Optical Generation of 60 GHz Downstream Data in Radio over Fiber Systems Based on Two Parallel Dual-Drive MZMs

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Abstract—This work proposes an easy-implement quadruple-frequency optical carrier suppression millimeter-wave (OCS-MMW) generation scheme for the generation and transmission of a 2.5 Gbps downlink data stream in a Radio over Fiber (RoF) system, based two commercially Dual-Drive Mach–Zehnder Modulator (DD-MZM). Theoretical analysis for back-to-back (B-T-B) transmission and optical fiber transmission is conducted. Simulation experiments are implemented and verified by our theoretical analysis and good agreement is achieved. Simulation results show that a 60 GHz MMW signal can be generated from a 15 GHz radio frequency (RF) oscillator with an optical sideband suppression ratio (OSSR) up to 39 dB and an radio frequency spurious suppression ratio (RFSSRR) exceeding 35dB when the extinction ratios (ERs) of the two parallel DD-MZM is 30dB. The transmission performance of the generated OCS MMW signal is investigated by referring to the eye pattern and bit-error-rate (BER) curve. The eye pattern is clearly opened even when the optical MMW signal is transmitted over 50km.

Keyword- Frequency-quadrupling, Optical Carrier Suppression Millimeter-Wave (OCS-MMW), Mach–Zehnder modulator (MZM)

I. Introduction

ROF is a technique by which light is modulated by a RF signal and transmitted over an optical fiber link making it simple to access to wireless networks, such as WiMAX and Wi-Fi [1]. The well known benefits of ROF such as immunity to electromagnetic interference, low propagation loss, low cost, and large bandwidth make it a promising technology for 4G mobile communication systems. In a RoF system, to facilitate the realization and minimize the cost, the optical generation of MMW signals are one of the important techniques that require nonstop development towards high-frequency ranges, mainly for the frequency further than 40 GHz and many techniques have been reported recently [2]-[8]. Amongst these modulation techniques, the optical MMW generation using an external modulator based on OCS modulation is preferred because it can produce low spectral occupancy, low bandwidth demand for RF signals, and high receiver sensitivity [9].

Several different approaches have been recently proposed to generate MMW signal. By employing two cascaded MZMs, Saw achieve the theoretical investigation for the generation of 60 GHz MMW signal [5]. To eliminate the optical carrier, a bragg grating filter (BGF) is required to be utilized which leads to large performance degradation. In [6], a novel approach to generate OCS MMW signal using a DD-MZM is proposed. However, the repetitive frequency of the optical MMW is only twofold the drive frequency. Thus, expensive electrical devices are required to generate the 60 GHz OCS MMW signal.

In this paper, we present a simple scheme to generate an OCS MMW signal by using two parallel DD-MZMs. Two parallel DD-MZMs (MZ-up and MZ-down) are biased at the minimum transmission bias point (MITBP) with 90° phase shift introduced between the RF driving signals applied to each MZM drive electrode. An electrical phase shifter with 180° phase shift is placed between the RF driving signals applied to MZ-up and MZ-down. At the output of the modulator, two strong second-order optical harmonics related to the optical carrier are generated with a frequency spacing of four times of the driving RF to the DD-MZMs

Section II explains the proposed frequency-quadrupling scheme based on two parallel DD-MZMs. In Section III, theoretical analysis of the proposed frequency-quadrupling scheme is presented. Section IV details the numerical simulation results. Finally, a brief summary is given in Section V.

II. Proposed Frequency-Quadrupling Scheme Based On Two parallel DD-MZMs

The proposed frequency-quadrupling scheme for 60GHz OCS MMW signal generation is shown in Fig.1a. From the left side to right side, a continuous wave (CW) generated from a distributed-feedback laser-diode (DFB-LD) is equally split into two branches, namely, I and II, by a 3-dB optical splitter. Then, the optical carriers in the two branches are coupled into two DD-MZMs. The DD-MZM along Branch I is identified as MZ-up while the one associated with Branch II is named by MZ-down. Four inputs are connected to each DD-MZM. Thus, parallel DD-MZMs have eight inputs called RF_1, RF_2, V_{DC1}, and V_{DC2} for MZ-up and RF_3, RF_4, V_{DC3}, and V_{DC4} for MZ-down. RF_1 and RF_2 represents the input RF driving signals applied to each MZ-up drive electrode with 90° phase difference. RF_3 and RF_4 represents the input RF driving signals applied to each MZ-down drive electrode with 90° phase difference. V_{DC1} and V_{DC2} represents the DC bias voltages applied to MZ-up bias electrodes. V_{DC3} and V_{DC4} represents the DC bias voltages applied to MZ-down bias electrodes. A 180° phase shift is introduced between the RF driving signals applied to MZ-up and MZ-down. MZ-up and MZ-down are biased at the MITBP, i.e., the DC bias voltage consisting of V_{DC2} and V_{DC4} is set to V_π. The other DC bias voltage consisting of V_{DC1} and V_{DC3} is set to 0 V. A 90° phase shift is introduced between the RF driving signals applied to the MZ-up and MZ-down drive electrodes. Thus, the RF driving signals applied to the four RF electrodes of the two DD-MZMs are $V_{RF}\cos(w_{RF}t+\pi/2)$, $V_{RF}\cos(w_{RF}t)$,$V_{RF}\cos(w_{RF}t+\pi/2)$, and $V_{RF}\cos(w_{RF}\,t)$. The output of MZ-up contains all nth order optical sidebands, except for n=4k, where k is an integer, as shown by solid arrows in Fig. 1b. The optical carrier, fourth-, and eighth-order optical sidebands are all suppressed, whereas the other optical sidebands are generated at the output of MZ-up. MZ-down is driven by the same RF signal with 180° phase shift. This condition will cause the polarities of the odd-order optical sidebands at the output of MZ-down to be in opposition to those at the output of MZ-up, as shown by dotted arrows in Fig. 1c, whereas the second-, sixth-, and tenth-order optical sidebands generated at the output of MZ-down are in same polarities with those at the output of MZ-up. At the output coupler, the odd-order optical sidebands generated by MZ-down will cancel out the odd-order optical sidebands generated by MZ-up (interfere destructively), whereas the optical sidebands of the order of second, sixth, and tenth at the outputs of two MZMs interfere constructively. Therefore, two strong second-order optical sidebands are generated at the output coupler in addition to two weak sixth-order optical sidebands, as depicted in Fig. 1d. By contrast, the tenth-order optical sidebands are generally ignored because of their very small value.

The principle of the proposed frequency-quadrupling technique based on a two parallel DD-MZM explained above is shown in Fig.2 in terms of the flow chart.

III.THEORETICAL ANALYSIS

The proposed 60 GHz MMW generation scheme based on two parallel DD-MZMs is shown schematically in Fig. 1a. The CW generated from a DFB-LD can be expressed as:

$$E_{in}(t) = E_o \exp\,(jw_o t) \tag{1}$$

The voltage of the RF-driven signal applied to MZ-up and MZ-down is:

$$V_{RF}(t) = V_{RF}\cos\,(w_{RF}\,t) \tag{2}$$

where E_0 and V_{RF} are the signal amplitudes and w_0 and w_{RF} are the angular frequency of the CW and the RF oscillator signal, respectively. MZ-up and MZ-down both biased at the MITBP. A phase shift 180^0 is introduced between the RF driving signals on MZ-up and MZ-down. If the ER of the two DD-MZMs is assumed to be infinite, i.e., ideal condition, the output field of the optical coupler (OC) can mathematically write as:

$$E_{out}(0,t) = E_I(0,t) + E_{II}(0,\mathrm{t}) \tag{3}$$

where E_I (0,t) is the optical field exported from MZ-up defined as:

$$\begin{aligned} E_I(0,t) &= \frac{E_o}{4} e^{jw_o t}\left[e^{j\frac{\pi}{V_\pi}V_{RF}\cos(w_{RF}\,t+\frac{\pi}{2})} + e^{j\frac{\pi}{V_\pi}V_{RF}\cos(w_{RF}\,t+\frac{\pi}{2})}.\,e^{j\frac{V_{DC2}}{V_\pi}.\pi}\right] \\ &= \frac{E_o}{4} e^{jw_o t}\left[e^{j\frac{\pi}{V_\pi}V_{RF}\cos(w_{RF}\,t+\frac{\pi}{2})} + e^{j\frac{\pi}{V_\pi}V_{RF}\cos(w_{RF}\,t+\frac{\pi}{2})}.\,e^{j\pi}\right] \\ &= \frac{E_o}{4} e^{jw_o t}\left[e^{j\frac{\pi}{V_\pi}V_{RF}\cos(w_{RF}\,t+\frac{\pi}{2})} - e^{j\frac{\pi}{V_\pi}V_{RF}\cos(w_{RF}\,t+\frac{\pi}{2})}\right] \end{aligned} \tag{4}$$

By applying the Jaccobi–Anger expansion to Eq. 4, E_I (0, t) becomes:

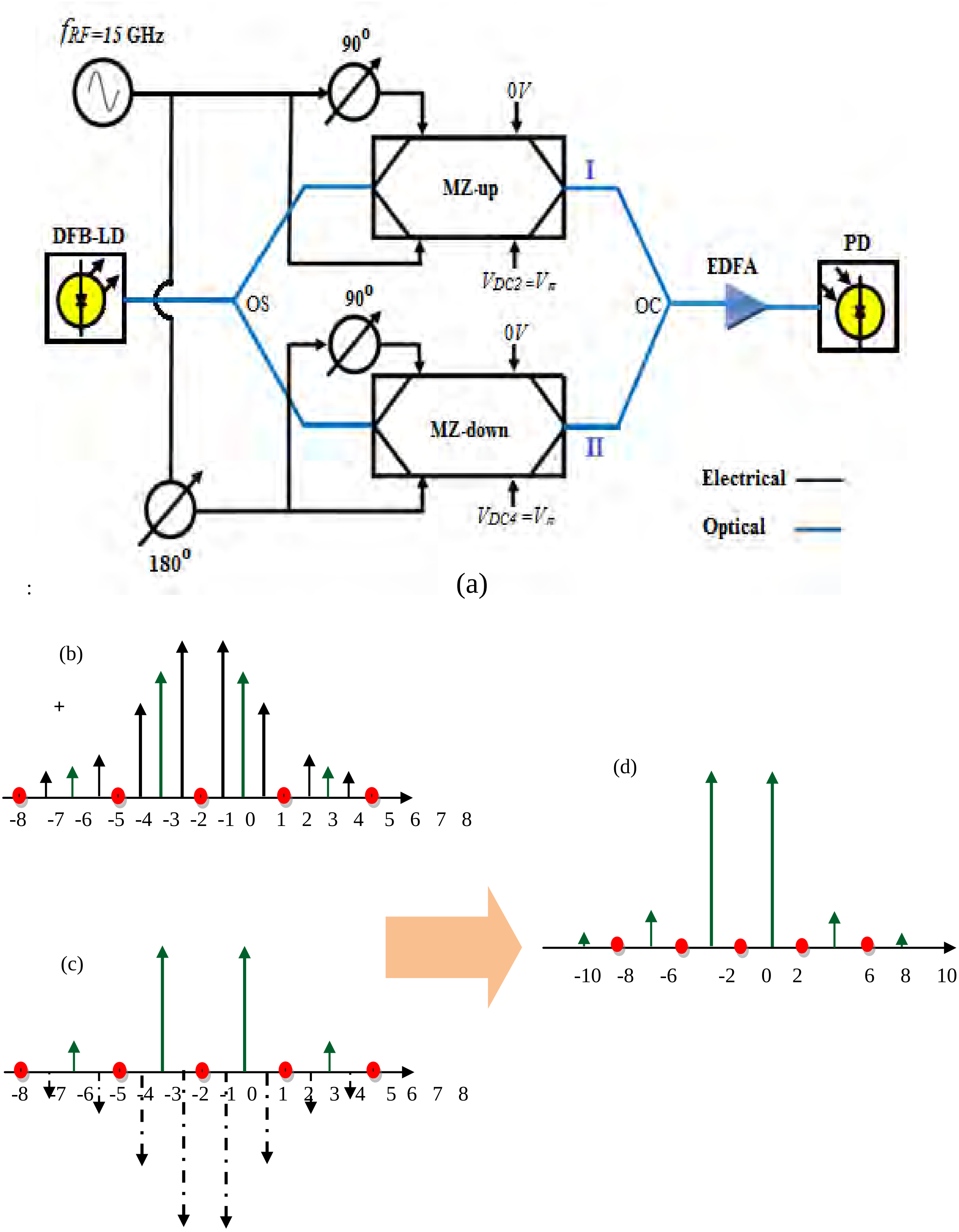

Fig. 1. Principle of the OCS MMW signal generation approach. (a) schematic diagram, (b) optical field exported from MZ-up, (c) optical field exported from MZ-down, (d) output field of the OC. (OS: optical splitter; OC: optical coupler; PD: photo diode; EDFA: erbium-doped fiber amplifier).

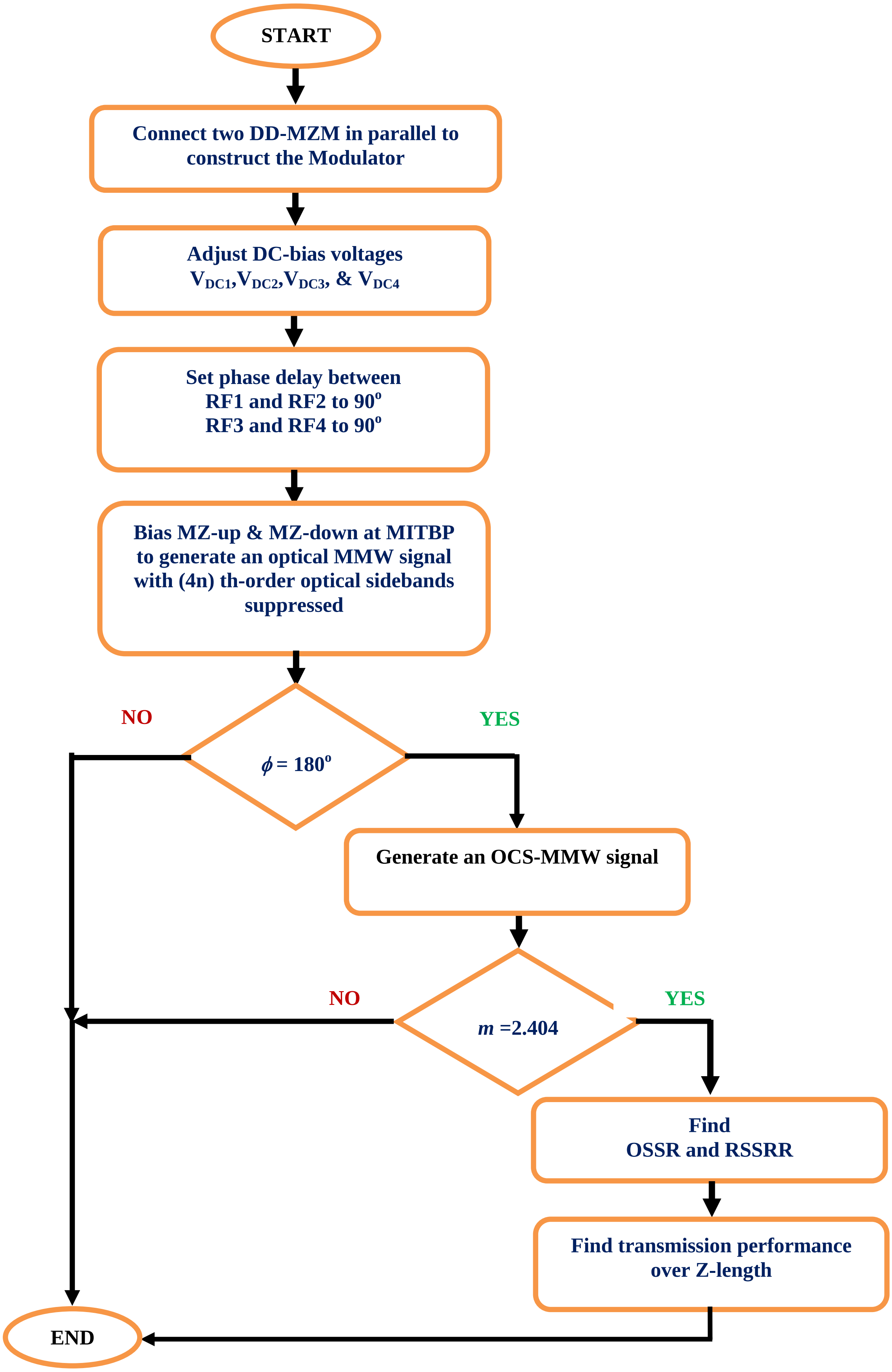

Fig. 2. Flow Chart of the proposed optical frequency-quadrupling technique.

$$E_I(0,t)=\frac{E_o}{4}e^{jw_ot}\left[\sum_{n=-\infty}^{\infty} j^n J_n(m)e^{jn(w_{RF}\,t+\frac{\pi}{2})}-\sum_{n=-\infty}^{\infty} j^n J_n(m)e^{jn(w_{RF}\,t)}\right]$$
$$=\frac{E_o}{4}e^{jw_ot}\left[\sum_{n=-\infty}^{\infty} J_n(m)\,e^{j(nw_{RF}\,t+n\pi)}-\sum_{n=-\infty}^{\infty} J_n(m)\,e^{j(nw_{RF}\,t+n\frac{\pi}{2})}\right]$$
$$=\frac{E_o}{4}e^{jw_ot}\left[\sum_{n=-\infty}^{\infty} J_n(m)\,e^{j\left(nw_{RF}\,t+\frac{3n\pi}{4}+\frac{n\pi}{4}\right)}-\sum_{n=-\infty}^{\infty} J_n(m)\,e^{j\left(nw_{RF}\,t+\frac{3n\pi}{4}-\frac{n\pi}{4}\right)}\right]$$
$$=\frac{E_o}{2}\left[\sum_{n=-\infty}^{\infty} J_n(m)\sin\left(\frac{n\pi}{4}\right).e^{j\left[(w_o+nw_{RF})t+\frac{3n\pi}{4}\right]}\right] \quad (5)$$

where V_π is the switching voltage of MZM, m is the RF modulation index defined as $m=V_{RF}.\pi/V_\pi$ and J_n is the n*th* order Bessel function of the first kind. Equation 5 indicates that the (4n) *th*-order optical sidebands are eliminated because of the term sin*(nπ/4)*. The optical field at the output of MZ-down can mathematically write as:

$$E_{II}(0,t)=\frac{E_o}{4}e^{jw_ot}\left[e^{j\frac{\pi}{V_\pi}V_{RF}\cos(w_{RF}\,t+\frac{\pi}{2}+\pi)}+e^{j\frac{\pi}{V_\pi}V_{RF}\cos(w_{RF}\,t+\pi)}.e^{j\frac{V_{DC4}}{V_\pi}.\pi}\right]$$
$$=\frac{E_o}{4}e^{jw_ot}\left[e^{j\frac{\pi}{V_\pi}V_{RF}\cos(w_{RF}\,t+\frac{3\pi}{2})}+e^{j\frac{\pi}{V_\pi}V_{RF}\cos(w_{RF}\,t+\pi)}.e^{j\pi}\right]$$
$$=\frac{E_o}{4}e^{jw_ot}\left[e^{jm\cos(w_{RF}\,t+\frac{3\pi}{2})}-e^{jm\cos(w_{RF}\,t+\pi)}\right]$$
$$=\frac{E_o}{4}e^{jw_ot}\left[\sum_{n=-\infty}^{\infty} j^n J_n(m)e^{jn(w_{RF}\,t+\frac{3\pi}{2})}-\sum_{n=-\infty}^{\infty} j^n J_n(m)e^{jn(w_{RF}\,t+\pi)}\right]$$
$$=\frac{E_o}{4}e^{jw_ot}\left[\sum_{n=-\infty}^{\infty} J_n(m)\,e^{j(nw_{RF}\,t+\frac{3n\pi}{2}+\frac{n\pi}{2})}-\sum_{n=-\infty}^{\infty} J_n(m)\,e^{j(nw_{RF}\,t+n\pi+n\frac{\pi}{2})}\right]$$
$$=\frac{E_o}{2}\left[\sum_{n=-\infty}^{\infty} J_n(m)\sin\left(\frac{n\pi}{4}\right).e^{j\left[(w_o+nw_{RF})t-\frac{n\pi}{4}\right]}\right] \quad (6)$$

Thus, the output field of the OC can be expressed as:

$$E_{out}(0,t)=E_I(0,t)+E_{II}(0,t)$$
$$=\frac{E_o}{2}\begin{bmatrix}\sum_{n=-\infty}^{n=\infty} J_n(m)\sin\left(\frac{n\pi}{4}\right).e^{j\left[(w_o+nw_{RF})t+\frac{3n\pi}{4}\right]}\\ +\sum_{n=-\infty}^{n=\infty} J_n(m)\sin\left(\frac{n\pi}{4}\right).e^{j\left[(w_o+nw_{RF})t-\frac{n\pi}{4}\right]}\end{bmatrix}$$
$$=E_o\left[\sum_{n=-\infty}^{\infty} J_n(m)\sin\left(\frac{n\pi}{4}\right).\cos\left(\frac{n\pi}{4}\right)e^{j\left[(w_o+nw_{RF})t+\frac{n\pi}{4}\right]}\right] \quad (7)$$

Equation 7 indicates that the nth-order sidebands are all eliminated, excluding n=4k-2, where k is an integer. Equation 7 also shows that the (4k-2) th-order sidebands interfere constructively and that the odd-order sidebands destructively interfere at the output of the OC. This is because the 180^o phase shift between the RF driving signals applied to the two MZMs which makes the polarities of the odd-order sidebands at the output of MZ-up to be in opposition to those at the output of MZ-down.

When generated optical MMW signals are transmitted over Z –length downlink fiber to the base station (BS), the two second-order sidebands will have various group velocities due to the fiber chromatic dispersion. The desired quadruple-frequency MMW signal is detected by using a PD, and the complex amplitude of its photodetected current can be written as:

$$I_{4w_{RF}}(Z,t)=\mu[E(Z,t)]^2=\mu[E(Z,t).E(Z,t)^*]$$
$$=E_o^{\,2}\,\alpha^2\,e^{-2\gamma Z}\,J_2^2(m)\mu\begin{bmatrix}\begin{pmatrix}e^{j[(w_o-2w_{RF})t-\beta(w_o-2w_{RF})Z]}.e^{-j\frac{\pi}{2}}\\ -e^{j[(w_o+2w_{RF})t-\beta(w_o+2w_{RF})Z]}.e^{+j\frac{\pi}{2}}\end{pmatrix}\\ .\begin{pmatrix}e^{-j[(w_o2w_{RF})t-\beta(w_o-2w_{RF})Z]}.e^{j\frac{\pi}{2}}\\ -e^{-j[(w_o+2w_{RF})t-\beta(w_o+2w_{RF})Z]}.e^{-j\frac{\pi}{2}}\end{pmatrix}\end{bmatrix}$$

$$I_{4w_{RF}}(Z,t)=2E_o^{\,2}\,\alpha^2\,e^{-2\gamma Z}\,J_2^2(m)\mu\,\{1+cos[4w_{RF}(t-\beta'(w_o)Z)]\} \quad (8)$$

.where γ is the fiber loss, *β*(w) is the propagation constant of the fiber and vg denotes the group velocity. Equation 8 indicates that the amplitude of the current for the desired MMW signal at $4w_{RF}$ is independent of fiber dispersion.

IV. SIMULATION AND RESULTS

A RoF system is build through OptiSystem Version 9.0" simulation software package to validate the transmission performance of the generated optical MMW signal, as depicted in Fig.3. The identical parameters are used for the identical components in Fig. 1a. The simulation was carried out at a rate of 2.5 Gbps over 0 km (back to back) and 50 km transmission distance with the ITU-T G.652 standard single-mode fiber (SSMF). All the dispersion (i.e. D=16.7 ps/nm km), attenuation (i.e. α =0.23 dB/km), and non linear effect was specified and activated in accordance with the typical industry standards to simulate the real environment as close as possible. After the proposed quadruple frequency MMW generation scheme, two second-order sidebands are generated and maximized, and the frequency spacing between them is 60 GHz. The two second-order sidebands are then intensity modulated with a 2.5 Gbps baseband signal by another MZM (MZ-c) with an ER of 30 dB, as shown in Fig. 3 inset (i). At the base station (BS), a PD detects the quadruple frequency optical MMW, and an electrical 1st-order Gaussian band pass filter centered at 60 GHz filters out the RF harmonics. To demodulate the 2.5 Gbps signal from the generated 60 GHz MMW signal, a 60 GHz RF oscillator, a mixer, and an electrical low pass filter with a bandwidth of 2.8 GHz are utilized. The performance of the RoF system was described by referring to the eye pattern and BER curve.

Figure 4a shows the simulated optical spectrum of the 60 GHz OCS MMW signal for transmission distance 0 km (B-T-B) when the ER of two the DD-MZMs is infinite. It is clearly composed of two strong second-order sidebands with spacing of 60 GHz in addition to two weak sixth-order sidebands with spacing of 180 GHz. The zeroth-, fourth-, and eighth-order sidebands are suppressed well. The OSSR is 42 dB and the second-order sideband power is greater than the sixth-order sideband power. Figure 4b shows the simulated optical spectrum of the 60 GHz OCS MMW signal when the ER of two the DD-MZMs is 30 dB. It is clearly that the power of the second-order optical sideband is maximum, and the OSSR is 39 dB.

The simulated electrical spectrum when the ER of two the DD-MZMs is 30 dB is consists of the required 60 GHz and spurious 120 GHz MMW signals, as shown in Fig. 5. The RFSSRR (the power ratio of the desired 60 GHz MMW signal to the spurious 120 GHz MMW signal) is 35.1 dB. The power of 60 GHz MMW signal is 39 dB and it is clearly greater than that of the 120 GHz MMW signal.

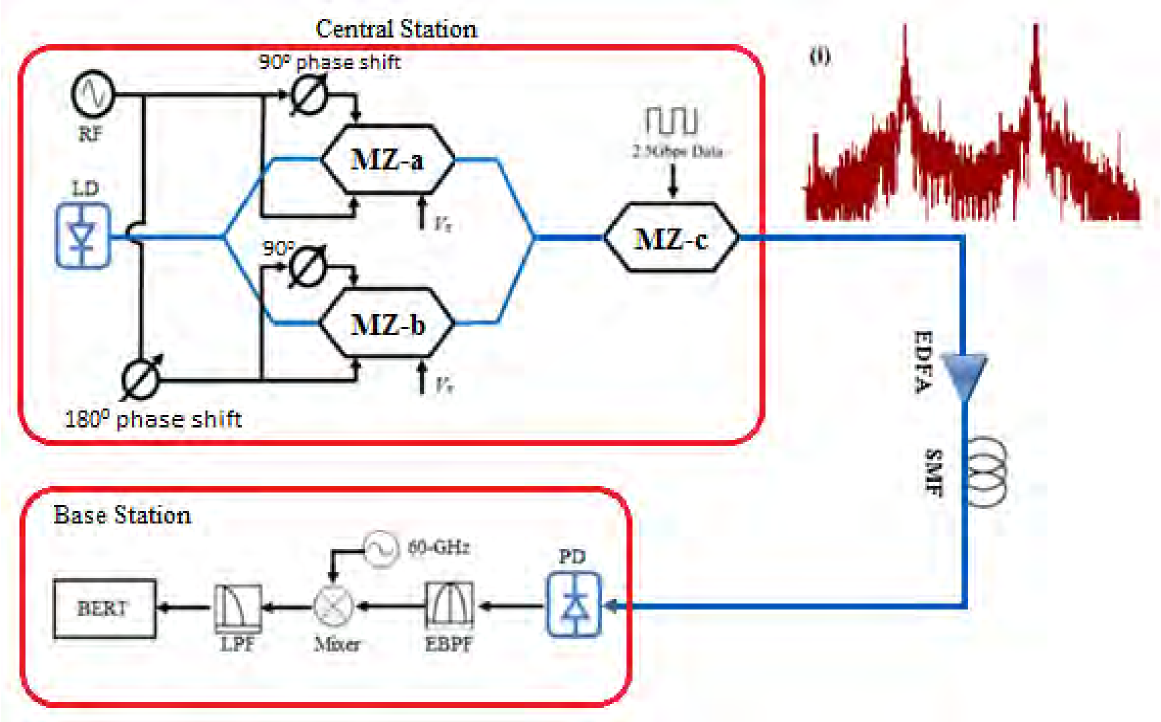

Fig. 3. RoF system based on the proposed quadrupling-frequency optical MMW generation scheme. (SMF: single-mode fiber; BPF, band pass filter; LPF, low pass filter; BERT: bit error rate tester).

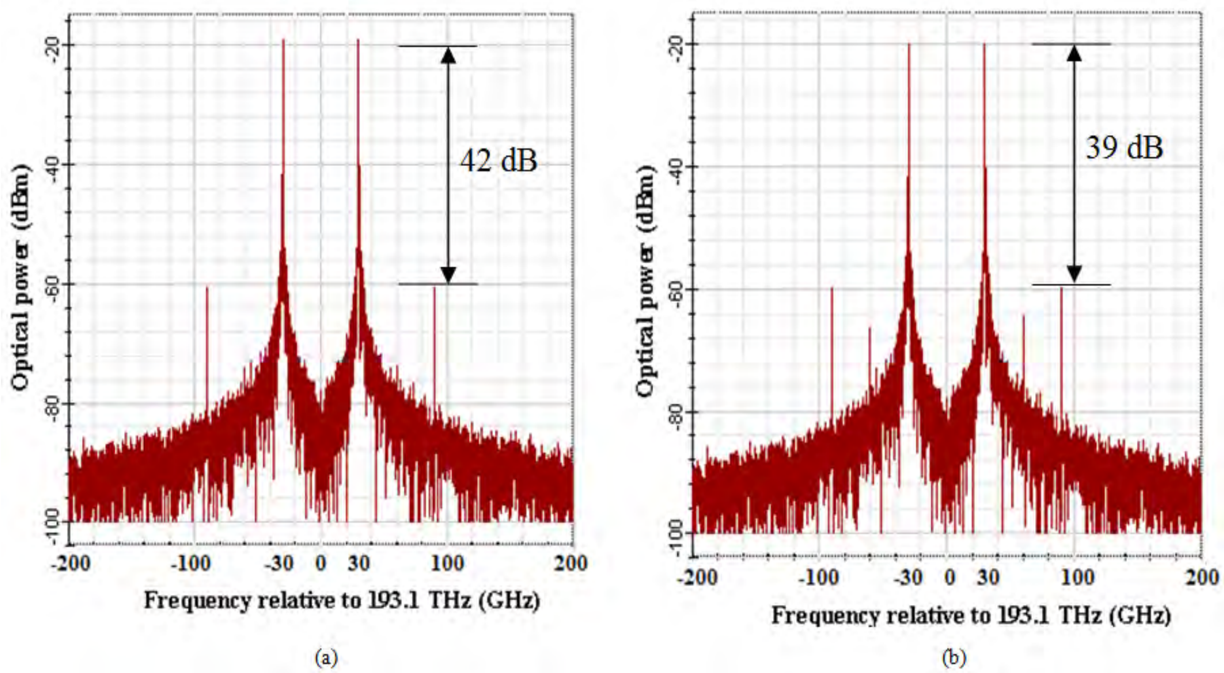

Fig. 4. Simulated optical spectrum of the 60 GHz OCS MMW signal when the ER: (a) infinite and (b) 30 dB.

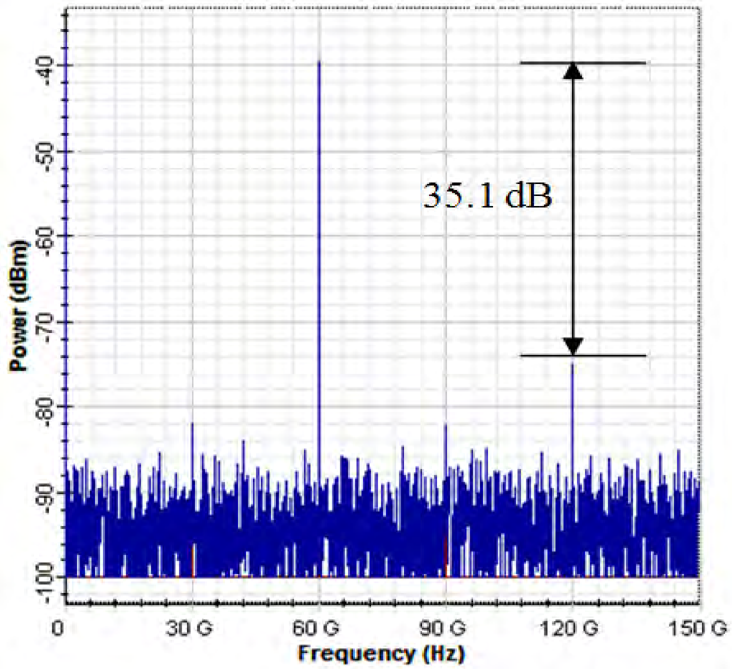

Fig. 5. Simulated electrical spectrum of the 60 GHz MMW signal when the ER is 30 dB.

Figure 6 shows the down-converted 2.5 Gbps electrical eye pattern of the 60 GHz MMW after transmission over 50 km fiber length. It can be seen that the eye patterns still clear and keeps open even when the optical MMW signals are transmitted over 50 km transmission and the outline of the eye patterns changes slightly. Thus, the performance of the generated MMW signal is acceptable.

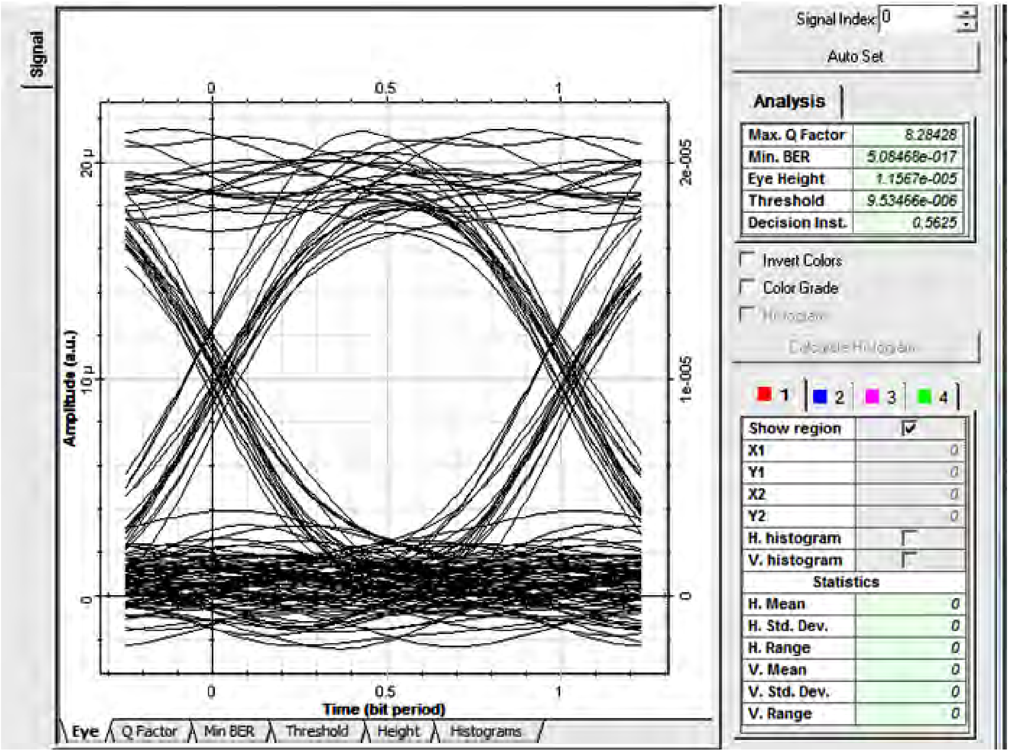

Fig. 6. Simulated eye pattern of the baseband signals using the proposed quadrupling-frequency scheme at the transmission distance of 50 km.

Figure 7 shows the BER curve of the down-converted 2.5 Gbps signal demodulated from the 60 GHZ MMW with different transmission distances. It clearly shows that the BER increases as the fiber length increases. When the effective light power Pr=0 dBm and the transmission distance is 60 km, the calculated BER is approximately 10^{-12}. When the effective light power is decreased to -5 dBm at 60 km transmission distance the system shows high bit error rate value (BER $\geq 10^{-2}$). The longer fiber length will present a larger dispersion and attenuation, as well as increasing the BER.

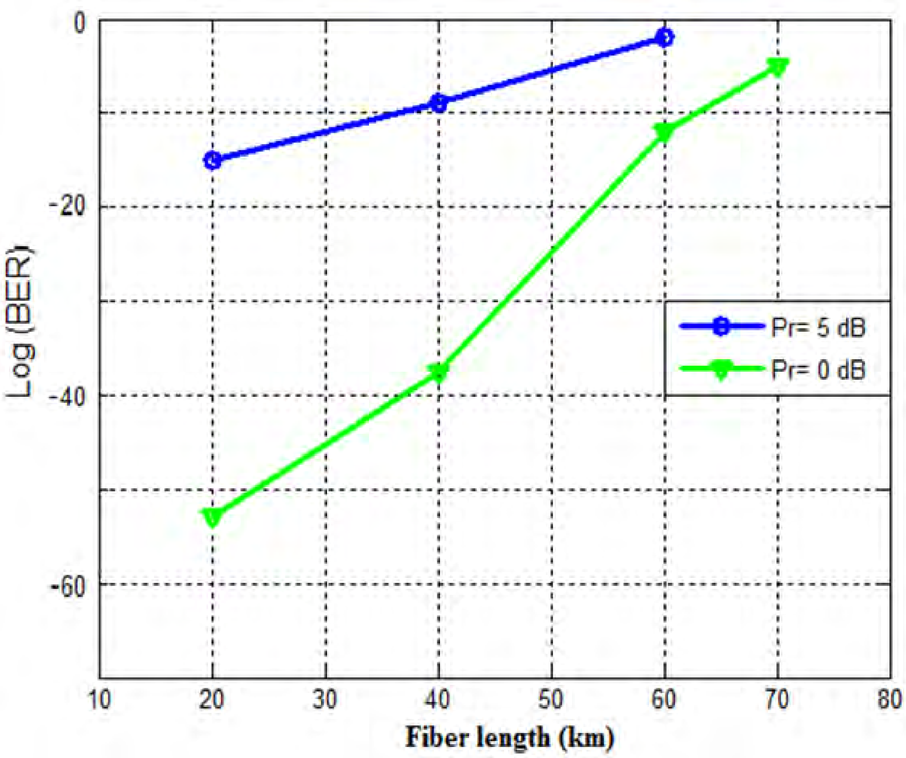

Fig. 7. BER versus fiber length with different transmission distances

V. CONCLUSION

In this paper, we have proposed an easy-implement scheme for the generation and transmission of a.2.5 Gbps downlink stream in a RoF system operating at 60 GHz, via two commercial parallel DD-MZMs , and investigated it is performance both theoretically and by simulation. The theoretical derived equations and simulation results are match well revealing that a 60 GHz MMW signal can be generated from a 15GHz RF oscillator with an OSSR as high as 39 dB and RFSSRR exceeds 35 dB without optical filter when the ER of the two DD-MZMs is 30 dB. This scheme minimizes the cost of the overall system which is vital for the commercial deployment of short range distribution in business buildings or home.

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