Ten gigabits per second 16-level quadrature amplitude modulated millimeter-wave carrier generation using dual-drive Mach–Zehnder modulators incorporated photonic-vector modulator

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A novel photonic-vector modulator architecture for the generation of 16 quadrature amplitude modulation (16 QAM) millimeter-wave carriers using dual-drive Mach–Zehnder modulators is proposed. Experimental generation of 5 Gbits/s 4 amplitude shift-keying (4 ASK) and 10 Gbits/s 16 QAM modulated 42 GHz carriers is reported. The multilevel modulated millimeter-wave signals are demodulated using an electrical receiver and its error-vector magnitude (EVM) estimated from the measurements, obtaining EVMs of −21.04 and −18.33 dB for 4 ASK and 16 QAM modulation formats, respectively.

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Wireless transmission of multigigabits per second signals has gathered much research effort lately [1–3]. The potential of radio-over-fiber technologies [4,5] to satisfy the stringent bandwidth and flexibility requirements imposed by these challenging communication systems, overcoming the main limitations of purely electrical approaches, has been reported in the literature [6,7]. However, conventional methods based on direct upconversion of the digital baseband signal [1–3] suffer from huge bandwidth constraints, in particular when thinking of realistic full-duplex deployments, where the used bandwidth is required in both downstream and upstream links. Therefore, the use of more spectrally efficient modulation formats such as multilevel quadrature amplitude or multilevel phase-shift keying is of high interest to alleviate such problems [6,7]. Recently, we proposed several photonic-vector modulation (PVM) architectures with low hardware requirements, both optical and electrical, showing the potential of this approach to generate up to 3.6 Gbits/s 16 QAM 40 GHz carriers [8–10].

In this Letter we propose a novel PVM technique employing a single cw laser source, dual-drive Mach–Zehnder modulators (DD-MZMs) combined with a balanced photodetector (BPD) for generating 16 QAM modulated millimeter-wave signals. One of the main advantages of this architecture compared to the previously proposed one for 16 QAM signal generation [9] is that it contains only one optical source, which reduces the total laser relative intensity noise (RIN) contribution to the signal and thus increases the signal-to-noise ratio (SNR). The multilevel signals are generated using the DD-MZMs and not using direct current modulation of the lasers as in [9], which have a lower extinction ratio compared to Mach–Zehnder (MZ) modulators. The quadrature condition is achieved using an optical delay line as proposed in [8]. The generation of a 10 Gbits/s 16 QAM 42 GHz carrier is reported.

In this PVM scheme, a single cw optical source is modulated with a millimeter-wave carrier using a Mach–Zehnder modulator (MZM) biased at the quadrature bias (QB) point. The millimeter-wave carrier modulated optical signal is split into two arms, I and Q, using a 3 dB power splitter. To induce a 90° phase shift between the I and Q millimeter-wave carriers, the Q arm optical signal is delayed by $\Delta T = 1/4f_{\mathrm{LO}}$ using a tunable optical delay line. This optical delay between the I and the Q arm opticals induces a 90° phase shift between the photodetected electrical carriers. Two DD-MZMs are used in each arm for modulating baseband data. Both modulators are biased at QB for generating amplitude modulation; the upper modulator is driven with two independent data $I_1(t)$ and $I_2(t)$ and the lower with data $Q_1(t)$ and $Q_2(t)$, where the amplitudes follow the condition $I_2 = I_1/2\ V$, and $Q_2 = Q_1/2\ V$ for generating four amplitude levels, resulting in 4 ASK signals in each arm. Figure 1 shows a schematic of the PVM archi-

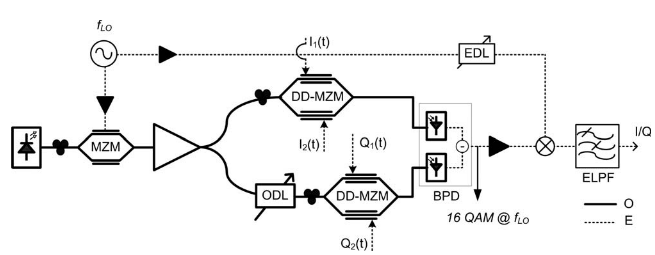

Fig. 1. Schematic of the proposed 16 QAM PVM architecture.

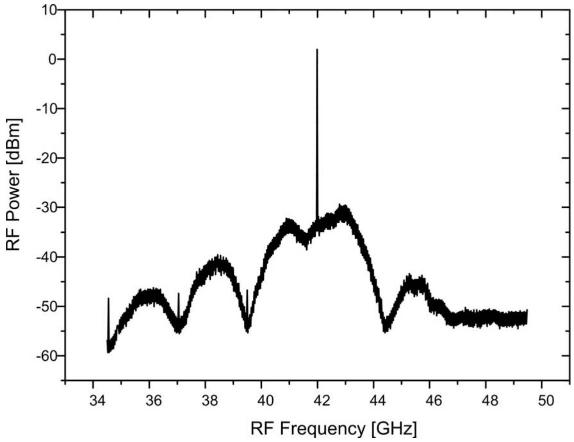

Fig. 2. Radio frequency spectrum at the output of the BPD.

tecture. The upper arm (I) and the lower arm (Q) are photo mixed and combined in a BPD. The electrical output of the photodetector is a 16 QAM modulated millimeter-wave carrier. Equation (1) represents the resulting photocurrent:

$$i_{\mathrm{PD}} = \frac{\Re P}{L_{\mathrm{tot}}} J_0(m_{\mathrm{LO}}) J_1(m_{\mathrm{LO}}) \times \left[\cos^2\left(\frac{\pi}{4V_\pi} I_1 (I_1(t) - I_2(t)) \right) \cos(\omega_{\mathrm{LO}} t) + \cos^2\left(\frac{\pi}{4V_\pi} Q_1 (Q_1(t) - Q_2(t)) \right) \sin(\omega_{\mathrm{LO}} t) \right], \tag{1}$$

where $\Re$ is the responsivity of the photodetector, P is the output power of the laser, L_{tot} is the total insertion losses, $m_{\mathrm{LO}} = \pi V_{\mathrm{LO}}/V_\pi$, and J_n is the Bessel function of nth order.

A cw DFB laser at 1555.4 nm with an output power of +15 dBm is externally modulated by a 42 GHz local oscillator carrier using a 50 GHz MZM biased at the QB point. The output of the MZM is amplified to +18 dBm using an erbium-doped fiber amplifier (EDFA) to compensate the 6 dB insertion losses of the modulator and the 3 dB losses due to QB. The output of the EDFA is divided into two arms using a 3 dB splitter: upper (I) and lower (Q). The Q arm optical signal is delayed using an optical delay line to generate a 90° phase shift between the I and Q modulated local oscillator (LO) carrier components. The I and Q optical components were corrected for polarization mismatch using a polarization controller. Two 40 GHz DD-MZMs biased at QB were used for generating the I and Q 4 ASK signals. The two arms of the I DD-MZM are driven with two 2.5 Gbits/s independent data I_1 and I_2 where I_1 was tuned to 1 V pp and I_2 to 0.5 V pp, resulting in 5 Gbits/s 4 ASK modulation. Similarly the Q arm DD-MZM was driven by 2.5 Gbits/s Q_1 and Q_2 data resulting in another 5 Gbits/s 4 ASK. The I and Q optical signals with both the baseband data and rf signal modulated on them were photodetected and added in a 45 GHz BPD with 0.53 A/W responsivity. The output of the balanced photodetector (BPD) is a 10 Gbits/s 16 QAM modulated 42 GHz carrier. Figure 2 shows the rf spectrum of the generated 16 QAM 42 GHz carrier.

To analyze the quality generated, the 16 QAM signal was demodulated using an electrical mixer. The 16 QAM signal output at the BPD was amplified and input to a 42 GHz broadband electrical mixer and mixed with the same LO used at the transmitter. The baseband output of the electrical mixer was filtered using an electrical low pass filter with a 3 dB cut-off frequency of 1.87 GHz. The I and Q components of the 16 QAM signal were demodulated electrically by tuning the phase of the LO carrier input to the mixer using a tunable electrical delay. When the electrical delay was tuned to have 0° phase between the LO and the received 16 QAM carriers, the I signal was demodulated and for 90° the Q signal was demodulated.

Figures 3(a) and 3(b) show the demodulated I and Q eye diagrams of the 10 Gbits/s 16 QAM millimeter-wave carriers generated by the above described PVM configuration. To analyze the quality of the received signal EVM is calculated from the statistical data of the eye diagrams. To calculate the EVM from the captured 4 ASK I and Q eye diagrams, the histogram of each level was plotted and the mean μ and the standard deviation σ were measured. Later a Gaussian distribution of each symbol was generated using the μ and σ and normalized to 1. The resulting symbols from the Gaussian distribution were compared with the ideal values for 16 QAM (1, 1/3, −1/3, −1) and the EVM computed. It should be noted that the EVM of the signal is calculated after the receiver stage, and an ideal receiver would improve the EVM. The EVM of the 10 Gbits/s 16 QAM modulated 42 GHz carrier was calculated to be −18.33 dB. The EVM calculated does not totally reflect the quality of the PVM but contains a contribu-

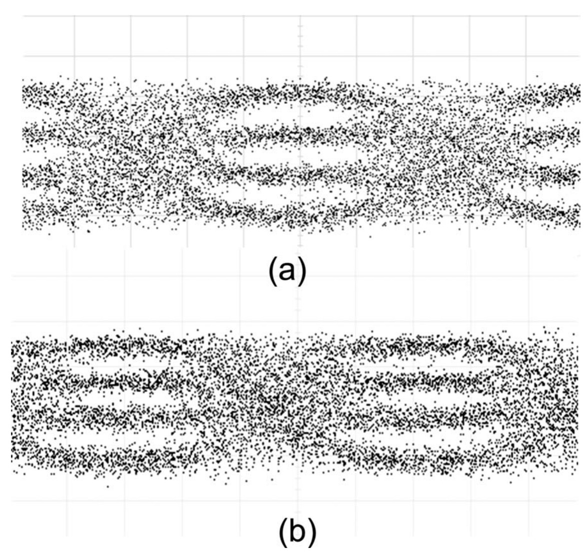

Fig. 3. Downconverted (a) I and (b) Q components of the 16 QAM signal.

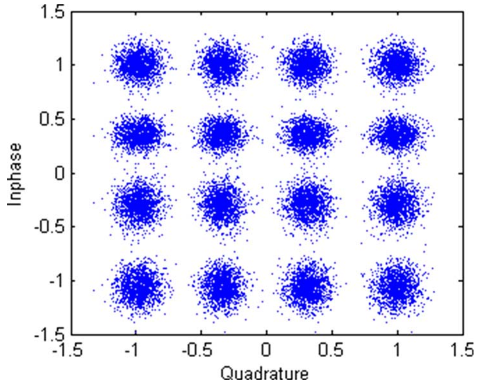

Fig. 4. (Color online) Resulting normalized constellation diagram of the 16 QAM signal.

tion from the electrical demodulation that incorporates bandwidth-limited components. For example, the mixer and the amplifiers have an electrical bandwidth of around 3 GHz. Also, the photodetector used in the PVM has an uneven response at 41 GHz, which can be noted from Fig. 4. The EVM can be improved by accurate phase matching at the electrical receiver by using a phase-locking mechanism. To prove this claim, instead of vectorial 16 QAM modulation, 5 Gbits/s 4 ASK modulation was performed (5 Gbits/s 4 ASK and 10 Gbits/s 16 QAM have the same electrical bandwidth: 5 GHz) with only one DD-MZM and at the same LO frequency, 42 GHz. The generated 4 ASK signal's EVM was calculated to be −21.04 dB, which is a 3 dB improvement at the same electrical bandwidth.

A novel PVM scheme for generating multigigabits per second 16 QAM modulated millimeter-wave carriers is presented. Generation of a 10 Gbits/s 16 QAM modulated 42 GHz carrier was experimentally demonstrated, and an EVM of −18.33 dB was calculated from measurements. This EVM value can be improved by using an enhanced phase-controlled demodulation that was demonstrated by generating a 5 Gbits/s 4 ASK modulated 42 GHz carrier with an EVM of −21.04 dB. The advantage of this scheme compared to the previously proposed technique in [9] is that it contains only a single cw source that reduces the total RIN contribution and increases the SNR.

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References

1. A. Hirata, M. Harada, and T. Nagatsuma, J. Lightwave Technol. **21**, 2145 (2003).
2. J. Yu, Z. Jia, L. Yi, Y. Su, G. Chang, and T. Wang, IEEE Photon. Technol. Lett. **18**, 265 (2006).
3. A. Wiberg, P. Perez-Milan, M. V. Anders, P. A. Anderkson, and P. O. Hedekvist, IEEE Photon. Technol. Lett. **17**, 1938 (2005).
4. A. J. Seeds and J. K. Williams, J. Lightwave Technol. **24**, 4628 (2006).
5. J. Capmany and D. Novak, Nat. Photonics **1**, 319 (2007).
6. W. D. Jemison, A. J. Kreuzberger, and E. Funk, IEEE Microw. Wirel. Compon. Lett. **12**, 125 (2002).
7. P. Candelas, J. M. Fuster, J. Marti, and J. C. Roig, J. Lightwave Technol. **21**, 496 (2003).
8. R. Sambaraju, M. A. Piqueras, V. Polo, J. L. Corral, and J. Marti, J. Lightwave Technol. **25**, 3350 (2007).
9. R. Sambaraju, M. A. Piqueras, V. Polo, J. L. Corral, and J. Marti, in *Proceedings of the European Conference on Optical Communications 2007* (VDE Verlag, 2007), paper Tu5.4.7.
10. M. A. Piqueras, B. Vidal, J. L. Corral, V. Polo, A. Martinez, and J. Marti, IEEE Photon. Technol. Lett. **17**, 1947 (2005).