Successful fabrication and integration of multifunctional photonic-crystal devices on bonded InP membrane chip

T. Stomeo[1*], T. F. Krauss[1], F. Van Laere[2], D. Van Thourhout[2], R. Baets[2], C. Cambournac[3], M. Ayre[3], H. Benisty[3]

[1]School of Physics and Astronomy, University of St. Andrews, Fife, KY16 9SS, St. Andrews, U.K.
*present address: tiziana.stomeo@unile.it
[2]Department of Information Technology (INTEC), Ghent University-IMEC, 9000, Gent, Belgium
[3]Institut d'Optique, CNRS, Campus Polytechnique, RD 128, 91127 Palaiseau Cedex, France

Abstract. *An ultra-compact photonic-crystal DeMUX for coarse-WDM applications is successfully integrated with a polarization-independent surface coupler on bonded InP membrane. The optimized technology allows to integrate the DeMUX with photodetectors as well, showing that both active and passive functionalities are implemented in III-V materials, without combining different material systems.*

Introduction

Nowadays, low-cost and small-footprint integrated optical devices for metropolitan optical network are actively demanded. One of the requirements for photonic integrated circuits is the need for system-oriented multi-functionality, *i.e.* the ability to perform different operations desired by system engineers, under the same materials technology simply by adjusting the geometry of the structure itself and by joining several devices together to form a complete integrated sub-system. This multi-functionality —a core concept of the EU project FUNFOX (IST-04582)— is addressed here by implementing two kinds of photonic-crystal (PhC) structures in bonded InP membranes.

The fabrication of these PhCs is typically carried out using electron-beam lithography and dry etching, and the precise fabrication of the 2D structure is always a critical issue for achievement of low-loss and high-quality components in photonic integrated circuits. Well-controlled pattern features are necessary in order to get a PhC device exhibiting the desired functions. There are various kinds of fabrication errors that might cause deviation from perfect photonic-crystal structures, such as the deviation of the periodicity due to the hole misplacement, hole size non-uniformity due to errors in the e-beam writing, proximity-effect-induced non-uniformity in the e-beam lithography, or systematic hole size change due to imperfect sidewall features formed during the dry etching process.

The variation of hole size due to fabrication errors could have a significant impact on the photonic bandgap. In this work, special attention is given to the electron-beam lithography (EBL) process for making the PhC patterns with well-controlled size, in order to integrate PhC DeMUX devices with 1D grating coupler without spectral mismatch. We also report on a highly controlled EBL approach to align different structures, which allows us to successfully fabricate efficient polarization diversity couplers integrated with photodetectors on bonded InP-membrane.

1D Grating Coupler integrated with 2D PhC DeMUX

The integrated device we implemented consists of 1D grating-coupled [1-2] PhC-based demultiplexer on bonded InP membrane, for application in coarse-WDM systems operating at 1500-1560 nm wavelength window. The DeMUX action is based on the anticrossing phenomenon, so-called mini-stopband (MSB) [3-4], supported by PhC multimode waveguides.

The basic heterostructure consists of a 300 nm-thick InP membrane sandwiched between air and benzocyclobutene (BCB, a low-index polymer, $n = 1.54$ at 1.55 µm) on a host substrate. The 1D coupler and the seven-channel DeMUX consisting of a W_{5+x} 2D PhC waveguide ($|x| < 0.26$) were written in a single step using a hybrid LEO Gemini 1530/RAITH ELPHY e-beam lithography tool operating at 30 kV. The ZEP520-A resist thickness of 400 nm was chosen to ensure sufficient durability as a mask for the RIE transfer of the pattern into an underlying SiO_2 layer and at the same time, to ensure good resolution of e-beam writing. The key issue in the fabrication process is to achieve PhC devices with well-controlled patterns size. A proximity error correction (PEC) had to be applied to reach this target. Moreover, in order to achieve smoother and circular holes and faster exposure, the EBL system was used in "circular mode". In this mode, every circular hole is exposed by the deflection of the beam along concentric circles.

High-quality grating coupler (660 nm period and 50 % duty cycle) and PhC DeMUX (362 nm hole diameter and 540 nm period) with well-controlled sizes were achieved after the resist development. The other demux-device's fabrication steps are described in [5]. In Fig. 1 are shown SEM pictures of the devices prior to bonding. The demultiplexing operation of the PhC device is demonstrated by the experimental data of Fig. 2. Note the precise 10 nm spacing, and the non-next-channel cross-talk of ~ –10 dB.

Polarization diversity grating-coupled 2D PhC DeMUX integrated with photodetectors

Thanks to the progresses in surface couplers on InP membrane [6-8], we could fabricate a complete integrated device consisting of (i) a polarization diversity surface coupler, (ii) a MSB-based DeMUX , and (iii) integrated photodiodes.

The basic system is always a BCB-bonded InP membrane. Also in this case a single e-beam process was performed, but it required a highly controlled approach to align the 2D polarization diversity coupler integrated with 2D PhC DeMUX to the photodetectors. The process is based on a two-step procedure: (i) First detector mesas and alignment marks have been defined using optical lithography and etching until the InP-membrane layer is reached; (ii) In a following step, 2D coupler, waveguides, and 2D PhC DeMUX have been aligned to the detector mesas using a controlled EBL process carried out by means of a hybrid LEO Gemini 1530/RAITH ELPHY e-beam lithography system. The approach is reproducible and widely applicable allowing tight alignment accuracy.

A complete layout of the device after e-beam alignment process and mask etch is shown in Figure 3. It involves a 2D polarisation diversity coupler on the input side, tapering down to single mode waveguides and bends, entering into the 2D PhC demultiplexer section. The subsequent detection of each wavelength is achieved by an integrated detector. The overall footprint is small but can be significantly shrunk to 100×150 µm with curved grating couplers and much shorter tapers. Figure 4 shows the spectral response (photo-current, linear scale) of the three rightmost channels and the through detector (Channel 4 was damaged). These results highlight that very high standards of fabrication accuracy need to be met in order to integrate high-quality multifunctional PhC devices.

Acknowledgements

Authors acknowledge the FP6 European Project IST-04582 “FUNFOX” (2004-2007).

References

[1] D. Taillaert et al., Jpn. J. Appl. Phys. 45, 6071-6077, 2006.
[2] F. Van Laere et al., IEEE J. Lightwave Technol. 25, 151-156, 2007.
[3] S. Olivier et al., Phys. Rev. B 63, 113311 (1-6), 2001.
[4] L. Martinelli et al., IEEE J. Lightwave Technol. 25, 2385-2394, 2007.
[5] T. Stomeo et al., “Integration of Grating Couplers with Compact PhC Demux on InP Membrane”, submitted to Optics Letters (2008).
[6] F. Van Laere et al., IEEE Phot. Technol. Lett. 19, 1919-1921, 2007
[7] F. Van Laere et al., IEEE Phot. Techn. Lett. 20, 318-320, 2008
[8] F. Van Laere, D. Van Thourhout, R. Baets, T. Stomeo, T. F. Krauss, M. Ayre, C. Cambournac, and H. Benisty, "Multifunctional Photonic Crystal Compact Demux-Detector on InP," paper OThM5, presented at OFC/NFOEC 2008, 25-28 Feb., San Diego, 2008.

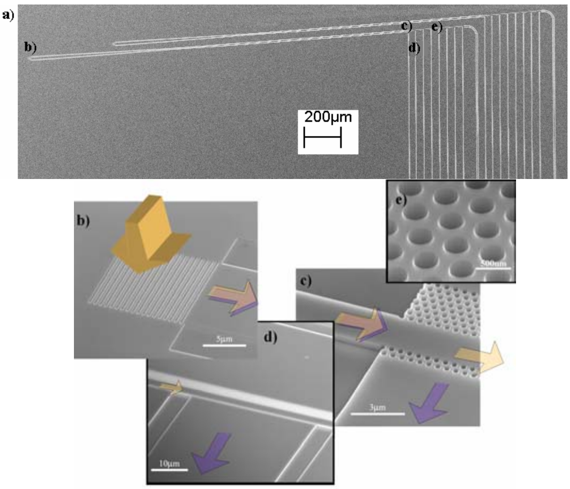

Figure 1:
(a) Complete device layout: 1D Grating Coupler integrated with PhC DeMUX.
(b) Input 1D grating coupler (shallow etch).
(c) Entrance of the PhC waveguide.
(d) Channel1, at DeMUX entrance.
(e) PhC holes (deep etch).

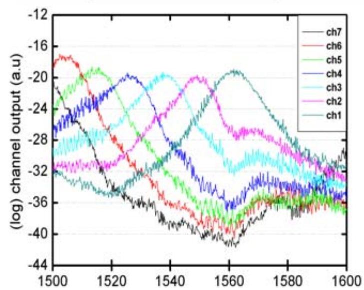

Figure 2: Experimental data from seven-channel demux with cleaved edge. A good separation of 7 optical channels with a spectral resolution of 10 nm nearly suitable for coarse WDM at 20 nm spacing is achieved.

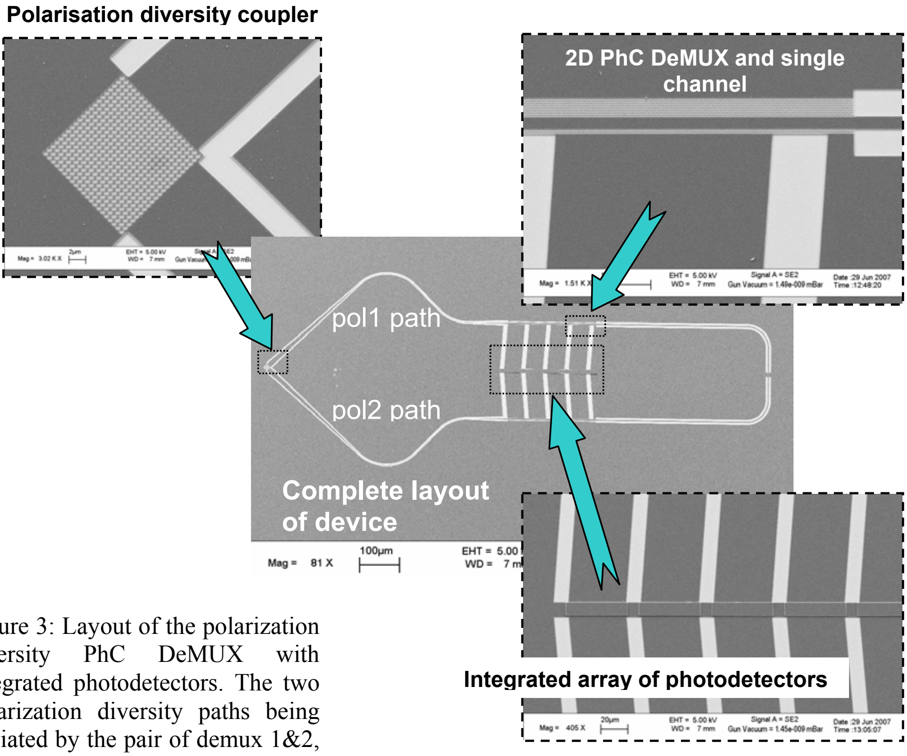

Figure 3: Layout of the polarization diversity PhC DeMUX with integrated photodetectors. The two polarization diversity paths being deviated by the pair of demux 1&2, and recombined in the array of photodiodes, including the 'through' waveguide.

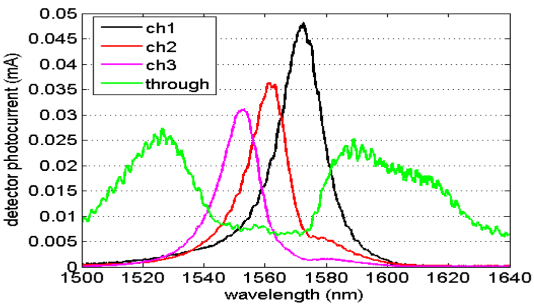

Figure 4: Spectral response (photo-current, linear scale) of the three rightmost channels and the through detector. Channel 4 was damaged.