Serial 100 Gb/s connectivity based on polymer photonics and InP-DHBT electronics

Vasilis Katopodis,[1,*] Christos Kouloumentas,[1] Agnieszka Konczykowska,[2] Filipe Jorge,[2] Panos Groumas,[1] Ziyang Zhang,[3] Antonio Beretta,[4] Alberto Dede,[4] Jean-Yves Dupuy,[2] Virginie Nodjiadjim,[2] Giulio Cangini,[5] George Von Büren,[5] Eric Miller,[5] Raluca Dinu,[5] Jung Han Choi,[3] Detlef Pech,[3] Norbert Keil,[3] Heinz-Gunter Bach,[3] Norbert Grote,[3] Antonello Vannucci,[4] and Hercules Avramopoulos[1]

[1]*National Technical University of Athens, Zografou 15573, Athens, Greece*
[2]*III-V Lab, Route de Nozay, Marcoussis, 91460, France*
[3]*Fraunhofer Institute for Telecommunications, HHI, Berlin 10587, Germany*
[4]*Linkra Srl, Via S.Martino 7, 20864 Agrate Brianza (MB), Italy*
[5]*GigOptix Inc.19910 North Creek Parkway Suite 100, Bothell, Washington 98011, USA*
[*]*vkat@mail.ntua.gr*

Abstract: We demonstrate the first integrated transmitter for serial 100 Gb/s NRZ-OOK modulation in datacom and telecom applications. The transmitter relies on the use of an electro-optic polymer modulator and the hybrid integration of an InP laser diode and InP-DHBT electronics with the polymer board. Evaluation is made at 80 and 100 Gb/s through eye-diagrams and BER measurements using a receiver module that integrates a pin-photodiode and an electrical 1:2 demultiplexer. Error-free performance is confirmed both at 80 and 100 Gb/s revealing the viability of the approach and the potential of the technology.

OCIS codes: (130.3120) Integrated optics devices; (230.4110) Modulators.

References and links

1. K. Roberts, M. O'Sullivan, K.-T. Wu, H. Sun, A. Awadalla, D. J. Krause, and C. Laperle, "Performance of dual-polarization QPSK for optical transport systems," J. Lightwave Technol. **27**(16), 3546–3559 (2009).
2. J. Theodoras and K. Grobe, "100 GbE – the future of ethernet," white paper, August (2009), *http://www.advaoptical.com/en/resources/white-papers/100gbe-the-future-of-ethernet.aspx*
3. M. A. Taubenblatt, "Optical interconnects for high-performance computing," J. Lightwave Technol. **30**(4), 448–457 (2012).
4. C. Kazmierski, A. Konczykowska, F. Jorge, F. Blache, M. Riet, C. Jany, and A. Scavennec, "100 Gb/s operation of an AlGaInAs semi-insulating buried heterojunction EML," Proc. OFC/NFOEC'09, OThT7 (2009).
5. J. Li, C. Schubert, R. H. Derksen, R. Makon, V. Hurm, A. Djupsjöbacka, M. Chacinski, U. Westergren, H.-G. Bach, G. G. Mekonnen, A. G. Steffan, R. Driad, H. Walcher, and J. Rosenzweig, "112 Gb/s Field trial of complete ETDM system based on monolithically integrated transmitter & receiver modules for use in 100GbE," Proc. ECOC'10, P4.03 (2010).
6. W. Freude, J. Leuthold, L. Alloatti, T. Vallaitis, D. Korn, R. Palmer, C. Koos, J. Brosi, P. Dumon, R. Baets, M. L. Scimeca, I. Biaggio, B. Breiten, F. Diederich, A. Barklund, R. Dinu, and J. Wieland, "100 Gbit/s electro-optic modulator and 56 Gbit/s wavelength converter for DQPSK data in silicon-organic hybrid (SOH) technology," Proc. IEEE Photonics Society, WB2.1 (2010).
7. H. Huang, J.-Y. Yang, Y. Yue, Y. Ren, S. R. Nuccio, R. Dinu, D. Parekh, C. J. Chang-Hasnain, and A. Willner, "100-Gbit/s amplitude and phase modulation characterization of a single-drive, Low-Vπ polymer mach-zehnder modulator," Proc. OFC/NFOEC'12, OW4F.5 (2012).
8. P. Groumas, Z. Zhang, V. Katopodis, Ch. Kouloumentas, D. de Felipe, R. Dinu, E. Miller, J. Mallari, G. Cangini, N. Keil, H. Avramopoulos, and N. Grote, "Complex monolithic and InP hybrid integration on high bandwidth electro-optic polymer platform," Opt. Lett. **37**(16), 3465–3467 (2012).
9. A. Konczykowska, J.-Y. Dupuy, F. Jorge, M. Riet, J. Moulu, and J. Godin, "InP DHBT delector-driver with 2 X 2.7swing for 100 Gbit/s operation," Electron. Lett. **45**(24), 1235–1236 (2009).
10. G. G. Mekonnen, H.-G. Bach, R. Kunkel, C. Schubert, D. Pech, T. Rosin, A. Konczykowska, F. Jorge, A. Scavennec, and M. Riet, "Hybrid co-packaged receiver module with pin-photodiode chip and DEMUX-IC for 107 Gb/s data rates," Proc. ECOC'09, paper 9.2.6 (2009).

#178174 - $15.00 USD Received 16 Oct 2012; revised 16 Nov 2012; accepted 16 Nov 2012; published 10 Dec 2012

1. Introduction

Physical layer implementations of 100 GbE rely today on technologies and techniques that allow the use of lower bandwidth photonic and electronic components at the system transceivers. For long-haul systems, coherent dual polarization quadrature phase-shift keying (DP-QPSK) appears as the modulation format of choice [1] necessitating 25G components. For links in metro networks, solutions based on optical duobinary (ODB) or combinations of phase- and amplitude-shift keying formats necessitate 40G components and represent alternatives that are attracting increasing attention [2]. Finally, for short reach optical interconnects, parallel 10x10 Gb/s or 4x25 Gb/s implementations relying on simpler non-return-to-zero on-off-keying (NRZ-OOK) format and space division multiplexing (SDM) represent simple and reliable 100 GbE solutions [3].

Despite this landscape, the efforts to remove barriers to higher bandwidth components and complete transmitters are strong and ongoing. Two are the main reasons for this: a robust solution for serial transmission of 100 Gb/s NRZ-OOK streams has the potential to revolutionize 100 GbE technology, especially in datacom applications, due to its advantages in terms of number of piece-parts, footprint, simplicity, power consumption, and eventually cost. Moreover, the availability of high-speed optical modulators and the availability of the underlying technology for high-speed electronics can define a new base for operating symbol rates, and can be further combined with coherent techniques and higher-order modulation formats towards 400 Gb/s and 1 Tb/s systems.

So far, two optical modulator technologies have shown a strong potential for 100 Gb/s NRZ-OOK operation: the InP travelling wave electro-absorption modulators (InP-TWEAMs) [4,5] and the polymer-based Mach-Zehnder modulators (MZMs) relying either on a silicon organic hybrid structure [6] or on a monolithic electro-optic (EO) polymer structure [7]. Compared to the InP-TWEAMs, the polymer-based MZMs can have faster response and the clear advantage of being able to additionally support higher-order formats involving both intensity and phase modulation. Their 100 Gb/s potential has been shown extensively in the past through bandwidth measurements, and was recently confirmed with digital data in the case of monolithic EO polymer MZMs [7].

Regarding electronics on the other hand, the InP-double heterojunction bipolar transistor (InP-DHBT) is a proven technology for 100 Gb/s multiplexers (MUX) and driver amplifiers [4,5]. However, further steps towards chip miniaturization, power efficiency and, most significantly, co-integration with the photonic part of the transmitter are still needed in order to improve the performance and reduce the cost of the final transmitter.

In this work, we innovate along this direction and we present the first integrated transmitter for 100 Gb/s NRZ-OOK operation. The transmitter is based on the hybrid integration of an EO polymer MZM with a 1550 nm distributed feedback (DFB) laser and with the electrical data multiplexing and driving circuits in a single transmitter box. The device is characterized through bit-error rate (BER) measurements up to 100 Gb/s using an integrated receiver. The latter comprises a pin-photodiode and an electrical 1:2 demultiplexing (DEMUX) circuit. Error free operation is confirmed at 100 Gb/s revealing the quality of operation of the transmitter and the viability of the technology. Further steps towards the development of complex transmitter modules based on the use of passive photonic structures on the EO polymer platform are outlined.

2. Concept and device

Figure 1 illustrates the main building blocks and the final assembly of the 100 Gb/s transmitter. More specifically, Fig. 1(a) presents a top view of the optical sub-assembly of the transmitter consisting of the polymer MZM chip and the hybridly integrated DFB laser. The structure of the EO polymer platform has been described in [8]. Its polymer stack is 6 μm thick and comprises the top cladding, the core layer and the bottom cladding of the waveguide. This polymer stack is placed on top of the 1 μm thick electrode that is laid in turn

#178174 - $15.00 USD Received 16 Oct 2012; revised 16 Nov 2012; accepted 16 Nov 2012; published 10 Dec 2012

over the silicon substrate of the platform. The top electrode is 5 μm thick and is placed only above the active regions of the MZM.

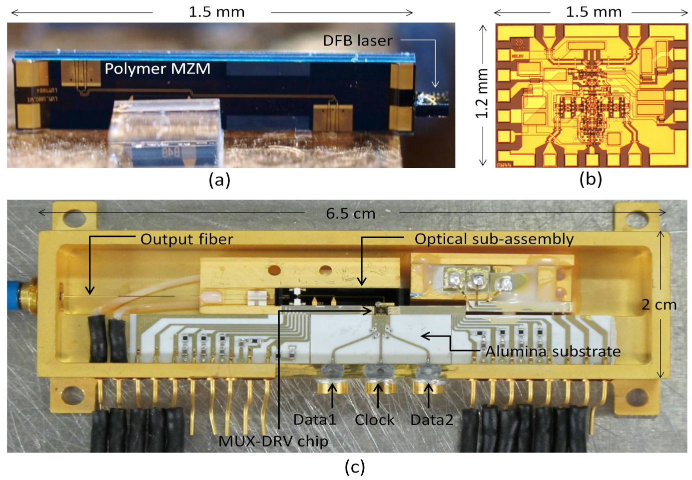

Fig. 1. Main building blocks and final assembly of the 100 Gb/s transmitter: (a) Optical sub-assembly consisting of the polymer MZM and the hybridly integrated DFB laser, (b) circuit microphotograph of the MUX-DRV chip, and (c) transmitter assembly in the box. Photographs of individual blocks and final assembly are not shown in scale.

The propagation loss of the single-mode waveguide is 1 dB/cm. The length of the single-drive MZM is 11 mm and the required voltage for phase-shift of pi rad (V_{pi}) is 3.5 V due to the strong field confinement and the high EO coefficient that the polymer material of the core features once poled (65 pm/V at 1550 nm). The possibility for integration of the polymer platform with InP elements has been demonstrated using the butt-coupling technique [8]. The achievable coupling loss at the polymer/InP interface is approximately 2 dB because of the imperfect overlap of the mode profiles inside the polymer and the InP waveguides. Due to the molecular properties of the polymer system, the EO effect is present only for transverse magnetic (TM) modes, thus necessitating the rotation of the transverse electric (TE) emitting laser by 90°. It is noted, however, that eliminating the need for mechanical rotation is in principle feasible by developing and using TM emitting lasers.

Figure 1(b) presents in turn the layout of the main electronic circuit, which is the improved version of the circuit reported in [9]. It is fabricated using the 0.7 μm InP-DHBT technology and integrates the 2:1 time division multiplexing (MUX) and the driver amplification (DRV) functionalities so as to limit to the minimum the 100 Gb/s electrical interfaces. It operates with two input data signals and a clock signal at half the final rate, and can provide a 2x2 V_{pp} signal at the output. As the polymer MZM is single-drive, only one of the complementary output streams is used, while the other is appropriately terminated. The lumped architecture of the driving output buffer allows for a very compact layout with only 1.5x1.2 mm^2 footprint. It is also worth mentioning that the total power consumption of the circuit is lower than 2 W.

Figure 1(c) shows the final assembly of the transmitter inside the FeNiCo package. Alumina-based striplines with 50 Ohm impedance interconnect the GPPO connectors to the MUX-DRV circuit, and wire-bonds with length below 150 μm interconnect the MUX-DRV output to the MZM. Apart from the MUX-DRV circuit, the DC connectors shown in Fig. 1(c) serve for the operation of the DFB laser, the thermal phase-shifter that is responsible for the bias point of the modulator, and the thermo-electric cooler (TEC) of the device. Finally, a lensed fiber is used for coupling the modulated light out of the polymer waveguide with 1.5 dB loss. The total optical loss inside the package is approximately 8.5 dB including the insertion loss of the MZM, and results in 0.8 dBm output power of the continuous wave (cw)

#178174 - $15.00 USD Received 16 Oct 2012; revised 16 Nov 2012; accepted 16 Nov 2012; published 10 Dec 2012

at the transmission peak of the modulator, when the DFB laser is operated with 120 mA injection current.

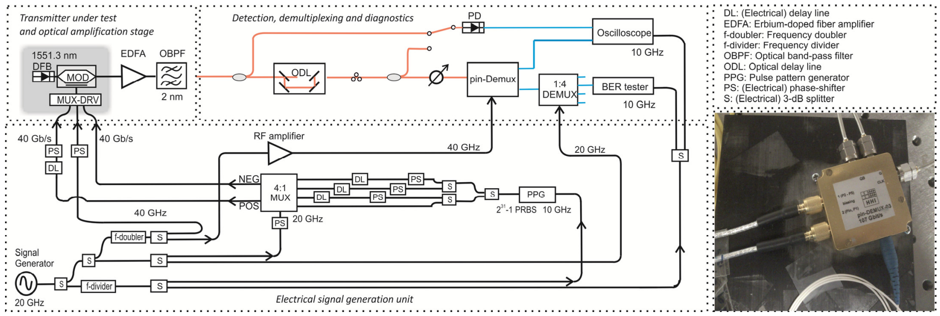

Fig. 2. Experimental set-up. The indicated frequencies and data rates correspond to 80 Gb/s operation and should be scaled accordingly for operation at 100 Gb/s. The picture on the right-hand side depicts the integrated pin-DEMUX receiver module that was utilized for the BER evaluation of the signals.

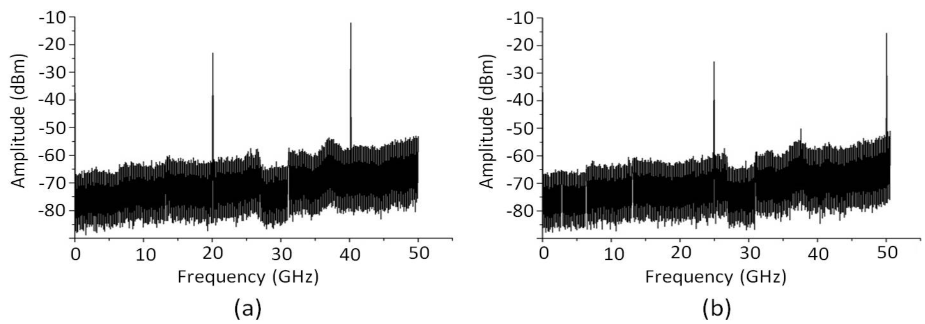

Fig. 3. RF-spectra of the clock signals at the output of the frequency doubler at (a) 40 GHz, and (b) 50 GHz. These clock signals feed the MUX-DRV circuit of the transmitter and the DEMUX circuit of the integrated receiver when operating at 80 or 100 Gb/s, respectively. The difference between the second harmonic and the fundamental harmonic is lower than 12.5 dB in both cases.

3. Experimental set-up and results

Figure 2 presents the experimental setup for the evaluation of the transmitter at 80 and 100 Gb/s. The frequencies of the sinusoidal signals and the bit-rates of the data signals outlined in the schematic correspond to operation at 80 Gb/s and should be scaled accordingly for 100 Gb/s. The signal generator is responsible to drive the pulse pattern generator (PPG), the oscilloscope, the BER tester, the external 4:1 MUX, the external 1:4 DEMUX, the integrated transmitter under test and the integrated receiver of the set-up by means of a frequency divider, a frequency doubler and a number of RF power splitters. Figure 3 shows specifically the RF-spectra of the 40 and 50 GHz outputs of the frequency doubler that feed the MUX-DRV circuit of the transmitter and the DEMUX circuit of the receiver for operation at 80 and 100 Gb/s, respectively, and reveals the presence of the fundamental harmonic in both spectra, which has an impact on the final performance of the system, as it will be shown below. Referring back to the set-up of Fig. 2, the PPG generates the 2^{31}-1 long pseudo-random bit sequence (PRBS) at 10 Gb/s, and feeds the 4:1 MUX through parallel phase shifters (PS) and delay lines (DL) that allow for bit-level synchronization and pattern decorrelation, respectively. Subsequently, the 40 Gb/s outputs at the positive (POS) and negative (NEG) ports of the 4:1 MUX serve as the two input 40 Gb/s data streams for the transmitter after further decorrelation and bit-level synchronization. At the transmitter output, the 80 Gb/s optical signal at 1551.3 nm is amplified and filtered. Part of it is detected by a 70 GHz photodiode for eye-diagram-based studies, while the rest of it is forwarded for BER measurements using the integrated 100 Gb/s receiver, which has been reported in detail in [10] and is illustrated in the inset of Fig. 2. It consists of a pin-photodiode with bandwidth in excess of 100 GHz and responsivity in excess of 0.5 A/W, and an 1:2 DEMUX circuit fabricated with InP-DHBT technology. The DEMUX circuit receives the electrical signal from the pin-photodiode, and delivers the 40 Gb/s tributary that is time aligned with the input 40 GHz clock (half DEMUX circuit). This tributary is further demultiplexed by the external 1:4 DEMUX module of the set-up, and the final 10 Gb/s channels are evaluated by the BER tester. It is noted that the second 40 Gb/s tributary can also be obtained by appropriately adjusting the optical delay line (ODL) in the path of the input optical signal.

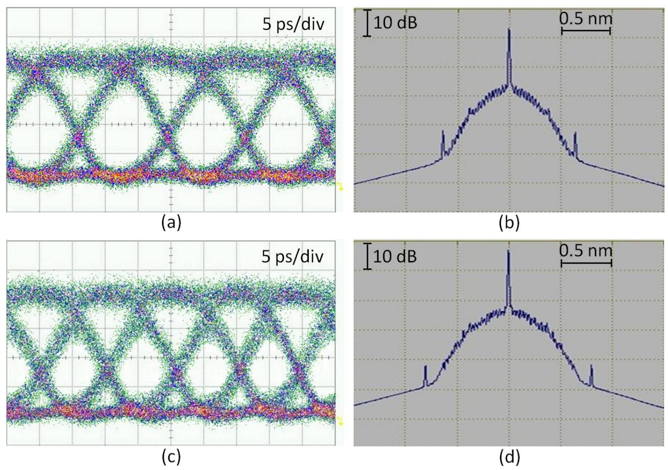

Fig. 4. Eye-diagrams (left panel) and corresponding optical spectra (right panel) at the output of the transmitter: (a)-(b) 80 Gb/s, and (c)-(d) 100 Gb/s. The optical spectra are centered at 1551.3 nm and are presented with 0.01 nm resolution.

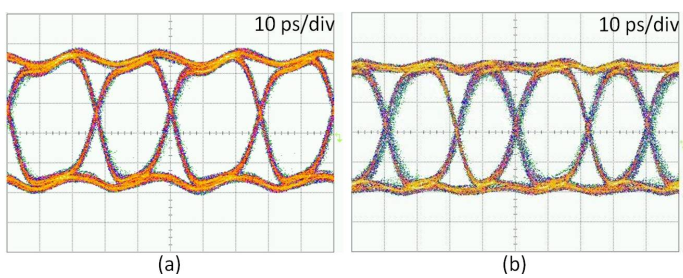

Fig. 5. Eye-diagrams of the electrical signals at the output of the integrated receiver after detection and 1:2 electrical demultiplexing: (a) Tributary at 40 Gb/s corresponding to 80 Gb/s optical signal, and (b) tributary at 50 Gb/s corresponding to 100 Gb/s optical signal.

Figure 4 presents the eye-diagrams of the optical signal at 80 and 100 Gb/s (left panel), and the corresponding NRZ-OOK spectra with 0.01 nm resolution (right panel). The clearly open eye-diagrams reveal the high bandwidth operation of the individual components and of the transmitter as a whole. In both cases (80 and 100 Gb/s) the root mean square (rms) timing jitter was lower than 0.9 ps and the extinction ratio was higher than 13.5 dB at the expense, however, of reduced optical power at the output of the device (−10 dBm) due to the significantly lower amplitude of the driving signal compared to the V_{pi} of the modulator. Figure 5(a) and 5(b) present in turn indicative eye-diagrams of the 40 and 50 Gb/s demultiplexed tributaries at the output of the receiver during system operation at 80 and 100 Gb/s, respectively. In both cases, an asymmetry in the width of adjacent pulses can be observed and attributed to the sub-optimal operation of the DEMUX circuit of the receiver

#178174 - $15.00 USD Received 16 Oct 2012; revised 16 Nov 2012; accepted 16 Nov 2012; published 10 Dec 2012

due to the strong presence of the fundamental harmonic in the RF-spectrum of the input clock, as shown in Fig. 3. It is noted that the second tributary had similar eye-diagram features in both cases.

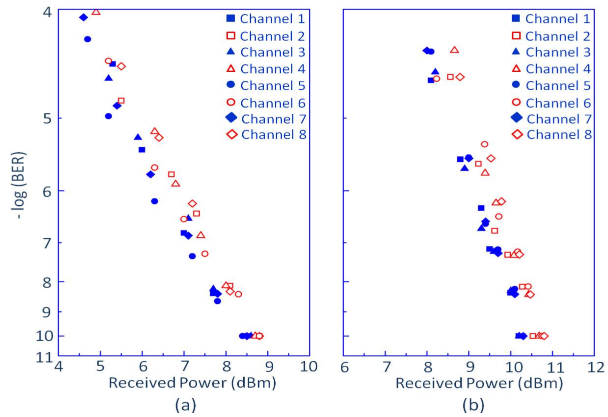

Fig. 6. BER evaluation of the integrated transmitter at: (a) 80 Gb/s, and (b) 100 Gb/s signal. In both cases, channels 1-4 correspond to the first 40 or 50 Gb/s tributary and channels 5-8 to the second one.

Figure 6(a) and 6(b) illustrate the BER curves of the eight tributaries at 10 or 12.5 Gb/s after the successive demultiplexing stages, which correspond to the 80 or 100 Gb/s optical signal, respectively. No error-floor is present in the two sets of curves for BER down to 10^{-10} confirming system operation that is free of errors both at 80 and 100 Gb/s. The required optical power at the input of the receiver for BER 10^{-9} is approximately 8 dBm at 80 Gb/s and 10.3 dBm at 100 Gb/s, and mainly depends on the responsivity of the pin-photodiode and the sensitivity of the DEMUX circuit. The required optical power is expected to be substantially reduced with the use of an integrated receiver that involves an amplification stage in the form of a travelling wave amplifier (TWA) in between the pin-photodiode and the DEMUX circuit.

4. Conclusions and next steps

We have reported on the development and the characterization of the first integrated transmitter for serial 100 Gb/s NRZ-OOK connectivity. It is based on a polymer modulator and its hybrid integration with a DFB laser and the InP-DHBT driving electronics. Compared to the first presentation of the device at ECOC 2012, we extended its characterization with BER measurements at 100 Gb/s using a receiver that integrates a high-speed pin-photodiode and an electrical 1:2 DEMUX circuit. Error free operation was confirmed at 100 Gb/s revealing the high-quality of the device and the viability of the approach.

Future plans related to the present work involve the exploitation of the recent progress on the monolithic integration on the EO polymer platform [8] for the development of complex transmitter modules with advanced flexibility and capacity. This progress refers to the demonstration of a tunable laser source with 17 nm tuning range based on a Bragg-grating on the polymer platform, and the demonstration of 1:2 and 1:4 multi-mode interference (MMI) couplers on the same platform. Through the integration of the tunable laser with a polymer modulator and its driving electronics, a tunable transmitter at 100 Gb/s will be developed. On the other hand, through integration of the MMI couplers with twin and quad modulator arrays and their electronics, transmitters with 200 and 400 Gb/s total throughput will be pursued. Possible applications involve metro, intra- and inter-datacenter connectivity scenarios.

Acknowledgments

The work was supported by the EU-funded project ICT-POLYSYS (Contract No. 258846).

#178174 - $15.00 USD Received 16 Oct 2012; revised 16 Nov 2012; accepted 16 Nov 2012; published 10 Dec 2012