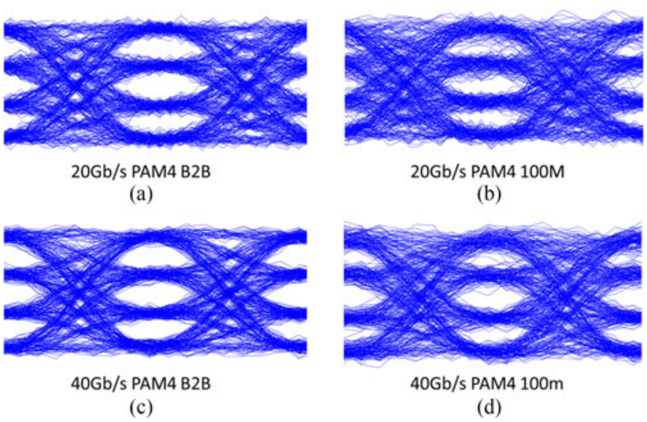
IEEE Photonics Journal
An IEEE Photonics Society Publication

Transmission of IM/DD Signals at 2 μm Wavelength Using PAM and CAP

Volume 8, Number 5, October 2016

Ke Xu, *Member, IEEE*
Lin Sun
Yongqiang Xie
Qinghai Song
Jiangbing Du, *Member, IEEE*
Zuyuan He, *Senior Member, IEEE*



20Gb/s PAM4 B2B
(a)

20Gb/s PAM4 100M
(b)

40Gb/s PAM4 B2B
(c)

40Gb/s PAM4 100m
(d)

DOI: 10.1109/JPHOT.2016.2602080

Transmission of IM/DD Signals at 2 μm Wavelength Using PAM and CAP

Ke Xu,[1] *Member, IEEE*, Lin Sun,[2] Yongqiang Xie,[1] Qinghai Song,[1] Jiangbing Du,[2] *Member, IEEE*, and Zuyuan He[2] *Senior Member, IEEE*

[1]Department of Electronic and Information Engineering, Shenzhen Graduate School, Harbin Institute of Technology, Shenzhen 518055, China.
[2]State Key Laboratory of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai 200240, China.

DOI:10.1109/JPHOT.2016.2602080

Manuscript received July 20, 2016; revised August 12, 2016; accepted August 18, 2016. Date of publication September 1, 2016; date of current version September 16, 2016. This work was supported by the National Natural Science Foundation of China under Grant 61505039, Grant 61307107, and Grant 61405113. This work was also supported in part by Shenzhen Municipal Science and Technology Plan Project under Grant JCYJ20150403161923530, Grant JCYJ20150327155705357, and Grant KQCX2015032409501296 and in part by Shanghai STCSM Science Foundation under Grant 13ZR1456200 and Grant 15511103100. Corresponding authors: K. Xu and J. Du (e-mail: kxu@hitsz.edu.cn; dujiangbing@sjtu.edu.cn).

Abstract: Advanced modulation formats with intensity modulation and direct detection (IM/DD) have shown promise in a short-reach optical communication system like data center interconnect. However, the conventional fiber transmission spectral window is mostly located at 850, 1310, and 1550 nm. Here, we experimentally demonstrated an amplifierless IM/DD link at the 2-μm spectral band. The signal is encoded with pulse amplitude modulation (PAM) and 3-D carrier-less amplitude and phase modulation (3-D-CAP). The encoded signal is transmitted through a 100 m-long solid-core fiber designed for single mode at 2-μm. We achieve a transmission with bit-rate of 40 Gbit/s using PAM-4 and 24 Gbit/s using CAP16. The measured bit error rates of both formats are below the forward error correction (FEC) limit of 3.8×10^{-3}. This study is the first demonstration of PAM4 and CAP transmission at 2-μm, and the results show a significant potential of advanced modulation for 2-μm optical communication.

Index Terms: Fiber optics communications, two μm wavelength.

1. Introduction

Optical fiber communication has been actively studied for many decades since the low-loss optical fiber was made. Optical data transmission links have also been massively implemented in the world. For a long time, the research and development in optical communication community have focused on the silica fiber transmission window at 850 nm, 1310 nm, and 1550 nm wavelength band for short, medium and long reach applications correspondingly. To satisfy the ever-increasing demand for bandwidth, we have observed intensive efforts devoted in photonics resulting in quite a few groundbreaking technologies. Wavelength division multiplexing [1], [2], polarization division multiplexing [3], [4], space division multiplexing [5]–[7], subcarrier multiplexing [8]–[10], and carrier-less [11]–[15] communications are demonstrated to enhance the channel capacity with the limited optical spectrum resources. Recently, the transmission band shifting from the conventional fiber communication window to the 2-μm band becomes possible since a special designed photonic

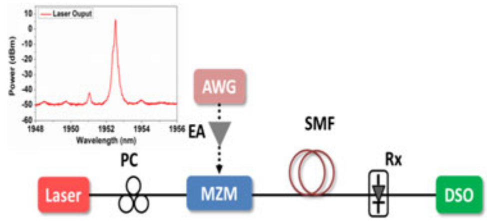


Fig. 1. Experimental setup for the 2 μm short-reach transmission link. MZM: Mach-Zehnder modulator, AWG: arbitrary waveform generator, EA: electrical amplifier, SMF: single mode fiber, Rx: receiver, DSO: digital sampling oscilloscope.

band-gap fiber is found to have a potential low loss (0.1 dB/km) at 2-μm wavelengths [16]. Besides, the available thulium doped fiber amplifier could cover ~250 nm at this band that makes it feasible to combat the fiber attenuation [17]. There are a few reported demonstrations of optical communication link at 2 μm wavelength. The first transmission experiment at two micron is reported for 8 Gbit/s non-return-to-zero (NRZ) with a transmission length of 300 meters [18]. Orthogonal frequency division multiplexing (OFDM) direct modulation combined with external on-off keying modulation was used to generate signal at 2-μm with 100 Gbit/s bit rate [19]. Optical injection locking based discrete multi-tone transmitter is also demonstrated using a laser direct modulation [20]. As a most competitive scheme for short reach communication, intensity modulation, and direct detection (IM/DD) using advanced modulation format like pulse amplitude modulation (PAM) or carrier less amplitude and phase (CAP) modulation however has not been studied in 2-μm band.

Since the components at 2 μm wavelength band are becoming mature, it has a good potential to be a supplement of O-band and C-band. In this paper, we experimentally demonstrate a 100-m amplifierless transmission link at 2 μm with PAM-4 and three dimensional CAP16 format using external modulation scheme. According to our best knowledge, this is the first demonstration of PAM4 and CAP fiber transmission at such a long wavelength. The performances are evaluated via measured constellations and bit error rates.

2. Experimental Setup

The experimental setup of the signal transmission is shown in Fig. 1. The light source used in the experiment is a narrow line width laser with the continuous wave (CW) output wavelength of 1952.52 nm. The optical spectrum of the laser output is obtained by the optical spectrum analyzer with 0.05 nm resolution and plotted in the inset of Fig. 1. The output power of the laser is set to be 15 mW to ensure a good signal quality at the receiver. The polarization of the CW light is aligned before the modulator by a polarization controller made by 2-μm single mode fiber to reduce the insertion loss. Then a Lithium Niobate Mach-Zehnder modulator (MZM) designed for 2 μm is used to encode the data. The modulator is a Z-cut type traveling wave modulator and is in push-pull configuration. The V_π measured at 1 GHz is ~5V. The modulator has an insertion loss of ~3.5 dB, extinction ratio of 20 dB and bandwidth of ~20 GHz. The electrical signal is generated by the arbitrary waveform generator (AWG) with 25-GHz bandwidth working at 60 GSa/s. An electrical amplifier is used to drive the MZM. The modulator is biased at an optimum point and its output is directly fed into 100 m solid core single mode fiber (SMF) designed for 1950 nm. The fiber core diameter is ~11 μm which is slightly larger than single mode fiber at 1550 nm. The fiber cladding has a diameter of 125 μm. The corresponding mode field diameter is ~13 μm. The dispersion parameter is ~35 ps/km/nm. The loss of this fiber is 10 dB/km and the measured loss of the 100 m fiber is ~1.5 dB. The optical power in the experiment is measured by a mid-IR power meter. Though the solid-core fiber has higher loss than the hollow core photonic bandgap fiber, it has lower fabrication and splicing difficulty hence lower cost. The signal after transmission is received by a photodetector with a responsivity of ~1 A/W and bandwidth of 12 GHz at 2 micron wavelength region. The detector is a InGaAs photodiode which has a cut-off wavelength of 2.2 μm at room

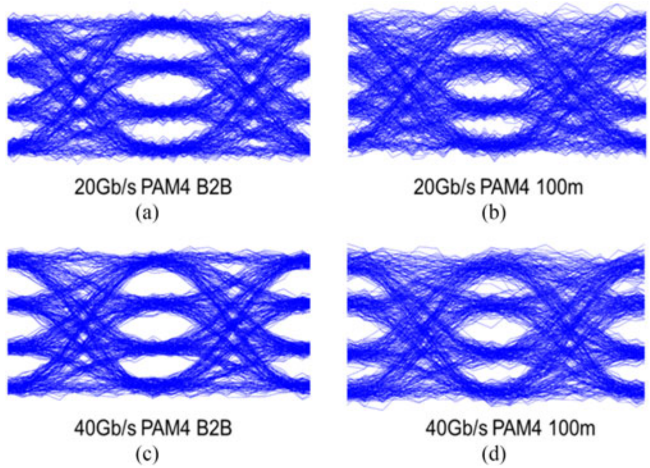


Fig. 2. Measured eye diagrams of the PAM4 signals. (a) Back to back (B2B) with 20 Gb/s, (b) 100 m SMF transmission with 20 Gb/s, (c) B2B with 40 Gb/s, and (d) 100 m SMF with 40 Gb/s.

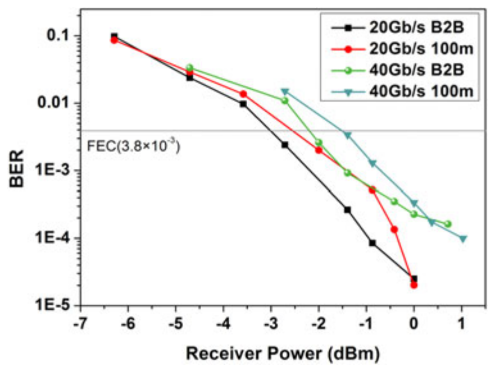


Fig. 3. BER curves for different bit rate and transmission distance.

temperature. Then, a real-time oscilloscope is used to sample and store the received signal. Offline signal processing is then applied to calculate the BER.

3. Results and Discussions

3.1. PAM-4

Fifty six-Gb/s PAM-4 has been considered as one of the most competitive solution for the next generation 56G/100G/400G optical interconnection. As one of the IM/DD formats, PAM-4 is the simplest method to lower the baud-rate without reducing the data rate. Here we first investigate the PAM-4 signal transmission at 2 μm wavelength using the setup described above. The pre-compensated four level electrical signal of the PAM-4 is directly generated from the AWG and the RF power is adjusted properly to drive the MZM. After the signal generation, transmission and detection, the eye diagrams of the signal for back-to-back (B2B) and 100 m SMF transmission scenario are captured by a sampling oscilloscope. The eye diagrams of the 20 Gbit/s and 40 Gbit/s signal for B2B and 100 m fiber transmission are shown in Fig. 2(a)–(d) correspondingly. It is observed that the eyes are clean and wide open for the B2B case. However, 100-m single mode fiber has induced a little signal degradation as shown in Fig. 2(b) and (d) but not that much. The eye of the 40 Gbit/s signals has lower extinction ratio compared with 20 Gbit/s signal. This is due to the limited bandwidth (12 GHz) of the photodetector. The signal BER is measured and plotted in Fig. 3. The BER curves indicate that for both B2B and 100 m SMF transmission of 20/40 Gb/s signals, the

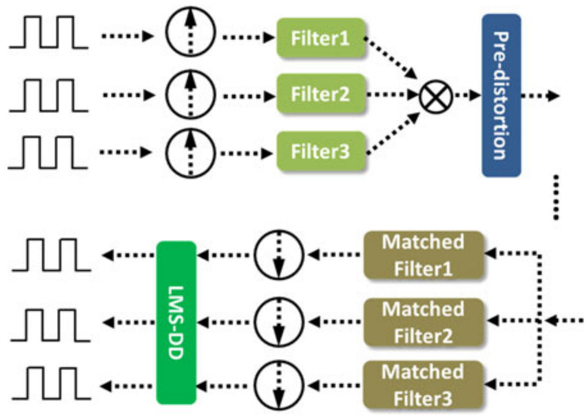


Fig. 4. Schematic block diagram of the transmitter and receiver.

BER could be achieved below the forward error correction (FEC) limit of 3.8×10^{-3}. Less than 1 dB power penalty is measured for 100 m transmission compared with B2B. We would expect error free operation is achievable with higher receiver power and baud rate higher than 20 Gbaud could be achieved if the photodetector with larger bandwidth is used.

3.2. 3-D-CAP

CAP is a modulation format utilizes digital filtering process to generate multiplexed signals without additional carriers and thus it offers a balanced performance of high spectral efficiency (SE) combined with moderate complexity. In CAP scheme, the SE can be increased by the means of multi-level coding and employments of efficient FIR waveforms [21]. Most previous works of CAP concentrate on the conventional two dimensional CAP and Multiband-CAP. Among them, multiband-CAP, with the capability to load signals with different sensitivity to different frequency bands, can achieve 100Gbps-plus per lambda transmission with improved performance in SMF and multimode fiber systems [14], [21].

In addition, CAP modulation can easily scale to multiple dimensions based on finite-impulse-response (FIR) filter design and thus provides enhanced SE and flexibility. For example, in a 3-D CAP (3-D-CAP) system, three independent data streams are multiplexed and de-multiplexed through the digital filters. The data streams of 3-D-CAP are kept parallel all the time without serial-to-parallel transform (SPT), inverse fast Fourier Transform (IFFT), storage, or any other signal processing. Therefore, multi-dimensional CAP is particularly suitable for multi-lane/single-fiber optical interconnection and thus may find applications for transceivers like Quad Small Form-factor Pluggable (QSFP), C Form-factor Pluggable (CFP), and so on. Since most of the transceivers over 10 Gbps are using paralleled multi-lane/multi-fiber configuration, the property of simplified paralleling of multi-dimensional CAP is of great significance to reduce the cost and increase the capacity with low complexity and latency.

In this section, experimental investigation of 3-D-CAP modulation and transmission in 2-μm system is carried out. The experiment setup of 3-D-CAP scenario is the same as that of PAM-4 but the electrical signal generation is different. The digital 3D-CAP16 signal is generated by up-sampled PAM-4 signals with filter shaping using the Matlab program. To design the matched filters for CAP modem system, the optimization problem at frequency domain is solved using Minimax algorithm. The up-sampling factor is 5, which is small enough for practical consideration. Three orthogonal filters are employed to shape the up-sampled data as shown in Fig. 4.

The correlation curves of the digital matched filters are shown in Fig. 5(a), indicating that the self-correlation values have their maximums at the sampling point when the perfect reconstruct condition is achieved, demodulated by matched filters. Pre-distortion is used to compensate the fading response of fiber channel. The digital signal to analog conversion is achieved by the AWG

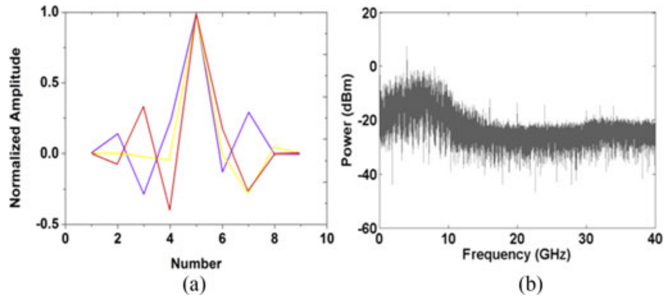


Fig. 5. (a) Correlation curves of matched filters in 3-D-CAP scheme. (b) Electrical spectrum of the B2B 3-D CAP16 signal.

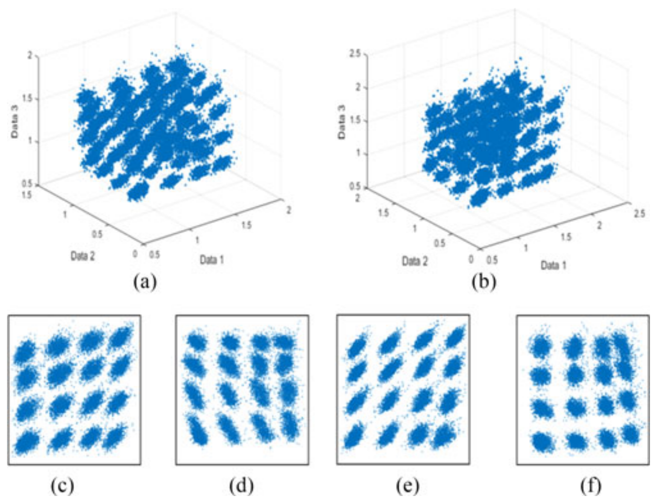


Fig. 6. (a) The 3-D-constellation in optical back-to-back case. (b) and (c) 2-D-constellations in two aspects. (d) The 3-D-constellation after 100 m fiber. (e) and (f) 2-D-constellations in two aspects.

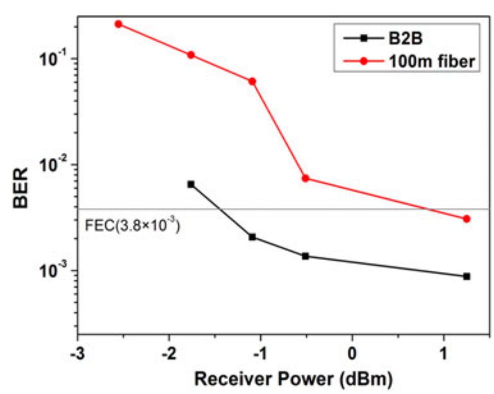


Fig. 7. BER measurement result for 3-D CAP16 signal for B2B and 100 m SMF transmission.

described in previous paragraph. We set the resampling factor as 3 to adapt the fixed sample rate of AWG. The effective bit rate of 3-D-CAP16 is 24 Gbit/s. An SHF@ linear amplifier with 40-GHz bandwidth is used to drive the MZM. At the receiver, the signal is received by a photodetector with 12-GHz bandwidth and sampled by a real time oscilloscope with 160 Gsa/s. The electrical signal is then processed by matched filtering to separate three orthogonal data streams.

The electrical spectrum of the back-to-back 3-D-CAP electrical signal is plotted in Fig. 5(b). We recover the 3-D-constellation for 3-D-CAP16 signal and show it in Fig. 6(a). The conventional constellation is mapped in two aspects, as shown in Fig. 6(b) and (c). Due to the unbalance noise effect on 3 dimensions, the constellation is distorted a bit. The 3-D-constellation of the signal after 100-m fiber transmission is shown in Fig. 6(d), and the planar constellation is shown in Fig. 6(e) and (f). The constellation diagram indicates that the 3-D-CAP signal after 100 m fiber transmission suffers from very negligible penalty compared with the B2B signal due to the short fiber length and the small amount of accumulated fiber dispersion. We measure the BER of the back-to-back scenario and the 100 m fiber transmission with no optical amplifier and plot it in Fig. 7. The BER of both B2B and 100 m fiber transmission case are measured to be below FEC limit of 3.8×10^{-3} with 1.2-dBm receiver power, and no significant error floor is observed from the results.

4. Conclusion

To conclude, we have demonstrated a short reach optical connection link at 2 μm wavelength using advanced modulation formats with intensity modulation and direct detection. The PAM-4 and 3-D CAP signals are generated by an external modulator working at long wavelength and transmitted through a 100-m solid core single mode fiber designed for 2 μm as well. From the results, we expect the transmission distance could be possibly extended to several kilometers range. We have achieved a signal transmission with 40 Gbit/s PAM-4 and 24 Gbit/s 3D CAP16 signals. The BER is measured to be below FEC limit.

Acknowledgment

The authors would like to thank F. Yang and L. Zheng for the help during the experiment.

Reference

[1] C. A. Brackett, “Dense wavelength division multiplexing networks: principle and applications,” *J. Sel. Areas Commun.*, vol. 8, no. 6, pp. 948–964, Aug. 1990.

[2] Q. Fang *et al.*, “WDM multi-channel silicon photonic receiver with 320 Gbps data transmission capability” *Opt. Exp.*, vol. 18, no. 5, pp. 5106–5133, 2010.

[3] Z. Chen *et al.*, “Transmission of multi-polarization-multiplexed signals: another freedom to explore?” *Opt. Exp.*, vol. 21, no. 9, pp. 11590–11605, 2013.

[4] D. Qian, N. Cvijetic, J. Hu, and T. Wang, “108 Gb/s OFDMA-PON with polarization multiplexing and direct detection,” *J. Lightw. Technol.*, vol. 28, no. 4, pp. 484–493, Feb. 2010.

[5] B. Zhu *et al.*, “112-Tb/s space-division multiplexed DWDM transmission with 14-b/s/Hz aggregate spectral efficiency over 76.8-km seven-core fiber,” *Opt. Exp.*, vol. 19, no. 17, pp. 16665–16671, 2011.

[6] F. Yaman, N. Bai, B. Zhu, T. Wang, and G. Li, “Long distance transmission in few-mode fibers,” *Opt. Exp.*, vol. 18, no. 12, pp. 13250–13257, 2010.

[7] P. J. Roberts, F. Couny, H. Sabert, B. J. Mangan, and D. P. Williams, “Ultimate low loss of hollow-core photonic crystal fibres,” *Opt. Exp.*, vol. 13, no. 1, pp. 236–244, 2005.

[8] W. Shieh, H. Bao, and Y. Tang, “Coherent optical OFDM: Theory and design,” *Opt. Express*, vol. 16, no. 2, pp. 841–859, 2008.

[9] K. Xu *et al.*, “Compatibility of silicon Mach–Zehnder modulators for advanced modulation formats,” *J. Lightw. Technol.*, vol. 31, no. 15, pp. 2550–2554, Aug. 2013.

[10] C. W. Chow, C. H. Yeh, C. H. Wang, F. Y. Shih, and S. Chi, “Signal remodulation of OFDM-QAM for long reach carrier distributed passive optical networks,” *IEEE Photon. Technol. Lett.*, vol. 21, no. 11, pp. 715–717, Jun. 2009.

[11] J. D. Ingham, R. V. Penty, and I. H. White, “40 Gb/s Carrierless Amplitude and Phase Modulation for Low-Cost Optical Datacommunication Links,” presented at the Opt. Fiber Commun. Conf., Los Angeles, CA, USA, 2009, Paper OThZ3.

[12] L. Tao, Y. Wang, Y. Gao, A. P. Lau, N. Chi, and C. Lu, “Experimental demonstration of 10 Gb/s multi-level carrier-less amplitude and phase modulation for short range optical communication systems,” *Opt. Exp.*, vol. 21. no. 5, pp. 6459–6465, 2013.

[13] M. I. Olmedo *et al.*, “Multiband carrierless amplitude phase modulation for high capacity optical data links,” *J. Lightw. Technol.*, vol. 32, no. 4, pp. 798–804, Feb. 2014.

[14] L. Sun, J. Du, and Z. He, “Multiband 3-dimensional carrierless amplitude phase modulation for short reach optical communications,” *J. Lightw. Technol.*, vol. 34, no. 13, pp. 3103–3109, Jul. 2016.

[15] L. Sun, J. Du, and Z. He, “Experimental demonstration of 30-Gbit/s 3D-CAP modulation for short reach optical interconnection,” in *Proc. Opt. Interconnects Conf.*, pp. 114–115, 2016.

[16] P. J. Roberts *et al.*, “Ultimate low loss of hollow-core photonic crystal fibres,” *Opt. Exp.*, vol. 13, no. 1, pp. 236–244, 2005.

[17] Z. Li *et al.*, “Diode-pumped wideband thulium-doped fiber amplifiers for optical communications in the 1800–2050 nm window,” *Opt. Exp.*, vol. 21, no. 22, pp. 26450–26455, 2013.

[18] M. N. Petrovich *et al.*, "First demonstration of 2 μm data transmission in a low-loss hollow core photonic bandgap fiber," *Opt. Exp.*, vol. 21, no. 23, pp. 28559–28569, 2013.
[19] H. Zhang *et al.*, "100 Gbit/s WDM transmission at 2 μm: Transmission studies in both low-cost hollow core photonic bandgap fiber and solid core fiber," *Opt. Exp.*, vol. 23, no. 4, pp. 4946–4951, 2015.
[20] Z. Liu *et al.*, "52.6 Gbit/s single-channel directly-modulated optical transmitter for 2-μm spectral region," presented at the Opt. Fiber Commun. Conf., Los Angeles, CA, USA, Mar. 2015, Paper Th1E.6.
[21] A. Shalash and K. K. Parhi, "Multidimensional carrierless AM/PM systems for digital subscriber loops," *IEEE Trans. Commun.*, vol. 47, no. 11, pp. 1655–1667, Nov. 1999.
[22] R. Puerta *et al.*, "107.5 Gb/s 850 nm multi- and single-mode VCSEL transmission over 10 and 100 m of multi-mode fiber," presented at the *Proc. Opt. Fiber Commun. Conf.*, Anaheim, CA, USA, 2016, Paper Th5B.5.