Comparison of carrier suppressed and quadrature bias point external modulation for 40 GHz millimeter-wave photonic generation using a 16-QAM signal with directly modulated laser

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***Abstract*—A directly modulated laser usage is proposed for 16-QAM signal transmission over hybrid optical links using two optical frequency multiplication schemes based on external modulation for 40 GHz millimeter-wave (mmW) signal generation. We provide an experimental comparison of two possible approaches: quadrature bias point external modulation system using additional optical filter and null transmission point with suppressed carrier. The systems are discussed in terms of cost and complexity of mmW photonic transmission. High error vector magnitude performance of mmW transmission over fiber and free space optics links is demonstrated and an estimation of the sensitivity of the systems is provided.**

Keywords—Directly modulated laser (DML), millimeter wave (mmW), free space optics communications (FSO), hybrid RoF/RoFSO.

I. INTRODUCTION

The fifth generation network (5G) is aimed for handling the new challenges of mobile networks, such as the incredible growth of data traffic, ultra-low latency or high number of connected devices. In this context, millimeter waves (mmW) up to 300 GHz will play a key role in 5G due to its enormous available bandwidth which provides high data transmission over the available unlicensed spectral bandwidth. Nevertheless, the huge propagation loss even for lower mmW bands, e.g. at 40 GHz, and the mmW signal generation by costly electronic stages are still challenges that need be properly addressed.

Radio over fiber (RoF) system, which can transport mmW signal over an optical carrier, has recently attracted attention for mmW transmission due to its advantages, such as low attenuation loss, immunity to radio frequency interference, transparency to modulation formats, high capacity, flexibility and dynamic resource allocation [1]. Furthermore, it is a promising solution in 5G cloud radio access network (C-RAN) architecture as a fronhaul link, which can transport mmW signals carrying data rates of Gb/s along tens of kilometres of optical fiber (OF) [2, 3]. Free space optics (FSO), as an optical wireless communication technology using extremely narrow beams in the infrared spectrum, is another alternative for 5G systems. Its main advantages are the enormous available bandwidth, substantially smaller losses compared with mmW and no requirements for licensing spectrum [4]. As demonstrated in the literature, it can provide links with a high data rate, i.e. up to hundreds of Gb/s [5]. Moreover, FSO channel has been recently deployed in proposed RoF links for 5G systems, so-called radio over FSO (RoFSO) [6].

Microwave photonics is an attractive solution for generating photonically mmW signals with low phase noise and frequency tunability [7]. Different mmW generation schemes have been demonstrated in the literature [8], from the basic heterodyne beating up to more sophisticated schemes based on non-linear effects. The optical frequency multiplication based on external modulation by a Mach-Zehnder modulator (MZM) is a convenient approach in terms of cost and complexity and allows to achieve up to 8-tupling frequency [9] with a high reduction of the electric bandwidth requirements and low phase noise. However, another MZM needs to be used to modulate the optical carrier with data signal in RoF schemes what brings additional costs. Different configurations of MZM have been demonstrated, such as two MZMs in a cascade [9, 10], dual parallel MZM [11] or a single MZM combining with a photonically mmW generation technique [12, 13].

In this context, directly modulated laser (DML) with data is an attractive approach that saves insertion losses, costs and complexity due to the second external modulator when carrier supressed regime is required. As it is well known, in a DML approach, the amplitude of the optical wave is modulated by the laser current driven by the data, so the performance of low-frequency response and non-linearity of the laser must be properly addressed. Previous works show the potential of this simplified technique in RoF systems, where a composed signal of data over the RF carrier is employed to modulate the laser carrier, i.e. a 64-quadrature amplitude modulation (QAM) signal of 100 MHz bandwidth is optically transmitted at 24 GHz in [6], 10 Gb/s 16-QAM- orthogonal-frequency-division-multiplexing (OFDM) at 60 GHz is transmitted in [14] by an injection-locked laser, or the transmission of 24 carriers of 100 MHz bandwidth using filtered-OFDM have been demonstrated successfully in [15].

In this work, we propose the use of the DML approach for 16-QAM signal transmission over hybrid optical links together with using an optical frequency multiplication scheme based on external modulation for 40 GHz mmW signal generation. We compare two schemes using null transmission point with carrier supression and quadrature bias point external modulation.

This contribution is structured as follows. Section II describes the proposed setup, Section III presents the experimental results and finally, the main conclusions are provided in Section IV.

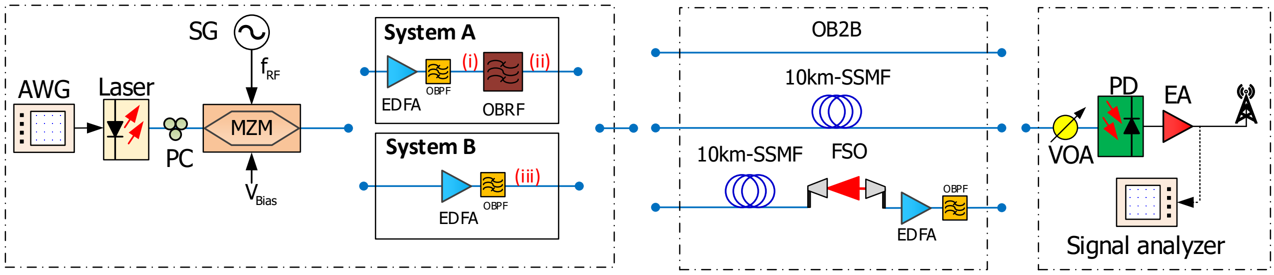

Figure 1. Experimental setup of a DML data signal modulation, carrier supression and RoF and RoFSO transmission. AWG: arbitrary waveform generator, PC: polarization controller, MZM: Mach-Zehnder modulator, SG: RF signal generator, EDFA: erbium doped fiber amplifier, OBPF: optical bandpass filter, OBRF: optical band-rejection filter, OB2B: optical back-to-back, SSMF: standard single mode fiber, FSO: free space optics, VOA: variable attenuator, EA: electrical amplifier, PD: photodetector.

II. Experimental Setup

The experimental setup of the proposed system is shown in Fig. 1. The distributed feedback (DFB) laser, which is directly modulated by a 16-QAM signal generated by an arbitrary waveform generator (AWG) (Tecktronix AWG7122C), emits an optical carrier at wavelength of 1553.88 nm with 5.63 dBm optical power. The state of polarization of the optical signal behind the DML is adjusted by a polarization controller (PC) and launched into the Mach-Zehnder modulator (MZM). The MZM (Photline MX-LN-40) is biased either at quadrature bias (Qbias) point, i.e. 4.77 V, in system A, or at null transmission point, i.e. 1.14 V, to obtain optical carrier suppression (CS) in system B, to modulate the optical carrier with a tone of 20 GHz frequency of 18 dBm power generated by a signal generator (SG) (Agilent E8267C). As depicted in Fig. 1, system A, employing the MZM biased in quadrature point, requires an optical band-rejection filter (OBRF) (Finisar Waveshaper 4000s) with $\Delta\lambda = 0.2$ nm to suppress the optical carrier.

In system A and B, the optically modulated signal is amplified by an erbium-doped fiber amplifier (EDFA) (Amonics AEDFA-23-B-FA) with 16.6 dBm and 18.5 dBm constant output power, respectively, to compensate the different optical losses. The amplified spontaneous emission (ASE) noise is filtered out by an optical band pass filter (OBPF) (Alnair BVF-100) with $\Delta\lambda = 2$ nm. In our setup, the optical back-to-back signal (OB2B) is first measured, then transmitted through an optical fiber link composed of 10 km SSMF fiber and finally through a full hybrid link with 10 km of SSMF and 1.5 m long FSO channel. Coupling between fiber and FSO is done by a graded-index pigtailed lens (GRIN, Thorlabs 50-1550A-APC) with an aperture of 1.8 mm and a plano-convex lens with a diameter of 25.4 mm. The optical beam is collimated at the receiver back to SSMF by the combination of the same lenses. Note that in our case, the FSO losses are 6.5 dB and another EDFA (Amonics AEDFA-27-B-FA) was needed. Then, the optical signal is launched into the photodetector (u2t BPDV2020R). Finally, the electrical signal is generated at 40 GHz by beating the first-order sidebands at the photodetector due to the absence of optical carrier in both A and B systems, amplified by an electrical RF amplifier (SHF Comm. Tech. AG SHF-810) with 29 dB gain and analysed by a RF spectrum analyzer (RFSA) (Agilent N9020A) and digital phosphor oscilloscope (DPO) (Tecktronix DPO72004C).

III. Results

A. *Optical and electrical mmW signal*

Fig. 2(a) shows the optical spectrum obtained in system A (at (i) in Fig. 1) with a carrier optical power of −14.1 dBm. It also depicts the filter transmission response showing higher than 40 dB insertion losses at the rejected band. Fig. 2(b) then shows the optical spectrum of this signal after filtering (at (ii) in Fig. 1) when a side-mode suppression ratio (SMSR) between the carrier and sidebands is measured as high as 34 dB . Fig. 2(c) displays the optical spectrum after CS modulation in system B (at (iiii) in Fig. 1) which leads to SMSR higher than 28 dB in our setup.

After opto-electronic conversion, the electrical signal at 40 GHz was down-converted (see scheme depicted in Fig. 3(a)) in order to capture the electrical spectrum of the modulated data with the electrical spectrum analyser (ESA) (Agilent N9020A). The mixer (Miteq M2640W1) down-converted the RF signal from 40 GHz to IF frequency at 10 GHz by using the local oscillator (LO) (Agilent N4373C) with 10 dBm output power and 30 GHz frequency.

Fig. 3(b) and (c) depict the spectra of the down-converted electrical signal obtained in systems A and B, using Qbias and CS modulation approaches, respectively, when transmitting

500 MHz bandwidth 16-QAM data signal. The down-converted signal is shown at 10 GHz and the measured RF power is −17.85 dBm and −12.9 dBm for the System A and B, respectively. In both cases, the upper data side bands show higher degradation than the lower side bands due to the mixer frequency response. The measured power of the lower band is −65 dBm meanwhile the power of upper band is lower than −69 dBm for both systems and a larger impact of non-linearities and noise is observed in RF spectrum for system A. Note that the electrical carrier at 20 GHz is also shown due to the lack of total cancellation of the optical carrier.

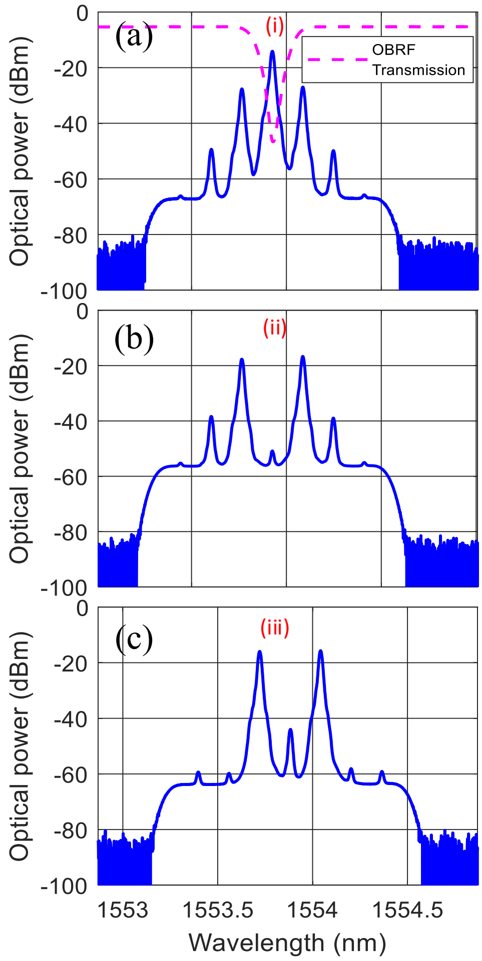

Figure 2. Optical spectra of: (a) Quadrature bias modulated signal (System A) before OBRF, (b) Quadrature bias modulated signal (System A) after OBRF, and (c) Carrier suppressed modulated signal (System B).

B. *Signal transmission*

In the next step, we evaluated the impact of the used signal bandwidth on the A and B systems´ performance. The laser was modulated with 16-QAM signal with 50, 100, 200 and 500 MHz bandwidth using an intermediate frequency of 2 GHz.

Fig. 4 shows the measured error vector magnitude (EVM) versus the received optical power of the optical back-to-back (OB2B) recovered signal after detection and post-amplification. As can be seen, measured EVM values in system B are lower than those obtained in system A. At 12.5 % EVM threshold level [16], the optical power difference between CS and QBias is 1 dB for 50 MHz, whereas it reaches 6 dB when bandwidth is increased up to 200 MHz. Note that 500 MHz bandwidth leads to higher EVM results with a minimum optical power of 3.2 dBm when CS modulation is employed, whereas Qbias point modulation does not provide acceptable EVM values in the range of received optical power values.

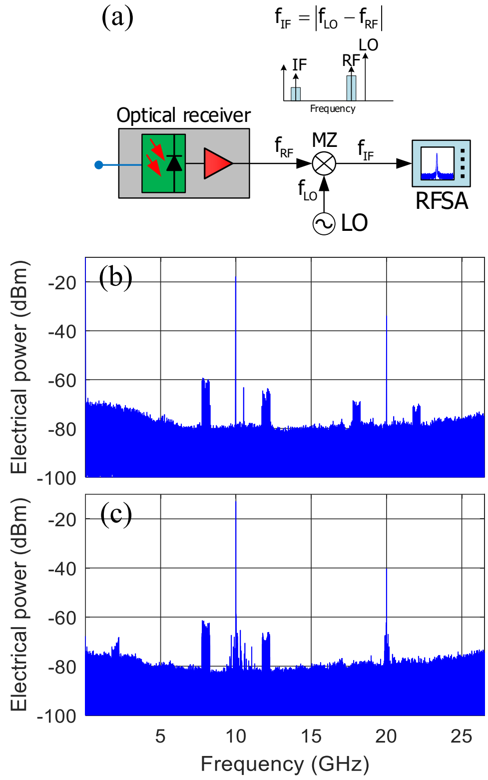

Figure 3. (a) Down-conversion scheme and electrical spectra (16-QAM data signal of 500 MHz bandwidth is transmitted), (b) System A with down-converted Qbias modulated signal, and (c) System B with down-converted CS modulated signal. LO: local oscillator, MZ: mixer, RFSA: RF spectrum analyzer.

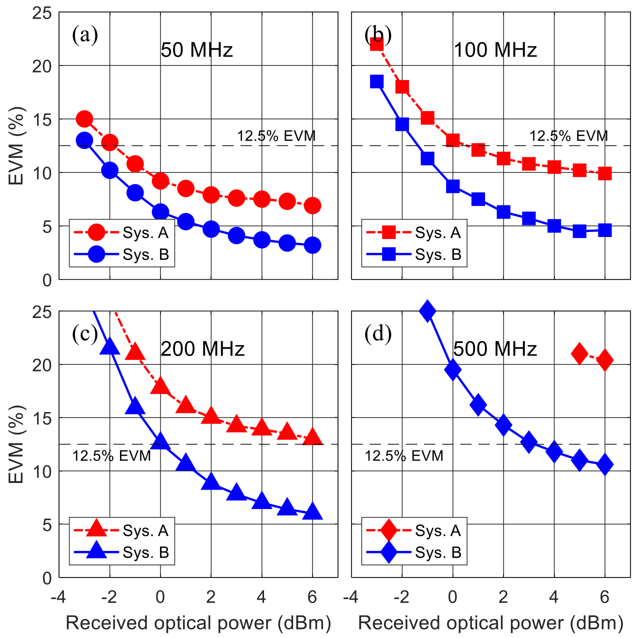

Figure 4. Error vector magnitude (EVM) of System A (Qbias) and System B (CS) for different signal bandwidths for optical back-to-back (OB2B). (a) 50 MHz, (b) 100 MHz (c) 200 MHz and (d) 500 MHz.

Results show that the System B using CS has significantly better EVM performance all over the whole tested bandwidth range. Therefore, in addition to its simpler configuration and lower cost and complexity due to the fact that no OBRF is required, system B represents a better solution for such a system. In the next step, the CS signal in system B was transmitted over different links and EVM was measured as depicted in Fig. 5, where examples of measured constellations are also shown as insets. No significant penalties were introduced by employing optical links and the minimum received optical power, i.e. sensitivity, for satisfying the 12.5 % EVM standard threshold level for 16-QAM with 200 MHz bandwidth is 0 and 0.4 dBm, respectively for OB2B and SSMF link. Moreover, hybrid transmission link shows slightly better EVM than SSMF link due to the additional EDFA.

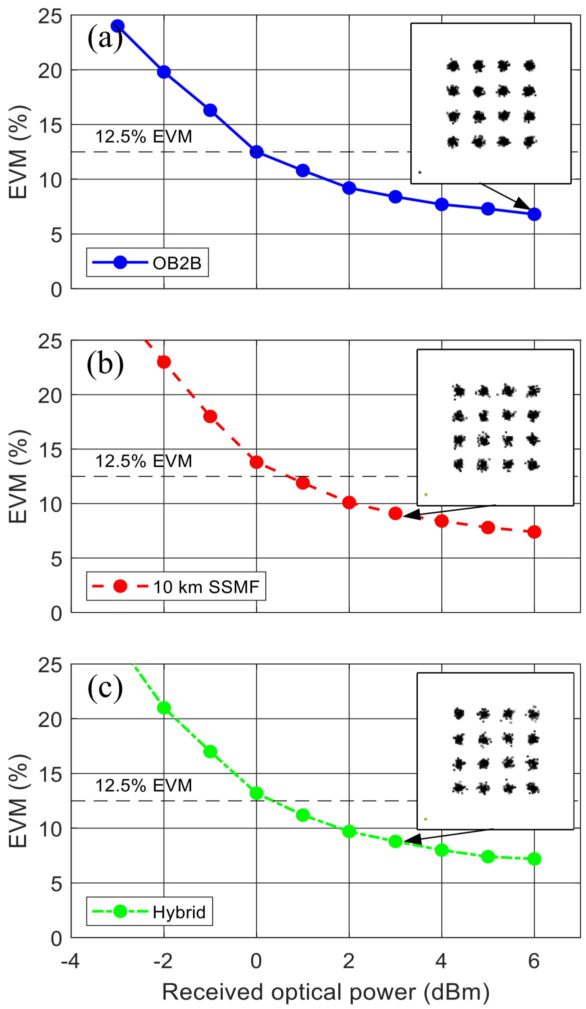

Figure 5. EVM performance of the System B transmitting a 16-QAM data signal with 500 MHz bandwidth for: (a) OB2B, (b) 10 km SSMF, and (c) full hybrid link with 10 km SSMF and 1.5 m long FSO channel . Insets show the constellations.

IV. Conclusions

In this paper we proposed a simple approach with a DML for 16-QAM signal transmission using an optical frequency multiplication scheme based on external modulation to photonically generate 40 GHz mmW signal. Quadrature bias point in MZM and carrier suppressed external modulation schemes following the DML have been evaluated for the sake of comparison showing the latter as the simpler approach with better performance over the tested bandwidth. Moreover, 16-QAM data with 200 MHz bandwidth have been transmitted using CS-modulation over 40 GHz and 0 dBm sensitivity has been obtained for OB2B measurements. Penalties induced by signal transmission over fiber and hybrid SSMF/FSO links under 1 dB have been measured at the EVM threshold level. EVM results show that a DML followed by a single MZM biased at null point is an excellent approach instead of using two cascade MZMs to transmit data over photonically generated mmW signals without need of additional filter. Therefore, a low cost and complexity millimeter wave photonic transmission system has been demonstrated as an enabling technique for the deployment of 5G networks.

Acknowledgment

This work was also supported by the Research Excellence Award Programme GVA PROMETEO 2017/103, the Spanish Ministerio de Ciencia, Innovación y Universidades RTI2018-101658-B-I00 FOCAL project, Ministry of Industry and Trade project MPO TRIO FV40089 and within COST CA16220.

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