Pure 2.5 Gb/s 16-QAM Signal Generation with Photonic Vector Modulator

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***Abstract* — A novel photonic vector modulator architecture for generating pure quadrature amplitude modulation (QAM) signals is presented. No electrical devices apart from the local oscillator are needed in the generation process. Both binary and multilevel digital signals can be used to generate quadrature phase shift keying (QPSK) or multilevel QAM (M-QAM) digital modulations at any carrier frequency. A pure 2.5Gb/s 16-QAM signal has been experimentally generated at a 42 GHz carrier frequency.**

***Index Terms* —Optical modulation, Optical signal processing, Quadrature amplitude modulation, Radio communication,.**

I. Introduction

The data rates required by broadband wireless systems are increasing, mainly due to the need of high performance voice, video, image and data communications. This increment in data rates is pushing the development of solutions for wireless transmission of Gb/s data rates, mainly in the millimeter wave frequency band. Millimeter wave photonic systems have been intensively investigated as a solution that can overcome the current limitations of purely electrical architectures, due to the inherent benefits of photonic components and optical fibers, such as huge bandwidth, scalability employing wavelength multiplexing techniques, compactness, or low transmission loss.

In recent years, the wireless transmission of data rates beyond 1 Gb/s has been demonstrated [1,2] at millimeter wave frequencies by employing both photonic techniques and advanced electrical circuitry. These transmissions have been realized by simply up-converting the base band digital signal up to the desired frequency which requires a huge electrical bandwidth in the wireless link. Then, an alternative solution is to reduce the utilized bandwidth by employing more efficient electrical modulation techniques such as quadrature amplitude modulation (QAM) as it is common in any actual digital wireless system. Photonic vector modulation (PVM) schemes have been presented to generate QAM signals by photonic processing [3,4]. However, these PVM schemes use complex electrical control circuit to translate binary data information into optical modulated signals and the demonstrated bit rate was limited to 1 Mb/s.

Recently, we have proposed new PVM architectures with low hardware, both optical and electrical, requirements [5-7]. With these PVM architectures, electrical quadrature amplitude modulations from 4-QAM up to 16-QAM and 3.6 Gb/s data rate has been experimentally demonstrated. However, these interesting PVM schemes show an important system limitation, the electrical QAM generated signal at the photodiode output includes a high level of electrical carrier when a real QAM signal would have no electrical carrier component at all. This undesired electrical carrier level will reduce the available electrical signal power level at the output of any power amplifier stage, reducing at the same time the coverage area of our wireless system.

In this paper, a modified PVM scheme is presented which generates a pure QAM signal without any undesired electrical carrier component and keeping the low hardware complexity of the original PVM scheme. Besides, this new PVM scheme is able to generate any M-QAM digital modulation without any modification in the PVM configuration, thus, being able to accommodate both binary and multilevel digital signals as electrical inputs to the photonic vector modulation process.

II. Photonic vector modulator architecture description

A schematic of the proposed PVM architecture is depicted in Fig. 1. Two semiconductor lasers, emitting at wavelengths λ_1 and λ_2, and linearly biased are directly modulated by two base band digital signals corresponding to the modulating $x_I(t)$ and $x_Q(t)$ driving currents. In order to generate a 4-QAM digital modulation both $x_I(t)$ and $x_Q(t)$ would correspond to binary digital signals. However, if a 16-QAM modulation is desired both $x_I(t)$ and $x_Q(t)$ will correspond to 4-level digital streams. A third continuous wave (CW) laser has been added to the previously proposed PVM scheme [5].

All three optical signals are combined and externally modulated by an electrical local oscillator (LO) frequency tone in an external quadrature biased Mach-Zehnder modulator (MZM). Then, the signals are transmitted over a standard single-mode fiber (SSMF) optical link, whose length and dispersion are L (m) and D (ps/km·nm) respectively, and finally photodetected.

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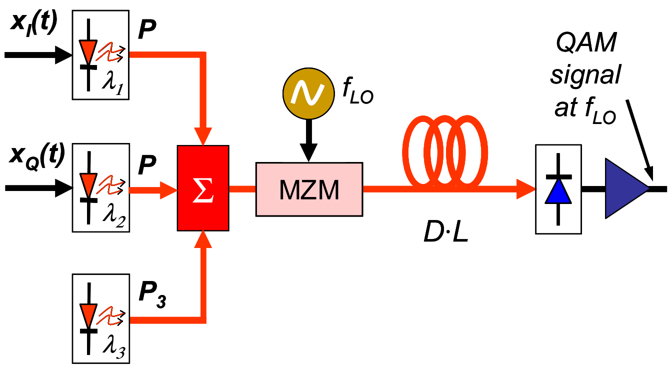

Fig. 1. Photonic Vector Modulator architecture for pure QAM generation.

The optical fiber chromatic dispersion induces a delay between both I- and Q-modulated optical signals equal to $\Delta\tau_{21} = D{\cdot}L{\cdot}\Delta\lambda_{21}$, where $\Delta\lambda_{21} = \lambda_2\text{-}\lambda_1$. This delay can be tuned by changing the fiber length or the wavelength spacing $\Delta\lambda_{21}$ in order to obtain a delay of a quarter of the electrical LO tone period (named quadrature condition), which corresponds with a differential phase of $\pi/2$ radians between the I- and Q-LO components. At the same time, a differential delay $\Delta\tau_{31} = D{\cdot}L{\cdot}(\lambda_3\text{-}\lambda_1)$, is induced between the unmodulated carrier λ_3 and the I-modulated optical carrier λ_1. When all these conditions are fulfilled, the LO component of the detected photocurrent would be:

$$i_{pd-LO}(t) \approx \frac{\Re}{L_o} 2J_1(m_{LO})J_0(m_{LO})\cdot$$
$$\left[P_3 \cos\left(\omega_{LO}t - \frac{\Delta\tau_{31}}{\Delta\tau_{21}}\frac{\pi}{2}\right) + P\sqrt{2}\cos\left(\omega_{LO}t - \frac{\pi}{4}\right) \right. \quad (1)$$
$$\left. + \eta\left[x_I(t)\cos(\omega_{LO}t) + x_Q(t)\cos\left(\omega_{LO}t - \frac{\pi}{2}\right)\right]\right]$$

where ω_{LO} is the LO angular frequency, $\Re$ is the photodiode responsivity in A/W, L_o are the optical losses from any laser output to the photodiode input, P is the mean optical power emitted by each of the optical sources λ_1 and λ_2, P_3 is the optical power emitted by the optical source λ_3, η is the slope efficiency of the laser diodes in W/A, J_0 and J_1 are the zero-th and first order Bessel functions of the first kind, respectively, and $m_{LO} = \pi V_{LO}/V_\pi$, V_{LO} being the amplitude of the local oscillator tone and V_π being the MZM half-wave voltage.

From (1) it can be observed that data signals are quadrature modulated over the LO carrier since a $\pi/2$ radians phase difference in the cosine argument is induced by the fiber chromatic dispersion. Moreover, if the wavelength of the third laser is selected to fulfill the ratio $\Delta\tau_{31} = 2.5\ \Delta\tau_{21}$ and its power to be $P_3=P{\cdot}(2)^{1/2}$ then the two first terms of (1) will cancel each other and a pure QAM signal at ω_{LO} will be obtained at the photodiode output.

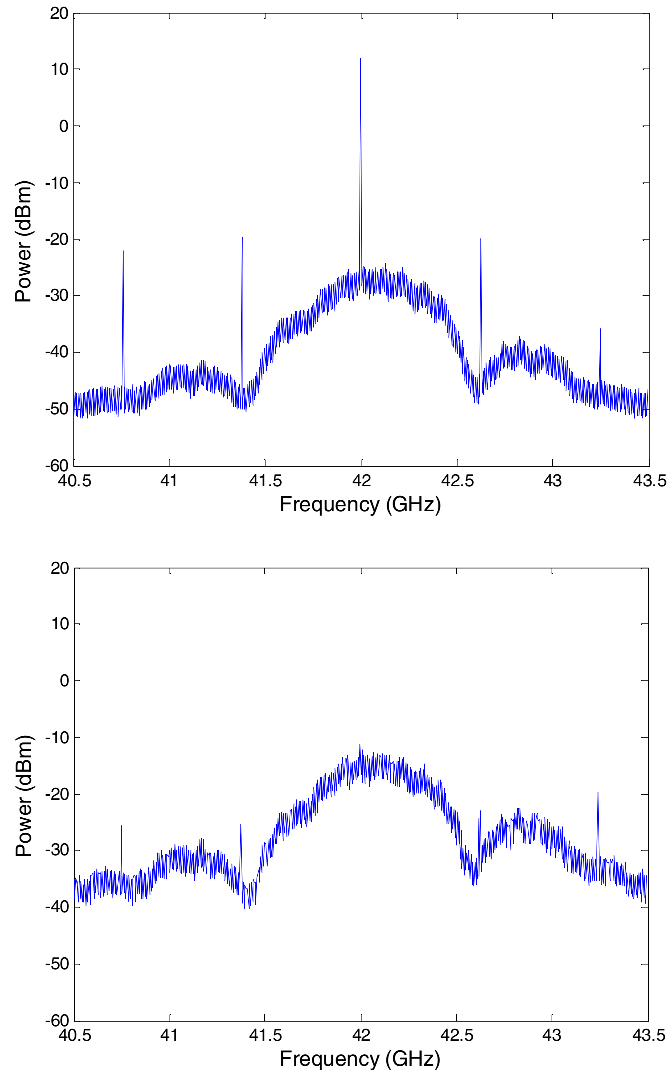

Fig. 2. Electrical spectrum at the photodiode output in the PVM scheme from Fig. 1 when the optical source λ_3 is OFF (above) and ON (below) corresponding to a 2.5 Gb/s 16-QAM signal at 42 GHz electrical carrier.

III. Experimental Results

The PVM scheme shown in Fig. 1 was employed to validate the proposed approach. A set of three DFB lasers (wavelengths, $\lambda_1 = 1550.92$ nm, $\lambda_2 = 1549.026$ nm and $\lambda_2 = 1547.356$ nm) with 1 GHz analog modulation bandwidth were used in order to generate a 2.5 Gb/s 16-QAM signal at a LO frequency equal to 42 GHz. Two 625 Mbaud NRZ (non-return-to-zero) digital streams with four amplitude level each were generated by means of an arbitrary waveform generator (AWG). Only two lasers (λ_1, λ_2) were directly modulated by the 1.25 Gb/s 4-levels digital signals with 2 V

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amplitude peak to peak. In all cases, the optical signals were polarization controlled and combined in a coupling matrix composed by two cascaded 3 dB optical couplers. All three optical signals were externally modulated by a +15 dBm LO tone at 42 GHz in a 50 GHz bandwidth MZM biased at the quadrature point. After the external modulation process, the optical signals are transmitted over a 340 meters of SSMF (D=16.5 ps/km·nm) in order to fulfill the dispersion induced phase conditions defined in Section II and photodetected.

The electrical spectra of the generated signals, measured with an electrical spectrum analyzer are shown in Fig. 2 for the cases in which the unmodulated laser is ON (right) or OFF (left). When the CW laser is OFF, the undesired LO carrier level can be clearly observed (Fig. 2 left). On the other hand, when the third laser was set active with an optical power level and wavelength according to Section II calculations, the undesired LO component is totally suppressed with a suppression ratio higher than 40 dB, as can be seen in Fig. 2 by comparing both spectra.

In order to measure the quality of the optically generated QAM signal, it was down converted to base band by mixing it in an electrical mixer with a phase adjusted replica of the LO tone used in the generation process as it is depicted in Fig. 3. The eye-diagrams for these demodulated baseband digital signals were measured using a digital communications analyzer (DCA). By changing the electrical phase of the LO replica, both I and Q digital signals were independently down converted confirming that the quadrature condition was obtained.

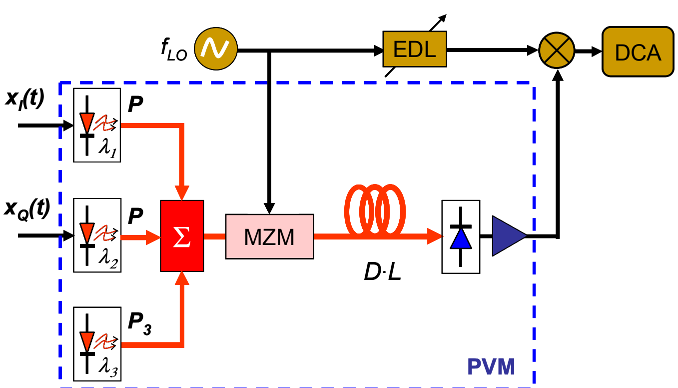

Fig. 3. Measurement setup to electrically analyze the quality of the QAM modulation generated by the PVM.

The measured eye diagrams are shown in Fig. 4 where the three eyes corresponding to the 4 amplitude levels of the digital signals are clearly identified. The relatively noisy eye diagrams form Fig. 4 are affected by the electrical components used to down convert the optically generated QAM signal to be measured by the DCA where no external electrical filter were used to reduce the electrical noise entering the equipment. Thus, the actual quality of the generated QAM signal is better than this value.

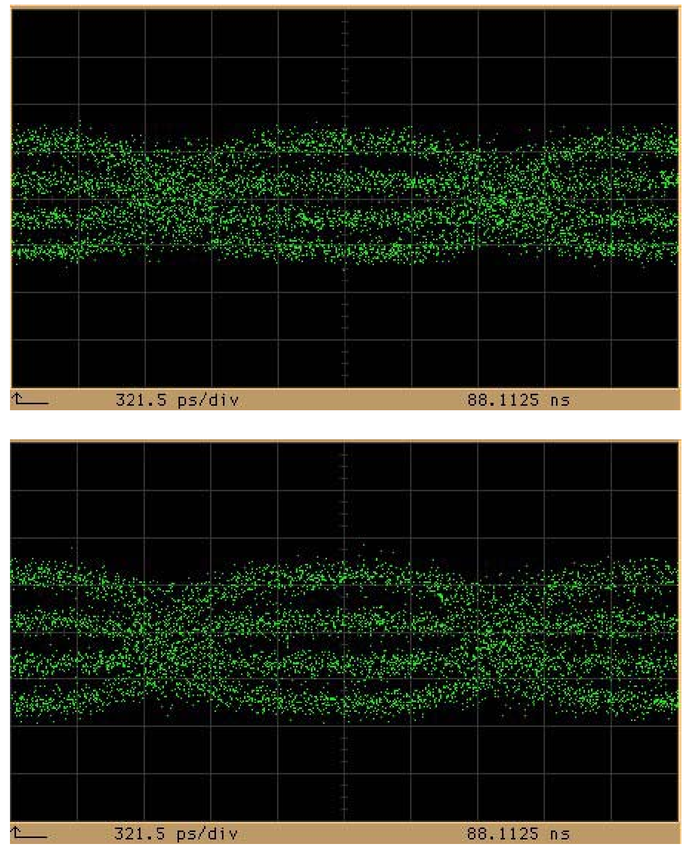

Fig. 4. Eye diagrams for the 1.25 Gb/s data signals corresponding to the electrically demodulated in phase (above) and quadrature (below) components of the 2.5 Gb/s 16-QAM signal generated at 42 GHz with the PVM shown in Fig. 1.

From the eye diagrams shown in Fig. 4, the signal constellation has been extracted by sampling at the center of the symbol period. The signal constellation is shown in Fig. 5 were the 16 symbols of the 16-QAM are clearly identified. From this constellation the EVM (Error Vector Magnitude) has been calculated and a value of -17.05 dB has been obtained. The constellation points from Fig. 5 are not equally spaced due to some compression at the driving conditions of the modulated lasers. This situation could be solved if more linear driver amplifiera and lasers with a broader modulation range were available for the measurements.

In order to check the influence of the insertion of the CW laser in the PVM scheme from Fig. 1 the same measurements were carried out in the configuration with only two lasers active. In this case the EVM was reduced to -17.85 dB which implies an increment in SNR (signal-to-noise ratio) of 0.8 dB. Thus, a 0.8 dB penalty in SNR is induced by the insertion of an unmodulated laser to eliminate the undesired LO carrier leakage at the PVM output.

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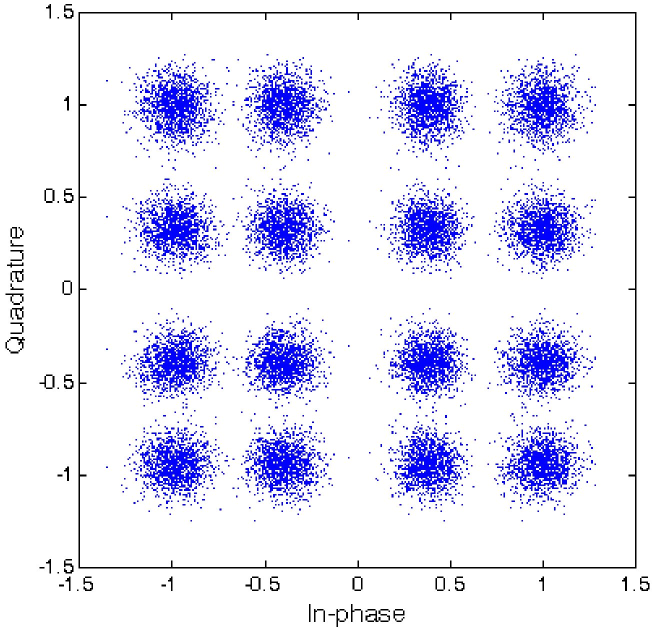

Fig. 5. 16-QAM signal constellation extracted from the electrically detected digital signals of the 2.5 Gb/s 16-QAM signal optically generated at 42 GHz with the PVM shown in Fig. 1.

IV. REMARKS AND CONCLUSION

In this work, a new photonic vector modulator architecture has been shown. This architecture offers a low optical hardware complexity combined with no additional electrical components but the local oscillator to generate the electrical carrier and the digital streams corresponding to the in-phase and quadrature components.

The proposed PVM scheme is a modification of PVM architectures previously proposed by the authors with the addition of an additional CW laser in order to generate a pure QAM signal, keeping at the same time the good performance of the previous PVM architecture. At the same time, it has been proved that this PVM scheme is able to generate M-QAM modulation by driving the laser with multilevel digital streams. The additional laser noise due to the additional laser is translated to an 0.8 dB penalty in the signal-to-noise ratio at the PVM output. Using this novel PVM technique, the generation of multi-Gb/s multilevel quadrature amplitude modulations (M-QAM) at mm-wave carriers is feasible. As a proof of concept a pure 2.5 Gb/s 16-QAM signal at 42 GHz carrier has been experimentally generated.

ACKNOWLEDGEMENT

This work has been supported by the European Commission FP6 under project IST-35317 IPHOBAC. Financial support by the Spanish MCyT and EU-FEDER under the project TEC2005-08298-C02-02 and the Valencia Regional Government under the project ACOMP2007/144 is gratefully acknowledged.

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