Arbitrary Bias Point Control for Mach-Zehnder Modulator Using a Linear-Frequency Modulated Signal

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***Abstract*— A versatile arbitrary bias control technology for Mach-Zehnder modulators (MZMs) based on a linear-frequency modulated (LFM) signal is proposed. An LFM signal is applied to the direct current (DC) port of an MZM together with a DC voltage. The output microwave signal is measured and cross-correlated with the fundamental and frequency-doubled components of the LFM signal. Their ratio serves as the feedback signal to control the bias point. An experiment is carried out. Compared to the conventional single-frequency pilot-based bias control technique, the peak power of the LFM component in the output electrical signal decreases by more than 27 dB, and the error vector magnitude (EVM) of the output microwave signal evaluated by 1000 symbols is reduced from 13.632% to 5.929%.**

***Index Terms*— Modulators, linear-frequency modulated signal, microwave photonics.**

I. Introduction

MACH-ZEHNDER modulator (MZM) has the advantages of large modulation bandwidth, small frequency chirp, and low driving voltage, making it an irreplaceable component in high-speed optical communication systems and microwave photonics [1], [2]. Generally, an MZM is biased at a specific point to optimize the system performance [3], [4], such as the quadrature bias point (QB), the maximum transmission bias point (MATB), the minimum transmission bias point (MITB), and so on. However, it is well-known that the direct current (DC) bias point of the MZM is easily drifting as the environment fluctuates (includes the charging effects, stress, temperature, *et al.*), which would degrade the performance of the system seriously [5], [6]. Therefore, DC bias control is required to stabilize the optimized operating bias point.

In general, there are mainly two categories of bias control technologies, i.e., the optical power-based technique [7]–[9] and the pilot-based technique [10]–[12]. The basic principle of the optical power-based technique is to monitor the power of the input or output optical signal of the MZM or the power ratio between them. The variation of the power or the power ratio indicates the drifting of the bias point. By feeding the drift information back to the MZM, the bias point of the modulator can be locked. This method can stabilize the bias point at an arbitrary point and has little impact on the spurious-free dynamic range of the system thanks to the "dither-free" characteristic. But it is easily affected by the optical power fluctuations and insertion loss variations [13]. The technique in the second category generally applies a dither tone to the bias port of the MZM together with the DC bias. By monitoring the power ratio between the 1st- and 2nd-order sidebands of the dither tone, the modulator can be maintained at a specific bias point. This method has been proved to be very robust and stable. However, to obtain an accurate bias control, the amplitude of the dither tone must be large enough to stimulate a sufficiently large 2nd-order harmonics, which would induce nonlinear distortions to the transmitted radio frequency (RF) signal [14] and further deteriorate the link performance [15], [16]. Reducing the amplitude of the dither signal is the simplest method to improve the purity of the transmitted signal, but the control accuracy would be worsened because of the reduced signal-to-noise ratio (SNR) [13].

In this letter, a novel bias control technology that utilizes a linear-frequency modulated (LFM) signal as a dither tone to lock an MZM at an arbitrary bias point is proposed and demonstrated. The LFM signal is injected into the DC bias port of the MZM together with the DC bias. The output microwave signal is measured and cross-correlated with the fundamental and frequency-doubled components of the LFM signal, respectively. The ratio is served as the feedback signal to adjust the DC bias. Thanks to the broadband nature of the LFM signal, the power spectral density is significantly decreased for a given SNR. As a result, the nonlinear distortions introduced by the LFM signal can be dramatically reduced while the bias control accuracy maintains unchanged.

II. Theoretical Analysis

Fig. 1 shows the schematic diagram of the proposed LFM pilot-based bias point control system. An optical carrier from a laser diode (LD) is sent into an MZM via a polarization controller (PC). The MZM is driven by an electrical RF signal, an LFM signal, and a DC voltage.

Supposing the expression of the optical carrier is $E_0 \exp(j\omega_0 t)$, where E_0 is the amplitude of the optical carrier

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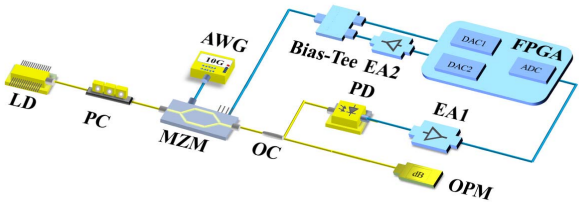

Fig. 1. Schematic diagram of the proposed MZM bias controller based on an LFM signal. LD: laser diode; PC: polarization controller; MZM: Mach-Zehnder modulator; AWG: arbitrary waveform generator; OC: optical coupler; OPM: optical power meter; PD: photodetector; EA: electrical amplifier; ADC: analog-to-digital converter; DAC: digital-to-analog converter; FPGA: field-programmable gate array.

and ω_0 is the angular frequency, the output optical signal of the MZM can be expressed as,

$$E_{out} = E_0 \exp(j\omega_0 t) \cdot \cos \Delta\varphi(t) \tag{1}$$

where $\Delta\varphi(t)$ represents the phase introduced by the electrical-driven RF signal, the LFM signal, and the DC voltage.

Supposing the expressions of the electrical driven RF signal and the LFM signal are,

$$V_{RF}(t) = V_{RF} \cos \omega_{RF} t \tag{2}$$

$$V_{LFM}(t) = V_{LFM} \cos(\omega_{LFM} t + \pi k t^2) \tag{3}$$

and that of the DC bias is V_{DC}, where V_{RF} and ω_{RF} represent the amplitude and angular frequency of the input RF signal, V_{LFM} and ω_{LFM} represent the amplitude and angular frequency of the input LFM signal, and k is the frequency modulation index of the LFM signal.

The phase of the optical signal in (1) can be rewritten as,

$$\Delta\varphi(t) = \frac{\pi}{2V_{\pi 1}} \left(V_{DC} + V_{LFM} \cos(\omega_{LFM} t + \pi k t^2) \right) + \frac{\pi}{2V_{\pi 1}} V_{RF} \cos \omega_{RF} t \tag{4}$$

where $V_{\pi 1}$ and $V_{\pi 2}$ are the half-wave voltages of the DC bias and the RF input of the MZM, respectively.

Using modulation indices m_{n} ($n = 1$ or 2) and DC phase φ_{DC} to simplify (4), we get

$$\Delta\varphi(t) = \varphi_{DC} + m_1 \cos \omega_{RF} t + m_2 \cos(\omega_{LFM} t + \pi k t^2) \tag{5}$$

where,

$$m_1 = \frac{\pi}{2V_{\pi 1}} V_{LFM} \tag{6}$$

$$m_2 = \frac{\pi}{2V_{\pi 2}} V_{RF} \tag{7}$$

$$\varphi_{DC} = \frac{\pi}{2V_{\pi 1}} V_{DC} \tag{8}$$

By injecting the output optical signal into a photodetector (PD) and ignoring the DC current, the output current can be expressed by,

$$I_{out} = E_0^2 \cos 2 \left(\varphi_{DC} + m_1 \cos \omega_{RF} t + m_2 \cos(\omega_{LFM} t + \pi k t^2) \right) \tag{9}$$

Expanding (9) with the Jacobi-Anger expansion, and ignoring the harmonics with orders higher than 2, the output current could be rewritten as,

$$I_{out} = E_0^2 \cdot \Big(-2 \cos 2\varphi_{DC} J_0(2m_2) J_2(2m_1) \cdot \cos 2(\omega_{LFM} t + \pi k t^2) - 2 \sin 2\varphi_{DC} J_0(2m_2) J_1(2m_1) \cdot \cos(\omega_{LFM} t + \pi k t^2) \Big) \tag{10}$$

where J_n represents the nth-order Bessel function of the first kind.

Cross-correlating I_{out} with the fundamental frequency of the LFM signal over a period of time T, the result can be expressed by,

$$R_1 = -\frac{E_0^2 \sin 2\varphi_{DC} J_0(2m_2) J_1(2m_1)}{\pi k t} rect\left(\frac{t}{T}\right) \cdot \sin(\pi k t - \frac{|t|}{t} \pi k t^2) \cos \omega_{LFM} t \tag{11}$$

Similarly, cross-correlating I_{out} with the frequency-doubled component of the LFM signal, the result can be expressed by,

$$R_2 = -\frac{E_0^2 \cos 2\varphi_{DC} J_0(2m_2) J_2(2m_1)}{2\pi k t} rect\left(\frac{t}{2T}\right) \cdot \sin 2(\pi k t - \frac{|t|}{t} \pi k t^2) \cos 2\omega_{LFM} t \tag{12}$$

The ratio of R_1 and R_2 at the maximum point ($t = 0$) is,

$$Q = \frac{R_1}{R_2} = \tan 2\varphi_{DC} \frac{J_1(2m_1)}{J_2(2m_1)} \tag{13}$$

As can be seen from (13), the ratio Q is related to the phase introduced by the DC bias. When the bias voltage changes, the ratio Q would be changed too. As a result, the ratio Q can be used to stabilize the bias at an arbitrary point.

III. Experimental Setup and Results

A proof-of-concept experiment is carried out based on the setup shown in Fig. 1. A 1550-nm optical carrier with a power of 18 dBm is generated by an LD (Agilent N7714A), which is then sent to a commercially-available MZM (Fujitsu FTM 7938EZ) with a 3-dB bandwidth of 40 GHz and a half-wave voltage of 5 V via a PC. The MZM is driven by an RF signal generated by an arbitrary waveform generator (AWG, Keysight M8195A). Its bias point is controlled by a DC voltage and an LFM signal generated by a field-programmable gate array (FPGA). The FPGA consists of two digital-to-analog converters (DAC1 and DAC2) and an analog-to-digital converter (ADC). DAC1 is used to generate the aforementioned LFM signal, and DAC2 is employed to produce the DC voltage. The resolution and the output range of the DACs are 14 bits and −5 to +5 V, respectively. An electrical amplifier (EA) is followed by DAC2 to amplify the DC voltage from 0-5 V to 0-12 V before its output combining with DAC1's output. The combined signal is applied to the DC bias port of the MZM. The output of the MZM is detected by a PD with a bandwidth of 16 GHz and a responsivity of 0.65 A/W, which is captured by the ADC in the FPGA after amplified by an amplifier (EA2). The sampling rate and the effective number of bits of the ADC are 100 MHz and 12 bit, respectively.

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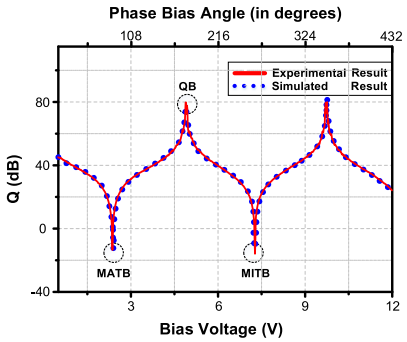

Fig. 2. The ratio of the cross-correlation results as a function of the bias voltage.

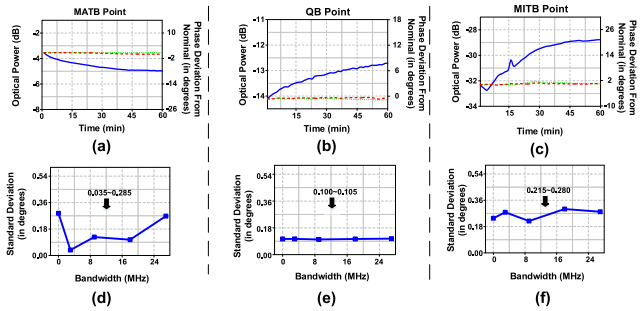

Fig. 3. (a∼c) Real-time optical power variations of the system at the MATB, QB, and MITB points, without control (blue-solid curve), with a signal-frequency pilot (red-dashed curve), and with an LFM pilot (green-dotted curve), (d∼f) Standard deviations of the LFM pilot-based system at the MATB, QB, and MITB points.

The data is then cross-correlated with the fundamental and frequency-doubled components of the LFM signal, respectively, which is stored in the FPGA's random access memory (RAM) in advance. Their ratio is calculated in the FPGA and used as the feedback signal to control the bias point.

Firstly, the cross-correlation ratio is calculated when an LFM signal with a frequency from 3 to 6 MHz, an amplitude of 100 mV, and a time duration of 1 s is employed. The measured cross-correlation ratio curve is shown as the red-solid curve in Fig. 2. As can be seen, the cross-correlation ratio is highly sensitive to the bias voltage variation, indicating that a small bias variation would lead to a large fluctuation of the cross-correlation ratio. Therefore, the ratio can be used as the feedback signal to stabilize the bias point. It should be noted that arbitrary bias points can be controlled as long as the cross-correlation ratio is pre-set and maintained by the feedback loop. The experimental result agrees very well with the simulated curve (shown as the blue-dot curve in Fig. 2).

The bias control performance of the proposed technique is evaluated by the drifting of optical power. Figs. 3 (a) - (c) show the measured powers of the output signal of the MZM with/without bias control at the MATB, QB, and MITB points over 60 minutes, respectively. The optical power is monitored by an optical power meter (OPM, JW3208). The blue-solid curves represent the output powers without bias control, and phase variations of 9.00 degrees for the MATB points, 8.81 degrees for the QB points, and 22.08 degrees for the MITB points are observed. The green-dotted curves show the output powers with the LFM pilot-based bias

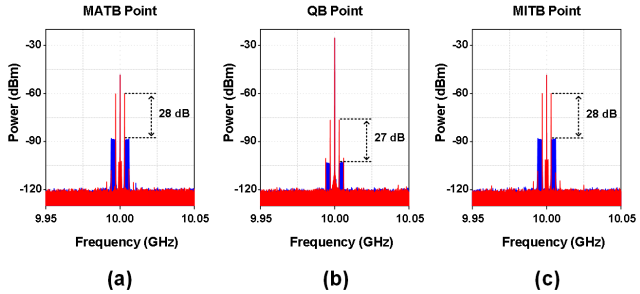

Fig. 4. The electrical spectrum of the output signal at the MATB, QB, and MITB points, where the pilot is a single-frequency signal (red curve), and an LFM signal (blue curve).

control, and the phase variations decrease to 0.43 degrees, 0.25 degrees, and 1.50 degrees, respectively. For comparison, the output powers of the MZM under single-frequency pilot-based bias controlling are also observed. A 3-MHz single-frequency signal with an amplitude of 100 mV and time duration of 1 s is served as the dither tone. The bias point is adjusted by monitoring the power ratio between the 1^{st}- and 2^{nd}-order sidebands of the dither tone. The results are illustrated as the red-dashed curves in Figs. 3 (a) - (c). As can be seen, the phase variations are 0.75 degrees, 0.25 degrees, and 1.06 degrees, respectively. Compared to the system without bias control, no matter the dither tone is an LFM signal or a single-frequency tone, the optical power is drifting within an extremely small range.

The impact of the bandwidth of the LFM signal on the bias point control performance is also evaluated. The bandwidth of the LFM signal is changed from 3 to 27 MHz. As shown in Figs. 3 (d) - (f), the standard deviation variations for the MATB, QB, and MITB points with bias control are 0.035-0.285 degrees, 0.100-0.105 degrees, and 0.215-0.280 degrees, respectively. Meanwhile, the standard deviations without bias control in degrees are 2.335 degrees, 2.350 degrees, and 7.995 degrees. That is to say, when the bandwidth is expanded, the results vary within a narrow range. However, the standard deviations are still very small compared to the system without bias control, indicating that the bandwidth of the LFM signal has little impact on the control effect.

Finally, the impact of the dither tone on the RF signal is explored. The frequency and power of the RF signal are 10 GHz and 16 dB, respectively. The RF signal is first modulated onto the optical carrier via the MZM and is then converted back to the electrical domain through a PD. The microwave signal is detected by an electrical spectrum analyzer (ESA, FSWP), and the electrical spectra of the output RF signal under different bias points are shown in Fig. 4. As can be seen, the peak power of the LFM signal component decreases by more than 27 dB, indicating that the proposed LFM pilot-based system would introduce a smaller degradation to the RF signal than the conventional pilot-based system.

The single-frequency RF signal is then replaced by a 10-GHz 16-ary quadrature amplitude modulation (16-QAM) signal to further explore the operational performance of the proposed method in an optical communication link. The output of the MZM is split into two paths, and two PDs

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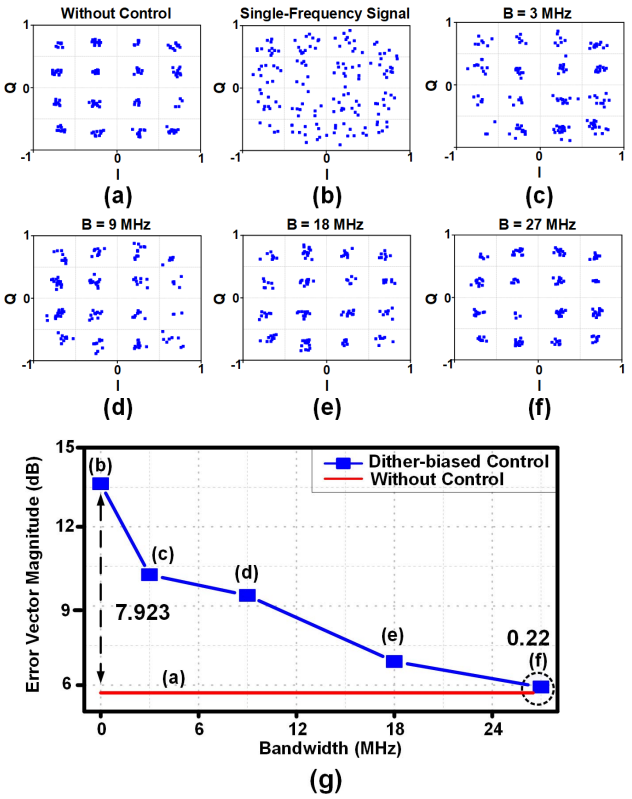

Fig. 5. Effect of the bias control on the 16-QAM signal. The constellation of the system (a) without bias control, (b) with a single-frequency pilot, (c)-(f) with an LFM pilot with bandwidths of 3, 9, 18, and 27 MHz, respectively. (g) The EVM as a function of the bandwidth of the LFM pilot.

(PD1 and PD2) are followed to convert the signal into the electrical domain. The output of PD2 is sent to a real-time oscilloscope (RTO, Agilent, DSO-X 92504A) to observe the constellation diagram of the QAM signal. In our experiment, the symbol rate of the 16-QAM signal is 120 Mbit/s, and the time duration of the LFM signal with different bandwidth is 1s. Fig. 5 (a) shows the output constellation diagram of the 16-QAM signal without bias control. The error vector magnitude (EVM) evaluated by 1000 symbols is 5.709 %. Fig. 5 (b) - (f) shows the constellation diagram of the 16-QAM signal at the output of the PD using different dither signals for bias point control. The EVMs evaluated by 1000 symbols are 13.632 % for a single-frequency pilot, 10.185 % for an LFM pilot with a 3-MHz bandwidth, 9.3948 % for an LFM pilot with a 9-MHz bandwidth, 6.8942% for an LFM pilot with 18-MHz bandwidth, and 5.929% for an LFM pilot with a 27-MHz bandwidth. When the bandwidth is around 27 MHz, the constellation in Fig. 5 (f) looks almost the same as that in Fig. 5 (a). The curve in Fig. 5 (g) indicates that the LFM-based bias control technology has a better performance than conventional pilot-based technologies, and the larger the bandwidth is, the better the bias point control performance will be.

IV. Conclusion

A novel and versatile LFM-signal-based bias control technology that can lock the MZM at arbitrary bias points has been proposed and demonstrated. The performances of systems without bias control, with single-frequency pilot-based bias control, and with LFM pilot-based bias control methods are evaluated. Since an LFM signal has a large bandwidth, its power is distributed to a large frequency range, making the power spectral density significantly decreased. Compared to the conventional single-frequency pilot-based bias control technique, the peak power of the LFM signal in the output electrical signal decreases by more than 27 dB, and the EVM of the output 16-QAM signal is reduced from 13.632% to 5.929%, indicating that the LFM dither-based bias control method has little impact on the transmitted signal. This bias control method provides a possible way to improve the performance of MZM-based microwave photonic links.

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