Linearization of Mach-Zehnder modulator using microring-based all-pass filter

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By applying the microring resonator to the Mach-Zehnder (MZ) optical modulator and employing the super-linear phase change characteristic of the all-pass filter, the sublinear modulation curve of the conventional MZ modulator is highly linearized. With properly controlled power coupling between the microring and the arm of the MZ modulator, the third-order distortion can be suppressed. If the transmission coefficient is set between 0.25 and 0.42, the linearity range larger than 90% can be easily achieved. The maximum linearity range is even up to 99.5%.

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Optical modulator is one of the key components for signal transmission and transduction systems, and various types of optical modulators have been reported[1−4]. With the rapidly increasing demand for linear external modulators in recent years, practical solutions to the improvement of the modulation linearity are highly desired. Although a number of approaches to improve the linearity of the modulation characteristic have been proposed and applied[5−9], the improvement of the modulation linearity mostly comes at the expense of simplicity of the device design, and up to now no practical device has been found. As we know, the Mach-Zehnder (MZ) interferometer is one of the simplest and most widely used configurations of optical modulators, but the large nonlinear distortion adversely affects its performance and limits its applications, especially in the analog signal processing and transmission systems. The nonlinearity of the MZ modulator is mainly caused by the sinusoidal modulation curve, showing the sublinear characteristic, and so the linearity may be enhanced by applying super-linear phase modulation to the arm(s) of the MZ interferometer. Using the configuration of the microring-based all-pass filter[10,11] and tuning it far from the resonance is a way to achieve the super-linear characteristic. In this paper, the linearity characteristics of the MZ modulator with the microring resonator coupled (MRC) to its arms are analyzed, and the results indicate that this MRC-MZ modulator can be highly linear.

Figure 1 shows the schematic diagram of the MRC-MZ modulator, in which a microring resonator is coupled with one of its arms. The modulation electrode is set along the microring. The output intensity of the MRC-MZ modulator can be written as

$$I_{\rm out} = \frac{I_0}{2}\left[1+\cos\left(\varphi_1+\varphi_{\rm r}-\varphi_2\right)\right], \qquad (1)$$

where I_0 is the intensity of the input light, and φ_1, φ_2, and $\varphi_{\rm r}$ are the phase delays introduced by arm 1, arm 2, and the microring, respectively. Similar to the conventional MZ modulator, the MRC-MZ modulator also operates at a quadrature point, i.e. the phase delay difference $\Delta\varphi = \varphi_1 - \varphi_2$ should be set to be $(m+1/2)\pi$, where m is integer. The microring and arm 1, in fact, form a microring-based all-pass filter, and the following phase delay $\varphi_{\rm r}$ can be derived[10,11]

$$\varphi_{\rm r} = -2\arctan\left(\frac{1+\rho}{1-\rho}\tan\theta\right), \qquad (2)$$

where $\rho=\sqrt{1-\kappa^2}$ is the transmission coefficient, κ is the ring-waveguide amplitude-coupling coefficient. θ is the phase delay of the light with a wavelength λ_0 in a round trip $L_{\rm r}$ of the microring. If the modulation signal is applied, θ can be described as $\theta = \theta_0 + \Delta\theta$, where $\theta_0 = 2\pi L_{\rm r} n_0/\lambda_0$ is an item independent of the external modulation, and $\Delta\theta = 2\pi L_{\rm e}\Delta n/\lambda_0$ is the modulated phase change. Here $L_{\rm e}$ is the length of the modulation electrode, n_0 is the effective index of the microring, and Δn is the change of the effective index when the modulation signal is applied. Analysis shows that $\varphi_{\rm r}(\Delta\theta)$ is a super-linear function when θ_0 is set at the value of $(2l+1)\pi$, where l is integer, and its super-linearity can be tuned by changing the value of ρ. As mentioned above, this super-linearity can be applied to linearize the sublinear sinusoidal characteristic of the

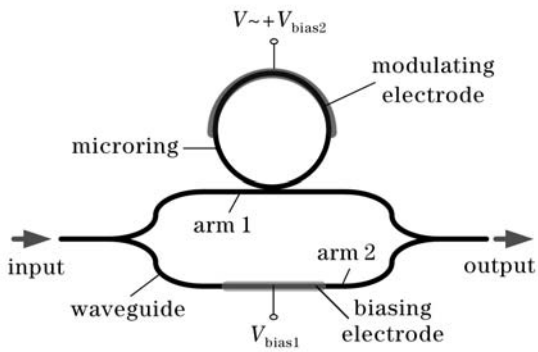

Fig. 1. Schematic diagram of the linearity-enhanced MZ modulator with a microring resonator coupled to one of its arms. The modulation signal is applied to the microring.

conventional MZ modulator. Biasing the modulator and setting $\Delta\varphi = (2m+1/2)\pi$ and $\theta_0 = (2l+1)\pi$, the output given by Eq. (1) can be re-written as

$$I_{\text{out}} = \frac{I_0}{2}\left[1 - \frac{1-\rho^2}{1+2\rho\cos\Delta\theta+\rho^2}\sin\Delta\theta\right]. \quad (3)$$

Figure 2 illustrates a modulation curve of the MRC-MZ modulator as well as its best linear fitting, in which the transmission coefficient ρ is assumed to be 0.35.

To assess the linearity of an optical modulator, two criterions are commonly used[12,5,8]. One criterion is the level of the spurious signals, also known as the nonlinear distortions, caused by the higher-order harmonic terms of the modulation curve. This criterion is normally used when the optical modulator is expected to be with a large spur-free dynamic range. It is well known that the even-order distortions can be effectively suppressed by biasing the modulator to the inflection point. For the MRC-MZ modulator, the even-order distortion of the modulation curve given by Eq. (3) has been eliminated by setting θ_0 to be $(2l+1)\pi$. The third-order harmonic terms of Eq. (3) can be expressed as

$$I_{\text{out}}^{(3)} = \frac{1}{3!}\frac{\partial^3 I_{\text{out}}}{\partial\Delta\theta^3}\Delta\theta^3 = -\frac{I_0}{2}\frac{(1-\rho)(1-4\rho+\rho^2)}{6(1+\rho)^3}\Delta\theta^3. \quad (4)$$

We calculated the coefficient ratio of the third-order harmonic term to the linear term, and the result is shown in Fig. 3. As the transmission coefficient ρ increases from zero, the ratio decreases from 0.167 (the value of the conventional MZ modulator). When ρ is tuned to be 0.268, the third-order term vanishes ($I_{\text{out}}^{(3)} = 0$).

Another quantitative criterion is the linearity range of the modulation curve[5,8]. The linearity range, in fact, is the maximum modulation depth at which the deviation of the modulation curve from the best linear fitting is still lower than a specified value η. It is a very important parameter to evaluate the lightwave transmission efficiency of an analog system. Assuming the best linear fitting is $f = f(\Delta\theta)$, we have the following expression of the linearity range m

$$m = \frac{I_{\text{out}}^{\text{U}} - I_{\text{out}}^{\text{L}}}{I_{\text{out}}^{\text{Max}}}, \quad (5)$$

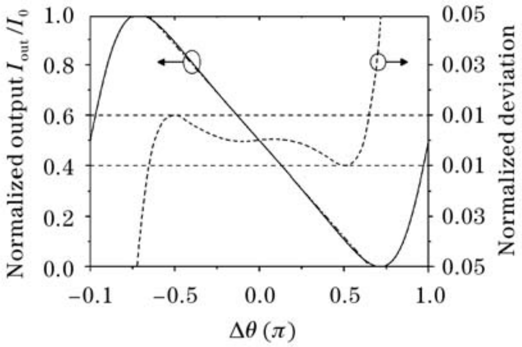

Fig. 2. Modulation curve (solid line) of the MRC-MZ modulator when the transmission coefficient ρ is 0.35. The best linear fitting (dash dot line) and the deviation of the modulation curve from the best linear fitting (dot line) are also presented.

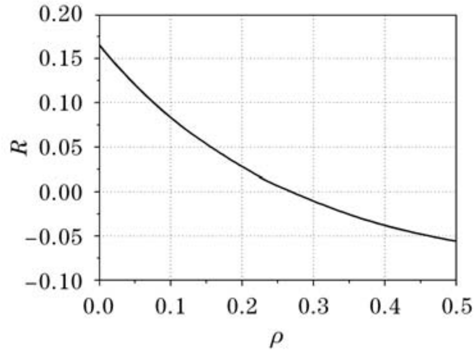

Fig. 3. Coefficient ratio (R) of the third-order harmonic term to the linear term versus the transmission coefficient ρ.

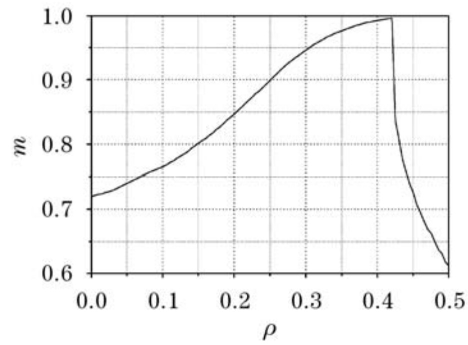

Fig. 4. Linearity range m of the MRC-MZ modulator with various transmission coefficients ρ. The deviation requirement is $\eta = 1\%$.

where $I_{\text{out}}^{\text{max}}$ is the maximum intensity of the output, and $I_{\text{out}}^{\text{U}}$ and $I_{\text{out}}^{\text{L}}$ are the output intensities corresponding to the upper and lower limits ($\Delta\theta^{\text{U}}$ and $\Delta\theta^{\text{L}}$) of the phase change range within which the following deviation condition is satisfied

$$|I_{\text{out}}(\Delta\theta) - f(\Delta\theta)| \leq \eta I_{\text{out}}^{\text{max}}, \quad \Delta\theta^{\text{L}} \leq \Delta\theta \leq \Delta\theta^{\text{U}}. \quad (6)$$

As an example, the deviation $[I_{\text{out}}(\Delta\theta) - f(\Delta\theta)]/I_{\text{out}}^{\text{max}}$ of the modulation curve from its best linear fitting curve $f(\Delta\theta) = -0.485\Delta\theta$ is also presented in Fig. 2. Under the requirement for the deviation of $\eta = 1\%$ which was commonly specified[5,8], a modulation depth of 97.3% can be calculated with this figure. Figure 4 illustrates the calculated linearity range of the MRC-MZ modulator with the variation of the transmission coefficient ρ under the same deviation requirement $\eta = 1\%$. It can be found that the linearity range is always larger than 90% when ρ is set between 0.25—0.42 and the maximum value can even reach up to 99.5% at $\rho \approx 0.42$. In comparison, when ρ is zero, the linearity range is only about 72%, which is the value of the conventional MZ modulator. We also calculated the maximum value of the linearity range under more severely required deviation conditions. Figure 5 illustrates the calculation results, in which the corresponding transmission coefficient is also presented. It can be found that the linearity range can still be about 80% even under the condition $\eta = 1‰$.

In conclusion, by using the microring resonator and taking advantage of the super-linearity of phase change curve of the microring-based all-pass filter, the sublinearity of the conventional MZ modulator can be effectively

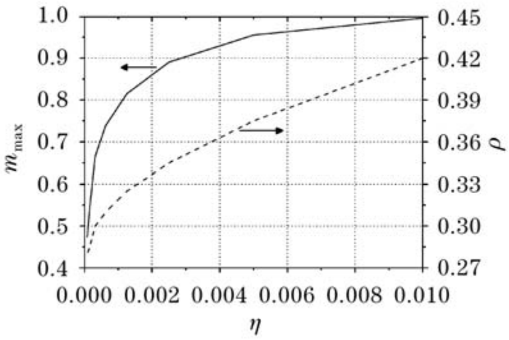

Fig. 5. Maximum linearity range $m_{\max}$ (solid line) of the MRC-MZ modulator under various deviation requirements η. The corresponding transmission coefficient (dash line) is also presented.

compensated and the highly linearized modulation characteristic can be achieved. With the properly set transmission coefficient ρ, the third-order harmonic term of the modulation curve can be removed. If ρ is tuned between 0.25 and 0.42, the deviation of the modulation curve from its best linear fitting is always below 1% over 90% of the entire interval of the modulation, and when ρ is 0.42, the maximum linearity range can reach 99.5%. Since the linearized MRC-MZ modulator is working at the off-resonance state of the microring and the power coupling between the microring and the coupled arm of the MZ interferometer is required to be strong (about 93% and 82% corresponding to $\rho = 0.268$ and 0.42, respectively), the influence of the optical loss in the microring is weak and high linearity can always be realized. Therefore, the MRC-MZ modulator offers a potential solution to attaining highly linear optical modulators with no special requirements for complicated configurations and/or precise electrical control.

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