Extinction ratio tolerant filterless millimeter wave generation using single parallel MZM

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Enhancing the spectral quality of the signal without varying the extinction ratio is a challenge for millimeter (MM) wave generation. Here, we propose a novel extinction ratio tolerant frequency 8-tupling technique using two Mach-Zehnder modulators (MZMs) with optimal splitting ratio in parallel configuration. Although the proposed technique is not affected by extinction ratio, a high quality MM wave is still obtained with complete unwanted sideband suppression. Two non-ideal MZMs with $\pi/2$ and π phase shifter realize MZM with optimal splitting ratio, which acts as a high extinction ratio modulator. The 80 GHz MM wave with 62 dB optical sideband suppression ratio (*OSSR*) and 54 dB radio frequency sideband suppression ratio (*RSSR*) is generated from 10 GHz local oscillator signal at 2.403 6 modulation index (*MI*). Performance of the present work has been evaluated using various *MIs*, phase drifts and extinction ratios. Sideband suppression ratio (*SSR*) greater than 10 dB is reported in a wide *MI* ranging from 2.36 to 2.47. Further, both the *SSRs* are tolerant towards MZM extinction ratio. The work is ideal for wavelength division multiplexing (WDM) applications due to its filterless characteristics.

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For catering the rising bandwidth demands, emphasis has been laid on millimeter (MM) wave band for the next generation systems. However, generating MM wave through conventional electronic equipments is a tedious task. Further, these high frequency MM wave signals suffer from propagation losses and thus could only be transmitted to a limited distance[1]. This limitation can be overcome by generating the MM wave in optical domain and then transmitting it by using the radio over fiber (RoF) technology[2]. Generating MM wave signal in optical domain and designing its transmission system has attracted the researcher's interest.

Several optical techniques have been presented in the past for generating high quality MM wave[3-8]. External modulation using Mach-Zehnder modulator (MZM) offers several advantages such as high frequency multiplication (FM), larger tunability and reliability[8]. But MM wave generation with low FM requires a high frequency local oscillator (LO) signal as compared to the generated high frequency MM wave. In most of the schemes, filter has been employed for generating MM wave signal. Although, optical filters not only enhance the complexity but also reduce the tunability of the system. By employing filter, the system is not capable of generating any MM wave by changing LO frequency[9-12].

The 72 GHz MM wave was generated from 3 GHz electrical signal through two cascaded integrated dual-drive MZMs[10]. The system was found to provide optical sideband suppression ratio (*OSSR*) of 33 dB and radio frequency sideband suppression ratio (*RSSR*) of 26 dB. An RoF system based on two modulation stages was utilized for the generation of multiple MM wave signal[13]. The transmission performance was observed for three encoding schemes, non return to zero (NRZ), return to zero (RZ) and Gaussian pulse with the variation of link distance and power of input signal. Cascaded dual-parallel dual-drive MZM (DP-DDMZM) configuration was used through optical self-heterodyning to generate MM wave signal which is 4 and 12 times the input radio frequency (RF) source frequency. The phase noise analysis of the generated MM wave was done for different offset frequencies[14]. The 40 GHz MM wave was generated through a simplified structure consisting of two parallel external modulators with *OSSR* of 15 dB and *RSSR* of 30 dB without using any electrical phase shifter[5]. A 90 GHz MM wave was successfully transmitted to 20 km fiber link after generated through external modulator and four wave mixing (FWM) in semiconductor optical amplifier (SOA)[15]. Another full duplex link between four base stations and a central station was designed and evaluated and found to perform well at the transmission rate of 5 Gbit/s with Q factor of 30.8 up to 90 km[16].

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Recently, a filterless frequency 8-tupled MM wave has been generated by using cascaded configuration of parallel MZM with 100 dB extinction ratio[17]. As reported in Ref.[2], MZM with 100 dB extinction ratio is practically not possible and extinction ratio is a crucial factor for determining the spectral purity of the signal, as minute variation in extinction ratio would give rise to undesired harmonics[8-15]. So, it is quite necessary to design a practical, stable and efficient MM wave geneartion system that does not rely on extinction ratio and still gives a highly conversant output with higher unwanted sideband suppression.

This paper presents an extinction ratio insensitive model for frequency 8-tupled MM wave generation using parallel MZM with 0.5 splitting ratio. The proposed technique generates a high quality MM wave signal with complete unwanted sideband suppression without imposing any stringent requirement on the extinction ratio of MZM. The 80 GHz MM wave is generated by 10 GHz LO signal with 62 dB *OSSR* and 54 dB *RSSR*. Further, both the *SSRs* are tolerant towards extinction ratio variation.

The mathematical modeling of the system design is presented in two parts, realizing MZM with 0.5 splitting ratio and generating frequency 8-tupling MM wave.

Fig.1 depicts the schematic diagram for modulation with MZM having splitting ratio of γ. Considering that the optical signal $E_c(t)$ emitted from laser diode (LD) is fed to MZM, MZM output can be written as[1]

$$E_{MZM}(t)=\alpha E_c(t)[\gamma e^{j\pi(\frac{V_2(t)}{V_\pi}+\frac{V_{b2}}{V_\pi})}+\{1-\gamma\}e^{j\pi(\frac{V_1(t)}{V_\pi}+\frac{V_{b1}}{V_\pi})}], \quad (1)$$

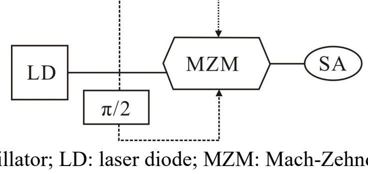
where α is the attenuation factor, γ is the splitting ratio, V_π is MZM half wave voltage, and V_1 and V_2 are LO driving voltages. The splitting ratio is related to MZM extinction ratio as[18]

$$\gamma=\frac{(1-\frac{1}{\sqrt{\mu_r}})}{2}, \quad (2)$$

$$\mu_r=10^{(\varepsilon_{MZM})/10}, \quad (3)$$

where ε_{MZM} is the extinction ratio of MZM.

For an ideal MZM, γ=0.5 corresponds to infinite extinction ratio of MZM. Let us assume that $1-\gamma=\beta$, $V_1(t)=V_m\sin(\omega_m t)$, $V_2(t)=V_m\sin(\omega_m t+\pi/2)$, and $V_{b1}=V_{b2}=0$. V_m is the LO voltage, and ω_m is the LO frequency.



LO: local oscillator; LD: laser diode; MZM: Mach-Zehnder modulator; SA: spectrum analyzer

Fig.1 Schematic diagram for MZM with arbitrary splitting ratio

Putting these values into Eq.(1), it can be re-written as

$$E_{MZM}(t)=\alpha E_c(t)\left[\gamma e^{jm_a\sin(\omega_m t+\frac{\pi}{2})}+\beta e^{jm_a\sin(\omega_m t)}\right], \quad (4)$$

where m_a is the modulation index (*MI*). The Jacobi Anger expansion is expressed as

$$e^{jm\sin\theta}=\sum_{n=-\infty}^{n=\infty}e^{jn\theta}, e^{jm\cos\theta}=\sum_{n=-\infty}^{n=\infty}j^n J_n(m)e^{jn\theta}. \quad (5)$$

Eq.(2) can be re-written in simplified form by utilizing Jacobi Anger expansion as:

$$E_{MZM}(t)=\alpha E_c(t)[\gamma\sum_{n=-\infty}^{\infty}J_n(m_a)e^{jn(\omega_m t+\frac{\pi}{2})}+\beta\sum_{n=-\infty}^{\infty}J_n(m_a)e^{jn(\omega_m t)}], \quad (6)$$

$$E_{MZM}(t)=\alpha E_c e^{j(\omega_c t)}\left[\sum_{n=-\infty}^{\infty}J_n(m_a)e^{jn(\omega_m t)}\right]\left\{(-1)^n\gamma+\beta\right\}. \quad (7)$$

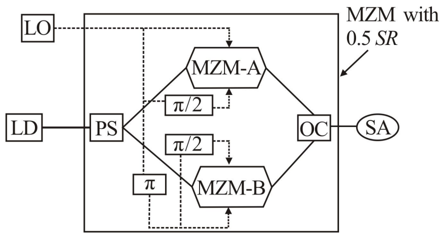
Eq.(7) represents the presence of all harmonics. However, the power of $(2n-1)$, i.e., odd harmonics, is less due to the $\{(-1)^n\gamma+\beta\}$ factor, which is reduced to $\{\beta-\gamma\}$ when n is odd.

Further, with the increasing order of Bessel function, the strength of the harmonics decreases as $J_n(m_a)$ is a decreasing function with respect to both n and m_a. If the MZM is considered to be ideal, i.e., γ=0.5, and $\beta=1-\gamma$=0.5, Eq.(7) can be expressed as

$$E_{MZM}(t)=\alpha E_c e^{j(\omega_c t)}\left[\sum_{n=-\infty}^{\infty}J_{2n}(m_a)e^{j2n\omega_m t}\right], \quad (8)$$

which depicts the existence of only $2n$ order sidebands, which is the optimum condition for MZM at maximum transmission point (MXTP).

Now, for cancelling out the effect of extinction ratio, we will describe that the output from MZM in ideal case can also be deduced from the non-ideal case as getting infinite extinction ratio MZM is not possible. The schematic diagram for realizing ideal MZM with optimal 0.5 splitting ratio is shown in Fig.2. It consists of two parallel non-ideal MZMs with non-infinite extinction ratio, which are driven by LO signal with a π phase shift.



PS: power splitter; OC: optical combiner

Fig.2 Schematic diagram for realizing MZM with optimal splitting ratio

The output of the system illustrated in Fig.2 is as follows

$$E_{MZM}(t)=\alpha E_c(t)\{[\gamma e^{j\pi\left(\frac{V_{2A}(t)}{V_\pi}+\frac{V_{b2}}{V_\pi}\right)}+(1-\gamma)e^{j\pi\left(\frac{V_{1A}(t)}{V_\pi}+\frac{V_{b1}}{V_\pi}\right)}]+$$

$$[\gamma \mathrm{e}^{\mathrm{j}\pi\left(\frac{V_{2B}(t)}{V_\pi}+\frac{V_{b2}}{V_\pi}\right)}+\left(1-\gamma\right)\mathrm{e}^{\mathrm{j}\pi\left(\frac{V_{1B}(t)}{V_\pi}+\frac{V_{b1}}{V_\pi}\right)}]\}, \qquad (9)$$

where $V_{1A}(t)=V_m\sin(\omega_m t)$, $V_{2A}(t)=V_m\sin(\omega_m t+\pi/2)$, $V_{1B}(t)=V_m\sin(\omega_m t+3\pi/2)$, $V_{2B}(t)=V_m\sin(\omega_m t+\pi)$, and $V_{b1}=V_{b2}=0$.

Eq.(9) can be re-written by utilizing above expressions as

$$E_{MZM}(t)=\alpha E_c(t)\{[\gamma \mathrm{e}^{\mathrm{j}m_a\sin\omega_m t}+\beta \mathrm{e}^{m_a\sin\left(\omega_m t+\frac{\pi}{2}\right)}]+$$
$$[\gamma \mathrm{e}^{\mathrm{j}m_a\sin\left(\omega_m t+\frac{3\pi}{2}\right)}+\beta \mathrm{e}^{m_a\sin(\omega_m t+\pi)}]\}. \qquad (10)$$

Eq.(10) can be further simplified by using Jacobi Anger expansion as follows

$$E_{MZM}(t)=\alpha E_c(t)\{[\gamma\sum_{n=-\infty}^{\infty}J_n\left(m_a\right)\mathrm{e}^{\mathrm{j}n\omega_m t}+\beta\sum_{n=-\infty}^{\infty}J_n\left(m_a\right)\mathrm{e}^{\mathrm{j}n\left(\omega_m t+\frac{\pi}{2}\right)}]+$$
$$[\gamma\sum_{n=-\infty}^{\infty}J_n\left(m_a\right)\mathrm{e}^{\mathrm{j}n\left(\omega_m t+\frac{\pi}{2}\right)}+\beta\sum_{n=-\infty}^{\infty}J_n\left(m_a\right)\mathrm{e}^{\mathrm{j}n(\omega_m t)}]\}. \qquad (11)$$

By putting $\beta=1-\gamma$, Eq.(11) can be rewritten as

$$E_{MZM}(t)=\alpha E_c \mathrm{e}^{\mathrm{j}(\omega_c t)}\left[\sum_{n=-\infty}^{\infty}J_n\left(m_a\right)\mathrm{e}^{\mathrm{j}n(\omega_m t)}\right]\left\{\left(-1\right)^n+1\right\}, \qquad (12)$$

$$E_{MZM}(t)=2\alpha E_c \mathrm{e}^{\mathrm{j}n\omega_c t}\left[\sum_{n=-\infty}^{\infty}J_{2n}\left(m_a\right)\mathrm{e}^{\mathrm{j}2n\omega_m t}\right]. \qquad (13)$$

Eq.(13) represents the existence of only $2n$ order sidebands, as in an ideal MZM at MXTP shown by Eq.(8), because MZM output is zero when n is odd. Thus, the output from MZM with 0.5 splitting ratio can be obtained through two non-ideal MZMs arranged in parallel configuration.

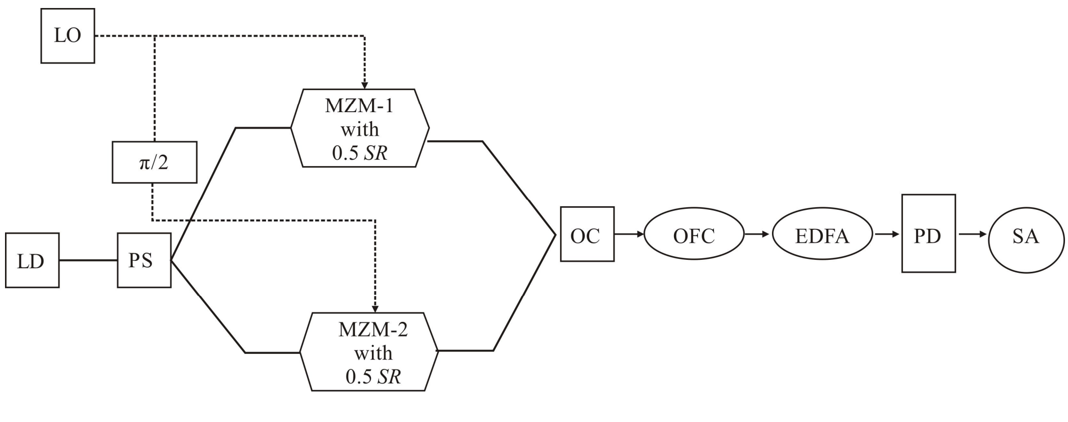
Fig.3 shows a schematic diagram for a frequency 8-tupling system realized through MZM with 0.5 optimal splitting ratio to make it extinction ratio tolerant.

The LO signal is fed to the parallel connection of modulators with a phase shift of 0 and $\pi/2$. Output from MZM is represented by Eq.(13). The outputs from both the modulators are combined at the optical coupler (OC). So, the input to OC is given as

$$E_{OC}(t)=\alpha E_c \mathrm{e}^{\mathrm{j}n\omega_c t}[\sum_{n=-\infty}^{\infty}J_{2n}\left(m_a\right)\mathrm{e}^{\mathrm{j}2n\omega_m t}+$$
$$\sum_{n=-\infty}^{\infty}J_{2n}\left(m_a\right)\mathrm{e}^{\mathrm{j}2n\omega_m t}\mathrm{e}^{\mathrm{j}n\frac{\pi}{2}}]. \qquad (14)$$

By expanding the summation terms, Eq.(14) can be rewritten as

$$E_{OC}(t)=\alpha E_c \mathrm{e}^{\mathrm{j}(\omega_c t)}\{[2J_2\left(m_a\right)\cos\left(2\omega_m t\right)+$$
$$2J_4\left(m_a\right)\cos\left(4\omega_m t\right)+2J_6\left(m_a\right)\cos\left(6\omega_m t\right)]+$$
$$[-2J_2\left(m_a\right)\cos\left(2\omega_m t\right)+2J_4\left(m_a\right)\cos\left(4\omega_m t\right)-$$
$$2J_6\left(m_a\right)\cos\left(6\omega_m t\right)]\}. \qquad (15)$$



EDFA: erbium doped fiber amplifier; PD: photodetector; *SR*: splitting ratio; OFC: optical fiber cable

Fig.3 Schematic diagram of frequency 8-tupling MM wave system with extinction ratio tolerance

Eliminating the higher order terms as the power of higher order terms is very negligible and the carrier frequency is completely suppressed when *MI* is set to 2.403 6. However, the 2nd and 6th order sidebands obtained at the outputs of the MZM-1 and MZM-2 are out of phase with each other as shown graphically in Fig.4.

So, they are cancelled out when combined at the OC and only the 4th order sidebands are obtained at the output of OC as shown in Fig.5.

Therefore, Eq.(15) can be presented as

$$E_{OC}(t)=4\alpha J_4\left(m_a\right)\cos(4\omega_m t). \qquad (16)$$

Eq.(16) depicts the presence of the 4th order sidebands at frequency ($\omega_c\pm4\omega_m$) obtained at the output of OC. Next section provides the framework and results obtained from the presented model.

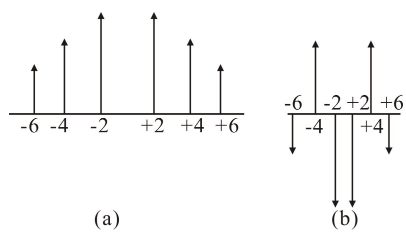


Fig.4 Graphical representation of output from (a) MZM-1 and (b) MZM-2

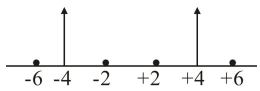


Fig.5 Graphical representation of output from OC

Fig.6 presents the simulation model of proposed extinction ratio tolerant model for frequency octupling MM wave generation. An LD emitting carrier frequency at 193.1 THz with 0 dBm optical power and 10 MHz linewidth acts as an optical source. An LO signal with 10 GHz frequency is applied to the parallel configuration of MZM with 0.5 splitting ratio as its internal subsystem.

The MZM with 0.5 optimal splitting ratio is realized through two non-ideal MZMs with 4 V half wave voltage and 0 dB insertion loss biased at MXTP with a 90° phase difference between the two arms of the modulator and 180° phase shift between both the modulators. The outputs of MZM-1 and MZM-2 consist of ($\omega_c\pm2\omega_m$) at 193.08 THz and 193.12 THz, ($\omega_c\pm4\omega_m$) at 193.06 THz and 193.14 THz, and ($\omega_c\pm6\omega_m$) at 193.04 THz and 193.16 THz, as shown in Fig.7.

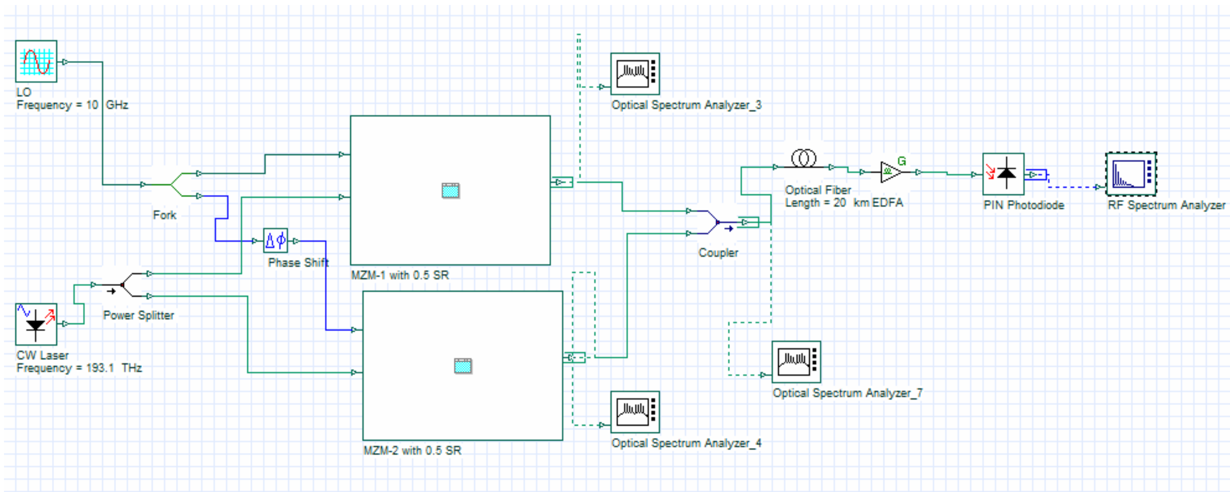


Fig.6 Proposed extinction ratio tolerant model for frequency octupling

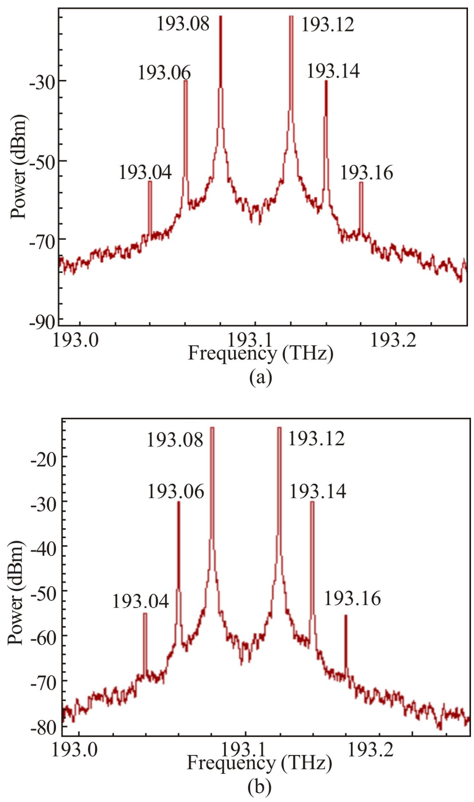
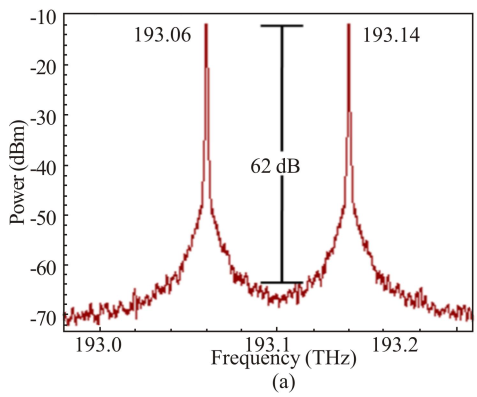
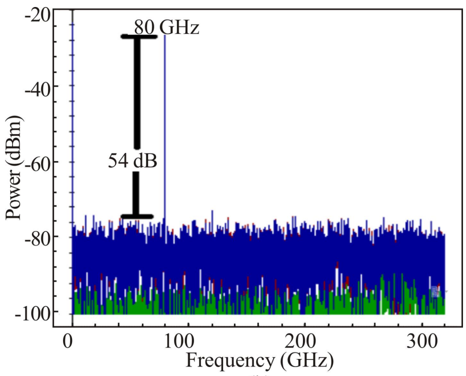


Fig.7 (a) Output from MZM-1; (b) Output from MZM-2

The outputs from both the MZMs are coupled through the OC and two 4th order sidebands are obtained at its output as presented in Fig.8(a). It can be clearly observed that all the unwanted sidebands are completely eliminated at *MI* value of 2.403 6. These sidebands are transmitted through the optical fiber to the photodetector (PD) after being optically amplified through the erbium doped fiber amplifier (EDFA). At the PD, both the sidebands beat to generate a high frequency electrical signal at 80 GHz. The RF spectrum of the photo-detected signal is shown in Fig.8(b) and the important parameters considered while carrying out simulation over the Optiystem v17.0.0 software are list in Tab.1.

For characterizing the system performance, the impacts of *MI*, extinction ratio and phase drift on *SSR* are examined. Firstly, the impact of *MI* is examined and shown in Fig.9.





(b)

Fig.8 (a) Optical spectrum output from optical coupler; (b) RF spectrum output from PD

Tab.1 Simulation parameters

Parameter	Value	Unit
Bit rate	10	Gbit/s
Symbol rate	10×10^{9}	symbols/s
Reference wavelength	1 550	nm
Laser frequency	193.1	THz
Laser linewidth	10	MHz
LO frequency	10	GHz
MZM extinction ratio	10—100	dB
Switching RF voltage	4	V
Optical fiber length	20	km
Dispersion coefficient	16.75	Ps/nm·km
EDFA gain	20	dB
EDFA noise figure	4	dB
PIN responsivity	1	A/W
PIN dark current	10	nA

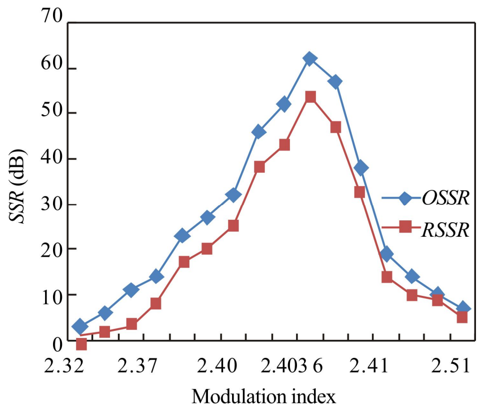


Fig.9 Variation of *SSR* with modulation index

Fig.9 shows the variations in *SSR* with respect to different *MI*. All the other parameters are kept the same and the *MI* is varied from 2.19 to 2.51. The power of carrier is higher than the 4th order sidebands and it goes on decreasing as the *MI* is increased. The carrier power becomes equal to the sidebands power when *MI* is adjusted to 2.3. The *OSSR* greater than 10 dB is reported when the *MI* varies in a wide range from 2.36 to 2.47. However, its peak value of 62 dB occurs at the value of 2.403 6 as depicted in Fig.8(a).

Fig.10 depicts the variations in *SSR* with respect to extinction ratio of MZM connected in parallel connection. The extinction ratio parameter is individually varied for the two MZMs with 0.5 splitting ratio, which in turn consist of two non-ideal MZMs. It can be clearly seen that the system is insensitive towards extinction ratio variation, i.e., the system is extinction ratio tolerant by making the system stable.

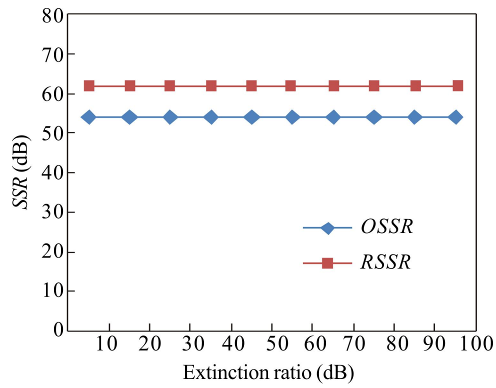


Fig.10 Variation of *SSR* with extinction ratio

The proposed technique consists of one π/2 phase shifter and two optimal 0.5 splitting ratio MZMs. The optimal splitting ratio MZM is further realized using two MZMs, two π/2 and one π phase shifters. For evaluating the systems performance on phase drift, the *SSR* variation with phase drift in phase shifters is evaluated and depicted in Fig.11.

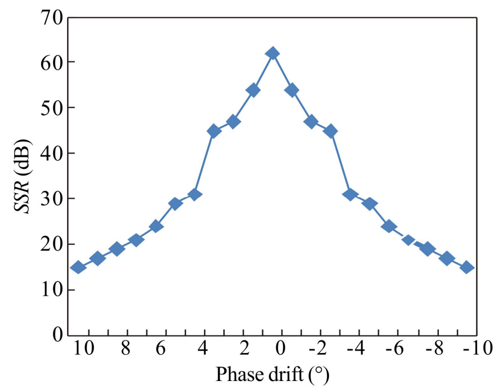


Fig.11 Variation of *SSR* with drift in phase shifter

It can be clearly seen that the system shows *SSR* higher than 15 dB for ±10° phase drift in the π/2 phase shifters. Thus, the system shows tolerance towards phase drift in the phase shifter.

An extinction ratio tolerant frequency 8-tupled model is presented using two optimal splitting ratio MZMs in parallel configuration. The optimal splitting ratio MZM is realized through two non-ideal MZMs, two π/2 and one π phase shifters. With appropriate biasing and phase shift adjustment, a high quality MM wave at 80 GHz is generated from 10 GHz LO signal with 62 dB *OSSR* and

54 dB *RSSR* when *MI* is adjusted to 2.403 6 without any restriction on extinction ratio. The proposed system does not require any filter. Therefore, it can generate any large tunable high frequency MM wave signal by octupling the LO input signal.

Further, the performance of the proposed technique is examined by varying different parameters, such as *MI*, phase drift and extinction ratio of MZM. The *SSR* higher than 10 dB is reported in a wide *MI* range of 2.36—2.47. Both the *SSRs* are found to be tolerant towards MZM extinction ratio and the scheme is insensitive towards ±10° phase drift in π/2 phase shifters. The presented work can be applied for WDM RoF applications.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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