A microwave photonic link with high spurious-free dynamic range based on a parallel structure*

WANG Shi-kui (王世奎)[1], GAO Yong-sheng (高永胜)[2], WEN Ai-jun (文爱军)[2], and LIU Ling (刘玲)[2]**

1. Aeronautic Computing Technique Research Institute, Xi'an 710072, China

2. State Key Laboratory of Integrated Service Networks, Xidian University, Xi'an 710071, China

(Received 19 December 2014; Revised 25 December 2014)

A microwave photonic link (MPL) with high spurious-free dynamic range (SFDR) is proposed and analyzed. The optical carrier is divided equally into two paths. The path 1 is modulated by radio frequency (RF) signals in a Mach-Zehnder modulator (MZM), and the phase of path 2 is controlled before the combination with path 1. By properly adjusting the phase difference of the two paths with the optical phase shifter, the third-order intermodulation distortion (IMD3) can be significantly suppressed. A proof-of-concept simulation is carried out. The results show that a reduction of 40 dB in the IMD3 and an improvement of 21.1 dB in the SFDR are achieved as compared with the conventional MZM-based MPL. The proposed MPL shows the advantages of simple structure, low cost and high efficiency.

Document code: A **Article ID:** 1673-1905(2015)02-0137-4

DOI 10.1007/s11801-015-4228-6

Microwave photonic links (MPLs) have shown a great potential in various applications, such as wireless communications, radars, antenna remoting and warfare systems, thanks to the advantages of high bandwidth, low transmission loss, low weight and immunity to electromagnetic interference as compared with the conventional coaxial analog links[1,2]. To impose a microwave signal on an optical carrier, the direct modulation with the distributed feedback (DFB) laser diodes (LDs) and the external modulation with phase modulators (PMs), intensity modulators (IMs) or polarization modulators (PolMs) have been demonstrated previously[3,4]. However, the intrinsically nonlinear transfer function of the modulator will distort the signals and limit the spurious-free dynamic range (SFDR) of the link.

Numerous techniques based on external modulation have been proposed in recent years to improve the SFDR of MPLs, such as optical filtering[5,6], distortion canceling with composite structures[7–11] and mixing polarization modulation[12,13]. Other SFDR improvement strategies with simple structures based on only one modulator have also been proposed[14–16].

A new linearized MPL is proposed in this paper. An optical carrier is divided into two paths. Path 1 is modulated by radio frequency (RF) signals in a Mach-Zehnder modulator (MZM), and path 2 is phase controlled by an optical delay line before combining with path 1. Analysis indicates that when the direct current (dc) bias of MZM and the phase difference between the two paths are properly adjusted, the third-order intermodulation distortion (IMD3) can be suppressed. Simulation results demonstrate that there is a significant improvement of 21.1 dB in SFDR as compared with the conventional MZM-based MPL. The proposed MPL also has the advantages of simple structure, low cost and high efficiency.

Fig.1 shows the schematic diagram of the proposed MPL. An optical carrier generated from a LD is given by $E_{\text{in}}(t)=E_0\exp(\text{j}\omega_c t)$, where E_0 and ω_c are the amplitude and the angular frequency of the optical carrier, respectively. The optical carrier is divided into two paths (path 1 and path 2) equally. An MZM with a half wave voltage of V_π is utilized to modulate an RF signal onto the upper optical carrier in path 1. The RF signal can be expressed as $V_{\text{RF}}\sin(\omega_{\text{RF}}t)$, where V_{RF} and ω_{RF} are the amplitude and the angular frequency, respectively. The bias phase shift θ_1 of MZM can be adjusted by its dc bias. Assuming the MZM has infinite extinction ratio, the optical signal at the output of MZM can be expressed as

$$E_1(t)=\frac{\sqrt{2}E_0}{4}\sqrt{a_1}\text{e}^{\text{j}\omega_c t}\cdot\left[\text{e}^{\text{j}(\theta_1/2+m\sin(\omega_{\text{RF}}t))}+\text{e}^{-\text{j}(\theta_1/2+m\sin(\omega_{\text{RF}}t))}\right]=$$
$$\frac{\sqrt{2}E_0}{4}\sqrt{a_1}\text{e}^{\text{j}\omega_c t}\cdot\sum_{n=-\infty}^{+\infty}J_n(m_1)\text{e}^{\text{j}n\omega_{\text{RF}}t}\left[\text{e}^{\text{j}\theta_1/2}+(-1)^n\text{e}^{-\text{j}\theta_1/2}\right],\quad(1)$$

where $m=\pi V_{\text{RF}}/(2V_\pi)$ is the modulation index (MI). $a_1\in(0,1)$ is the power ratio of the output signal to input signal of MZM when biasing at the maximum transmission point, and it is related to the insertion loss. The optical signal after processing in path 2 can be expressed as

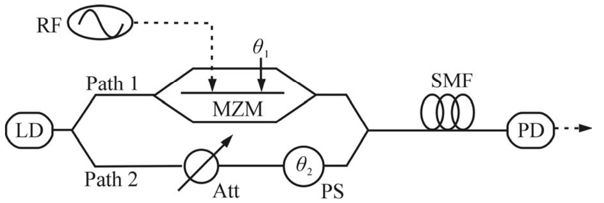
* This work has been supported by the Fundamental Research Funds for the Central Universities (No.JB142001-9), and the Programme of Introducing Talents of Discipline to Universities China 111 Project (No.B08038).

** E-mail: ajwen@xidian.edu.cn

$$E_{\text{out2}}(t)=\frac{\sqrt{2}E_0}{2}\text{e}^{\text{j}\omega_c t}\cdot\left(\sqrt{a_2}\text{e}^{\text{j}\theta_2}\right), \tag{2}$$

where $a_2\in[0,1]$ is the power ratio of the output signal to input signal of the attenuator, and θ_2 is the phase shift introduced by the optical phase shifter. The optical signal after the combination of two paths can be then expressed as

$$E_{\text{out}}(t)=\frac{E_0}{4}\text{e}^{\text{j}\omega_c t}\cdot$$
$$\left\{\sqrt{a_1}\sum_{n=-\infty}^{+\infty}J_n(m)\text{e}^{\text{j}n\omega_{\text{RF}}t}\left[\text{e}^{\text{j}\theta_1/2}+(-1)^n\text{e}^{-\text{j}\theta_1/2}+2\sqrt{a_2}\text{e}^{\text{j}\theta_2}\right]\right\}. \tag{3}$$



LD: laser diode; Att: optical attenuator; PS: optical phase shifter; MZM: Mach-Zehder modulator; SMF: single mode fiber; PD: photodiode

Fig.1 Schematic diagram of the proposed MPL

Neglecting the single mode fiber (SMF) transmission, the photocurrent of the desired signal at the angular frequency of ω_{RF} can written as

$$i_{\omega_{\text{RF}}}=\eta\frac{E_0^2}{8}\text{je}^{\text{j}\omega_{\text{RF}}t}\cdot$$
$$\{-2a_1\cdot\sum_n J_n(m)J_{n-1}(m)(-1)^n\sin\frac{\theta_1}{2}\cos\frac{\theta_1}{2}+$$
$$4\sqrt{a_1a_2}J_1(m)\sin\frac{\theta_1}{2}\cos\theta_2\}, \tag{4}$$

where η is the responsivity of PD. Considering the MI is usually small, we can simplify expand the Bessel function, and Eq.(4) can be approximately rewritten as

$$i_{\omega_{\text{RF}}}\approx\eta\frac{E_0^2}{8}\text{je}^{\text{j}\omega_{\text{RF}}t}\cdot$$
$$\left\{-4a_1\sin\frac{\theta_1}{2}\cos\frac{\theta_1}{2}\left[-\frac{m}{2}+2\left(\frac{m}{2}\right)^3\right]+\right.$$
$$\left.4\sqrt{a_1a_2}\sin\frac{\theta_1}{2}\cos\theta_2\left[\frac{m}{2}-\frac{1}{2}\left(\frac{m}{2}\right)^3\right]\right\}=$$
$$\eta\frac{E_0^2}{8}\text{je}^{\text{j}\omega_{\text{RF}}t}\left\{m\cdot 2a_1\sin\frac{\theta_1}{2}\left(\cos\frac{\theta_1}{2}+\sqrt{\frac{a_2}{a_1}}\cos\theta_2\right)+\right.$$
$$\left.\left(\frac{m}{2}\right)^3\left(-2a_1\sin\frac{\theta_1}{2}\right)\left(4\cos\frac{\theta_1}{2}+\sqrt{\frac{a_2}{a_1}}\cos\theta_2\right)\right\}. \tag{5}$$

From Eq.(5), we can clearly see that the first term on the right-hand side represents the recovered fundamental RF signal and the second term can produce the IMD3 components. The coefficients of electrical power for the fundamental term (C_1) and the IMD3 term (C_3) can be expressed as

$$C_1\propto\left[2a_1\sin\frac{\theta_1}{2}\left(\cos\frac{\theta_1}{2}+\sqrt{\frac{a_2}{a_1}}\cos\theta_2\right)\right]^2, \tag{6}$$

$$C_3\propto\left[a_1\sin\frac{\theta_1}{2}\left(4\cos\frac{\theta_1}{2}+\sqrt{\frac{a_2}{a_1}}\cos\theta_2\right)\right]^2. \tag{7}$$

The IMD3 terms are considered most troublesome in an MPL, because they usually fall at frequencies near the fundamental terms and cannot be filtered, thus limiting the improvement of SFDR. In the proposed scheme, the IMD3 can be easily suppressed (C_3=0) by properly adjusting the phase bias shift of the MZM, the attenuator and the optical phase shifter. The IMD3 suppression condition can be written as

$$\cos\frac{\theta_1}{2}=-\frac{1}{4}\sqrt{\frac{a_2}{a_1}}\cos\theta_2. \tag{8}$$

The modulation efficiency, which is defined as the power ratio of the recovered fundamental RF signal after PD to the RF signal driving the modulator, is also a key indicator of the performance in an MPL. After the suppression of IMD3, the coefficient of electrical power for fundamental term in Eq.(6) can be rewritten as

$$C_1\propto\left|3a_1\sin\theta_1\right|^2. \tag{9}$$

Assuming that the insertion loss of the MZM is 3 dB (a_1=0.5), we can find out from Eqs.(8) and (9) that the recovered fundamental signal can achieve its maximum power when

$$a_2=1,\theta_2=0,\theta_1=1.23\pi$$
$$\text{or}: a_2=1,\theta_2=\pi,\theta_1=0.77\pi, \tag{10}$$

which indicates that the attenuator is unnecessary, and only the optical phase shifter is required in path 2 to adjust the phase difference of the two paths.

A comparison between the modulation efficiency of the proposed MPL and that of the MZM-based MPL is also analyzed. According to Eqs.(1)–(5), if only one path with an MZM is used in the MPL, the coefficient of electrical power for fundamental component after PD can be expressed as

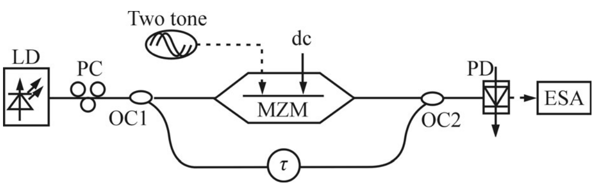
$$C_{1-\text{MZM}}\propto\left|4a_1\sin\theta_1\right|^2. \tag{11}$$

The maximum efficiency is achieved when the MZM works at the quadrature transmission point (θ_1=0.5π). According to Eqs.(9) and (11), the modulation efficiency ratio of these two MPLs is

$$10\log\frac{C_1}{C_{1-\mathrm{MZM}}}=10\log\frac{\left(3a_1\sin\theta_1\right)^2\big|_{\theta_1=1.23\pi}}{\left(4a_1\sin\theta_1\right)^2\big|_{\theta_1=0.5\pi}}=-6.1\ \mathrm{dB}\,. \tag{12}$$

The enhanced linearity comes at the expense of reducing the modulation efficiency, which is similar with most linearization schemes. However, the reduction of modulation efficiency in the proposed MPL is only 6.1 dB, and is partly due to the decrease of the optical carrier after the combination of the two paths. Because of the optical power reduction at PD, the proposed MPL can have a lower noise floor.

A computer simulation is conducted by VPI transmission Maker 8.5 to investigate the performance of the proposed MPL, and the schematic diagram is shown in Fig.2. A continuous-wave light with wavelength of 1 550 nm, power of 10 dBm, linewidth of 1 MHz and relative intensity noise (RIN) of –150 dB/Hz is generated from a LD and polarization controlled before being divided into two paths by an optical coupler. In path 1, two-tone probe signal with the frequencies of 6 GHz and 6.1 GHz are applied to an MZM via its RF port. The extinction ratio of MZM is 20 dB, and the half-wave voltage is 5 V. An optical delay line is placed in path 2 to adjust the phase difference between the two paths. The optical signals in the two paths are combined by another optical coupler, and then detected by a PD. The PD has a responsivity of 0.6 A/W. An electrical spectrum analyzer (ESA) is used to show the recovered two-tone signals and measure the power of the fundamental and IMD3 components and the noise floor.



PC: polarization controller; OC: optical coupler; τ: optical delay line; ESA: electrical spectrum analyzer

Fig.2 Simulation setup of the proposed MPL

The simulation results of the conventional MZM-based MPL and the proposed linearized MPL are demonstrated for comparison. At the first step, only path 1 with the MZM biasing at the quadrature transmission point is used to modulate the two-tone RF signals. The powers of the two-tone signals are both 8 dBm. The recovered two-tone signals at the ESA for the conventional MZM-based MPL are shown in Fig.3(a), in which strong IMD3 components are observed. Then the proposed MPL with two paths are demonstrated. The dc signal of MZM is biased to achieve the transmission point at 1.23π, and the optical delay line is adjusted to set the phase difference of the two paths to be zero according to Eq.(10). The recovered two-tone signals at the ESA for the proposed linearized MPL are shown in Fig.3(b). As can be seen from Fig.3, the IMD3 components in the proposed scheme can be suppressed by 40.2 dB as compared with those in the conventional MZM-based scheme.

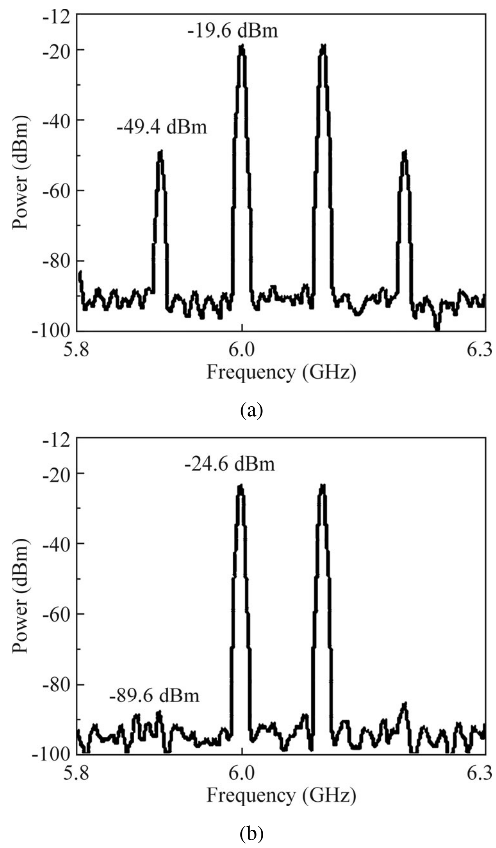
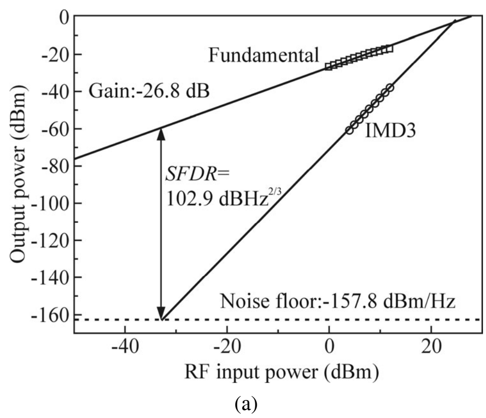


Fig.3 Electrical spectra of the two-tone signals for (a) the conventional MZM-based link and (b) the proposed link

To investigate the SFDR improvement of the proposed scheme, the measurements of the output powers of the fundamental and IMD3 components in the two schemes are performed, and the results are shown in Fig.4. The measured SFDR is 102.9 dB·Hz$^{2/3}$ in the conventional MZM-based link, and the measured SFDR in the proposed link is 124 dB·Hz$^{4/5}$ with an improvement of 21.1 dB.

A reduction in the modulation efficiency or a system gain of 6 dB is also observed, which is in good accordance with the theoretical calculation in Eq.(12). Notably, the modulation efficiency reduction in the proposed scheme is partly due to the decrease of the optical power at PD. So the noise floor of the proposed MPL is only 162 dBm/Hz, which is 4.2 dB lower than that in the MZM-based MPL.



(a)

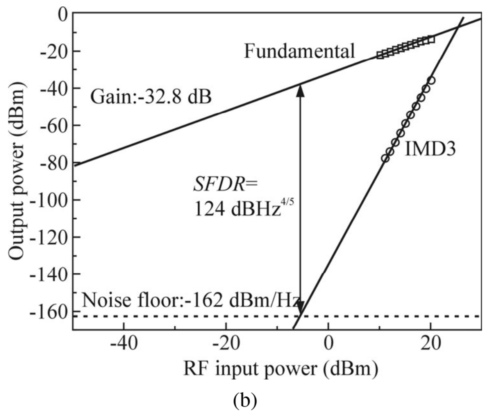


Fig.4 Output powers of the fundamental and IMD3 components as a function of the input RF power for (a) the conventional MZM-based link and (b) the proposed link

A 25 MSym/s 16-quadrature amplitude modulation (16QAM) signal at a center frequency of 6 GHz is utilized to investigate the performance of the conventional MZM-based link and the proposed link. The received optical powers at PD are set as 7 dBm in both of the two links. As can be seen from Fig.5(a), when the input RF power is below –3 dBm, the error vector magnitude (EVM) values of both links decrease as the increase of input RF power. Then the EVM in the conventional MZM-based link increases rapidly. However, the EVM in the proposed link decreases continuously until the input RF power is above 10 dBm. Particularly for the 16QAM RF signal with the input power of 15 dBm, the measured EVM values for the conventional MZM-based link and the proposed link are 7.9% and 0.4%, respectively, and the corresponding recovered RF spectra and constellations are shown in Fig.5(b) and (c). It is obvious that the qualities of the spectrum and constellation are greatly improved in the proposed link as compared with those in the conventional MZM-based link.

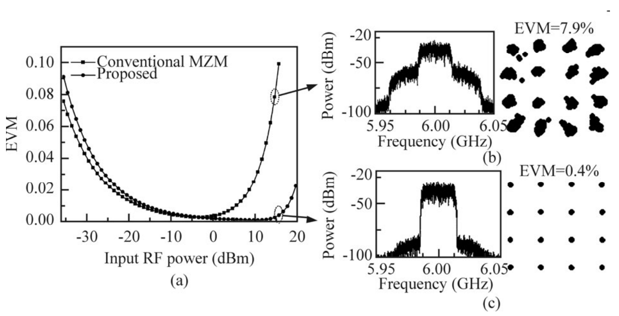


Fig.5 (a) EVM versus the input RF power for the conventional MZM-based link and the proposed link; The recovered RF spectra and constellations for (b) the conventional MZM-based link and (c) the proposed link

In conclusion, a linearized MPL based on a parallel structure is proposed and analyzed. By properly adjusting the dc bias of the MZM and the phase difference of the two paths, the IMD3 is suppressed. Simulation results demonstrate that the proposed link can increase the SFDR by 21.1 dB as compared with the conventional MZM-based link. The proposed MPL also has the advantages of simple structure, low cost and high modulation efficiency.

References

[1] Charles H. Cox, Analog Optical Links: Theory and Practice, UK: Cambridge University Press, 2004.

[2] ZHU Zi-hang, ZHAO Shang-hong, LI Yong-jun, CHU Xing-chun, ZHANG Hui, WANG Xiang and ZHAO Gu-hao, Journal of Optoelectronics·Laser **24**, 500 (2013). (in Chinese)

[3] ZHOU Wei, ZOU Xi-hua, PAN Wei, YAN Lian-shan, LUO Bin and LU Bing, Journal of Optoelectronics·Laser **24**, 2332 (2013). (in Chinese)

[4] WANG Zhao, MA Jian-xin, ZHANG Rui-jiao, LI Yan-jie, ZHANG Qi-qi, ZHANG Qi, LIU Ren-hao and YU Jian-guo, Journal of Optoelectronics·Laser **25**, 1709 (2014). (in Chinese)

[5] Lim C., Nirmalathas A., Lee Ka-Lun, et al. Novak D. and Waterhouse R., Journal of Lightwave Technology **25**, 1602 (2007).

[6] Chen X., Li W. and Yao J., IEEE Photonics Technology Letters **25**, 1373 (2013).

[7] Jian Dai, Kun Xu, Ruimin Duan, Yan Cui, Jian Wu and Jintong Lin, Optical Linearization for Intensity-Modulated Analog Links Employing Equivalent Incoherent Combination Technique, IEEE International Topical Meeting on Microwave Photonics & Microwave Photonics Conference, 230 (2011).

[8] Kim Seong-Ku, Liu Wei, Pei Qibing, Dalton Larry R., Fetterman Harold R., Optics Express **19**, 7865 (2011).

[9] Huang M., Fu J. and Pan S., Optics Letters **37**, 1823 (2012).

[10] Betts G. E., O'Donnell F. J., IEEE Photonics Technology Letters **8**, 1273 (1996).

[11] Zhang H., Pan S., Huang M. and Chen X., Linear Analog Photonic Link Based on Cascaded Polarization Modulators. Asia Communications and Photonics Conference, 1 (2012).

[12] Haas B. M. and Murphy T. E., IEEE Photonics Technology Letters **19**, 729 (2007).

[13] Chen Z., Yan L., Pan W., Luo B., Zou X., Guo Y., Jiang H. and Zhou T., Optics Express **21**, 20999 (2013).

[14] Li S., Zheng X., Zhang H. and Zhou B., IEEE Photonics Technology Letters **22**, 1775 (2010).

[15] Li W. and Yao J., Optics Express **21**, 15692 (2013).

[16] Gao Y., Wen A., Chen Y., Zhang H. and Xiang S., Optics Communications **338**, 1 (2015).