Linearized analog photonic links based on a dual-parallel polarization modulator

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A linearized analog photonic link (APL) is proposed based on an integratable electro-optic dual-parallel polarization modulator (DPPolM), which consists of two polarization beam splitters and two polarization modulators (PolMs). Theoretical analysis shows that the APL is potentially free from the third-order nonlinear distortion if a polarization controller placed before the DPPolM is carefully adjusted. A proof-of-concept experiment is carried out. A reduction of the third-order intermodulation components as high as 40 dB and an improvement of the spurious-free dynamic range as large as 15.5 dB is achieved as compared with a single PolM-based link. The DPPolM-based APL is simple, compact, and power efficient since it requires only one laser, one modulator, and one photodetector. © 2012 Optical Society of America

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Analog photonic links (APLs) have attracted great interest since the 1980s for applications including phased array antennas, signal processing, radar systems, and radio over fiber, thanks to numerous advantages such as low loss, high bandwidth, relatively low weight, and immunity to electromagnetic interference [1]. Different APLs based on direct modulation of a laser diode [2], external phase modulation [3–5], or intensity modulation [6–10] have been demonstrated. In general, APL based on the direct modulation of a laser diode can only achieve limited performance due to the high intermodulation distortion (IMD) and small modulation bandwidth. Although a phase modulator can provide high linearity with bias-free operation, the demodulation scheme in the receiver side is always complicated and costly. On the other hand, intensity modulation and direct detection link is simple, but its dynamic range is limited due to the inherent sinusoidal transfer function of the intensity modulators [6–10]. Several approaches to linearize the transfer function of the intensity modulators have been proposed, including predistortion [6], feedforward [7], and dual-parallel modulation [8–10]. Among them, the dual-parallel modulation scheme can achieve much larger bandwidth since no high-speed electrical devices and no electrical loop is needed. However, two high-quality laser sources or balanced detection have to be used to avoid the interference in the optical domain [9,10], which increases significantly the cost of the entire system. In addition, an additional laser source would introduce more relative intensity noise (RIN), and the APL based on balanced detection can not accommodate long-distance transmission since two fibers with an identical length should be used [10].

In this Letter, an APL with large spurious-free dynamic range (SFDR) is proposed based on a novel dual-parallel polarization modulator (DPPolM). A theoretical analysis and an experiment are performed to validate the feasibility of the approach for effective suppression of the third-order distortion components. The proposed method is possibly attractive since it requires only one laser, one modulator, and one photodetector.

Figure 1 shows the schematic diagram of the proposed linearized APL. A lightwave from a laser diode (LD) is sent to a DPPolM. The DPPolM is an integratable modulator consisting of two polarization beam splitters (PBSs) and two polarization modulators (PolMs). In the DPPolM, the lightwave is split by the first PBS (PBS1) into two branches. Because of the polarization dependence of the PBS, the power splitting ratio can be flexibly adjusted by simply tuning a polarization controller (PC) placed before the DPPolM. In each branch, a PolM is built to perform polarization modulation. Then, the signals from the two branches are combined again by the second PBS (PBS2). The principal axes of each PolM are aligned to have an angle of 45° to those of the first and second PBSs. An electrical signal is divided into two paths by an electrical power divider and sent to the two PolMs via their RF ports. The output optical signals from the DPPolM are then detected by a PD.

According to [11], a PolM in conjunction with a PBS is equivalent to an intensity modulator. When a linearly polarized incident light oriented at an angle of 45° to one principal axis of the PolM is sent to the PolM, the optical field of the output signal from the PBS can be expressed as

$$E_0 = \frac{\sqrt{P}}{2}(\cos[\omega_c t + \beta\phi(t)/2 + \phi_0] + \cos[\omega_c t - \beta\phi(t)/2]), \quad (1)$$

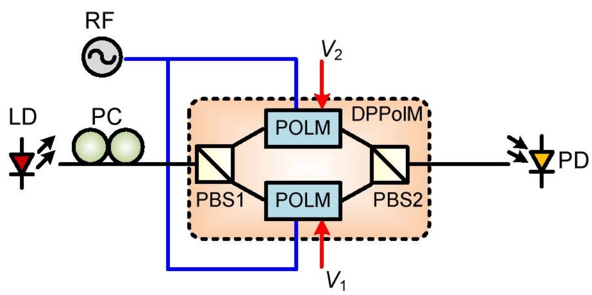

Fig. 1. (Color online) Proposed analog photonic link based on a dual-parallel polarization modulator: LD, laser diode; PC, polarization controller; PBS, polarization beam splitter; PolM, polarization modulator; PD, photodetector.

where P represents the optical power, ω_c is the angular frequency of the optical carrier, β is the phase modulation index, $\phi(t)$ is the modulating signal, and ϕ_0 is the phase difference between the two signals, which can be controlled by changing the DC bias of the PolM.

For the DPPolM, the signals from the upper and the lower PolMs are combined by a same PBS, which not only converts the polarization modulation in each branch into intensity modulation, but also realizes orthogonal polarization multiplexing. The combined signal at the output of the PBS can be written as

$$\begin{bmatrix} E_1 \\ E_2 \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{P_1}}{2}(\cos[\omega_c t + \beta_1\phi(t)/2 + \phi_1] + \cos[\omega_c t - \beta_1\phi(t)/2]) \\ \frac{\sqrt{P_2}}{2}(\cos[\omega_c t + \beta_2\phi(t)/2 + \phi_2] + \cos[\omega_c t - \beta_2\phi(t)/2]) \end{bmatrix}, \tag{2}$$

where P_n, β_n, and $\phi_n (n = 1, 2)$ are the optical power, phase modulation index, and phase bias in the lower or upper branch. When the signal in Eq. (2) is sent to a PD for square law detection, we obtain

$$I_{ac} = \Re(|E_1|^2 + |E_2|^2) = \frac{\Re P_1}{4}\cos[\beta_1\phi(t) + \phi_1] + \frac{\Re P_2}{4}\cos[\beta_2\phi(t) + \phi_2], \tag{3}$$

where $\Re$ is the responsivity of the PD. As can be seen from Eq. (3), the incoherent combination of the optical signals in the optical domain results in the coherent combination of the microwave signal in the electrical domain. To linearize the modulation in the DPPolM, we let $\phi_1 = -\pi/2$, $\phi_2 = \pi/2$, so Eq. (3) can be rewritten as

$$I_{ac} \propto P_1 \sin[\beta_1\phi(t)] - P_2 \sin[\beta_2\phi(t)] = (P_1\beta_1 - P_2\beta_2)\phi(t) - \frac{1}{6}(P_1\beta_1^3 - P_2\beta_2^3)\phi^3(t) + \ldots. \tag{4}$$

To investigate the nonlinear distortions, the input signal is set to be a two-tone microwave signal, given by

$$\phi(t) = \cos(\omega_1 t) + \cos(\omega_2 t). \tag{5}$$

Substituting Eq. (5) into Eq. (4) and applying the trigonometric relation, we get

$$\begin{aligned} I_{ac} \propto \frac{\Re}{4}\Big\{ &\Big(P_1\beta_1 - \frac{3}{8}P_1\beta_1^3 - P_2\beta_2 + \frac{3}{8}P_2\beta_2^3\Big) \\ &\times[\cos(\omega_1 t) + \cos(\omega_2 t)] + \Big(-\frac{1}{24}P_1\beta_1^3 + \frac{1}{24}P_2\beta_2^3\Big) \\ &\times[\cos(3\omega_1 t) + \cos(3\omega_2 t)] + \Big(-\frac{1}{8}P_1\beta_1^3 + \frac{1}{8}P_2\beta_2^3\Big) \\ &\times[\cos(2\omega_1 t + \omega_2 t) + \cos(2\omega_2 t + \omega_1 t)] \\ &+ \Big(-\frac{1}{8}P_1\beta_1^3 + \frac{1}{8}P_2\beta_2^3\Big) \\ &\times[\cos(2\omega_1 t - \omega_2 t) + \cos(2\omega_2 t - \omega_1 t)]\Big\}. \end{aligned} \tag{6}$$

From Eq. (6), the third-order nonlinear effect generates $3\omega_1, 3\omega_2, 2\omega_1 + \omega_2, 2\omega_2 + \omega_1, 2\omega_1 - \omega_2$ and $2\omega_2 - \omega_1$ components, in which the $2\omega_1 - \omega_2$ and $2\omega_2 - \omega_1$ components are the most undesirable ones since they are very close to the signals for transmission. Therefore, we should let the coefficient of the $2\omega_1 - \omega_2$ and $2\omega_2 - \omega_1$ terms equals to zero, i.e.,

$$\frac{P_1}{P_2} = \frac{\beta_2^3}{\beta_1^3}. \tag{7}$$

In addition, the linear term should be kept with a small attenuation, so we have

$$\frac{P_1}{P_2} \neq \frac{\beta_2}{\beta_1} \neq 1. \tag{8}$$

Equations (7) and (8) can be easily satisfied using the DPPolM by introducing an imbalance to the electrical powers to the two PolMs, to let $\beta_1 \neq \beta_2$, and then adjusting the PC before the DPPolM to fit Eq. (7).

An experiment is carried out based on the setup shown in Fig. 2. Since the DPPolM has not been fabricated, we implement it by an equivalent setup using separated devices, including two PBSs, four PCs, two PolMs, and a tunable optical delay line. The four PCs are used to align the principal axes of each PolM to have an angle of 45° to those of the PBSs because our scheme is not polarization maintained, and the tunable optical delay line is incorporated to ensure that the lengths of the two signal paths are identical. A two-tone RF signal with frequencies of 5 and 5.02 GHz is generated by a vector signal generator (Agilent E8267D), split by a power divider into two paths, and then introduced to the two PolMs via their RF ports. A 3 dB microwave attenuator is inserted in the lower path to introduce imbalance to the microwave powers in the two paths (17 and 14 dBm, respectively). Other parameters of the system are listed as follows: the optical power from the LD (Agilent N7714A) is 13 dBm, the PolMs (VersaWave, Inc.) have a bandwidth of 40 GHz and a half-wave voltage of ~3.5 V, and the PD has a responsivity of 0.65 A/W and a bandwidth of 40 GHz. The total insertion loss of the optical link is ~11 dB, including 1 dB per PBS, 0.5 dB per PC, 3.2 dB for PolM, 3 dB for polarization modulation to intensity modulation conversion, and 1.8 dB for fiber connectors and other devices. The electrical spectrum is measured by an electrical spectrum analyzer (ESA, Agilent E4447AU).

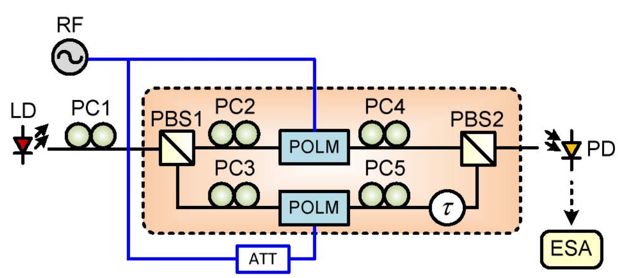

Fig. 2. (Color online) Experiment setup: ATT, attenuator; τ, optical tunable delay line; ESA, electrical spectrum analyzer.

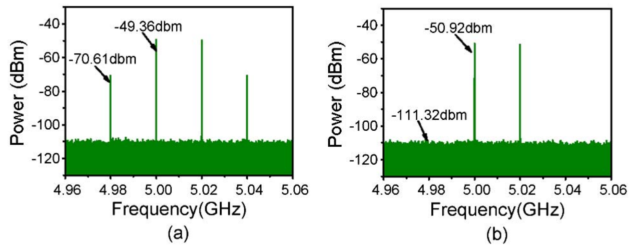

Fig. 3. (Color online) Electrical spectra of the two-tone input tests for the (a) single polarization modulator (PolM)-based intensity-modulated link and (b) DPPolM-based link.

At the first step, the lower optical branch is disconnected. The PolM, in conjunction with the PBS in the upper branch, will form an intensity-modulated link. PC1 is adjusted to divide the optical power equally into the two paths, and PC2 and PC4 are adjusted to maximize the gain of the link. Figure 3(a) shows the electrical spectrum obtained at output of the PD when the two-tone RF signal is introduced to the PolM. Strong IMD3 components are observed, indicating that considerable third-order nonlinear effects are present in the PolM-based intensity modulation. Then we enable both branches. PC3 and PC5 are also adjusted to maximize the gain of the link. PC1 is adjusted to optimize the power ratio of the two optical paths, by which Eqs. (7) and (8) are satisfied. The electrical spectrum of the two-tone input test is shown in Fig. 3(b). As can be seen, the IMD3 components are below the noise floor of the ESA. A reduction of the IMD3 component as high as 40 dB is achieved. Since no optical attenuator is applied, the proposed link is power efficient, which is very important for constructing links with large gain and low noise figure.

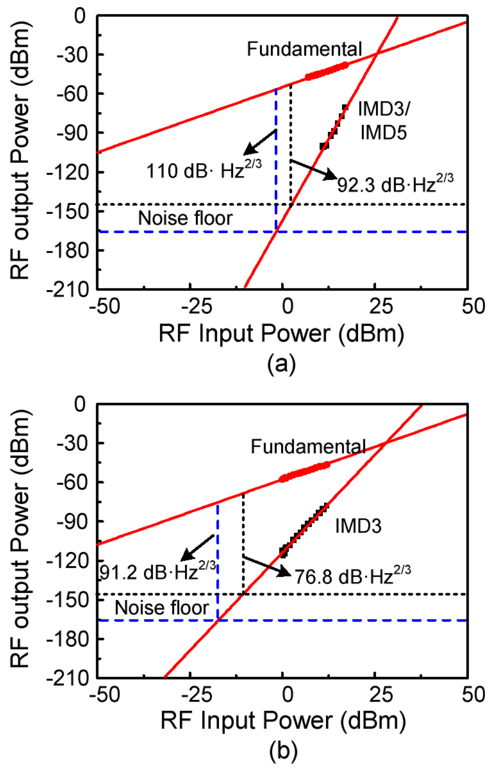

Fig. 4. (Color online) Measured fundamental and IMD3 output powers as a function of the input RF power for the (a) DPPolM based link and (b) link with the upper path alone.

The SFDR of the DPPolM-based link is also measured. The experimental results are shown in Fig. 4, where the fundamental and IMD3 output powers are plotted as a function of the input RF power. As can be seen from Figs. 4(a) and 4(b), the SFDR of the DPPolM-based link is 92.3 $\mathrm{dB \cdot Hz^{2/3}}$, which is 15.5 dB higher than that of the single PolM-based, intensity-modulated link. In addition, the slope for the IMD3 components in the DPPolM-based link is 5, rather than 3, in the single PolM-based intensity-modulated link, indicating that the third-order nonlinear effect is almost fully suppressed and only fifth-order nonlinear effect is left. It should be noted that in our implementation, the noise floor is −145 dBm/Hz due to the strong RIN of the laser. If a high performance LD with a narrow linewidth is applied, a noise floor as low as −166 dBm/Hz is possible [5]. In that case, the SFDR of the DPPolM link can reach 110 $\mathrm{dB \cdot Hz^{2/3}}$, which is 18.8 dB higher than that of the single PolM-based intensity-modulated link. It should be noted that the SFDR can be further improved by increasing the laser power since, in our experiment, the optical power to the PD is only 1.2 dBm.

In conclusion, a linearized APL was proposed using a novel dual-parallel polarization modulator. From a theoretical analysis, the APL could be totally free from third-order nonlinear distortion. A proof-of-concept experiment was performed, demonstrating that the proposed DPPolM-based link could reduce the IMD3 by more than 40 dB and increase the SFDR by 15.5 dB as compared with the conventional intensity-modulated link.

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