

Framework for optical millimetre-wave generation based on tandem single side-band modulation

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Abstract: A novel scheme for optical millimetre-wave (mm-wave) generation based on tandem sub-carrier multiplexing in hybrid communication systems is suggested. The method is analysed mathematically for optimum settings. The tandem single side-band (TSSB) method is tolerant to fibre chromatic dispersion. However, the TSSB technique is prone to critical interference of unwanted harmonics which may result in poor data transmission bit error rate (BER). Based on the proposed mathematical derivation for TSSB modulation, a framework is provided to enhance the mm-wave generation system performance. Up to 2 Gb/s data transmission over multiple 60 GHz sub-bands is considered. The model includes a single-mode fibre with chromatic dispersion factor of 16 ps/(nm km). Two cascaded dual electrode Mach–Zehnder modulators are used to generate TSSB 60 GHz sub-bands. Three oscillators are required to generate two tandem mm-wave signals. A proper selection of these three frequencies is vital to guarantee a successful data transmission. Mathematical analysis is carried out to verify the proposed scheme and a summary of appropriate frequency sets is presented and discussed. The BER curves are obtained. The results verify that the TSSB-based mm-wave generation framework proposed in this study guarantees data transmission with an acceptable BER.

1 Introduction

Wireless transmission in the lower microwave band is congested by applications such as wireless fidelity, global system of mobile etc. Thus, unlicensed 60 GHz frequency band (57–64 GHz) and 70–94 GHz band have been considered in the past few years [1–4]. Since propagation loss is the biggest problem for millimetre-wave (mm-wave) wireless communication, this technology can be used for short distances. In addition, geographical consideration is crucial for antenna base stations (BSs) installment. Owing to large number of required BSs and the high throughput of each BS, deployment of an optical fibre backbone is necessary. This network provides a broadband link between central office (CO) and BSs. The hybrid network can decrease the complexity and cost of the BSs by moving the routing, switching and processing functionalities to the CO. This way the cost of equipment can be shared among antenna BSs.

Optically mm-wave frequency (mmf) up-conversion obtained more attention because of electronic components' limited frequency response [5]. Three optical intensity modulation methods are used for the generation of mm-wave signals over optical fibre (i.e. direct intensity modulation, external modulation and remote heterodyning). However, external modulation is considered more often because of its wide bandwidth, small power consumption and large saturation power for input signals. However, electro-absorption modulator has small saturation input power. Thus, only a Mach–Zehnder modulator (MZM) can be used for multi-channel up-conversion [6]. Through different biasing points for MZM, different types of optical mm-wave signals can be generated. These types include optical double side band (ODSB), optical single side band (OSSB) and optical carrier suppression (OCS) [7].

The fibre dispersion effect on optically transmitted signals is critical to be controlled specifically for a long fibre link. To eliminate this impairment, OCS and OSSB techniques can be leveraged [8–11].

ODSB cannot be applied for long distances of fibre. The reason is that experienced phase shifts of light beams are different for various frequencies (i.e. upper and lower ODSB side bands) travelling through a dispersive fibre. Thus, this phase difference affects the detected radio-frequency (RF) power at the photodetector (PD). For the OSSB, there is only one side-band and consequently no

RF power degradation will happen. Optical tandem single side-band (TSSB) method is suited to increase optical spectral efficiency. The TSSB carriers are easier to be filtered than those of the OSSB technique [12]. This method can also tolerate the fibre chromatic dispersion.

2 TSSB modulation

In TSSB method, two different RF modulated signals can be transmitted on each side band of the same optical wavelength. In comparison with OSSB format, two different RF modulated sub-carriers are spaced twice apart from each other [12].

2.1 Theoretical analysis

The TSSB signal can be obtained using one dual electrode MZM [12]. Considering the dual electrode MZM, the applied electrical signals to the upper and lower MZM electrodes are as follows

$$V_{\text{RF-upper}} = V_{\text{rf}_2}(t) + V_{\text{rf}_1}(t + \pi/2); \quad V_{\text{DC-upper}} = V_{\pi}/2 \quad (1)$$

$$V_{\text{RF-lower}} = V_{\text{rf}_1}(t) + V_{\text{rf}_2}(t + \pi/2); \quad V_{\text{DC-lower}} = 0 \quad (2)$$

where $V_{\text{rf}_1}(t)$ and $V_{\text{rf}_2}(t)$ are two different RF signals which can be further elaborated as given in the following

$$V_{\text{rf}_1}(t) = V_{\text{ac}_1} \cos(w_{\text{rf}_1} t); \quad m_1 = V_{\text{ac}_1}/V_{\pi} \quad (3)$$

$$V_{\text{rf}_2}(t) = V_{\text{ac}_2} \cos(w_{\text{rf}_2} t); \quad m_2 = V_{\text{ac}_2}/V_{\pi} \quad (4)$$

where V_{ac_1} and V_{ac_2} are RF signals amplitudes. The angular frequencies of two RF signals are w_{rf_1} and w_{rf_2} . The MZM switching voltage is V_{π} . Parameters m_1 and m_2 are defined as applied RF normalised amplitudes. Assume a continuous wave (CW) laser with output optical field of $E_{\text{in}} e^{jw_c t}$ is modulated by the applied electric signals. The E_{in} and the w_c represent laser optical field and optical frequency, respectively. The output optical field $E_{\text{out}}(t)$ (assuming equal 50/50 split ratio) for the MZM is represented in (5) [13].

Considering (5), $E_{\text{out}}(t)$ for TSSB is obtained using (1)–(4).

Consequently, the power spectral density of MZM output is derived for the positive half of the frequency domain ($f > 0$) as in (6) where J_n is the n th-order Bessel function. In (6), the first term shows optical carrier and the second and third terms represent two RF sub-carriers. The other terms (term number 4 and above) are unwanted harmonics which must be considered in case the TSSB method is utilised for mm-wave generation. Based on (6), and using MATLAB[®] software, a flexible framework is proposed in this paper. Thus, the three oscillator frequencies should be chosen considering some constraints to prevent critical system performance degradation because of the unwanted harmonics' interference.

2.2 Framework for mm-wave generation

For generation of mm-wave signal, optical or non-optical techniques can be utilised. However, limited frequency response of electrical devices makes electrical methods inefficient. Numerous optical techniques that are based on external modulation have been suggested [14–16]. The mm-wave generation framework proposed in this paper is based on mathematical analysis of the TSSB modulation. Two cascaded MZMs are applied in this paper to generate mm-wave signals. The first MZM is biased at the quadrature point to generate the optical tandem spectra of two different modulated RF signals. The cascaded MZM is biased at its null point in order to up-convert the RF frequencies to 60 GHz range. Fig. 1 represents the block diagram of the suggested method for optical mm-wave generation.

The power spectral density of the first MZM output is the same as (6). All frequencies in (6) will be shifted in both directions (right and left) by f_3 after the second MZM. The f_1 and f_2 are two different sub-carrier frequencies applied to the first MZM, whereas f_3 represents the oscillating signal frequency applied to the second MZM. For this method to operate successfully, a proper selection of the three frequencies is vital. This requirement is studied through a

mathematical algorithm based on (6). This algorithm is implemented using MATLAB[®] software, and the results are summarised in Table 1.

Table 1 represents those sets of frequencies (12 GHz $\leq f_1, f_2$ and $f_3 \leq 25$ GHz) which can be used for the proposed system to generate 57 GHz $\leq$ mmfs $\leq$ 64 GHz without interference while $|\text{'mmf'}_1 - \text{'mmf'}_2| \geq 3$ GHz. In addition, the three frequencies f_1, f_2 and f_3 are considered so that the unwanted harmonics appear at least 3 GHz (in section A) or 2 GHz (in section B) away from the mm-wave generating frequencies ($-f_1 - f_3, f_3, -f_3, f_2 + f_3$). If frequencies f_1, f_2 and f_3 are not chosen properly, interference between unwanted harmonics and mm-wave generating signals will occur which will drastically degrade the system performance. This degradation is discussed more in Section 3.

3 System model and results

3.1 System model

Fig. 1 is implemented as the simulation model of the link in order to generate optical mm-wave signals. First, a pseudo random binary sequence of order 9 is used to generate data with a rate of 1 Gb/s for each channel. RF signals (which are generated by two oscillators with frequencies of f_1 and f_2) are modulated by non-return to zero smoothed data pulses. Then, the two RF modulated signals are optically modulated by two MZMs in series. The first MZM (i.e. MZM₁) is biased at the quadrature point ($V_\pi/2 = 8.2/2$ V) and the second MZM (i.e. MZM₂) is biased at the null point ($V_\pi = 8.2$ V). A sinusoidal signal with the frequency of f_3 is applied to MZM₂ electrodes with 180° phase difference to up-convert RF to the 60 GHz band. Both dual electrode MZMs have extinction ratios of 30 dB. Two different sets of frequencies are examined to verify the model performance. The frequency set #1 of $f_1 = 30$ GHz, $f_2 = 27$ GHz and $f_3 = 15$ GHz, which is not included in Table 1, is chosen randomly. In addition, from Table 1, the frequency set #2

$$E_{\text{out}} = \text{Real} \left\{ [E_{\text{in}} e^{j\omega_c t} / 2] [\exp(j(\pi V_{\text{RF-upper}}(t)/V_\pi + \pi V_{\text{DC-upper}}/V_\pi)) + \exp(\pm j(\pi V_{\text{RF-lower}}(t)/V_\pi + \pi V_{\text{DC-lower}}/V_\pi))] \right\} \quad (5)$$

$$\begin{aligned} S_E(f) = & (E_{\text{in}}^2/32) [J_0^2(m_1\pi)J_0^2(m_2\pi)\delta(f-f_c) + 2J_0^2(m_2\pi)J_1^2(m_1\pi)\delta(f-f_c+f_{\text{rf1}}) \\ & + 2J_1^2(m_2\pi)J_0^2(m_1\pi)\delta(f-f_c-f_{\text{rf2}}) + J_1^2(m_2\pi)J_1^2(m_1\pi)\delta(f-f_c+(f_{\text{rf2}}-f_{\text{rf1}})) \\ & + J_1^2(m_2\pi)J_1^2(m_1\pi)\delta(f-f_c-(f_{\text{rf2}}-f_{\text{rf1}})) + J_1^2(m_2\pi)J_1^2(m_1\pi)\delta(f-f_c+(f_{\text{rf2}}+f_{\text{rf1}})) \\ & + J_1^2(m_2\pi)J_1^2(m_1\pi)\delta(f-f_c-(f_{\text{rf2}}+f_{\text{rf1}})) + 2J_1^2(m_1\pi)J_2^2(m_2\pi)\delta(f-f_c+(2f_{\text{rf2}}-f_{\text{rf1}})) \\ & + 2J_1^2(m_1\pi)J_2^2(m_2\pi)\delta(f-f_c-(2f_{\text{rf2}}+f_{\text{rf1}})) + 2J_2^2(m_1\pi)J_1^2(m_2\pi)\delta(f-f_c+(2f_{\text{rf1}}+f_{\text{rf2}})) \\ & + 2J_2^2(m_1\pi)J_1^2(m_2\pi)\delta(f-f_c-(2f_{\text{rf1}}-f_{\text{rf2}})) + J_0^2(m_2\pi)J_2^2(m_1\pi)\delta(f-f_c+2f_{\text{rf1}}) \\ & + J_0^2(m_2\pi)J_2^2(m_1\pi)\delta(f-f_c-2f_{\text{rf1}}) + J_2^2(m_2\pi)J_0^2(m_1\pi)\delta(f-f_c+2f_{\text{rf2}}) \\ & + J_2^2(m_1\pi)J_2^2(m_2\pi)\delta(f-f_c-2f_{\text{rf2}}) + J_2^2(m_1\pi)J_2^2(m_2\pi)\delta(f-f_c+2(f_{\text{rf2}}+f_{\text{rf1}})) \\ & + J_2^2(m_2\pi)J_2^2(m_1\pi)\delta(f-f_c+2(f_{\text{rf2}}-f_{\text{rf1}})) + J_2^2(m_2\pi)J_2^2(m_1\pi)\delta(f-f_c-2(f_{\text{rf2}}-f_{\text{rf1}})) \\ & + J_2^2(m_2\pi)J_2^2(m_1\pi)\delta(f-f_c-2(f_{\text{rf2}}+f_{\text{rf1}})) + 2J_0^2(m_2\pi)J_3^2(m_1\pi)\delta(f-f_c-3f_{\text{rf1}}) \\ & + 2J_0^2(m_1\pi)J_3^2(m_2\pi)\delta(f-f_c+3f_{\text{rf2}}) + J_3^2(m_1\pi)J_1^2(m_2\pi)\delta(f-f_c+(3f_{\text{rf1}}+f_{\text{rf2}})) \\ & + J_1^2(m_2\pi)J_3^2(m_1\pi)\delta(f-f_c-(3f_{\text{rf1}}-f_{\text{rf2}})) + J_1^2(m_2\pi)J_3^2(m_1\pi)\delta(f-f_c+(3f_{\text{rf1}}-f_{\text{rf2}})) \\ & + J_3^2(m_1\pi)J_1^2(m_2\pi)\delta(f-f_c-(3f_{\text{rf1}}+f_{\text{rf2}})) + J_3^2(m_2\pi)J_1^2(m_1\pi)\delta(f-f_c+(3f_{\text{rf2}}+f_{\text{rf1}})) \\ & + J_1^2(m_1\pi)J_3^2(m_2\pi)\delta(f-f_c-(3f_{\text{rf2}}-f_{\text{rf1}})) + J_3^2(m_2\pi)J_1^2(m_1\pi)\delta(f-f_c+(3f_{\text{rf2}}-f_{\text{rf1}})) \\ & + J_3^2(m_2\pi)J_1^2(m_1\pi)\delta(f-f_c-(3f_{\text{rf2}}+f_{\text{rf1}})) + \dots] \end{aligned} \quad (6)$$

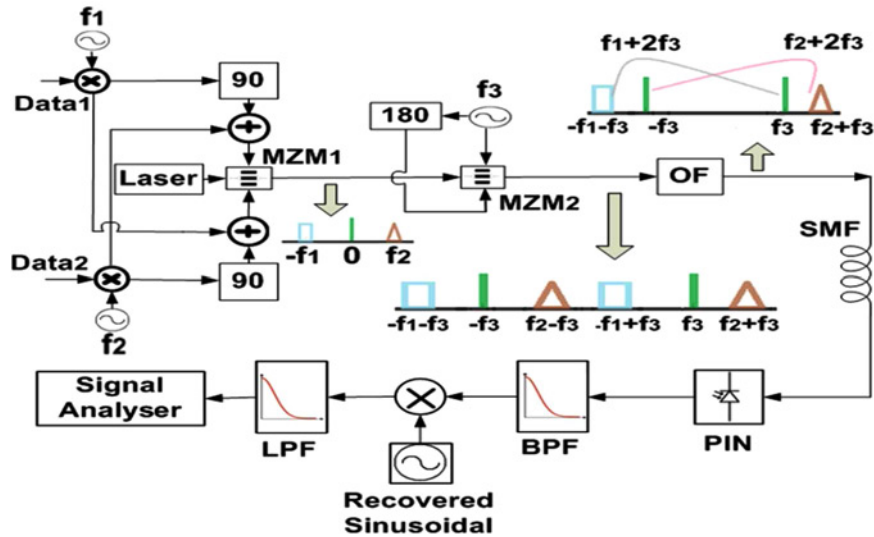


Fig. 1 Block diagram of the suggested method for optical mm-wave generation

that consists of $f_1 = 25$ GHz, $f_2 = 22$ GHz and $f_3 = 18$ GHz is examined. A CW laser which emits a beam with line-width of 7 MHz and power of 1 mW feeds the first MZM. The emission wavelength of the laser is 1553 nm. The MZM₂ output is filtered by a band stop filter to remove the unwanted signals. Transmission is done over 400 km of single-mode fibre with the dispersion factor of 16 ps/(nm km). Attenuation of the fibre is not considered in the first step in order to focus only on the chromatic dispersion effect of the fibre. A high-speed PD with responsivity of 0.5 A/W is applied. Dark current and thermal noise of the PD are 1 pA and 5 pA/(Hz)^{0.5}, respectively; shut noise is also included. After the PD, the 60 GHz range RF modulated channels are separated

using band pass filters. Then, they are mixed with their corresponding synchronised carriers in order to detect the data. After the low-pass filter at the receiver side of the link, an analyser is used to evaluate the link performance.

The model is also examined when a fibre attenuation of 0.1 dB/km is included and the data rate is increased to 2 Gb/s. To compensate for the attenuation effect, an optical amplifier is added to the set-up. The link performance is still acceptable for the frequency set #2, and for the fibre length of about 250 km. In the next section, how to choose the model oscillators' frequencies to guarantee the system performance is discussed in more detail.

3.2 Results and discussion

First, consider the frequency set #1 of $f_1 = 30$ GHz, $f_2 = 27$ GHz and $f_3 = 15$ GHz. It can be seen that the unwanted harmonics $-2f_1 + f_3$ and $f_1 + f_2 - f_3$ interfere with mm-wave generating frequencies at $-f_1 - f_3 = -30 - 15 = -45$ GHz and $f_2 + f_3 = 27 + 15 = 42$ GHz, respectively. In addition, shifted version of optical carrier harmonic at -15 GHz is interfered by shifted version of $-f_1/f_3$ to the right ($-f_1 + f_3$). These interferences prevent an acceptable mm-wave signal generation at the PD. The generated mm-wave electrical spectra at the PD for this frequency set is obtained using simulation software VPI® and is shown in Fig. 2a. As expected from mathematical analysis in (6), unwanted harmonics interfere with the RF frequencies and result in the performance degradation. The signal distortion is recognisable from Fig. 2a for channel frequency of $f_2 = 27$ GHz. This channel generates 57 GHz at the PD. The

Table 1 Frequency sets that guarantee the system performance based on mathematical analysis

A			At the PD	
f_1 , GHz	f_2 , GHz	f_3 , GHz	mmf_1 , GHz	mmf_2 , GHz
21	24	18	57	60
25	22	18	61	58
25	22	19	63	60
18	15	21	60	57
16	19	22	60	63
15	12	24	63	60
B			At the PD	
21	25	18	57	61
24	20	19	62	58
25	20	19	63	58
19	23	20	59	63
21	17	20	61	57
24	18	20	64	58
24	19	20	64	59
15	20	21	57	62
20	16	21	62	58
22	16	21	64	58
22	17	21	64	59
22	18	21	64	60
18	14	22	62	58
20	14	22	64	58
16	12	23	62	58
18	13	23	64	59

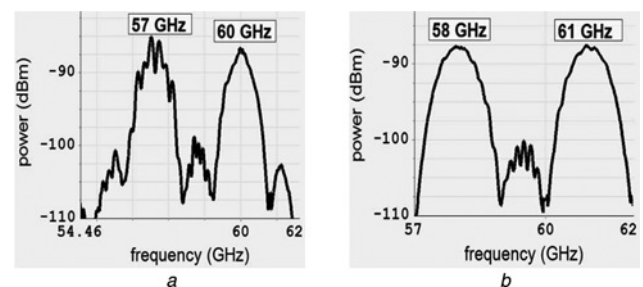


Fig. 2 Generated mm-wave electrical spectra at the PD
a For frequency set #1
b For frequency set #2

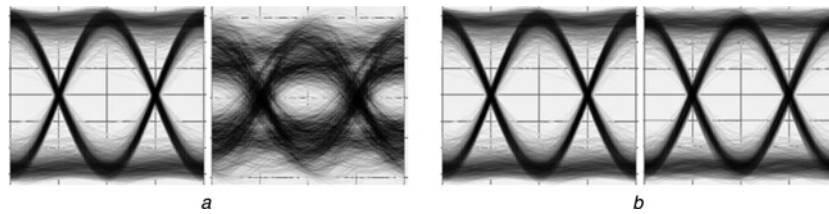


Fig. 3 Eye diagrams of the detected mm-wave signals
a For frequency set #1: $f = 60$ GHz (left) and $f = 57$ GHz (right)
b For frequency set #2: $f = 61$ GHz (left) and $f = 58$ GHz (right)

normalised RF amplitude is set to 0.15 ($m_1 = m_2 = 0.15$). To guarantee the system performance, the frequency set needs to be chosen from the proposed Table 1. For instance, from Table 1, frequency set #2 including $f_1 = 25$ GHz, $f_2 = 22$ GHz and $f_3 = 18$ GHz is examined. Fig. 2b shows acceptable spectra at the PD for this set. Figs. 3a and b represent eye diagrams for set #1 and set #2, respectively. An acceptable bit error rate (BER) performance is obtained for both channels of frequency set #2 (for mmf = 58 GHz the BER is 1.08×10^{-17} and for mmf = 61 GHz the BER is 1.62×10^{-16}). However, for the set #1 the BER of the detected 57 GHz channel is 0.005776, which is not applicable for data transmission. Therefore, the frequency set #1 is not appropriate for the system. Although, as the eye diagram shows an acceptable performance for mmf = 60 GHz, we need to consider both channels' performances of the frequency set. For Figs. 2 and 3, fibre length is 400 km while only chromatic dispersion of 16 ps/(nm km) is included (attenuation effect in this step is neglected to focus on the dispersion effect) and the data rate is 1 Gb/s.

For the second examination of the system, the data rate is increased to 2 Gb/s. A fibre length of 220 km with dispersion of 16 ps/(nm km) and attenuation of 0.1 dB/km is included. Fig. 4 represents BER curves for both frequency sets against normalised RF amplitude. It is apparent from this figure that channel frequency selection, regardless of the normalised RF power adjustment, has a critical impact on the BER level of the received data. The BER curves (in green and black) for the frequency set #2 are better for any normalised RF amplitude adjustment. The 30 GHz channel BER curve (in blue) does not show an acceptable BER level for any normalised RF amplitude value.

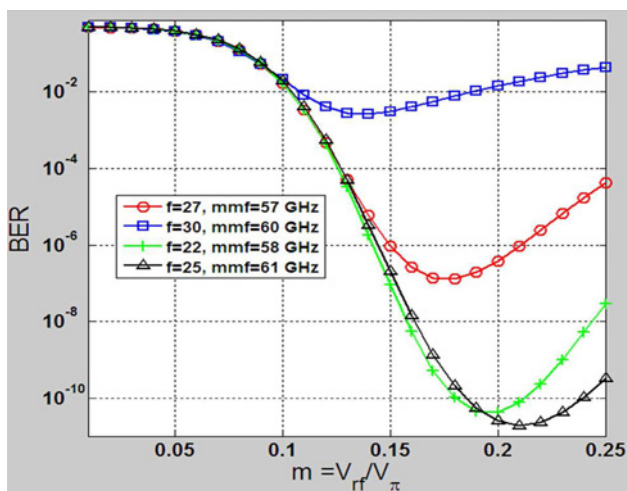


Fig. 4 BER of both frequency sets obtained at the receiver analyser against normalised RF amplitude 'm'

4 Conclusion

The novel scheme for optical mm-wave generation of RF modulated signals is suggested based on TSSB modulation method. Equation derivation is done for mathematical analysis of the proposed scheme. To guarantee performance of this method, proper selection of frequencies of the RF oscillators is required. Several appropriate frequency sets that can be used for the proposed scheme are obtained and presented based on the mathematical framework. The results and graphs verify that the unwanted harmonics must be considered carefully in order to avoid interference when generating mm-wave signals. These unwanted harmonics can degrade the system performance drastically. However, a proper RF frequency set selection for the system guarantees its high performance.

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6 References

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