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Nonlinearity modelling of an on-board microwave photonics system based on Mach-Zehnder modulator

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For the nonlinearity distortion problem of Mach-Zehnder modulator (MZM) applied in the on-board microwave photonics system, the situation for two input radio frequency (RF) signals with different frequencies and phases is discussed, and an exact analytical solution is derived with the method of expanding Bessel series and Graf addition theory. According to the analytical expression, the nonlinearity characteristics of the modulator can be precisely predicted, and the system performance can be optimized. The correctness of the analytical solution is approved by simulation results. Analytical results indicate that the nonlinearity distortion is suppressed as the decrease of modulation index, the increase of direct current bias phase shift and phase difference between two input RF signals. When the phase difference equals zero or π and the direct current bias phase shift is π/2, there are only odd-order distortion terms. When the phase difference equals zero or π and the direct current bias phase shift is π, there are only even-order distortion terms.

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Microwave photonic technology is emerging as a key in future satellite sub-systems, not only for improving critical aspects such as mass, size and isolation, but also for supporting broadband, transparent data transmission and processing[1-3]. In inter-satellite microwave photonics links, the multiple radio frequency (RF) signals received from ground station need to transport from one satellite to another after being modulated onto the laser beam[4-7]. A dual-drive Mach-Zehnder modulator (DD-MZM) plays an important role due to its wider modulation bandwidth and higher performance compared with direct modulation[8]. However, the RF signals suffer more serious deterioration due to inter-modulation distortion caused by the nonlinearity of DD-MZM, and it results in the degradation of the dynamic range for the overall link.

To the best of our knowledge, most of the previous works on the nonlinearity of DD-MZM are limited to small-signal modulation or some special cases with approximation[9-11]. Results of the more general and rigorous analyses have been presented in terms of infinite series[12]. However, this work is only for single-subcarrier modulation or electrooptical upconversion where only one subcarrier is applied to the DD-MZM. Therefore, an exact analytical model using DD-MZM with multiple input RF signals is needed. If closed-form expressions are available, it will be a convenient and powerful tool to understand nonlinear distortion in such systems.

For the DD-MZM applied in the on-board microwave photonics system, the situation for two input RF signals with different frequencies and phases is discussed, and an exact analytical solution for arbitrary nonlinear distortion is derived in this paper. With the presented analytical expression, it is convenient to precisely predict the nonlinear characteristics of the on-board microwave photonics system and optimize the performance of the system.

Fig.1 describes the structure of the on-board microwave

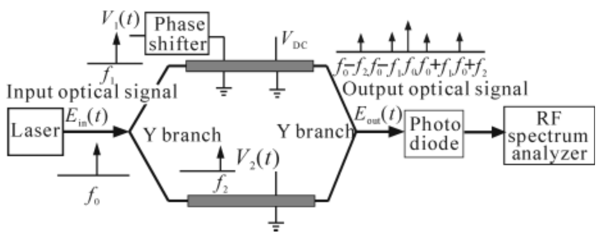

Fig.1 Schematic diagram of the on-board microwave photonics system

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photonics system. The two input RF signals with different frequencies and phases received from the ground station are optically modulated by a laser diode (LD) with a DD-MZM. The output signal of the DD-MZM is transmitted via free space channels between telescopes. The received signals are detected by the photodetector (PD).

With Bessel expansion, the envelope of optical signal before passing PD can be written as

$$E_{\mathrm{out}}(t)=\frac{\alpha}{2}E_{\mathrm{in}}\{\mathrm{e}^{[\mathrm{j}m_1\cos(w_1t+\beta)+\mathrm{j}\theta]}+\mathrm{e}^{[\mathrm{j}m_2\cos(w_2t)]}\}=$$
$$\frac{\alpha}{2}E_{\mathrm{in}}[\sum_{p=-\infty}^{+\infty}a_p\,\mathrm{e}^{\mathrm{j}p(w_1t+\beta)}\,\mathrm{e}^{\mathrm{j}\theta}+\sum_{q=-\infty}^{+\infty}b_q\,\mathrm{e}^{\mathrm{j}qw_2t}]\ , \tag{1}$$

where α is the insertion loss of DD-MZM, E_{in} is the amplitude of LD, $m_1=\pi V_1/V_\pi$ and $m_2=\pi V_2/V_\pi$ are modulation indices of the two branches of modulator, V_1 and V_2 define the amplitudes of two input RF signals, respectively, V_π is the switching voltage of modulator, w_1 and w_2 are the respective angular frequencies of input RF signals, β is the phase difference between the drives of the two branches, $\theta=\pi V_{\mathrm{DC}}/V_\pi$ is the DC bias phase shift, and V_{DC} is the bias voltage. $a_p=j_pJ_p(m_1)$, $b_q=j_qJ_q(m_2)$, where $J_k(\bullet)$ is the kth order Bessel function of the first kind.

With Fourier transformation, Eq.(1) can be written as

$$E_{\mathrm{out}}(w)=\pi\alpha E_{\mathrm{in}}[\mathrm{e}^{\mathrm{j}\theta}\sum_{p=-\infty}^{+\infty}a_p\,\mathrm{e}^{\mathrm{j}p\beta}\,\delta(w-pw_1)+$$
$$\sum_{q=-\infty}^{+\infty}b_q\delta(w-qw_2)]\ . \tag{2}$$

Through direct detection, the intensity of photocurrent can be obtained as

$$I(w)=\eta\frac{1}{2\pi}E_{\mathrm{out}}(w)*\overline{E_{\mathrm{out}}(w)}=$$
$$\frac{\eta\pi\alpha^2E_{\mathrm{in}}^2}{2}\{\sum_{p_1=-\infty}^{+\infty}\sum_{p_2=-\infty}^{+\infty}a_{p_1}\overline{a_{p_2}}\,\mathrm{e}^{\mathrm{j}(p_1-p_2)\beta}\,\delta[w-(p_1+p_2)w_1]+$$
$$\mathrm{e}^{\mathrm{j}\theta}\sum_{p=-\infty}^{+\infty}\sum_{q=-\infty}^{+\infty}a_p\overline{b_q}\,\mathrm{e}^{\mathrm{j}p\beta}\,\delta(w-pw_1-qw_2)+$$
$$\mathrm{e}^{-\mathrm{j}\theta}\sum_{p=-\infty}^{+\infty}\sum_{q=-\infty}^{+\infty}\overline{a_p}b_q\,\mathrm{e}^{-\mathrm{j}p\beta}\,\delta(w-pw_1-qw_2)+$$
$$\sum_{q_1=-\infty}^{+\infty}\sum_{q_2=-\infty}^{+\infty}b_{q_1}\overline{b_{q_2}}\delta[w-(q_1+q_2)w_2]\}\ , \tag{3}$$

where η is the responsivity of the PD, * represents convolution, and ¯ represents conjugation.

The first coefficient of Eq.(3) is

$$T_1^M=\frac{\eta\pi\alpha^2}{2}E_{\mathrm{in}}^2\sum_{p_1=-\infty}^{+\infty}\mathrm{j}^{p_1}J_{p_1}(m_1)\,\mathrm{j}^{-M+p_1}J_{M-p_1}(m_1)\,\mathrm{e}^{\mathrm{j}(2p_1-M)\beta}=$$
$$\frac{\eta\pi\alpha^2}{2}E_{\mathrm{in}}^2\,\mathrm{j}^{-M}\,\mathrm{e}^{-\mathrm{j}M(\beta+\varphi)}J_M(R)\ , \tag{4}$$

where M is integer number and represents the order of frequency w_1.

With Graf addition theory[13-15], R and φ can be obtained from

$$\begin{cases}m_1[1-\cos(2\beta)]=R\cos(\varphi)\\ m_1\sin(2\beta)=R\sin(\varphi)\\ R=\sqrt{2}m_1\sqrt{1-\cos(2\beta)}\end{cases}\ . \tag{5}$$

The second coefficient of Eq.(3) is

$$T_2^{M,N}=\frac{\eta\pi\alpha^2}{2}E_{\mathrm{in}}^2a_M\overline{b_N}\,\mathrm{e}^{\mathrm{j}(M\beta+\theta)}=$$
$$\frac{\eta\pi\alpha^2}{2}E_{\mathrm{in}}^2\,\mathrm{j}^{M-N}J_M(m_1)J_N(m_2)\,\mathrm{e}^{\mathrm{j}(M\beta+\theta)}\ , \tag{6}$$

where N is integer number and represents the order of frequency w_2.

The third coefficient of Eq.(3) is

$$T_3^{M,N}=\frac{\eta\pi\alpha^2}{2}E_{\mathrm{in}}^2\overline{a_M}b_N\,\mathrm{e}^{-\mathrm{j}(M\beta+\theta)}=$$
$$\frac{\eta\pi\alpha^2}{2}E_{\mathrm{in}}^2\,\mathrm{j}^{-M+N}J_M(m_1)J_N(m_2)\,\mathrm{e}^{-\mathrm{j}(M\beta+\theta)}\ . \tag{7}$$

The fourth coefficient of Eq.(3) is

$$T_4^N=\frac{\eta\pi\alpha^2}{2}E_{\mathrm{in}}^2\sum_{q_1=-\infty}^{+\infty}\mathrm{j}^{q_1}J_{q_1}(m_2)\,\mathrm{j}^{-N+q_1}J_{N-q_1}(m_2)=$$
$$\frac{\eta\pi\alpha^2}{2}E_{\mathrm{in}}^2\,\mathrm{j}^{-N}J_N(0)\ . \tag{8}$$

Thus, Eq.(3) can be simplified as

$$I(w)=\frac{\eta\pi\alpha^2}{2}E_{\mathrm{in}}^2\{\mathrm{j}^{-M}\mathrm{e}^{-\mathrm{j}M(\beta+\varphi)}J_M[\sqrt{2}m_1\sqrt{1-\cos(2\beta)}]\times$$
$$\delta(w-Mw_1)+2\cos[\frac{\pi}{2}(M-N)+M\beta+\theta]J_M(m_1)\times$$
$$J_N(m_2)\delta(w-Mw_1-Nw_2)+\mathrm{j}^{-N}J_N(0)\delta(w-Nw_2)\}\ . \tag{9}$$

The analytical solution of arbitrary nonlinear distortion can be derived through Eq.(9).

In order to confirm our analytical solution and analyze the effect of modulation index on nonlinearity, the OptiSystem tool is utilized to simulate the entire system. Assume that the phase difference between the drives of the two branches is

$\beta = 0.2\pi$, and the DC bias phase shift is $\theta = 0.4\pi$. We define the second-order harmonic distortion ratio (HDR2) as P_{2w_1}/P_{w_1}, the second-order inter-modulation distortion ratio (IMR2) as $P_{w_1+w_2}/P_{w_1}$, the third-order harmonic distortion ratio (HDR3) as P_{3w_1}/P_{w_1}, and the third-order inter-modulation distortion ratio (IMR3) as $P_{2w_1-w_2}/P_{w_1}$. The relation between the nonlinear distortion ratio and modulation index of the modulator is shown in Fig.2.

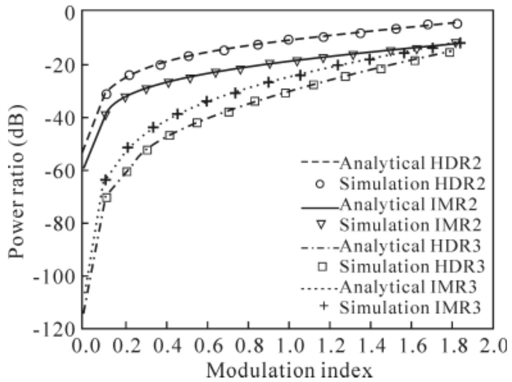


Fig.2 Relation between the nonlinear distortion ratio and modulation index of the modulator with $\beta = 0.2\pi$ and $\theta = 0.4\pi$

It can be seen that the simulation results are well matched with the analytical ones. The second-order harmonic distortion is bigger than the second-order inter-modulation distortion, while the third-order harmonic distortion is smaller than the third-order inter-modulation distortion. When the modulation index is increased to 1.7, the second-order inter-modulation distortion is equal to the third-order inter-modulation distortion. The nonlinearity is increased as the increase of modulation index, so the nonlinearity can be suppressed by decreasing the modulation index.

Since the analytical solution of inter-modulation distortion is derived, we can calculate the second-order and third-order inter-modulation intercepts, as shown in Figs.3 and 4. It can be seen from Fig.3 that the fundamental power is equal to the second-order inter-modulation power when the modulation index is 2.76, and the further increase of the modulation index can lead to the power of the second-order inter-modulation bigger than the fundamental power. It can be seen from Fig.4 that the fundamental power is equal to the third-order inter-modulation power when the modulation index is 2.58, and the further increase of the modulation index can lead to the power of the third-order inter-modulation bigger than the fundamental power.

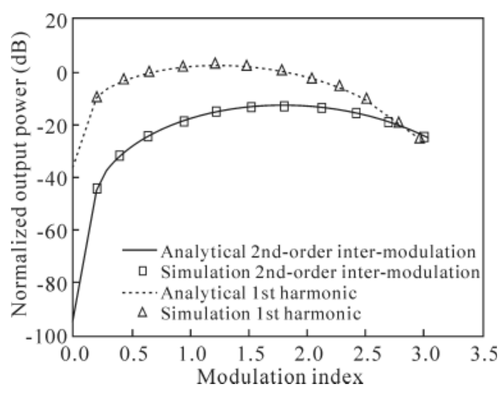


Fig.3 Second-order inter-modulation intercept of the modulator with $\beta = 0.2\pi$ and $\theta = 0.4\pi$

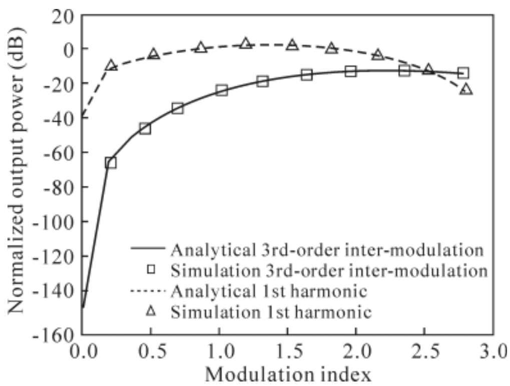
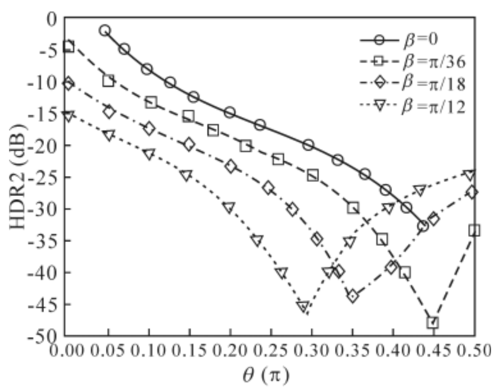


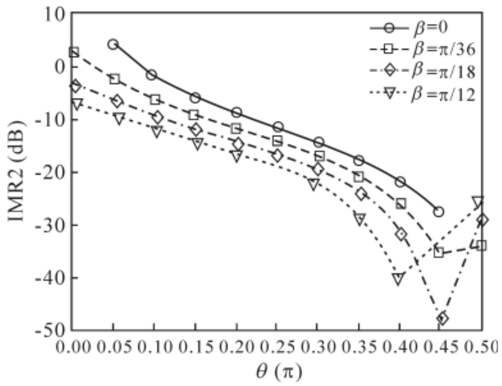
Fig.4 Third-order inter-modulation intercept of the modulator with $\beta = 0.2\pi$ and $\theta = 0.4\pi$

In order to analyze the effects of phase difference and DC bias point on nonlinearity, the variations of HDR2 and IMR2 with the phase difference and DC bias phase shift when the modulation index is 0.5 are plotted in Fig.5. It can be seen that the second-order nonlinear distortion decreases as the increase of the phase difference between two input RF signals and DC bias phase shift in a certain range. When the phase difference is 0 or π and the DC bias phase shift is π/2, there is no even-order harmonic or inter-modulaiton term.

Fig.6 shows the variations of HDR3 and IMR3 with the phase difference and DC bias phase shift when the modultion index is 0.5. It can be seen that the third-order nonlinear distortion decreases as the increase of the phase difference between two input RF signals and DC bias phase shift in a certain range. When the phase difference is 0, the third-order

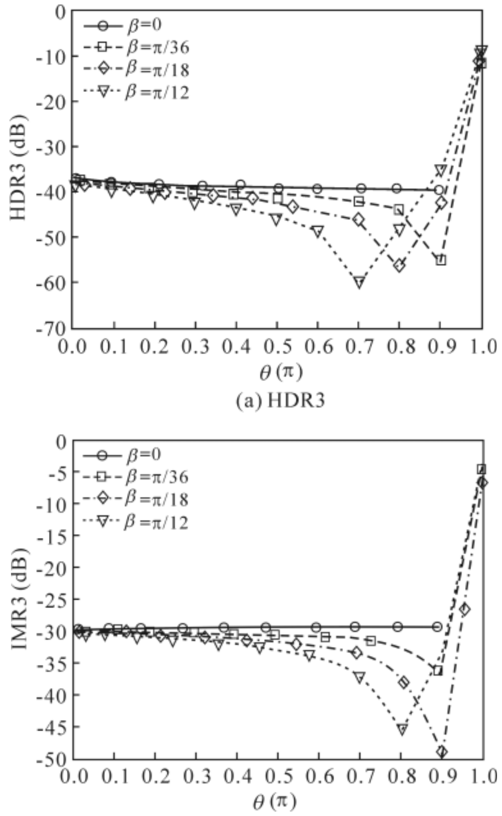


(a) HDR2



(b) IMR2

Fig.5 Variations of the second-order harmonic and inter-modulation distortion ratios



(b) IMR3

Fig.6 Variations of the third-order harmonic and inter-modulation distortion ratios

nonlinear distortion is independent of the DC bias phase shift. When the phase difference between two input RF signals is 0 or π and the DC bias phase shift is π, there is no odd-order harmonic or inter-modulaiton term.

The analytical solution for nonlinear distortion of the on-board microwave photonics system under two input RF signals with different frequencies and phases is derived in this paper. The simulation results are well matched with the analytical ones. Analytical results indicate that when the phase difference between two input RF signals is 0 or π and the DC bias phase shift is π/2, there are only odd-order distortion terms. When the phase difference is 0 or π, and the DC bias phase shift is π, there are only even-order distortion terms. In addition, the nonlinear distortion can be suppressed by decreasing the modulation index or increasing the phase difference between two input RF signals and DC bias phase shift.

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