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Photonic Implementation of 4-QAM/QPSK Electrical Modulation at Millimeter-Wave Frequency

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Abstract—We propose a photonic method for generating millimeter-wave 4-QAM/QPSK modulated signals. The method is based on optical phase modulation by multilevel electrical signals and optical carrier-suppression. Simulation results are presented for 2.5 Gsymbol/s 4-QAM and QPSK signals at a 36 GHz carrier. Furthermore, this method can be extended to generate millimeter-wave $m$-PSK signals and can be incorporated into broadband radio-over-fiber systems to support wireless/ wireline converged access network.

I. INTRODUCTION

The continue demand from end-users for high capacity wireless communication links encourages us to research for techniques to realize high frequency wireless systems carrying high bit rate signals[1]. Conventional signal generation at radio frequencies (RF) requires signal modulation at baseband or intermediate frequency followed by one or more mixing, amplification, and filtering stages for up-conversion to the desired carrier frequency and removal of undesired spectral components. Radio-over-fiber (RoF) system has recently received considerable attention due to its well-know advantages of high bandwidth, low loss, etc. It is foreseen that hybrid optical wireless systems will be used to delivered to the end user both high capacity and flexibility. Therefore, the generation of millimeter-wave (mm-wave) signals for remote signal delivery in wireless and wireline access networks using photonic techniques is highly desired.

Up to date, most efforts in photonic generation of modulated millimeter wave signals have been focused on the development of broadband all-optical binary phase-shift keying (BPSK) modulation [2–4]. However to enhance the capacity and the spectral efficiency of communications links, it is necessary to be able to implement more complex formats such as quaternary phase-shift keying (QPSK), $m$-PSK and $m$-quadrature amplitude modulation ($m$-QAM) which are commonly employed in wireless communication systems. In this sense, some approaches have been proposed for photonic generation of vector modulation subcarrier [5-7]. Typically, they are based on the vector summation technique, which consists in achieving the desired carrier phase and amplitude

II. OPERATION PRINCIPLE

The proposed configuration for photonic generation of millimeter-wave 4-QAM/QPSK signals is shown in Figure 1. The continuous wave (CW) from the output of a laser is intensity modulated using a Mach-Zehnder modulator (MZM) which is driven by a radio frequency (RF) signal at frequency.
\( \omega_{RF} \). In order to achieve carrier suppression modulation, the MZM is biased at its minimum transmission point. In the optical domain, we can observe two wavelengths with frequency separation of \( 2\omega_{RF} \), as shown in point A of Figures 1 and 2. These two wavelengths are split by a narrow band fiber Bragg grating (FBG). In this case, as shown in points B and C in Figure 1, one wavelength is reflected to the upper optical path and the second is transmitted to the lower optical path. The wavelength in the upper path is phased encoded by a four-level electrical signal by an electro-optic phase modulator (PM). The four-level signal can be achieved by using weighted and summing technology. In this way, we apply two different intensity factors to two pseudo pattern generator (PPG) channels (1 for 1st channel and 2 for 2nd channel) and sum them. At point E of the system, these two optical signals are combined in a 3 dB optical coupler and fed to a high-speed photodetector (PD). QPSK modulated millimeter-wave at frequency of \( 2\omega_{RF} \) is generated by the resulting frequency beating of the two wavelengths as shown at point F in Figures 1 and 2.

For the reason of simplicity, assuming that the phase deviation between marks and spaces at PM is \( 2\pi \), the optical field at the input of PD can be given as:

\[
E_{in} = \sqrt{P_1} \exp[i(\omega_0 + \omega_{RF})t + \phi_0] + \sqrt{P_2} \exp[i(\omega_0 - \omega_{RF})t] + \text{(other terms)}
\]  

Here \( \omega_0 \) is the optical angular frequency of the CW output from laser, \( \phi_0 (i=0, 1, 2, 3) \) are normalized electrical level inputs to PM, respectively. At the output of the PD, the generated electrical signal can be expressed as:

\[
E_{out} = 2\sqrt{P_1P_2} \cos[2\omega_{RF}t + \phi_0 + 2\pi]
\]

Therefore, when \( \phi_0 = 1/8 \cdot 2i \) and \( \phi_0 = 1/8 \cdot (2i+1) \) \( (i=0, 1, 2, 3) \), 4-QAM and QPSK modulated millimeter-wave is obtained, respectively.

### III. Simulation Results and Discussions

In order to test the proposed scheme, a series of computer simulation using VPITransmissionMaker tool are performed. The system simulated follows the configuration shown in Figure 1. An 18 GHz RF modulating frequency and 2.5 Gbps PPG are used. As shown in Figure 3, an electrical signal with normalized amplitude-levels of 0, 1/3, 2/3 and 1 is obtained by controlling the weighting factor and delay time. When the phase deviation is set as \( 3\pi/2 \), the generated millimeter-wave will have phase states of 0, \( \pi/2 \), \( \pi \) and \( 3\pi/2 \). The inset indicates the corresponding eye diagram. At the input of the PD, the optical spectrums of the combined optical signals coming from the two optical paths are shown in Figure 4. We can observe that the optical signals at longer wavelength are modulated with digital information. In principle, the second optical signals at shorter wavelength should have no modulation. Due to the limited suppression ratio of FBG, the modulation at shorter wavelength is very weak comparing to that of longer wavelength.

To analyze the generated millimeter-wave 4-QAM, the output optical signals are detected in a high-speed PD and the subcarrier signal is synchronously demodulated using a mixer driven by a local oscillator (LO) which has double frequency of that deployed in the transmitter. A lowpass filter with cut-off frequency of 1.8 GHz is used to remove high frequency components. Figure 5 displays the electrical frequency spectrum at the output of the PD. The demodulated signals can be observed using a sampling scope, and the digital constellation and the demodulated Q-component eye diagram are depicted in Figure 6. By adjusting the phase-shift of the LO to demodulate the different quadrature signals, Figures

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**Figure 2** Representation for signal generation at the A-F points shown in Figure 1.

**Figure 3** Electrical signals with normalized amplitude-levels of 0, 1/3, 2/3 and 1 at point G of Figure 1, used to generate 4-QAM modulation. Inset: eye-diagram of four-level signal.

**Figure 4** Optical spectrums at the input of PD.
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