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Linearization of Photonic Link Based on Phase-Controlled Dual Drive Dual-Parallel Mach–Zehnder Modulator

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Abstract
This paper presents analytical analysis for a linearization method of a microwave photonic (MWP) link based on dual-drive dual-parallel Mach–Zehnder Modulator. Electric phase shifters are utilized to suppress intermodulation distortion terms and to further increase linearity of the link. A simulation model is designed to evaluate spurious free dynamic range (SFDR) against third order intermodulation distortion as it is a key performance measurement parameter of MWP link. A suppression of 68 dB is found in intermodulation terms and SFDR enhances by 16 dB which ensures the improvement in performance of link against intermodulation terms.

Keywords MWP · SFDR · IMD · DD-DPMZM

1 Introduction

A potential solution to meet user's ever rising demand for higher bandwidth is to exploit high frequency band of radio spectrum as low frequency spectrum is already over occupied [1]. These high frequency waves i.e. millimeter (mm waves) offers broad bandwidth at cost of lesser distance travelled [2]. This limitation can be overcome by modulating high radio frequency (RF) signal upon an optical carrier [3]. This modulated signal is carried over an optical fiber up to a base station and then received on a mobile station wirelessly [4]. This technique is termed as radio-over-fiber (RoF) technology and offers low insertion losses, low transmission losses and remains immune to electro-magnetic interference [5].

The key requirement for designing an efficient RoF link is to find out a method to modulate RF signal while suppressing all possible losses [6]. However, most commonly used modulator in RoF system is Mach–Zehnder modulator (MZM) and perceived as one of the external modulator [7]. These modulators introduces numerous non-linear terms during modulation process due to modulator's inherent non-linearity but considered as promising

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candidate due their high stability and spectral purity [8]. These non-linear terms and photoelectric detection can significantly degrade SFDR of link during direct detection [9]. Out of these terms, third order intermodulation distortion (IMD3) needs to be taken care as they interfere with fundamental signal frequencies [10].

So far many linearization schemes to enhance SFDR against IMD3 have been investigated based on dual- parallel MZM (DPMZM) [11–18]. Linearization in DPMZM arrangements is achieved either by controlling optical power being fed to two different sub-MZMs [11–14] or by adjusting bias voltages of DPMZM and by changing phases of driving RF signals [15–18]. These schemes results in partial cancellation of IMD3 and asymmetrical splits ratios of optical powers results in receded output power of fundamental signal [18]. Thus, link SFDR is still IMD3 limited.

In the present paper, a method for complete suppression of IMD3 in microwave photonic (MWP) link is investigated and demonstrated. A dual- drive DPMZM (DD-DPMZM) with only two simple electrical phase shifters is used for optimizing the biases of two sub modulators. A theoretical analysis of dual tone is also appended to understand the cancellation of IMDs. A simulation model has been designed and results have been drawn which are found to be in agreement with theoretical analysis, showing complete elimination of IMD3. An increment of 16 dB is observed in SFDR when compared with conventional non-linearized MWP link.

2 Operation and Principle

Figure 1 shows the schematic diagram of the proposed linearized MWP link. This model utilizes a laser diode (LD), RF sources, two electric phase shifters, a photo-diode (PD) and one DD-DPMZM.

The modulator further consists of two sub-MZMs which are configured as intensity modulated and quadrature biased MZM. RF sources are used to produce two RF tones i.e. RF_1 and RF_2 of same amplitude and of frequencies Ω_1 and Ω_2 respectively. Upper MZM is biased at V_π i.e. half wave voltage of modulator and phase difference between two RF signals fed on two electrodes of modulator is π which generates single sideband optical carrier suppression (OCS) modulation. OCS promises constructive information transmission. Whereas, lower MZM is biased at $V_\pi/2$ and phase difference between the two RF signals fed at two electrodes is 0. Therefore, quadrature modulation is achieved at lower MZM.

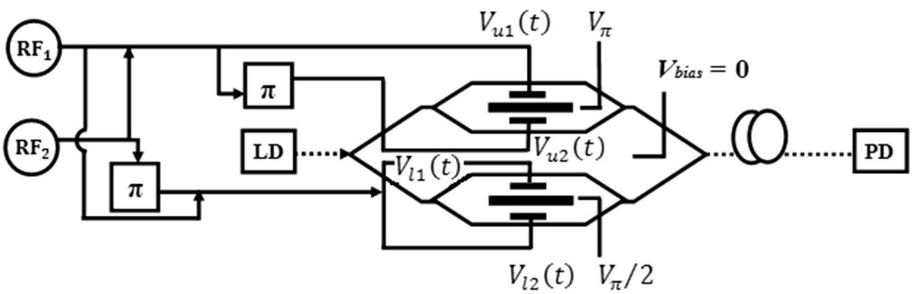

Fig. 1 Schematic diagram of the linearized MWP link using DD-DPMZM and phase shifters

Optical carrier from LD is launched in DD-DPMZM having an optical field $E_{in}(t)$ and can be expressed as:

$$E_{in}(t) = \mathrm{X}_0 \exp\left(\mathrm{j}\omega_0 \mathrm{t}\right)$$

where X_0 and ω_0 is the amplitude and angular frequency of optical carrier. To eliminate IMD3 completely, drive voltages at four electrodes of MZMs with DC biases are given as [11]

$$V_{u1}(t) = V_0\left(\cos \Omega_1 t + \cos \Omega_2 t\right) + V_\pi/2$$

$$V_{u2}(t) = V_0\left[\cos(\Omega_1 t + \pi) + \cos(\Omega_2 t + \pi)\right] - V_\pi/2$$

$$V_{l1}(t) = V_0\left[\cos \Omega_1 t + \cos(\Omega_2 t + \pi)\right] + V_\pi/4$$

$$V_{l2}(t) = V_0\left[\cos \Omega_1 t + \cos(\Omega_2 t + \pi)\right] - V_\pi/4$$

Here V_0 is the amplitude of input electrical signal. $V_{u1}(t)$, $V_{u2}(t)$, $V_{l1}(t)$ and $V_{l2}(t)$ are the drive voltages on electrodes of upper MZM and lower MZM. The field at output of upper MZM can be expressed as:

$$E_1(t) = \left[\exp\left(\mathrm{j}\pi V_{u1}(t)/V_\pi\right) + \exp\left(\mathrm{j}\pi V_{u2}(t)/V_\pi\right)\right]\mathrm{E_{in}(t)}$$

It can further be simplified as

$$E_1(t) = \begin{bmatrix} exp\left(\mathrm{jm}\cos \Omega_1 t\right) * exp\left(\mathrm{jm}\cos \Omega_2 t\right) * exp(\mathrm{j}\pi/2) + \\ exp\left(-\mathrm{jm}\cos \Omega_1 t\right) * exp\left(-\mathrm{jm}\cos \Omega_2 t\right) * exp(-\mathrm{j}\pi/2) \end{bmatrix}\mathrm{E_{in}(t)}$$

where $m = \pi V_0/V_\pi$ is the modulation depth.

$$E_1(t) = \left[\mathrm{jexpjm}\left(\cos \Omega_1 t + \cos \Omega_2 t\right) - \mathrm{jexp(-jm)}\left(\cos \Omega_1 t + \cos \Omega_2 t\right)\right]\mathrm{E_{in}(t)}$$

By using Taylor series expansion, above eqn. can be expended to the third power of m and rewritten as

$$E_1(t) = -2\left[m\left(\cos \Omega_1 t + \cos \Omega_2 t\right) - m^3\left(\cos \Omega_1 t + \cos \Omega_2 t\right)^3/3!\ldots\right] \tag{1}$$

Similarly, the output optical field at lower MZM can be expressed as:

$$E_2(t) = \left[\exp\left(\mathrm{j}\pi V_{l1}(t)/V_\pi\right) + \exp\left(\mathrm{j}\pi V_{l2}(t)/V_\pi\right)\right]\mathrm{E_{in}(t)}$$

$$\begin{aligned} E_2(t) &= \begin{bmatrix} exp\left(\mathrm{jm}\cos \Omega_1 t\right) * exp\left(-\mathrm{jm}\cos \Omega_2 t\right) * exp(\mathrm{j}\pi/4) + \\ exp\left(\mathrm{jm}\cos \Omega_1 t\right) * exp\left(-\mathrm{jm}\cos \Omega_2 t\right) * exp(-\mathrm{j}\pi/4) \end{bmatrix}\mathrm{E_{in}(t)} \\ &= \exp\mathrm{jm}\left(\cos \Omega_1 t - \cos \Omega_2 t\right)\left[\exp(\mathrm{j}\pi/4) + \exp(-\mathrm{j}\pi/4)\right]\mathrm{E_{in}(t)} \end{aligned}$$

Again, by using Taylor series expansion and expanding above eqn. to the third power of m, $E_2(t)$ is given as

$$E_2(t) = \sqrt{2}\begin{bmatrix} \left\{1 - m^2\left(\cos\Omega_1 t - \cos\Omega_2 t\right)^2/2! + \cdots\right\} + \\ j\left\{\mathrm{m}\left(\cos\Omega_1 t - \cos\Omega_2 t\right) - m^3\left(\cos\Omega_1 t - \cos\Omega_2 t\right)^3/3! + \cdots\right\} \end{bmatrix}\mathrm{E_{in}(t)} \quad (2)$$

The total optical field at the output of DPMZM can be given as $E_{out}(t) = \left[E_1(t) + E_2(t)\right]/\sqrt{2}$ by biasing it to zero point. Now, photocurrent produced at output of PD can be expressed as $I(t) = \Re E_{out}(t) * E^*_{out}(t)$, $\Re$ represents the responsivity of PD. Therefore, expression for output photocurrent can be derived as

$$I(t) = \Re * P_{in} * \begin{bmatrix} 1 - 2\sqrt{2m}\left\{\cos\Omega_1 t + \cos\Omega_2 t\right\} \\ +m^2\left\{\begin{matrix} 1 + (1/2)\cos 2\Omega_1 t + \cos\left(\Omega_1 - \Omega_2\right)\mathrm{t} \\ +(1/2)\cos 2\Omega_2 t + \cos\left(\Omega_1 + \Omega_2\right)\mathrm{t} \end{matrix}\right\} \\ +m^3\sqrt{2}\left\{\begin{matrix} (1/3)\cos 3\Omega_1 t + \cos\Omega_2 t \\ (1/3)\cos 3\Omega_2 t + \cos\Omega_1 t \end{matrix}\right\} + \cdots \end{bmatrix} \quad (3)$$

In Eq. (3), only fundamental terms can be seen while frequency terms i.e. $(2\Omega_1 - \Omega_2)$ and $(2\Omega_2 - \Omega_1)$ are removed completely. These frequency terms impart non-linearity and are majorly responsible for degradation of SFDR of the link. Hence, a linearized MWP link with better performance is obtained with complete suppression of IMD3 terms by employing DD-DPMZM.

3 Results and Discussion

A simulation model is built according to the set up as shown in Fig. 1 with Optsim to verify the cancellation of intermodulation distortion. A comparison between conventional scheme based on quadrature biased MZM and linearized scheme based DD-DPMZM is obtained through numerical simulation based on MATLAB. To analyze the performance of considered MWP link, an optical carrier of 1550 nm with the power of 16 dB from LD is sent to sub-MZMs. Two RF signals of frequencies 9.1 and 9.5 GHz are generated by signal generator and introduced to upper and lower MZMs through two different paths and phase shifters are set to achieve the designed arrangement as discussed earlier. Modulation loss and half wave voltage of DD-DPMZM are taken as 5 dB and 5 V. The responsivity of PD is considered as 0.8 A/W and modulation depth is chosen as 0.8 for performance evaluation. Output of DD-DPMZM is sent to PD where electric spectrums are generated using electric spectrum analyzer (ESA).

In Fig. 2, as power of RF input signal increases, variations in fundamental and IMD3 power are outlined to evaluate SFDR. In Fig. 2a, b, SFDR for conventional quadrature biased MZM is measured as 114.8 dB $\mathrm{Hz}^{2/3}$ which improve to 130.8 dB $\mathrm{Hz}^{4/5}$ in linearized DD-DPMZM link after IMD3 compensation. Noise floor is taken −161 dBm/Hz. Also, slope for intermodulation power changes from 3 to 5 which indicate that third order non-linear distortion product terms are suppressed and link performance is limited by fifth order IMDs. An enhancement of 16 dB in SFDR is obtained through this arrangement.

Figure 3a, b shows optical spectrum at the output of upper MZM and lower MZM. In Fig. 3a, as upper MZM is biased at V_π and π is the phase difference between the signals of two electrodes, OCS is generated at the output of upper MZM with centre frequency of 193.414 THz. OCS promises effective information transmission as useful

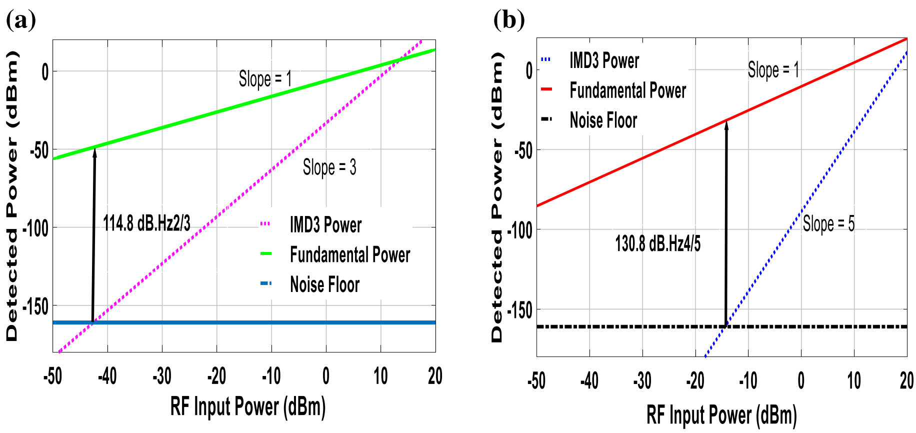

Fig. 2 Measured SFDR for link based on **a** quadrature biased MZM and **b** linearized DD-DPMZM

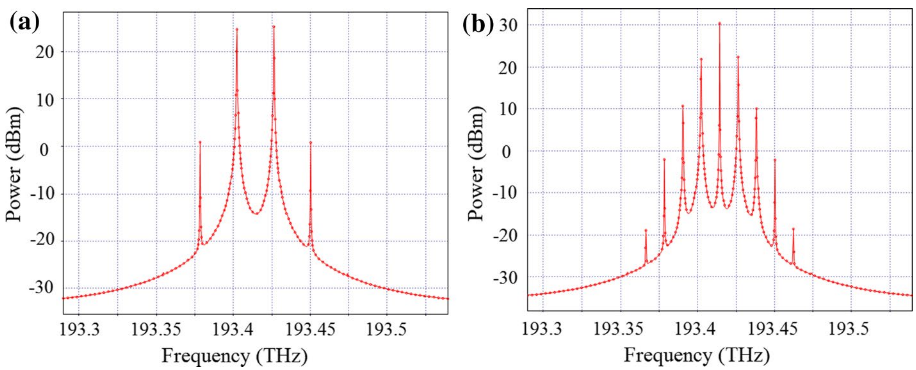

Fig. 3 Measured optical spectrum at the output of **a** upper and **b** lower MZM

signal gains more power on optical side bands. Whereas, in Fig. 3b, two electrodes of lower MZM modulate same electrical signal biased at $V_\pi/2$ results in simple quadrature biasing action.

Electrical spectrum at the output of PD for conventional as well as linearized DPMZM link is shown in Fig. 4. In Fig. 4a, at frequencies 8.7 and 9.9 GHz prominent signal peak can be seen. These frequencies are perceived as IMD3 frequencies and need to be suppressed for better performance of link. However, these frequencies are completely eliminated or much lower and only modulated signal frequency peak can be seen at 9.1 and 9.5 GHz in Fig. 4b. A suppression of approximately 68 dB is seen in IMD3 for considered DD-DPMZM link as compared to conventional link.

Figure 5 shows the power variation of detected power as a function of input RF power for fundamental and intermodulation power. IMD3 is suppressed using DD-DPMZM as the slope of intermodulation product power is slope 5 which ensures the linearity of the link. Hence, it is quite clear that link's non-linearity can be improved by employing a phase-controlled DD-DPMZM.

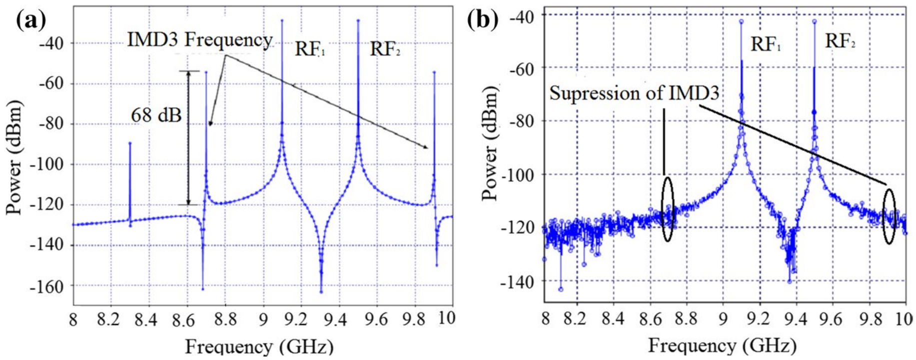

Fig. 4 Measured electrical spectrum at the output of PD for **a** quadrature biased MZM and **b** linearized DD-DPMZM

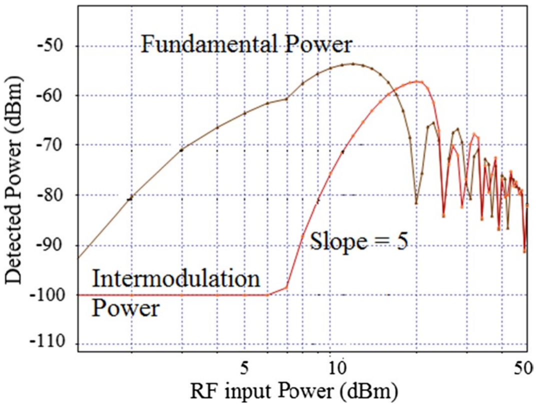

Fig. 5 Comparison of detected fundamental power and intermodulation power

4 Conclusion

In this paper, a photonic link is linearized using electric phase shifters and optimizing the biases of the DD-DPMZM. Simulation results are in good accordance with theoretical work. A suppression of 68 dB is observed in IMD3 terms and SFDR is improved by 16 dB when SFDR for linearized dual-drive DD-DPMZM is found to be 130.8 dB $Hz^{4/5}$ while the SFDR for conventional system was 114.8 dB $Hz^{2/3}$. This improvement in SFDR helps to improve the design and stability of the MWP link without using any digital processing.

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