Filterless Photonic Millimeter Wave Generation and Data Transmission for 5G Indoor Wireless Access

Belkacem Anes[1], Borsali Ahmed Riad

Abstract – **A filterless optical carrier suppressed (OCS) millimeter wave generation and data transmission based on single tone modulation with wavelength reuse is proposed. We have conducted a simple and cost-effective high quality 38 GHz OCS millimeter wave generation by quadrupling a 9.5 GHz radio frequency local oscillator signal via only two dual-drive parallel Mach-Zehnder modulators (DD-MZMs) without filtering. The quality factors (Q factors) of the received signals using adaptable data rates of 1.25 and 2.5 Gbps are measured and analyzed for downlink and uplink. The obtained simulation results revealed that the designed full-duplex radio over fiber (RoF) system maintained good performance and offered an error free transmission (bit error rate, BER< 10^{-9}) over long distances up to 100 km with high quality eye diagram patterns.**

Keywords – **Microwave photonics, Radio over fiber, Quadrupling technique, Millimeter wave, Optical carrier suppression.**

I. Introduction

Due to the exponential growth in mobile data traffic, mobile network operators around the world are working intensively to support the ever-increasing bandwidth demands for the new applications and services. The sub-6 GHz microwave band is overcrowded and limited which leads to a lack of radio resources to serve more users and services. On the other hand, the interference effects in this congested band would severely limit the data rates [1]. Thereby, it is necessary to move towards high radio frequency (RF) range in the millimeter-wave (MMW) bands due to its huge bandwidth availability. Recently, MMW bands have been opened up by the communication industry regulators to be used for the first time in the new era of mobile communication systems that is named the fifth generation (5G) new radio (NR) [2].

The overall target of the next-generation mobile systems is to deliver to the end users reliable communication link anywhere and anytime. According to several surveys and studies, more than 80% of mobile and wireless data traffic originates in indoor environments [3].

There are a lot of crucial issues to be considered in MMW communication systems. Regarding the scope of this work, two main challenges could be focused on; which are MMW generation and distribution. Millimeter wave generation in the electrical domain using conventional electronics is a bottleneck due to the limited radio frequency components response, and it is considered very expensive especially for systems operating beyond 24 GHz [4]. Whereas, concerning the wireless distribution via the air, millimeter waves are more susceptible to blockages effects due to its physical characteristics such as high power losses when is penetrated walls, buildings, trees, or any obstacles, and absorption due to the atmospheric condition (rain, gaseous, snow, turbulence, etc.) [5]; which makes a serious problem in coverage, and therefore restraints their utilization to serve indoor applications and services. Also, the distribution of MMWs over metal waveguides for indoor applications is not practical due to the large propagation losses, and limited bandwidth of these waveguides themselves.

So, it is necessary to find a compromise solution to overcome the trade–off between complexity and efficiency to cover the indoor areas such as in-buildings, subway stations, airports, and so on by the 5G MMW technology. In this context, in order to encounter the indoor coverage area problem and offer multi-gigabit services to mobile users, hybrid microwave photonic MMW generation including fiber-wireless data transmission has become a very promising solution, known as millimeter wave radio over fiber (MMW-RoF) [6].

Optical generation techniques of MMWs have been widely studied in the last three decades using different methods over many MMW bands. Among them, MMW generation based on the external modulation has great attention, and it is mainly revolved around two types, which are directly by frequency up-conversion and via optical frequency multiplication (OFM).

Many works have been recently proposed to generate MMW signal using frequency up-conversion technique through different modulation schemes including double-sideband (DSB) [7], single-sideband (SSB) [8], and optical carrier suppression (OCS), [9]. However, these techniques need more than one optical filter or external modulator to eliminate unwanted optical sidebands. Furthermore, the repetitive frequency of the generated optical MMW is generally only twofold the radio frequency (RF) sinusoidal signal that used to drive the optical modulators (frequency doubling). Hence, it is not sufficient to reduce requirements of the optical and electrical components [10]. Besides all that, the propagation distance over fiber is severely limited due to the effects of power fading and bit walk-off caused by the chromatic dispersion [11].

On other hand, optical MMW signal generation based on OFM has been considered more attractive in modern MMW RoF systems due to its high spectral purity, stability, simplicity, and reliability [12]. More importantly, it can further minimize the frequency requirements for generating

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MMW signal in terms of optical modulator bandwidth and RF local oscillator (LO) drive frequency. Also, OFM method permits flexible adjusting of the frequency spacing at any desired optical MMW signal by tuning the RF LO drive signal frequency [13].

As examples of simple OFM systems, the authors in [14], [15] are implemented two parallel dual drive Mach Zehnder Modulators (DD-MZMs) based on a multiplication factor of four of a local oscillator frequency to generate 60 GHz and 72 GHz MMW, respectively. But, although these MMW RoF systems have been carried out using OFM, they are still sensitive to chromatic dispersion due to the fact that data signals are carried onto both optical tones of the generated optical MMW (dual-tone modulation) [16], and also there is a need for an optical source at the base station for uplink data transport.

To solve both problems, a single tone data modulation of the generated optical MMW is indispensable to overcome fiber dispersion degradations; while the remained sideband is kept unused during the downlink transmission to be used as an optical carrier for uplink data signal delivery. In this regard, several approaches have been reported to generate different MMW signals based on OFM through numerous configuration stages of MZMs including various frequency multiplication factors (FMFs) of 4, 6, 8,10 and 12 [17-21] up to 24 [22] and above [23] targeting to achieve high tolerance against bit walk-off effect, and hence no large transmission power penalties due to the dispersion; moreover, the capability to design simplified remote antenna sites based on wavelength reuse is possible.

Regarding the aforementioned techniques related to the OFM, the configuration will be more complicated by increasing the desired frequency multiplication factor. Furthermore, the frequency multiplication factor above four suffers from low conversion efficiency due to the higher modulation index [24]. As a result, it should be select an appropriate FMF carefully depending on the applications that we interesting in.

For wireless applications at MMW frequencies less than 40 GHz, frequency multiplication factor of four know as frequency quadrupling technique is very enough to reduce the requirements of the electrical components, and can generate a steady MMW signal with high modulation efficiency and compact structure [24]. By standing behind these reasons, we have adopted frequency quadrupling as the best choice for our proposed scenario that is envisioned to cover indoor Gbit/s enhanced mobile broadband (eMBB) applications at 38 GHz for fifth mobile generation New Radio (5G NR).

In this work, the feasibility study and transmission performance analysis of full-duplex photonic frequency MMW generation and data transmission based on the quadrupling technique by two parallel DD-MZMs is proposed. A photonic generation of high-purity 38 GHz MMW signal with only 9.5 GHz radio frequency local oscillator is realized. No optical or electrical filtering is utilized, which minimizes the complexity and system cost significantly. Furtherly, we have focused to design a MMW RoF system to be practical as much possible for future commercial deployment by enabling the wavelength reuse at the remote base station.

The remainder of this paper is organized as follows. In Section 2, we elaborate on a general description of the proposed OCS MMW RoF system in its full mode of operation. In Section 3 we present the adopted simulation scheme and its associated setups, while in Section 4, the system performance is investigated through results and discussions. Finally, the conclusion and future work are given in Section 5.

II. Architecture and Principle of the Proposed Full-Duplex OCS MMW RoF Transmission System

In this section, the general principle of the whole fiber-wireless link with the photonic generation method of MMW and wavelength reuse is presented. The schematic diagram of the proposed full-duplex OCS RoF system based on frequency quadrupling is shown in Fig. 1. It consists of four main parts which are: central office (CO), optical distribution network (ODN), radio access unit (RAU) and mobile terminal (MT). The CO and the RAU are connected via an ODN and the interconnection between the RAU and MT is wireless. The RAU could be placed in indoor environments such as airports, conference centers, stadiums, in-buildings, hotels, homes, dead zones, small offices and so on as a hotspot to deliver ubiquitous and broadband wireless access services. The proposed system can be integrated with the already deployed passive optical networks (PONs) to use the benefits of a shared ODN infrastructure.

The photonic MMW generator is modeled based on parallel configuration consisting of two dual-drive Mach Zehnder modulators (DD-MZMs) supplied by the same optical continuous wave (CW) laser source, and each of them is driven by a radio frequency (RF) local oscillator (LO) signal into both ports. The lower DD-MZM output is connected directly with an electrical phase shifter to perform certain polarity against specific optical harmonics to attain destructive interferences with other harmonics that are obtained at the output of the upper DD-MZM. The upper and lower DD-MZMs outputs are then combined by an optical coupler in order to produce an optical suppression carrier (OCS) signal based on quadrupling technique, which means obtaining two dominant optical sidebands separated by a frequency four times of the input RF signal used by the LO oscillators.

In practical systems, the dual parallel-Mach Zehnder modulator (DP-MZM) is a commercially available device that could be fabricated on a single chip, which means it is driven by only single LO oscillator as employed in different experimental setups in [24-25].

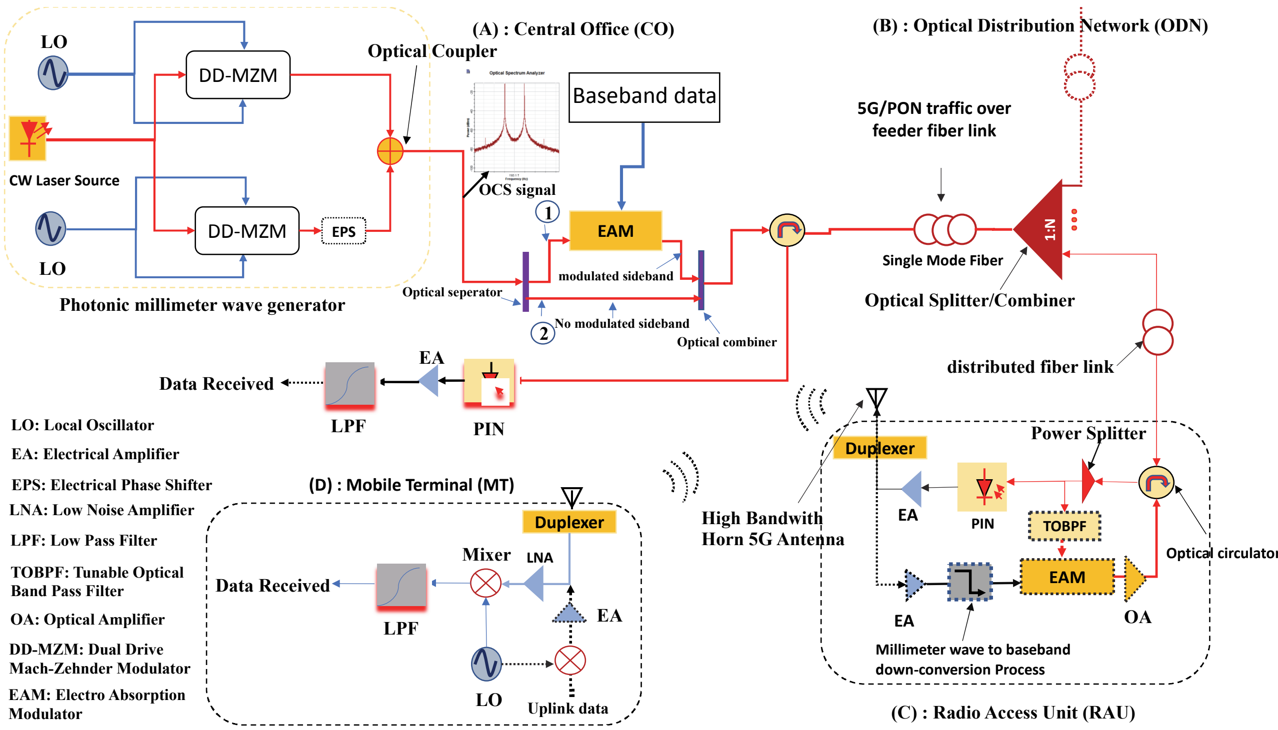


Fig. 1. Schematic diagram of the proposed full duplex OCS MMW RoF system based on wavelength reuse

The generated OCS signal at the desired MMW passes through a dedicated modulation process that is equipped by an optical separator, modulator and then combiner. Firstly, the optical separator can be an optical interleaver [26] or a wavelength division demultiplexer [22] which is used to disassociate the two major optical tones of the OCS signal from each other into two paths (1) and (2) as depicted in Fig. 1. Then, in the path (1), the first optical tone is intensity modulated by the baseband data using an electro-absorption modulator (EAM), while in the path (2) the second optical tone left unmodulated. Finally, an optical combiner as a wavelength division multiplexer can be used to joint again the two OCS sidebands to be transported over the feeder fiber link to the distributed fiber links using an optical splitter towards multiple remote stations known as radio access units (RAUs).

At the RAU and after the optical circulator that allows the down and up links to be flow independently, the optical signal is divided into two equal branches via a power splitter. In the upper branch, the two optical sidebands beat a high-speed photodetector (PD) to produce an electrical modulated MMW at a frequency four times of the input RF signal that used in the CO. The generated RF photocurrent that holds the required baseband data signal at the desired MMW is radiated directly after an electrical amplification into the air via an appropriate antenna for wireless access.

The MMW signal is wirelessly transmitted through a distance of air to be delivered to the mobile terminal (MT), where it is captured by a dedicated antenna and then pre-amplified by a low noise amplifier (LNA) to perform an electrical down-conversion through coherent demodulation for retrieving ultimately the original baseband binary data. The coherent demodulation is achieved by an electrical mixer and a RF local oscillator produce a frequency of 38 GHz generated by a 1: 3 frequency multiplier of 12.67 GHz signal.

In real systems, both RAU and MT use a duplexer to circulate the transmitting and receiving wireless signals from and to the antenna simultaneously.

For MMW uplink direction, after the RAU antenna, a certain electrical process could be performed to down-convert this uplink MMW RF signal into a base band signal. In the lower branch after the optical splitter, a tunable optical band pass filter (TOBF) is used to stop the modulated optical sideband and reserve the unmodulated one to use it as a carrier to bear the upstream baseband signal. Hence, the remote access units are simplified significantly, since no optical source is needed at the RAU.

A fiber Bragg grating (FBG) can be integrated at the RAU to abstract the optical carrier of the uplink [27], but in the real system; the FBG is too sensitive to the environment such as the temperature, and this needs a composite control system to regular its operation [28]. So, the purpose of using a TOBF in our prosed system is because it could operate over a wide range in the C band to select any unmodulated optical sideband when the quadrupling-based OCS modulator has a tunable laser source at the CO or tuning the input frequency of the RF LO signals to the DP-MZM to generate different optical MMW bands. Also, the necessity of using a TOBF will be appear when the proposed scheme is integrated in wavelength division multiplexing systems based on flexible optical comb source generator [29].

Subsequently, the reflected modulated optical component is amplified by an erbium doped fiber amplifier (EDFA) to promote the optical signal power due to the power losses coming from downlink transmission and different insertion losses in the optical circulator, power splitter, optical band pass filtering and electro-optical modulation, respectively. The amplified optical signal is sent back to the CO through the same optical fiber, where at the CO; the baseband uplink signal can be recovered easily by a photodetector (PD) involving a simple direct detection.

III. Simulated System and Parameters Setup

The entire OCS RoF system is built by using an advanced industry simulation software package Optisystem version 15.2 to verify the transmission performance. The design of the simulated system is shown in Fig. 2. The simulation results of the corresponding inset points in the Fig. 2 which are the optical and electrical spectrums besides the adopted metric of performance in the form of eye diagrams will be presented in the results and discussion Section.

Since our research mainly focuses on the RoF link and investigate its performances in optical domain (MMW generation, data modulation, and transmission over fiber), the wireless transmission is not considered and the modulated optical MMW is down-converted at the RAU using LO operates at 38 GHz and mixer as shown in Fig. 2.

In order to design a reliable RoF-based access network infrastructure based on MMW transmission, the MMW generator should be carefully designed to generate high purity MMW signal, and as consequence, allow an improved data signal transmission using the generated MMW over the optical fiber link.

For this purpose, here we present all the required system parameters adopted in our proposed system from the CO to the RAU by considering the uplink direction.

A. Photonic MMW Generator Based on Quadrupling Technique

In the CO, a centralized Continuous Wave (CW) laser source operates at a wavelength of 193.1 THz (1552.5 nm) is injected into two identical Dual-Drive Mach-Zehnder Modulators (DD-MZMs) connected in parallel format via a power splitter. Each DD-MZM is biased at the minimum transmission bias point and driven by a 9.5 GHz RF LO source with 90 degree phase shifted frequency introduced between the RF-driving signals applied to each MZM drive electrode. An electrical phase shifter with 180 degree phase shift is applied at output of the lower DD-MZM, and this will cause the polarities of the odd order sidebands at the output of the lower DD-MZM to be in opposition (out of phase) with the generated odd order ones at the output of the upper DD-MZM.

Therefore, an optical coupler is used to couple the outputs of the upper and lower DD-MZMs. In this point, the odd-order sidebands generated by lower DD-MZM will cancel out the odd-order sidebands generated by upper DD-MZM due to destructive interference and only the second order sidebands are kept due to their in-phase nature. An ER of 60 dB is adopted in order to attain only two desired second order optical tones with high optical sideband suppression ratio (OSSR) as we will demonstrate in the next Section.

All the photonic MMW generator parameters used in the simulation setup are listed in Table I.

TABLE I
PARAMETERS SETUP OF THE PHOTONIC MMW GENERATOR BASED ON QUADRUPLING TECHNIQUE

Device	Parameter	Value
CW laser source	Optical frequency Optical launch power Linewidth	193.1 THz 0 dBm 10 MHz
RF LO driving signal	Radio frequency	9.5 GHz
DD-MZM	Bias voltage Switching bias voltage Switching RF voltage Extinction Ratio (ER) Insertion loss	0 4V 4V 60 dB 5 dB

B. Data Modulation

As our proposed system is full duplex based on wavelength reuse, a single tone data modulation is used to transport the baseband binary signal for downlink, whereas, the unmodulated tone is reserved to be used at the RAU as a carrier for uplink data transmission. To perform this process; three steps should be respected as follow keeping in account the points A, B, C, D, E and F depicted in Fig. 2.

1. Separation:

A 1×2 wavelength division demultiplexer is employed to separate the two desired second order sidebands generated from the DP-MZM (A) into two (B) and (C).

2. Data modulation:

One of the separated sidebands (upper in our case) is modulated with multi-Gbit/s baseband NRZ data signal (D) using an EAM (E), while the lower sideband is left blank (C).

3. Combination:

Finally, these two sidebands (modulated and the unmodulated tones) are combined using 2×1 wavelength division multiplexer (F).

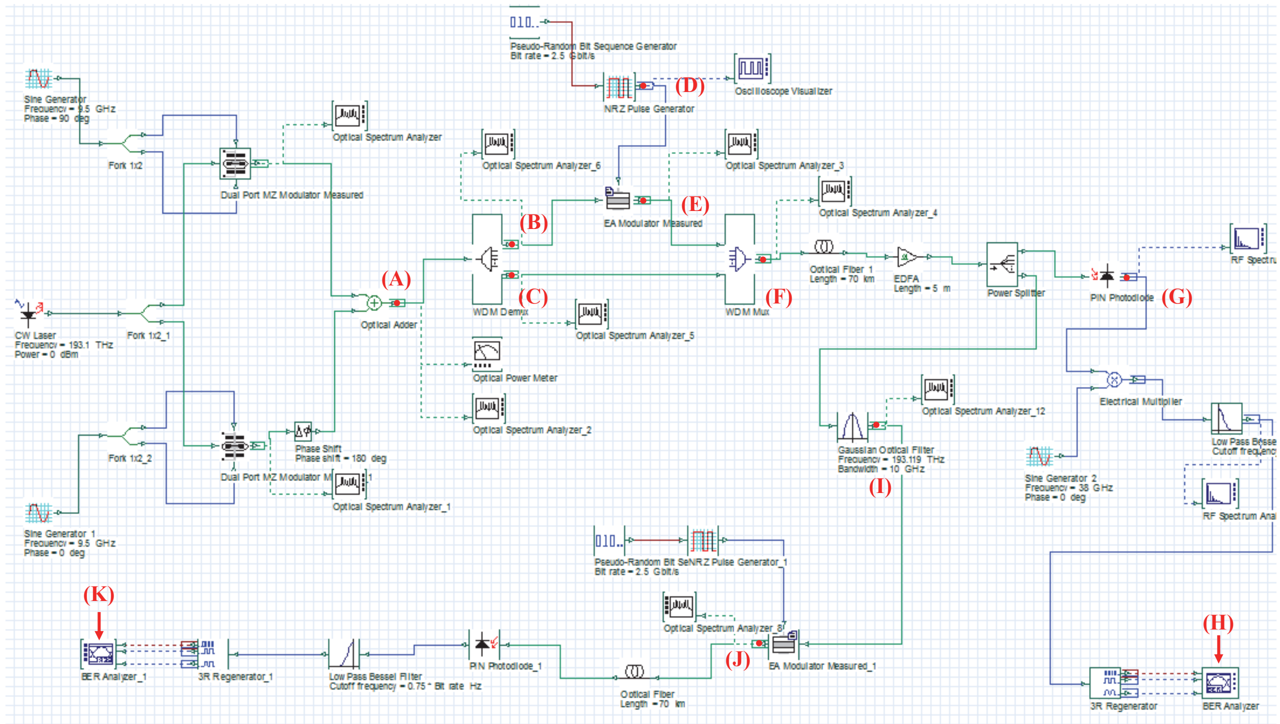


Fig. 2. The simulated full-duplex OCS MMW RoF system

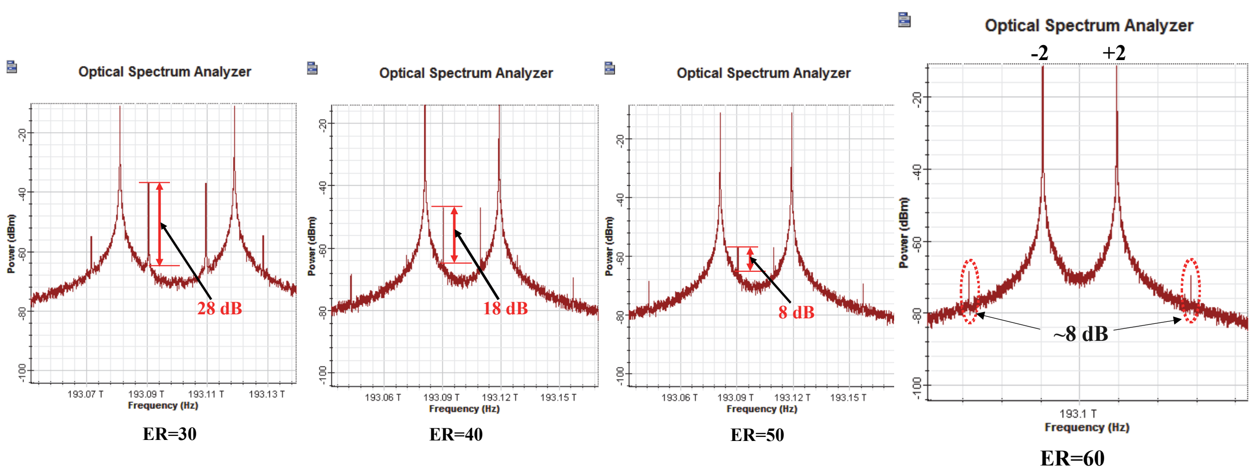


Fig. 3. The influence of the DD-MZMs extinction ratio (ER) on the generated OCS MMW

C. *Fiber Link*

The obtained optical MMW after wavelength multiplexing is injected into the optical fiber link to be transmitted to the corresponding RAU. Linear and non-linear effects were specified and activated in the fiber link channel in conformity with the common industry standards to simulate the real environment as much as possible. The single mode fiber (SMF) link parameters that simulate these practical values are summarized in the Table 2.

TABLE II
PARAMETERS SETUP OF THE USED OPTICAL FIBER FOR DOWN AND UP LINKS

Parameter	Value	Unit
Attenuation coefficient	0.2	dB/km
Chromatic dispersion	16.75	ps/(nm.km)
Dispersion slop	0.075	$ps/(nm^2 \times km)$
PMD coefficient	0.05	$ps/km^{\frac{1}{2}}$
Non-linear index	26×10^{-21}	m^2/w

After the fiber link transmission, an EDFA is used to boost the signal power of the downlink optical quadrupled MMW signal due to the different optical power losses that occurred during the optical MMW generation, modulation and data transmission.

D. RAU

At the receiver side, a square law photodetector (PD) with 1 A/W responsivity and 10 nA dark current is utilized to detect the modulated optical signal. After that, the baseband signal is coherently demodulated from the obtained electrical MMW using 38 GHz RF LO and an electrical mixer. Then, the demodulated data is low pass filtered with a cut-off frequency of 0.75 times the bitrate and sent to a BER tester for analysis.

E. Uplink Transmission Based on Wavelength Reuse

For wavelength reuse, in the simulation design we assume the received MMW wireless uplink signal is already down-converted to baseband, and it is ready to intensity modulate the EAM to be transmitted to the CO as illustrated in Fig. 2. In this regard, we have not added an optical amplifier after the data modulation using EAM, and this adopted intentionally to track the effectiveness of the used unmodulated tone as a carrier for uplink stream. Furthermore, in order to investigate the robustness of the abstracted unmodulated tone in an independent manner, we have used separate fiber links for downlink and uplink, which also means no optical circulators are used in both sides at the CO and RAU.

IV. Simulation Results and Discussion

A. Quality of the Generated 38 GHz MMW at the CO

In this subsection, optical spectrums of the generated optical MMW before data modulation measured at point A of the Fig 2 are depicted and evaluated in order to show the influence of extinction ratio (ER) of the DD-MZMs in terms of the unwanted sidebands and then on the optical sideband suppression ratio (OSSR) using the optimum ER.

The variation in optical spectrums of the generated sidebands power versus the DD-MZMs ER is shown in Fig. 3 when the ER is varied to 30, 40, 50 and 60, respectively.

The analysis is mainly focused on the disparity in power between the two desired second ±2 order sidebands and the unwanted ones. According to the obtained results showed in Fig.3, when the ER is increased from 30 dB to 50 dB, the optical power of the unwanted sidebands located in-between the two desired ones (±2 order sidebands) is reduced sharply by 20 dB (28 dB to 8 dB) in harmony with the added ER value (10 dB), and they are highly suppressed at an ER of 60 dB which results in a high-quality optical MMW signal.

As we have shown in Fig. 3, although the ER is controlled over different values; at on the sides of the generated optical MMW, two unwanted optical harmonics remains constant have small magnitudes (~8 dB), and this mainly is due to the non-ideality of the photonic MMW generator.

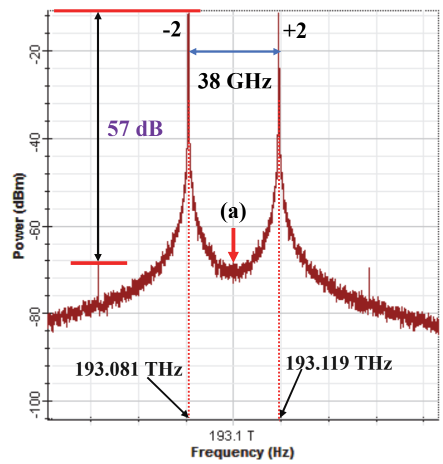


Fig. 4. The generated optical MMW at 38 GHz

Furtherly, we have analyzed the target optical MMW based on another dimension known as optical sideband suppression ratio (OSSR), and this is conducted by measuring the optical power difference between the desired second order tones over the unsuppressed on the side harmonics. Hence, for better performance, the OSSR must be kept high much as much possible. In the simulation design, the ER is set to 60 dB as an optimum to enable our DP-MZM MMW generator to ensure the higher OSSR. The optical spectrum of the generated MMW is exhibited in Fig. 4 indicating a relatively high OSSR of 57 dB.

It can be seen clearly that the proposed scheme can generate an optical MMW consisted of two pure, strong and coherent optical tones centred at 193.081 THz and 193.119 THz have equal amplitude with a frequency spacing of 38 GHz, which is precisely four-fold the input drive RF LO frequency (optical multiplication by factor of 4). More importantly, it is worth mentioning here that the optical carrier (193.1 THz) is completely suppressed to a great extent as shown in Fig. 4(a) which means we did not need any optical filter accompanied with the DP-MZM modulator to generate the desired optical MMW. In addition to that, the selected ER value is feasible from a practical point of view, and the obtained optical MMW will not suffer from power fading induced by fiber dispersion due to its stability and purity [15].

B. Downlink Single Tone and Uplink Baseband Data Modulations

In the OCS modulation scheme, the data signals which are carried by optical MMW with two order sidebands will suffer from the time shifting of the codes due to the different group velocities caused by fiber chromatic dispersion [11]. In order to deal with this effect, one optical tone of the obtained MMW is used in our scheme to carry the baseband data, and this has a great benefit in the point of view that the unmodulated one will be transmitted blank to use it as an uplink carrier at the RAU. Therefore, the proposed single tone optical MMW modulation can resist both the fading and bit walk-off effects caused by the fiber dispersion [26], and at the same time; a colorless RAU is guaranteed.

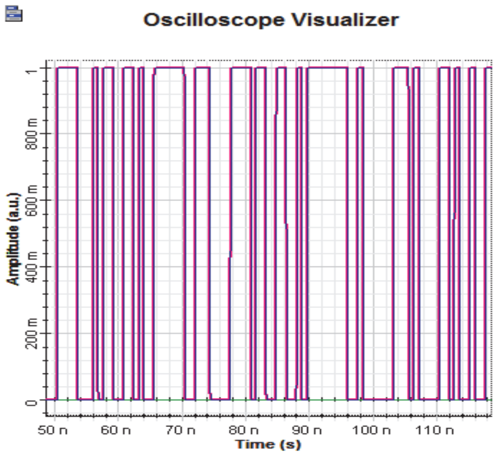


Fig. 5. The transmitted electrical NRZ signal at (D)

The user binary data generated by a $2^{11}-1$ pseudorandom bit sequence (PRBS) generator is coded to an electrical NRZ signal using a NRZ pulse pattern generator before the optical modulation, and its electrical format generated at the point (D) in Fig. 2 is depicted in Fig. 5.

The spectrum analyzer results of the generated signals at the output of points B, C, E, F, I and G in the system configuration of Fig. 2 are shown in Fig. 6.

The electrically encoded binary data (D) is intensity modulated onto the right optical tone centered at 193.119 THz (C) of the photonic generated 38 GHz MMW by an EAM, and hence, the modulated optical spectrum version by the user data is shown in Fig. 6(E). At the output of the WDM MUX (F) in Fig. 2, the modulated optical sideband is broadened by baseband data signal as compared with the spectrum of no modulated sideband (B) as Fig. 6(F) indicate. Then, the modulated and unmodulated optical signals are injected to different SMF distances. For uplink data provision, the baseband signal is modulated onto the abstracted unmodulated optical sideband at 193.081 THz via another EAM integrated at the RAU as shown in Fig. 7(I) and (G), respectively.

C. Data Transmission and System Performance Analysis

At the RAU, after the power splitter, by beating the two second order sidebands at high-speed positive-intrinsic-negative photodetector (PIN-PD), a RF frequency of 38 GHz is generated. Fig. 7 shown the obtained RF photocurrent signal after the PD (point G in Fig. 2) in high quality has low noise (~ −92 dBm) includes the baseband signal onto the electrical RF MMW signal at 4 times (38 GHz) of the used input RF LO frequency signal at the CO (9.5 GHz).

In order to analyze the proposed system performance for the single tone MMW data modulation in downstream and baseband data modulation onto the unmodulated tone for upstream, the signals are distributed over fiber links using different data rates of 1.25 Gbps or 2.5 Gbps. The received signals in both directions were assessed for different transmission distances up to 100 km by monitoring the eye diagrams quality using eye diagram analyzers as shown in the simulative configuration at points (H) and (K) in Fig. 2 where also the Q factor and its equivalent BER can be measured statistically.

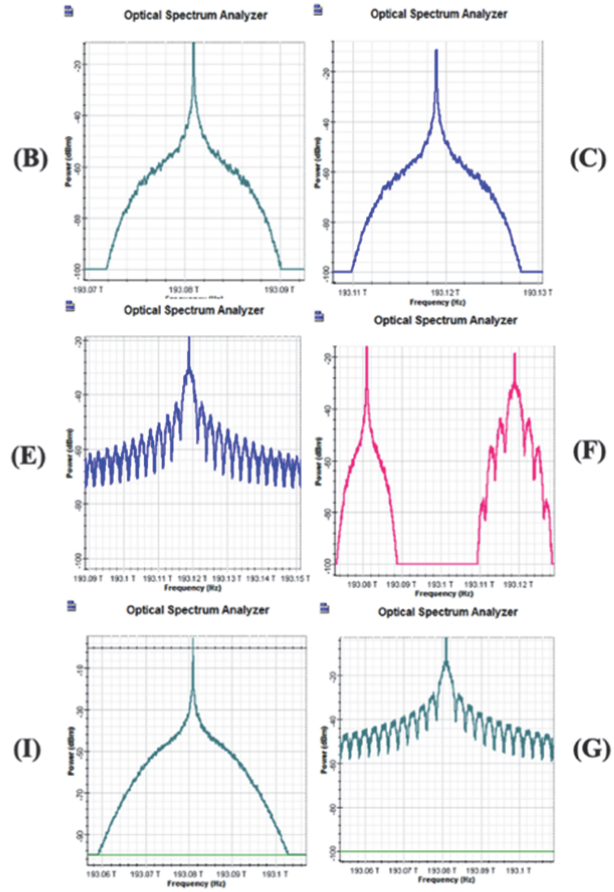


Fig. 6. The optical spectrum analyzer results at the corresponding points B, C, E, F, I and G in Fig. 2

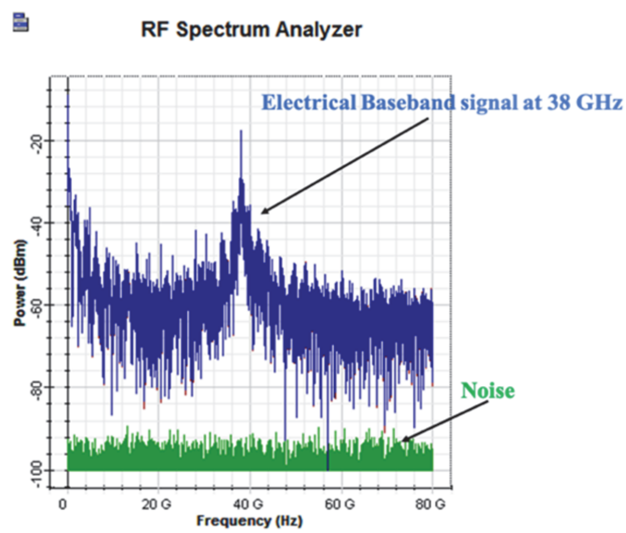


Fig. 7. The MMW generated RF signal at 38 GHz

Noteworthy, in this work; we have used Q factor and BER interchangeably; the former is used to quantify the quality of the transmitted signals and the latter to identify precisely the reliability of the proposed RoF system in terms of error free transmission (BER $<10^{-9}$) along to the covered link distance.

The Q factor curves of the baseband signal that coherently demodulated from the 38 GHz electrical MMW for different data rates as a function of distances up to 100 km are measured as illustrated in Fig. 8.

For downlink transmission as shown in Fig. 8, although the 2.5 Gbps is the double of the 1.25 Gbps, the measured Q factor is slightly different over the transmitted distances which prove the robustness of the single tone data modulation that would not suffer severely from the walk-off effect caused by fiber dispersion [26].

On another hand, the Q factor curves of the baseband signal that directly detected in uplink for different data rates along different fiber lengths up to 100 km are measured as illustrated in Fig. 9.

Concerning uplink baseband data transmission; approximately a similar behavior as that occurred in the downlink case of both data rates which indicates the effectiveness of the unmodulated optical tone to convey a broadband baseband signal for the uplink.

For both directions, the Q factors that are obtained for 1.25 Gbps is slightly higher than 2.5 Gbps bit rate, and this is due to the high data rate is less capable to overcome the effect of attenuation and chromatic dispersion. As a consequence, both graphs indicate that the Q factor degraded obviously when the traveled distance is increased.

The uplink baseband signal performance outperforms the downlink for both simulated data rates, and this could be contributed to the uplink signal has a baseband nature (known as baseband over fiber) that can deal effectively with chromatic dispersion [30], moreover, since there is only single peak carried the data which means the fiber dispersion has small effect, in contrast to the downlink case.

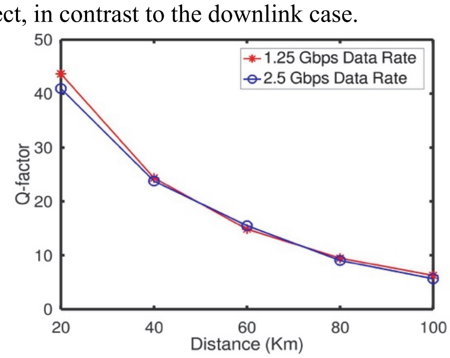


Fig. 8. Measured Q factors of the coherent demodulated signal for different data rates in downlink up to 100 km fiber link distance

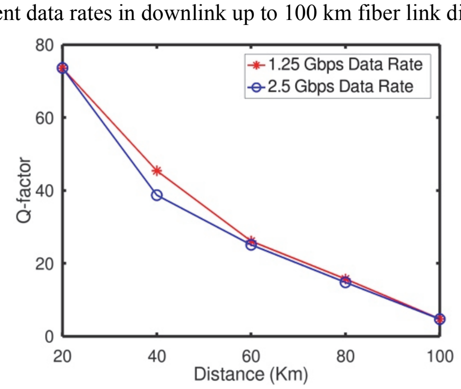


Fig. 9. Measured Q factors of the direct detected signal for different data rates in uplink up to 100 km fiber link distance

According to the Figs. 8 and 9, it is worth to mention here, for both data rates; the transmission performance of downstream optical MMW is found superior than the baseband uplink signal at 100 km, and this mainly could attribute to the high loss due to the round-trip path transmitted by the unmodulated optical carrier in downlink and non-amplified baseband modulated in upstream as the system simulation in Fig. 2 shown, but in practical systems; it is recommended to use an optical amplifier as we explained in Section 2 according to Fig. 1.

Figs. 10 and 11 show the obtained eye diagrams from the demodulated downlink and uplink signals after transmission over different fiber lengths up to 100 km at a data rate of 2.5 Gbps.

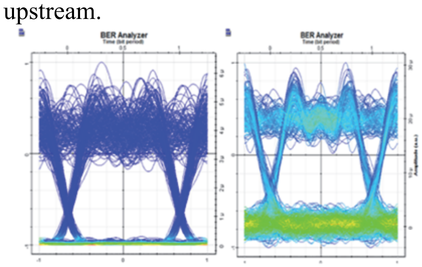
From these eye diagrams, we have noticed that the increase in the fiber length is inversely proportional to the eyes opening. But generally, the eye diagrams have preserved good outlines, still remain open although the data signals were reached a distance of 80 km realizing error free transmission ($BER<10^{-9}$), and this is greatly improved compared to other schemes that are based on OCS frequency up-conversion [8], or OCS dual-tone data modulation based on OFM [22] which are limited to only 40 and 60 km, respectively, and without wavelength reuse.

Both MMW signal (downlink) and baseband signal (uplink) are exceeded their maximum limited BER to offer an error free transmission above the 80 km distance. In this context, at a distance of 100 km as observed in Figs. 10 and 11; the eye patterns become closed and thereby the performance is unacceptable, and BERs of $4.38\text{x}10^{-9}$ and $1.19\text{x}10^{-6}$ are achieved for downlink and uplink data transmission, respectively.

In order to extend the transmission distance up to 100 km if needed in a certain scenario to obtain an error free transmission avoiding the use of forward error correction (FEC), we have increased the optical power of the centralized laser source to 2 dBm to show the link (downlink/uplink) performance in terms of BERs and eye diagrams by keeping the highest data rate of 2.5 Gbps.

The eye diagrams of the coherently demodulated downlink signal and the direct detected baseband uplink signal are observed in the Fig. 12(a)–(b), respectively. Both eye diagram patterns were improved if we have comparing them with the results obtained in Figs. 10 and 11 at 100 km.

For an optical power of 2 dBm, we have achieved an error free transmission ($BER<10^{-9}$) over 100 km SMF transmission, which is $3.93\text{x}10^{-13}$ for downstream and $6.29\text{x}\ 10^{-12}$ for upstream.



(*a*) (*b*)

Fig. 12. Eye diagrams of the received signals at 100 km using an optical laser power of 2 dBm: (a) downlink and (b) uplink

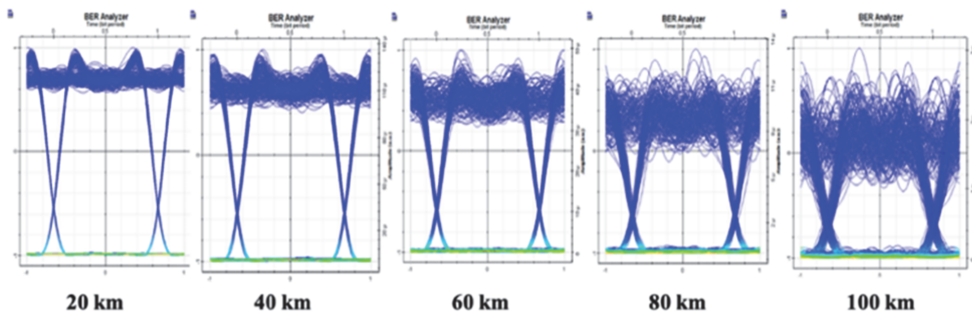


Fig. 10. The eye diagrams of the 2.5 Gbit⁄s downlink MMW signal coherently demodulated at different fiber distances

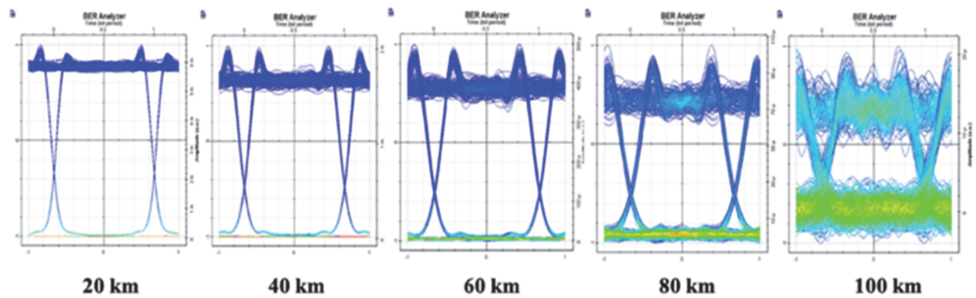


Fig. 11. The eye diagrams of the 2.5 Gbit⁄s uplink direct detected signal at different fiber distances

V. Conclusion

In this study, we have proposed and demonstrated a simple, cost-effective and reliable full-duplex OCS RoF system with focus on a photonic generation method of MMW enabled by one DP-MZM modulator without filtering to realize ubiquitous 5G indoor wireless access. This procedure is elaborated based on the optical generation of a 38 GHz MMW by multiplying the frequency of an input RF signal at 9.5 GHz by a factor of 4, known as quadrupling technique.

To reduce the overall system cost and its complexity to make it practical, a wavelength reuse approach is adopted by placing an OBPF at the RAU in order to extract unmodulated optical tone from the downlink OCS MMW signal to be used as a carrier to bear the upstream signal. As a consequence, a single tone data modulation scheme is used to transmit the downlink user data.

An optimum ER of 60 dB of the DP-MZMs is selected to obtain a high-purity optical MMW with the elimination of the unwanted optical sidebands that could deteriorate the system performance, and thus, a high OSSR up to 57 dB was obtained.

The simulation results clearly prove the ability of the proposed system to deliver multi-gigabit services over long distances up to 100 km in both directions offering an error free transmission with a BER less than 10^{-9}.

We have measured the Q-factors and observed the eye diagram outlines for two data rates of 1.25 and 2.5 Gb⁄s, and the performance analysis revealed high-quality transmission up to 80 km which could be attributed to the effectiveness of the used single tone data modulation against the bit walk-off effect for downlink, and to the robustness of the pure unmodulated optical tone re-used for uplink. As a result, we could flexibly transmit different data rates from the CO according to the requirement of the end-users.

Results also show the effect of increasing the optical power on the measured BER that achieved an error-free transmission up to 100 km in a full-duplex operation at a 2.5 Gbps data rate when the input optical power of the photonic MMW generator is tuned to 2 dBm.

The proposed system ensures a practical solution to be considered as a compelling candidate for 5G eMMB applications to cope with the demands of multi-Gb⁄s data transmissions in indoor wireless access networks.

Enabling multi-level modulation formats is one of the among our future work to be integrated in this RoF system due to its notable advantages in improving the spectral efficiency and the system capacity owing to its capability to encode multiple bits per symbol, and from another perspective, it is expected to further extend the transmission distance due to its ability to mitigate impairments such as chromatic dispersion and fiber nonlinearities.

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