Cascade configuration of two dual parallel polarization modulators with frequency 16 tupling for photonic signal generation

M. BASKARAN[1,*], K. JEYAPIRIYA[1], S. PRASATH KUMAR[2], S. SEVAGAN[3]
[1]*Department of Electronics and Communication Engineering, Sri Sairam Engineering College, West Tambaram, Chennai-600044, India*
[2]*Department of Electronics and Communication Engineering, Sri Sai Ram Institute of Technology, West Tambaram, Chennai-600044, India*
[3]*Department of Electronics and Communication Engineering, SRM Valliammai Engineering College, Kattankulathur, Chennai-603203, India*

Burgeoning data rates are demanding a shift towards millimeter wave frequencies to combat the pressure on the congested spectrum that is in existence today. This paper elucidates how to generate a 160 GHz millimeter wave signal with a series parallel combination of polarization modulators (PolMs) using a frequency 16 tupling technique based on polarization property. A 160 GHz optical signal is produced by adjusting the phases between the PolM stages and selecting the right modulation index. Only marginal deviations in the optimally determined phase shift values cause minimal changes in sideband suppression ratios, according to research. At each level of the simulation, the outcomes are mathematically verified. The optical sideband suppression ratio (OSSR) and the radio frequency spurious suppression ratio (RFSSR) have been determined to be 65 and 51.4 dBm, respectively.

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Keywords: Millimeter wave signal, Optical sideband suppression ratio, Polarization modulators, Radio frequency photonics, Radio frequency spurious suppression ratio

1. Introduction

Because of the continuous advancement of technology and communication, people requesting for available spectrum is rapidly increasing. As a result, the spectrum's use is restricted. Various studies are being conducted to address the spectral dilemma, and numerous solutions have been proposed. Millimeter wave (MMW) frequencies are one of their potential answers. The focus of researchers has shifted to millimeter wave generating techniques. Microwave signals in the 1 to 10 GHz range are generated by optical comb producers using mode locked lasers. External modulation methods [1] have gained popularity due to their simplicity, economic viability, and stability [2] and other techniques include nonlinear MMW generating techniques such as Stimulated Brillouin Scattering (SBS) and Four Wave Mixing (FWM) [3].

In optical filtering technologies, tunability is a drawback. The methodology in [4] is an inter-leaver or a filter implementation. The filter's challenge is to select proper stop band frequencies with aim of carrier frequencies are totally neglected and only the side band frequencies are preserved. This constraint forces the search for a filter-less generating method. Many filter-free approaches have been devised, however they have a number of drawbacks, including bias offsets, phase divergence between two sub MZM electrodes. Also the drawbacks include multiplication factors and extinction ratio values [5]. The frequency multiplication 12-tupling approach is introduced in a united MZM [6], where the OSSR value drops to -1 dB from 38 dB and the bias voltage varies by 20%. Li et al. [7] suggested a method for generating millimeter waves using two dual-parallel MZMs; An RFSSR with a value of 31 dB and 29 dB OSSR is obtained with the frequency 8-tupling method. As a result, the extinction ratio is unfitting. OSSR can only reach its maximum value if ER exceeds 38 dB. If the value of ER is between 18 and 38 dB, the value of RFSSR remains unchanged. It was proposed [8] to use 2 stage cascaded MZMs to produce frequency multiplication of 16-tupled, with resultant signal's RFSSR value set to 48dB and The OSSR is set to 61dB, however the ER and bias offsets vary, hurting the system's performance. Chen [9] used several frequency multiplication strategies to create two cascaded MZMs in his analysis. The generating efficiency of four cascaded MZMs is improved [10], tunability of frequency multiplication for system [11] and extinction ratio tolerant [12]. It was reported the scheme of generating frequency 16-tuple signal uses two MZMs [13] FWM in semiconductor optical amplifier [14] and frequency multiplication of 18-tupled photonic millimeter-wave using external modulator. However, the problem with the approaches so far presented is the picking of appropriate modulation index; also the constant modulation index and values of Extinction Ratio (ER) depreciates the overall behavior of the system; however, the RFSSR and OSSR values have increased, this increases the cost of the complete system.

The present approaches for implementing MZMs, such as ER value and bias offset, have significant drawbacks. These constraints are circumvented by polarization modulators. Polarization modulators have the advantage of being able to switch high ER RF and bias voltages. Using polarization modulators, many ways have been created and [15] has an excellent review of different mm-wave generation techniques with current problems. Dual polarization modulators in parallel are used to implement frequency sextupling [16]; The OSSR was found to be 38 dB and the RFSSR to be 32.8 dB in this case. OSSR is 56.36 dB, and RFSSR is 49.24 dB, according to the frequency octupling method [17]. A TM-TE mode converter and LiNbO3 intensity modulator were used to realize frequency quadrupling [18], with a fixed modulation index and finite ER value providing low harmonic suppression ratios. Using two cascaded PolMs, frequency octupling, sextupling, octupling [19, 20] and 12-tupling millimeter wave generating methods are suggested [21].

The OSSR of frequency quadrupling, sextupling and octupling are 19.13 dB, 17.16 dB and 10.06 dB respectively. The maximum multiplication factor is set to 8 in all of the techniques so far. OSSR of 62dB and RFSSR of 36dB are achieved by frequency 16-tupling using four parallel Polarization modulators [22], two cascaded with parallel PolMs [23] and use of remodulation mm-wave for wave generation [24]. To generate millimeter wave from the frequency 16 tupling, the suggested method uses four cascaded polarisation modulators. Section II delves into the ideas underlying the proposed approach, Section III delves into the interpretation of the results gained, and Section IV brings to the end of the article.

2. Principle

The proposed system as shown in Fig. 1, consists of two-dual parallel polarization modulators (PolM) connected in cascaded manner. PolM structure contains two phase modulators that have complimentary modulation which is followed by a polarizer. The optical spectrum output obtained from PolM1 is given by

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} exp(j\omega_c t + jmcos\omega_{rf} t) \\ exp(j\omega_c t - jmcos\omega_{rf} t) \end{bmatrix}$$

where modulation index m = $\frac{\pi V_{rf}}{V_\pi}$ = 3.901 for V_{rf} = 1.27279 V

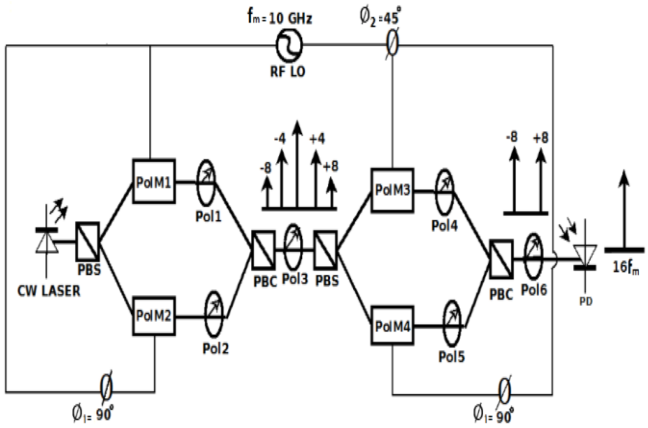

Fig. 1. Schematic of the proposed system generating millimeter wave signal

The transmission axes of each Polarizer is positioned at 45° in respect of x-axis. The output after polarizer 1 is given by

$$E_{U1} = E_c e^{j\omega_c t}\{J_0(m) - 2J_2(m)\cos 2\omega_{rf}t + 2J_4(m)\cos 4\omega_{rf}t - 2J_6(m)\cos 6\omega_{rf}t + 2J_8(m)\cos 8\omega_{rf}t\} \quad (1)$$

A 90° electrical phase shift occurs between upper and lower arms due to which the Polarizer 2 output is

$$E_{LI} = E_c e^{j\omega_c t}\{J_0(m) + 2J_2(m)\cos 2\omega_{rf}t + 2J_4(m)\cos 4\omega_{rf}t + 2J_6(m)\cos 6\omega_{rf}t + 2J_8(m)\cos 8\omega_{rf}t\} \quad (2)$$

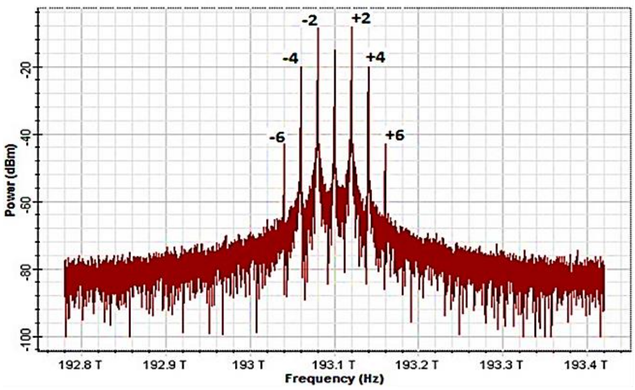

Fig. 2. Output after polarizer 1 (color online)

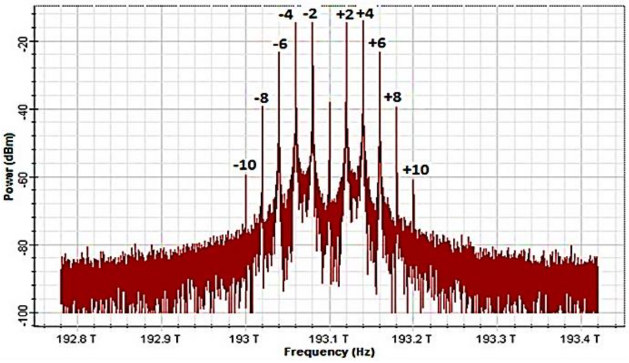

Fig. 3. First dual parallel stage output (color online)

On combining both upper and lower arms, the output of first dual parallel (DP) stage is given by

$$E_{DP1} = E_c e^{j\omega_c t}\{J_0(m) + 2J_4(m)\cos 4\omega_{rf}t + 2J_8(m)\cos 8\omega_{rf}t\} \tag{3}$$

A 45° phase shift is introduced between the 2 cascade stages. Output after Polarizer 4 is given by

$$E_{U2} = E_c e^{j\omega_c t}[J_0^2(m) - 2J_4^2(m) + 2J_8^2(m)] + [2J_0(m)J_2(m) - 2J_4(m)J_6(m) - 2J_6(m)J_8(m)] \sin 2\omega_{rf}t + [2J_2(m)J_4(m) - 2J_0(m)J_6(m) + 2J_2(m)J_8(m)]\sin 6\omega_{rf}t + [4J_0(m)J_8(m) - 2J_4^2(m)]\cos 8\omega_{rf}t + [2J_2(m)J_8(m) - 2J_4(m)J_6(m)]\sin 10\omega_{rf}t + J_8^2(m)\cos 16\omega_{rf}t\} \tag{4}$$

As a result of 90° phase shift between the two arms in the 2nd dual arm stage, we would expect an equation similar to equation 4 expect for a change of signs in the alternate terms at the lower arm of that stage. This difference between signs is similar to that observed between equations (1) and (2). The 2nd, 6th and 10th order sidebands are suppressed.

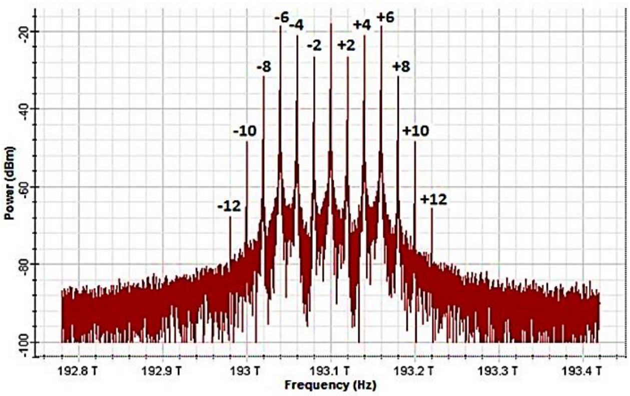

Fig. 4. Output after polarizer 4 (color online)

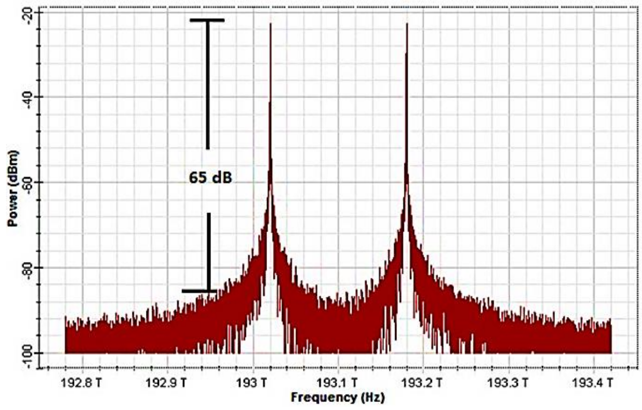

Fig. 5. The generated mm wave signal (color online)

Output obtained after final polarizer (Pol 6) has 2 strong 8th order sidebands with rest of the harmonics suppressed.

$$E_{DP2} = E_c e^{j\omega_c t}\{[2J_0(m)J_8(m) - J_4^2(m)]\cos 8\omega_{rf}t + J_8^2(m)\cos 16\omega_{rf}t\} \tag{5}$$

$$\text{OSSR} \approx 10log_{10}\left[\frac{2J_0(3.901)J_8(3.901) - J_4^2(3.901)}{J_8^2(3.901)}\right]^2 \approx 65 \text{ dB} \tag{6}$$

$$\text{RFSSR} \approx 10log_{10}\left[\frac{[J_0(3.901)J_8(3.901) - J_4^2(3.901)]}{2[J_0(3.901)J_8(3.901) - J_4^2(3.901)]J_8^2(3.901)}\right]^2 \approx 51 \text{ dB} \tag{7}$$

3. Results and simulation

The settings and values required to produce the desired output are shown in Table 1. For the experiment, a 50 kilo meter (Km) long optical cable with a 0.2 dB attenuation was used. Fig. 1 depicts the block diagram of millimeter wave signal generator.

The initial polarization modulator is operated by a RF Local Oscillator at 10 GHz having an amplitude of 1.272 Volts and a Continuous Wave (CW) laser generating 193.1 THz optical carrier frequency and operating at 0 dBm optical power. At the maximum transmission point (MATP), the PolMs are biased by switching bias voltage of 4 Volts, ER of 30 dB and the modulation index of 3.901.

Table 1. Various simulation parameters

S. No.	ATTRIBUTES	VALUE
1.	Carrier frequency of LD	193.1 THz
2.	Launched signal power	0 dBm
3.	Line Width of Laser Diode	10 MHz
4.	Frequency of RF Local Oscillator	10 GHz
5.	Photo Diode -Dark Current	10 nA
6.	Photo Diode - Responsivity	0.8 A/W

As illustrated in Fig. 2, the PolM has even order sidebands alone, since it is biased at the MATP. When looking at the first Dual Parallel stage (DP stage), the output following the first polarizer (Fig. 2) indicates that there are even order sidebands and is consistent with equation 1. The lower arm produces a similar output, but the phases change due to the 90° electrical phase shift introduced in between the two arms. The output after the first DP step is shown in Fig. 3. This accords well with equation 2.

The output following polarizer 4 (Fig. 4) can be transferred to equation 4 in the second DP stage. Figs. 5 and 6 show that OSSR and RFSSR are approximately 65 and 51 decibels, respectively. The two eighth order peaks are shown in Fig. 5 at 193.02 THz and 193.18 THz. The frequency spacing is 160 GHz, which is 16 times higher than the 10 GHz input LO frequency. As illustrated in Fig. 5, the fourth PolM's final output has just the 8th order sidebands with an output power of -11.7557 dBm, suppressing all other sidebands.

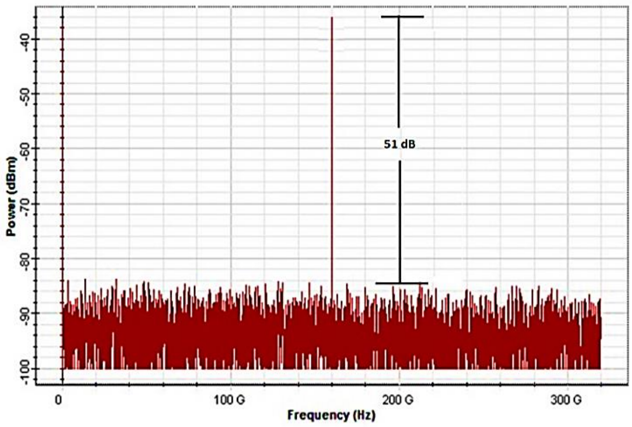

Fig. 6. Electrical spectrum of the generated mm wave signal (color online)

Because of this proposed cascaded modulators structure, the frequency 16 tupling produces maximum power in the eighth order sidebands located at 193.07 THz and 193.13 THz frequencies. 160 GHz is discovered to be the frequency deviation existing between the two eighth order sidebands. The MZM modulates a 10 Gbps baseband transmission with the 8th order side bands from Polarizer 6 and has a 40dB of ER value. The final output from MZM is then sent through a 50 Km optical cable with a 0.2 dB/Km attenuation. To compensate for transmission losses, an optical amplifier with the needed gain can be used in the radio over fiber link. A PIN photo diode with a dark current of 10 nA and a responsivity of 0.8 A/W is used at the receiving end of the base station (BS) to receive the optical millimeter wave signal and then converts to an equivalent electrical signal, after which it is given to an electrical Gaussian band pass filter with a center frequency of 160 GHz to remove the RF harmonics.

At the receiver section, the optical 160 GHz millimeter wave signal is demodulated by a RF local oscillator followed by a mixer and an electrical Low Pass Filter. 160 GHz millimeter wave generated with the help of 10 GHz RF LO frequency is depicted in Fig. 6. Phase noise of a frequency multiplied signal can be expressed as [25]

$$10log_{10}[S(f)] = 10log_{10}[S_{res}(f)] + 10log_{10}[m^2 S_e(f)] \tag{8}$$

where $S_{res}(f)$ and $S_e(f)$ are the power spectra representations of residual phase noise induced by the system and microwave drive signal respectively, and m represents the FMF.

It has been verified and proved by experiment that the phase noise due to an external modulation system is negligible and hence the above equation can be approximated to

$$10log_{10}[S(f)] \approx 10log_{10}[S_e(f)] + 20log_{10}[m] \tag{9}$$

Thus, the phase noise of the signal that is generated by the proposed frequency multiplication method [26-29] is majorly dependent on the phase noise of the above-mentioned microwave drive signal and FMF. But in the case considered here, since the FMF is 16, the phase noise would improve by $20log_{10}[16] \approx 24$ dB from that of RF drive signal.

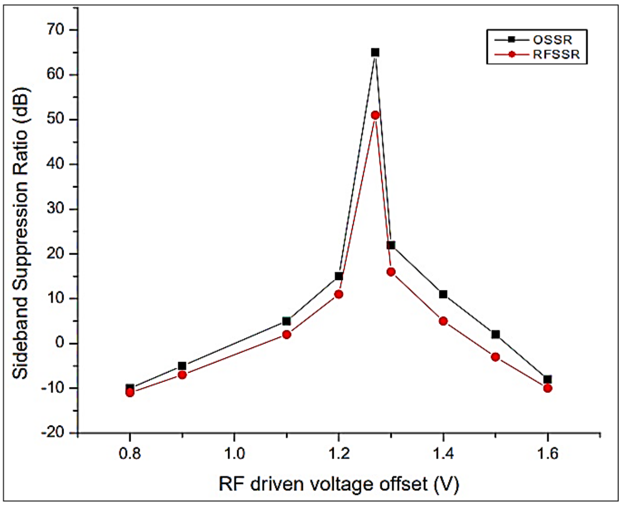

Fig. 7. Influence of RF voltage variation (color online)

Fig. 7 depicts the consequence due to the deviation or variation of RF drive voltage with respect to its optimum value. No variation is observed in OSSR and RFSSR, when the RF voltage deviates very slightly from its optimum value. When the RF voltage varies remarkably from its optimum value, there occurs a proportional increase in the deterioration of sideband suppression ratios. It is observed that less than 1 V deviation of RF voltage is significant to obtain an ORFSSR greater than 50 dB and OSSR value to be greater than 60 dB.

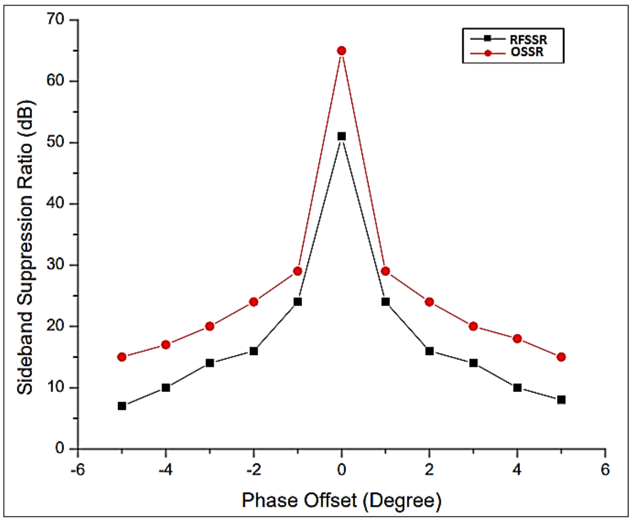

Fig. 8. Influence of phase difference (color online)

Fig. 8 shows the drifting in the phase shift that occurs between the microwave drive signals that are applied to PolMs and its optimum value. OSSR value greater than 50 dB and RFSSR value greater than 45 dB are attainable for less than 10° phase shift drift.

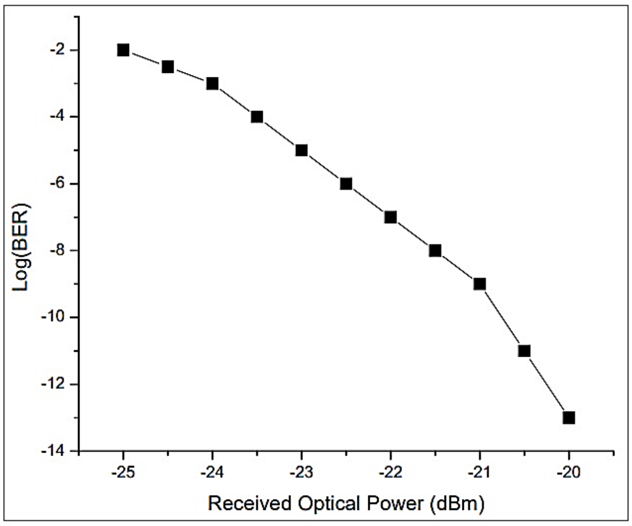

Fig. 9. BER Vs Received optical power

Sensitivity of receiver is defined as the minimal optical power necessary to attain a required Bit Error Rate (BER). A broadly used criterion for receiver performance lies on the level of optical signal power that creates a Bit Error Rate (BER) of 10^{-9}. When using Back-To-Back (BTB) transmission, BER is calculated for various received optical signal power values. As shown in Fig. 9, the calculated value of BER is found to be 10^{-9} at received optical signal power of -21 dBm. As a result, to obtain a BER of less than 10^{-9}, the received optical signal power in the proposed technique must be more than -21 dBm.

4. Conclusion

The use of polarization property in a 16-tupling method for millimeter wave signal production has been proposed. Instead of MZM, the inherent shortcomings of MZM-oriented systems have been mitigated by using PolM, which has a high extinction ratio and operates in a bias-free state. This scheme's frequency tunability enables further wireless applications to be implemented. The achieved electrical and optical side harmonic suppression ratios are quite high, indicating that minor deviances in the non-ideal circumstances will not degrade the signal feature.

Using a very low modulation index and a lower RF local oscillator frequency benefits this technology more practicable to execute. As a result, a 65 dB OSSR and a 51 dB RFSSR are achieved. In comparison to four cascaded and parallel PolM architectures, the proposed dual parallel PolM design delivers high quality millimeter wave signals.

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*Corresponding author: baski.maha@gmail.com