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Photonic Integrated Multichannel WDM Modulators for Data Read-Out Units

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Abstract—This study presents the recently developed monolithic photonic-integrated circuits that provide efficient amplitude modulation for wavelength division multiplexed optical channels. The circuits were designed for application as a read-out unit in a high-energy physics experiment, and are sufficiently general to be applied in various types of high-speed photonic transmitters. They were constructed using basic building blocks provided in an indium phosphide-based generic integration technology process and fabricated in a multi-project wafer run. Two variants of the circuits, utilizing modulators in Mach–Zehnder and Michelson interferometer configuration, are discussed. A modulation bandwidth of 18.6 GHz was measured and error-free transmission of a 10-Gb/s signal through 85 km of optical fiber was achieved.

Index Terms—Electro-optical amplitude modulator (AM), indium phosphide (InP), generic integration technology, Mach–Zehnder interferometer, Michelson interferometer, multi-project wafer (MPW), photonic integrated circuit, wavelength division multiplexing (WDM).

I. INTRODUCTION

DATA read-out unit is a key element of currently deployed and newly designed sensor networks, which in turn are an essential part of monitoring systems, smart grid networks and intelligent buildings. Distributed sensing systems, based on fiber-optic components are also commonly deployed in high-energy physics experiments, where the advantages of the highest reliability and high data transfer rates are of primary significance. A web of sensors, monitoring advanced physical experiments, tends to generate a large number of digital or analog signals on a distributed area. The read-out system is responsible for collecting all of these signals and for transporting the data to an offline data storage system. In selected cases it should have also additional functionality of initial data processing and evaluation. A read-out system has often a star network topology, comprising a control station as the central node and front-end read-out units connected directly to the remote sensors, while the physical connection is established over a fiber-optic network. Both the read-out and the central station equipment is based on microelectronic and optoelectronic components and devices.

This type of scheme was already used for projects such as ANTARES [1], NEMO [2], NESTOR [3], and a similar one is going to be applied in KM3NeT [4]. All of these are high-energy physics experiments aiming at tracking neutrinos by means of detection of the Cherenkov radiation in water with a distributed network of photomultiplier tubes (PMTs). For KM3NeT the PMTs are housed inside glass spheres, so-called digital optical modules (DOMs), which are deployed at the bottom of the Mediterranean sea in order to decrease the background radiation from cosmic rays. The generated signal, which is a series of digital ones and zeros, indicating that a single PMT was hit by a photon or not, has to be transmitted to the central analysis station located on the shore.

For the front-end read-out units the most important parameter is its operational speed as well as power consumption, which is essential for applications such as KM3NeT. The requirements imposed by this experiment on the read-out system is that the sampling frequency should be at least 1 GHz and the total amount of power consumed by a single module is smaller than 7 W. So far the direct read-out functionality was performed by purely microelectronic devices. They sampled and digitized the analog output signals of the PMTs and prepared the transmission using a specific protocol, e.g. optical Ethernet [1]. The electronic circuits were also used to drive all photonic elements of the read-out system, i.e. lasers, modulators, photodetectors, while the optical functionality was limited to establishing a communication link through an optical fiber.

In our previous works we reported direct photonic data read-out units [5], [6]. Those are monolithically integrated optical pulse serializers, which utilize optical time division multiplexing technique. The read-out performance is provided by an optical sampling signal, onto which the information from the PMTs is encoded using electro-optical amplitude modulators (AMs).

The motivation of the present work is to propose a different architecture of a photonic integrated circuit with an improved functionality in terms of the maximum sampling frequency for a single PMT. The developed solution utilizes a parallel read-out scheme by means of wavelength division multiplexed (WDM) signals. It was designed according to the KM3NeT architecture.
and requirements, but the principle of operation is sufficiently general to apply it in different sensor network experiments, where even higher speed (exceeding 10 GHz) might be required. The parallel optical read-out is advantageous in terms of operational speed as the output signal from a single PMT can be sampled with a very high frequency, limited only by the bandwidth of the modulator applied. Furthermore, the power consumption may be significantly reduced, as much less electronics has to be assembled inside an optical module.

Fig. 1 presents the concept of the proposed read-out system for a single DOM of the telescope. It can be divided into two main parts—the central shore station and the underwater DOM. An array of lasers, each operating at a different WDM channel, generates sampling signals—optical pulse trains with a minimum repetition rate of 1 GHz and pulse duration shorter than 500 ps. As a single DOM comprises 31 photomultipliers, 32 WDM channels are being utilized and the remaining channel is left for a slow control signal. All of the signals are multiplexed into a single optical fiber and transmitted through a 100 km of SMF (single mode fiber) to the DOM, where they are demultiplexed. Electro-optic AMs are used to encode the digitized output signals of the PMTs onto the optical carriers. The sampling signals are multiplexed again to a single optical fiber, amplified and transmitted back to the shore station. The WDM signal is then demultiplexed and detected by an array of photodiodes.

II. FABRICATION TECHNOLOGY

Indium phosphide (InP) based technology allows fabrication of photonic integrated circuits, comprising nowadays even hundreds of components, both active and passive, monolithically integrated on a single semiconductor chip [7]. Advanced epitaxy, deposition and etching techniques enable accurate, submicron definition of the 3-D geometry of the photonic structures. Thus, a monolithic PIC can comprise a large variety of components such as semiconductor optical amplifiers (SOAs), electro-optical phase modulators, electro-absorption modulators, DBR gratings, DFB lasers, p-i-n photodiodes, wavelength demultiplexers in arrayed waveguide grating (AWG) configuration, filters, ring resonators, power splitters, couplers, on-chip reflectors and many others. Light amplification and/or detection is provided by a quaternary alloy InGaAsP, the bandgap of which can be tuned within the wavelength range of 900–1650 nm [8], depending on the composition of the elements. The phase control is supported by electro-optic effects occurring in InP-based semiconductors. In bulk quaternary materials the phase change is linear with the applied voltage, while it is combined with a quadratic quantum confined Stark effect (QCSE) [9], [10], if the waveguiding layer has a quantum well structure. The light is detected in a direct way through absorption of photons and generation of carriers inside a p-i-n diode under reverse bias.

Despite significant progress in modeling, design and fabrication technology, photonic ICs have not penetrated the market yet. At present, there are only few examples of commercially available large-scale photonic integrated circuits [11]. The reason for that is the lack of a standardized technological process, which would allow fabrication of sophisticated PICs at relatively low cost. During the last few years, the key European industrial and academic players in the field of InP-based photonics have been working on establishing and standardizing a fabrication process in which more advanced circuits could be synthesized from a limited set of basic active and passive optical components. This is a basic assumption of the generic approach, well known from the CMOS microelectronics, where billion-element circuits, such as complicated modern microprocessors, are constructed using mainly three basic elements - transistors, capacitors and resistors. This novel kind of photonic IC manufacturing has already been trialled and tested by several foundries [12]. As a result, many photonic ICs for various applications, e.g., for telecommunications and sensing, have been designed, fabricated and characterized, which proved their very good overall performance [5], [13]–[19].

The multichannel modulators reported in this paper are examples of such circuits. We utilized an integration platform which supports (1) deeply and shallowly etched waveguides, (2) electro-optic phase modulators and (3) SOAs. The technology is based on an n-doped InP substrate. The guiding layer contains multiple InGaAsP quantum wells, on top of which the p-doped InP layers are grown. The active elements have a common n-contact on the back-side of the substrate, and separate p-contacts on the top side of the chip.

For the deeply etched passive waveguide the minimum width allowed by the fabrication technology is $w_{\text{min}} = 1.0 \mu m$. The total measured propagation loss is $L = 5 \text{ dB/cm}$ for $w = 1.5 \mu m$ and $\lambda = 1550\text{nm}$. The dominating mechanism is the loss introduced by the p-doping of the upper cladding. This doping is necessary for obtaining efficient operation of the electro-optical phase modulators [20] that have the same cross section as the deeply etched passive waveguides. Although this doping has a graded profile, with the lowest level close to the optical field and increasing towards the top of the cladding, the resulting loss in the passive waveguides is still significant. This is a trade-off between the lowering the attenuation and increasing the modulation efficiency—reducing the doping will reduce the efficiency of the modulators [20]. The second contribution is scattering due to waveguide roughness, which is around 1 dB/cm, i.e. equal to the attenuation of the undoped waveguides. By comparing loss of the waveguides with and
without p-doping the contributions from doping and roughness could each be quantified.

In such a structure the linear electro-optic effect is enhanced by quadratic QCSE [9], which results in a value of $V_\pi$ equal to 3.5 V at $\lambda = 1550$ nm and 1 mm-long modulator. The waveguide width for the modulator sections is fixed at $w_{EOPM} = 1.2$ $\mu$m.

The gain sections have a shallowly etched waveguide structure with quantum well active layer of InGaAsP (bandgap 1.55 $\mu$m). The width of the active waveguide is fixed at $w_{SOA} = 1.9$ $\mu$m. The amplifiers can provide up to 13 dB of gain in case of a 500-$\mu$m-long section and a supply current of 80 mA.

After the fabrication the chips were anti-reflection coated, which resulted in a power reflection coefficient smaller than $R_{AR} = -27$ dB.

III. CIRCUIT DESIGN

The circuits were designed as proof-of-concept devices based on the requirements imposed by the KM3NeT project. However, for testing the system concept, the circuits were designed to work with eight channels. The schematic of the chips is shown in Fig. 2(a) and (b), for transmitting and reflecting configurations, respectively, and the corresponding mask layouts are presented in Fig. 3.

The input signals are demultiplexed by the input AWG, which is designed with a channel spacing of 3.2 nm (400 GHz) and a free spectral range of 25.6 nm, centered around 1550 nm. The carrier is then modulated by the output voltage of the PMTs by using electro-optical AMs either in Michelson (reflecting) or Mach–Zehnder (transmitting) interferometer configuration. The transmitting circuit utilizes $2 \times 8$ AWGs in order to make a design compliant with a newly developed packaging scheme [21], which also requires that the angled optical IOs are on a single side of the chip. The remaining IOs are deployed on two sides of the chip in order to make the characterization process easier.

For the reflecting configuration the signal is sent back and is demultiplexed by the same AWG and the input is separated from the output by a $1 \times 2$ MMI power splitter. In the transmitting circuit the outgoing signals pass through a second AWG. The 500-$\mu$m-long SOA sections are used to compensate for on-chip propagation loss and for the insertion losses introduced by the passive components. They can provide up to 13 dB optical gain. The interconnect waveguides utilize deeply etched waveguides with a width of 1.5 $\mu$m. Fig. 2 shows also the photograph of fabricated circuits, with dimensions $3.2 \times 1.8$ mm$^2$ and $6.0 \times 2.0$ mm$^2$.

The Michelson modulators are built with a $1 \times 2$ MMI power splitter and two 500-$\mu$m-long phase shifter sections and MMI-based reflectors. Fig. 4 presents an enlarged microscope photograph of the Michelson modulator and a SEM picture of the MMI based reflectors. The Mach-Zehnder modulators have two 1-mm-long phase-shifter sections and both an input and output $1 \times 2$ MMI power splitter/combiner.

Both configurations of the AMs operate around $\lambda = 1550$ nm, the value of the switching voltage, $V_\pi$, is 3.5 V and the simulated extinction ratio is around 26 dB. Both these parameters are wavelength dependent. Generally, the shorter wavelengths are characterized by a lower $V_\pi$, but experience higher losses under the same reverse bias. Both facts are due to the character of the QCSE [10], which takes place inside the phase modulators.

The advantage of the Michelson configuration is that a similar performance can be obtained with a photonic component of half the size. Furthermore, as there is only one AWG, there is no risk of misalignment of the passbands, what might happen, e.g. due to fabrication imperfections, when two separate multiplexers are used in the transmitting circuit.

On the other hand, the modulation characteristic of the Michelson modulator may be affected by spurious reflections
at the input MMI splitter. The power reflection coefficients for the splitter are indicated in Fig. 5. The reflected power becomes noise and will coherently interfere with the main signal. The influence of the reflection at the input ($|S_{11}|$) can be neglected, as it is smaller by approximately 18 dB than the extinction ratio of the modulator. However, the spurious reflections represented by $|S_{22}|$, $|S_{23}|$, $|S_{32}|$, and $|S_{33}|$ significantly contribute to the effective transmission of the modulator. Fig. 6(a) presents the characteristics when the spurious reflections are taken into account - depending on the phase difference between the signals the level of the minimum goes up or down in comparison to the ideal case.

By contrast, this process is not significant for the Mach–Zehnder modulator. First of all, it requires occurrence of two reflections, which is presented in Fig. 6(b). The first one takes place at the output MMI combiner and then again at the input MMI and thus the effective reflection coefficient is in the order of $R_2 = |S_{22}|^2$, $|S_{22}|^2 \approx -50$ dB, i.e. significantly smaller than the modulator extinction ratio. As a result, influence of spurious reflections can be neglected, as the power level of the minimum of the simulated transmission characteristic changes only by a factor of $\Delta P = 0.2$ dB.

The complex components, such as the $1 \times 2$ MMI power splitters/combiners, the MMI reflectors and the AWGs, were designed using the building blocks available for the generic technology. The process was supported with dedicated design kits, consisting of the software capable of performing simulations and mask generation of a single component [22]–[24]. Mode solvers based on the finite-difference and film-mode-matching methods have been used. Simulation of propagation of optical signals utilize algorithms such as the beam-propagation method, the finite-difference-time-domain method and the eigen-mode-expansion method. Circuit level simulations have been possible due to implementation of the time-domain-traveling-wave model. Finally, the module for mask layout generation was supported with libraries of the foundry building blocks and design rule checking algorithms.

### IV. Characterization Results

For all measurements tunable lasers were used that covered the spectral range between 1497 nm and 1577 nm. In the case of the reflecting circuit a circulator was used to separate input and output signals as only one optical interface (IO) could be used at the same time on one side of the chip. A polarization controller and a polarizing beam splitter enabled selective excitation of the fundamental TE mode in the circuits, as the circuit components are polarization sensitive. A polarization maintaining lensed fiber with a spot diameter ($1/e^2$) of 2.5 μm was used for optical coupling. The circuit was driven with precise current sources for driving the SOAs (Thorlabs LDC 80xx) and voltage sources (Keithley 2400/2600 series) for the DC bias of the modulators. A bias tee was used to separate the DC from the RF signals.

For the RF measurements the chips were mounted on ceramic submounts (see Fig. 7) and the circuit components were wire-bonded to the gold DC pads and RF ground-signal-ground coplanar transmission lines. The RF-probes were positioned on the other side of the RF tracks. The impedance matching was provided by two 100 Ω parallel resistors (i.e. 50 Ω effective resistance) between the signal track and the ground of the transmission lines. The temperature of the device was set to 19 °C, monitored by a thermistor and controlled by a Peltier element.

The RF signals source was either a lightwave component analyzer (LCA, Agilent’s N4373B 67 GHz) or a pseudo random bit sequence (PRBS) generator. In static measurements the outgoing optical signal was detected by a power meter; for the RF characterization the LCA was deployed in the case of bandwidth measurements; a digital communication analyzer (DCA, a
Fig. 8. Measurement setups used for (a) RF bandwidth characterization (b) digital modulation and transmission experiments. CW—continuous wave tunable laser diode; PC—polarization controller; PBS—polarizing beam splitter; PIC—photonic integrated circuit; EDFA—erbium doped fiber amplifier; TF—tunable optical filter; LCA—lightwave component analyzer; SMF—single mode fiber; DCF—dispersion compensation fiber; VOA—variable optical attenuator; PD—photodiode; PRBS—pseudo-random bit sequence generator; BER—bit error rate tester. Red solid lines—optical fiber connections; Blue dashed lines—electrical connections.

Fig. 9. Measured AWG transmission characteristic.

Fig. 10. Measured static transmission characteristic of the Mach–Zehnder modulator (CH4).

Fig. 11. Measured static transmission characteristic of the Michelson modulator.

The channel spacing $\Delta \lambda$ is close to the design value of 3.2 nm, however the central wavelength $\lambda_c$ is shifted by 9.5 nm.

For the AWGs of the transmitting circuit these parameters are similar, i.e. the measured $\Delta \lambda = 3.2$ nm and $\lambda_c$ was found to be shifted by 9.0 nm. The channel positions of the input AWG are matching those of the output AWG. Therefore, the propagating signal does not experience extra loss.

Secondly, the static performance of the modulators was evaluated. The dc reverse bias applied to one of the phase shifter arms was changed from 0 V to 10 V, while the second arm was grounded. The driving current of SOA was set to 50 mA. The extinction ratio obtained for all measured Mach–Zehnder modulators was between 25 and 32 dB. Fig. 10 presents example transmission characteristics of the CH4 modulator, for two wavelengths, $\lambda_1 = 1558.4$ nm and $\lambda_2 = 1533.1$ nm, i.e. for operation within a different FSR of the AWG. As the electro-optic effect is stronger for shorter wavelengths, the on-off driving voltage is smaller for $\lambda_2 (V_2 = 3.4$ V). Despite the full symmetry of the design, the transmission curves reveal a slight imbalance of the modulators. This is most likely caused by fabrication imperfections, which influence the phase of optical signals.

The Michelson modulator is a reflective variant of the Mach–Zehnder configuration. Therefore, similar properties were expected for these devices. The measurements confirmed high values of the extinction ratios, which are typically between 26 and 34 dB. The values of the driving voltage ranged between 2.7 and 4.5 V. The example transmission characteristics are presented in Fig. 11. It should be mentioned that the shape of all curves is influenced by parasitic reflections within the circuit itself and within the measurement setup: at the $2 \times 1$ MMI power combiner ($R = -44$ dB), at the lensed fiber tip ($R = -30$ dB) and also by the crosstalk at the circulator ($-40$ dB).

To determine the electro-optical modulation efficiency of the Mach–Zehnder and Michelson modulators the RF characterization was performed. A continuous wave laser signal (optical carrier), at wavelength compliant with the measured channel, was coupled to the circuit. The SOAs driving current was set at 80 mA. The DC bias point of the modulators was set to obtain the best RF performance. The RF driving signal was generated by
the LCA and applied to the photonic chip through an RF-probe connected to the G-S-G lines. The modulated optical output signal was then detected by the LCA module and analyzed by the network analyzer. Fig. 12 shows the characteristics of the magnitude of the $S_{21}$ parameter for both types of modulators. The measured 3 dB bandwidth of the Mach–Zehnder structures is between 10.9 and 11.4 GHz, while for the Michelson structures it is between 17.2 and 18.6 GHz, which means approximately 50% increase of performance. This is due to the fact the the phase shifter sections of the Michelson modulators are twice as short, which results in a smaller parasitic capacitance and therefore also a smaller $RC$ time constant.

Finally, we performed tests of digital modulation of the circuits and transmission experiments through a certain length of an SMF fiber. The DC bias was set as before and the modulators were driven by a digital signal from the PRBS generator, with a $2^{31} - 1$ word length, and equal probability of the symbols. The SOA driving current was set at 80 mA. Again the CW carrier was coupled to the chip and the outgoing signal was either visualized on the oscilloscope or detected by a digital receiver and then analyzed by the BER tester. An EDFA was used to boost the output power at the receiver side. A tunable filter was used to reduce the on-chip SOA and EDFA noise outside the analyzed wavelength channel. In the transmission experiment a variable optical attenuator was used to set the power going into the receiver.

Fig. 13 presents the recorded back-to-back (BTB) eye-diagrams of the Mach-Zehnder modulator (CH5, $\lambda = 1534.9$ nm) for 1, 5 and 10 Gb/s data rates. The measured dynamic extinction ratio is as good as 14.7, 13.2 and 12.4 dB, respectively. Fig. 14 presents the eye diagrams for 10 Gb/s after transmission of the digital signal through 25 km and 50 km of SMF fiber in comparison to the BTB case. For the 50 km the eye opening degrades significantly, so an additional test was performed where a piece of dispersion compensation fiber (DCF) fiber was used to compensate the dispersion. As a result, the eye-opening was improved.

Fig. 15 shows the measured eye-diagrams for the Michelson modulators (CH7, $\lambda = 1551.3$ nm) in BTB configuration, for 10 and 12.5 Gb/s modulation. The measured dynamic ER was 10.7 and 12.7 dB, however at slightly different bias conditions. The results of the transmission experiments are visualized in Fig. 16 for the Mach–Zehnder and Fig. 17 for the Michelson modulators. For the first case we performed the tests for CH4 modulator at $\lambda = 1560.2$ nm, in back-to-back configuration, and also for propagation through 25 km and 50 km of SMF. The
Fig. 14. Eye diagrams for the transmission circuit of 10 Gb/s signals (a) back-to-back, (b) after 25 km of SMF fiber, (c) after 50 km of SMF fiber, (d) after 50 km of SMF and extra piece of a DCF fiber.

Fig. 15. Eye diagrams for the reflecting circuit in the back-to-back configuration (a) 10 Gb/s, (b) 12.5 Gb/s.

experiment was performed with 1, 5 and 10 Gb/s NRZ signals. For 10 Gb/s signal after 50 km SMF a DCF fiber was attached for dispersion compensation. The measured power penalty for 10 Gb/s at BER = 10^{-10} was 3.3 and 3.9 dB for 25 and 50 km, respectively.

Similar tests were performed for the reflective circuit, and the results are presented in Fig. 17. In this case the power penalty after propagation of 10 Gb/s signal through 85 km of SMF fiber was 1.5 dB.

V. DISCUSSION

We have designed, implemented and tested photonic integrated WDM modulator circuits in Mach-Zehnder and Michelson configuration. The most significant achievements are excellent extinction ratio of the modulators in both configurations. The measured static ER is better than 25 dB and dynamic better than 10 dB. The analog RF performance is also very good—the electro-optical bandwidth of Mach-Zehnder structures is around 11 GHz and reaches the value of 18.6 GHz for the Michelson configuration. The recorded eye diagrams under digital modulation with the data transfer rate up to 12.5 Gb/s are wide open and the quality of the signal was evaluated in transmission experiments. As a result, error free operation (i.e. BER below 10^{-10}) of the 10 Gb/s signal was observed for 50 km in case of the transmitting circuit and up to 85 km for the reflecting circuit. The power consumption is kept at a moderate level of 160 mW, when the two SOAs are driven with 80 mA.

The observed performance of the multi-channel modulators makes them suitable for high-speed data read-out operation. It
is predicted that a transmission of a 20 Gb/s signal is feasible making use of Michelson-type modulators. The tests, however, were not performed due to limitation of the available equipment. The power consumption, extrapolated for a 32-channel circuit, should be kept within 640 mW. Both these values are much better than the requirements imposed by the KM3NeT experiment, i.e. 1 GHz sampling frequency and 2.5 W for the read-out circuitry (out of the total 7 W assigned to a single optical module).

The multi-channel WDM circuits were tested under digital modulation with NRZ signals from a PRBS generator. Additional tests, however, are required for sampling the electrical signal connected directly to the modulators with an optical pulse train, which would emulate the conditions of a real sensor system. The results which we obtained in a different experiment proved feasibility of such a read-out operation [5], [6].

Although the performance of both configurations of the WDM multi-channel modulators is very good, there is still some room for further improvements. The transmission experiment revealed some problems associated with the transmitting circuit design. The measured bandwidth of the modulators, which is around 11 GHz, indicates that transmission of a 10 Gb/s signal should be feasible without significant problems. However, the experiment revealed a power penalty of 3.9 dB after propagation through 50 km of an SMF fiber, despite adding a dispersion compensation fiber. This fact is most likely due to a relatively low power level at the input of the modulator section. The power at the end of the lensed fiber was 2 dBm and taking into account a fiber-chip coupling loss of 5 dB, an AWG loss of 5 dB, a waveguide attenuation of 3 dB (6 mm × 5 dB/cm), this results in an input power level around −11 dBm. Before the signal is amplified prior to the modulation. A higher optical power will result in a better OSNR coefficient and, as a consequence, also in better parameters of the transmission. The only cost of this solution is that the power consumed by the chip will increase by 0.2 W.

The design of the reflective circuit may utilize a 2 × 2 MMI coupler instead of the 1 × 2 power combiner, which is used for the input and output signal separation. The unused port of this coupler could then be terminated with a PIN diode for full light absorption and to offer a monitoring function. In the 2 × 2 MMI the spurious reflection coefficient is smaller by a factor of 10, and the 3 dB split of the input power is equivalent to the loss introduced by the 1 × 2 MMI in the combiner mode.

The influence of other parasitic effects will be minimized in the real conditions of operation. Due to the packaging requirements, the optical IOs were positioned on the same side of the chip, which complicated the measurements. The circuit was designed to work with both IOs, one serving as the input and the other as the output so that the outgoing signal could interfere neither with the reflected at the fiber tip nor with the CW signal due to the crosstalk in the circulator.

VI. CONCLUSION

The study on the photonic integrated circuits presented in this work is the first stage in the development of a fully optical, WDM data read-out unit. It should be mentioned that excellent properties of the chips were achieved only by optimized design of the circuits, without any changes in the technology process. The design utilized standardized building blocks, from which more complex components and eventually the full circuits were constructed. Furthermore, the chips were compliant with a newly developed, generic packaging scheme. The whole process was supported with dedicated software design kits, enabling simulation of the component performance and optimization, as well as design of the circuit layout. The characterization of the fabricated devices confirmed excellent performance in terms of analog and digital modulation, as well as digital transmission parameters. The measurements also helped to identify the parasitic effects, such as reflections, influencing on the performance of the devices. Altogether, the main results achieved in this work prove the feasibility of application of photonic integrated circuits for direct optical data read-out.

REFERENCES


Stanislaw Stopinski received the M.Sc. degree in electronics and computer engineering in 2008 from the Warsaw University of Technology, Warsaw, Poland. In September 2009, he started combined Ph.D. studies at the Warsaw University of Technology and at the Eindhoven University of Technology, Eindhoven, the Netherlands, in the framework of a joint doctoral programme. His current research is focused on application, design, and characterization of photonic-integrated circuits.

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