Microwave Photonic Link With Improved Dynamic Range Through π Phase Shift of the Optical Carrier Band

Yiying Gu, *Member, IEEE*, and Jianping Yao, *Fellow, IEEE, Fellow, OSA*

***Abstract*—A microwave photonic link (MPL) with an improved spurious-free dynamic range (SFDR) by introducing a π phase shift to the spectral complements in the optical carrier band (OCB) is proposed and experimentally demonstrated. The fundamental concept to improve the SFDR is to suppress the third-order intermodulation distortion (IMD3) terms while retaining a high gain for the fundamental terms, which is achieved by introducing a π phase shift to the OCB with the joint use of an electrical 90° hybrid coupler and a dual-parallel Mach–Zehnder modulator (DP-MZM). When detecting the optical signal from the DP-MZM at a photodetector, the IMD3 components originated from the beating between different optical sidebands can be fully cancelled, while the gain for the fundamental terms remains reasonably high. Therefore, the SFDR of the MPL is significantly increased. The proposed MPL is experimentally demonstrated. An SFDR of 108.1 dB·Hz$^{2/3}$ or 120.4 dB·Hz$^{2/3}$ for a noise floor of −146.9 or −163.9 dBm/Hz is achieved, which is 14 dB or 15 dB higher than that of a conventional intensity-modulation direct-detection MPL.**

***Index Terms*—Microwave photonic link (MPL), parallel intensity modulators, spurious-free dynamic range (SFDR), third-order intermodulation.**

I. Introduction

MICROWAVE signal transmission based on photonic links is considered an effective solution for wideband and low-loss analog microwave signal transmission, which can find applications in next generation wireless networks, radar and electronic warfare systems [1]–[3]. A conventional intensity-modulation direct-detection (IMDD) microwave photonic link (MPL) utilizes a Mach-Zehnder modulator (MZM) to impose a microwave signal on an optical carrier and directly detect the microwave signal at a photodetector (PD). The system is simple and can be easily implemented. Due to the inherent nonlinear transfer function of an MZM, high order intermodulation (IMD) components are generated which will limit the spurious-free dynamic range (SFDR) [4], [5]. The SFDR of an MPL, defined as the power range between the smallest power of a fundamental signal that is above the noise floor and the largest power that makes the power of the IMD terms, say the third-order intermodulation (IMD3) terms, equal to the power of the noise floor, is a measure to characterize the linearity of an MPL. A large SFDR means a large power range of an input signal that can be detected. Among the IMD terms, the IMD3 terms are the most significant components which have higher powers than the fifth-order intermodulation (IMD5) terms and their frequencies fall within the frequency band of the fundamental signals and cannot be easily filtered out. Therefore, the existence of IMD3 terms will limit the SFDR.

To increase the SFDR of an MPL, the IMD3 terms must be suppressed. Numerous methods have been proposed and experimentally demonstrated in recent years. Electrical linearization is an effective solution to alleviate the IMD3 components, such as electronic predistortion [6], post processing [7], [8], and feed-forward linearization [9], [10]. However, the bandwidth of an electronic circuit, either analog or digital, is very limited.

To achieve a wide bandwidth and highly linear MPL, optical techniques have been proposed. The SFDR of an MPL can be improved by increasing the link gain, reducing the link noise floor, or suppressing the IMD components [11]. For example, an improvement in SFDR via increasing the link gain was achieved by low biasing an MZM to partially suppress the optical carrier [12], [13]. By maintaining the same total input power to the PD, the gain of the MPL is increased, which leads to the increase in the SFDR. By employing a class-AB MPL [14], [15], the SFDR can also be increased. Since the shot noise generated at the PD is proportional to the input optical power, a class-AB MPL has a lower input optical power to the PD, which leads to a lower noise floor, enabling a higher SFDR.

Instead of using IMDD, the use of phase modulation and coherent detection (PMCD) with the support of a digital signal processor (DSP) can also reduce the IMD3 terms [16]. Theoretically, a PMCD link is purely linear. The SFDR of a practical PMCD link is finite, which is mainly limited by the resolution, the bandwidth, and the relative phase error of the DSP.

Directly suppressing the IMD terms is another effective way to increase the SFDR, which can be done by using a pair of

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MZMs [17] or polarization modulators (PolMs) [18] that are operating in a complementary fashion to cancel the IMD3 terms, or through optical carrier band (OCB) processing [19], [20]. However, the approaches in [12]–[20] have some limitations. In [12], [13], the major limitation is that the even-order distortions especially the second-order intermodulation distortion (IMD2) terms will be enhanced when increasing the link gain, which is not expected especially for the multi-octave operation of an MPL. In a class-AB MPL [14], [15], the noise floor is decreased, but the IMD3 terms are not reduced. The use of PMCD will have the best performance in terms of SFDR [16], but the implementation requires a high-speed DSP, making the link with a smaller bandwidth due to the limited speed of a DSP. The use of a pair of MZMs [17] or PolMs [18] to cancel the IMD3 terms is an effective solution to increase the SFDR. However, when the IMD3 terms are cancelled, the fundamental signals are also partially cancelled, making the link gain reduced. In addition, in a parallel complementary MPL, an optical tunable delay line (TDL), a pair of PDs or single PD with two polarization controllers (PCs) and a polarization beam splitter (PBS) are used, the MPL is complicated and the stability becomes poor. In an MPL through OCB processing, an optical phase shifter, which was a waveshaper in [19], [20], was used to change the phase of the OCB, which would increase the complexity and cost of the MPL, and limit the application of the MPL due to the limited processing bandwidth of the waveshaper.

In this paper, we propose a new and simple scheme by introducing a π phase shift to the OCB in a parallel complementary MPL to improve the SFDR while maintaining a reasonably high link gain without the processing bandwidth limitation. In the proposed MPL, a dual-parallel Mach-Zehnder modulator (DP-MZM) and an electrical 90° hybrid coupler (HC) are used. The DP-MZM consists of two sub-MZMs embedded in a parent MZM. The upper sub-MZM driven by a microwave signal is biased at a positive low-bias point to generate a partially carrier-suppressed double-sideband signal. The lower sub-MZM driven by the same microwave signal after the electrical 90° HC is biased at the maximum transmission point to generate π-phase shifted second-order sidebands. The parent MZM is biased at the minimum transmission point to introduce a π phase shift between the optical signals from the two sub-MZMs, which results in a π phase shift to the OCB. If the optical powers into the two sub-MZMs are considered to be identical, by adjusting the bias point of the upper sub-MZM at an appropriate low-bias point, the IMD3 components originated from two different channels will have opposite phase with equal power and will be fully cancelled. In addition, the gain for the fundamental terms will remain large which is also instrumental in improving the SFDR of the link. The proposed MPL is experimentally evaluated. The experimental results show that an SFDR of 108.1 dB·Hz$^{2/3}$ or 120.4 dB·Hz$^{2/3}$ for a noise floor of -146.9 or -163.9 dBm/Hz is achieved, which is 14 dB or 15 dB higher than that of a conventional IMDD MPL.

II. Operation Principle

The operation principle of the proposed MPL with an increased SFDR is illustrated in Fig. 1. The MPL consists of a laser diode (LD), a PC, a DP-MZM, an electrical 90° HC, an erbium-doped fiber amplifier (EDFA), and a PD. A continuous-wave optical carrier from the LD is coupled into the DP-MZM which consists of two sub-MZMs embedded in a parent MZM. In order to minimize the polarization-dependent loss, the PC is connected before the DP-MZM to align the polarization direction of the optical carrier with the principal axis of the DP-MZM to minimize the polarization-dependent loss. The optical carrier is modulated by a microwave signal at the DP-MZM. Two bias voltages, V_{DC1} and V_{DC2}, are applied to the upper and lower sub-MZMs, respectively. The upper sub-MZM is biased at the low-bias point on the positive slope of the transfer function to generate a partially carrier-suppressed double-sideband signal. The lower sub-MZM is biased at the maximum transmission point to generate an odd-order-suppressed optical signal. A two-tone microwave signal generated by a signal generator is split into two channels by an electrical 90° HC, with the 0° output port connected to the upper sub-MZM, and the 90° output port connected to the lower sub-MZM, to introduce a 90° phase difference between the microwave signals applied to the upper and lower sub-MZMs. The parent MZM is biased at the minimum transmission point via controlling a third bias voltage, V_{DC3}, to realize a π phase difference between the output signals from the two sub-MZMs. After amplification by the EDFA, the microwave-modulated optical signal at the output of the DP-MZM is sent to the PD to recover the microwave signal. Positive and negative IMD3 components, generated due to the beating between optical sidebands, will be fully cancelled at the output of the PD due to the destructive combination of the positive and negative IMD3 components which are controlled to be equal in magnitude.

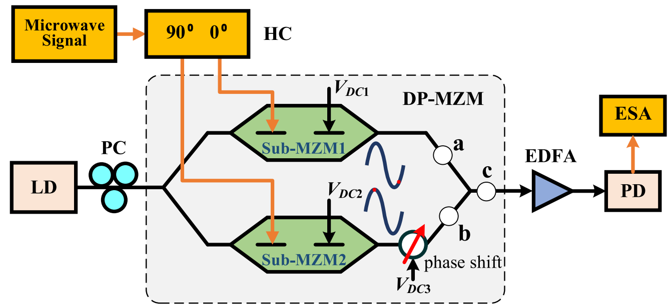

Fig. 1. Schematic diagram of the proposed MPL. HC: electrical 90° hybrid coupler, LD: laser diode, DP-MZM: dual parallel Mach-Zehnder modulator, PC: polarization controller, EDFA: erbium-doped fiber amplifier, PD: photodetector, ESA: electrical spectrum analyzer.

First, we analyze the main contribution to the IMD3 components in a conventional IMDD MPL if only the upper sub-MZM of the DP-MZM is considered, as shown in Fig. 1. The electrical field of the optical carrier from the LD is given by

$$E_{in}\left(t\right) = E_0 \exp\left(j\omega_c t\right) \tag{1}$$

where ω_c is the angular frequency of the optical carrier, and E_0 is the electrical field amplitude. Assuming the sub-MZM has no insertion loss, a two-tone microwave signal at two angular frequencies of Ω_1 and Ω_2 is modulated on the optical carrier, and the electrical field at the output of the upper sub-MZM can

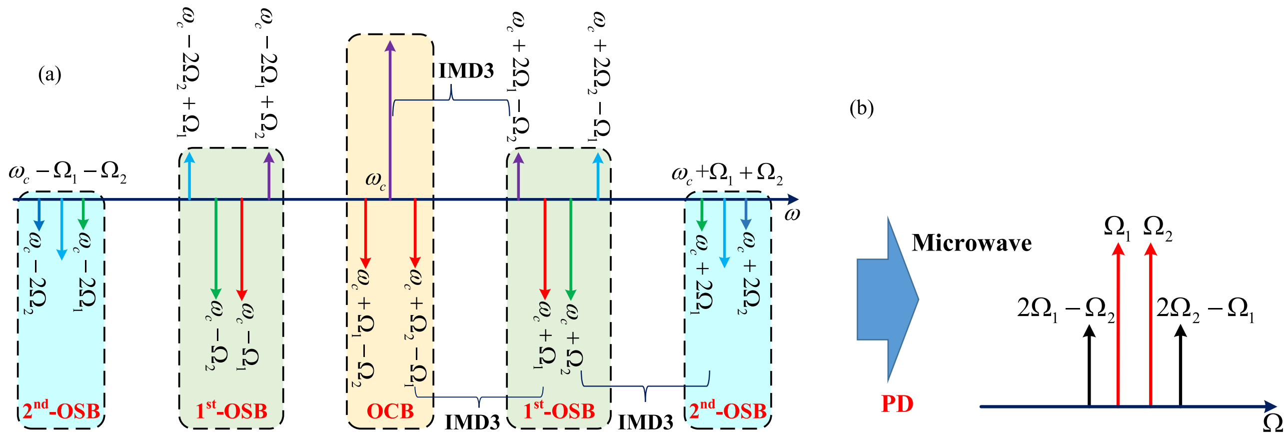

Fig. 2. Illustration of the generation of the IMD3 components of a conventional MPL, in which the MZM is biased at the quadrature point. (a) The optical spectral components at the output of the MZM, and (b) the spectrum of the detected electrical signal by the PD.

be expressed as

$$E_{out1}(t) = \frac{1}{2}E_0 \exp(j\omega_c t) \times \begin{Bmatrix} \exp\left[j\frac{\pi}{2V_\pi}\left(V_{DC1} + V_{MW}\cos\Omega_1 t + V_{MW}\cos\Omega_2 t\right)\right] \\ + \exp\left[-j\frac{\pi}{2V_\pi}\left(V_{DC1} + V_{MW}\cos\Omega_1 t + V_{MW}\cos\Omega_2 t\right)\right] \end{Bmatrix} \tag{2}$$

where V_π is the microwave half-wave voltage of the upper sub-MZM, V_{DC1} is the bias voltage applied to the upper sub-MZM, and V_{MW} is the amplitude of the input two-tone microwave signal. Using Bessel expansion, (2) can be further expressed by

$$\begin{aligned} E_{out1}(t) = {} & \frac{1}{2}E_0 \sum_{p=-\infty}^{+\infty}\sum_{q=-\infty}^{+\infty}\left[\exp\left(j\frac{\varphi}{2}\right) + (-1)^{p+q}\exp\left(-j\frac{\varphi}{2}\right)\right] \\ & \cdot j^{p+q} \cdot J_p\left(\frac{m}{2}\right)J_q\left(\frac{m}{2}\right)\exp\left(j\omega_c t + jp\Omega_1 t + jq\Omega_2 t\right) \end{aligned} \tag{3}$$

where $m = \pi V_{\mathrm{MW}}/V_\pi$ is the modulation index, $\varphi = \pi V_{DC1}/V_\pi$ is the bias angle of the upper sub-MZM, $J_p(m/2)$ and $J_q(m/2)$ are the Bessel functions of the first kind of orders p and q. Ignoring the higher order sidebands and the intermodulation terms (≥3), the optical field at the output of the upper sub-MZM is given by

$$\begin{aligned} E_{out1}(t) &\approx \frac{1}{2}E_0 \sum_{p=-2}^{+2}\sum_{q=-2}^{+2} a_{p,q}\exp\left(j\omega_c t + jp\Omega_1 t + jq\Omega_2 t\right) \\ a_{p,q} &= j^{p+q} \cdot J_p\left(\frac{m}{2}\right)J_q\left(\frac{m}{2}\right)\left[\exp\left(j\frac{\varphi}{2}\right) + (-1)^{p+q}\exp\left(-j\frac{\varphi}{2}\right)\right] \end{aligned} \tag{4}$$

In a conventional IMDD MPL, the MZM is always biased at the quadrature point to achieve high linear modulation, then we have $\varphi = \pi/2$. As can be seen, the optical signal at the output of a conventional IMDD MPL contains the optical carrier, different orders of sidebands and IMD components, as shown in Fig. 2(a). These sidebands and IMD components, based on their spectral locations, can be considered in groups. If higher order components are not considered, we have five groups, the one centered at the optical carrier or the OCB, two first-order optical sidebands (1st-OSBs), and two second-order optical sidebands (2nd-OSBs), as shown in Fig. 2(a). Two spectrum components with the same color are grouped as a pair to generate an IMD3 term when beating at a PD. When the output optical signal is sent to a PD, any two optical components will beat, leading to the generation of the fundamental signals at Ω_1 and Ω_2 and the IMD3 components at $2\Omega_1 - \Omega_2$ and $2\Omega_2 - \Omega_1$, as shown in Fig. 2(b).

Then, the operation of the proposed scheme, shown in Fig. 1, is analyzed. In the proposed MPL, a DP-MZM consisting of two sub-MZMs is employed. In the upper channel, the sub-MZM is biased at the low-bias point, and the output optical field is given by (4). The spectral components in the OCB, the 1st-OSBs, and the 2nd-OSBs are shown in Fig. 3(a). In the lower channel, the sub-MZM is biased at its maximum transmission point where the optical carrier is modulated by the two-tone microwave signal after an electrical 90° HC to generate odd-order suppressed signals. When ignoring the higher order sidebands and the intermodulation terms (≥3), the optical field at the output of the lower sub-MZM is given by

$$\begin{aligned} E_{out2}(t) \approx {} & E_0 \cdot J_0\left(\frac{m}{2}\right)J_0\left(\frac{m}{2}\right)\exp\left(j\omega_c t\right) \\ & - E_0 \cdot J_1\left(\frac{m}{2}\right)J_1\left(\frac{m}{2}\right)\exp\left[j\omega_c t \pm j\left(\Omega_1 - \Omega_2\right)t\right] \\ & + E_0 \cdot J_0\left(\frac{m}{2}\right)J_2\left(\frac{m}{2}\right)\exp\left(j\omega_c t \pm j2\Omega_1 t\right) \\ & + E_0 \cdot J_0\left(\frac{m}{2}\right)J_2\left(\frac{m}{2}\right)\exp\left(j\omega_c t \pm j2\Omega_2 t\right) \\ & + E_0 \cdot J_1\left(\frac{m}{2}\right)J_1\left(\frac{m}{2}\right)\exp\left[j\omega_c t \pm j\left(\Omega_1 + \Omega_2\right)t\right] \end{aligned} \tag{5}$$

Compare with the MPL without 90° HC, the spectral components in the 2nd-OSB are introduced with a π phase shift.

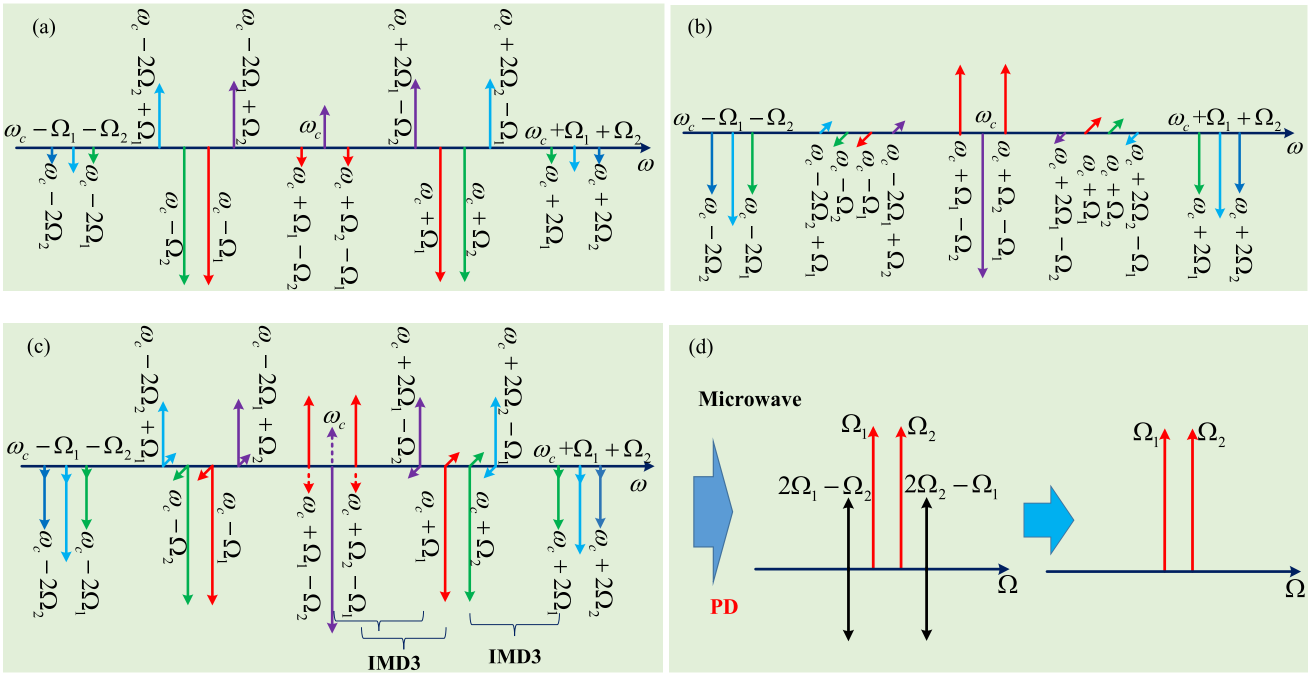

Fig. 3. The optical spectral components at (a) point a, (b) point b, and (c) point c in Fig. 1. (d) The recovered microwave signal at the output of the PD.

The spectrum of the optical signal from the lower channel after a π phase shift induced by the parent MZM is shown in Fig. 3(b), and the optical field is given by

$$\begin{aligned} E_{out2}(t) &\approx -E_0 J_0\left(\frac{m}{2}\right) J_0\left(\frac{m}{2}\right)\exp(j\omega_c t) \\ &+ E_0 J_1\left(\frac{m}{2}\right) J_1\left(\frac{m}{2}\right)\exp[j\omega_c t \pm j(\Omega_1-\Omega_2)t] \\ &- E_0 J_0\left(\frac{m}{2}\right) J_2\left(\frac{m}{2}\right)\exp(j\omega_c t \pm j2\Omega_1 t) \\ &- E_0 J_0\left(\frac{m}{2}\right) J_2\left(\frac{m}{2}\right)\exp(j\omega_c t \pm j2\Omega_2 t) \\ &- E_0 J_1\left(\frac{m}{2}\right) J_1\left(\frac{m}{2}\right)\exp[j\omega_c t \pm j(\Omega_1+\Omega_2)t] \end{aligned} \tag{6}$$

When the optical signals from the upper and lower channels are combined, the optical field of the output signal from the DP-MZM is expressed by

$$E_{out}(t) = E_{out1}(t) + E_{out2}(t) \tag{7}$$

The optical carrier is partially suppressed and the spectrum of the optical signal is shown in Fig. 3(c). The OCB is π phase shifted compared with that shown in Fig. 2(a).

As can be seen from Fig. 3(c), since the IMD3 terms, generated by beating the optical carrier ω_c with $\omega_c + 2\Omega_{1,2} - \Omega_{2,1}$ and by beating $\omega_c + \Omega_{2,1} - \Omega_{1,2}$ with $\omega_c + \Omega_{1,2}$, are equal in magnitude but out of phase with the IMD3 term generated by beating $\omega_c + \Omega_{2,1}$ with $\omega_c + 2\Omega_{1,2}$, thus the IMD3 terms will be cancelled completely at the output of the PD by tuning the low-bias point of the upper sub-MZM, as shown in Fig. 3(d).

The generated microwave signal $I(t)$ at the output of the PD is given by

$$\begin{aligned} I(t) &\approx \\ & A(\varphi)\left[1-\cos\left(\frac{\varphi}{2}\right)\right] J_0^3\left(\frac{m}{2}\right) J_1\left(\frac{m}{2}\right)\cdot\cos(\Omega_{1,2}t) \\ & - A(\varphi)\cos\left(\frac{\varphi}{2}\right)\begin{bmatrix} 2J_0^2\left(\frac{m}{2}\right) J_1\left(\frac{m}{2}\right) J_2\left(\frac{m}{2}\right) \\ +J_0\left(\frac{m}{2}\right) J_1^3\left(\frac{m}{2}\right)\end{bmatrix} \\ & \quad\cdot\cos[(2\Omega_{1,2}-\Omega_{2,1})t] \\ & + A(\varphi)\left[J_0\left(\frac{m}{2}\right) J_1^3\left(\frac{m}{2}\right)\right]\cdot\cos[(2\Omega_{1,2}-\Omega_{2,1})t] \end{aligned} \tag{8}$$

where $A(\varphi) = 2\Re G P_0 \cdot \sin(\frac{\varphi}{2})$, G is the gain of the EDFA, $\Re$ is the responsivity of the PD, and $P_0 = {E_0}^2/2$ is the output power of the LD. The coefficients for the fundamental and IMD3 terms, I_1 and I_2, are given by

$$I_1 = A(\varphi)\left[1-\cos\left(\frac{\varphi}{2}\right)\right] J_0^3\left(\frac{m}{2}\right) J_1\left(\frac{m}{2}\right) \tag{9}$$

$$I_2 = A(\varphi)\left\{\begin{matrix} J_0\left(\frac{m}{2}\right) J_1^3\left(\frac{m}{2}\right) - \\ \cos\left(\frac{\varphi}{2}\right)\begin{bmatrix} 2J_0^2\left(\frac{m}{2}\right) J_1\left(\frac{m}{2}\right) J_2\left(\frac{m}{2}\right) \\ +J_0\left(\frac{m}{2}\right) J_1^3\left(\frac{m}{2}\right)\end{bmatrix}\end{matrix}\right\} \tag{10}$$

In order to increase the SFDR of the proposed link, the coefficient of IMD3 terms I_2 has to be zero, and the coefficient of fundamental signal I_1 should not be suppressed much.

Assuming that the optical power sent to the PD is 10 dBm, the microwave power is 0 dBm, V_π is 4V, $\Re$ is 0.6 A/W, we evaluate the relationship between the normalized link gain, the

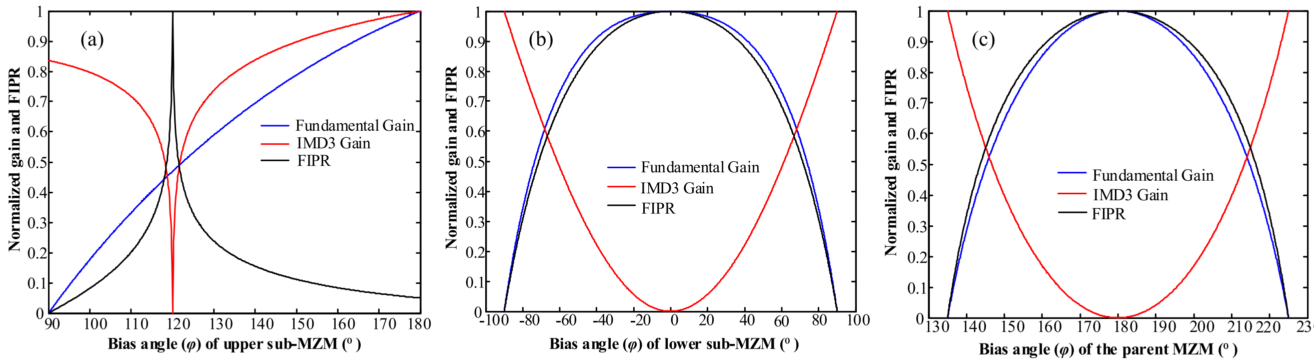

Fig. 4. Normalization gains of the fundamental microwave signal and the IMD3 terms, and the normalization FIPR versus (a) bias angle of the upper sub-MZM when both the lower sub-MZM and the parent MZM are biased at the minimum transmission point, (b) bias angle of the lower sub-MZM when the biasing angle of the upper sub-MZM is about 120° and the parent MZM is biased at the minimum transmission point, (c) bias angle of the parent MZM when the biasing angle of the upper sub-MZM is about 120° and the lower sub-MZM is biased at the minimum transmission point.

normalized fundamental to IMD3 power ratio (FIPR), and the bias angle of the upper sub-MZM, shown in Fig. 4(a).

As shown in Fig. 4(a), as the bias point of the upper sub-MZM moves to its minimum transmission point (from 90° to 180°), the link gain of the fundamental microwave signal keeps increasing, but the gain of the IMD3 signal will firstly decrease, and then increase. Also, it can be seen that the variation tendency of the FIPR value is inverse to that of the IMD3 signal gain. The maximum FIPR when the IMD3 terms are fully cancelled can be obtained when the biasing angle of the upper sub-MZM is about 120° while the gain of the fundamental microwave signal is still large, which is almost half as compared with that of the upper sub-MZM biased at its minimum transmission point. Furthermore, under small signal approximation, by making $J_n(m) \approx m^n / (2^n n!)$, we can conclude that, when

$$\cos\left(\frac{\varphi}{2}\right) \approx 0.50 \tag{11}$$

the upper sub-MZM is biased near the minimum transmission point, the generated IMD3 terms will be suppressed due to the destructive combination of the photocurrent at the PD while retaining a reasonably high fundamental signal gain. Utilizing the same method of analysing the effect of the biasing angle of the upper sub-MZM, Fig. 4(b) shows the relationship between the normalized link gain, the normalized FIPR, and the bias angle of the lower sub-MZM when the biasing angle of the upper sub-MZM is about 120° and the parent MZM is biased at the minimum transmission point. Fig. 4(c) shows the effect of phase shift induced by the parent MZM when the biasing angle of the upper sub-MZM is about 120° and the lower sub-MZM is biased at the minimum transmission point. As can be seen from Fig. 4(b) and (c), when the biasing angle of the upper sub-MZM is about 120°, the IMD3 terms will be fully cancelled when both the lower sub-MZM and the parent MZM are biased at the minimum transmission point.

III. Experiment

An experiment based on the proposed MPL configuration shown in Fig. 1 is performed to verify the effectiveness of the proposed approach for SFDR improvement. In the experiment, a light wave from a tunable laser source (TLS, Yokogawa AQ2201) operating at 1551.81 nm with an output power of 10 dBm is sent to a DP-MZM (Fujitsu FTM7980EDA). The half-wave voltage and the bandwidth of the DP-MZM are 6.3 V and 10 GHz, respectively. A two-tone microwave signal is applied to the upper sub-MZM which is biased at the positive low-bias point to generate a partially carrier-suppressed double-sideband signal. The lower sub-MZM driven by the two-tone microwave signal is biased at the maximum transmission point. The parent MZM is biased at the minimum transmission point to realize a π phase difference between the outputs of two sub-MZMs.

The two-tone microwave signal of 10 GHz and 10.01 GHz, generated by a signal generator (Agilent E8254A) and a network analyzer (Agilent E8364), is applied to the DP-MZM via the electrical 90° HC. An EDFA is used to amplify the generated optical signal, and the optical power sent into the PD is controlled to be 6.5 dBm. The signal at the output of the EDFA is sent to the PD (Discovery Semiconductors, DSC10ER). The PD has a responsivity of 0.54 A/W and a bandwidth of more than 50 GHz. The detected microwave signal from the PD is then sent to an electrical spectrum analyzer (ESA, Agilent E4448) to evaluate the transmission performance. To evaluate the performance improvement of the proposed MPL against a conventional IMDD MPL, we utilize this DP-MZM to make it function as an MZM that is biased at the quadrature point, which is done by letting the upper sub-MZM operate at the minimum transmission point (corresponding to $\varphi = 180°$) and the lower sub-MZM unmodulated. Note that the phase shift introduced by the parent MZM is zero. In addition, the main optical contribution to IMD3 is the beating between the optical carrier ω_c with $\omega_c + 2\Omega_{1,2} - \Omega_{2,1}$, but it is slightly less than that of a conventional IMDD MPL using an MZM.

First, the FIPR performance is measured. The power for each of the two input microwave signals is set at 5 dBm. Fig. 5 shows the spectrum of the electrical signal at the output of the PD with and without IMD3 suppression. Fig. 5(a) shows the output electrical spectrum of a conventional IMDD link without

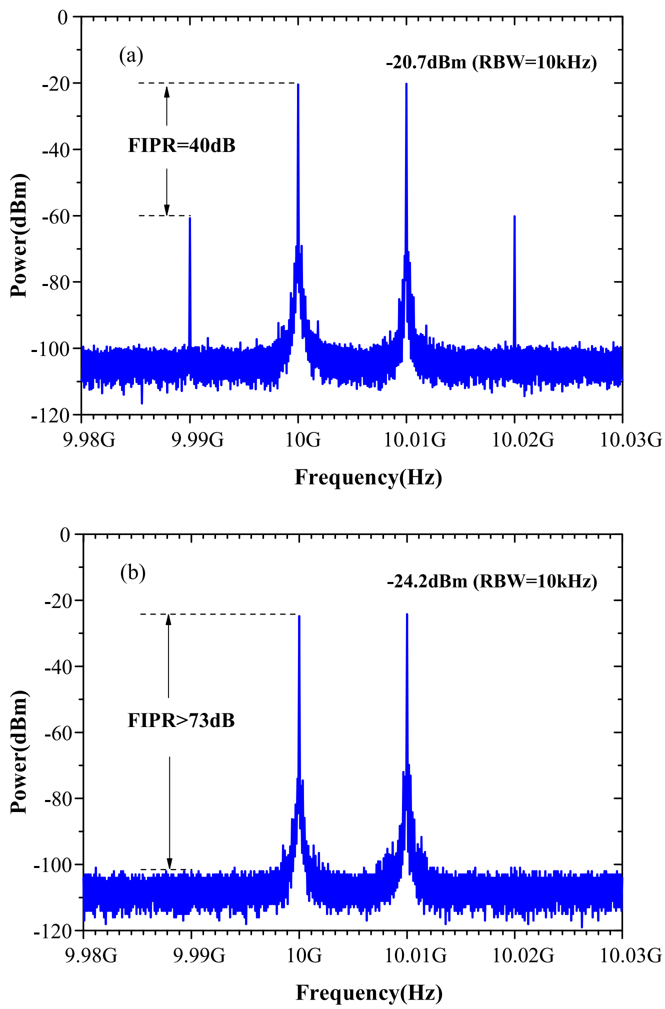

Fig. 5. Electrical spectrum of the microwave signal at the out of the PD. (a) A conventional IMDD link without IMD3 suppression, and (b) the proposed IMDD link with IMD3 suppression.

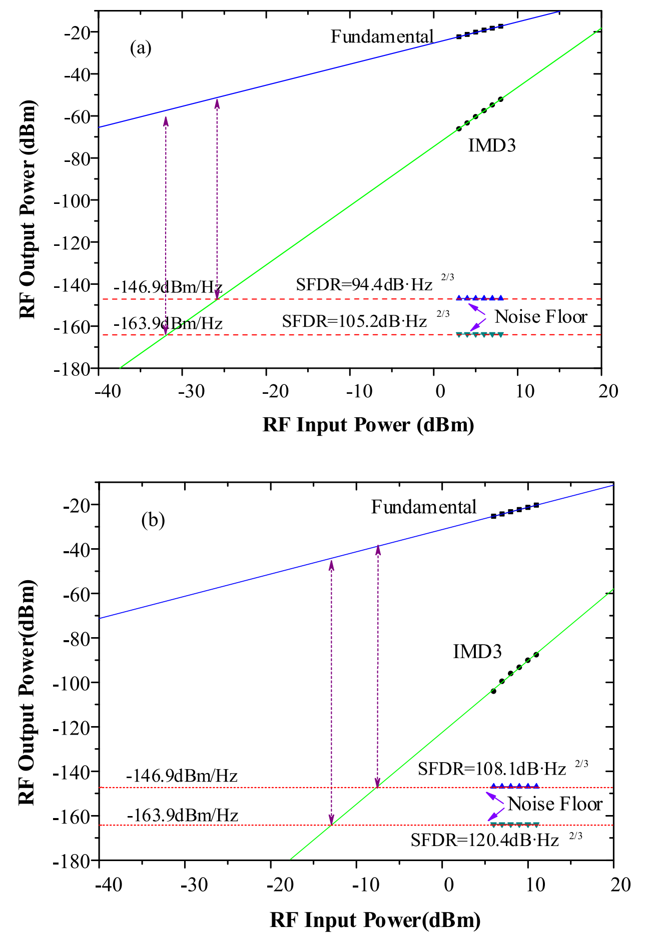

Fig. 6. Measured SFDR of the MPLs with and without IMD3 suppression. (a) Conventional IMDD MPL without IMD3 suppression, and (b) the proposed MPL with IMD3 suppression.

IMD3 suppression. As can be seen, strong IMD3 components are observed and the FIPR is measured to be 40 dB. Fig. 5(b) shows the electrical spectrum of the proposed MPL. It can be seen that the FIPR is increased, which is more than 73 dB, 33 dB higher than that of the uncompensated link.

Then, the SFDR performance is measured and the results are shown in Fig. 6. Fig. 6(a) shows the experimental results for the DP-MZM based conventional IMDD link. The SFDR is 94.4 dB·Hz$^{2/3}$ for a noise floor of -146.9 dBm/Hz. For the proposed link with IMD3 suppression, as shown in Fig. 6(b), an SFDR of 108.1 dB·Hz$^{2/3}$ is achieved for a same noise floor of -146.9 dBm/Hz. The improvement of the SFDR is about 14 dB.

Usually, in an MPL with an optical power of a few dBm, the largest contribution to the output noise is the shot noise. Here, if we assume that the proposed MPL is a shot noise limited MPL, the noise floor can be -163.9 dBm/Hz when the optical power sent to the PD is 6.5 dBm. Then, the SFDR of the conventional MPL is 105.2 dB·Hz$^{2/3}$ and that of the proposed MPL is 120.4 dB·Hz$^{2/3}$, which is 15 dB higher than that of the uncompensated conventional IMDD MPL for the same noise floor.

IV. Conclusion

An MPL with an improved SFDR by suppressing the IMD3 terms through introducing a π phase shift to the OCB was proposed and experimentally demonstrated. The fundamental concept of the approach was to generate complementary IMD3 terms to have them fully cancelled at the PD, which was done by introducing a π phase shift to the OCB. Through lowering bias point of the upper sub-MZM, the IMD3 terms can be fully cancelled while maintaining the gain of the fundamental terms reasonably high. The proposed approach was analyzed theoretically and evaluated through simulations. The simulation results showed that the IMD3 terms were fully suppressed while the gain of the fundamental terms was controlled to be half that of a conventional IMDD MPL, which was high. The theoretical analysis was further confirmed by an experiment. The experimental results show that an improvement in SFDR of 14 dB or 15 dB was realized for a noise floor of -146.9 dBm/Hz or -163.9 dBm/Hz.

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