Optical CS-DSB Schemes for 5G mmW Fronthaul Seamless Transmission

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***Abstract*—This paper describes the experimental demonstration of the hybrid optical/millimeter wave signal generation and transmission over combined optical fiber and free space optics fronthaul network with a seamless antenna link. An electrical bandpass filter is used to filter out the spectrum after photodetection in order to realize the seamless antenna transmission. The successful transmission of 64/256-quadrature amplitude modulation (QAM) 5G signal with up to 200 MHz bandwidth is presented by using two different setups: one is based on two Mach-Zehnder modulators (MZM) and the other employs a directly modulated laser (DML) to provide more cost efficient fronthaul solution. The DML based approach reveals mildly better performance in comparison to the MZMs in terms of higher achieved signal-to-noise ratio and lower error vector magnitude (EVM). More specifically, the best signal-to-noise ratio and EVM achieved with the DML based setup has been 31.5 dB and 3. 3%, respectively, compared to 30.3 dB and 3.8% with the MZMs based setup while transmitting 256-QAM signal with 100 MHz bandwidth. However, both setups kept the EVM well below the given 9% and 4.5% limit for 64- and 256-QAM, respectively.**

***Index Terms*—Optical fiber, free space optics, 5G, fronthaul, millimeter wave.**

I. Introduction

THE exploitation of the millimeter wave (mmW) frequency bands has become the crucial step to provide enough bandwidth for high capacity connection in fifth generation network (5G). The lowest mmW frequency band, i.e., above 6 GHz, stands for frequencies between 24.25 and 27.50 GHz [1]. It is this band that provides not only desired capacity but also reasonable propagating losses, compared to the upper frequency bound considered in 5G, which is up to 86 GHz [1]. Nevertheless, the mmW technology brings issues related to the significant power losses, increased costs and technology limitations. Therefore, the usage of microwave photonics represents a versatile solution for the mmW networks combining radio and optical technologies together and thus provides a better technology convergence [2]. In particular, the analog mmW transmission through optical fiber infrastructure, called radio over fiber (RoF), can be effectively used for the optical fronthaul network [3]. For this scenario, it is considered to connect a centralized pool of baseband or distributed units, which are responsible for communication through the physical interface, and remote radio units by the analog RoF technology [4]. Another option to increase the radio access network (RAN) flexibility is to use free space optics (FSO) technology in order to overcome obstacles in the optical fiber way [5]. However, the FSO propagation is subjected to atmospheric propagation effects including rain, fog or turbulences, and thus, the effects are needed to be taken into the consideration when using the radio over FSO (RoFSO) system [6], [7].

Compared to the classic analog RoF transmission with external modulation technique, mostly based on the linearly biased LiNbO3 Mach-Zehnder intensity modulator (MZM) [8], the photonic up-conversion can be performed by a MZM biased at null transmission point, which then works in carrier suppression (CS) regime. In the CS regime, the driving radio frequency (RF) signal creates two sidebands in the optical domain at the output of the MZM, which consequently beat each other in the photodiode (PD) what results in a frequency doubling [9]. The photonic frequency doubling then significantly reduces requirements for the transmitting side in terms of the half frequency handling for electrical signal sources and circuits.

Two experimental campaigns have been carried out by using two MZMs to double the incoming frequency to desired 25 GHz band and modulate data with a fiber, FSO and mmW antenna seamless transmission in [10] and [11]. Both works used long term evolution (LTE) wireless standards to evaluate the transmitted signal quality with the maximal bandwidth of 20 MHz and 64-quadrature amplitude modulation (QAM). The main focus was put on the impact of atmospheric turbulence, which affects the signal in FSO channel with a maximal experimental indoor FSO range of 40 m. The measured system performance in [10] and [11] were consequently used for simulated extended wireless ranges to provide maximal coverage. Although there was successfully transmitted mmW signal over up to 50 km of optical fiber, 40 m of FSO and 40 m of seamless antenna channel, the used LTE transmission frames with 20 MHz bandwidth seem to be insufficient for the high-capacity RAN. The beating of the two optical tones to generate mmW signal at 95 GHz was

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also used in [12] for an RF wireless transmission. The authors exploited a dual-drive MZM to generate the two-tone optical signal while a phase MZM was used for data modulation. The proposed system was afterward tested over 20 km of single mode fiber (SMF) and then the mmW up-conversion was realized at a self-fabricated high frequency optical-to-electrical converter. A successful 5 m long wireless transmission of orthogonal frequency division multiplexing (OFDM) 32-QAM signal with 3 GHz bandwidth at 95 GHz was demonstrated with the error vector magnitude (EVM) as low as 12.1%. A high throughput, i.e., 1.4 Gb/s, has been demonstrated for the analog RoF 5G fronthaul transmission with 9 m long antenna seamless link at 25.5 GHz by using multicore fibers as the optical medium in [13] and [14].

Also a low-frequency directly modulated laser (DML) can be used for the system using photonic frequency doubling by beating of the optical sidebands at the direct photodetection, as outlined in [15]. The usage of DML represents a less complex and cost effective solution by substituting the continuous wave (CW) laser and one MZM for data modulation. There was described the photonic signal generation of 40 GHz mmW and transmission over 10 km of SMF and 1.5 m long FSO channels by using the combination of DML and MZM. Up to 1 GHz signal bandwidth and up to 64-QAM modulation format with the maximal bit rate of 2 Gb/s were received in the system and evaluated in terms of EVM. The combination of DML and MZM was used also for the experimental comparison of remote and local photonic mmW signal generation in [16]. In order to reveal the impact of either local or remote photonic generation at 40 GHz, a quadrature phase shift keying (QPSK) signal was employed by the authors with the maximal bandwidth of 250 MHz. The local and remote generation in fact relied on the location of the MZM, which was biased at the null point and was responsible for the optical carrier suppression. In the experiment, the MZM was placed behind or in the front of the optical distribution network, consisting of up to 25 km of SMF. It has been revealed that remote generation leads to a higher frequency response than a local generation. It is worth to mention that no antenna transmission has been realized in [15] or [16]. The low frequency DML was used as well as a low cost solution for intermediate frequency (IF) over fiber (IFoF) transmission in [17], where authors experimentally demonstrated end-to-end fiber wireless fronthaul. The proposed approach introduced a broadband IFoF transmission combined with narrow band IFoF by using the low-frequency DML and classic analog RoF approach utilizing CW laser and MZM for 28 GHz RoF transmission with a seamless 10 m long antenna channel. The total system capacity was 34.2 Gb/s over 20-km broadband IFoF, 1 km narrowband IFoF, 500 m RoF and 10 m wireless mmW links. For the system performance evaluation, the authors used a 5G new radio (NR) signal with QPSK and 64-QAM modulations while all recorded EVM magnitudes after the wireless link satisfied the 8% criterion.

The most comprehensive comparison between the classical analog RoF and the photonic frequency doubling system with CS mmW transmission for mobile optical fronthaul using 5G NR signals has been experimentally demonstrated in [18]. For the sake of systems comparison, an optical channel consisting of 10 km of SMF and 4 m long FSO channels was deployed while the FSO channel was subjected to artificially induced variable turbulence levels. A chromatic dispersion resilience was presented for the CS dual sideband scheme for up to 40 GHz frequency and for the optical fiber length up to 30 km. The system was tested by using predefined 5G NR test models with maximal bandwidth of 400 MHz and modulation schemes QPSK/64-QAM/256-QAM at the carrier frequencies of 27 and 39 GHz. However, the seamless antenna transmission was not realized even for 27 or 39 GHz in the case of the frequency doubling scheme because of the inconvenient power conditions after the sidebands beating at the photodetector (PD). It has been described that for the frequency doubling scheme using a RF bandwidth higher than approximately 100 MHz, it is not appropriate to employ the mmW antenna channel directly behind the PD.

We present in this paper an experimental demonstration of a photonically doubling RoF and RoFSO system for the mmW 5G optical fronthaul network with seamless antenna transmission at 26 GHz. Two approaches are here considered, namely mmW generation and data transmission using two MZMs and a low-cost solution exploiting the combination of DML and MZM. Here we point out the main contributions of this work with regards to the references mentioned above:

1. Two different setups for mmW generation and transmission are used: i) two MZMs and ii) low cost DML with MZM, and their comparison is provided.
2. Transmission of 5G NR standard signals with wide bandwidth and up to 256-QAM modulation over SMF, FSO and a seamless antenna link at mmW frequency.
3. The data are evaluated directly at the target frequency of 26 GHz without any down-conversion.
4. Less complex and expensive components are used for the transmission system, i.e., single drive intensity MZM or low frequency DML.
5. An electrical filter is leveraged to optimize output spectrum for the broadband antenna seamless transmission.

It is worth to mention that these points are the whole of attributes, which makes this work novel, and therefore, the authors believe that the presented paper has a considerable scientific contribution for the future deployment of analog optical systems in mmW wireless networks.

II. Experimental Setup

Two setups have been considered for the optical mmW up-conversion in fronthaul network using combined fiber and FSO channels. The first setup (denoted in the paper as an external modulation setup, EM setup) uses a continuous wave (CW) laser and two MZMs, as shown in Fig. 1. This setup exploits the photonically frequency doubling technique, presented, e.g., in [18], and is based on one MZM (#1, Sumimoto Osaka, T.DEH1.5-40PD-ADC) biased at the null point to suppress the optical carrier and a second MZM (#2, Avanex PowerBit F-10) biased at quadrature point for data modulation. The optical source is a distributed feedback laser (Yenistu Optics, Tunics T100S-HP) at the wavelength of 1550 nm and the output power

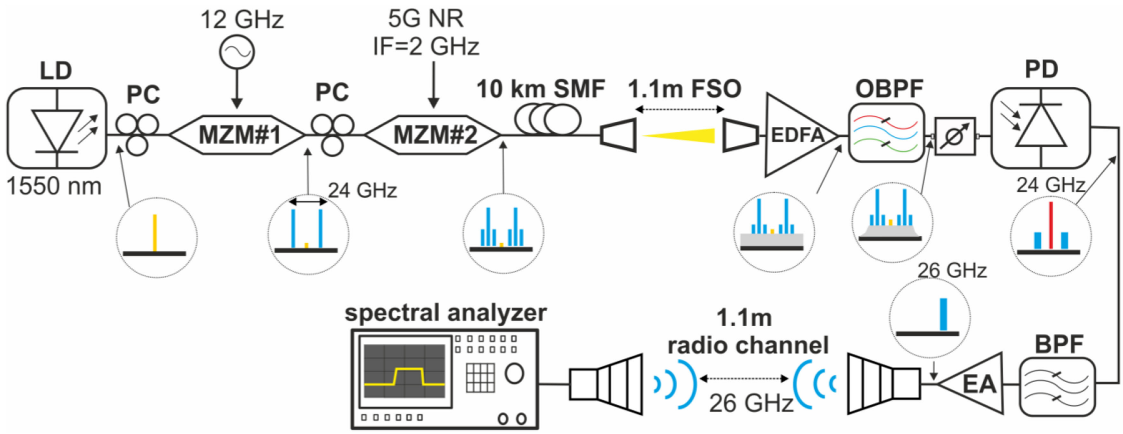

Fig. 1. EM setup for optical mmW generation at 26 GHz with the seamless transmission, insets illustrate spectra at given points.

of 11.3 dBm. A polarization controller is used to adjust the polarization state before MZM#1. Whereas the MZM#1, which is biased at the null point, is fed by a 12 GHz single tone signal from a signal generator (Agilent 8267C), the MZM#2, biased in linear point, has a 5G NR driving signal at 2 GHz IF. Note that the single RF carrier and IF data power levels are 23 and 1 dBm, respectively.

The optical distribution network consists of 10 km of SMF and a 1.1 m long FSO channel, which is realized by pair of doublet collimators (Thorlabs F810APC-1550), making seamless fiber-to-FSO and vice versa connection. Note that the FSO channel loss is 8.4 dB and the FSO range was limited by the available space in the laboratory. An optical erbium doped fiber amplifier (EDFA, Amonics AEDFA-23-B-FA) is used to compensate for the system loss, and an optical bandpass filter (OBPF, Alnair Labs BVF-100) is further employed to reduce the amplified spontaneous emission (ASE) produced by the EDFA. The EDFA was placed at the remote node in the laboratory setup to provide high optical output power (i.e., 16 dBm) and therefore, provide system characterization by adding a VOA just before detection while keeping a safe power level along the FSO link. However, real scenarios will place the EDFA at the CO for the sake of sharing resources. Before the optical-to-electrical conversion, realized by a high frequency PD (Finisar XPDV2320R), a variable optical attenuator (VOA, Thorlabs EVOA 1550A) is used to adjust the received optical power. After the direct detection by means of PD, the bandpass filter (BPF, Mini Circuits ZVBP-25875-K+) is employed to filter out the newly generated carrier, the second sideband and all unwanted intermodulation products present in the electrical spectrum in order to obtain a single band centered at 26 GHz for further processing. Note that the passband of the filter lays between 24.25 and 27.5 GHz. Regarding the usage of the filter, it is crucial to point how to use EM setup for a seamless optical and mmW antenna transmission with reasonable signal-to-noise ratio (SNR) while adopting higher signal bandwidth at mmW frequency range, i.e., >100 MHz, which is described in [18]. The signal after the BPF is amplified by using a broadband electrical amplifier (EA, SHF810) and then radiated to a 1.1 m long antenna channel by means of the pair of

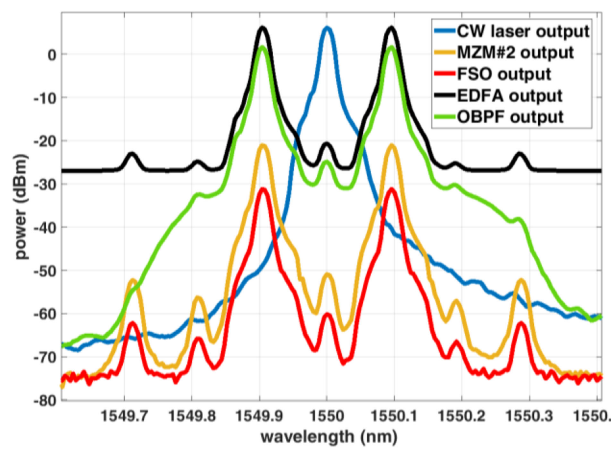

Fig. 2. Optical spectra obtained by the optical spectrum analyzer in the EM setup for optical mmW generation with the resolution of 0.02 nm.

double ridged horn antennas (RFSpin, DRH40). Afterward, the signal is received and evaluated in a spectral and signal analyzer (R&S FSW43). The optical spectra, captured at selected parts of the EM setup and corresponding to the scheme shown in Fig. 1, are depicted in Fig. 2. Whereas the difference between optical spectra at the MZM#2 and FSO outputs stands only for the SMF and FSO loss, the difference between EDFA and OBPF outputs shows both loss of the OBPF and, more importantly, the reduced ASE noise produced by EDFA. Even though the maximal resolution of the optical spectral analyzer has been set, i.e., 0.02 nm, the IF data at 2 GHz cannot be seen, so only the optical sidebands at 12 GHz spacing with the suppressed optical carrier can be observed. Note that the CS ratio is 30 dB after the MZM#2. The key parameters of the experimental campaign are summarized in Table I.

Next, we demonstrate a low-cost and less complex fronthaul solution with the mmW signal generation using DML and one MZM biased at null point (denoted in the paper as a direct modulation setup, DM setup) while the DM setup is depicted in Fig. 3. Instead of using CW laser and external MZM for data

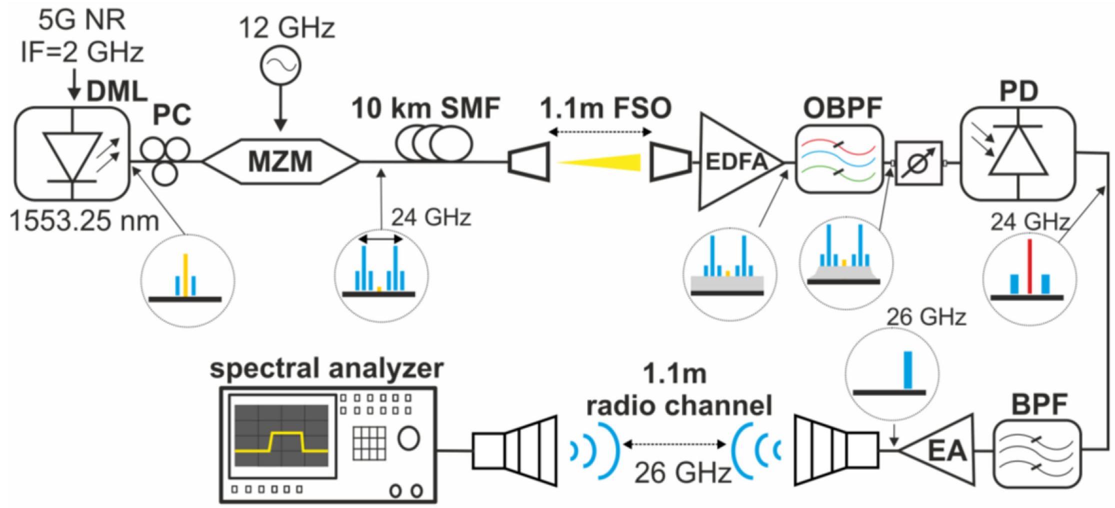

Fig. 3. DM setup for optical mmW generation at 26 GHz with the seamless transmission, insets illustrate spectra at given points.

TABLE I
SYSTEM PARAMETERS

Parameter	Value
SMF length	10 km
FSO length	1.1 m
FSO channel loss	8.4 dB
EDFA output power	16 dBm
EDFA noise figure	<6 dB
PD responsivity @1550 nm	0.65 A/W
PD dark current	<10 nA
Antenna channel length	1.1 m
Free space loss @26 GHz	61.6 dB
Rx/Tx antenna gain @26GHz	14 dBi
EA gain	29 dB
EA noise figure	6 dB
BPF bandwidth	3.25 GHz (24.25 – 27.5 GHz)

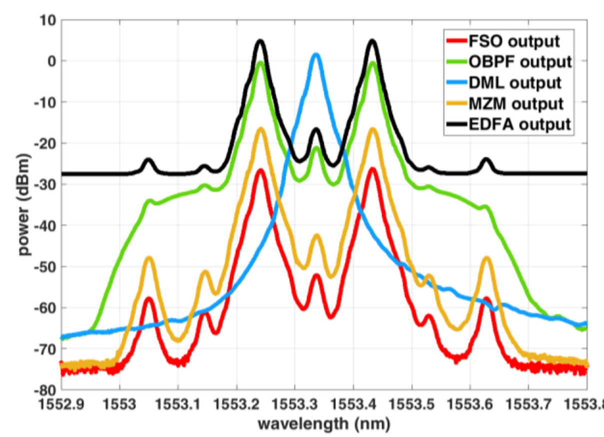

Fig. 4. Optical spectra obtained by the optical spectral analyzer in the DM setup for optical mmW generation with the resolution of 0.02 nm.

modulation, in this setup a DML (Optical Zonu OZ516) serves as both the light source and the electrical-to-optical modulator. Since the electrical 3-dB bandwidth of the DML is low, i.e., 7.75 GHz, but high enough to modulate IF data, it is considered as a low-cost solution due to the component availability compared to DML with high bandwidth presented e.g., in [19]. The central wavelength of the laser is 1553.25 nm and the output power is 7 dBm. After direct modulation by the IF data from the signal generator, an MZM (Sumimoto Osaka, T.DEH1.5-40PD-ADC) is employed for the optical CS to generate mmW signal at the double of the incoming frequency. The rest of the DM setup remains the same as in the EM setup with two MZMs, while the cost for the DM setup is at least 2 000 USD lower compared to the EM setup. The corresponding optical spectra, analogically to Fig. 2, are shown in Fig. 4.

At the first look, the spectra are very comparable to the previous setup except of the slightly different laser wavelength. However, it is caused especially by the fact that IF data cannot be seen due to the optical spectral analyzer resolution because here the DML output already contains the modulated 5G signal at the frequency of 2 GHz. The CS ratio for DM setup is 26 dB at the MZM output.

Note that, for the generation and evaluation of the received signal in both setups, we used Rohde & Schwarz vector signal generator and spectral/signal analyzer with the predefined test models according to the European Telecommunications Standards Institute specification corresponding to release 15 [20] for channel estimation, equalization and EVM evaluation. The measured EVM was averaged over all allocated downlink resource blocks with the considered modulation scheme in the frequency domain, and a minimum of 10 downlink sub-frames. The predefined 5G NR test models are mainly proposed for the 5G base stations testing [20].

III. RESULTS

In this section, we present the experimental results obtained from the measurements. At first, we focused individually on the particular setup and determined their performance. As has

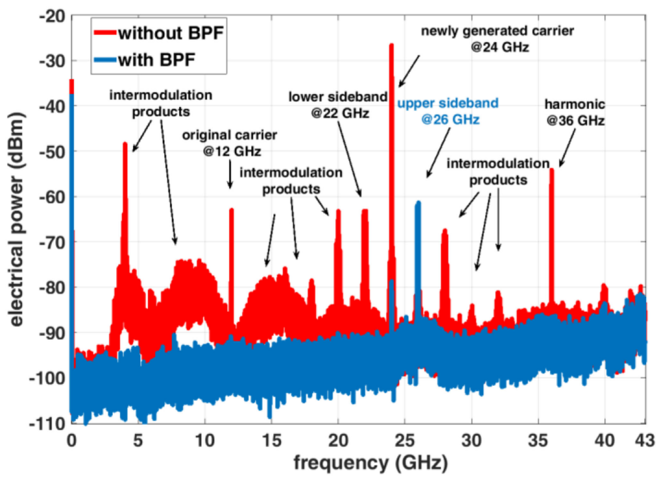

Fig. 5. Electrical spectra w/ o and w/ BPF employed in the EM setup at the PD output for 200 MHz bandwidth.

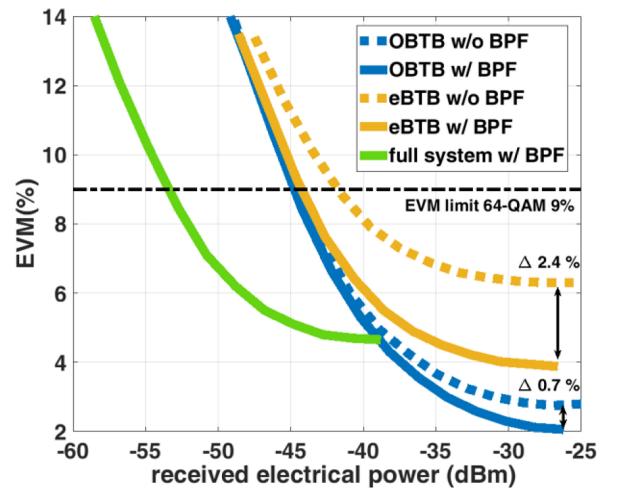

Fig. 6. Performance of EM setup with 64-QAM and 200 MHz bandwidth at 26 GHz.

been demonstrated in [18], the optical CS regime with dual sideband modulation format used for the mmW generation is very effective for the optical/RF seamless transmission toward 5G and beyond networks, especially in terms of the lower requirements on the signal source and the immunity to chromatic dispersion. Furthermore, the frequency doubling technique for analog RF transmission does not significantly deteriorate the phase noise of the whole system [21]. Also, the evaluated signal performance in terms of SNR and EVM meets requirements for the 5G NR signals when the signal is evaluated directly behind the PD [18]. In that case, the electrical spectrum of the final generated signal does not play as significant role as with the seamless transmission when the signal needs to be amplified to a sufficient power level and filtered before it is radiated to free space by an antenna. If the optical CS reaches an adequate level, i.e., >25 dB, the mmW conversion is very efficient, resulting in a strong generated mmW carrier with two sidebands, shifted by IF, i.e., 2 GHz. But then, when the signal is amplified prior to antenna transmission, the amplifier is overloaded by the strong mmW carrier, whereas the data signal band is not amplified to a sufficient level, and thus the received data signal has not enough power for the optimal processing what consequently results in the poor system performance. This is crucial in particular for higher transmitted signal bandwidth, i.e., approximately more than 100 MHz. Moreover, to achieve high optical carrier suppression, a high power level for the driving RF signal into the MZM is required, e.g., 23 dBm in our case, and then a lot of intermodulation products could appear in the electrical spectrum after the beating in the photodiode due to the nonlinearity. For that reason, we used a BPF between the PD and the EA to optimize the output spectrum and the overall signal performance. Therefore, we show here the comparison of the electrical spectra received in the spectral analyzer after PD with and without the usage of the BPF. At first, results for EM setup with 64-QAM 5G NR signals having a bandwidth of 200 MHz are shown in Fig. 5.

It is evident the most distinct element in the spectra without using the BPF (red data in Fig. 5) is the generated mmW carrier at 24 GHz. Besides that, two signal bands at IF of ± 2 GHz appear in the spectrum with harmonics and many other intermodulation products, which are caused especially by the relatively high input power to the MZM. As was mentioned above, this significantly limits the system performance in terms of SNR and EVM and it needs to be treated for the antenna connection. When the BPF is employed (blue data in Fig. 5), only the upper sideband remains with a small part of the newly generated mmW carrier and otherwise, the other elements are filtered out. The filtered signal is then amplified by EA and radiated through a 1.1 m long mmW wireless channel.

In order to determine the impact of having the BPF filter implemented after the PD, we transmitted 5G NR signal with the predefined test model TM 3.1 using 64-QAM and 200 MHz bandwidth representing a maximal bit rate of 1.2 Gb/s. Fig. 6 shows the measured EVM dependence on the received electrical power. We compared the system performance in terms of EVM for optical back-to-back (OBTB) consisting of the transmission system without fiber, FSO or antenna. Then electrical BTB (eBTB) stands for the full system without radio channel, i.e., without antennas and the signal is evaluated after the PD. Finally, we show the system performance using the complete system with the seamless antenna link. Note that in the full system scenario, there was not possible to even receive a sufficient signal quality without the BPF, and thus only the system performance with the usage of the BPF is shown in Fig. 6. While there is no considerable difference between the EVM performance with and without the BPF for OBTB, when eBTB is employed, i.e., 10 km of SMF and 1.1 m long FSO without antenna channel, we can observe a 2.4% better EVM for the maximal received electrical power with the applied BPF. Also the difference between the system with and without the BPF tends to be less significant when the received power is decreasing. Note that the received electrical power was tuned by increasing of the VOA IL and therefore the figure shows the effect of the optical IL increase

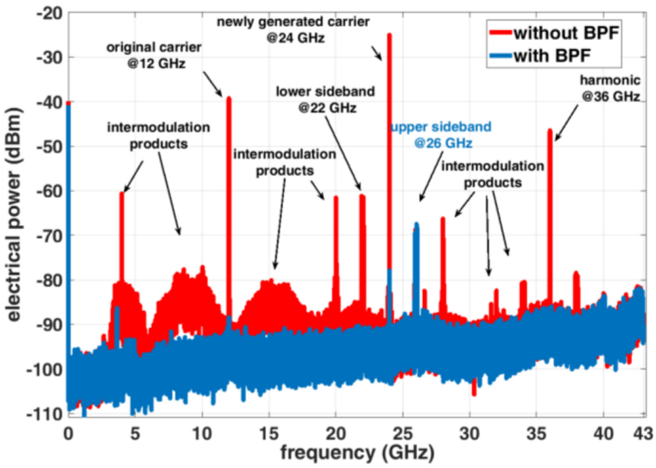

Fig. 7. Electrical spectra w/ o and w/ BPF employed in the DM setup at the PD output for 200 MHz bandwidth.

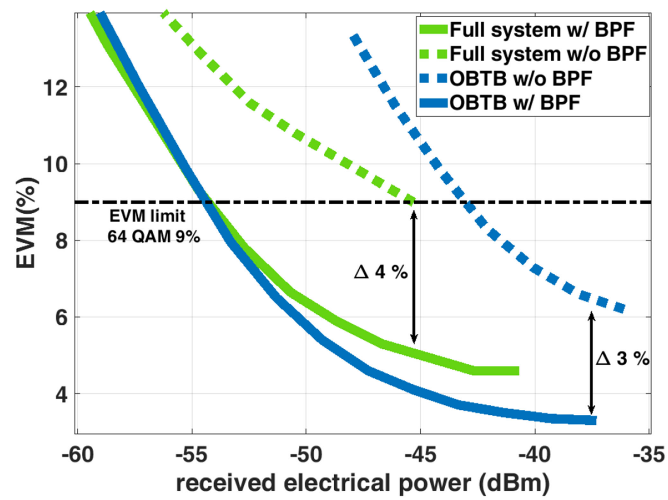

Fig. 8. Performance of DM setup with 64-QAM and bandwidth of 200 MHz at 26 GHz.

in fact. The lowest observed EVM by using the BPF for OBTB and eBTB are 2.1 and 3.9%, respectively. The minimal received EVM for the full system with 200 MHz bandwidth and 64-QAM modulation scheme is 4.7%. In other words, to comply 9% EVM limit, the required electrical power level for the full system is −52.6 dBm. Analogically, the required received power levels for the eBTB without BPF, eBTB with BPF are −41.5 dBm and -44.6 dBm, respectively. The minimal received powers for OBTB are identical, i.e., −45 dBm.

In the next step, we have deployed the DM setup according to the scheme in Fig. 3, which employs a DML and MZM for data modulation and mmW generation, respectively. In general, DML offers satisfactory RF to optical conversion efficiency and linearity but has relatively low output power and the modulation chirp is generally higher than the external modulation techniques. The system performance tests have been carried out in the same way as in the case of the EM setup with the same transmitted signal. As was mentioned above, the usage of low-frequency DML represents an effective low-cost approach for such an optical fronthaul network combining optical source and modulator into the one device and thus forming a less complex solution. Moreover, by using the DML, the IL from MZM#2 is eliminated and therefore, the optical power budget becomes significantly better. The electrical spectra received after the PD with and without the use of the BPF in the DM setup are shown in Fig. 7.

In analogy to the EM setup, there can be seen many intermodulation products and other unwanted frequency components in the spectrum without BPF, displayed in red color. On the other hand, the electrical spectrum without BPF evinces, compared to the EM setup, less disruptive features in terms of the number and strength of the unwanted elements while using DML, which is attributed to better linearity. More precisely, the DM setup´s spectrum without BPF evidenced more power in the carrier frequency and its multiples, which are 12, 24 and 36 GHz. This is mainly because of the lower CS ratio in the optical domain compared to the EM setup, i.e., 26 vs 30 dB. However, there is a significantly lower amount of the power assigned to the intermodulation products, which are located mostly in frequencies lower than 22 GHz, as can be seen in Fig. 7.

There are also shown the EVM results plotted against the received electrical power in Fig. 8 for the DM setup in order to demonstrate the system performance compared to the EM setup. For this setup, we have not measured the electrical BTB and therefore only the OBTB and the full system performance results are shown in Fig. 8. The results show a not-negligible difference between the EVM curves with and without BPF for OBTB, which is 3% at -37 dBm of the received power. This is more evident in the EVM performance for the full system including 10 km of SMF, 1.1 m long FSO link and 1.1 m long antenna link. The EVM could be evaluated even for the full system without the BPF, however the magnitude is right at the EVM limit given for 64-QAM, which is 9% [20]. Compared to that, the EVM profile while using the DML and BPF is as low as 4.6% for the maximal received electrical power. Moreover, to obtain the same EVM value, i.e., 9%, with BPF as without the BPF, the 9 dB lower received electrical power is needed. It is worth to mention that lower electrical power, i.e., about -37 dBm, was achieved for the OBTB configuration in the DM setup compared to EM, which resulted in lower SNR and corresponding higher EVM magnitude although the electrical spectra without filter showed better linearity of the system and slightly lower noise floor. It should be also noted that new intermodulation products in the electrical spectrum appeared in the electrical spectrum when reasonable received electrical power is achieved in the full link, including antennas. It could be emphasized that to achieve excellent EVM performance, the DML requirements are sufficiently high optical power, narrow linewidth and high linearity.

Finally, the comparison between both setups for data transmission and mmW generation, respectively, has been carried out with respect to the measured SNR. For this purpose, we have used 5G NR signal employing 256-QAM modulation with 100

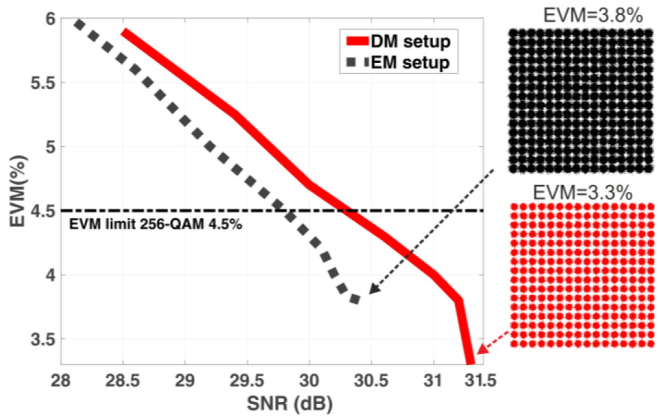

Fig. 9. The comparison between the both systems for 256-QAM signal with 100 MHz bandwidth and full channel configuration in terms of EVM characteristic with corresponding constellation diagrams.

MHz bandwidth to demonstrate high QAM-order transmission. The data have been measured over the whole proposed network including optical channel and seamless antenna transmission at 26 GHz with the use of the BPF after PD. The results are then shown in Fig. 9. The SNR was changed by the increasing of the VOA insertion loss (IL), so the maximal SNR values correspond to the 0 dB IL. It can be seen the EVM difference between the EM and DM setup for the same SNR value. It is attributed to the fact that for the same measured SNR value, the EM setup has higher received electrical power, compared to the DM setup. Note that the SNR was measured in the spectral domain by using the spectral analyzer.

It can be seen that the DM setup achieves lower minimal EVM, which is 3.3%, compared to 3.8% with the EM setup. Also shown in Fig. 9 are the corresponding constellation diagrams for the maximal SNR. It is worth to mention that also about 1 dB higher SNR, i.e., 31.3 dB, has been achieved with the DM setup using DML for this transmitted signal with 100 MHz bandwidth. However, both approaches represent a suitable platform for a fronthaul seamless link at mmW frequency when filtering out the generated mmW carrier.

IV. Conclusion

A hybrid optical and mmW generation with the seamless antenna transmission at 26 GHz have been demonstrated using both the fiber and FSO to mimic an analog optical fronthaul. In particular, the usage of additional filtering enabled to demonstrate the seamless transmission of 5G NR signals with the bandwidth exceeding 100 MHz. Furthermore, two setups have been presented for the mmW signal generation and seamless antenna transmission. Whereas one exploited two MZMs for the optical CS and the data modulation, the latter used MZM for the optical CS and DML for the data modulation, representing an effective and low-cost solution for the analog fronthaul networks. We have shown that the 5G NR 200MHz/64-QAM signal performance in terms of EVM was as low as 4.7% and 4.6% for the EM and DM setups, respectively, while the additional BPF was required to remove unwanted elements from the electrical spectra. The successful transmission of 256-QAM/100 MHz signal over the whole proposed infrastructure, including seamless antenna transmission at 26 GHz, has been also presented.

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