COMPARISON OF THREE DIFFERENT EOU TECHNIQUES FOR FIFTH−GENERATION MM−W WIRELESS NETWORKS

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Abstract - **Fifth−generation (5G) and millimeter−waves (MM−W) hold tremendous promise to provide opportunities to revolutionize education, healthcare, business, and agriculture. Nevertheless, the generation of MM−W in the electrical−domain is infeasible due to the bandwidth limitation of electronic components and radio frequency (RF) interference. The capability to generate MM−W in the optical−domain can provide transportation of MM−W with low loss from switching center to remote base stations. The present paper is focusing on electro−optical up−conversion (EOU) techniques for optical generation and transmission of 60−GHz MM−W signal. A comparative study is carried out between three different EOU techniques: frequency−quadrupling, frequency sextupling and frequency−octotupling. The comparative study aims at showing the strengths and weaknesses of three EOU techniques and evaluating each technique in terms of electrical spurious suppression ratio (ESSR), as well as in terms of the influence of non−ideal phase shifting. The performance of the three EOU techniques after transmission over optical fiber is evaluated by eye pattern test. The results of the simulation confirm that the frequency−quadrupling outperforms frequency− sextupling and frequency− octotupling techniques.**

Keywords - Millimeter−waves, 5G, EOU techniques, ESSR, OHD

I. INTRODUCTION

5G systems introduced unorthodox frequency bands known as the MM−W bands. The benefit that can be reaped from these bands is doubled. First, most of these bands appear to be unused and free, suggesting no interference from other technologies. Second, greater bandwidth provides higher data rates for all users, with more users connected in a small geographic area, i.e., the Internet of Things (IoT) [1].

However, MM−W electrical generation and transmission poses many challenges with respect to coverage area restrictions, signal attenuation, path loss and penetration, as well as scattering [2]. Besides, MM−W cannot easily move through buildings or obstacles and they can be absorbed by leaves and rain [3]. Hence optical MM−W generation and radio−over−fiber (R−O−F) transportation techniques were proposed. The optical MM−W generation techniques can be broken down into optical heterodyne detection (OHD) [4−7] and EOU techniques. Though these two MM−W generation techniques, EOU gained much attention due to its higher modulation bandwidth, stability, and flexibility.

In this paper, a comparative study is carried out on three EOU techniques, namely frequency−quadrupling, frequency−sextupling and frequency−octotupling to cost effectively generate 60−GHz MM−W signal. Comparison has been achieved between three selected EOU systems with different modulation indices. Obtained ESSR for each modulation index have compared to show the trade−off between techniques complexity and the cost−effective. Additionally, the effect of non−ideal phase shifting on ESSR has been investigated. From the numerical results, frequency−quadrupling outperforms other techniques since a stable 60−GHz MM−W signal can generate with less modulation index.

The remainder of this paper is organized as follows: Section 2 gives a brief description of the three EOU techniques. Section 3 details the simulation results and discussion. Subsequently, Section 4 gives conclusion and future work.

II. ELECTRO−OPTICAL UP-CONVERSION TECHNIQUES

EOU is a technique based optical frequency−multiplication wherein high−order optical harmonics are created by using a laser diode with an external modulator driven by a sinusoidal RF signal. By multiplying the upper and lower optical harmonics in PD, many of the MM−W signals can be generated. Compared with the OHD technique, EOU can generate a high−purity optical MM−W signals without the use of complex mechanisms for phase noise repression [8].

A. *Frequency−quadrupling Technique:*

A novel frequency−quadrupling technique that can generate a high−quality 60−GHz MM−W optical carrier suppression signal using two parallel MZMs was introduced by Al−Shareefi [9]. Two parallel MZMs <u>are</u> biased at the MITBP with a 90^{O} phase shift applied to the RF drive signals to the MZM. The optical MM−W signal can be written as [9]

$$E_{Mod.}(t) = 2E_o.J_2\left(2.404\right).\left\{\begin{matrix}\cos\left[\left(\omega_o-2\omega_E\right)t\right]\\ +\cos\left[\left(\omega_o+2\omega_E\right)t\right]\end{matrix}\right\} \qquad (1)$$

where ω_0, ω_E are the frequency of the optical signal and electrical driving signal and J_2 is the first kind Bessel function of the 2nd −order.

OHDSR is the power difference between the main optical carrier and the non−desired optical sidebands. To achieve high OHDSR, the 2nd −order optical sidebands must be maximal and the non−desired 6th −order optical sidebands are minimal. The equation of OHDSR can be derived using Equation (1):

$$E_{Mod.} = \begin{bmatrix} J_6 \left(e^{j\left[(\omega_0+6\omega_E)t+\frac{3\pi}{2}\right]} - e^{j\left[(\omega_0-6\omega_E)t-\frac{3\pi}{2}\right]} \right) \\ +J_2 \left(e^{j\left[(\omega_0-2\omega_E)t-\frac{\pi}{2}\right]} - e^{j\left[(\omega_0+2\omega_E)t+\frac{\pi}{2}\right]} \right) \end{bmatrix} \qquad (2)$$

There are only 2nd − and 6th −order harmonics. Using Equation (2), OHDSR is given by

$$OHDSR = 10 \log \left[\frac{\left| J_2 \left(e^{j\left[(\omega_0-2\omega_E)t-\frac{\pi}{2}\right]} - e^{j\left[(\omega_0+2\omega_E)t+\frac{\pi}{2}\right]} \right) \right|^2}{\left| J_6 \left(e^{j\left[(\omega_0+6\omega_E)t+\frac{3\pi}{2}\right]} - e^{j\left[(\omega_0-6\omega_E)t-\frac{3\pi}{2}\right]} \right) \right|^2} \right] \qquad (3)$$

Simplifying the above Equation

$$\Rightarrow \left| J_2 \left(e^{j[(\omega_0-2\omega_E)t-\frac{\pi}{2}]} - e^{j[(\omega_0+2\omega_E)t+\frac{\pi}{2}]} \right) \right|^2$$

$$= \begin{bmatrix} \left(J_2\, e^{-j\left[(\omega_0-2\omega_E)t\right]}\, e^{j\frac{\pi}{2}} - J_2\, e^{-j\left[(\omega_0+2\omega_E)t\right]}\, e^{-j\frac{\pi}{2}} \right). \\ \left(J_2\, e^{j\left[(\omega_0-2\omega_E)t\right]}\, e^{-j\frac{\pi}{2}} - J_2\, e^{j\left[(\omega_0+2\omega_E)t\right]}\, e^{j\frac{\pi}{2}} \right) \end{bmatrix}$$

$$= \begin{pmatrix} J_2^2 - J_2^2\, e^{j[(\omega_0+2\omega_E-\omega_0+2\omega_E)t]}\, e^{j\pi} + \\ J_2^2 - J_2^2\, e^{j[(\omega_0-2\omega_E-\omega_0-2\omega_E)t]}\, e^{-j\pi} \end{pmatrix}$$

$$= 2J_2^2.\left(\cos(4\omega_E t) + 1 \right) \qquad (4)$$

In the same way the **denominator** of Equation (3)

$$= 2J_6^2.\left(\cos(12\omega_E t) + 1 \right) \qquad (5)$$

$$\Rightarrow OHDSR = 10 \log \left[\frac{|\text{Eq. (4)}|}{|\text{Eq. (5)}|} \right] = 42 \text{ dB} \qquad (6)$$

ESSR is the power difference between the wanted electrical and unwanted MM−W signal. To achieve high ESSR, the wanted electrical MM−W signal must be maximal while the unwanted harmonics are minimal. The equation of ESSR can be derived using photo detected Equation:

$$I = \left| E_{Mod.} \right|^2 = \left[E_{Mod.}.E_{Mod.}^{\;*} \right] \qquad (7)$$

$$= \begin{bmatrix} \begin{pmatrix} J_6.e^{j[(\omega_0+6\omega_E)t]}.e^{j\frac{3\pi}{2}} - J_6.e^{j[(\omega_0-6\omega_E)t]}.e^{-j\frac{3\pi}{2}} \\ +J_2.e^{j[(\omega_0-2\omega_E)t]}.e^{-j\frac{\pi}{2}} - J_2.e^{j[(\omega_0+2\omega_E)t]}.e^{j\frac{\pi}{2}} \end{pmatrix} \\ \times \begin{pmatrix} J_6.e^{-j[(\omega_0+6\omega_E)t]}.e^{-j\frac{3\pi}{2}} - J_6.e^{-j[(\omega_0-6\omega_E)t]}.e^{j\frac{3\pi}{2}} + \\ J_2.e^{-j[(\omega_0-2\omega_E)t]}.e^{j\frac{\pi}{2}} - J_2.e^{-j[(\omega_0+2\omega_E)t]}.e^{-j\frac{\pi}{2}} \end{pmatrix} \end{bmatrix}$$

Equation (7) can be further simplified as

$$= \begin{pmatrix} J_2^2 + J_2^2\, e^{-j4\omega_E t} + J_2 J_6\, e^{-j8\omega_E t} - J_2 J_6\, e^{j4\omega_E t} + J_2^2 + J_2^2\, e^{j4\omega_E t} \\ +J_2 J_6\, e^{-j4\omega_E t} + J_2 J_6\, e^{j8\omega_E t} + J_6^2 + + J_2 J_6\, e^{j4\omega_E t} + \\ J_2 J_6\, e^{j8\omega_E t} + J_6^2 + + J_2 J_6\, e^{-j4\omega_E t} + J_2 J_6\, e^{-j8\omega_E t} \end{pmatrix} \qquad (8)$$

By utilizing equation (8), ESSR is given by

$$ESSR = 20 \log \left[\frac{\left(2J_2^2 + 4J_2.J_6 \right)}{4J_2.J_6} \right] = 36 \text{ dB} \qquad (9)$$

Using this technique, an OHDSR of 42 dB and an ESSR of 36 dB are attained at a modulation index m =2.404.

B. *Frequency−Sextupling Technique:*

A frequency−sextupling technique that can generate a 60−GHz MM−W signal using an integrated MZMs (IMZM) was developed by [10]. The technique uses an IMZM which is composed of three sub−MZMs. The sub−MZMs are biased at MITBP. The optical MM−W signal is given by [10]

$$E_{Mod.}(t) = \frac{1}{2} E_O.J_3\left(3.831\right).\begin{Bmatrix} e^{i(\omega_c+3\omega_E)t}.(1+e^{3i\square\phi}) \\ -e^{i(\omega_c-3\omega_E)t}.(1+e^{-3i\square\phi}) \end{Bmatrix} \qquad (10)$$

To achieve high OHDSR, the optical power of the 3rd −order optical sideband should be maximal, while 7th −order optical sideband is minimal. OHDSR at a m= 3.831 and IMZMs with infinite ER is given by [10]

$$OHDSR = 10\log\left[\frac{J_3(3.831)^2}{J_7(3.831)^2}\right] = 30\text{ dB} \qquad (11)$$

ESSR obtained using this technique is given by [10]

$$ESSR = 20\log\left[\frac{J_3(3.831)}{2J_7(3.831)}\right] = 25\text{ dB} \qquad (12)$$

C. *Frequency−Octotupling Technique:*

A frequency−octotupling Technique that can generate a MM−W signal using four nested MZMs was developed by [11]. The technique consists of two parallel frequency−quadrupling systems. Each system is consisting of two cascaded MZMs. The optical MM−W signal can be written as [11]

$$E_{Mod.}(t) = -2E_O.J_4(3.831).\left\{\begin{matrix}\cos\left[(\omega_O-4\omega_E)t\right]\\ +\cos\left[(\omega_O+4\omega_E)t\right]\end{matrix}\right\}$$

□□□□

The technique offers a high−purity electrical MM−W generation, ESSR=44 dB, at m=3.831. In addition, the system is unaffected by the MZM bias drift. However, cost and complexity are the limitations of this technique.

III. Simulation Results and Discussion

The Simulated experimental setup before transmission over optical fiber is set up for the three techniques by using “Optisystem 10”, to evaluate the value of ESSR.

Figure 1 reveals the simulated experimental setup for the frequency−quadrupling. Figure 2 reveals the simulated experimental setup for the frequency−six-tupling Technique.

Figure 3 reveals the simulated results of the RF spectrum for Technique [9]. A strong 60−GHz signal and undesired harmonic 120−GHz signal are generated at once. The power of the desired 60−GHz is −20 dBm and its ESSR is 36 dB. Figure 3 shows that the simulation results are in good agreement with Equations 9 in section 2.1

Figure 4 reveals the simulated results of the RF spectrum for Technique [10]. The 60−GHz and unwanted 40−GHz signals are generated at the same time and its ESSR is 25 dB.

Figure 5 reveals the simulation results of the RF spectrum for Technique [11]. The RF spectrum consists only the desired 60−GHz and its ESSR is 44 dB.

Figures 3, 4 and 5 reveal that the high-quality electrical MM−W signal, i.e. ESSR, can be obtained with different modulation indexes. However, techniques [10] and [11] require a high modulation index than technique [9], which in turn requires a high input RF signal power, i.e. not cost−effective techniques.

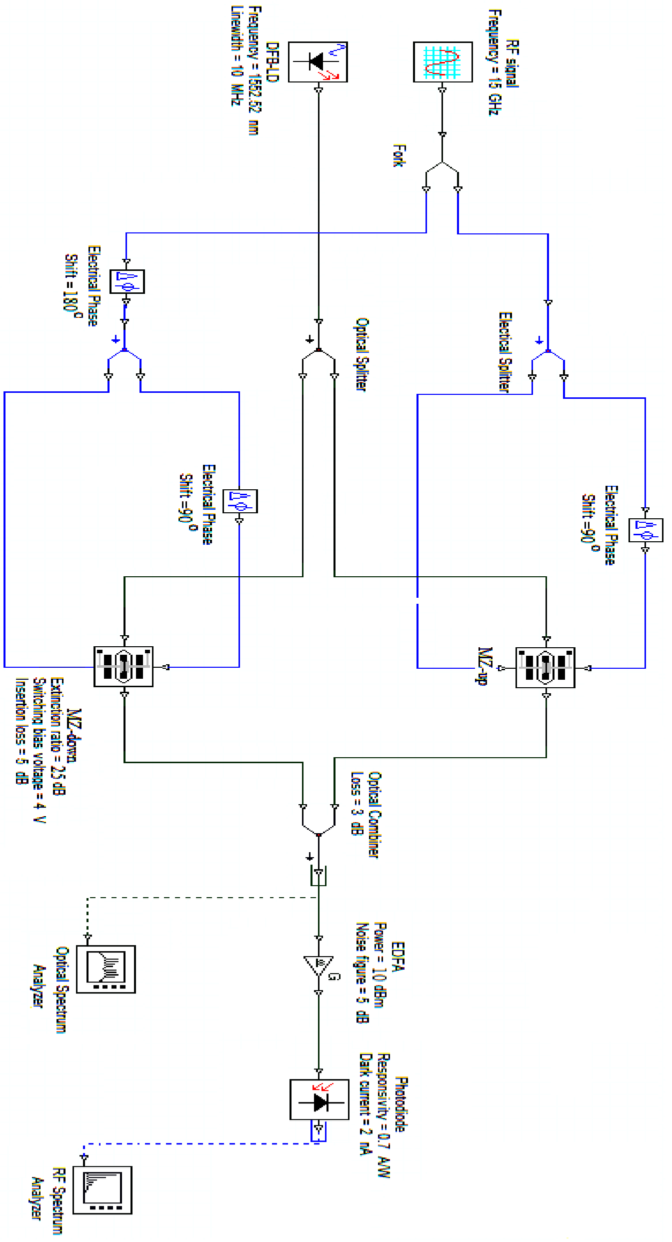
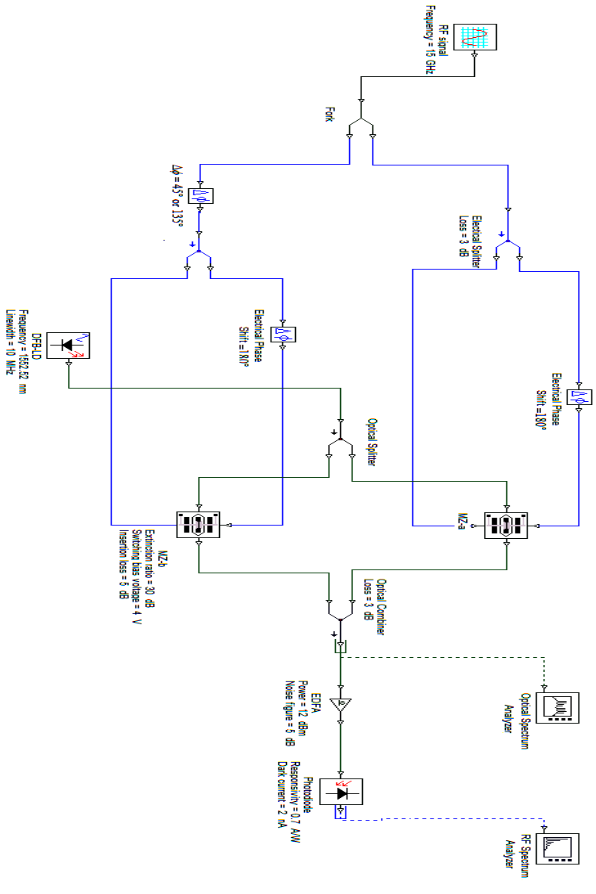


Figure (1): Experimental set-up for technique [9]



Figure(2) : Experimental set-up for technique [10]

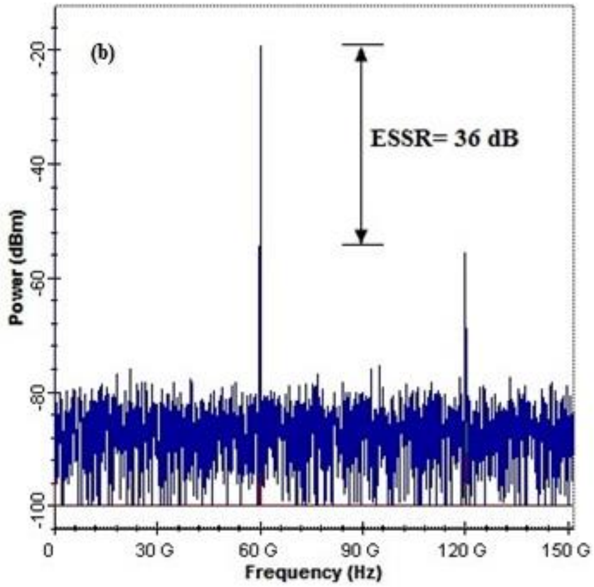


Figure (3): RF spectrum for technique [9]

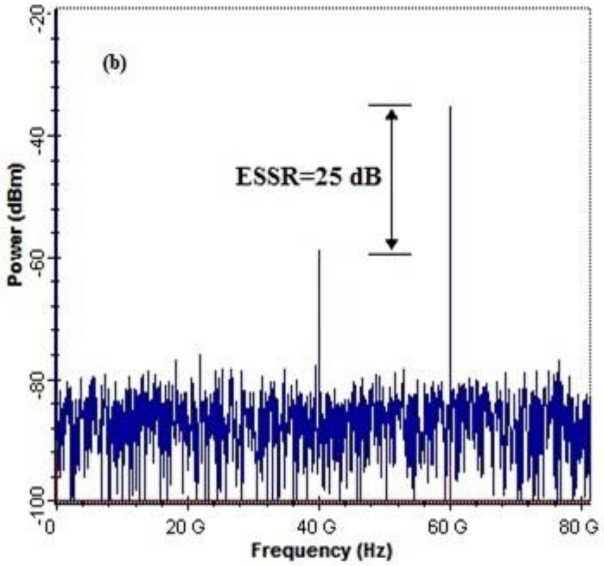


Figure (4): RF spectrum for technique [10]

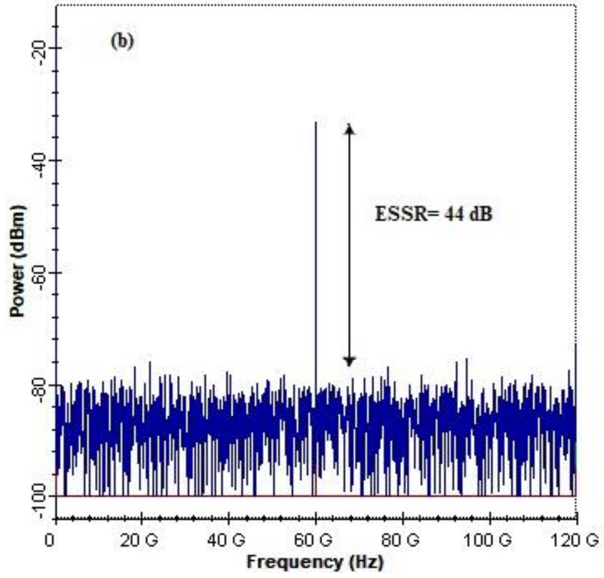


Figure (5): RF spectrum for technique [11]

To assess the influence of phase shifting the on ESSR for the EOU techniques, the phase shift is varied from −9 O to 9 O, and its influence on ESSR is shown in Figure 6. Compared with sextupling and octotupling techniques, ESSR for the frequency−quadrupling technique is uninfluenced by a phase shifting with a value of approximately 35.2 dB. This is because the deviation of phase shift does not affect the ratio of OCS. Consequently, the MM−W is the result of multiplying optical sidebands at ±2ωE, so that negative and positive interactions severely take places. The phase shifting has a lower influence on the performance of frequency−quadrupling technique.

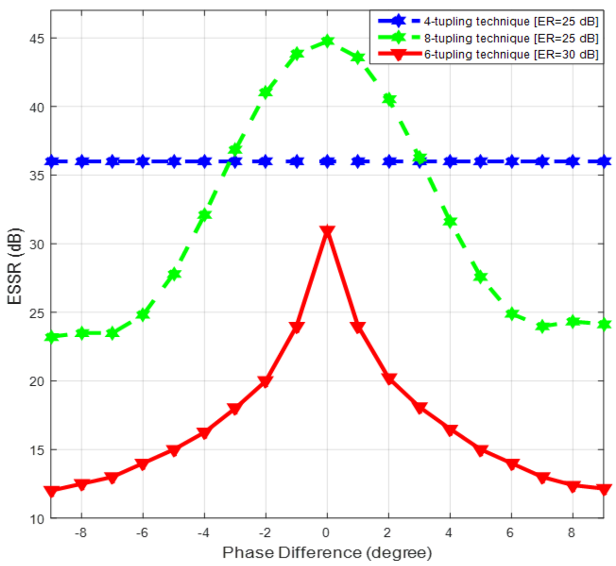


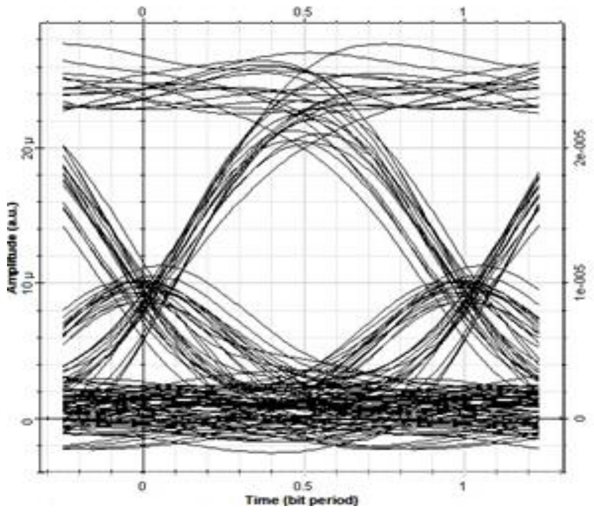
Figure (6): Effect of phase shifting on ESSR

To assess the performance of each EOU technique, simulated electrical eye patterns are shown in Figure 7. In this simulation model, we used a 60km single mode fiber (SMF) link. SMF has attenuation 0.2dB/km, and dispersion 16.7 ps/nm km. The PMD effect was neglected.

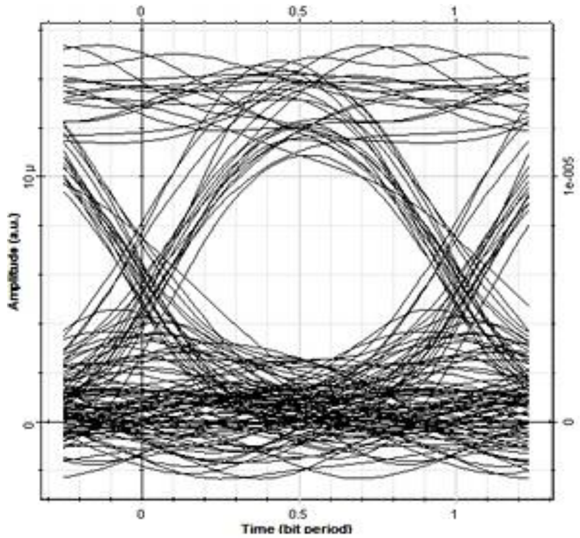
Figure 7a shows the simulated electrical eye pattern of the demodulated data signal for technique [9]. The outline of the eye patterns remains open and clear in spite of the MM−W signal is transported more than 60 km.

Figure 7b shows the simulated electrical eye pattern of the demodulated data signal for technique [10]. The eye pattern keeps open and the pulse width of the recovered baseband signal becomes broader. The pulse width becomes broader and broader with increasing fiber length and that the bit walk-off effect [12] gradually becomes serious, especially at 65 km.

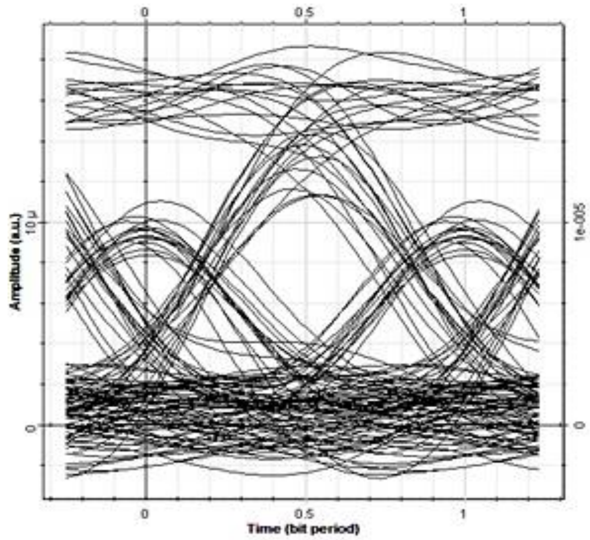
Figure 7c shows the simulated electrical eye pattern for technique [11]. The eye pattern closes and the performance becomes unacceptable at a distance of 60 km.



(a)



(b)



(c)

Figure (7): Eye diagrams at a distance of 60 km.
(a) Technique [9]
(b) Technique [10]
(c) Technique [11]

IV. CONCLUSIONS AND FUTURE WORKS

This study confirms that the frequency−quadrupling is a feasible method for generating MM−W signals. By comparing the ESSR values of the EOU techniques, the frequency−quadrupling technique can generate a steady MM−W signal with a lower modulation index than the frequency sextupling and octotupling techniques. Furthermore, the optical MM−W signal can resist the fading caused by phase shift variation. Nevertheless, the frequency−quadrupling technology is not enough to reduce the requirements on the electrical components for wireless applications at frequencies higher than

GHz 120. Frequency sextupling and octotupling techniques can significantly reduce the requirements. However, the strict demand for large RF drive power (high modulation index) is required, i.e. not cost−effective. For future works, comparison can be expanded to include other EOU techniques for optical generation and transmission of MM−W signal such as 12−, 16− and 24-tupling. Furthermore, the influences of non-ideal parameters for the three different EOU techniques, such as imperfect ER, non-ideal voltage on ESSR can be taken into account.

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