Independently Self-calibrated Frequency Response Measurements of High-speed Modulators and Photodetectors with Same Setup

Shangjian Zhang[1,2,*], Chong Zhang[2], Heng Wang[1], Yong Liu[1], John E. Bowers[2]
[1] *School of Optoelectronic Information, University of Electronic Science and Technology of China, Chengdu 610054, China*
[2] *Department of Electrical & Computer Engineering, University of California, Santa Barbara, Santa Barbara CA 93106, USA*
sjzhang@ece.ucsb.edu

Abstract: A self-calibrated method based on the frequency-shifted heterodyne scheme is proposed and demonstrated for independent frequency response measurement of high-speed Mach-Zehnder modulators (MZMs), phase modulators (PMs) and photodetectors (PDs) with the same setup.
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1. Introduction

High-speed modulators (MODs) and photodetectors (PDs) are basic components in optical communication systems and microwave photonics links. Frequency responses of MODs and PDs are critical to the precise electrical-to-optical or optical-to-electrical signal conversion for the wideband applications especially at the microwave regime [1]. In the last decades, numerous measurement methods have been reported, in which the swept frequency method is widely used for the high-resolution frequency response measurement due to the developed vector network analyzer [2-6]. However, no matter what device under test (DUT), the measured results are always contributed by both the MOD and the PD in the setup [2,6], and this method relies on the extra calibration for de-embedding the contribution of the assistant devices except the DUT [6,7]. So, methods that enable high-resolution swept frequency measurement, and at the meantime avoid any extra calibration are of particular interest.

In this paper, the frequency-shifted heterodyne is proposed and demonstrated for the self-calibrated measurement of Mach-Zehnder modulators (MZMs), phase modulators (PMs) and PDs with the same setup. Frequency response of each device can be independently self-calibrated measured, and the influence from assistant devices is totally eliminated. Moreover, our method extends double measuring frequency range through setting a specific frequency relationship between the driving microwave signals.

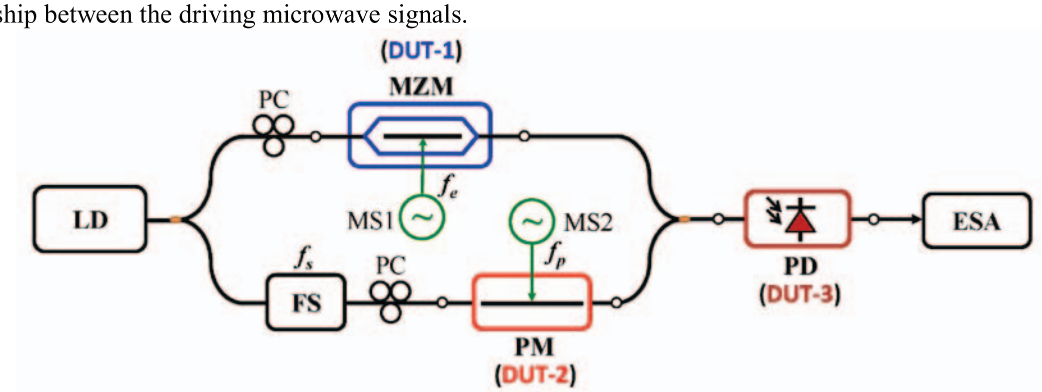

Fig. 1. Schematic setup of the self-calibrated frequency resoponse measurement method.

2. Operating principle

As shown in Fig.1, the schematic setup consists of a heterodyne interferometer (HI), where a MZM is located in one branch and a PM is located in the other branch together with a frequency shifter (FS). The optical carrier at angular frequency ω_0 in the upper branch of HI is intensity modulated in the MZM by a microwave signal $\upsilon_1(t)=V_e \sin\omega_e t$. The same optical carrier in the lower branch of HI is frequency shifted by ω_s in the FS and then phase modulated in the PM by another microwave signal $\upsilon_2(t)=V_p \sin\omega_p t$. The combined optical signals at the end of HI are detected by a PD to generate a photocurrent given by

$$i = R\left|e^{j\omega_0 t}\left[\left(e^{jm_1 \sin\omega_e t}+\gamma e^{jm_2 \sin\omega_e t + j\varphi}\right)+\eta e^{j\omega_s t + jm_p \sin\omega_p t}e^{j\psi}\right]\right|^2 \tag{1}$$

with the modulation depths m_i (i=1,2) and asymmetric factor γ ($0\leq\gamma\leq1$) of the two arms of MZM, the modulation depth m_p of PM, the responsivity R of PD, and the relative amplitude η and phase ψ between the two branches of HI, respectively. From Eq. (1), the heterodyne spectrum can be quantified with the Jacobi-Anger expansion as

$$i_\varphi\left(k\omega_e \pm l\omega_p \pm \omega_s\right) = 2\eta R\left(k\omega_e \pm l\omega_p \pm \omega_s\right) J_l\left(m_p\right)\left[J_k^2\left(m_1\right) + 2\gamma J_k\left(m_1\right) J_k\left(m_2\right)\cos\varphi + \gamma^2 J_k^2\left(m_2\right)\right]^{1/2}, k,l = 0,\pm1\ldots \quad (2)$$

In the case of MZM as DUT (DUT-1), the microwave frequency ω_e is set close to twice of ω_p ($\omega_e\approx2\omega_p>>\omega_s$) so that the assumption of $R(\omega_e\text{-}\omega_p\text{-}\omega_s)\approx R(\omega_p\text{-}\omega_s)$ is standing. Thus, the modulation depths and half-wave voltage of MZM can be extracted from

$$\frac{J_1\left(m_i\right)}{J_0\left(m_i\right)} = \frac{i_0\left(\omega_s\right)\left[i_0\left(\omega_e-\omega_p-\omega_s\right)-\left(-1\right)^i i_\pi\left(\omega_e-\omega_p-\omega_s\right)\right]}{\left[i_0\left(\omega_s\right)-\left(-1\right)^i i_\pi\left(\omega_s\right)\right] i_0\left(\omega_p-\omega_s\right)}, \left(i=1,2\right),\ V_\pi^m = \frac{\pi V_e}{m_1-m_2}. \quad (3)$$

In the case of PM as DUT (DUT-2), the microwave frequency ω_p is set close to twice of ω_e ($\omega_p\approx2\omega_e>>\omega_s$) so that $R(\omega_p\text{-}\omega_e\text{-}\omega_s)\approx R(\omega_e\text{-}\omega_s)$ is satisfied. So, the modulation depth and half-wave voltage of PM can be determined by

$$\frac{J_1\left(m_p\right)}{J_0\left(m_p\right)} = \frac{i_\varphi\left(\omega_p-\omega_e-\omega_s\right)}{i_\varphi\left(\omega_e-\omega_s\right)}, V_\pi^p = \frac{\pi V_p}{m_p}. \quad (4)$$

In the case of PD as DUT (DUT-3), the microwave frequency ω_e is set close to ω_p ($\omega_e\approx\omega_p>>\omega_s$) and the lowest frequency $\omega_e\text{-}\omega_p\pm\omega_s$ is fixed and close to DC. The relative resonsivity of PD at $\omega_e+\omega_p\pm\omega_s$ at can be expressed by

$$R_f = \frac{R\left(\omega_e+\omega_p\pm\omega_s\right)}{R\left(\omega_e-\omega_p\pm\omega_s\right)} = \frac{i_\varphi\left(\omega_e+\omega_p\pm\omega_s\right)}{i_\varphi\left(\omega_e-\omega_p\pm\omega_s\right)}. \quad (5)$$

It is worthy noticing that the MZM, PM and PD can be independently self-calibrated measured at different modulation frequencies with the same setup, since the influence from the assistant devices is fully cancelled out by carefully choosing the frequency relationship between the driving microwave signals. Moreover, our method extends double measuring frequency range, since the frequency response at ω is determined from the heterodyne spectrum at about $\omega/2$ (MZM and PD case), or with two driving signals at about $\omega/2$ (PD case). Besides, our method holds without the small-signal assumption, indicating the operation at different driving levels.

3. Experiments and results

In the experiment, the optical carrier from a semiconductor laser diode (LD) at 1550.36 nm is modulated by a $LiNbO_3$ MZM (SWT MOD-1550) in the upper branch of HI. The same optical carrier is frequency-shifted by an acousto-optic FS (CETC YSG70) and then modulated by a PM (COVEGA 10027, DUT-2) in the lower branch of HI. The MZM and PM are driven by two microwave sources (MS1, R&S SMB 100A; MS2, HP86320A), respectively. The combined optical signal is detected by a PD (HP 11982A) and analyzed by an electrical spectrum analyzer (ESA, R&S FSU50). The modulated signals in the upper or lower branch are also partially monitored by an optical spectrum analyzer (OSA, YOKOGAWA AQ6370C) for the accuracy comparison.

In the MZM measurement, the driving microwave frequencies are set as $f_e=2f_p$-0.02 (GHz). The bias phases φ are achieved by changing the applied bias voltage of MZM, where the minimum and maximum amplitudes of $i(f_s)$ denote $\varphi=\pi$ and 0, respectively. Figure 2(a) show the typical heterodyne spectra in the case of f_e=16 GHz, f_p=8.01 GHz and f_s=70 MHz. The desired frequency components of 70 MHz (f_s), 7.92 GHz ($f_e\text{-}f_p\text{-}f_s$) and 7.94 GHz ($f_p\text{-}f_s$) are measured to be -32.89 dBm, -54.24 dBm and -42.80 dBm at $\varphi=\pi$, and -19.90 dBm, -64.30 dBm and -30.93 dBm at φ=0. Therefore, the modulation depths m_1=0.146 rad, m_2=-0.121 rad and half-wave voltage V_π^m=8.91 V can be determined at 16GHz. The modulation depths and half-wave voltages are measured as a function of modulation frequency, as shown in Fig.2(b), where the results obtained using the OSA method are given for comparison.

In the PM measurement, the frequency relationship is set as $f_p=2f_e$+0.01 (GHz). Figure 2(c) shows the heterodyne spectrum in the case of f_p=10.01 GHz, f_e=5 GHz and f_s=70 MHz. From the power ratio of -14.54 dB between the frequency components at 4.94 GHz ($f_p\text{-}f_e\text{-}f_s$) and 4.93 GHz ($f_e\text{-}f_s$), the modulation depth and half-wave voltage of PM are solved to be m_p=0.37 rad and V_π^p=7.57 V at 10.01 GHz, respectively. As shown in Fig. 2(d), the modulated depths and half- wave voltages of the PM are measured at different modulation frequencies up to 30 GHz, where the results with the OSA method are also illustrated for comparison.

In the PD measurement, the driving frequencies are set by $f_e\text{-}f_p$=100 MHz and $f_e\text{-}f_p\text{-}f_s$=30 MHz. Figure 2(e) shows the heterodyne spectrum in the case of f_e=10.2 GHz, f_p=10.1 GHz and f_s=70 MHz, from which the electrical powers

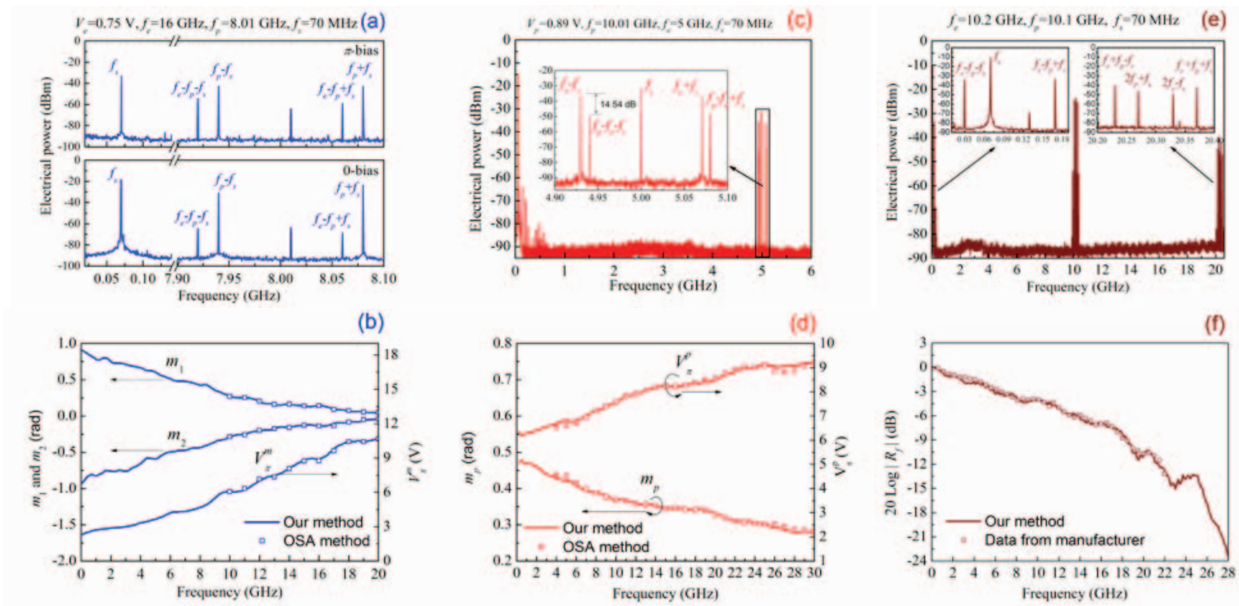

Fig. 2. Typical heterodyne spectra in the (a) MZM, (c) PM and (e) PD measurement, and the measured frequency responses of (b) MZM, (d) PM and (f) PD.

at 20.23GHz (f_e+f_p-f_s) and 20.37 GHz (f_e+f_p+f_s) is 10.36 dB and 10.30 dB lower than those at 30 MHz (f_e-f_p-f_s), and the relative responsivity of PD are determined to be -10.36 dB at 20.23 GHz and -10.30 dB at 20.37 GHz. The frequency responses of PD are illustrated as a function of modulation frequency in Fig. 2(f), in which the data from manufacturer Agilent Technologies, Inc. are provided for comparison.

In our experiment, the heterodyne spectra in our measurement show extremely narrow spectrum lines due to the inherent coherence of all modulated optical signals originating from the same optical carrier. In the case of MZM and PD as DUT, the modulation depths at f_e or f_p are extracted from the electrical spectrum lines at around f_e/2 or f_p/2, while in the case of PD as DUT, the frequency response at about f_e+f_p is obtained with two driving microwave signal at f_e and f_p, verifying the doubled measuring frequency range of our method. Moreover, our measurement is insensitive to the amplitude imbalance and phase difference of HI because of the frequency-shifted self-heterodyne scheme. It is also worthy noticing that a specially optimized bias phase of MZM is not necessary for the PM and PD measurement, since the bias phase has same influence on the desired electrical components. In practice, the larger $\cos\varphi$ is recommended for better signal amplitude and signal-to-noise ratio.

4. Conclusions

We have proposed and demonstrated independently self-calibrated microwave measurements of MZM, PM and PD with the same setup based on the frequency-shifted heterodyne. Modulation depths and half-wave voltages of MZM and PM and relative responsivity of PD at microwave frequencies were evaluated by the heterodyne spectrum of the modulated and frequency-shifted optical signals. Our method enables high-resolution self-calibrated frequency response measurement of MZMs, PMs and PDs, and eliminates the need to correct the influence from other assistant devices in the setup, which largely simplifies the microwave characterization of high-speed optoelectronic devices.

5. References

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