# e-Newsletter Issue 2

## December 2011

# "Compact OTDM / WDM Optical Receivers based on Photonic Crystal Integrated Circuits"

## Welcome from the Coordinator!

Welcome to the second edition of the COPERNICUS project e-Newsletter! It has been an exciting year for our project consortium with many exciting achievements and results. I hope you will enjoy learning about our recent progress within this e-Newsletter.

I would also like to take this opportunity to wish you an enjoyable holiday season and a successful 2012!

*Alfredo de Rossi, Project Coordinator*

## Welcome from the Editor!

Welcome to our second e-Newsletter! Our project is progressing well and my colleagues and I are pleased to bring you news of our progress. I hope that you find this e-Newsletter informative and visit our website to find out more.

By visiting our website, www.copernicusproject.eu, you can access our previous e-Newsletter as well as a range of other project documents. In the meantime, if you have any comments or questions, please email me using the address below.

*Steve Bull, Editor*
*Email: editor@copernicusproject.eu*

## In this issue…



## Latest News

The second year of the COPERNICUS project has seen many excellent developments and exciting results across the breadth of the project. These have included:

- Photonic crystal (PhC) photodetectors (PDs) with a bandwidth >40 GHz (see below)
- Wavelength drop filters with a drop efficiency of 50% and an extinction ratio of 30dB (see article)
- 42.7Gbit/s transmission through both the drop and bus channels of a filter (see next page)
- A tunable wavelength drop filter (see next page)
- An InP-based all-optical-gate (AOG)
- Reproducibility of PhC resonators across wafers
- Successful shock testing of tapered PhC couplers
- Improved design and validation of optical couplers
- Development of design tools for AOGs and PDs, including 2D & 3D CW PD models, yielding good agreement with experiment

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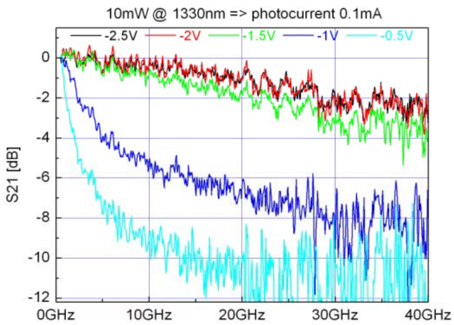
**High-speed photodetectors**

A high-speed PD compatible with PhC technology has been developed and fabricated at DTU Fotonik (see photo). Small signal dynamic measurements (0–40GHz) have been performed to evaluate the PD bandwidth. A network analyser calibrated with a U2T 50GHz PD and a 50GHz GSG (ground-signal-ground) probe were used for the measurements. The $S_{21}$ curves (see graph) show that our PD has a 3dB bandwidth > 40GHz at -2V bias.



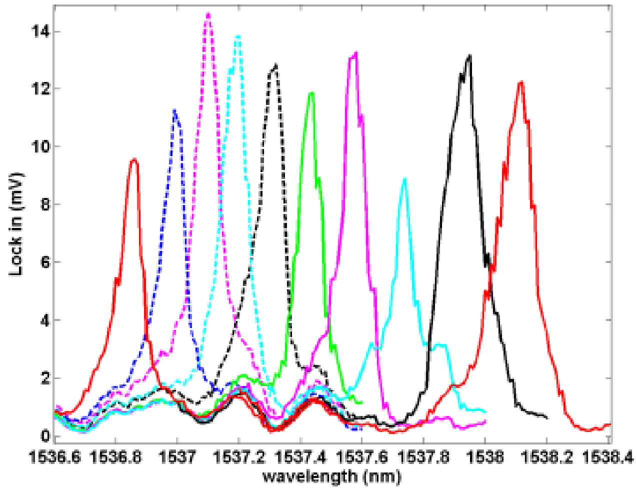

***$S_{21}$ measurements (above) and image of a fabricated PD (right)***

## Latest News

**Wavelength drop filters**

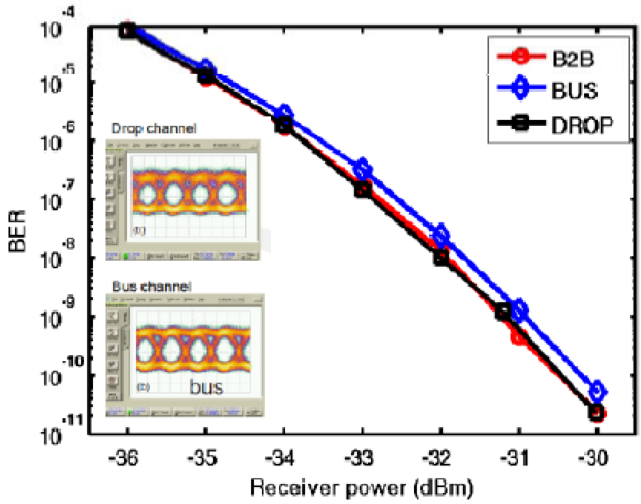
At TRT, the fabrication of PhC-based filters for the WDM receiver has continued with design support from UniFe and high bit rate characterisations at FOTON. We have recently demonstrated a GaAs-based PhC membrane filter with 50% drop efficiency and 30dB extinction ratio (see full article for further details).

We have also demonstrated the tunability of our filters through integrated electric heaters. A 1nm shift in the resonance requires 0.7mW of electrical power and we expect to achieve a tuning range of 10nm in our next iteration.




***Tuning of the filter resonance by an electric heater***

Finally, high bit rate characterisations have shown that our first generation filter introduces no penalty in the bit error rate or eye diagrams when tested with a NRZ data signal at 42.7Gb/s.




***BER measurements and eye diagrams of the signal through the Bus and Drop channels and comparison to Back to Back (B2B) transmission***

*Presented at 17th Microoptics Conference, Sendai, Japan, Nov. 2011*

## CNRS: Laboratory for Photonics and Nanostructures (LPN)

The Laboratoire de Photonique et de Nanostructures, LPN, (47 permanent research staff, 38 technical staff) is a unit of the Centre National de la Recherche Scientifique (CNRS). LPN's research activities are within the general context of nanoscience, from fundamental research and development of novel concepts to their implementation and demonstration of new devices. LPN's research is organised in six major themes: Quantum & Nonlinear Optics; Nanostructure, Electron Gas & Spin Electronics; Heterostructures Physics & Growth; Semiconductor & Nanostructure Processing & Analysis; Microelectronics & Photonics Devices; and Microfluidics & Nano-structures for Chemistry & Biology. Its research activities impact areas of quantum information processing, optical communications, all-optical signal processing, high density data storage and microfluidic devices.

LPN has a longstanding reputation for pioneering work in nonlinear optics and III-V semiconductor active devices (nanolasers, bistable devices, 2nd harmonic generators). LPN was the first to demonstrate the heterogeneous integration of a III-V semiconductor photonic crystal laser on SOI. This was followed by a demonstration of optical bistability in a hybrid nanolaser. A record small wire cavity nanolaser (~5µm$^2$), with a very low threshold, has also been obtained.

### Activities within COPERNICUS

Within the project, the main roles of LPN are: growth of InP active layers; modelling, design and processing of all-optical gates (AOGs); time resolved measurements and nonlinear optical experiments related to the AOGs.

### Further Information

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## CNRS: Optical Functions for Information and Communication Technologies (FOTON)

The CNRS associated laboratory FOTON (Fonctions Optiques pour les Technologies de l'InformatiON) involves three teams in the towns of Lannion, Brest and Rennes. Its research topics are the engineering of optical functions for information technologies covering a very broad area from materials to optical telecommunication network modelling.

FOTON benefits from many strong interactions with local companies and SMEs, some of which are spin-offs from FOTON itself. FOTON is involved in various national programmes (ANR) and European projects. In Lannion, 50 permanent and non permanent researchers work on a number of research topics in the area of optical functions.

At FOTON, the Persyst platform is a characterisation platform for the testing of and research on optical telecommunications systems. It is well equipped for high bit rate telecommunication experiments and has strong experience in the field of all optical signal processing. The CCLO platform develops skills in integrated optics, technologies for coupling optics and also in optical characterisation.


*From the beach to the labs !*

### Activities within COPERNICUS

Within the project, the main roles of FOTON are: microlensed fibre modelling, fabrication and optimisation of microlensed fibres; nonlinear gate architecture design; far field measurements; high bit rate characterisation: bit error rate measurements, eye diagrams at 25 Gbit/s and 100 Gbit/s; polarisation effect assessments; and the final functionality assessment of the devices produced.

### Further Information

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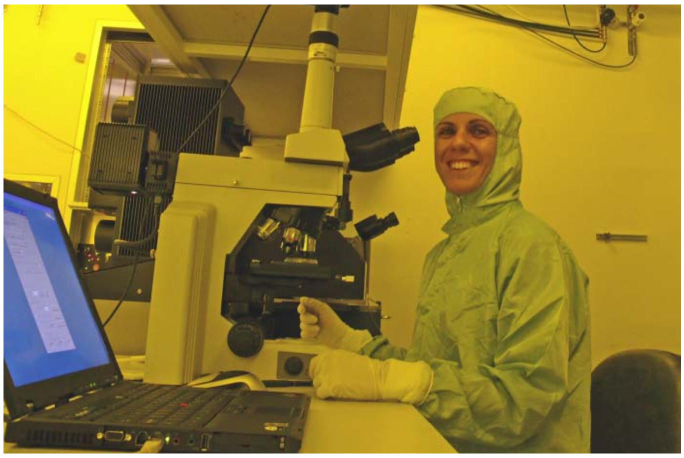
## Technical University of Denmark (DTU)

DTU Fotonik (DTU) started in 1998 (then named COM DTU) with a mission to strengthen the Danish education and research effort on optical and communication technologies. The department comprises around 180 researchers including Ph.D. students and has a unique integration of activities spanning from materials and components to systems and networks.

DTU Fotonik has access to a full III-V semiconductor process line at the national cleanroom facility Danchip, including MOVPE crystal growth, e-beam lithography and metrology. DTU Fotonik also has state-of-the-art optical laboratories, including femtosecond spectroscopy and high-speed systems characterisation. Advanced models and software are available for simulating the properties of semiconductor devices.

DTU Fotonik has had a long-term collaboration with DTU Mechanical Engineering on topology optimisation of photonic crystal structures and members of this department are also part of the DTU group engaged in COPERNICUS.



### Activities within COPERNICUS

Within the project, the main roles of DTU are to fabricate the photodetectors and to provide modelling for the non-linear gates and topology optimisation of the optical structures. In addition, the DTU cleanroom facilities are used jointly with the other project partners to provide redundancy, especially with respect to MOVPE growth and e-beam writing.

### Further Information

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# Design and Fabrication of Key Photonic Crystal Devices

## 1. Introduction

The aim of the COPERNICUS project is to develop cutting-edge photonic crystal technology for the high density integration of basic optical functions. This article summarises the COPERNICUS approach to the design and the realisation of key photonic crystal devices.

## 2. Key devices and fundamental components

The global objectives of the COPERNICUS project target the development of compact demultiplexing receivers for 100Gb/s optical time division multiplexed (OTDM) and wavelength division multiplexed (WDM) signals, all based on photonic crystal technology. These devices are built by combining different fundamental blocks including all-optical gates, wavelength drop filters and high-speed photodetectors. Several partners (DTU, TRT, UniFe, UNott) are responsible for various aspects of the design of these components and a range of modelling techniques, as detailed in [1], are employed. LPN leads the activities related to material engineering, while the fabrication of the devices is then performed at DTU, LPN and TRT. Final characterisations are performed by both FOTON and TRT, while U2T are responsible for packaging of the chips. Finally, TSA leads the demonstration and exploitation activities.

### *2.1 OTDM Receiver and All Optical Gates*

The realisation of an all-optical time domain receiver operating at 100Gb/s is a real challenge for today's optical technology. The All Optical Gate (AOG) is the core component of the OTDM receiver. In this component, the extraction of the output signal from the input frame is obtained by means of an optical control pulse, which detunes the resonance of the cavity via optically induced changes in the carrier density and/or cavity temperature. Material and structural properties influence each other and a thorough understanding of both physical material properties (e.g. carrier lifetime) and their complex dynamics are required. A deep knowledge of both the properties of suitable materials and the technological processes available for device fabrication are therefore fundamental. In depth investigations have been carried out at LPN with the particular aim of obtaining a short carrier lifetime, which is a necessity for fast AOGs. Pump-probe experiments are performed to explore the dynamics of the switching of a suitable cavity. Changes in the resonant wavelength are measured as a function of the pump-probe delay and one example of these results is illustrated in Fig. 1 (left). Design and modelling of the AOG is also vital. The key tools for the modelling of the AOG are coupled mode theory (CMT) in the time domain and FDTD (both linear and nonlinear). The central section of Fig. 1 shows a SEM image of a fabricated AOG. The results of an all-optical modulation of a CW probe experiment are shown in Fig. 1 (right). For this device, when operating in linear regime, the resonance is centred at 1542nm and the measured quality factor is Q ~ 5000.

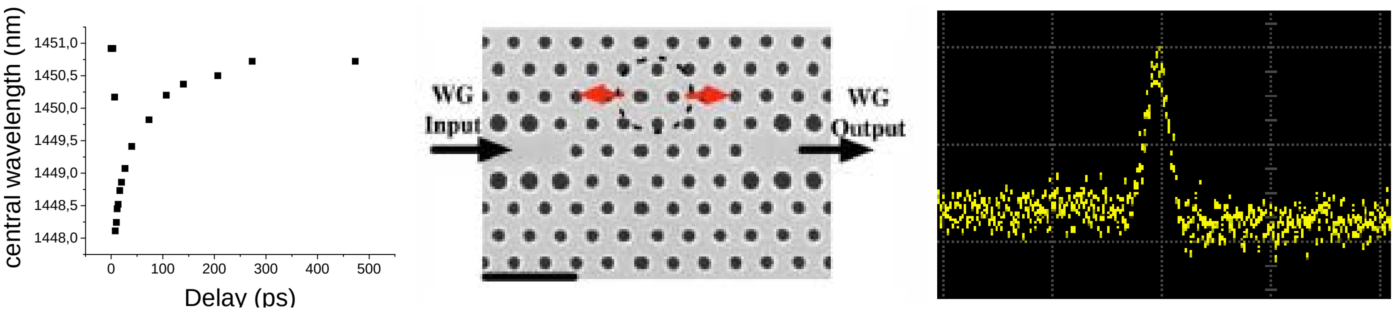


***Figure 1: Shift in the resonant wavelength of the cavity as a function of the pump-probe delay measured at LPN (left); SEM image of an AOG fabricated at TRT (centre); All-optical modulation of a CW probe experiment performed at FOTON with trains of 100ps pulses at 500MHz (vertical axis: 1mV/div; horizontal axis: 200ps/div) (right).***

### *2.2 WDM Receiver and Wavelength Drop Filters*

The second key device being developed within COPERNICUS is a four channel WDM receiver operating at 25Gb/s per channel. At the core of this device are wavelength drop filters that must match the performance specifications for WDM in terms of crosstalk rejection, bandwidth and frequency spacing.

Many different filter topologies have been considered, with the aim of obtaining high drop efficiencies and suitable linewidths. Filters based on a mirror cavity configuration were initially investigated. In this configuration, the first cavity acts as resonant tunnelling-based channel drop filter whereas the second resonator is used to realise a wavelength-selective reflection feedback in the bus waveguide. Detailed CMT analysis and intensive 3D-FDTD simulations have allowed the design and the optimisation of different topologies based on this concept. As an example, Fig. 2 (left) illustrates one topology of a filter used for the design in both C- and O-bands. In the same image, the reflection coefficient at the input port and the transmission curves at the output ports as a function of wavelength (O-band operation) are plotted. For this configuration, the resonance is around 1315nm, the efficiency is close to 80% and the linewidth is ~ 2nm. TRT has fabricated high-performance filters in the C-band based on air-clad InP membranes. Filters based on a single H0 cavity had a drop efficiency of 50% and an extinction ratio of 30dB (see Fig. 2 (centre & right)).

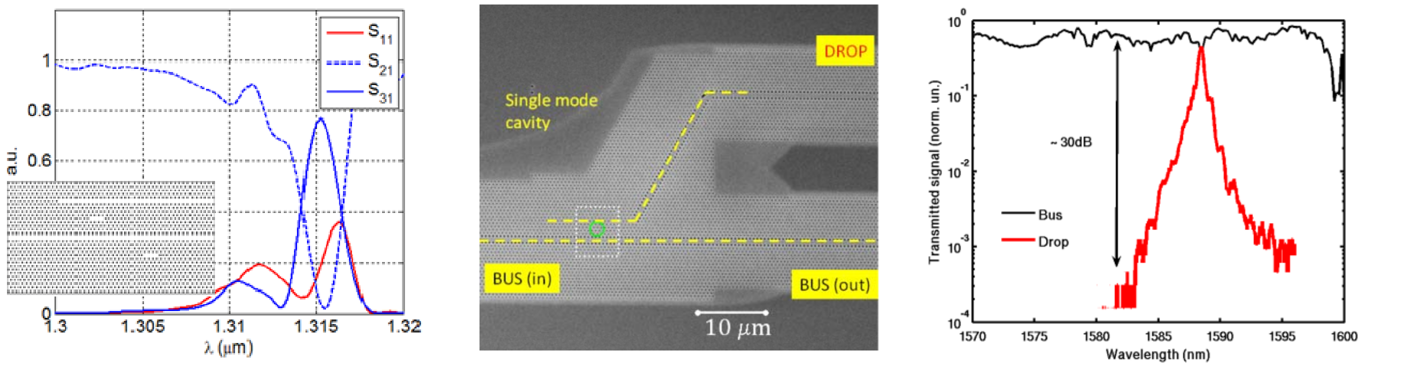


***Figure 2: Transmission curves of a filter operating in the O-band (Red curve: reflection coefficient ($S_{11}$); Blue dotted curve: transmission for the bus waveguide ($S_{21}$); Solid blue curve: transmission towards the drop port ($S_{31}$)) – the inset shows the top view of the 3-port filter based on a mirror cavity configuration (left); SEM image of a single cavity drop filter fabricated at TRT (centre) and measured transmission curves as a function of the wavelength (right) [2].***

### *2.3 Photodetectors*

In both receivers, the electronic output is provided by a compact integrated photodetector. The key requirements for this device are a high responsivity (>0.5A/W) and a fast response (>28GHz). The realisation of this component presents a number of design challenges. For example, a vertical p-i-n structure with an absorbing layer must be integrated with the PhC waveguide. To meet the bandwidth specification, devices with a small RC time constant are required, so the junction area must be kept small. For high responsivity, the optical field must be transmitted from a single-mode PhC waveguide into the small photodetector, requiring careful optical matching and efficient lateral optical confinement.

Optical and electrical simulations have been performed using FDTD (UniFe) and bipolar electro-thermal models (UNott), respectively [1]. The first PhC photodetectors have been fabricated and characterised by DTU. As reported in the latest news section earlier in this e-Newsletter, a 3dB bandwidth of >40GHz at a reverse bias of 2V has been achieved.

### *2.4 Photonic Crystal Circuitry*

The key components (AOGs, filters and photodetectors) of each receiver must be properly connected by means of single mode optical "circuitry" integrated on the same chip. Examples of circuit components include splitters, bends and delay lines.

To optimise the layout, DTU and UniFe have established a design procedure based on 3D-FDTD simulations and topology optimisation (TO). This procedure has been successfully applied to the design of a Y-junction and a double 60° bend, whose optimised layout is illustrated in Fig. 3. Figure 3 also shows the transmission ($S_{21}$) and the reflection ($S_{11}$) coefficients for the optimised (solid lines) and the unoptimised (dashed lines) configurations – the impressive positive effects of the TO are clearly evident. In the C-band, the worst reported values for the reflection and transmission coefficients are $S_{11}$ = -10.49dB ($\lambda$ = 1.58µm) and $S_{21}$ = -1.01dB ($\lambda$ = 1.57µm), respectively.


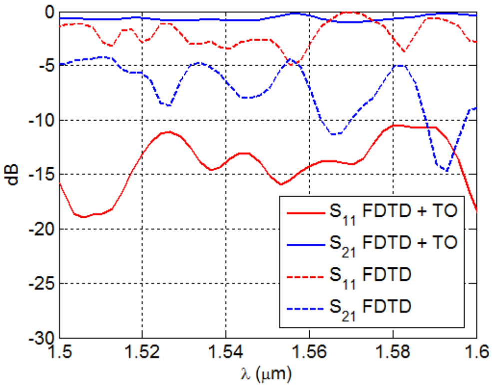


***Figure 3: Optimisation procedures for the design of a double 60° bend with the initial and final layouts shown. The transmission ($S_{21}$) and reflection ($S_{11}$) coefficients for both the optimised (solid lines) and the unoptimised (dashed lines) configurations are also shown (right).***

### *2.5 Coupling and Packaging*

The major breakthrough brought by photonic integrated circuit devices for future optical communication systems relies on their ability to be miniaturised. Many of the costs for miniaturised components are generated by the required precision for the alignment of individual components. Thus, packaging can often account for 40-70% of the costs for components, using classical micro-lenses and optical fibre couplers. In order to drastically reduce costs for complex IT- or data-transmission devices, key developments are focussed on integrating the maximum number of functions and reducing the number of connections while maximising information transfer. Within COPERNICUS, inverse tapers are used to couple lensed fibres fabricated by FOTON with the PhC circuits [3]. To optimise the coupling and relax the constraints due to misalignments, a proper design is needed. The collaboration between FOTON, TRT and UniFe on this topic has allowed the design of tapers and lensed fibres which present losses of about 4dB per coupler. An example of the design activity is given in Fig. 4 (left), which shows the field pattern at the output of a tapered coupler. U2T and FOTON have worked on the PhC to fibre coupling process in order to solve problems related to instability and performance degradation due to possible misalignments in the final packaging. Reliability testing with shock and vibration cycling, pursuant to industrial standards, has been performed on mounted PhC waveguides with tapered input/output couplers. After testing, no damage to the PhC waveguides or tapers is observed (see Fig. 4 (right)).

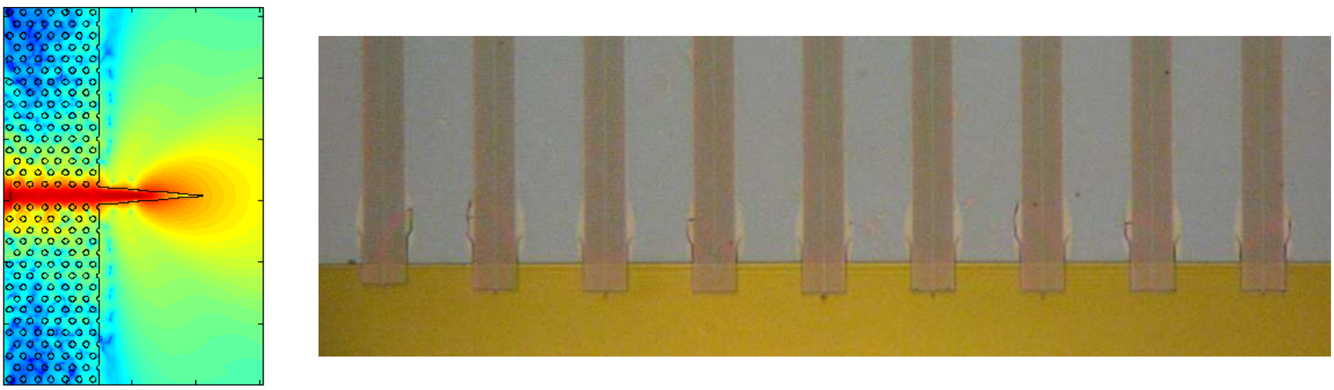

***Figure 4: Output field pattern (top view) at the end of the tapered PhC waveguide (left); Photograph of a PhC sample containing several waveguides with tapered couplers taken after shock and vibration testing (right).***

## 3. Summary

The key building blocks for the realisation of both OTDM and WDM receivers based on photonic crystal technology have been outlined together with details of current progress within the COPERNICUS project. Further details can be found in the listed references and on our project website, http://www.copernicusproject.eu.

***References:***

[1] S. Malaguti, *et al.*, "Numerical Modelling in Photonic Crystals Integrated Technology: The COPERNICUS Project," in Proc. 11th Int. Conf. on Numerical Simulation of Optoelectronic Devices (NUSOD), Rome, Italy, 5th -8th Sept. 2011, paper TuD3.

[2] S. Combrié, *et al.*, "40 Gb/s Wavelength Division Demultiplexing with a PhC Filter," post-deadline paper presented at 17th Microoptics Conference (MOC'11), Sendai, Japan, 30th October - 2nd November 2011.

[3] A. Akrout *et al*, "Coupling between PhC Membrane and Lensed Fibre: Simulations and Measurements," in Proc. 11th Int. Conf. on Numerical Simulation of Optoelectronic Devices (NUSOD), Rome, Italy, 5th -8th Sept. 2011, paper TuD5.