 2D photonic crystal membrane", J. Vac. Sci. Techn. B, **22**, 1, 70-73 (2004).

5. H. T. Hattori, C. Seassal, E. Touraille, P. Rojo-Rmeo, X. Letartre, G. Hollinger, P. Viktorovitch, L. Di Cioccio, M. Zussy, L. El Melhaoui, and J. M. Fedeli, "Heterogeneous integration of microdisk lasers on silicon strip waveguides for optical interconnects", IEEE Photon. Technol. Lett., **18**, 1, 223–225 (2006).

6. G. Roelkens, J. Brouckaert, D. Van Thourhout, R. Baets, R. Notzel and M. Smit, "Adhesive bonding of InP/InGaAsP dies to processed silicon-on-insulator wafers using DVS-bis-benzocyclobutene", J. Electrochem. Soc. **153**, G1015-G1019 (2006).

7. D. Taillaert, F. Van Laere, M. Ayre, W. Bogaerts, D. Van Thourhout, P. Bienstman, R. Baets, "Grating couplers for coupling between optical fibers and nanophotonic waveguides", Jpn. J. Appl. Phys. **45**, 6071-6077 (2006).

8. F. Van Laere, G. Roelkens, M. Ayre, J. Schrauwen, D. Taillert, D. Van Thourhout, T. F. Krauss, R. Baets, "Compact and highly efficient grating couplers between optical fiber and nanophotonic waveguides", IEEE J. Lightwave Technol. **25**, 151-156 (2007).

9. E. Viasnoff-Schwoob, C. Weisbuch, H. Benisty, C. Cuisin, E. Derouin, O. Drisse, G. H. Guan, L. Legouezigou, O. Legouezigou, F. Pommereau, S. Golka, H. Heidrich, H. J. Hensel and K. Janiak, "Compact wavelength monitoring by lateral outcoupling in wedged photonic crystal multimode waveguides", Appl. Phys. Lett. **86**, 101107-1-3 (2005).

10. L. Martinelli, H. Benisty, O. Khayam, G. H. Duan, H. Heidrich and K. Janiak, "Analysis and optimization of compact demultiplexer monitor based on photonic crystal waveguide", IEEE J. Lightwave Technol. **25**, 2385-2394 (2007).

11. L. Martinelli, H. Benisty, O. Drisse, E. Derouin, F. Pommereau, O. Legouezigou and G. H. Duan, "Impact of lithographic grid irregularity assesser on photonic crystal device selectivity", IEEE Photon. Technol. Lett. **19**, 282-284 (2007).

12. M. Ayre, C. Cambournac, H. Benisty, O. Khayam, H. Benisty, T. Stomeo and T. F. Krauss, "Photonic crystal waveguides for coarse-selectivity devices", Photon. Nanostruct.: Fundam. Applic., doi:10.1016/j.photonics.2007.09.004 (2007).

13. S. Olivier, H. Benisty, C. Weisbuch, C. J. Smith, T. F. Krauss and R. Houdré, "Coupled-mode theory and propagation losses in photonic crystal waveguides", Opt. Express **11**, 13, 1490-1496 (2003).

14. S. Olivier, M. Rattier, H. Benisty, C. J. M. Smith, R. M. De La Rue, T. F. Krauss, U. Oesterle, R. Houdré, and C. Weisbuch, "Mini stop-bands of a one-dimensional system: The channel waveguide in a two-dimensional photonic crystal", Phys. Rev. B **63**, 11, 113311-1-6 (2001).

15. T. Niemi, L. H. Frandsen, K. K. Hede, A. Harpoth, P. I. Borel, and M. Kristensen, "Wavelength -division demultiplexing using photonic crystal waveguides," IEEE Phot. Technol. Lett., **18**, 226-228 (2006).

16. Y. Akahane, T. Asano, H. Takano, B.-S. Song, Y. Takana, and S. Noda, "Two-dimensional photonic-crystal-slab channel-drop filter with flat-top response," Opt. Express, **13**, 2512-2530 (2005).

17. J. Brouckaert, W. Bogaerts, P. Dumon, D. Van Thourhout, and R. Baets, "Planar Concave Grating Demultiplexer Fabricated on a Nanophotonic Silicon-on-Insulator Platform," IEEE J. Lightwave Technol., **25,** 1269-1275 (2007).

18. W. Lijun, M. Mazilu, T. Karle, T.F. Krauss, " Superprism phenomena in planar photonic crystals", IEEE J. Quantum Electronics, **38**, 915-918 (2002).

Figure captions

Fig.1. (a) Layout of the PhC demultiplexer with 7 output channels. (b) Overall test circuit comprising shallow-etched grating and PhC demultiplexer, flip-chipped and BCB-bonded to a host substrate.

Fig. 2. SEM pictures of the devices prior to bonding. (a) Complete device layout: 1-D Grating Coupler integrated with PhC DeMUX. (b) Input grating coupler (shallow etch). (c) Entrance of the PhC waveguide. (d) Single-channel view. (e) PhC holes (deep etch).

Fig. 3. (a) Grating coupler spectrum control. (b) Channel output normalized to the grating coupler spectrum. (c) Coupled-mode theory modeling rendering most spectral details.
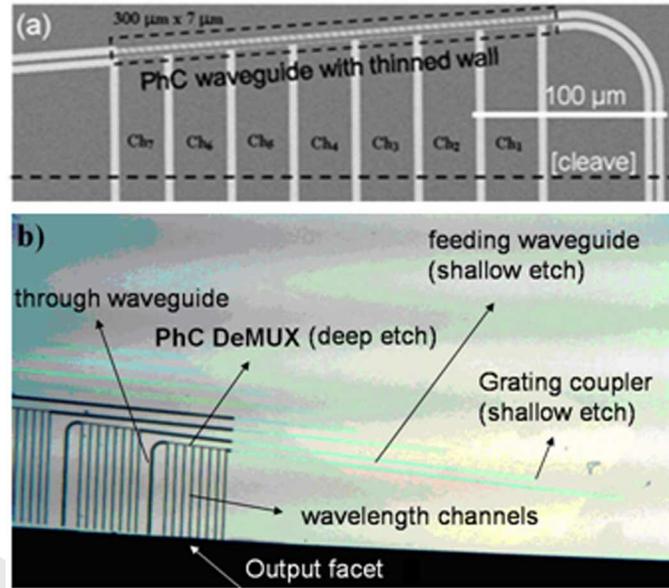
Figure 1

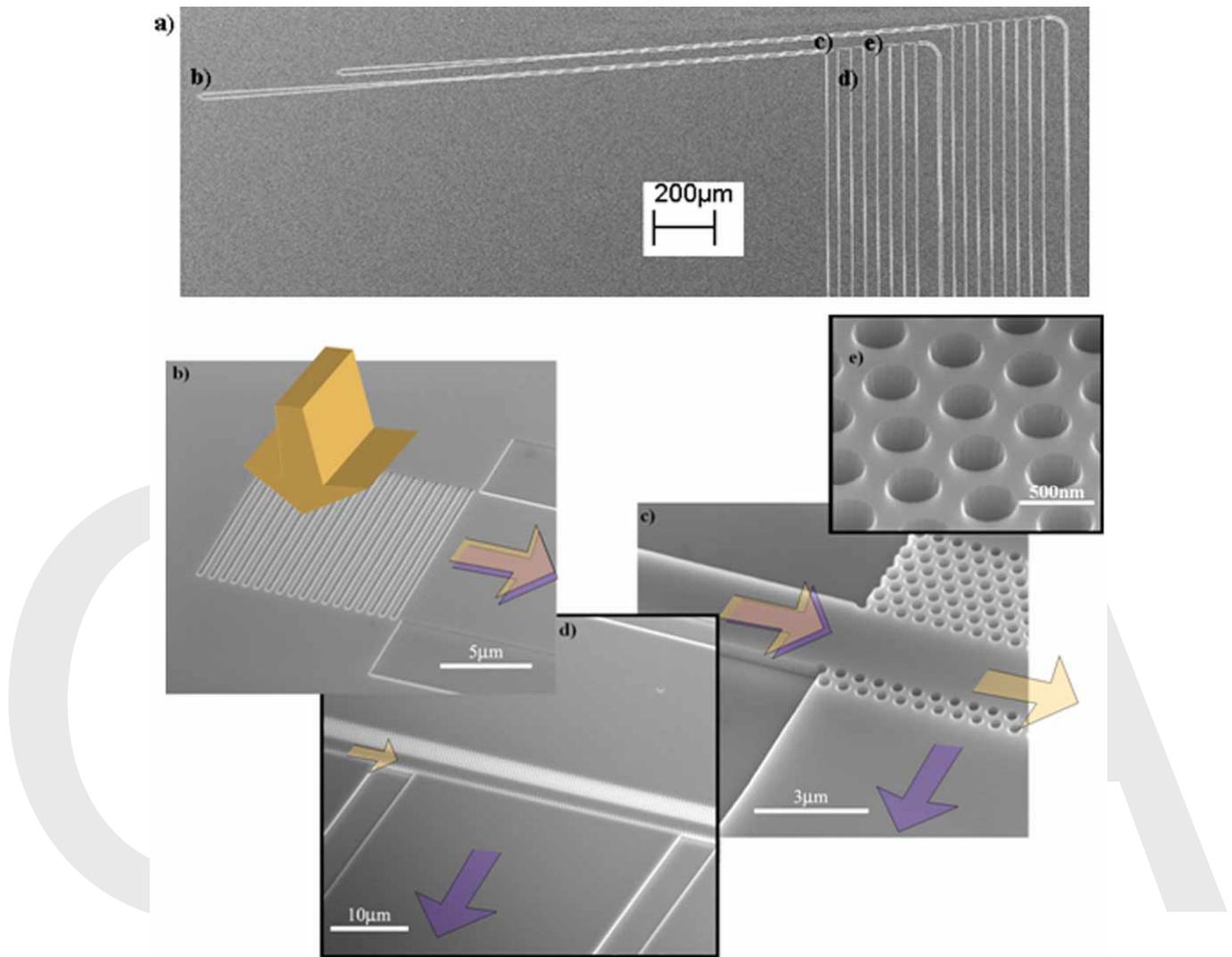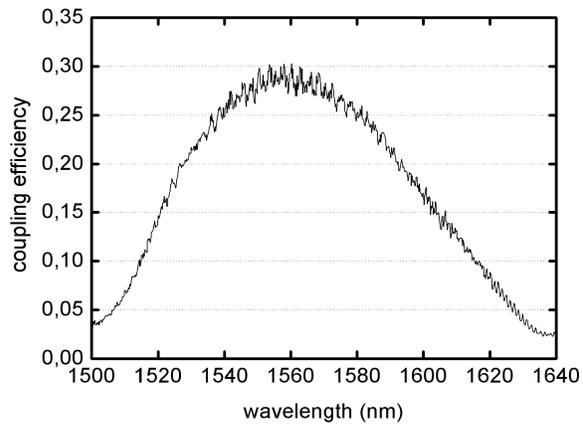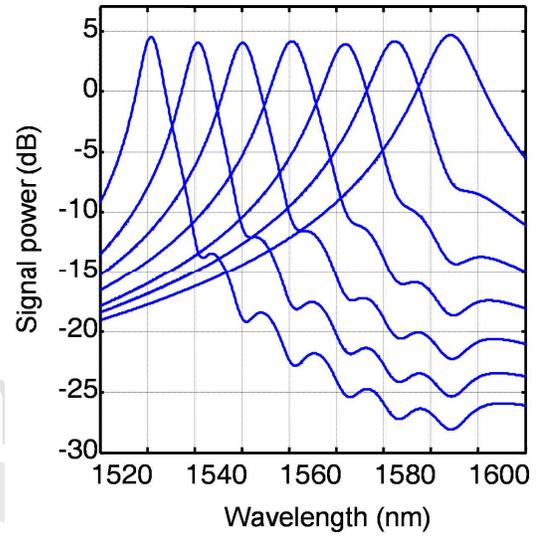(a) 300 μm x 7 μm
PhC waveguide with thinned wall
100 μm
Ch₇ Ch₆ Ch₅ Ch₄ Ch₃ Ch₂ Ch₁
[cleave]

b)
through waveguide
feeding waveguide
(shallow etch)
PhC DeMUX (deep etch)
Grating coupler
(shallow etch)
wavelength channels
Output facet

Figure 2

Figure 3

a)

b)

c)