Microwave Photonic Link With Improved Dynamic Range Using a Polarization Modulator

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***Abstract*— A microwave photonic link (MPL) using a single polarization modulator (PolM) with an improved spurious free dynamic range (SFDR) is proposed and experimentally demonstrated. The proposed MPL is designed based on the destructive combination of the distortion signals in the electrical domain, which is realized using a PolM with its output split into two channels. In the upper channel, the PolM, a polarization controller (PC), and a polarization beam splitter (PBS) form an equivalent Mach–Zehnder modulator (MZM) that is biased at the quadrature point. The optical carrier is suppressed using a phase-shifted fiber Bragg grating (PS-FBG). In the lower channel, the PolM, another PC, and the PBS form a second equivalent MZM that is also biased at the quadrature point but at the opposite slope of the transfer function. The signals from the two channels are sent to a photodetector (PD). If the optical powers into the two channels are identical, the third-order intermodulation terms are completely suppressed. An experiment is performed. An enhancement in SFDR of 10 dB is achieved. The insertion loss of the proposed MPL is also estimated, which is 9.5 dB smaller than a phase modulator based MPL.**

***Index Terms*— Microwave photonic link, polarization modulator, phase-shifted fiber Bragg grating, spurious-free dynamic range, suppressed-carrier.**

I. Introduction

MICROWAVE photonic links (MPLs) for the transmission of analog microwave signals have been extensively investigated in the last few years. An MPL has numerous advantages as compared with a conventional coaxial analog link, such as much smaller loss, lower weight and greater bandwidth. In addition, an MPL is immune to electromagnetic interference which is extremely important for applications where the electromagnetic environment is complex [1]. To impose a microwave signal on an optical carrier, a modulator is always employed. In an MPL, the use of intensity modulation (IM) and direct detection (DD) can simplify the implementation, but the inherent nonlinear transfer function of a Mach–Zehnder modulator (MZM) will impose a limit on the dynamic range [1], [2]. To improve the dynamic range, numerous techniques have been proposed in recent years. For example, the dynamic range can be improved based on electronic linearization, including feed-forward [3], predistortion [4], and feedback linearization [5]. The limitation of the electronic linearization approach is the small bandwidth due to the limited bandwidth of electronic circuits. Optical linearization can be employed to overcome the limitation. Those techniques include the use of a dual-cascaded linearized modulator [6], an MZM operating at the opposite slopes of the transfer functions for two different wavelengths [7], [8] and a pair of parallel MZMs operating at opposite slopes of the transfer functions [9]–[12]. The major limitation of the techniques in [6]–[12] is that a pair of MZMs, two high-quality laser sources or a pair of balanced photodetectors (PDs) are needed, which will increase the cost of the whole system. To reduce the cost, a single lithium-niobate phase modulator (PM) which supports two polarization modes (TE mode and TM mode) with different anisotropic electrooptic coefficients is used to fully cancel the third-order intermodulation (IM3) [13], [14]. The major limitation of this technique is that the link loss is large since the cancellation of the IM3 will also cancel a large portion of the fundamental signal.

In this letter, we propose and experimentally demonstrated a novel MPL with an improved SFDR using a single PolM while maintaining a low link loss. The IM3 terms are completely suppressed based on the destructive combination of two intensity-modulated signals with one of the signal having a suppressed optical carrier realized by using a phase-shifted fiber Bragg grating (PS-FBG) as a notch filter. If the optical powers into the two channels are identical, the IM3 terms are completely suppressed. The proposed approach is theoretically analyzed, which is then validated by an experiment. An improvement in SFDR of 10 dB is achieved. The insertion loss of the proposed MPL is also estimated which is 9.5 dB smaller than that using a PM [13], [14].

II. Principle of Operation

Fig.1 shows the schematic of the proposed MPL. A linearly polarized incident light wave from a tunable laser source (TLS) at λ_c is sent to a PolM through a polarization controller (PC_0). The polarization direction of the light wave incident to the PolM is adjusted to have an angle of 45° relative to one principal axis of the PolM. The PolM is a special phase modulator that supports phase modulation along the two principal axes with complementary phase modulation indices. The modulated light wave from the PolM is split by a 3-dB coupler into two channels with identical powers. In the lower channel (Channel 1), the PolM, a PC (PC_1) and a

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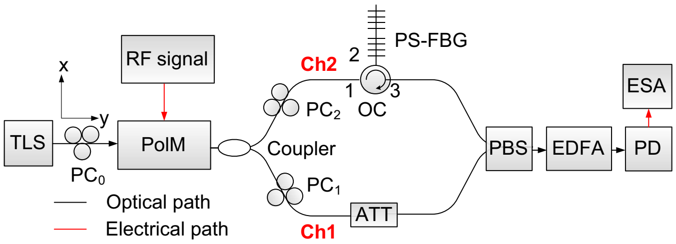

Fig. 1. Schematic diagram of the proposed MPL. ATT: attenuator, RF: radio frequency, TLS: tunable laser source, PolM: polarization modulator, PD: photodetector, PC: polarization controller, OC: optical circulator, PBS: polarization beam splitter, PS-FBG: phase-shifted fiber Bragg grating.

polarization beam splitter (PBS) form an equivalent MZM that is biased at the quadrature point [15]. An attenuator is included in Channel 1 to balance the insertion loss between the two channels. In the upper channel (Channel 2), the PolM, a second PC (PC_2) and the PBS form again an equivalent MZM that is again biased at the quadrature point, but at the opposite slope [15]. The optical carrier is suppressed by using a PS-FBG. The signals from the two channels are sent to a PD after amplification by an erbium-doped fiber amplifier (EDFA). The IM3 terms will be canceled at the output of the PD due to the destructive combination of the distortion signals.

Mathematically, the optical field at the output of the PolM along the principle axes (x and y) can be expressed as

$$\begin{bmatrix} E_x(t) \\ E_y(t) \end{bmatrix} = \frac{1}{\sqrt{2}} E_{in} \begin{bmatrix} \exp(j\omega_c t + j\beta \sin \Omega t) \\ \exp(j\omega_c t - j\beta \sin \Omega t) \end{bmatrix} \tag{1}$$

where E_{in} is the optical field at the input of the PolM, ω_c is the angular frequency of the optical carrier, β is the phase modulation index, and Ω is the angular frequency of the RF signal.

For Channel 1 (lower channel), applying the two signals to the PBS with its principal axis aligned at 45° relative to one principle axis of the PolM, we have

$$E_1(t) = \frac{1}{2\sqrt{2}} E_{in} \left\{ \begin{array}{l} \exp[j\pi s_{RF}(t)/2V_\pi] \\ +\exp[-j\pi s_{RF}(t)/2V_\pi - j\phi_1] \end{array} \right\} \tag{2}$$

where $s_{RF}(t)$ is the input RF signal and ϕ_1 is a static phase term introduced by the PC_1 placed before the PBS, V_π is the half-wave voltage of the PolM. For two-tone analysis, the RF input signal can be written as

$$s_{RF}(t) = V_s \cos(\Omega_1 t) + V_s \cos(\Omega_2 t) \tag{3}$$

where V_s is the amplitude of the RF signal. Then, (2) can be rewritten as

$$E_1(t) = \frac{1}{2\sqrt{2}} E_{in} \times \begin{bmatrix} \exp\{j\beta[\cos(\Omega_1 t) + \cos(\Omega_1 t)]/2\} \\ + \exp\{-j\beta[\cos(\Omega_1 t) + \cos(\Omega_2 t)]/2 - j\varphi_1\} \end{bmatrix} \tag{4}$$

where $\beta = \pi V_s / V_\pi$. By using the Jacobi-Auger expansions, we can further expand (4), given by

$$\begin{aligned} E_1(t) &= \tfrac{E_{o1}}{2} \sum_{p=-1}^{+1} \sum_{q=-1}^{+1} a_{p,q} exp[j(p\Omega_1 + q\Omega_2)t] \\ a_{p,q} &= j^{p+q} \cdot J_p(\beta/2) J_q(\beta/2) \begin{bmatrix} \exp(j\phi_1/2) \\ +(-1)^{p+q} \exp(-j\phi_1/2) \end{bmatrix} \\ E_{o1} &= \tfrac{1}{\sqrt{2}} E_{in} \exp(-j\phi_1/2) \end{aligned} \tag{5}$$

J_p and J_q are the Bessel functions of the first kind. In this analysis, the higher order terms are not included so that we can first pinpoint the main contributors to the IM3. The signal in (5) is sent to a PD for square law detection. When we set $\phi_1 = \pi/2$ and only Channel 1 is connected to the PBS, the RF signal at the output of the PD is given by

$$\begin{aligned} I_{ac1}(t) &= \Re |E_1|^2 \\ &= 2\Re P_1 \left\{ \begin{array}{l} \begin{bmatrix} 2J_1^3\left(\frac{\beta}{2}\right) J_0\left(\frac{\beta}{2}\right) \\ -J_0^3\left(\frac{\beta}{2}\right) J_1\left(\frac{\beta}{2}\right) \end{bmatrix} \begin{bmatrix} \cos(\Omega_1 t) \\ +\cos(\Omega_2 t) \end{bmatrix} \\ +J_1^3\left(\frac{\beta}{2}\right) J_0\left(\frac{\beta}{2}\right) \cos(2\Omega_1 \pm \Omega_2)t \\ +J_1^3\left(\frac{\beta}{2}\right) J_0\left(\frac{\beta}{2}\right) \cos(2\Omega_2 \pm \Omega_1)t \end{array} \right\} \end{aligned} \tag{6}$$

where $\Re$ is the responsivity of the PD. $P_1 = E_{in}^2/2$ is the input optical power for Channel 1. Note that (6) is obtained when only the fundamental and the IM3 terms are taken into account.

Now we derive the expression for Channel 2. The only difference between Channel 1 and Channel 2 is that in Channel 2 a narrow-band PS-FBG is used to suppress the optical carrier while in Channel 1 it is not used. In Channel 2, b is set to be the optical carrier suppression index, and the optical field of the output signal from the PBS can be expressed as

$$\begin{aligned} E_2(t) &= \frac{E_{o2}}{2} \sum_{\substack{p=-1 \\ p\neq 0}}^{+1} \sum_{\substack{q=-1 \\ q\neq 0}}^{+1} a_{p,q} \\ &\quad \times \exp[j(p\Omega_1 + q\Omega_2)t] + \frac{E_{o2}}{2} a_{0,0} b \\ a_{p,q} &= j^{p+q} \cdot J_p(m/2) J_q(m/2) \\ &\quad \times \begin{bmatrix} \exp(j\phi_2/2) \\ +(-1)^{p+q} \exp(-j\phi_2/2) \end{bmatrix} \\ E_{o2} &= \frac{1}{\sqrt{2}} E_{in} \exp(-j\phi_2/2) \end{aligned} \tag{7}$$

When we set $\phi_2 = -\pi/2$, which is again a static phase term introduced by PC_2 placed before the PBS, and only Channel 2 is connected to PBS, after photodetection at the PD, the generated photocurrent is given by

$$\begin{aligned} I_{ac2}(t) &= \Re |E_2|^2 \\ &= 2\Re P_2 \left\{ \begin{array}{l} -\begin{bmatrix} 2J_1^3\left(\frac{\beta}{2}\right) J_0\left(\frac{\beta}{2}\right) \\ -bJ_0^3\left(\frac{\beta}{2}\right) J_1\left(\frac{\beta}{2}\right) \end{bmatrix} \begin{bmatrix} \cos(\Omega_1 t) \\ +\cos(\Omega_2 t) \end{bmatrix} \\ -J_1^3\left(\frac{\beta}{2}\right) J_0\left(\frac{\beta}{2}\right) \cos(2\Omega_1 \pm \Omega_2)t \\ -J_1^3\left(\frac{\beta}{2}\right) J_0\left(\frac{\beta}{2}\right) \cos(2\Omega_2 \pm \Omega_1)t \end{array} \right\} \end{aligned} \tag{8}$$

where $P_2 = E_{in}^2/2$ is the input optical power for Channel 2. From (8) we can see that the photocurrents of the IM3 terms from the two channels are identical. Since we let $\phi_1 = \pi/2$, $\phi_2 = -\pi/2$, the two equivalent MZMs operate at the opposite slopes of the transfer functions, which results in the opposite amplitudes of the IM3 terms, thus the combination of the signals in the electrical domain will cancel the IM3 terms. When Channel 1 and Channel 2 are both connected to the PBS, at the output of the PD we have

$$I_{ac}(t) = \Re\left[|E_1|^2 + |E_2|^2\right] = \left\{ \begin{array}{l} \Gamma_1 \left[\cos(\Omega_1 t) + \cos(\Omega_2 t)\right] \\ +\Gamma_2 \left[\cos(2\Omega_1 \pm \Omega_2)t + \cos(2\Omega_2 \pm \Omega_1)t\right] \end{array} \right\} \quad (9)$$

where the coefficients for the fundamental and IM3 components Γ_1 and Γ_2, are given by

$$\Gamma_1 = 2\Re \left[\begin{array}{l} (P_2 - P_1)\, 2J_1^3\left(\frac{\beta}{2}\right) J_0\left(\frac{\beta}{2}\right) \\ -(P_2 - bP_1)\, J_0^3\left(\frac{\beta}{2}\right) J_1\left(\frac{\beta}{2}\right) \end{array} \right]$$
$$\Gamma_2 = 2\Re (P_2 - P_1)\, J_1^3\left(\frac{\beta}{2}\right) J_0\left(\frac{\beta}{2}\right) \quad (10)$$

Because P_2 and P_1 are equal, we have $\Gamma_2 = 0$, which indicates that the main contributors to the IM3 components are eliminated. The coefficient for the fundamental components is then given

$$\Gamma_1 = -2\Re P_2 (1-b)\, J_0^3\left(\frac{\beta}{2}\right) J_1\left(\frac{\beta}{2}\right) \neq 0 \quad (11)$$

Note that in [14] where a PM that supports TE and TM modes is employed. To cancel the IM3, the ratio of TM to TE power has to be more than 27. Since most of the input power is in the TM mode, the equivalent half-wave voltage for the PM is 3 times more than that for a conventional PM supporting only TE mode. The increased half-wave voltage leads to more than 10 dB reduction of the fundamental signal power. However, in the proposed MPL, if the optical carrier is totally suppressed, which means that b in (11) equals zero, the power of the fundamental signal will not be reduced. Compared with the MPL using a PM in [14], the cancellation of the fundamental is much smaller for the proposed MPL, thus the link provides a much lower loss as compared with the PM-based MPL.

III. Experimental Results

An experiment based on the setup shown in Fig.1 is conducted. A light wave at 1550.35 nm from a TLS (Anritsu MG9638A) is sent to a PolM (Versawave) via PC_0. The polarization direction of the light wave incident to the PolM is adjusted to be 45° relative to one principal axis of the PolM such that the power is equally projected to the two principal axes (x and y directions). A two-tone RF signal of 5 GHz and 6 GHz generated by a Signal Generator (Agilent E8254A) and a Network Analyzer (Agilent E8364) is applied to the PolM via the RF port. As explained in Section II, the PolM is a special PM that supports phase modulation with complementary modulation indices along the two principal axes. The PolM has a bandwidth of 40 GHz and a half-wave voltage of about 3.5 V. The phase-modulated signals are split into two channels via a 3-dB coupler. The lengths of the two channels are controlled to be identical. In the upper channel, a PS-FBG with a bandwidth of about 120 MHz is incorporated to suppress the optical carrier.

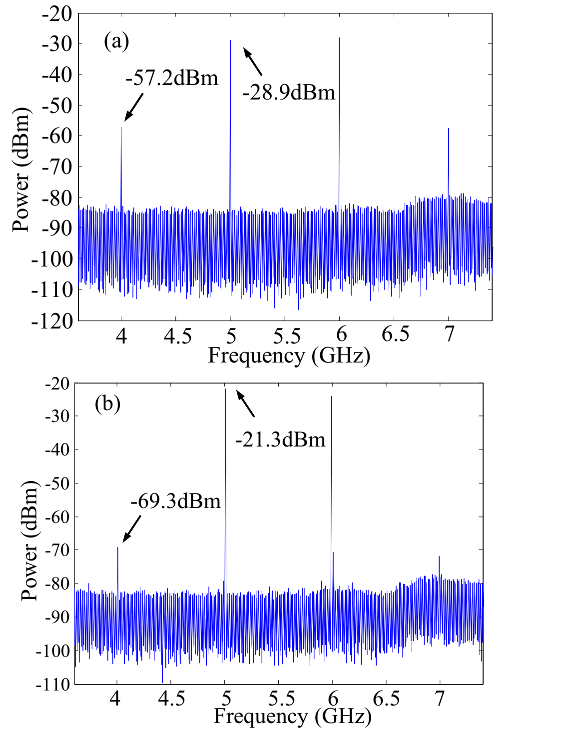

Fig. 2. Electrical spectrums of the RF signal at the output of the PD when a two-tone RF signal is applied to the PolM. (a) Only Channel 1 is connected, and (b) both Channel 1 and Channel 2 are connected.

In the lower channel, an optical attenuator is used to adjust the insertion loss of the channel such that the insertion losses for the two channels are identical. The signals from the two channels are combined at the PBS and then applied to the PD (u^2t, SPDV2150R). The PD has a responsivity of 0.65 A/W and a bandwidth of 50 GHz. In this experiment, the total optical power of the optical signals sent to the PD is about 5.5 dBm. The detected RF signal from the PD is then sent to an Electrical Spectrum Analyzer (Agilent E4448) to evaluate the transmission performance.

We first measure the carrier-to-interference ratio (CIR) for two cases: 1) only Channel 1 is connected, and 2) both channels are connected. If only Channel 1 is connected, the system is considered as a conventional MPL based on external modulation. Fig. 2(a) shows the electrical spectrum obtained at the output of the PD when a two-tone RF signal is applied to the PolM. As can be seen strong IM3 components are observed. The CIR is 28.3 dB. Then, both channels are connected. In Channel 2, the optical carrier is suppressed by the PS-FBG of about 10 dB. The electrical spectrum is shown in Fig. 2(b). As can be seen a CIR of more than 48 dB is achieved.

Then, the SFDR performance is measured. To do so, the measurements of the powers of the fundamental signal and the IM3 as a function of the input RF power are performed.

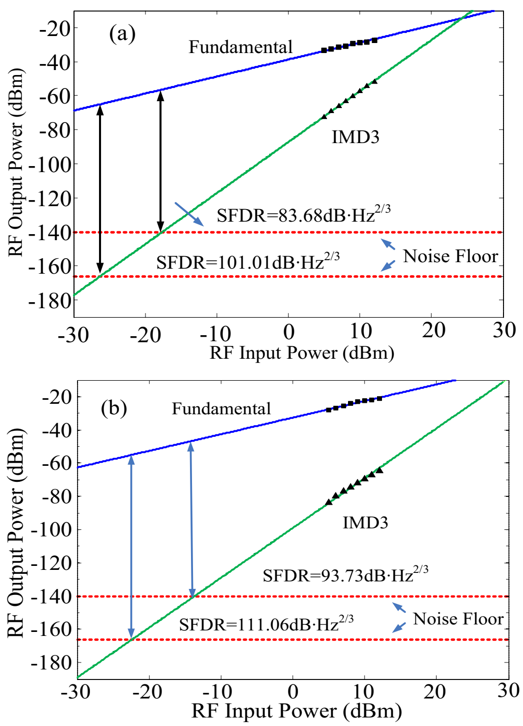

Fig. 3. Measured RF powers of the fundamental and the IM3 at the output of the PD when a two-tone signal is applied to the PolM. (a) Only Channel 1 is connected, and (b) both Channel 1 and Channel 2 are connected.

When performing the measurement, the optical power to the PD is controlled to be 5.5 dBm. Fig. 3(a) shows the results when Channel 1 is connected. The SFDR is 83.68 dB·Hz$^{2/3}$ for a noise floor of 140 dB/Hz. Fig. 3(b) shows the results when both Channel 1 and Channel 2 are connected. The SFDR is 93.73 dB·Hz$^{2/3}$ for a noise floor of 140 dB/Hz. As can be seen the SFDR for the proposed MPL is 10 dB higher than that of a conventional MPL. In the experiment, the noise floor of 140 dB/Hz is limited by the noise of the electrical spectrum analyzer. If a noise floor of -166 dB/Hz is considered, the SFDR of the proposed MPL is 111.06 dB·Hz$^{2/3}$. In addition, if the input optical power to the PD can be increased or the suppression of the optical carrier can be larger, a further improved SFDR can be obtained.

The RF power loss of the proposed link is measured to be 32 dB. In [14], if the optical power sent to the PD is also 5.5 dBm, the loss of the PM-based MPL is 41.5 dB, which is 9.5 dB more than that for the proposed MPL link.

IV. Discussion and Conclusion

Compared with a conventional MZM-based MPL, an MZM-based MPL with linearization could lead to an improvement in SFDR of 10 dB. Among the MPLs with linearization, the proposed scheme provides the same SFDR performance, but with the simplest structure.

In conclusion, we have proposed and experimentally demonstrated a novel MPL with an improved SFDR using only a single PolM. The fundamental concept of the approach is the use of a PolM that functions as two equivalent MZMs operating at the opposite slopes. By using a PS-FBG to suppress the optical carrier of one channel and splitting the optical powers into the two channels with identical power, the IM3 was completely suppressed. The proposed MPL was experimentally demonstrated. The results showed that an improvement in SFDR of 10 dB was achieved. Compared with a PM-based MPL, the proposed MPL could also provide a smaller link loss. It was shown the link loss is 9.5 dB smaller than that of a PM-based MPL.

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