e-Newsletter Issue 3

August 2013

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

Welcome from the Coordinator!

Welcome to our third and final project e-Newsletter! From its very inception, *COPERNICUS* was expected to be a challenging project. The efforts of our dedicated team, however, have brought many exceptional results, of which we are duly proud.

I hope that you find our latest results as exciting and interesting as we do and I thank you all for your continued readership over the last three and half years.

Alfredo de Rossi, Project Coordinator

A final word from the Editor!

Sadly, the *COPERNICUS* project has now reached its conclusion and this is our final project e-Newsletter! I hope that you have enjoyed following the progress of our project over the last three years, just as much as we have enjoyed working on it.

Our website, www.copernicusproject.eu, continues to be updated with our latest results and details of project-related publications and will remain in place beyond the project end. As always, if you have any comments or questions, please email me using the address below.

Steve Bull, Editor
Email: editor@copernicusproject.eu

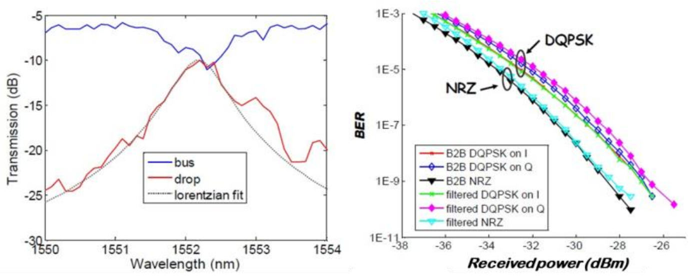
In this final issue...

Latest News

The final period of the *COPERNICUS* project has seen many excellent developments and results, including:

- Successful demonstration of 100 Gbit/s wavelength division multiplexing using a 4-channel photonic crystal (PhC) drop filter *(see next page)*
- Realisation of hybrid InP on SOI PhC nanocavities and successful demonstrations of their use for all-optical wavelength conversion and amplitude noise reduction of 10 Gbit/s NRZ signals *(see article)*
- Efficient second harmonic generation demonstrated in membrane PhC waveguides and applied to optical performance monitoring at 40 Gbit/s
- Design and realisation of wavelength drop filters in BCB-embedded PhC membranes *(see next page)*
- Realisation of high drop efficiency PhC filters for advanced telecom modulation formats *(see below)*
- Development of advanced design tools for all-optical gates and photodetectors, which couple 2D electro-thermal models with both 2D and 3D FDTD code
- Successful environmental testing of membrane PhCs, demonstrating both their reliability and technological/ economical compatibility with conventional CMOS

High drop efficiency PhC filters for advanced telecom modulation formats

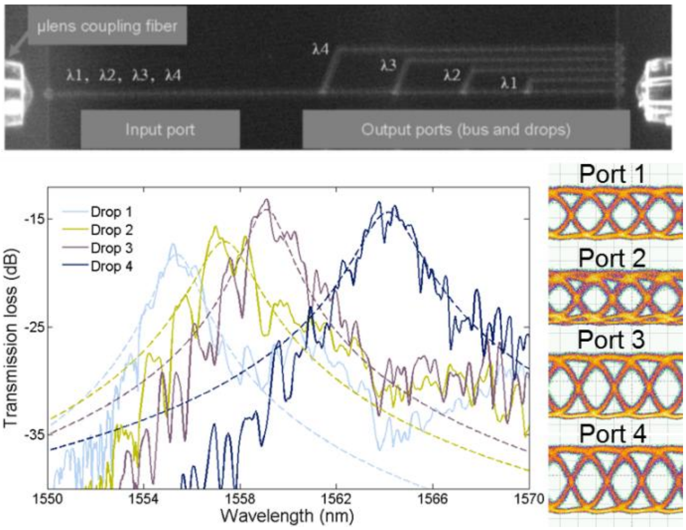


A 2D photonic crystal 3-port filter has been realised with a drop efficiency of 47% and total insertion losses of 6 dB for the bus channel and 10.5 dB for the drop channel. Error free filtering operation with low penalty (<0.5 dB at BER of 10^{-9}) is demonstrated for 28 Gbit/s On-Off Keying and 56 Gbit/s Differential Quadrature Phase Shift Keying (DQPSK) modulation formats.

Latest News (contd.)

100 Gbit/s WDM using a 4-channel PhC drop filter

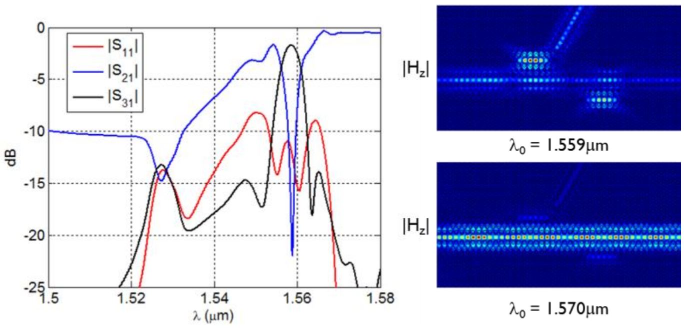
The wavelength demultiplexing of a 100 Gbit/s NRZ signal to 4 channels at 25 Gbit/s has been demonstrated using a device based on resonant structures implemented in a GaInP membrane photonic crystal. The measured device characteristics show good transmission performance for all channels and open eye diagrams after demultiplexing.



An image of the 1.3 mm long WDM filter is shown above. The single input port and 4 output ports are clearly seen. Below the image, the plot shows the transmission through each of the channels of the PhC filter (the input power is normalised to 0 dBm). Eye diagrams are shown of the output at each port after the wavelength demultiplexing of a 100 Gbit/s NRZ signal into 4 channels at 25 Gbit/s.

λ-drop filters in BCB-embedded PhC membranes

3-port filters using a BCB-embedded PhC membrane have been developed to be compatible with the photodetector fabrication process (see e-Newsletter issue 2). The vertical confinement is reduced in the presence of the embedding material and accurate device design is therefore essential.



The modelled S-parameters of one filter design are shown above (left). At the resonant wavelength (λ = 1.559 µm), the reflection coefficient S_{11} = -12.87 dB, the bus transmission S_{21} = -21.50 dB and the drop transmission S_{31} = -1.69 dB. This corresponds to a drop efficiency of ~68%. |Hz| field patterns are shown above (right) for when the filter is on resonance (upper image) and off resonance (lower image).

University of Ferrara (UniFe)

The University of Ferrara (UniFe) is one of the oldest academic institutions in Italy, dating back to 1391. The Department of Engineering was founded in 1996 and has about 60 permanent members of staff and more than 50 PhD students who carry out research in specific areas in the fields of civil engineering, industrial engineering and information communication technology. The department manages various laboratories for teaching and research in different engineering areas (civil, mechanical, electronic) and is equipped with two anechoic chambers for acoustic and electromagnetic compatibility / antenna applications.

The main area of interest of the electromagnetism group involved in the Copernicus Project is optics, though it has carried out research in other fields of electromagnetics including antennas and microwave heating. In the context of optics, the electromagnetics group has strong expertise in the theoretical description and numerical modelling of optical propagation, the design and analysis of linear and nonlinear optical devices, as well as in the investigation of complex phenomena due to light-matter interactions.

The group is well known internationally for contributions to the area of nonlinear optics, which include the theory of parametric wavelength conversion, instabilities in fibre optic devices, the theory and observation of optical solitons, studies of the nonlinear response of cavities and propagation in periodic nonlinear media and dispersive shock waves. In addition, the group has also developed different numerical tools for the analysis of optical propagation in both time and frequency domains (BPM, FDTD, mode solvers, etc.), the most demanding of which run on a cluster of personal computers.

Activities within COPERNICUS

Within the project, UniFe is providing theoretical and numerical support to the design and the optimisation of optical circuitry (waveguides, couplers, bends, splitters) and devices (filters, photodetectors and all-optical gates).

Further Information

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u²t Photonics (U2T)

U2T is a small medium enterprise based in Germany with ~150 employees. Its market orientation is clearly focused on ultra high-speed photonic components for optical communication systems. U2T Photonics AG (Berlin, Germany) was founded in January 1998 as a spin-off company of the HHI. The core competence is the development of ultrafast optoelectronic components for fibre optic applications, such as communication super highways and microwave photonic systems, which require operation frequencies of 40 GHz and beyond. U2T has expert knowledge starting from device design and chip manufacture to system configuration and testing. As result of more than 10 years R&D, high end opto-electronic components have been brought to market. Examples include high-speed waveguide integrated photodetectors with 90 GHz bandwidth for test and measurement applications, photoreceivers for application in 100 Gbit/s communication systems and a high-power 60 GHz photoreceiver for analog applications.

Activities within COPERNICUS

As a SME partner in the project, U2T will use their accumulated excellence in the field of high-speed device design to develop a package for the receiver components. Moreover, U2T will contribute its expertise in fibre-chip coupling of waveguide-based photodetectors. U2T is expert in epoxy-based single mode fibre alignment and uses both manual and automated alignment processes in production. Packaging experience in the assembly of optoelectronic components suitable for high-frequency operation up to 100 GHz, using advanced wire-bonding techniques, will be applied to the devices developed in the project. The strong market position of U2T in the 100 Gbit/s system and 100 GHz test and measurement market will contribute to efficient exploitation of project results.

Receiver assembly (left) and fibre-chip coupling (right)

Further Information

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Thales Systèmes Aéroportés (TSA)

Thales Systèmes Aéroportés provides all the capabilities demanded by customers for on-board equipment, sub-systems, systems, prime contracting and high value-added services, both in civil and military markets. The company has gathered the skills of more than 2,000 engineers within an industrial and technological core that is unique in Europe. TSA employs this accumulated know-how for the design, development and manufacturing of electronic equipment, particularly mastering the following techniques / technologies: power electronics, antennas and radomes, microelectronics, analogue and microwave circuits, digital data processing, information systems and manufacturing technologies. The activities of TSA in photonics and microwave optics date back 20 years. They have followed a comprehensive process to set new photonic solutions in the heart of the highest end-up electronic systems.

Today, the main activities in this field concentrate on high performance analogue and digital optical networks to be used with highly integrated T/R modules applicable to future active antennas. TSA is also involved in developing new techniques for the photonic-assisted sampling of communication signals. A specific element of the research undertaken is the design and realisation of optical links, including driving circuits. The target is the realisation and production of the smallest optically interfaced switches and T/R modules. Photonic-crystal-based technology will help to drastically shrink the dimensions of such modules, their electrical interconnection with the external system and also reduce power consumption, thereby easing their insertion in future conformal antennas.

Activities within COPERNICUS

TSA participates in the project as a potential integrator of the developed technologies in its current/future systems. The Microwave Photonics Laboratory provided end-user requirements at the project start and has then participated in evaluating the developed components and functions, with respect to their potential industrial applications.

Further Information

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Photonic crystal based all-optical gate technology
State-of-the art advances resulting from the COPERNICUS project

1. Introduction

The key component of a photonic crystal (PhC) based demultiplexer for optical time division multiplexed (OTDM) signals is the all-optical gate (AOG). Over the last three years, the *COPERNICUS* project has delivered significant advances in AOG technology. Membrane AOG devices based on GaAs were investigated, but attempts to use these devices to perform switching with real signals failed because of the very small switching contrast (1 dB) and the very fast photo-induced oxidation of the patterned GaAs surface. As a result, a membrane technology based on InP was developed at TRT and later at DTU. An alternative approach based on the heterogeneous integration of a III-V PhC on a silicon photonic chip was pursued by CNRS-LPN. Both approaches, membrane InP and heterogeneous integration, have been successful and both have demonstrated good switching properties and their suitability for all-optical signal processing. In this article, the fabrication at CNRS-LPN of both two- and three-port devices based on heterogeneous integration is discussed. Experiments performed at CNRS-LPN have shown that both devices are capable of fast switching. High-bit rate and applications-oriented experiments have been performed at CNRS-FOTON. These include successful demonstrations of the optical signal processing operations of wavelength conversion and noise limiting.

2. Two-Port AOG based on Hybrid III-V/Silicon Technology

2.1 Device description

The two-port sample, fabricated at CNRS-LPN, consists of a hybrid III-V photonic crystal nanobeam cavity on a silicon on insulator (SOI) waveguide, as shown in Fig. 1. Quantum wells are positioned at the surface of the cavity in order to enhance the surface recombination of the carriers and obtain fast operation. The sample is also fully encapsulated in silica in order to increase heat sinking, which enables high bit rate measurements to be performed.

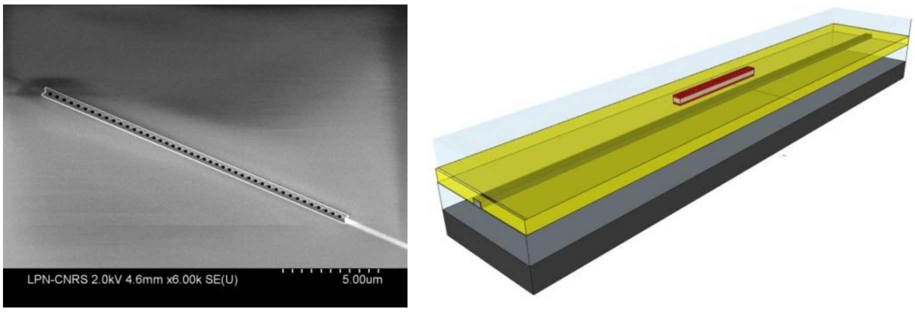

Figure 1: SEM image (left) and schematic view (right) of the fabricated two port hybrid III-V/SOI structure.

2.2 Demonstration of fast switching

Following fabrication, degenerate pump-probe experiments were performed at CNRS-LPN to validate the fast non-linear response of the structure. As can be seen in Fig. 2, the typical switching times were around 12 ps. Here the switching energy was 40 fJ. This result gave the first proof that these structures are capable of high bit rate operation.

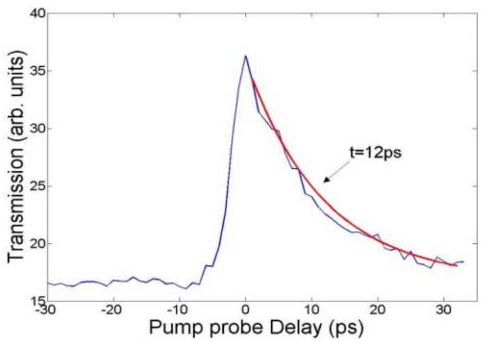

Figure 2: Probe signal transmission -vs- pump-probe delay for a pump pulse energy of 40fJ.

2.3 Demonstration of wavelength conversion

The ability of the hybrid III-V/SOI switch to perform wavelength conversion was assessed by CNRS-FOTON at both 10 and 20 Gbit/s. The possibility of using both resonances of the device for pumping and probing was also explored.

A 10 Gbit/s Pseudo Random Bit Sequence (PRBS) was used as a pump signal at one resonance and a CW signal as a probe signal at the other resonance of the device. At the maximum available pump power (corresponding to a coupled peak power of 6 mW), a clearly open converted eye diagram was obtained, as shown in Fig. 3 (left). Bit Error Rate (BER) measurements show error free operation on the converted signal (grey circles). However a 4 dB penalty is measured at a BER of 10^{-9}. In order to investigate the origin of this penalty, the BER of the back-to-back (B2B) coupled fibres was measured with a degraded extinction ratio of 3.6 dB (full symbols). This data is very close to that of the converted signal, demonstrating that the penalty is a result of the low extinction ratio of the converted signal which arises from a limitation of the switching contrast.

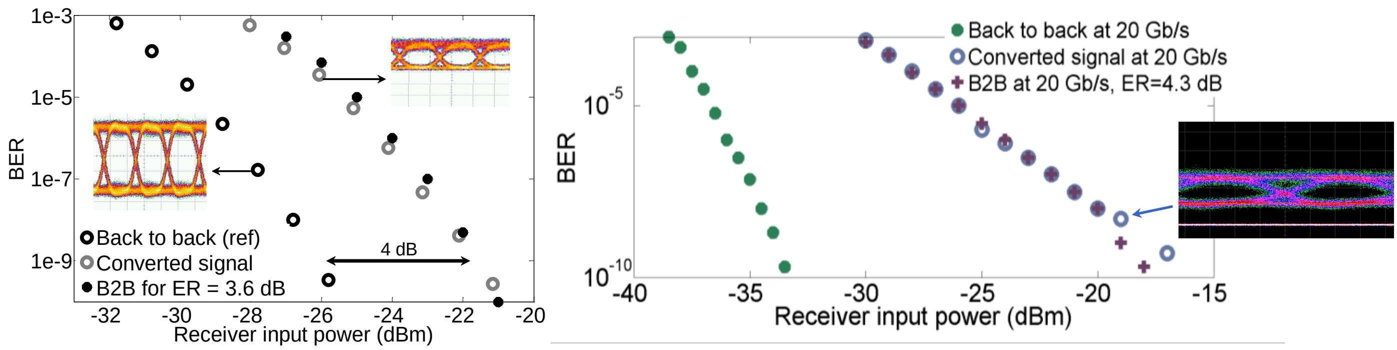

Figure 3: Demonstration of 10 Gbit/s (left) and 20 Gbit/s (right) wavelength conversion.

A similar experiment was performed at 20 Gbit/s with a coupled peak power of 9 mW. The eye diagram is still quite open, as shown in Fig. 3 (right). Error free operation can be obtained, but with a consequent increase of the penalties. As in the previous experiment, the back-to-back curve with a degraded extinction ratio shows that the limiting factor at this bit rate is still the extinction ratio of the converted signal.

2.4 Demonstration of noise limiting function

The two-port switch was also tested as a power limiter at 10 Gbit/s and its noise reduction capabilities assessed by CNRS-FOTON. Amplitude fluctuations were generated by two different methods, as shown in Fig. 4.

In the first experiment, intensity noise was generated using a CW laser modulated through an external modulator driven by a 1 GHz bandwidth noise diode. The relative intensity noise (RIN) of this signal was varied by adjusting the noise diode voltage. This noisy optical source was then modulated at 10 Gbit/s with a sequence length of 2^{31}-1 bits into a second modulator and injected into the component at a slightly blue shifted wavelength (with respect to the cavity resonance). In Fig. 5 (left), the eye diagrams clearly show the amplitude noise reduction at the device output. The output SNR as a function of the input SNR curve clearly shows noise reduction as it is located above the linear transmission curve.

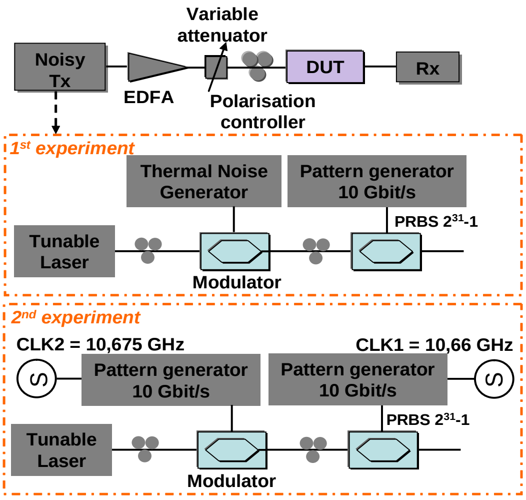

Figure 4: Two setups for demonstrating the noise limiting function of the two-port device.

In the second experiment, to increase the noise bandwidth, the noise diode was replaced with a second 10 Gbit/s pattern generator (2^7-1 PRBS sequence). There was no synchronisation with the pattern generator used for the BER measurements owing to a 15 MHz frequency shift. Figure 5 (right) shows a BER measurement with the back-to-back reference signal (crosses), the degraded signal (grey circles) and the regenerated signal (black circles). This measurement shows a penalty reduction of 4.5 dB at 10^{-9} BER with a coupled peak power as low as 1 mW.

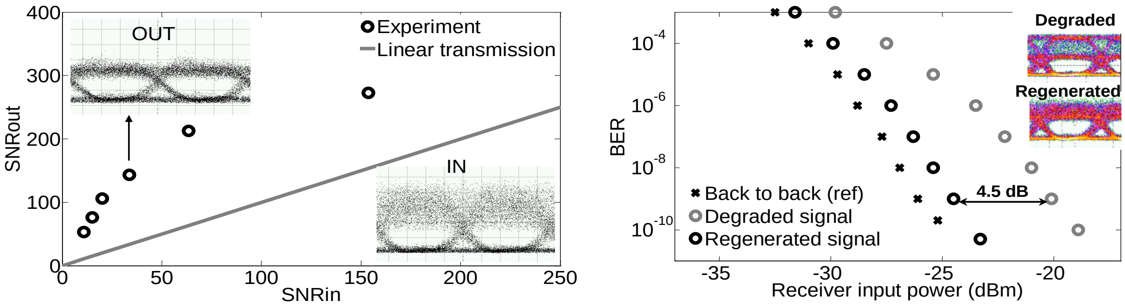

Figure 5: Output SNR -vs- input SNR with eye diagrams at SNR_{in} = 34 (left) and BER curves of the noise limiter (right).

3. Three-Port AOG based on Hybrid III-V/Silicon Technology

3.1 Device description

The hybrid III-V/SOI technology, developed at CNRS-LPN was also employed to realise a three-port AOG. Again, surface quantum wells and silica encapsulation were used to enable high bit rate operation. Here, the III-V level consisted of a nanobeam cavity coupled to a wire waveguide, ended on one side by a high reflectivity mirror. The other side was positioned right above a second SOI waveguide in order to couple light evanescently. It was terminated by a narrow tip in order to avoid back reflections. SEM images of the fabricated sample are shown in Fig. 6.

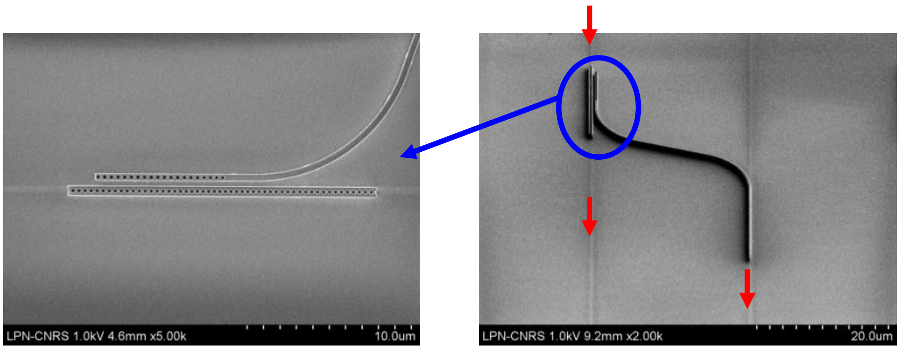

Figure 6: SEM images of the fabricated three-port hybrid III-V/SOI AOG.

3.2 Demonstration of fast switching

Non-degenerate pump-probe experiments were again performed at CNRS-LPN to demonstrate the fast switching operation of the three-port device. A 150 fs probe pulse was applied to the SOI bus waveguide, around the resonant wavelength of the cavity. A 150 fs pulse at 810nm was then used to excite carriers in the cavity and shift its resonant wavelength. The dynamics of the nonlinearity were then followed by exploring this wavelength shift as a function of the pump-probe delay. The results are plotted in Fig. 7, where the intrinsic response time of this gate is around 16 ps.

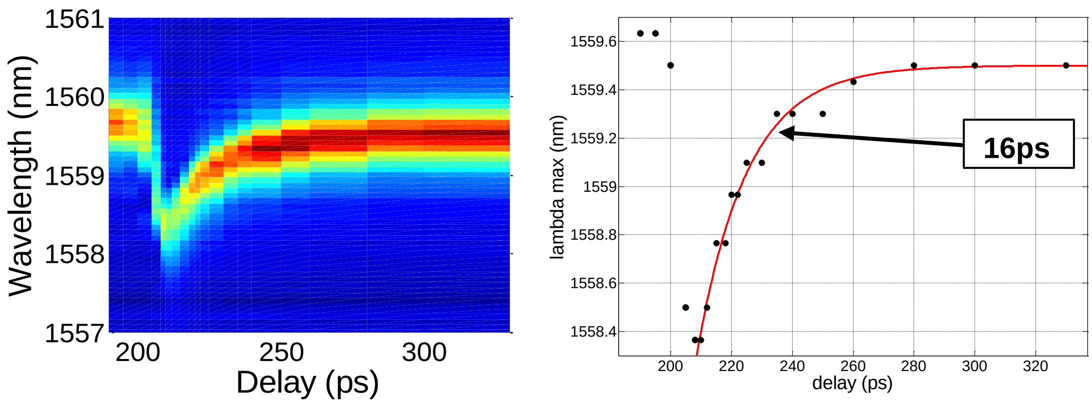

Figure 7: Transmission spectrum as a function of pump-probe delay (left) and resonant wavelength -vs- pump-probe delay (right).

3.3 High bit rate experiments

Following the demonstration of fast switching, the hybrid three-port AOG was tested with telecommunication signals at CNRS-FOTON. The cavity that gave the best switching contrast was selected and the measured transmissions through the drop and bus channels are plotted in Fig. 8 (left). A 690 MHz pump-probe experiment with 100 ps pump pulses was performed and achieved a 6.2 dB switching contrast with an estimated 18 mW of coupled pump peak power into the SOI waveguide (1.2 mW average power), as shown in Fig. 8 (right). Unfortunately, this contrast value is too low for 10 Gbit/s wavelength conversion or OTDM demultiplexing, as the instantaneous power decreases with the increase of the repetition rate. The switching contrast at 10 Gbit/s would hence be below 1 dB.

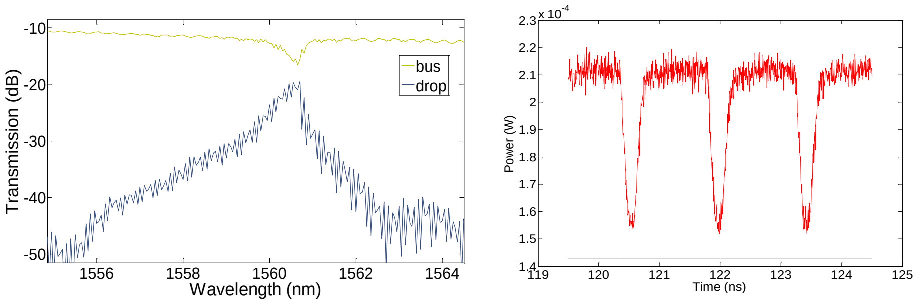

Figure 8: Measured transmission characteristics (left) and modulated probe signal through the three-port device (right).

For the two-port AOG made using the same technology, the switching contrast at this repetition rate reached 11 dB. It might seem surprising that the contrast was worse for the three-port device as the quality factor of the resonance was increased (which should have led to a higher switching contrast with the same resonance shift). However, in the three-port sample, a wavelength shift of the resonance (caused by a process issue) meant that only one resonance was reachable by the source laser available. Consequently, in the two-port component, the pump and probe signals were positioned at two different resonances and pumping right into the resonance was efficient. In the case of the three-port component, the pump and probe had to be positioned around a single resonance. The pump cannot be located right into the resonance in the case of a non-degenerate pump-probe and this results in a less efficient pump and process. Future three-ports devices that better fit the telecom band should give access to two resonances and allow the switching contrast to be improved and higher bit rate operation to be demonstrated.

4. Outlook

Within *COPERNICUS*, two AOG technologies have been developed and all-optical processing capabilities have been demonstrated on both. As reported in this article, hybrid III-V/SOI technology has enabled wavelength conversion of telecom data up to 20 Gbit/s and these devices can function as noise limiters. Both two- and three-port devices based on this technology have been demonstrated. Although not discussed in detail here, the InP PhC membrane technology has demonstrated wavelength conversion at 10 GHz and operation as an all-optical mixer for microwave photonics up to 20 GHz. These results demonstrate the potential of both technologies to create components for all-optical signal processing with very small footprints and which have extremely low energy consumption.

List of Selected Journal Publications *(For a full list, please see our project website, www.copernicusproject.eu)*

- Nguyen *et al.*, "100 Gbit/s Wavelength Division Demultiplexing using a Photonic Crystal 4-Channel Drop Filter" *IEEE Photon. Technol. Lett.*, **25**, 813 (2013).
- Lenglé *et al.*, "Efficient Second Harmonic Generation in Nanophotonic Waveguides for Optical Signal Processing" *Appl. Phys. Lett.*, **102**, 151114 (2013).
- Malaguti *et al.*, "Tailored Design of WDM Filters in BCB Embedded PhC Membranes" *Opt. Quantum Electron.*, **45**, 329 (2013).
- Heuck *et al.*, "Improved Switching using Fano Resonances in Photonic Crystal Structures" *Opt. Lett.*, **38**, 2466 (2013).
- Malaguti *et al.*, "Optimizing Pump-Probe Switching Ruled by Free-Carrier Dispersion" *Opt. Express*, **21**, 15859 (2013).
- Kristensen *et al.*, "Optimal Switching using Coherent Control" *Appl. Phys. Lett.*, **102**, 041107 (2013).
- Nguyen *et al.*, "Non-Destructive Method to Measure Coupling and Propagation Losses in Optical Guided Structures" *J. Opt. Soc. Am. B*, **29**, 3393 (2012).
- Lenglé *et al.*, "Wavelength Division Demultiplexing and Cross-Talk Assessment of a Photonic Crystal Filter" *IEEE Photon. Technol. Lett.*, **24**, 2109 (2012).
- Malaguti *et al.*, "Temporal Gap Solitons and All-Optical Control of Group Delay in Line-Defect Waveguides" *Phys. Rev. Lett.*, **109**, 163902 (2012).
- Colman *et al.*, "Blue Self-Frequency Shift of Slow Solitons and Radiation Locking in a Line-Defect Waveguide" *Phys. Rev. Lett.*, **109**, 093901 (2012).
- Armaroli *et al.*, "Oscillatory Dynamics in Nano-Cavities with Non-Instantaneous Kerr Response" *Phys. Rev. A*, **84,** 053816 (2011).
- Malaguti *et al.*, "Self-pulsing driven by Two-photon Absorption in Semiconductor Nanocavities" *Phys. Rev. A*, **83,** 051802(R) (2011).
- Xu *et al.*, "Simple and Efficient Methods for the Accurate Evaluation of Patterning Effects in Ultrafast Photonic Switches" *Opt. Express*, **19,** 155 (2011).