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Evaluation of OFU Techniques for Optical Generation of mm-W Signals in Future Broadband Cellular Communication Networks

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Abstract: Cellular networks that use the millimeter-Wave (mm-W) spectrum holds a great promise to revolutionize wireless industry. Nevertheless, the generation and transportation of mm-W signals in the electrical-domain are unfeasible owing to the high air link loss and electromagnetic interference. Generating mm-W signals in the optical-domain, i.e., over an optical fiber will allow sending wireless signals for a long distance. This study presents an evaluation of the Optical Frequency Upconversion (OFU) techniques based on advanced Mach-Zehnder Modulator (MZM) for optical generation and transportation of mm-W wireless signals. Four types of OFU techniques will be compared: frequency-doubling, frequency-quadrupling, frequency-sixtupling and frequency-octupling. We begin by reviewing selected OFU techniques that enable to double, quadruple, sixtuple or octuple an Radio Frequency (RF) and highlighting drawbacks and benefits. Then, a comparison in terms of modulation index, bias drifting and modulation efficiency is presented to show the trade-off between OFU techniques complexity and cost. Comparison of OFU techniques and results from simulation analysis reveal that the frequency quadrupling technique is a robust and more desirable choice for optical generation and transportation of mm-W wireless signals.

Key words: OFU techniques, optical mm-W signal generation, 5G, frequency quadrupling, MZM, wireless signals

INTRODUCTION

Industries and researchers have identified 5G of cellular technology that will use mm-W band as a key enabler to offer unprecedented wireless access services. Bandwidth-hungry applications like high definition telepresence are now available and need huge bandwidth (Gubbia *et al*., 2013). These applications force the requirement for a link that can carry high data rates. The usage of microwave frequency range leads to an increase in the amount of traffic congestion which increases the time delay (Li *et al*., 2016). Moreover, the microwave signal is not preferred for long-distance transmission because of fading effect and low sampling rate (Khawaja and Cryan, 2008). The 5G mm-W wireless channel bandwidths will be 10 times more than today's 4G LTE 20-MHz cellular channels in addition it is a promising solution to the spectral congestion (Rappaport *et al*., 2017).

The optical generation techniques of mm-W signals can be classified into Optical Heterodyne Detection (OHD) (Kitayama *et al*., 1996; Kuri *et al*., 2003; Chuyanov *et al*., 2005; Hyodo *et al*., 2009) and OFU (Mohamed *et al*., 2007; Al-Shareefi *et al*., 2013a, b) techniques. OFU is a technique wherein high-order optical sidebands are produced utilizing a CW laser with an external optical modulator driven by a sinusoidal RF signal. By multiplying any two high-order optical sidebands in the PD, numerous mm-W signals may be produced. Compared with the OHD technique, OFU can generate a high quality optical mm-W signals without the use of complex optical injection locking and optical phase locked loop mechanisms for phase noise suppression.

In this study, we have demonstrated an evaluation of OFU techniques for the optical generation of mm-W wireless signals. We have also investigated the puirty of the generated optical mm-W signals for selected OFU techniques considering the impact of non-ideal phase difference between RF-driven signals and non-ideal MZM Extinction Ratio (ER).

Electrical approaches for mm-W wireless signals transportation: The electrical transportation of mm-W wireless signals presents a challenge due to high cost and

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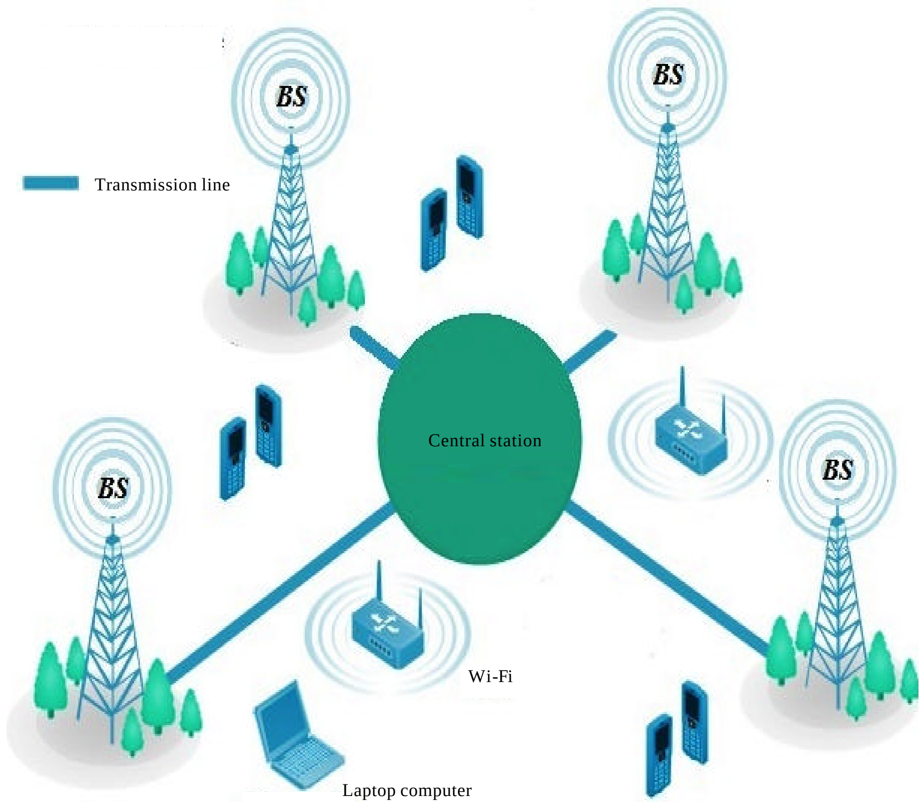

Fig. 1: Electrical transportation system for mm-W signals

high propagation loss of such waveguides or coaxial cables. Thus, the central generation and transmission of mm-W wireless signals become impractical and that the data signals should be transmitted at a low Intermediate Frequency (IF) or a Baseband (BB) to BSs. At each BS, the IF or BB signal should be upconverted to the desired mm-W signal, amplified and radiated. This process leads to an increase in BS complexity.

Figure 1 shows the typical electrical transportation system for mm-W wireless signals. The system composed of a switching center, BSs and a number of repeaters over the transmission lines to overcome signal degradation caused by noise and signal attenuation. The main drawback of this system is that the covered area from a switching center is restricted because of the degradation in the signal to noise ratio. Based on above discussion, we can deduce that the electrical approaches for the generation and transportation of modulated mm-W signals are roughly limited in both cost and performance.

OFU techniques

Frequency doubling technique: This technique optically generates an mm-W frequency double that of the input RF. This can be done by generating an Optical Double Sideband (ODSB) signal, i.e., optical carrier and two 1st order optical sidebands, after that filtering the optical carrier.

Frequency doubling using a single MZM without optical filter: This frequency doubling technique was developed by O'Reilly *et al.* (1992). An frequency-doubling was achieved by biasing a Dual Drive-MZM (DD-MZM) at Minimum Transmission Bias Point (MITBP). The component at ω_O (the optical carrier) will suppressed as well as the entire components at $\omega_0 \pm 2n\omega_{RF}$. Thus, two strong 1st order optical sidebands separated by $2w_{RF}$ are obtained. This optical mm-W generation technique is immune to fiber CD because the generated mm-W signal originates from the beat of the two strong 1st order optical sidebands.

Frequency doubling without using DC bias adjustment: Chien and Hsueh proposed a technique to generate a frequency doubling optical mm-W signal by using an optical PM and a BGF (Chien *et al.*, 2010). Phase-modulated carrier is generated by modulating the phase of a CW generated from a DFB-LD with a sinusoidal RF

Table 1: Comparison of OFU techniques for optical generation and transmission of mm-W signals

Technique	Advantages	Disadvantages
Frequency doubling	Simple configuration	Not adequate to minimize requirements on the electrical components
	Suitable for long distance transimission of the optical fiber	Low efficiency frequency upconversion
Frequency quadrupling	Cost effective	Not adequate to minimize requirements on the electrical components
	Low RF popwer is needed to achieve high OHDSR	for application at frequencies above 100 GHz
Frequency sixtupling	Driving RF at one sixth the required mm-W frequency	High modulation index requirement
		Bias drifting problem
		mm-W signal suffers from power fading caused by fiber CD
Frequency octupling	Driving RF at one eight the required mm-W frequency	High modulation index requirement
	Adequate ti minimize requirements on the electrical requirements	Complicated
		The mm-W signal is more susceptible to bit walk-Off eccect

signal by using PM. After filtering high-order optical sidebands by using a BGF with a bandwidth (2-4ω_m), the phase modulated signal composed of the optical carrier, 1st and 2nd order optical sidebands. The key benefit of using this technique is that the frequency doubling can be accomplished without particular DC bias adjustment thus eliminating the bias drifting difficulty (Qi *et al*., 2005). However, to remove the undesired optical sidebands, a BGF should be used. The BGF is sensitive to temperature. Moreover, most optical power will be lost because of BGF reflection (Yu *et al*., 2006) (Table 1).

Frequency quadrupling technique

Frequency doubling using a single MZM without optical filter: Qi *et al.* (2005) demonstrate a technique that can achieve quadruple-frequency optical mm-W signal generation utilizing single MZM. The MZM is biased at the Maximum Bias Point (MATBP). By multiplying the 2nd order optical sidebands at a high-speed PIN-PD a quadruple-frequency mm-W signal is generated. Nevertheless, the main problem in this technique is: the purity of the optical mm-W signal is low. Moreover, an ultra-narrowband optical filter is needed to vanish the optical-carrier, thus, resulting in a system that has poor stability and high cost.

Frequency quadrupling using two cascaded MZMs: By Mohamed *et al.* (2012) present a technique to generate quadruple frequency optical mm-W signal: two cascaded DD-MZMs biased at the QBP with a phase shift 180° between the two DD-MZMs. When the light is injected into the first DD-MZM, the optical carrier and upper 1st order optical sideband are generated while the lower 1st order sideband is suppressed. Then, the upper 1st order optical sideband is removed after the second DD-MZM. Thus, only the optical carrier and the upper and lower 2nd order optical sidebands are generated after the second DD-MZM. However, the mm-W generation is caused by the multiplying of optical sidebands at $\pm 2\omega_{RF}$ and the multiplying of the optical carrier optical with sidebands at $\pm 2\omega_{RF}$, thus, producing destructive and constructive interactions to occur and causing fiber dispersion induced power fading on the desired mm-W (Al-Shareefi *et al*., 2013a, b).

Frequency quadrupling using two parallel MZMs: A frequency-quadrupling technique that can produce a high-purity\60 GHz Optical Carrier Suppression (OCS) mm-W signal using two commercially available DD-MZMs is developed by Al-Shareefi *et al.* (2013a, b). Two parallel DD-MZMs biased at the MITBP with a 90° phase among the RF drive signals applied to every DD-MZM electrodes and a 180° phase among the RF drive signals applied to the DD–MZMs are used. By using this technique an Optical Harmonic Distortion Suppression Ratio (OHDSR) more than 42 dB can be achieved. Therefore, high upconversion efficiency can be attained with less non-linear distortion effect. A typical modulation index m = 2.4048 is required to drive the MZMs that is cost-effective.

Frequency sixtupling technique

Frequency sixtupling using two cascaded DD-MZMs: By Qin and Sun (2012) present an approach to generate a six-fold frequency optical mm-W signal. This frequency sixtupling technique uses two DD-MZMs (MZM1 and MZM2) and a Gaussian Optical Band Pass Filter (GOBPF). MZM1 is biased at the MITBP whereas MZM2 is biased at MATBP and is used for modulating the data signal. Utilizing this technique, the required 3rd order optical sidebands are maximized while the unwanted optical sidebands are significantly removed. Hence, high efficiency frequency upconversion is achieved with minimum nonlinear distortion impact. The major limitation of this technique is the bias drift of DD-MZMs which makes the optical mm-W generation scheme a sophisticated control. Moreover, GOBF is required to achieve mm-W signal generation, thus, resulting in a system that has poor stability (Zhang, 2011).

Frequency sixtupling using an integrated MZM: By Shi *et al.* (2011) present a new frequency sixtupling technique for the mm-W signal generation. The frequency sixtupling technique uses an integrated MZM that is composed of three MZMs. The sub-MZMs are biased at MITBP. The phase difference among the two RF drive signals of the two sub-MZMs is 72°. Utilizing this technique an OHDSR higher than 29 dB can be obtained, i.e., high-purity optical mm-W signal generation. However, to obtain a high OHDSR, a modulation index m = 3.8317 is required to drive the IMZM, thus, suggesting that a high RF power is needed that is not cost-efficient.

Frequency octupling technique

Frequency octupling utilizing four nested MZMs: By Shang *et al*. (2012) proposes a filterless optical mm-W signal generation technique with frequency octupling utilizing four nested MZMs. The frequency octupling mm-W generation system consists of two parallel frequency quadrupling systems. Each frequency quadrupling system is consist of two cascaded MZMs with a 90° phase delay between the two RF signals. The proposed technique offers a high--quality optical mm-W generation, i.e., OHDSR = 40 dB at 80 GHz. In addition, the system is unaffected by MZM bias drift which indicates a higher stability. However, complexity and cost are the major limitations of this technique.

Frequency octupling cutilizing two cascaded MZMs: By Chen *et al*. (2010) used two cascaded MZMs to produce optical mm-W signals with 8-fold input RF signal. The mm-W generation technique is composed of two cascaded MZMs biased at the MATBP and an RF drive signal that is applied to the cascaded MZMs with a -90° phase shift. The technique minimizes the frequency demand of the oscillator and the modulator. However, the modulation efficiency of the technique is low. The modulation efficiency is the produced optical power measured after the optical modulator versus the input RF power (Lin *el al*., 2009a, b). Moreover, modulators have large insertion losses especially when cascaded (Alavi *et al*., 2016). Table 1 summarizes the drawbacks and benefits of the OFU techniques in this study.

MATERIALS AND METHODS

The flow chart that describes the research methodology is illustrated in Fig. 2. The main objective of the chart is to visualize input and output from the stages of the research for a better understanding of the evaluation of the OFU techniques.

Figure 2 provides an assessment of OFU techniques based on the MZM for optical generation and the transmission of wireless signals mm-W. As depicated in Fig. 2, the flow chart consists of three parts:

Review of the OFU techniques: we start by reviewing specific OFU techniques that enable to double, quadruple, sixtuple or octuple an RF, gives a brief description of these techniques and highlighting obstacles and benefits.

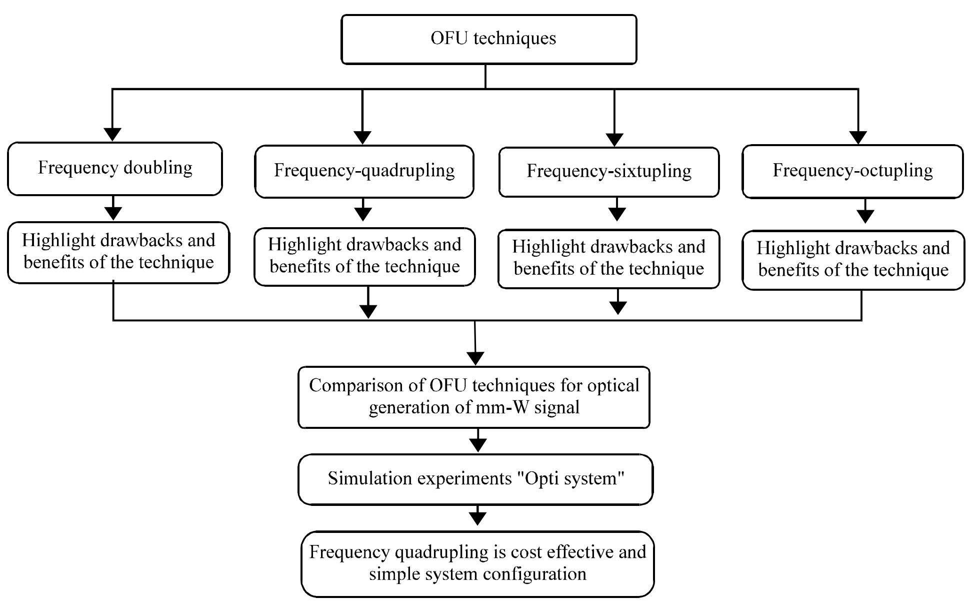

Fig. 2: Research methodology

Nine OFU techniques were reviewed: two for frequency-doubling, frequency-sixtupling, frequency-octupling and three for frequency-quadrupling.

Comparison of OFU techniques: Four types of OFU techniques is compared, namely, frequency-doubling, frequency-quadrupling, frequency-sixtupling and frequency-octupling. Comparison is made in terms of several parameters such as: modulation index, OHDSR, ESSR, bias drifting and modulation efficiency to show the trade-off between the complexity of OFU techniques and their costs.

Report the results: Computer simulation with "OptiSimTM 9.0" package have been carried out for the selected OFU techniques to assess the purity of the optical and RF mm-W signals. OHDSR and ESSR for the selected OFU techniques for diffent modulation index values have been compared. Additionally, the impact of phase shift, MZM extincation ratio and the frequency of the RF driving signal was also investegated. Simulation results showed that frequency-quadrupling was a more powerful and desirable option for optical generation and the transmission of mm-W wireless signals.

RESULTS AND DISCUSSION

Computer simulation with "OptiSimTM 9.0" package have been performed for the selected OFU techniques to assess the purity of the optical and RF mm-W signals when MZM ER is 100 dB. The ER of 100 dB can be considered to be infinite.

Figure 3 shows the output optical and RF spectra for technique (O'Reilly *et al*., 1992), i.e., frequency-doubling. The power of the 1st order sideband is -10 dBm and its OHDSR is 40 dB as depicted in Fig. 3a. The desired 60-GHz and with 150 GHz harrmonic mm-W signals are generated with an electrical spurious suppression ratio (ESSR) of 30 dB as depicted in Fig. 3b. The modulation index m = 2.4048. Figure 4 shows the output optical and RF spectra for technique (Al-Shareefi *et al*., 2013a, b), i.e., frequency-quadrupling. The power of the 2nd order sideband is -15 dBm and its OHDSR is 40 dB as depicted in Fig. 4a. The required frequency quadrupling 60 GHz and 120 GHz harmonic mm-W signals are generated with an ESS of 35 dB as depicted in Fig. 4b. The modulation index m = 2.4048.

Figure 5 shows the output optical and RF spectra for technique (Shi *et al*., 2011) i.e., frequency-sixtupling. The power of the 3rd order sideband is -20 dBm and its OHDSR is 30.1 dB as shown in Fig. 5a. The 60 GHz and specious 40 GHz mm-W signals are generated with an ESSR of 25 dB as depicted in Fig. 5b. The modulation index m = 3.831.

Figure 6 shows the output optical and RF spectra spectra for technique (Shang *et al*., 2012) i.e., frequency-octupling. The power of the 4th order sideband is -20 dBm and its OHDSR is 42 dB as depicted in Fig. 6a. The RF spectrum comprises of a dc component and the 80 GHz and its ESSR is 44 dB as depicted in Fig. 6b. The modulation index m = 3.831.

Figures 3-6 reveal that the high purity optical mm-W signal can be produced with different modulation indexes. However, technique (Shi *et al*., 2011) and technique (Shang *et al*., 2012) require a high modulation index, i.e., require a high input RF power, i.e., not cost effective techniques.

In previous simulation analysis, a fixed ER is utilized. The OHDSR is affected by non-ideal MZM ER. To assess the impact of the alteration of MZM ER on OHDSR

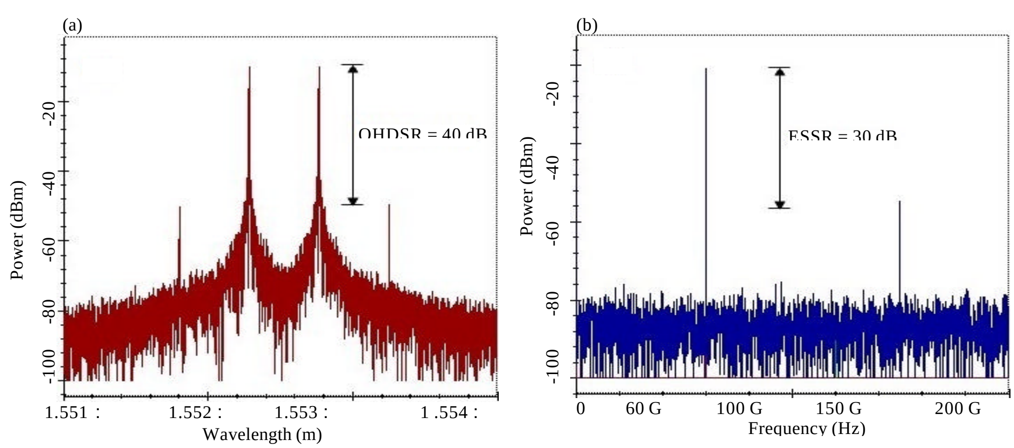

Fig. 3: a) Optical spectrum and b) RF spectrum. B-T-B case for Technique (O'Reilly *et al*., 1992). OHDSR = 40 dB, ESSR = 30 dB, m = 2.4048, RF oscillator = 30-GHz

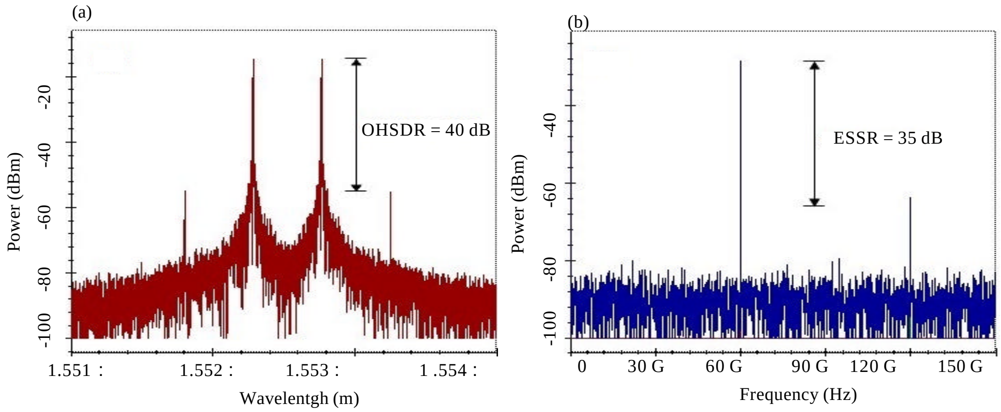

Fig. 4: a) Optical spectra and b) RF spectrum. B-T-B case for technique (Al-Shareefi *et al*., 2013a, b). OHDSR= 40 dB, ESSR=35 dB, m = 2.4048, RF oscillator = 15-GHz

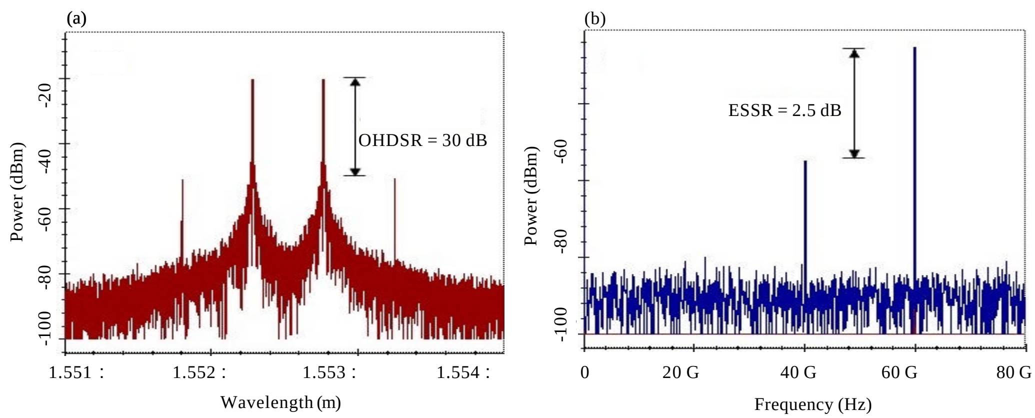

Fig. 5: a) Optical spectra and b) RF spectrum B-T-B case for technique (Shi *et al*., 2011). OHDSR = 30 dB, ESSR = 25 dB, m = 3.831, RF oscillator = 10 GHz

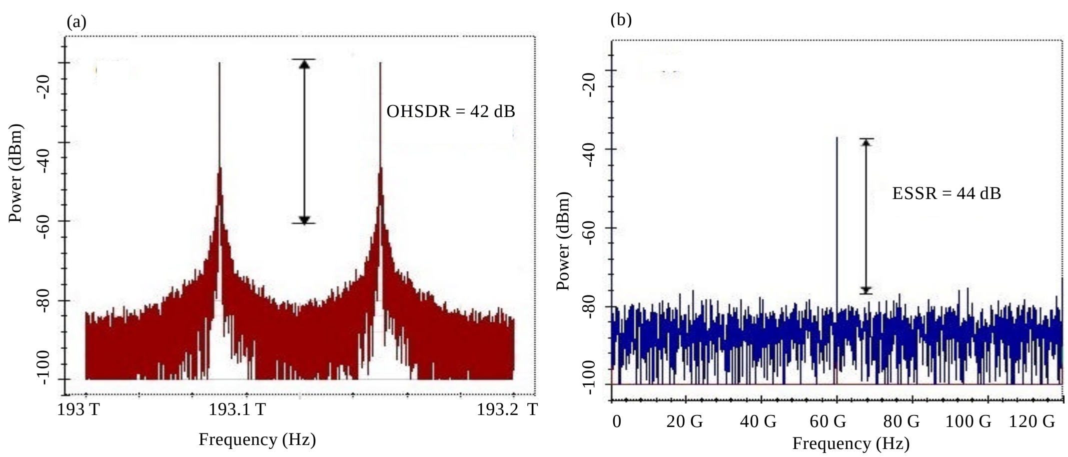

Fig. 6: a) Optical spectra and b) RF spectrum. B-T-B case for technique (Shang *et al*., 2012). OHDSR = 40 dB, ESSR = 40 dB, m = 3.831, RF oscillator = 7.5-GHz

for the OFU techniques, the MZM ER is increased from 20-70 dB and its impact on OHDSR is depicted in Fig. 7.

Figure 7 shows that the value OHDSR for technique (Al-Shareefi *et a l*., 2013a, b) increases from 35 dB at ER of 20 dB and reaches its greatest value of 42 dB when ER

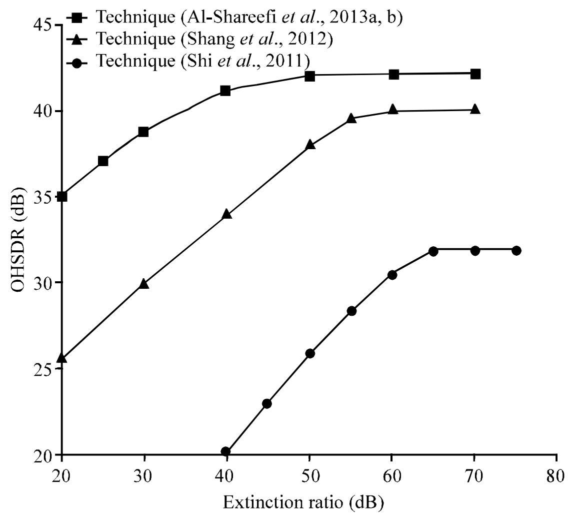

Fig. 7: Effect of non-ideal MZM ER on OHDSR

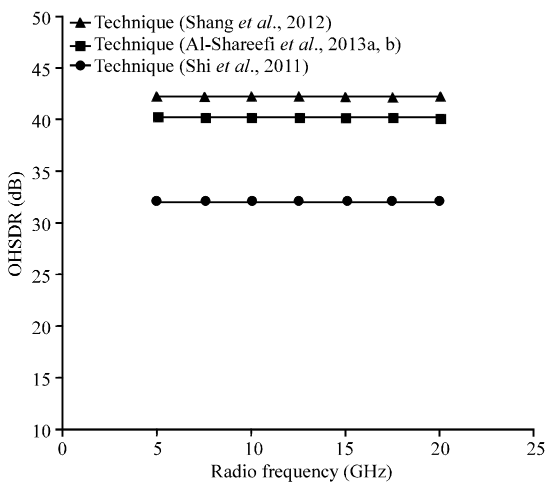

Fig. 8: Effect of RF oscillator on OHDSR

is 50 dB, after which it will remain fixed while OHDSR for technique (Shi *et al*., 2011) increases from 20 dB at ER of 40 dB and it reaches greatest value of 32 dB when the ER is 65 dB then it stays fixed. OHDSR for technique (Shang *et al*., 2012) increases from 25 dB at 20 dB ER and reaches its greatest value of 41 dB when ER is 60 dB and then remains fixed.

The increase of the ER value will increase the power of the desired 2nd-4th order optical sidebands, i.e., increasing OHDSR and thereby ESSR. Note that technique (Al-Shareefi *et al*., 2013a, b) is nearly unchanged by the non-ideal MZM ER.

To access the impact of the alteration of the frequency of the RF driving signal on OHDSR for the OFU techniques, the frequency is changed from 7.5-22.5 GHz and its impact on OHDSR is depcited in Fig. 8.

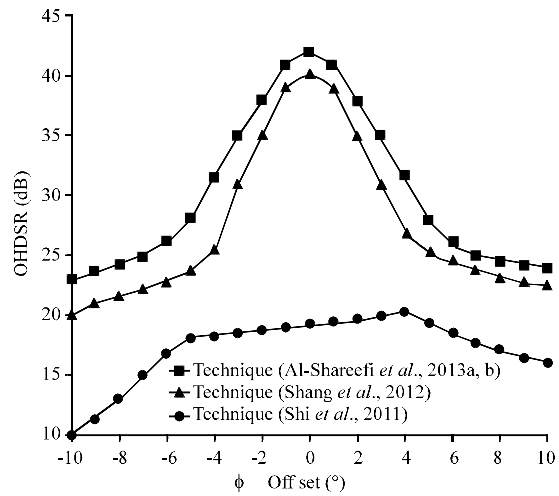

Fig. 9: Effect of phase shifting on OHDSR

For technique Al-Shareefi *et al*. (2013a, b) the generated wireless mm-W signal alters from 30-90 GHz. For technique Shi *et al*. (2012) the generated wireless mm-W signal alters from 45-135 Ghz. For technique Shang *et al*. (2012) the generated wireless mm-W signal alters s from 60-180 GHz. It is clear from Fig. 8 that the OHDSR remain fixed at 40, 32 and 42 dB for the techniques with the increase of frequency of the RF driving signal. Hence, the OFU techniques are independent of the alteration of the oscillator frequency.

To evaluate the impact of the alteration of phase shifting on OHDSR for the techniques, the phase shift value is changed from -10-10° and its impact on OHDSR is shown Fig. 9. For technique Al-Shareefi *et al*. (2013a, b). The highest OHDSR can be achieved for a phase shift near the 0°. The value then decreases slowly with the increment of the phase shift deviation value, i.e., 0°. An OHDSR greater than 24 dB can be achieved if the deviation is within 9°. The ER is equal to 25 dB. For technique Shi *et al*. (2011) and technique Shang *et al*. (2012) an ER of 40 and 30 dB are utilized and OHDSR is susceptible to nonideal phase difference deviation.

CONCLUSION

This study has provided an evaluation of of the OFU techniques for generation and transportation of mm-W wireless signals; highlighting the drawbacks and benefits of these techniques. The frequency-doubling technique is simply achieved with a single MZM. However, the frequency doubling technique is not adequate to minimize requirements on the electrical and optical components. Frequency-sixtupling and octupling techniques can minimize the demands significantly. However, strict demand on high modulation index is desired, i.e., not cost effective. Moreover, in the frequency sixtupling and octupling the conversion efficiency is small and the mm-W signal suffers from oscillation in RF power and bit walk-off effect caused by the fiber dispersion. The frequency-quadrupling technique can be simply achieved by using a single MZM. But the frequency quadrupling technique is not adequate to minimize requirements on the electrical components for wireless applications at frequencies above 100 GHz. Therefore, frequency quadrupling technique is a more desirable choice to generate the mm-W signal.

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