Optoelectronic frequency response measurement of photodiodes by using high-extinction ratio optical modulator

Keizo Inagaki^{1a)}, Tetsuya Kawanishi¹, and Masayuki Izutsu²

¹ Photonic Network Research Institute, National Institute of Information and Communications Technology

4–2–1 Nukui-Kitamachi, Koganei, Tokyo 184–8795, Japan

² Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology

4259 Nagatsuta-cho, Midori-ku, Yokohama 226–8503, Japan

a) k-inagaki@nict.go.jp

Abstract: We propose a measurement method of photodetector frequency response. This technique is based on a heterodyne principle, where a high-extinction ratio Mach-Zehnder modulator is used to generate a two-tone lightwave as a stimulus signal up to millimeter-wave frequency bands. Our proposing method can provide a relatively short traceability chain to optical and electric power standards.

Keywords: photodetector, frequency response, optoelectronic transfer standard, high-extinction ratio Mach-Zehnder modulator, two-tone stimulus signal

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

References

- [1] T. Kawanishi, T. Sakamoto, and M. Izutsu, “High-speed control of light-wave amplitude, phase, and frequency by use of electrooptic effect,” *IEEE J. Sel. Topics Quantum Electron.*, vol. 13, no. 1, pp. 79–91, Jan. 2007.
- [2] P. D. Hale, C. M. Wang, R. Park, and W. Y. Lau, “A transfer standard for measuring photoreceiver frequency response,” *J. Lightw. Technol.*, vol. 14, no. 11, pp. 2457–2466, Nov. 1996.
- [3] P. D. Hale and C. M. Wang, “Calibration service of optoelectronic frequency response at 1319 nm for combined photodiode/RF power sensor transfer standards,” *NIST Special Publication 250-51*, Dec. 1999.
- [4] “Specifications for optical to electrical measurement at 1550 nm,” *Agilent N4373C 40/50/67 GHz single-mode lightwave component analyzer for 40/100 G electro-optical test data sheet*, Agilent, p. 11, Oct. 2010 [Online] <http://www.home.agilent.com/>
- [5] T. Kawanishi, T. Sakamoto, A. Chiba, M. Tsuchiya, and H. Toda, “Ultra high extinction-ratio and ultra low chirp optical intensity modulation for

- pure two-tone lightwave signal generation,” *Proc. CLEO 2008*, San Jose, U.S.A., CFA1, May 2008.
- [6] K. Inagaki and T. Kawanishi, “Calibration Method of Optoelectronic Frequency Response Using Mach-Zehnder Modulator,” *Proc. MWP 2010*, Montreal, Canada, WE4-25, Oct. 2010.

1 Introduction

Photodetectors (PDs) play important roles in optical fiber transmission, to achieve broadband electric-to-optical signal conversion. Frequency responses of high-speed PDs can extend from DC to millimeter-wave bands. In addition, precise signal conversion would be very important in digital transmission systems with advanced modulation formats and analog radio-on-fiber system [1]. Thus, precise estimation of conversion efficiency of PDs in high-frequency region would be very important. Optical heterodyne methods which use optical two-tone signals as stimulus have been commonly used for such purposes. Two lasers can be used as a two-tone signal source. However, it is rather difficult to apply the signal source with two lasers to laboratory or factory use, because complex feedback loops would be needed to stabilize optical frequency, polarization, etc [2, 3]. Measurement instrument traceable to a national standard is commercially available, where PDs whose responses are measured by two lasers with feedback stabilization control can be distributed to end users as reference calibrated optic-to-electric conversion devices. However, its “absolute frequency response uncertainties” are specified around ± 2 dB, which seem insufficient [4]. This would be due to long calibration periods of PDs.

An MZM with minimum transmission bias can generate a double-sideband suppressed-carrier (DSB-SC) signal consisting of the first order upper and lower sidebands. The optical frequency separation between the sidebands is quite stable without using feedback control, so that the DSB-SC signal would be applicable to the optical heterodyne method for laboratory or factory use. However, an ordinary MZM generates unwanted optical carrier and modulation harmonics. The powers of the desired two spectrum components could have some difference caused by fabrication imperfections. They will increase measurement uncertainties.

In this paper, we propose an optical heterodyne based PD response measurement technique using a high-extinction (ER) MZM using active trimmers [5] and a power equalization technique. A high-ER MZM with low modulation index can suppress the unwanted carrier and higher modulation harmonics. Theoretical analysis shows that biasing at a minimum carrier power point results in the equalized two-tone powers. Since the measurement system is directly based on the heterodyne principle, it can provide a shorter traceability chain to the optoelectronic transfer standard, compared with conventional instruments.

2 Heterodyne principle

It is well known that the output spectrum of an MZM modulated by a monotone RF signal can be expressed as a multi-tone optical signal. Here, the heterodyne principle is briefly summarized in the case of multi-tone signal of

$$E_{opt} = \sum_{n=-\infty}^{\infty} E_n e^{i(\omega_n t + \phi_n)}, \quad P_{opt} = \sum_{n=-\infty}^{\infty} P_n, \quad (1)$$

$$P_n \propto |E_n|^2 / Z, \quad \omega_{n+1} - \omega_n = \omega_{RF},$$

where P_{opt} is the total average power, and ω_{RF} is the angular frequency of modulating RF signal that corresponds to the angular frequency difference between adjacent optical tones. In this paper, we assume that the wave impedance Z for lightwave is unity to simplify the equations.

Assuming the MZM operated in a DSB-SC mode, only two tones of $n = \pm 1$ are dominant with the same power. Then, the amplitudes have relations of

$$|E_{-1}| = |E_{+1}| \gg |E_n| \quad (n \neq -1, +1),$$

$$P_{opt} \propto |E_{-1}|^2 + |E_{+1}|^2 = 2|E_{-1}|^2, \quad |E_{-1}||E_{+1}| = |E_{-1}|^2 \propto P_{opt}/2, \quad (2)$$

where the following conditions should be satisfied.

1. Suppression of optical carrier and higher order sidebands should be large enough.
2. Frequency difference between the two desired components should be tunable and stable.
3. Polarizations of the two spectral components should be well aligned.
4. Power difference of the two spectral components should be small enough.

The instantaneous optical power p_{opt} illuminating the PD is calculated as

$$p_{opt} \propto \left| E_{-1} e^{i(\omega_{-1} t + \phi_{-1})} + E_{+1} e^{i(\omega_{+1} t + \phi_{+1})} + \sum_{n=-\infty}^{\infty} E_n e^{i(\omega_n t + \phi_n)} \right|^2, \quad (3)$$

$$(n \neq -1, +1)$$

$$\propto P_{opt} + P_{opt} \cdot \cos(2\omega_{RF} t + \phi)$$

where $\phi = \phi_{-1} - \phi_{+1}$, and $|E_n|$ ($n \neq -1, +1$) related terms are neglected from the last equation. The PD under test outputs a DC and an RF photocurrent as a response. The RF photocurrent i_{RF} is expressed as

$$i_{RF} = \sqrt{\kappa} \cdot P_{opt} \cdot \cos(2\omega_{RF} t + \phi) = I_{RF} \cos(2\omega_{RF} t + \phi), \quad (4)$$

where κ is the frequency response of the PD under test at $2\omega_{RF}$, and I_{RF} is the peak photocurrent. The average RF power P_{RF} driving a load Z_L of 50Ω is expressed as

$$P_{RF} = \frac{I_{RF}}{\sqrt{2}} \cdot \frac{I_{RF}}{\sqrt{2}} Z_L = 25 I_{RF}^2. \quad (5)$$

From Eq. (4) and (5), the frequency response κ of the PD is calculated as

$$\kappa = \frac{I_{RF}^2}{P_{opt}^2} = \frac{P_{RF}}{25P_{opt}^2}. \quad (6)$$

Note that κ can be calculated only from the input optical and the output RF average powers of the PD under test, which are traceable to the national standards with relatively short traceability chain [6]. In the heterodyne measurement system, κ does not depend on frequency response of the MZM used for two-tone generation.

3 Proposed measurement system

3.1 System configuration

Fig. 1 illustrates the proposed measurement system of PD frequency response by using a high-ER MZM. Active trimmers are integrated to two arms of the main-MZ, which allow adjusting optical power balance. By setting the bias-3 at its minimum transmission point, the high-ER MZM is operated in DSB-SC mode with the carrier suppression ratio of greater than 30 dB. Moreover, higher modulation harmonics can also be suppressed significantly by optimizing the modulation index. As a result, the output lightwave is dominated by the first upper and lower sidebands. The frequency difference between them is precisely defined as double the modulation frequency, which is tunable by an RF synthesizer. Their polarizations are well aligned.

Fig. 1. Configuration of the proposed measurement system using a high-ER MZM.

3.2 Power equalization technique

In order to equalize optical power of the two-tone signal, we propose setting the bias-3 at its minimum transmission point. The amplitudes and powers of the carrier and the two tones are derived as follows.

Assuming a push-pull type MZM driven by a monotone RF signal of ω_{RF} as shown in Fig. 1, the field of its output lightwave can be expressed as

$$\begin{aligned}
 E &= L \frac{E_{input} e^{i\omega_0 t}}{2} \left[\left(1 + \frac{\eta}{2}\right) e^{i\{A_1 \sin(\omega_{RF} t + \phi_1) + \phi_{B1}\}} \right. \\
 &\quad \left. + \left(1 - \frac{\eta}{2}\right) e^{i\{A_2 \sin(\omega_{RF} t + \phi_2) + \phi_{B2}\}} \right] \\
 &= L \frac{E_{input} e^{i(\omega_0 t + \phi_{B1})}}{2} \sum_{n=-\infty}^{\infty} e^{in(\omega_{RF} t + \phi_1)} \left[\left(1 + \frac{\eta}{2}\right) J_n(A + \alpha_A) \right. \\
 &\quad \left. + \left(1 - \frac{\eta}{2}\right) J_n(-A + \alpha_A) e^{i(n\phi + \phi_B)} \right]
 \end{aligned} \quad (7)$$

where L is the loss factor inside the MZM, and $J_n(x)$ is the Bessel function of the first kind of order n . The values of ϕ_{B1} , ϕ_{B2} , ϕ_B are the bias phases, η is the optical intensity imbalance, ϕ_1 , ϕ_2 , ϕ are the skews, and A_1 , A_2 , A , α_A are the chirp related parameters defined as

$$\begin{aligned}
 \phi_B &= \phi_{B2} - \phi_{B1}, \\
 (P_1, P_2) &\propto \frac{|L \cdot E_{input}|^2}{4} \left(\left(1 + \frac{\eta}{2}\right)^2, \left(1 - \frac{\eta}{2}\right)^2 \right), \quad |\eta| < 1 \\
 \phi &= \phi_2 - \phi_1, \\
 (A_1, A_2) &= (A + \alpha_A, -A + \alpha_A), \quad |A| > |\alpha_A|
 \end{aligned} \quad (8)$$

Eq. (7) and (8) are well known for showing good agreements with the actual performance of MZMs, because four major error parameters of MZMs are all included [5]. The powers of the carrier, the upper sideband, and the lower sideband, (named “0”, “+1”, and “−1”, respectively) are derived as

$$\begin{aligned}
 P_0 &\propto |E_0|^2 = \frac{|L \cdot E_{input}|^2}{4} \{R^2 + S^2 + 2RS \cos \phi_B\} \\
 P_{+1} &\propto |E_{+1}|^2 = \frac{|L \cdot E_{input}|^2}{4} \{T^2 + U^2 - 2TU \cos(\phi_B + \phi)\} \\
 P_{-1} &\propto |E_{-1}|^2 = \frac{|L \cdot E_{input}|^2}{4} \{T^2 + U^2 - 2TU \cos(\phi_B - \phi)\} \cdot \\
 R &= \left(1 + \frac{\eta}{2}\right) J_0(A + \alpha_A), \quad S = \left(1 - \frac{\eta}{2}\right) J_0(A - \alpha_A) \\
 T &= \left(1 + \frac{\eta}{2}\right) J_1(A + \alpha_A), \quad U = \left(1 - \frac{\eta}{2}\right) J_1(A - \alpha_A)
 \end{aligned} \quad (9)$$

In the case of the MZM is biased at its minimum transmission point, which corresponds to the case of $\phi_B = \pi$, the powers of P_0 , P_{+1} , and P_{-1} are calculated as

$$\begin{aligned}
 P_0 &\propto \frac{|L \cdot E_{input}|^2}{4} (R - S)^2 \\
 P_{+1} &= P_{-1} \propto \frac{|L \cdot E_{input}|^2}{4} \{T^2 + U^2 + 2TU \cos \phi\}
 \end{aligned} \quad (10)$$

Eq. (10) means that when the MZM is biased at a minimum transmission point, the carrier power P_0 become minimum. Simultaneously, the upper and the lower sideband powers of P_{+1} and P_{-1} become equal. Therefore, by adjusting the bias voltages of the high-ER MZM to maintain the carrier power at minimum, the powers of the two tones automatically become equal. Note that Eq. (10) is satisfied independently from the other parameters of η ,

α_A , and ϕ . Further, this technique is consistent with that of suppressing the carrier power.

Monitoring the carrier power is easier than measuring each power of the two-tone signal. In the frequency response measurement, we use two different techniques of optical and RF method, according to the measurement frequency range. For the frequency range higher than 10 GHz, a narrow-band optical band-pass filter directly extracts the carrier lightwave, and its optical power is monitored. For the frequency range lower than 10 GHz, an RF spectrum analyzer monitors the RF signal from the reference PD, which has a practically flat frequency response from DC to 10 GHz. The RF signal power at half the measurement frequency (ω_{RF}) is proportional to the carrier amplitude.

4 Measurement results

The proposed measurement method is verified by experiment. Fig. 2(a) shows a typical optical spectrum of two-tone stimulus source generated by the high-ER MZM. Only the first upper and lower sidebands dominate the spectrum, while the carrier is suppressed to 51 dB lower than the dominant tones and higher modulation harmonics are also reduced by 43 dB. An automatic bias control maintains the carrier suppression ratio at least 30 dB during the measurement. Fig. 2(b) shows a typical RF response signal from the PD under test. Within the frequency range from DC to 50 GHz, only a monotone signal at 30 GHz is observed, which is very pure as shown in the inset graph of 10 kHz span. These RF spectra prove that the two-tone light source satisfies the second criterion.

We measured the frequency responses of two PDs with 3 dB bandwidths of 20 GHz and 50 GHz [6]. Fig. 3 shows the measured results of their frequency responses from 1 GHz to 50 GHz. Differences in their performance in 3 dB bandwidth are clearly demonstrated.

Fig. 2. Example of a two-tone stimulus signal and a pure RF response.

Fig. 3. Measured results for two PDs with 3dB bandwidth of 20 GHz and 50 GHz.

5 Conclusion

To measure a frequency response of PD, we propose a heterodyne measurement method using a high ER-MZM for generating a two-tone lightwave as a stimulus signal. The measurement system is simple, easy to use, and operated up to millimeter-wave frequency range. The heterodyne principle provides relatively short traceability chain, which will result in smaller uncertainties compared to the conventional instruments. A power equalization technique is theoretically derived from the MZM formula that includes four major imperfection parameters. Comparison with the conventional methods and detailed error analysis will be reported in the future work.