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Two-tone intensity-modulated optical stimulus for self-referencing microwave characterization of high-speed photodetectors

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ABSTRACT

The two-tone intensity modulated optical stimulus is proposed and demonstrated for measuring the high-frequency response of photodetectors. The method provides a narrow linewidth and wide bandwidth optical stimulus based on the two-tone modulation of a Mach–Zehnder electro-optical intensity modulator, and achieves the self-referenced measurement of photodetectors without the need for correcting the power variation of optical stimulus. Moreover, the two-tone intensity modulation method allows bias-independent measurement with doubled measuring frequency range. In the experiment, the consistency between our method and the conventional methods verifies the simple but accurate measurement.

1. Introduction

Photodetectors are key devices for achieving optical-to-electrical signal conversion in the microwave photonic link and radio-over-fiber system, especially those with flat and linear frequency responses [1–3]. With the operation frequency goes up to several tens of gigahertz, simple and accurate frequency response measurement of photodetectors has become more and more important.

In recent decades, many methods have been proposed for measuring the frequency responses of high-speed photodetectors with the all-optical or electro-optical stimulus.

The all-optical stimulus methods provide microwave-component-free ultra-wideband optical stimulus, such as the optical heterodyning method and the intensity noise method. The optical heterodyning method needs only a single or two tunable lasers [4–8]; however, the optical stimulus results in the additional calibration for the broadened linewidth and fluctuated optical power. The intensity noise method provides a calibration-free measurement based on spontaneous–spontaneous beat noise, and it suffers from low signal-to-noise ratio (SNR) and small dynamic measurement range [9–12].

In contrast to the all-optical stimulus methods, the electro-optical stimulus methods provide very narrow linewidth optical stimulus by the wideband electro-optical modulation, including the swept frequency method, the harmonics analysis method, the twice modulation method and the carrier-suppressed modulation method, etc. The swept frequency method is based on the cascaded measurement with a wideband optical transmitter, which requires extra de-embedding the contribution of the optical transmitter from the total results [13–15]. The carrier-suppressed modulation method extracts the frequency responses of phtotodetectors from the comparison between the optical and microwave power of the optical stimulus consisting of the pair of the first-order sidebands of a double-sideband suppressed-carrier (DSB-SC) optical signal [16–17], which requires strict microwave driving levels for suppressing the undesired optical carrier and higher-order sidebands. The harmonics analysis method and the twice modulation method are based on the nonlinear harmonic or cascaded intensity modulation [18–20]; however, they are very sensitive to the bias drifting of the intensity modulators and require active bias control to obtain stabilization. So, methods capable of providing a narrow linewidth and wide bandwidth optical stimulus, and at the same time avoiding to correcting the power variation of optical stimulus are of particular interest.

Recently, we proposed for the first time a self-referenced frequency response measurement of high-speed photodetectors based on frequency-detuned optical heterodyne, where the optical stimulus consists of acousto-optic frequency shifting and two-tone

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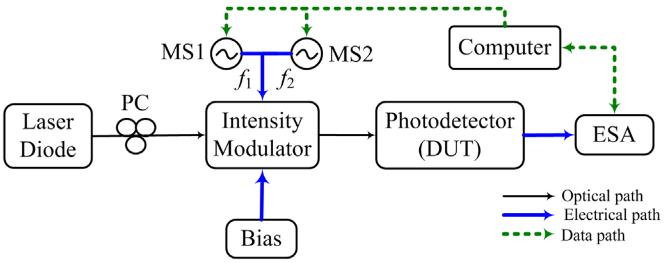

Fig. 1. Schematic setup of the proposed self-referencing method. MS: microwave source, DUT: device under test, PC: polarization controller, ESA: electrical spectrum analyzer.

phase modulation in a Mach–Zehnder interferometer [21]. However, the method needs a complex and costly optical stimulus due to the requirement of both the phase modulation and frequency shifting, which might limit its widespread application. In this paper, we propose a much simple but improved optical stimulus based on two-tone intensity modulation for the self-referenced measurement of frequency responses of high-speed photodetectors. As is shown in Fig. 1, the method consists of a Mach–Zehnder electro-optical modulator driven by two closely spaced sinusoidal tones. The two-tone intensity modulation generates the harmonic sidebands in the optical spectrum and their sum-and-difference frequency products in the electrical spectrum after photodetection allows direct extraction of frequency responses of photodetectors.

The proposed method holds very narrow linewidth due to the inherent coherence of the two-tone intensity-modulated sidebands originating from the same laser source. It avoids any calibration for the uneven responses of intensity modulator because they can be totally canceled out through carefully choosing the two-tone frequency. Moreover, our measurement is independent of the bias voltage of the intensity modulator, since it depends on the relative amplitude instead of the absolute amplitude of the desired electrical signals. Theoretical description is presented to elaborate our method as well as experimental demonstration. Frequency responses as a function of modulation frequency are measured for a commercial photodetector, and consistency between our method and the conventional method is fully investigated to check the accuracy.

2. Theoretical description

As is depicted in Fig. 1, an optical carrier with angular frequency ω_0 is sent to the intensity modulator onto which two closely spaced sinusoidal tones $\upsilon_1(t)=V_1\sin(\omega_1 t+\varphi_1)$ and $\upsilon_2(t)=V_2\sin(\omega_2 t+\varphi_2)$ are applied. The output optical field of the intensity modulator can be written by

$$E_m(t) = A_0 e^{j\omega_0 t}\left[1+\gamma e^{jm_1\sin(\omega_1 t+\varphi_1)+jm_2\sin(\omega_2 t+\varphi_2)+j\varphi_b}\right] \tag{1}$$

where A_0 is the amplitude of the optical carrier, γ is splitting ratio of the intensity modulator, and φ_b is phase bias from the bias voltage. The modulation depth m_i of the intensity modulator can be expressed by

$$m_i = \pi V_i/V_{\pi i}\quad (i=1,2) \tag{2}$$

with the half-wave voltage $V_{\pi i}$ of the modulator at the modulation frequency ω_i.

The two-tone modulated optical signal is detected by the photodetector under test to generate a photocurrent given by

$$\begin{aligned} i(t) &= R\,|E_m(t)|^2 \\ &= RA_0^2\left\{1+\gamma^2+2\gamma\cos\left[m_1\sin(\omega_1 t+\varphi_1)+m_2\sin(\omega_2 t+\varphi_2)+\varphi_b\right]\right\} \end{aligned} \tag{3}$$

with responsivity R of the photodetector. Applying the Jacobi–Anger expansion [22] to Eq. (3), we have

$$i(t) = RA_0^2\left[1+\gamma^2+2\gamma\sum_{p=-\infty}^{+\infty}\sum_{q=-\infty}^{+\infty}J_p(m_1)J_q(m_2)\cos(p\omega_1 t+q\omega_2 t+p\varphi_1+q\varphi_2+\varphi_b)\right] \tag{4}$$

where $J_p(\cdot)$ and $J_q(\cdot)$ are the pth or qth-order Bessel function of the first kind, respectively. From Eq. (4), we can quantify the frequency components ($p, q=\pm 1$), which can be expressed by

$$i(\omega_1\pm\omega_2) = 4\gamma A_0^2 J_1(m_1)J_1(m_2)\cos\varphi_b\cdot R(\omega_1\pm\omega_2) \tag{5}$$

It is obvious that the frequency components at $\omega_1\pm\omega_2$ have the same amplitude factor of $4\gamma A_0{}^2 J_1(m_1)J_1(m_2)\cos\varphi_b$, and their amplitude difference only depends on the frequency response R of photodetector at the frequencies of $\omega_1\pm\omega_2$.

In our measurement, the closely spaced two-tone frequencies ω_1 and ω_2 are carefully chosen so that their frequency difference $\omega_1-\omega_2$ is fixed and close to DC. In this case, the frequency response of the photodetector can be obtained from the relative amplitude between the sum-and-difference frequency components at $\omega_1\pm\omega_2$ given by

$$R_f = \frac{R(\omega_1+\omega_2)}{R(\omega_1-\omega_2)} = \frac{i(\omega_1+\omega_2)}{i(\omega_1-\omega_2)} \tag{6}$$

It is worthy noticing that our measurement only depends on the relative amplitude instead of the absolute amplitude of the desired frequency components, so the optical power variation induced by the bias voltage can be canceled out, and our method realized a self-referencing and bias-independent measurement of high-speed photodetectors. Moreover, the desired frequency components at $\omega_1\pm\omega_2$ hold a frequency span of $2\omega_1$ or $2\omega_2$ ($\omega_1\approx\omega_2$), indicating a doubled measuring frequency range.

3. Experimental demonstration

In our experiment, the $LiNbO_3$ Mach–Zehnder modulator (AVANEX XS1700) and the photodetector (Agilent 11982A) are used as the optical stimulus and the device under test, respectively. The optical carrier comes from a DFB laser diode with a wavelength of 1550.20 nm and an optical power of 5.5 dBm. The two-tone signal keeps a constant frequency difference of 1 MHz, and sweeps from 0.1 to 14 GHz with a frequency step of 0.2 GHz, which is generated from two microwave sources (MS, HP 86320A, R&S SMB100A) and one power combiner (HP 11667A). The DC power supply (Agilent E3620A) is used to change the bias voltage of the intensity modulator. The two-tone intensity modulated optical signal is directly injected into the photodetector under test for photodetection and then collected by an electrical spectrum analyzer (ESA, R&S FSU50) for analysis. For an automatically swept measurement, both the MS and the ESA are connected and controlled by a computer through NI-VISA data bus, with which the output microwave power and frequency of the two MS are set and the data from ESA are acquired by a written Matlab program. In order to reduce the residual reflection as much as possible, all the optical components are connected with angle polished (APC) finishes. For a better efficiency, the polarization controller is used to align the polarization between the optical carrier and the intensity modulator. In order to ensure the linear conversion, the input optical power of PD is kept no more than 0 dBm in our measurement, which is significantly lower than the maximum input power of 10 dBm.

Fig. 2 shows a typical electrical spectrum of the two-tone