Frequency response measurement of high-speed photodetectors using the spectrum power method in a delay self-heterodyne system

1 Introduction

As one of the most important optical devices, a photodetector has been developed to work in ultra-broadband range for application in high-speed optical transmission systems. For improving the performance of such optoelectronic devices, wideband measurement techniques are demanded for characterizing the frequency responses of photodetectors.

In recent decades, a variety of methods for characterizing the frequency responses of photodetectors have been reported, including the optical pulse sampling method [1], the optical modulation method [2], the interferometric FM sideband method [3], and the white noise method [4, 5]. These methods are unable to accurately measure the frequency response of photodetectors with bandwidths beyond 20 GHz [6, 7]. Recently, the optical heterodyne technique utilizing the coherence of light has been developed. The technique has proven to be accurate and reliable for measuring the frequency responses of high-speed photodetectors [8, 9]. In addition, this technique is promising for photonic generation of microwave signals [10].

In the conventional optical heterodyne method, two lasers with extreme frequency-stability and polarization mode matching are needed. One laser is used to produce fixed wavelength, the other is tunable in its wavelength by adjusting the temperature or the cavity length of the laser. However, this technique has two disadvantages:

1. It is expensive and complicated because of the fabricating of a temperature controller and a micro-electromechanical (MEMS) mirror;
2. Slight drifts in the operating condition of one laser relative to the other can cause unwanted frequency and power fluctuations which strongly affect the measurement accuracy of the frequency response.

These problems can be avoided by using the self-heterodyne method proposed by Hou et al. in 1989 [11]. However, in Hous method, the authors neglected the effect of linewidth variation. It is well known that for a DBR laser, the linewidth varies over a wide range when the injected current is changed. Such a variation of the linewidth will cause measurement error in the measuring frequency response. Recently, Zhu et al. proposed an improved delay self-heterodyne method to measure the frequency responses of high-speed photodetectors [12]. The measurement results were calibrated by considering linewidth variation. Zhu’s method is very successful in accurately measuring the frequency responses of photodetectors, but the method is technically complicated in measurement and data processing.

In this paper, we present a new method using a measurement scheme that is similar to Zhu’s scheme. The advantage of our method is that the frequency response is obtained by measuring the power spectrum of beat signals. We will show that by this method we do not need any additional calibration procedure to get accurate measurements. Furthermore, we investigate how the phase-tuning-voltage in different ranges affects the measurement accuracy. Using this method, we have measured the frequency response of an Agilent 11982A O/E converter. Experiments show that the frequency response ob-
tained by using our method agrees well with the frequency response data provided by the manufacturer Agilent.

2 Theory

In optical heterodyne detection, the mixed optical intensity $I(t)$ of two single frequency laser beams with a frequency difference $\nu_b$ is given by

$$I(t) = I_1 + I_2 + 2\cos \varphi \sqrt{I_1 I_2} \cos(\nu_b t), \quad (1)$$

where $I_1$ and $I_2$ are the received optical intensities, $\varphi$ is the angle between polarized directions of the two beams, and $t$ is the time. The photocurrent $i_c(t)$, therefore, is written as

$$i_c(t) = \frac{e\eta}{h \nu} \left[ I_1 + I_2 + 2F(\nu_b) \cos \varphi \sqrt{I_1 I_2} \cos(\nu_b t) \right], \quad (2)$$

where $e$ is the electron charge, $\eta$ is the quantum efficiency, $h\nu$ is the photon energy, and $F(\nu_b)$ is the frequency responses of photodetectors. The last item of the equation corresponds to the beat signal with a frequency of $\nu_b$. The power of the beat signal can be expressed as follows

$$P(\nu_b) = \left[ i_{\text{rms}} \right]^2 \Omega, \quad (3)$$

where $\Omega = 50 \Omega$ is the input impedance of the frequency spectrum analyzer. $\left[ i_{\text{rms}} \right]$ is the mean square root of the beat frequency photocurrent. $\left[ i_{\text{rms}} \right]$ is given by

$$\left[ i_{\text{rms}} \right] = \frac{2}{\sqrt{2}} \frac{e\eta}{h \nu} F(\nu_b) \cos \varphi \sqrt{I_1 I_2}. \quad (4)$$

Thus, the frequency response of photodetectors can be expressed as

$$F(\nu_b) = \frac{1}{\sqrt{2} I_{\text{rms}}^2 \sqrt{I_1 I_2} \Omega} \left[ P(\nu_b) \right]^{1/2}. \quad (5)$$

From (5), it can be seen that if the output optical intensities of two lasers, $I_1$ and $I_2$, and the polarization difference $\varphi$ can be kept as constants, the frequency responses $F(\nu_b)$ of the photodetectors can be obtained by measuring the power of the beat signals $P(\nu_b)$.

3 Photodetectors response measurement

3.1 Experimental setup

The proposed frequency response measurement scheme is shown in Fig. 1. This system is composed of an optical source, an interferometer and some test instruments. The optical source is a 1.55 m three-electrode tunable DBR laser consisting of an active section, a phase-matching section and a Bragg wave-guide section. In this system, a fiber ring interferometer is used. On comparing with a conventional Mach–Zehnder interferometer, the interference efficiency can be increased by 7 dB for fiber ring interferometer [12].

In this experiment, the active section of the laser was biased using a 60 mA DC current source of low noise. Under this bias condition, the optical output power was about 280 $\mu$W. The phase section was biased using a square wave voltage (duty cycle is 50%) to tune the output wavelength. A 270 $\Omega$ resistance was used in the phase circuit to limit the phase current. For eliminating light absorption and the charge accumulation in the Bragg section, the Bragg section was short-circuited. To prevent any optical feedback toward the cavity, a 42 dB optical isolator was inserted into the output port of the laser. For temperature control, a Peltier element was used in the laser packaging to avoid the wavelength-shift introduced by temperature fluctuation.

With the application of a square wave voltage, a tunable DBR laser is operated in two states corresponding to high and low levels of a square-wave voltage. The low level state is used to produce a fixed wavelength light, and the high level state is used to produce tuned wavelength light. Thus, the laser switches periodically between two optical wavelengths. After output, light passes through a fiber ring interferometer with a polarization controller, the beat signals between the delayed and the undelayed light are generated at the face of the photodetectors.

For obtaining a maximum beat signal power, the relation between the square wave frequency $f$ and the length of the delay fiber $L$ should satisfy the following equation,

$$f = \frac{n c}{2\tau} = \frac{n c}{2n_{\text{eff}} L}, \quad n = 1, 3, 5, \ldots, \quad (6)$$

where $n_{\text{eff}}$ is the effective refractive index of the fiber, $c$ is the speed of light, and $\tau$ is the delay time. A 1.8 km G653 fiber was used as delay line of the interferometer in our experiment. In the case of $n = 1$, the half-period of a square-wave voltage is just equal to the fiber delay time. According to (6), for a 1.8 km G653 fiber, a square wave frequency of 55.5 kHz should be used to obtain maximum beat signal. This square wave voltage was generated by an Agilent 33250A.