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3D Photonic integration platform
based on multilayer PolyBoard and TriPleX technology
for optical switching and remote sensing and ranging applications

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List of abbreviations

ANSI/TIA	American National Standards Institute / Telecommunications Industry Association
AWGR	Arrayed Waveguide Grating Router
COTS	Commercial Off-The-Shelf
DAC	Digital to Analog Converter
DC	Datacenter
DC	Direct Current
DCN	Datacenter Network
DUT	Device Under Test
EC	European Commission
FPGA	Field-Programmable Gate Array
HPC	High Performance Computing
ICT	Information and Communications Technology
IQ	In-phase / Quadrature
IR	Infrared
IT	Information Technology
ITU	International Telecommunication Union
LDV	Laser Doppler Vibrometer
LVDS	Low-Voltage Differential Signaling
MEMS	Micro-Electro-Mechanical-Systems

MEP	Mechanical, Electrical and Plumbing
MG-Y	Modulated Grating Y-branch
MMI	Multimode Interference
MPI	Message Parsing Interface
MZI	Mach-Zehnder Interferometer
NA	Not Applicable
PBS	Polarization Beam Splitter
PCB	Printed Circuit Board
PD	Photodiode
PER	Polarization Extinction Ratio
PIC	Photonic integrated circuit
PM	Polarization Maintaining
PZT	Lead Zirconate Titanate
RF	Radio-frequency
RIN	Relative Intensity Noise
SDN	Software Defined Networking
SMB	SubMiniature version B
SMF	Singlemode Fiber
SOA	Semiconductor Optical Amplifier
SPI	Serial Peripheral Interface
TBD	To Be Defined
TCP	Transmission Control Protocol
TDMA	Time-Division Multiple Access
TE	Transverse Electric
TEC	Thermo-Electric Cooler
TIA	Transimpedance Amplifier
TM	Transverse Magnetic
USB	Universal Serial Bus
WDM	Wavelength-Division Multiplexing

1 Summary of Project context and Objectives

3PEAT intends to provide a powerful photonic integration technology that meets all size, functionality, and quality requirements in order to allow a wide range of optical applications, such as optical switching and remote sensing, achieve commercial success.

3PEAT invested in a combination of a polymer platform (PolyBoard) and a silicon-nitride platform (TriPleX) as motherboards in hybrid photonic integrated circuits (PICs) because they are both passives, very flexible, and have low loss. In more detail, the project created a technology for heterogeneous polymer material integration behind etched windows on TriPleX chips, allowing for true hybrid integration of the two platforms into single-die PICs with ultra-high functionality and compactness. 3PEAT proposed an innovative technology for fabricating a fully functional 3D photonic integrated structure with numerous waveguiding layers for the PolyBoard component of these PICs. Following the electronic integration paradigm, in which the introduction of stacked layers and Through Silicon Vias (TSVs) enabled the development of ultra-dense electronic chips, 3PEAT used vertical Multi-Mode Interference (MMI) couplers as the optical analogy of TSVs for seamless transition between the layers. Parallel to this, 3PEAT worked on a number of additional major achievements on the PolyBoard and TriPleX platforms, which provided disruptive potential in terms of hybrid 3D PIC functions. These developments included: a) the use of heterogeneous integration of lead zirconium titanate (PZT) films on the TriPleX platform and the development of a new generation of phase shifters with higher energy efficiency (20) and the ability to operate in the 50 MHz regime, b) the development of a disruptive external cavity laser on the same platform with only 1 kHz linewidth, c) the development for the first time of an integrated circulator on the PolyBoard platform with >25 dB isolation, and d) the development of flexible waveguiding boards on PolyBoard for the physical interconnection in a practical way of two hybrid PICs, when the scale of integration on a single one has exploded.

This massive amount of innovation content was used to fully realize the promise of optical switching and remote sensing applications, which were used by 3PEAT to validate its integration technology. The main switching module that was built was an active 4x4 optical switch that can be extended to a 36x36 case and operates with a 300 ns switching time, providing an amazing combination of switching scale and speed. The main sensing module, on the other hand, was a ground-breaking Laser Doppler Vibrometer (LDV), which had all of its optical components (including its optical beam scanning unit) integrated on a single 3D PIC. The use of the multilayer PolyBoard platform in these 3D PICs was not only allowed for scaling the integration density, but also for enabling a number of functionalities and operation modes not possible on standard 2D PICs, such as avoiding waveguide crossings and implementing a 2D optical phased array (OPA).

The next nine (9) objectives presented the project's step-by-step methodology, in which it attempts to enhance specific platforms, enable their integration, and assist its overall exploitation paths:

Objective 1. Advance PolyBoard: Develop a disruptive 3D photonic integration technology based on a multilayer PolyBoard platform

Objective 2. Advance PolyBoard: Develop an integrated optical circulator and Optical FlexLines for single-mode PIC-to-PIC interconnects

Objective 3. Advance TriPleX: Use heterogeneous integration of PZT films on TriPleX and develop polarization insensitive phase shifters and switches with 20 ns response time, low power consumption and large integration scale (>1000 elements)

Objective 4. Advance TriPleX: Develop an integrated laser source with ultra-narrow linewidth (< 1 kHz)

Objective 5. Bring PolyBoard and TriPleX together and create a powerful hybrid integration platform: Develop a hybrid integration engine for seamless integration of PolyBoard and TriPleX sections

Objective 6. Leverage the disruptive potential of the hybrid integration platform: Develop 3D PICs for large-scale optical switches with 20 ns switching time inside data center networks

Objective 7. Leverage the disruptive potential of the hybrid integration platform: Develop 3D PICs for the interrogation and optical beam scanning unit of Laser Doppler Vibrometers

Objective 8. Develop methods and tools, and proceed with the packaging, system integration and performance evaluation of the switching and sensing (LDV) modules of 3PEAT

Objective 9. Explore the spectrum of application fields for 3PEAT integration technology and prepare a trial for its provision as a foundry service to external customers.

2 Main scientific and technical results

To achieve 3PEAT goal and reach the objectives of the project, the project work plan is broken into nine (7) Work Packages (WPs). The project management, coordination of all technical work-packages was successfully completed within WP1. The dissemination and exploitation activities were completed within WP7. The work during 3PEAT implementation was carried out in the framework of the following technical WPs:

WP2: System design and methodologies for integration and packaging processes

WP2 is devoted to the system design, identification and definition of the system specifications and system level simulations. Within this work package, the application scenarios have been specified, as well as the data center network architecture for 3PEAT switching technology and definition of system level specifications for the 3 switching modules. Similarly, the application scenarios for the use of 3PEAT sensing technology and the definition of the system-level specifications for the 3 LDV modules have been defined. Moreover, the system-level specifications for the individual components and their interfaces inside the 6 modules in order to ensure the compatibility during integration have been defined. With emphasis on the heterogeneous integration of the PolyBoard and the TriPleX platform on a single die, the integration and packaging process flow has been defined. To this direction, living specification documents have been created, that include also the blue-print of the 6 modules. Furthermore, the calibration, operation and configuration algorithms have been developed that help for the control of the 6 modules. Finally, appropriate testbeds have been built up for the characterization and evaluation of the 3PEAT modules.

WP3: Monolithic and heterogeneous integration on TriPleX platform

WP3 is devoted to the upgrade of the TriPleX photonic platform with the new functionalities and components. LioniX and SolMateS have optimized the deposition process for PZT films in order to develop fast phase shifters, switches and modulators. In parallel LioniX and UTwente have developed the narrow linewidth laser. Leveraging these developments, LioniX has designed, fabricated, and characterized the TriPleX chips for the switching and LDV modules of the project. Within WP3, SolMateS worked with LioniX on the integration of the PZT process from SolMateS with the TriPleX waveguide structures from LioniX. Two types of configurations of the PZT layer on top of the waveguide structures have been developed and tested: top-top actuation and top-bottom actuation.

LioniX completed and successfully tested the BTO/PZT development route for top-top actuation at the device level. The PZT material was designed to grow directly on the waveguide's SiO2 layer. Between the TriPleX stack and the PZT film, a non-conductive BaTiO3 (BTO) seed layer was introduced and tailored for this purpose. In addition, SolMateS and LioniX developed and tested a new bottom electrode adhesion layer composition for the top-bottom layout. Ti is the traditional adhesive layer for Pt bottom electrodes. However, the Ti layer created flaws (hillocks) and device failures due to diffusion and oxidation. Alternative materials for Ti have been investigated. These had fewer flaws but had poor film adhesion. As a result, PLD built a "new" LaNiO3 adhesion layer. The LaNiO3 contributed to overall improvement of device performance, stability, and yield.

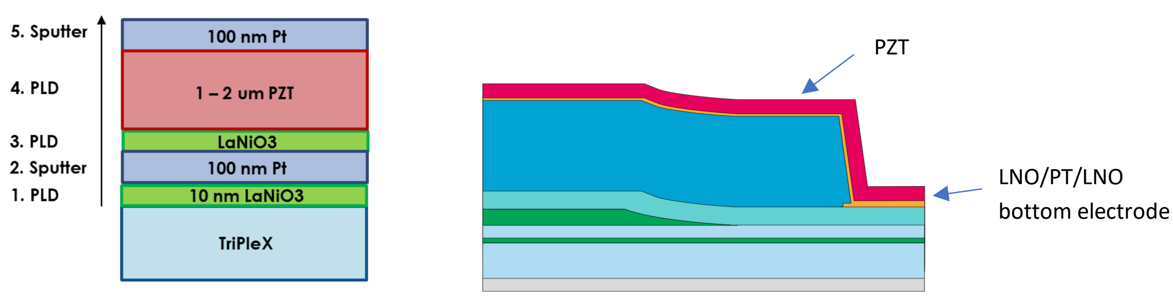


Figure 1. (left) shows the top-bottom configuration deposition stack on top of TriPleX. (right) Bottom electrode + PZT deposited on top of TriPleX structure.

Figure 2 shows the schematic structures that resulted. After waveguide etching, the dome shape that naturally results from the deposition of all materials is left in place. It functions as a lens, projecting stress onto the waveguide to improve the PZT actuator's efficiency. Figure 3 depicts the actual

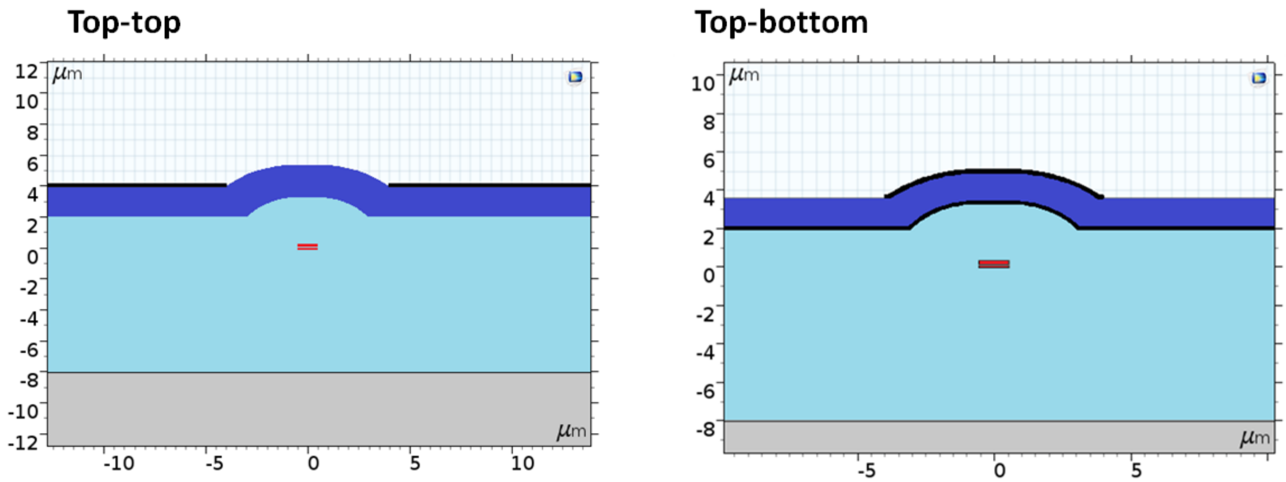


Figure 2. Left: Schematic drawing of the top-top configuration stack near the waveguide. The BaTiO3 layer is too thin to observe on this scale. Right: Schematic drawing of the top-bottom configuration. The LaNiO3 layers are too thin to observe on this scale.

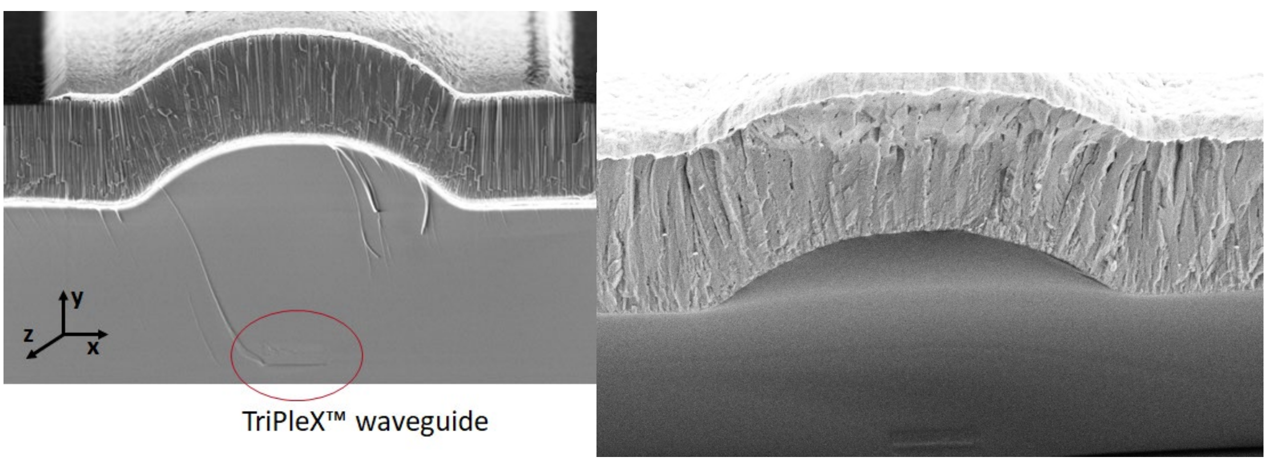


Figure 3. SEM cross-section of the PZT layers. Left: top-bottom configuration. Right: top-top configuration.

An InP gain chip from Fraunhofer HHI, a TriPleX-based feedback circuit, a PolyBoard-based isolator, and an output fiber make up the laser source created within 3PEAT. As demonstrated in Figure 4, all three chips are hybridized and packaged in one package. The device is characterized by UTwente and has an intrinsic linewidth of 2 kHz. The laser's lower bus-to-ring coupling coefficients of 5% are responsible for the improvement.

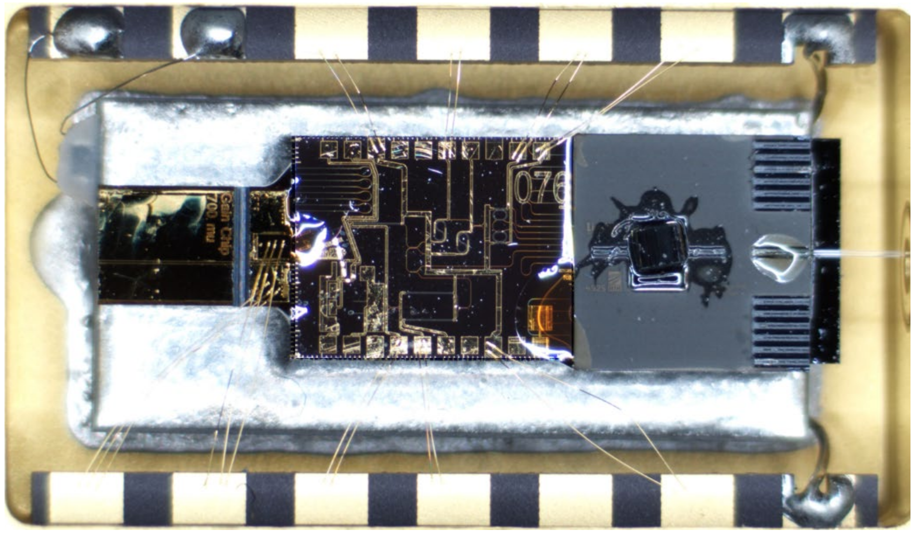


Figure 4. Photo of the hybrid assembly of the amplifier, feedback chip isolator and output fiber

WP4: Monolithic and heterogeneous integration on PolyBoard and hybrid integration with TriPleX platform

WP4 was responsible for upgrading the PolyBoard platform and developing a hybrid TriPleX-PolyBoard integration method. Multilayer PolyBoard structures and vertical MMIs for light passage between them have been created by FhG-HHI. The optical isolator and OFLs were also developed by FhG-HHI. FhG-HHI and LioniX collaborated on the hybrid integration engine and built and tested the PICs for the project's six modules.

The integration of thermo-optical and complicated integrated functions with multilayer PolyBoard techniques was the focus of 3PEAT. Thermally tunable arrayed waveguide gratings were studied in particular.

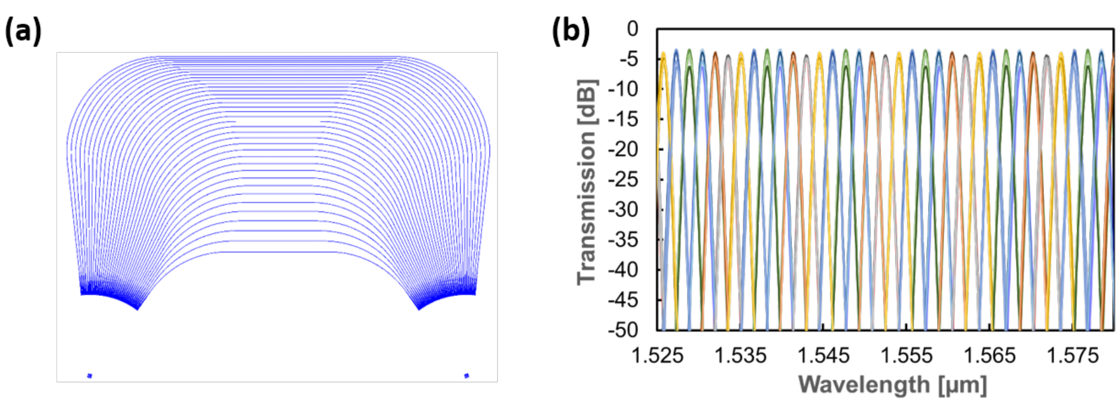


Figure 5. Optimized design of 6-channel cyclic AWG (a) and simulated transmission spectra (b).

The transmission spectra in Figure 5 (b) clearly illustrate that the optimized design achieves the desired cyclic behaviour: The channels with a width of 200 GHz span the entire C band. The various colours represent various combinations of input and output waveguides.

While numerical simulations of AWGs produce reliable channel spacing and bandwidth figures, experience indicates that the absolute position of wavelength channels is highly dependent on minor process errors and fluctuates throughout a single wafer. AWGs that must fit a specified wavelength grid are frequently actively tuned as a result. Because it is required to match not only a single AWG to a wavelength grid, but up to 12 AWGs to the same grid, this tuning is very critical for the optical switching PICs described here.

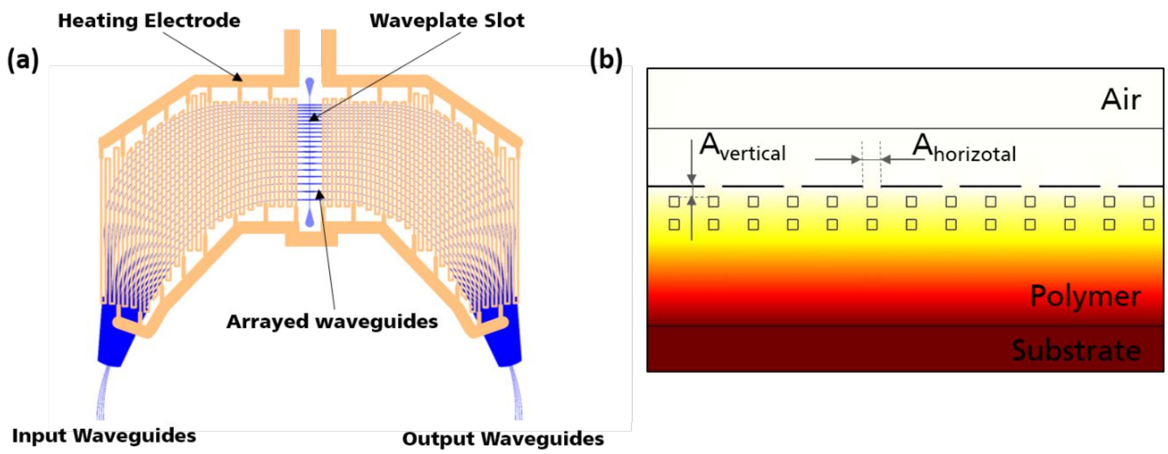


Figure 6. Electrode design for AWG (a) and simulation of the thermal profile across the waveguide layers (b).

The thermo-optical effect is used to alter the optical phase required for adjusting the channel wavelengths of the AWG in the PolyBoard platform. Because normal implementations of thermos-optical elements in the PolyBoard platform only use a single waveguide layer, the heating electrodes have to be substantially redesigned. Figure 6 depicts the outcome of this redesign (a). Above the arranged waveguide region with an opening for the HWP, the heating electrodes meander.

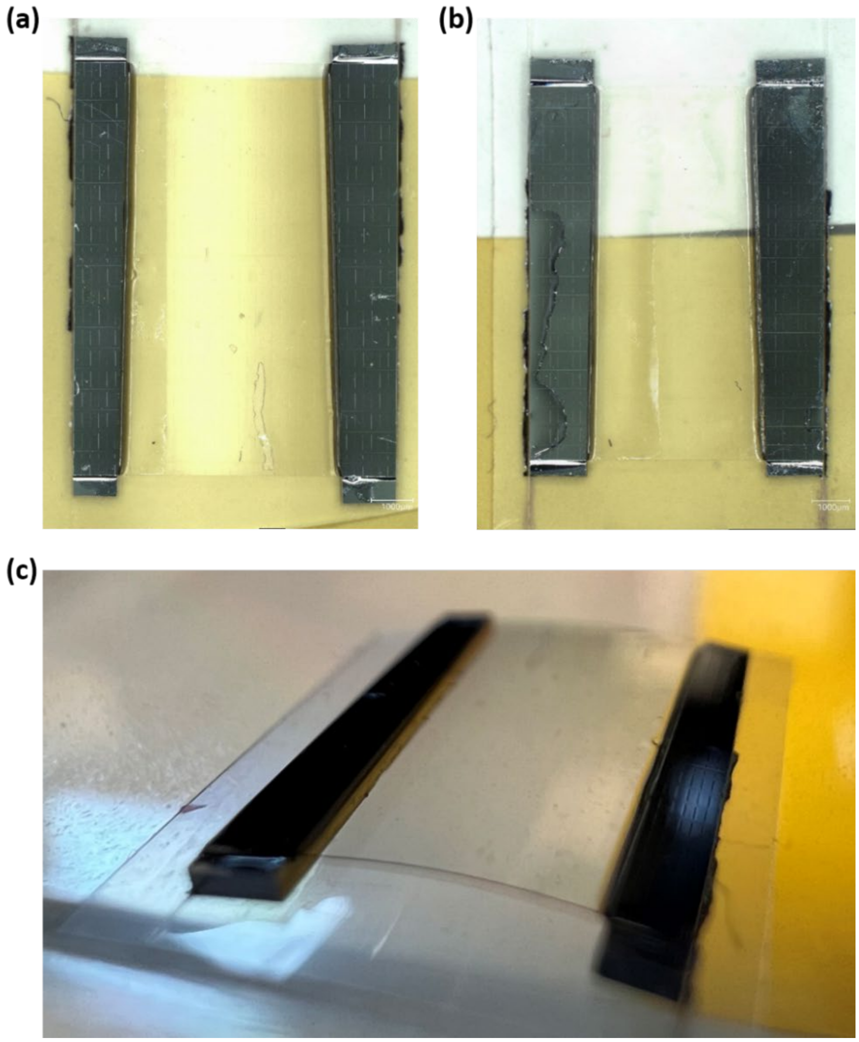


Figure 7. Two fabricated FlexLine chips with parallel optical waveguides for PIC interconnection (a+b) and close-up of a FlexLine chip (c).

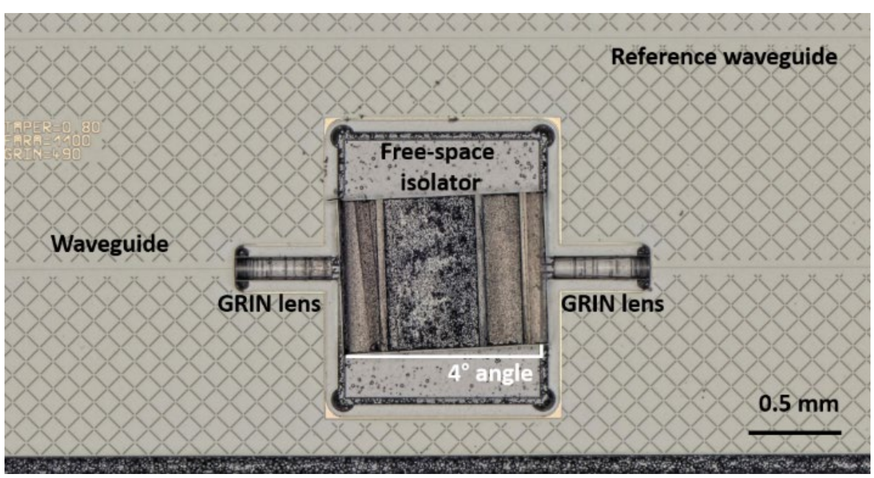


Figure 8. Integration of a free-space isolator before applying index matching glue. The isolator is inserted into a free-space section formed by two GRIN lenses coupled to the polymer waveguides.

A built PIC-based optical isolator is shown in Figure 8. Inside the free-space sector, the isolator is tilted by 4 degrees to decrease interference effects in the transmission spectrum and improve optical isolation.

Low on-chip losses and high isolation make this implementation, to our knowledge, the best-performing PIC-integrated optical isolator yet demonstrated, leading to multiple publications and lectures at scientific conferences.

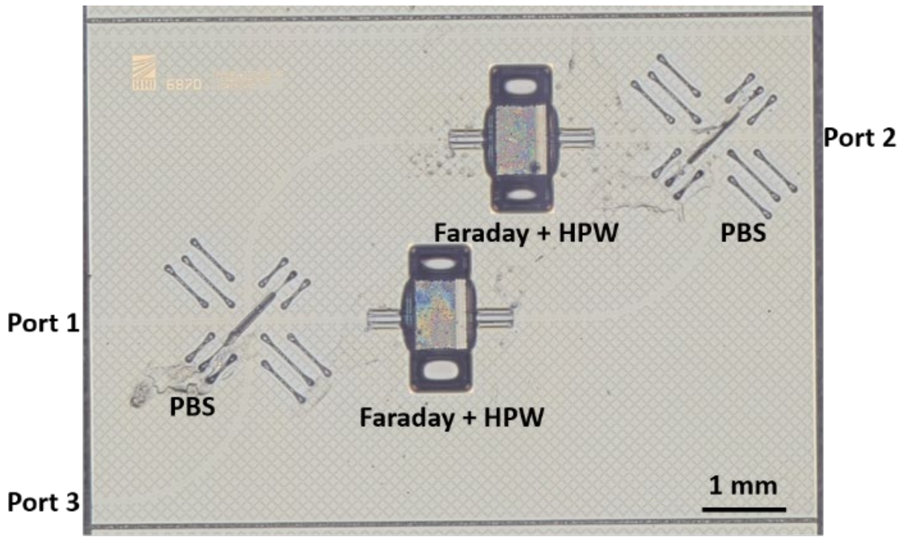


Figure 9. Assembled integrated circulator comprising an input and output polarization beam splitter (PBS) and two free-space sections with an integrated Faraday rotator and half-wave plate (HWP).

Similarly, to the optical isolator, the PBS-based circulator chips were fabricated and equipped with PBS filters and assemblies of Faraday rotators and HWPs. A final device is shown in Figure 9. This circulator concept was presented in a talk at Photonics West 2020.

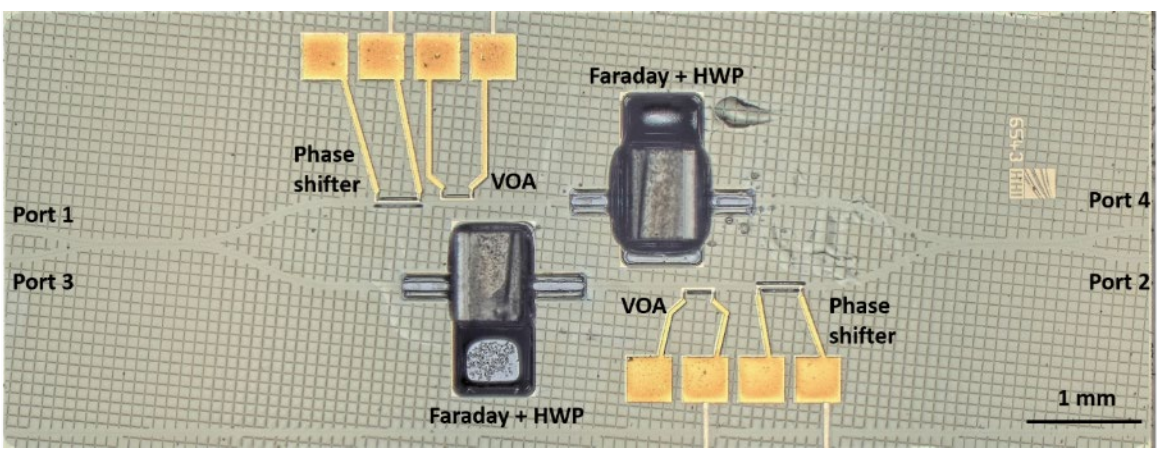


Figure 10. Fabricated optical circulator based on a Mach-Zehnder-interferometric design that comprises a Faraday rotator plus HWP together with a phase shifter and VOA in each arm.

Figure 10 shows a Mach-Zehnder-based circulator based on the second layout. In the picture of the fabricated device, the additional heating electrodes for phase shifters and VOAs are well visible. It was therefore possible to demonstrate two optical circulator concepts in 3PEAT. Further development work, especially in terms of loss reduction, will concentrate on the PBS-based circulator, because no active tuning is necessary during the operation of the device**.**

WP5: Development of integration engine and packaging of 3PEAT prototypes

The final packaging of the 2D and 3D PICs has been finished within WP5. Cordon handled optical coupling to external components using fiber pigtails and collimating lenses, electrical coupling to external electronic control units with wire-bonds and suitable electrical interposers, and thermal and mechanical management within the packages. WP5's goal was to create industry-compatible technologies for linking light to complicated PICs with many waveguides while still allowing straightforward electrical access. The package structure for each 3PEAT module was successfully specified after electrical and thermal simulations, and the resulting packaging techniques were used to assemble the demonstrations.

For assembly, the 3PEAT modules need edge-coupled light at the photonic chips' input and output. This can be done with single fibers or fiber array block units in general. The first method is appropriate when the number of optical ports on each facet of the PICs is restricted to a few units well-spaced among each other. In this scenario, fibers are more practical in terms of alignment technique and cost. This strategy, however, becomes increasingly impractical as the number of optical connections grows. When multiple I/Os need to be accessed optically, the pitch required to glue single fibers is around 600 um, which can be excessive. Working with a large number of fibers in close proximity also poses reliability and mechanical robustness challenges. Fiber arrays are preferred in these situations. Although a single fiber array is more expensive than individual fibers, the ability to link light to multiple ports with a single item provides substantial reliability and assembly time advantages. The alignment procedure is quicker because it is only done once. Fiber arrays were employed in each assembly because all 3PEAT modules contain more than four optical ports per facet. The type of FA and the number of channels for each module have been tuned to best adapt to the various PICs and packaging designs.

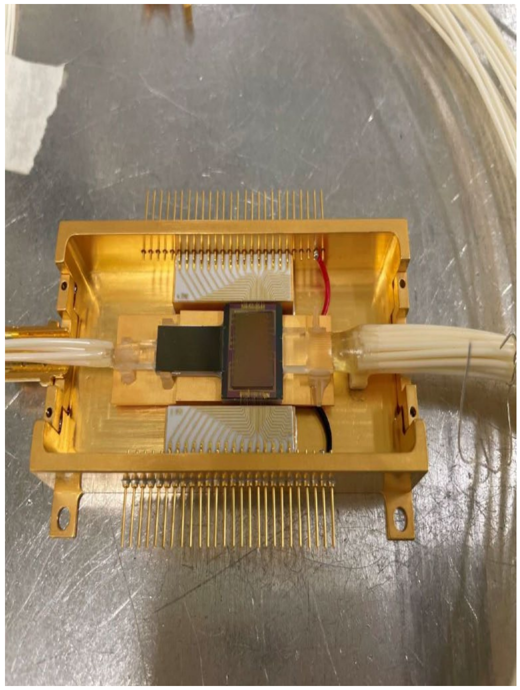


Figure 11. Photograph of a complete 3PEAT module, highlighting the input and output fiber arrays.

Fiber arrays are beneficial in multichannel systems, but they must meet a few requirements in order to achieve smooth optical coupling. Of course, the on-chip waveguides must have the same pitch as the FA. There are various conventional pitch possibilities (range from 125 m to 625 m), however custom fiber arrays with a non-standard pitch can be produced at a greater cost if the application requires it. FA can access chips with perpendicular and angled input-output waveguides with respect to the facet. The first option is simpler and more straightforward in terms of PIC design and assembly. When light is coupled to and from lasers or optical amplifiers, the second approach is used to minimize back reflections. In order to use a standard FA in this situation, the angle and pitch of the PIC waveguides must be appropriately constructed, taking into account the refraction that light experiences as it travels from the chip to the FA. Because the 3PEAT modules were all built with perpendicular waveguides and standard pitch, no special FA was necessary. Another issue to consider while using fiber arrays is the type of facet on the photonic chip. A standard FA can be used because no collision between the array and the chip is possible if the facet is polished. When the chip material or manufacturing procedure inhibits facet polishing and a step-like profile is present, FA with thin lids is required. They are specifically intended for these applications, however they are more expensive, have slightly larger insertion losses, and are less dependable. Because the 3PEAT PolyBoard and TriPleX chips all have flat polished facets, Standard FA was chosen.

The project's switching modules have been refined in order to achieve compact and dependable assemblies. The PICs were housed in metal packaging, necessitating a thorough examination of thermal management issues in order to determine the size and kind of thermo-electric cooling elements. Custom interposers were put within the packages and connected to industry compatible connectors on the outside of the enclosures to provide electrical connections to the PICs. Large fiber arrays were required for optical coupling. The optical connections' resilience has been assured by constructing chip submounts effectively and using holders to keep the fiber arrays as stable as feasible. The project partners have received the assembled modules.

The sensing modules were packaged using the chips-on-board approach since they required hefty circuitry near the PICs to get the greatest potential performance. For electronic reading and stimulation, the PICs were mounted on a metal holder and wire bonded to the corresponding PCBs. When direct chip-to-PCB wire bonding was not practicable or reliable enough, custom electrical interposers were employed in the modules. Optical access has been secured using polarization-maintaining fiber arrays, which allow for accurate optical beam creation and detection. A plastic cover has been placed over the PICs to boost the modules' durability. The project partners have received the assembled modules.

WP6: System integration, testing, and performance evaluation

This work package was dedicated to the system integration of modules based on Optagon's control units, which will apply the algorithms created in WP2. ICCS was in charge of system testing the modules in lab environments as part of WP6. System testing of the switching and LDV modules in quasi-real circumstances is handled by MLNX and Polytec, respectively.

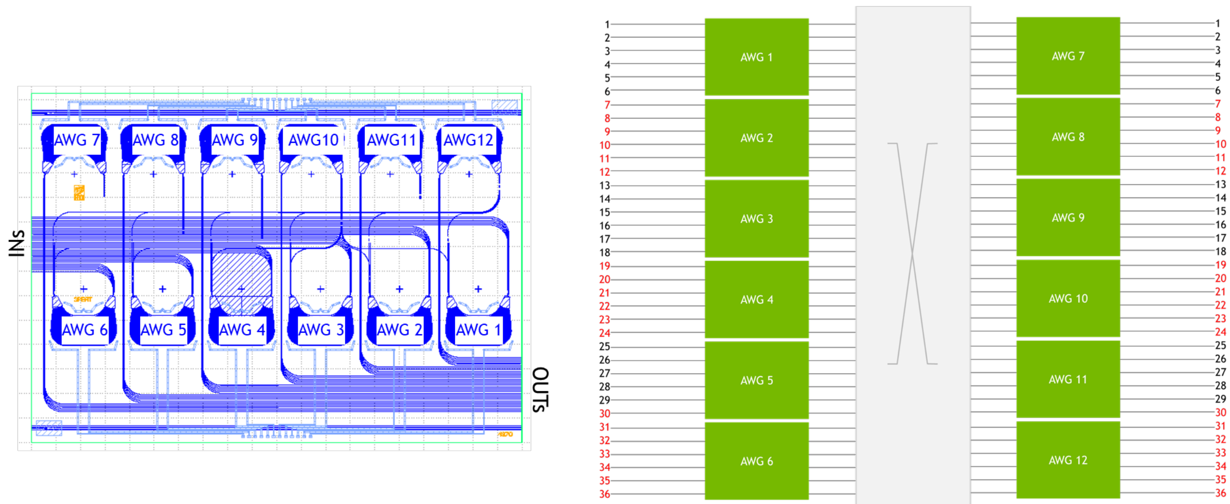
Driving solutions and amplifier chips that could provide high driving voltage and the needed bandwidth were investigated throughout the time period described. Differing driving solutions were created in the first development curve, since two PZT designs (top-top and top-bottom) were examined, each with different voltage driving needs. Because there was no universal solution that could give high output voltage (>100V) and high bandwidth, multiple driving systems were examined, with trade-offs in output voltage and driving speed. The strategic choice was to build driving solutions that could handle all types of situations, from extremely high voltage but low speed to moderate voltage output but higher speed. The initial circuits investigated were low-speed (5 kHz) circuits with output voltages greater than 100V. These were built around a 32-channel driving chip that came in the form of five separate boards that could be stacked to drive up to 160 PZT components. A microprocessor and a DAC gave digital and analogue signals to control them. These were combined with the uController and the DAC on a single PCB board to create a standalone driving solution. Another driver for top-bottom PZT elements was created that could produce up to 60 V of output voltage and had a better bandwidth of around 100 kHz, allowing it to drive components with capacitance of roughly 5 nF. The rise and fall times were measured in tens of nanoseconds. These were made in eight-channel arrays, with four such arrays totaling 32 channels.

Several devices were studied in the search for an MHz driving solution that could also give output of tens of voltage. Custom boards were built and fabricated after the candidate driving chips were assessed utilising their commercial assessment platforms. Different combinations of the driving chips were investigated by designing different variations of the custom boards. It integrated two and three-stage amplifier chains with various gain combinations. The driving solution was designed to target the PZT found on LDV modules. The second generation of these drivers increased the output voltage to 60 V and enabled sine and sawtooth functions to be operated at 2.5 MHz. It was first created in a single channel form and then tested on Module 4, a rudimentary serrodyne version. An enhanced driver amplifier design based on a new driving chip that can deliver > 60 V of output voltage at tens of MHz and can drive PZTs with one common electrode with multiple signals, as in the sophisticated and 4-branch shifters, was examined. The created driver amplifier circuit is a four-channel driving unit that takes voltage signals from DAC outputs as input and amplifies them up to 71 V. Driving options for the heater electrodes that could give the required current to both the TriPleX and PolyBoard heaters were also studied. Originally designed as low-side mosfet current generators controlled by an analogue voltage signal, they were built into an array of eight channels. Test loads that simulated the TriPleX and PolyBoard heater resistance values (680 Ohm and 15 Ohm, respectively) were used to characterise the develop current sources, and they satisfactorily produced the current necessary. In the instance of the PolyBoard heaters, the implemented design had trouble supplying current below 20 mA, hence different designs were looked into. A universal control electronics module was built to regulate the heater elements on the three various LDV shifter variants (Simple, Sophisticated, and 4-branch). It included a microcontroller, a 16-ch DAC, 16 current sources, and a power supply. A Graphical User Interface written in Python and running on the microcontroller allows the module to control 16 heaters. For standalone operation, the module can be linked to a monitor and a keyboard/mouse.

Regarding the control of the switches with digital signals, an architecture based on the same FPGA eval board was realized. This was able to accommodate all channels that would be used in Module 1. The digital part consists of two firmwares, a graphical user interface implemented in Python that would run on a desktop and would control the setting of each channel of the module to either ON or OFF which would translate to a specific setting CROSS or BAR. The settings are translated to bytes and are transferred through UART to the FPGA eval board. At the FPGA side, the processor side (ARM) of the Zynq SoC is used. This SoC UART receives the bytes and decodes them to the specific setting for each switch, that in turn is translated to a LOW or HIGH state for the Zynq's GPIOs. The firmware at the Zynq ARM side is implemented in C++ using the Xilinx libraries.

The system integration of the switch prototype (Module-1) was performed in the Mellanox premises in Athens, by ICCS, Optagon and MLNX. The target of this activity was to test and demonstrate Module-1 with commercial networking equipment. The controller FPGA board, provided by Optagon, controls the optical switch and enables different paths periodically. The result is that "server 1" is connected to "server 2" for the timeslot *t* and to "server 3" for the timeslot *t+1*. The three servers, run a file transfer application. Each of the servers has attached a MLNX ConnectX NIC and a C-band pluggable transceiver. The first step of the experiment was to demonstrate link bringup through the optical switch: the commercial NICs and pluggable TRxs have specific requirements in terms of link quality that the optical switch needs to respect. The link bringup was achieved through the two paths that are required to connect "server 1" with "server 2" and "server 3" respectively. Since the insertion loss of the optical switch is higher than the TRxs' margin EDFAs (Erbium-Doped Fiber Amplifier) were added to the paths among the servers to amplify the optical signal. The second step of the experiment involved the switching among the servers.

Regarding Module-2, a summary of the 36x36 AWGR evaluation results developed for the 3PEAT project is following. The design of the Module-2 is illustrated in Figure 12 (a) and it is explicitly described in deliverable D4.4. Figure 12 (b) shows a simplified schematic of the interior of the 36x36 AWGR, which consist of two stages of six identical AWGR. To facilitate the measurement process, we assigned the inputs and the outputs to a specific AWG, i.e. from AWG 1 to AWG12. It should be noted that each AWG has a heater for fine-tuning and alignment purposes.



(a) (b)

Figure 12. a) The schematic of the 36x36 AWGR, consisting of two stages of 6 AWGRs. (b) Building blocks overview of the 36x36 AWGR

Regarding LDV modules, ICCS defined all the necessary information for its operation, including guidelines for system testing that were supplied to Polytec. The operation of the PZT driving electronics and the phase heaters (PHs) driving electronics, both of which were developed by Optagon, are included in these instructions.

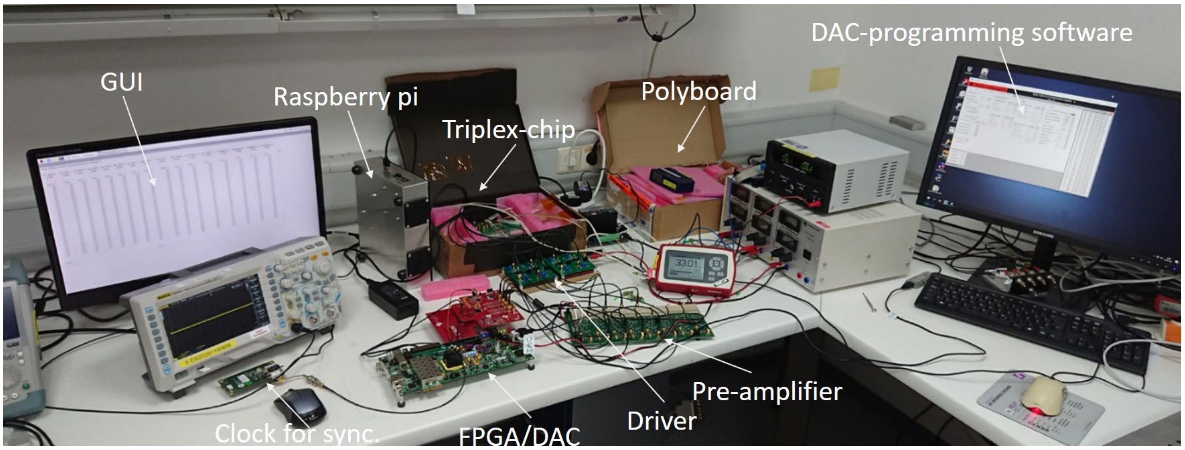


Figure 13. Lab set-up used for assessment of Module-4 at Polytec lab.

The lab setting used for the evaluation of the full Module-4 is shown in Figure 13. In case of the evaluation of Module-4, a grid of 5x5 points with a spacing of 5 mm was manually scanned on the loudspeaker membrane. Data acquisition on different spots was synchronized by triggering. A comparison with a measurement conducted on the same surface with a Polytec's PSV-500 vibrometer (shown in Figure 14) shows, that the membrane has a non-symmetric deformation. It is apparent from Figure 14, that for a detailed modal analysis a high number of scanning points is necessary. However, with adequate scanning optics (which are part of Module-6) scanning measurements with LDV Module-4 are possible.

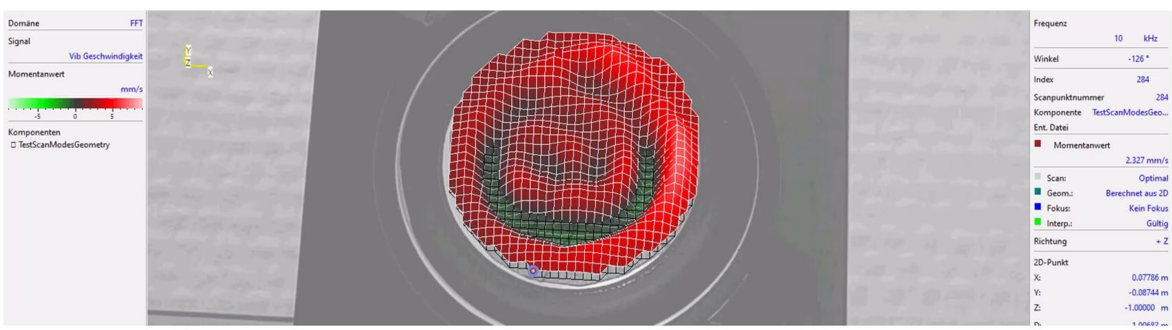


Figure 14. Scanning measurement on a loudspeaker membrane with Polytec's commercially available scanning vibrometer PSV-500.

Regarding Module-5, during the characterization procedure, ICCS proceed with the modulation applied signal. Indicative results are presented below, where the modulation scheme of 100 kHz (left) and 500 kHz (right) in 3 out of 4 PZT was applied, and the signal was received in an external photodiode.

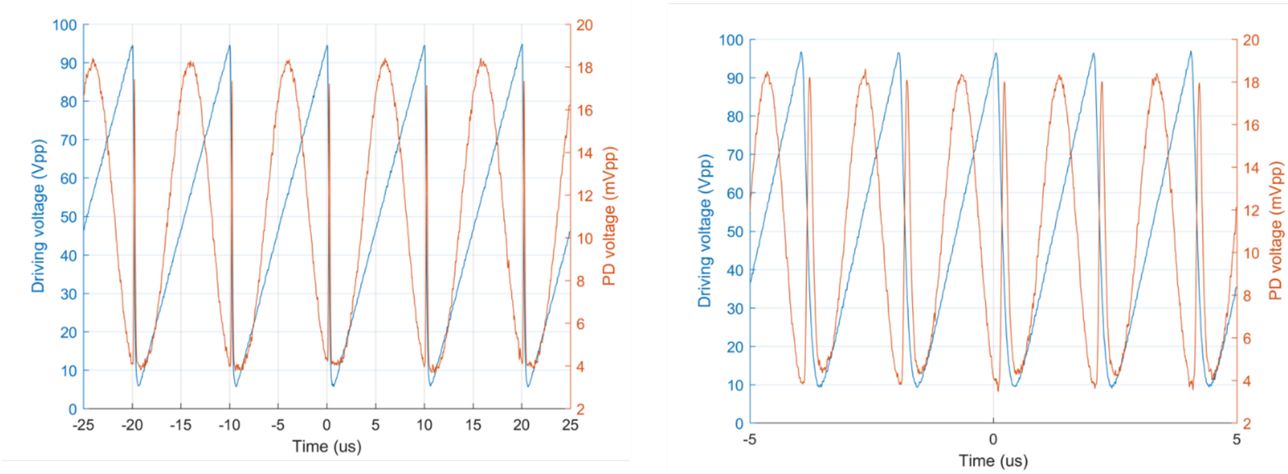


Figure 15. Modulation of 100 (left) and 500 (right) kHz signal was applied in 3 working out of 4 PZTs.

The control electronics that have been developed from Optagon have been used by ICCS for the basic characterization of the PolyBoard OPA PICs.

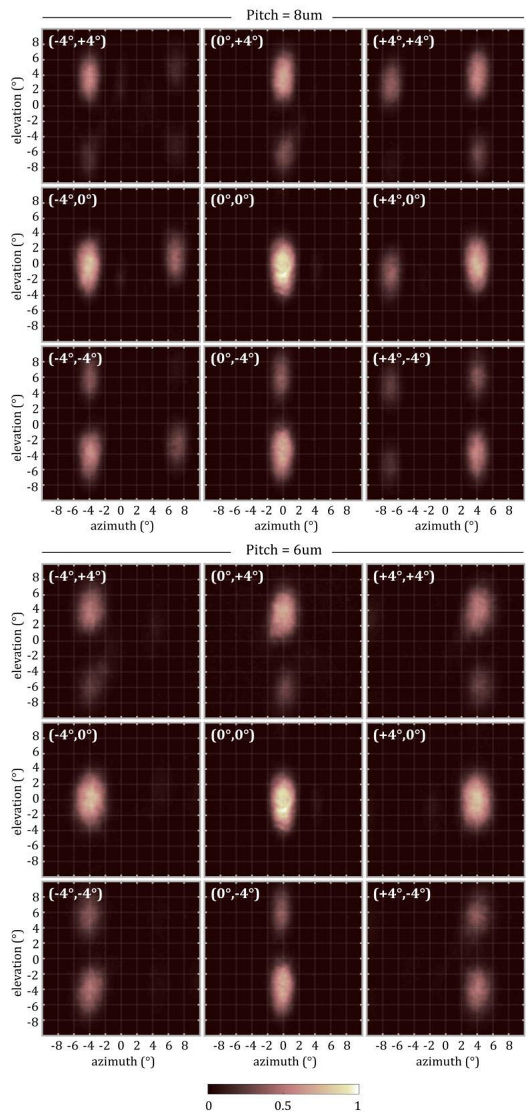


Figure 16. Experimentally captured images (radiation patterns) of the 2×4 OPAs with 8 µm (upper subgroup) and 6 µm (lower subgroup) lateral pitch. Within each subgroup, nine beam steering scenarios are presented corresponding to angles from -4° to +4° with 2° step on the azimuthal and the elevation plane.

Figure 16 shows a new set of experimental images that further validated 3PEAT's beam scanning approach and revealed the presence of grating lobes in the PolyBoard OPA PICs' radiation patterns. Figure 16 shows two subgroups of pictures in great depth.

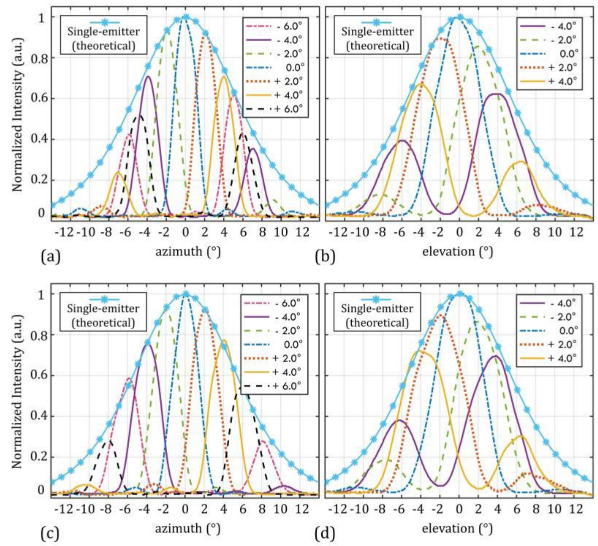


Figure 17. Analysis of experimental images from two 2×4 OPAs with 8 and 6 μm lateral pitch. Eleven beam steering scenarios were investigated for each OPA corresponding to 0° elevation angle and azimuthal angle from -6° to $+6^{\circ}$ with 2° step, and to 0° azimuthal angle and elevation angle from -4° to $+4^{\circ}$ with 2° step: a) 8 μm pitch: Intensity distribution on the azimuthal plane for 0° elevation angle. b) 8 μm pitch: Intensity distribution on the elevation plane for 0_{o} azimuthal angle. c) 6 μm pitch: Intensity distribution on the azimuthal plane for 0° elevation angle. d) 6 μm pitch: Intensity distribution on the elevation plane for 0_{o} azimuthal angle. In all diagrams, the theoretical intensity distribution of the PolyBoard edge-emitting waveguide is drawn as envelope.

Finally, Figure 17 shows results from a more detailed examination of experimental photographs. Figure 17a shows the radiation intensity of a 24 OPA with an 8 um pitch when the beam was scanned in the azimuthal plane from -6^{o} to $+6^{o}$ with a 2^{o} angle step and the elevation angle was kept constant at 0^{o}.

3 Exploitation of the results

The partners have successfully organized their strategy and their plans for the exploitation and commercialization of the project technology and have described these plans in deliverable D7.8. Highlights of this work related to the plans of the partners include:

ICCS

3PEAT offered the opportunity to ICCS to build further its expertise on optical switching and remote sensing. At the same time, it offered the possibility to consolidate its know-how on integration and packaging methodologies for the envisioned 3PEAT modules. Relevant efforts have already started in the first period of 3PEAT. Finally, the project offered the opportunity to ICCS to extend its expertise in the development of the algorithms for the control of the 2D optical phased arrays and the operation of the LDV modules.

In parallel, the scientific personnel of ICCS have been actively involved with the education activities in the School of Electrical and Computer Engineering (SECE) of the NTUA. ICCS has already exploited the 3PEAT project in order to improve the content of these activities with appropriate type of description of 3PEAT technical approaches. More specifically, the basic research lines and the theoretical background of 3PEAT project has been already incorporated in the Photonics Communications lectures of NTUA and is now presented to undergraduate and postgraduate students of the SECE in the fall and spring semesters.

Finally, one senior researcher with 3 PhD students have been worked on the research lines of 3PEAT project and developed further ideas for research along these ideas in the Photonics Communications Research Laboratory of NTUA.

LioniX

The functionality of the TriPleX technology of LioniX International is combined with the PZT and PolyBoard functionalities. In order to enable the use of this technology in applications LXI will use the combined functionalities in its new application specific modules for a variety of applications. In addition, the access barrier for external users will be lowered by offering the (hybrid) combination of technologies in the PDK. With this PDK users can design new PIC functionality based on a set of building blocks. Making the technology easily accessible is an essential part of the exploitation of these new technologies.

FhG-HHI

Due to the great progress on the integration of the non-reciprocal optical elements in the micro-optical bench in 3PEAT, yielding on-chip losses of 0.7 dB for the integrated optical isolator, this functionality is now offered as a standard functionality of the PolyBoard platform. Furthermore, the vertical MMI couplers for the interconnection of multiple waveguide layers are also incorporated into the platform and enable the marketing of the PolyBoard platform towards applications in optical phased arrays. FhG-HHI offers the upgraded PolyBoard platform to its customers and academic partners for the fabrication of photonic integrated circuits. Additionally, the micro-optical bench is the basis of FhG-HHI's work in the H2020 Quantum Flagship project UNIQORN and the German national quantum communication initiative QuNET, where it serves for the integration of non-linear optical crystals for the generation of single and entangled photons.

SolMateS

Within the 3PEAT project SolMateS has demonstrated that it's Pulsed Laser Deposition equipment is capable of depositing high quality PZT thin films that are integrated in photonic devices. The process know-how and developed deposition recipes will be exploited to showcase the unique benefits of PLD for the deposition of advanced piezoelectric thin films. SolMateS will target markets where such thin films are a unique differentiator for device functionality. Target markets and applications for piezoelectric thin films are:

- Photonics - EO modulators
- RF – BAW and SAW resonators
- MEMS – PMUT, PMIC, inertial devices, timing devices

During the second periodic period of 3PEAT SolMateS already gained traction with several customers and end-users in these segments. SolMateS foresees a market entry of PLD for high volume manufacturing in the next two years.

UTwente

UTwente exploits the project results in various ways. First, the project is used for experimental and theoretical training of students of various levels. Within the framework of the course Experimental Laser Physics and Nonlinear Optics (ELPNO) and the bachelor and master assignments, students can acquaint themselves with the technology of integrated photonics in general and hybrid extended cavity semiconductor lasers in particular. Second, results obtained within this project are used to illustrate various topics that are part of the Laser Physics (LP) course. Third, 3PEAT has opened employment options for UT students, introduced by internships, then followed up as staff, which applies also to companies that are part of the UT and Lionix integrated optics ecosystem.

Cordon

Cordon focuses its short/mid-term business strategy in the Space Communication market segment, leveraging the 2D-3D hybrid integration process developed in the 3PEAT project. The outcomes of the 3PEAT project will be firstly applied in new integrated modules for Quantum Communication (QKD systems) in which the hybrid integration between PolyBoard platform and passive/active components will be exploited by Cordon in the next 3-5 years for Security and Aerospace applications.

Optagon

Within 3PEAT project Optagon has mainly focused on the development of the electronic units for the operation of the switching and LDV modules of the project, and on the development of the smart control unit for the configuration and operation of the optical phased array (OPA) that is part of the last LDV module of the project (Module-6). Within this framework, Optagon has defined and is working on the following exploitation paths:

- The commercialization of driving units for the operation of active elements (gain chips for laser diodes and semiconductor optical amplifiers) and thermal phase shifters in various photonic integration technologies and platforms. The development of these units was substantially supported by 3PEAT, continued with the help of other funding sources, and is now at a level of maturity that can lead to the commercialization of these units short after the end of 3PEAT project (i.e., within 2022).
- The commercialization of driving units for the operation of capacitive loads (PZTs in photonic platforms and various MEMS components). The core knowhow for the design and development of drivers with optimum tradeoffs between the operation speed and the output amplitude was developed within 3PEAT and resulted in multi-channel prototypes with bandwidth in excess of 10 MHz and output voltage in excess of 70 MHz that enabled the operation of PZTs in the LDV and

switching modules of the project. Further development and commercialization of these units remain within the exploitation plans of Optagon.

- The development of novel OPA operation concepts for remote sensing applications, and the development of relevant IP. To this direction, an ambitious international PCT patent application was filed short before the end of the project (PCT/IB2022/050789). Efforts for further protection and commercial exploitation of the operation concept described in this application will be made by Optagon in the months and years to come.

MLNX

The exponential growth of datacenter network (DCN) traffic is stimulating the development of faster switches in the datacenter. Current state-of-the-art switches are capable of handling 25.6 Tb/s of traffic by employing ASICs equipped with 256 data lanes, each operating at 100 Gb/s (or 512 lanes operating at 50 Gb/s each). In order to cope with the steep traffic growth inside the datacenter the next generations of 51.2 Tb/s and 102.4 Tb/s switches will be needed in the next few years. However, migration to higher switch ASIC bandwidths stumbles upon a multitude of challenges, spanning from the slow-down of Moore’s scaling to power density concerns and pressing I/O density limitations in the package. Various concepts have been proposed enabling close integration of the ASIC with the photonic transceivers, with the most notable (and mature) being on-board optics and co-packaged optics. However, industry’s expectation is that these approaches alone cannot take the application beyond the 100 Tb/s switch era primarily due to power density limitations. Hence, alternative architectures are expected to be applied in this timeframe. In this context and in parallel to efforts in photonics-electronics co-packaging that could address the challenge in the short-term, MLNX is investigating optical switching as an alternative, future-proof approach for overcoming the bottlenecks of switch ASICs and scaling switch speed and number of ports without hitting on the energy wall.

MLNX is considering optical switching as a highly complementary technology to its current product portfolio of electronic switches and network adapters (NICs). Over the past four years the company has carried out proof-of-concept investigations towards the evaluation of various off-the-shelf switch hardware technologies as well as towards the end-to-end integration of optical switching in the datacenter ecosystem. Within these activities MLNX has gained valuable insights in the overall system architecture of an optical data center network (ODCN) as well as on the new functionalities that need to be integrated in its networking equipment (e.g., NICs) in order to facilitate optical data center networking from the data plane and control plane perspectives.

One of the main lessons learned within these activities was that the application field is currently lacking a suitable technology for optical switch hardware with a high number of ports (>32) and sufficiently high switching speed (μs scale). This technological shortcoming is impacting the viability of the associated network architectures and is inhibiting the commercial deployment of ODCNs. An evaluation of currently available optical switch technologies reveals a trade-off between the number of ports and the switch reconfiguration time. In order to enable practical applications of optical switching in the datacenter, a scalable and manufacturable technology is sought. Within 3PEAT MLNX aims to access a technology for photonic integrated switches with low optical insertion loss, low crosstalk and fast reconfiguration time that rely on proven fabrication technologies and therefore can lead to viable switch products. MLNX has tested the 3PEAT switch prototypes in realistic application settings within its testbed in order to showcase the feasibility and technological maturity of ODCNs. Project results have been very encouraging on the potential of the technology, but it has been recognized that further development steps are needed for commercial exploitation. Once the 3PEAT integrated switch chips reach the required maturity level the company will proceed to the commercialization of the technology following two directions in parallel:

- commercialization of the switch hardware based on the 3PEAT technology providers (HHI, LioniX). MLNX is a fabless IC designer and has broad experience in engaging with foundries and contract manufacturers. If necessary, in order to ramp up production MLNX will involve additional players from its extensive supply chain. MLNX will also work closely with the 3PEAT technology providers in order to verify the reliability of the components according to the usual standards for the application.
- incorporation of necessary network functionalities into its NICs (and/or switches, if applicable) in order to facilitate operation in an ODCN (e.g., per flow buffering, time synchronization etc.).

Through the co-development of the optical switch hardware and the networking equipment MLNX will be able to introduce a fully functional product within 2-3 years after the end of the project. During the entire development phase, the company will further intensify its interaction with potential customers in order to identify the most suitable application field for launching the product (using as a starting point the three application scenarios that are elaborated in WP2).

Polytec

The current application range of Laser-Doppler-Vibrometers is restricted to industrial markets, as the devices are rather large, and the necessary sensitivities require expensive, high-quality components. To overcome this, Polytec entered with 3PEAT the field of photonic integrated chip technology for Laser-Doppler-Vibrometry. Based on the prepared system level specs in WP2, an in-depth knowledge about the possibilities of this disruptive technology for Laser-Doppler-Vibrometry was gained and the current status and availability of the key building blocks for short-term exploitation was revealed. This allows Polytec to investigate in detail the exploitation potential of this new interferometer and scanning technology in combination with upcoming new markets, e.g. in the field electromobility, haptic sensing and others, which can have a high market impact.

Polytec continues investigating photonic chip technology as an alternative, future-proof approach for overcoming the bottlenecks of traditional bulk optics which particularly makes sense when larger quantities of vibrometers are needed. Thus, Polytec is considering photonic chip technology as a highly competitive technology to bulk optics when larger numbers of identical vibrometers are needed, although a number of technological hurdles still have to be overcome. Due to the various promising findings and technological achievements within the project, Polytec will conduct further development and research in this field, in order to pave the way to a fully integrated IR-LDV solution. There is the clear potential to access new cost sensitive markets with a compact, light weighted and low-priced IR-LDV, for example as integrated-sensor in consumer products or for onsite metrology. On a short- and mid-term basis, Polytec will use the building blocks investigated in 3PEAT for further research and development activities with the goal of fast commercialization of new LDV products. This is particularly given for components with a high technology readiness level as e.g. the integrated lasers or MZIs. In this regard, the contacts established within the project to PIC chip manufacturers and the acquired in-depth knowledge serves as a starting point for future collaboration in order to establish a stable supply chain for the new Laser-Doppler-Vibrometer products.

4 Dissemination of the results

Publications

Type of publication	Number
Publication in conference proceedings	**17**
Publication in Scientific Journals	**8**

The 3PEAT consortium continuously pursued to promote the research results of the project to the scientific community, to the industrial community and to the general public. An open access dissemination model was followed, and specific guidelines were provided to the project partners for properly sharing publications, respecting the publisher's copyright policies.

Press releases: were officially launched by all partners during the project.

Website availability: The 3PEAT Project Website (https://ict-3peat.eu/) was developed and made available in the beginning of M04. The website was implemented by the ICCS web-developer and the Project Coordinator ICCS. The website is hosted, with all the relevant files, at the server hosted in the network operations center of the National Technical University of Athens (NTUA) premises. The website is being updated regularly, announcing all events such as plenary meetings

Social media accounts: Accounts on LinkedIn, Twitter and Facebook has been created for the 3PEAT project for promoting the scientific achievements of 3PEAT and is being actively managed.

LinkedIn page (https://www.linkedin.com/company/ict-3peat/)

Twitter account (https://twitter.com/ICT_3PEAT)

Facebook account (https://www.facebook.com/ICT.3PEAT/)

5 Impact

ICCS/NTUA

ICCS aims to bring its know-how on the photonic techniques and their application to the field of switching and sensing, closer to the market. Additionally, ICCS has and will benefit from the ongoing strategic partnerships with the industrial partners of 3PEAT. The theoretical background of 3PEAT has been incorporated in lectures for undergraduate and postgraduate students, and the main activities of ICCS in the project has been linked to diploma theses, PhD topics and new research lines in the academic group.

LioniX

The market of PIC-based modules is maturing, and users are enabled to system level design their PICs based on Process Design Kits (PDK). LXI also has a PDK for TriPleX and since the last 2 MPW runs also a hybrid combination to InP is enabled. Lowering the access barrier for customers using the hybrid integration of PIC-based technologies will increase the speed of application development based on these technologies. The impact of these technologies can therefore be enlarged by lowering the barriers for end-users. For that reason, the PZT tuning and the PolyBoard integration are considered for future integration into the LXI PDK.
The availability of hybrid PIC-based tunable lasers is also an enabler for the market using these narrow linewidth components as a Commercially Off The Shelf (COTS) component. This prevents high entry cost for new users.

FhG-HHI

The impact of the work of FhG-HHI is in line with the impact projected in section 2 of the DoA. The knowledge gained in WP4 regarding the design, the fabrication and integration of state-of-the-art photonic structures on the PolyBoard platform is applicable beyond the scope of 3PEAT. Two successful developments conducted in 3PEAT have the greatest impact on current and future R&D work. Firstly, the developed optical isolator/circulator technology has matured to a point where it is now a standard functionality of the PolyBoard platform with widespread use in PICs for communications, sensing and quantum technologies. Secondly, the well-performing vertical MMI couplers will also be integrated in the platform. Both novel functionalities are the basis for several scientific publications. They have been received with great interest and are already in use in new R&D projects.

SolMateS

The next generation of mobile technology (Wifi-6, 6G), offers enormous benefits for businesses and the individual customers as it will facilitate faster downloads, reduce latency and improve energy efficiency – crucial attributes to achieving the Internet of Things (IoT) and the use of mobile networks to connect and operate autonomous cars, remotely controlled industrial robots, telehealth systems, and smart city infrastructure. However, the ability to manufacture optical and RF components for this technology is crucial for its success. SolMateS demonstrated that it has a unique value proposition where Pulsed Laser Deposition can be an enabler for such next generation devices. PLD will become a game changer in the 200mm deposition equipment market for RF and photonics.

UTwente

UTwente continues to exploit the 3PEAT foreground knowledge through the involvement of their scientific personnel with the education activities in the Department of Science and Technology (TNW) of the UTwente. The theoretical background of 3PEAT is already partly incorporated in lectures for undergraduate and postgraduate students of the TNW, and the main activities of UTwente in the project will be linked to diploma theses, PhD topics and new research lines in the academic group. In parallel the UTwente with the collaboration of LioniX and other companies develop the ultra-narrow linewidth hybrid-integrated laser. Based on research projects, connections and technological options stimulated by 3PEAT, Further research lines based on narrowband lasers are currently being pursued, such as diode pumped Kerr comb generation, operation as mode-locked lasers, or extension of the wavelength range of hybrid integrated diode lasers into the visible spectral range.

Cordon

3PEAT gave Cordon the opportunity to develop new assembly processes and packaging approaches for hybrid integration of different materials, comprising both electronics and optical functions. The gained knowhow on hybrid integration techniques and 3D integrated photonic platform offers Cordon a competitive advantage, making the company a unique player in that market sector. Cordon was able to enlarge its technological assembly platform with the introduction of integration processes for multifunctional polymer platform, low loss high density TriPleX technology and InP PICs. A strategic partnership with a worldwide leader in automated photonic assembly equipment has been set up and will open new short/medium term opportunities as services provider in photonic markets. In 3PEAT project Cordon consolidated its position in the European Photonics supply chain as packaging house to support companies, SMEs, Universities and Research Centers in the development and manufacturing of new Optoelectronic and Photonic components and modules. This adds to Cordon's participation in the European consortia JePPIX (http://www.jeppix.eu/) and in the Photonic Packaging Pilot Line (PIXAPP project: https://www.pixapp.eu/).

Optagon

The participation in 3PEAT had a substantial impact on the consolidation of the business plan of Optagon as a young SME, on the development of its baseline technology for the development and the commercialization of meaningful and viable products, and on the conduction of efforts for the development of intellectual property (IP). In detail:

- In alignment with its work in 3PEAT, Optagon identified and highlighted the development of control electronics for the operation of large-scale PICs as one of its main business areas.
- Within 3PEAT, Optagon developed technology and prototypes that constituted the basis for the design of driving electronics products for operation of large-scale PICs and support of relevant

experimentation in research labs. Commercialization of these products is now expected to take place short after the conclusion of the 3PEAT project (within 2022).

- Within 3PEAT, Optagon developed the baseline technology that makes possible the development and combination of smart algorithms and software with its driving electronics.
- In alignment with its work on the modelling, design, and operation control of OPAs, Optagon filed an international Patent Cooperation Treaty (PCT) application on 29/01/2022 with application number PCT/IB2022/050789. The key claims and the title of the application are still kept confidential, as per the rules and the rights of the international PCT applications.
- Last but not least, through the participation in 3PEAT, Optagon came in contact with elite industrial and academic partners from Europe in the field of photonics, became aware of their technology, and developed the basis for substantial collaboration with these partners. A prominent example of this process has been the familiarization of Optagon with the silicon nitride platform of LioniX (TriPleX), the development of an original idea by Optagon for the development of an optical equalizer that can best be materialized in a silicon nitride platform, the preparation of a PCT (WO2020089661) and a European Patent (EP) application (EP 19809135.7) regarding this idea, and the collaboration of Optagon with LioniX outside 3PEAT on the development of a prototype of this equalizer: https://www.LioniX-international.com/about-us/blog/low-error-data-transmission-with-an-integrated-photonic-optical-equalizer/.

Mellanox

MLNX will be the driving force in the exploitation of the hybrid integration platform for the development of optical switching solutions for DC networks. The company has identified optical switching as a potential enabler of dramatic energy savings in the network. Optical switches consume orders of magnitude less energy compared to their electronic counterparts and remain data-transparent, facilitating seamless bandwidth upgrades. However, their deployment in the datacenter has been hindered due to the limitations of current products. Relying on electro-mechanical components they consume valuable rack real-estate, cost too much (for the market segment) and have slow reconfiguration time. Migration to integrated switches is a no-brainer for saving cost and rack space, increasing speed and reaching datacenter-relevant volumes. The active optical switches of the project represent a viable path for introducing integrated optical switches into datacenter networks as they combine low optical loss, large port count, low crosstalk and high speed. Considering the benefits brought by optical switching that include much lower latency, higher throughput, reduction in power consumption up to 90% and possibility for cost reduction up to 94%, Mellanox can have the impact of redesigning the higher layers of the switching hierarchy inside DCs and reduce the number of electrical switches from these layers while optimizing their utilization. MLNX is working on novel network architectures and DC concepts enabled by this new switching technology and aims to maximize the range of opportunities in this burgeoning market.

Polytec

Currently, LDVs are rather large in size and expensive, so that the application field is restricted to industrial research and testing applications. In contrast, the 3PEAT technology approach combines miniaturization of otherwise bulky optical components (e.g., MZI, detectors, lasers) with the possibility of a significant reduction in production costs. While bulk optic alignment is time consuming and difficult, with PIC technology the adjustment is already part of the chip fabrication process. Furthermore, as e.g., scanning mirrors can be potentially replaced by OPA-arrays and opto-acoustic-modulators can be substituted by integrated phase-shifters, the functional density can even be enhanced. Thus, it is feasible to lower power consumption while simultaneously shrinking size and weight of LDVs with this disruptive technology approach. Taking together all the benefits of PIC technology, PIC based LDVs could allow Polytec to address and enter otherwise cost sensitive markets. Since a large number of different components were examined in the project (e.g., narrow linewidth lasers, OPA-array, PZT-shifters, integrated MZI, TriPleX and PolyBoard-technology) it is conceivable, that partial results are exploited separately from each other, while simultaneously further research is conducted on components with a currently to low technology readiness level. Furthermore, the 3PEAT-project allowed Polytec to step deeper into photonic integrated chip technology and to establish strategic partnerships beyond the project.

6 Conclusions

This document summarizes the progress achieved in the framework of 3PEAT project and concludes the technical progress throughout the project, the dissemination and exploitation of the results, the communication activities followed and the impact that 3PEAT project had to the involved partners.

List of Figures