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A Novel Measurement Approach for the Half-wave Voltage of Phase Modulator based on PM-MZI Photonic Link

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This paper presents a new method for measuring the half-wave voltage V_π of an electro-optic phase modulator based on a phase-modulated photonic link with interferometric demodulation. By using this method, the V_π can be obtained with the RF voltage amplitude input required to achieve 1-dB gain compression of link and the differential delay of a Mach-Zehnder interferometer. We measure the V_π of a commercial phase modulator by using the presented method and the carrier/the first sideband intensity ratio method. Furthermore, we compare the two measurements with the typical value provided by the manufacturer. The experiment shows that this novel measurement method is feasible, straightforward, and accurate.

Keywords : Half-wave voltage, Phase modulator, Microwave photonic link
OCIS codes : (250.4110) Modulators; (120.5060) Phase modulation; (060.2360) Fiber optics links and subsystems

I. INTRODUCTION

The use of photonic approaches to transmit and process microwave signals has been an interesting research area for several decades, due to its advantages of large bandwidth, low loss, and immunity to electromagnetic interference (EMI) [1]. Owing to the more linear conversion of input voltage to optical phase and requiring no bias controller, the $LiNbO_3$ electro-optic phase modulator (PM) attracts a great deal of attention and has a host of applications [2, 3], such as microwave photonic links [4], optoelectronic oscillators [5, 6], optical comb generators, and all-optical microwave filters [7]. The half-wave voltage (V_π) is one of the most significant parameters to characterize a PM, which is the voltage required to produce π radians optical phase shift and represents the modulation efficiency of the PM. Therefore, the measurement of V_π is important for PM manufacturers and end users.

Recently, several different methods for measuring the V_π of a PM in the optical domain using an optical spectrum analyzer (OSA) have been proposed, such as the carrier nulling method [8], sideband nulling method, Carrier/the first sideband (FSB) intensity equalization method and Carrier/FSB intensity ratio method [9]. Nevertheless, most of these methods require high driving power with peak-to-peak voltage significantly higher than V_π, which may change optoelectronic properties of PM and damage the device under test. And it is inconvenient to fine-tune the RF power manually at each frequency point to meet the critical measurement condition. Moreover, the resolution of commercial OSA is generally larger than 2 GHz, so that it is hard to measure the V_π of PM in the lower frequency range by using these methods.

The method for measuring V_π of PM in the electric domain based on the gain of phase-modulated link is also demonstrated [10]. Although this method eliminates the manual adjustment of RF power at each frequency point and does not require high driving power, lots of factors that have to be calibrated beforehand may degrade the measurement accuracy, such as the optical power of laser, optical insertion loss and responsivity of photodiode (PD). Even worse, the responsivity of PD is also frequency-dependent and it is hard to calibrate as well.

In this paper, we propose a method for measuring the V_π of a PM based on a phase-modulated Mach-Zehnder interferometric demodulation (PM-MZI) photonic link. In the measurement, the V_π only depends on the RF voltage amplitude input required to achieve 1-dB gain compression

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of the link ($V_{RF,in,1dB}$) and the differential delay of Mach-Zehnder interferometer (MZI). And the $V_{RF,in,1dB}$ can be automatically swept using a network analyzer (NA), eliminating the manual adjustment of RF power at every frequency point. The $V_{RF,in,1dB}$ of the link can be reached at low driving power, which ensures the safe operation of the PM under test. Moreover, V_π can be measured in the low frequency range. Additionally, this method does not depend on the frequency response of the PD.

II. PRINCIPLE

The Fig. 1 shows a PM-MZI link which comprises a laser, an external PM, an asymmetric MZI and a PD. Firstly, the signal is modulated on the phase of optical carrier by the PM. Then, the optical carrier is fed into the MZI which converts phase modulation into intensity modulation. And finally, the RF signal can be directly recovered by a PD. The photocurrent output of the PD is given as follows with the MZI set at quadrature [11]:

$$I(t) = I_{dc}\left\{1+\sin\left[\phi(t)-\phi(t-\tau)\right]\right\} \tag{1}$$

where $I_{dc} = aP_0\Re/2$, a is the total optical insertion loss of the link, P_0 is the optical power output of the laser, $\Re$ is the PD responsivity, τ is the differential delay of the MZI, and $\phi(t) = \pi V_{RF}\sin(\omega t)/V_\pi$ with $V_{RF}\sin(\omega t)$ as the driving signal.

The photocurrent given in the Eq. (1) can be expanded using the Bessel function of the first kind [12] and it is given by

$$I(t) = I_{dc} + 2I_{dc}\sum_{n=1}^{+\infty} J_{2n-1}\left[\frac{2\pi V_{RF}}{V_\pi}\sin(\omega\tau/2)\right] \sin\left[(2n-1)\omega t\right] \tag{2}$$

where J_{2n-1} is the (2n-1)th order Bessel function of the first kind. According to the Eq. (2), the RF power output at the fundamental frequency ($P_{RF,out}$) of the link can be derived with n = 1. And it is given by

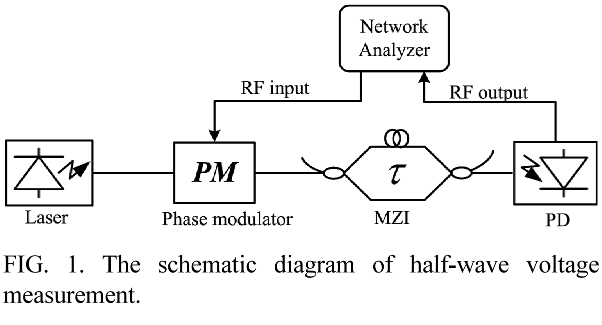

FIG. 1. The schematic diagram of half-wave voltage measurement.

$$P_{RF,out} = 2\left\{I_{dc}J_1\left[2\frac{\pi V_{RF}}{V_\pi}\sin(\omega\tau/2)\right]\right\}^2 Z_L \tag{3}$$

where Z_L is the output impedance. Owing to the nonlinearity of the first order Bessel function, the $P_{RF,out}$ will be compressed when the RF power input is large enough. Generally, the small signal approximation of the RF power output at the fundamental frequency ($P_{RF,out,ss}$) can be obtained using the linear approximation of the 1st order Bessel functions $J_1(x) = x/2$. And it is given as follows:

$$P_{RF,out,ss} = 2\left[I_{dc}\frac{\pi V_{RF}}{V_\pi}\sin(\omega\tau/2)\right]^2 Z_L \tag{4}$$

With $P_{RF,in} = V_{RF}^2/(2Z_{in})$ and Eq. (4), the small-signal RF gain of the PM-MZI link is

$$G = 4\left[I_{dc}\frac{\pi}{V_\pi}\sin(\omega\tau/2)\right]^2 Z_{in}Z_L \tag{5}$$

As can be seen from Eq. (5), the PM-MZI link exhibits a frequency-dependent gain dictated by the differential delay of MZI. And the free spectral range (FSR) of the gain is equal to the reciprocal of the differential delay of MZI ($FSR = 1/\tau$).

With the quotient (4) over (3) set to $10^{0.1}$(1 dB), Eq. (6) can be obtained. In this case, the V_{RF} equals the RF voltage amplitude input required to achieve 1-dB gain compression ($V_{RF,in,1dB}$) of the link.

$$\frac{\pi V_{RF}\sin(\omega\tau/2)/V_\pi}{J_1\left[2\pi V_{RF}\sin(\omega\tau/2)/V_\pi\right]} = 10^{0.05} \tag{6}$$

In order to find the relational expression of V_π, we expand the first order Bessel function of the first kind to the ninth-order polynomial based on the following formula [12]

$$J_n(x) = \sum_{l=0}^{\infty}\frac{(-1)^l}{2^{2l+n}l!(n+l)!}x^{2l+n} \tag{7}$$

Consequently, an eighth-degree polynomial equation with the unknown of V_π is obtained. The relational expression of V_π can be found by numerically solving this eighth-degree polynomial equation and is given by

$$V_\pi = 2.104\pi\sin(\omega\tau/2)V_{RF,in,1dB} \tag{8}$$

As can be seen from Eq. (8), the V_π of the PM can be calculated directly with the $V_{RF,in,1dB}$ and the differential delay of the MZI. Importantly, the measurement of V_π is independent of the responsivity of PD, the optical power as well as the optical insertion loss.

The RF voltage amplitude input required to drive the link into 1-dB compression is related to V_π by

$$V_{RF,in,1dB} \cong \frac{0.15}{\sin\left(\omega\tau/2\right)} V_\pi \qquad (9)$$

Obviously, the smallest peak-to-peak voltage swings 30% of V_π when $|sin(\omega\tau/2)| = 1$. The required peak-to-peak voltage input based on this method is much smaller than for the previous methods, such as carrier nulling method ($V_{RF,in,pp} \cong 1.53\ V_\pi$) [8], sideband nulling method ($V_{RF,in,pp} \cong 2.439\ V_\pi$), and Carrier/FSB intensity equalization method ($V_{RF,in,pp} \cong 0.914\ V_\pi$) [9]. Therefore, the method presented here with low RF drive voltage ensures the safe operation of the PM.

III. EXPERIMENT

The experimental setup of V_π measurement is shown in Fig. 1, which is constructed with an Emcore 1772 DFB laser, a Covega LN53 PM, a DSC40S-HLPD PD and an asymmetric MZI. We sweep and normalize the gain of the PM-MZI link by using a network analyzer (Agilent PNA-X N5242A). The FSR of the gain is measured and it is equal to 3.37 GHz, as shown in Fig. 2.

The Eq. (8) shows that the V_π can be calculated directly from the $V_{RF,in,1dB}$ and the differential delay of MZI. According to $FSR = 1/\tau$, the differential delay of MZI can be calculated and it is equal to 297 ps. Therefore, the $V_{RF,in,1dB}$ is required to be measured. The N5242A network analyzer could automatically track the 1-dB gain compression point and the RF power input required to achieve 1-dB gain compression ($P_{RF,in,1dB}$). With the measured $P_{RF,in,1dB}$, the $V_{RF,in,1dB}$ can be calculated by using $V_{RF,in,1dB} = \sqrt{P_{RF,in,1dB}/\left(2Z_{in}\right)}$.

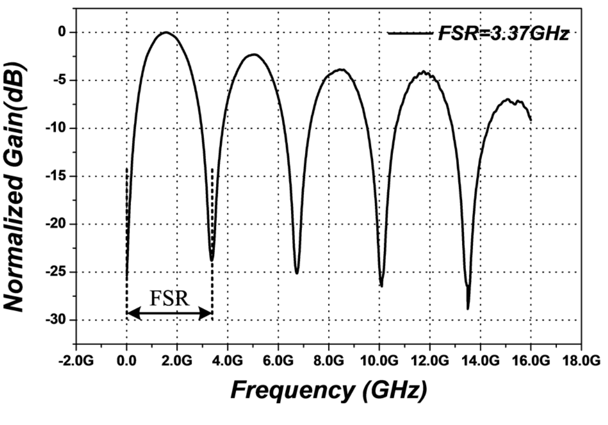

FIG. 2. The normalized gain of the PM-MZI link with FSR = 3.37 GHz.

We measure the $P_{RF,in,1dB}$ below 16 GHz with different optical power outputs of laser (P_0 = 60.1 mW, 40.2 mW and 20.8 mW). The error bar chart of $P_{RF,in,1dB}$ is shown in Fig. 3.

As shown in Fig. 3, the $P_{RF,in,1dB}$ of the PM-MZI link is frequency-dependent and does not rely on the optical power output of the laser, which agrees well with Eq. (9). The frequency-dependent $P_{RF,in,1dB}$ is dictated by the differential delay of MZI. Usually, with small MZI differential delay, the $P_{RF,in,1dB}$ varies gently with frequency due to the large FSR. But $P_{RF,in,1dB}$ can not be measured at low frequency because it is so large that it exceeds the maximum output power of the network analyzer. Whereas, with large MZI differential delay, the $P_{RF,in,1dB}$ swings frequently with frequency because of small FSR. And more frequency points meet $|sin(\omega\tau/2)| = 1$. Therefore, the MZI with large differential delay is recommended for our V_π measurement method.

According to the measured $P_{RF,in,1dB}$ in Fig. 3, the $V_{RF,in,1dB}$ can be obtained. Then, the V_π of PM can be calculated with $V_{RF,in,1dB}$ and the differential delay of MZI τ based on Eq.

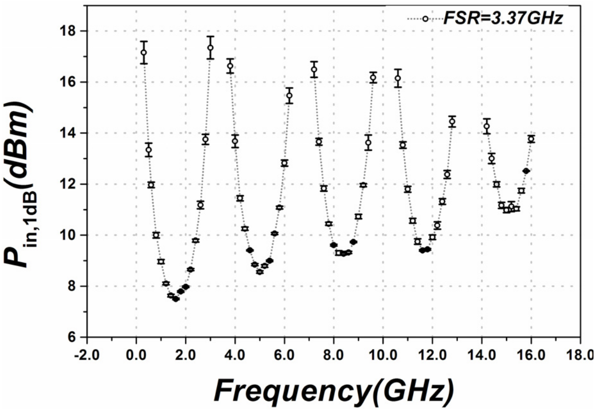

FIG. 3. The error bar chart of $P_{RF,in,1dB}$, which is measured below 16 GHz with different optical power outputs of the laser (P_0 = 60.1 mW, 40.2 mW and 20.8 mW).

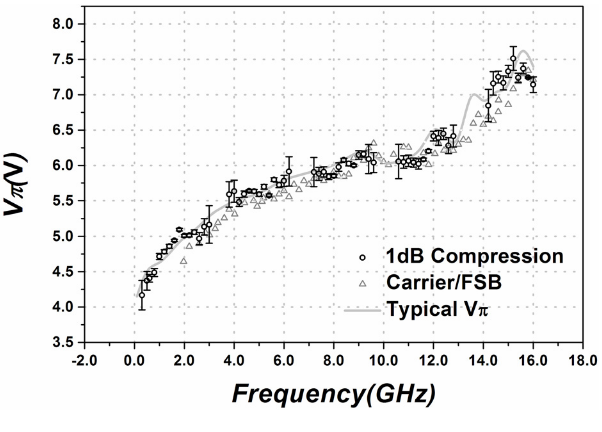

FIG. 4. The measured Vπ of phase modulator and the typical Vπ provided by the manufacturer.

(8). Furthermore, we also measure the V_π of the PM using OSA (YOKAGAWA AQ6370) based on the carrier/FSB intensity ratio method [9]. The V_π measurements based on the novel method (circles) and the carrier/FSB intensity ratio method (triangles) are shown in Fig. 4. As can be seen, the two V_π measurements and the typical value of V_π provided by the manufacturer increase with frequency and vary between 4 V and 8 V below 16 GHz. Overall, the two V_π measurements agree well with the manufacturer's typical value. The measurement error of carrier/FSB intensity ratio method is less than *0.4 V*. However, the measurement error of the proposed method is not more than *0.2 V* at the frequency that $|sin(\omega\tau/2)|$ is close to 1, and less than *0.4 V* at the frequency that $|sin(\omega\tau/2)|$ is away from 1. Therefore, compared with the carrier/FSB intensity ratio method, this method exhibits high accuracy, especially when the measurement is implemented with a large MZI differential delay because more frequency points meet $|sin(\omega\tau/2)| =1$.

IV. CONCLUSION

In this paper, we report a novel and simple method for measuring the V_π of a PM based on PM-MZI photonic link. The theory shows that the V_π of a PM can be calculated directly with $V_{RF,in,1dB}$ and the differential delay of MZI. In the experiment, we measure the V_π of a PM using the proposed method and the carrier/FSB intensity ratio method, respectively. And the two V_π measurements agree well with the typical value provided by the manufacturer.

Compared with the previously reported methods, this novel method avoids the process of manual adjustment of RF power and eliminates the dependence on responsivity of PD, optical power and optical insertion loss. Moreover, Based on this method, the V_π of a PM can be measured in the low frequency range and with low lever RF driving amplitude, smaller than 0.5 V_π, which ensures the safe operation of the device under test. Therefore, it is an attractively alternative method to measure the V_π of PM.

REFERENCES

1. R. C. Williamson and R. D. Esman, "RF photonics," J. Lightwave Technol. **26**, 1145-1153 (2008).
2. V. J. Urick, F. Bucholtz, J. D. McKinney, P. S. Devgan, A. L. Campillo, J. L. Dexter, and K. J. Williams, "Long-haul analog photonics," J. Lightwave Technol. **29**, 1182-1205 (2011).
3. V. J. Urick, F. Bucholtz, P. S. Devgan, J. D. McKinney, and K. J. Williams, "Phase modulation with interferometric detection as an alternative to intensity modulation with direct detection for analog-photonic links," IEEE Trans. Microwave Theory Tech. **55**, 1978-1985 (2007).
4. J. D. McKinney and K. J. Williams, "A linearized phase-modulated analog optical link," in *Proc. Conf. Quantum Electron. Laser Sci. Conf. Lasers Electro-Opt.* (San Jose, CA, United States, May 2008), pp. 235-236.
5. T. Sakamoto, T. Kawanishi, and M. Izutsu, "Optoelectronic oscillator using a $LiNbO_3$ phase modulator for self-oscillating frequency comb generation," Opt. Lett. **31**, 811-813 (2006).
6. Y. Chong, C. Yang, X. Li, and Q. Ye, "A frequency-doubling optoelectronic oscillator using a three-arm dual-output Mach-Zehnder modulator," J. Opt. Soc. Korea **17**, 491-493 (2013).
7. Z. Fei and Y. Jianping, "Investigation of phase-modulator-based all-optical bandpass microwave filter," J. Lightwave Technol. **23**, 1721-1728 (2005).
8. R. Tench, J. M. P. Delavaux, L. Tzeng, R. W. Smith, L. L. Buhl, and R. Alferness, "Performance evaluation of waveguide phase modulators for coherent systems at 1.3 and 1.5 um," J. Lightwave Technol. **5**, 492-501 (1987).
9. S. Yongqiang, Y. Lianshan, and A. E. Willner, "High-speed electrooptic modulator characterization using optical spectrum analysis," J. Lightwave Technol. **21**, 2358-2367 (2003).
10. Q. Ye, C. Yang, Y. Chong, and X. Li, "An alternative phase modulator half-wave voltage measurement based on photonic link," Chin. Opt. Lett. **11**, 71202 (2013).
11. J. D. McKinney, K. Colladay, and K. J. Williams, "Linearization of phase-modulated analog optical links employing interferometric demodulation," J. Lightwave Technol. **27**, 1212-1220 (2009).
12. F. W. J. Oliver, "Bessel functions of integer order," in *Handbook of Mathematical Functions* (1972), pp. 355-434.