Frequency Response Characterization of Microwave Photonics Components

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ABSTRACT

This paper reviews the research activities in Microwave Photonic component frequency characterization at Department of Electrical Engineering, Chiang Mai University. Optical detector frequency response calibration is based on a two-tone technique where the two-tone stimulus light is generated by a Mach Zehnder Modulator. We present a calibration system where standard Mach Zehnder Modulator is used instead of a high extinction ratio one. The two-tone light power is also controlled by an optical amplifier. Once the photodiode is calibrated, it can be used to measure frequency characteristics of other components such as directly modulated lasers.

Keywords: *Microwave Photonics, Optoelectronic Devices, Frequency Response*

1 INTRODUCTION

Microwave Photonics (MWP) concerns the generation, transmission and detection of high frequency analog signals onto optical carriers. It has been increasingly researched and deployed recently due to the need of high capacity system beyond the current digital optical systems coupled with the advances in large bandwidth and high speed photonic devices. Examples of MWP applications range from generation of millimeter-wave signal using photonic technique, photonic signal processing, radio-over-fiber to biomedical applications.

It is evident that the components in MWP system, such as modulators and receivers, should have wideband frequency characteristics. Device characterization techniques are therefore crucial to determine how the device will perform in a system. There are a few methods to measure frequency response of optoelectronic devices. In this paper, we review how frequency response, or more specifically scattering parameters, of MWP components can be measured. The recently proposed technique of optoelectronic frequency response calibration using Mach Zehnder Modulator (MZM) [1-2] is presented in detail. We present the results obtained from the calibration test system that is set up at our laboratory at the Department of Electrical Engineering, Faculty of Engineering, Chiang Mai University.

2 MICROWAVE PHOTONICS TRANSMISSION SCHEMES

2.1 Detection schemes

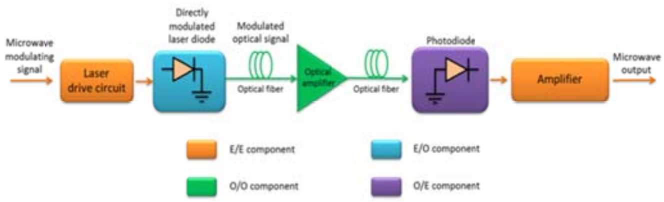

Fig.1 *A microwave fiber-optic link*

A basic MWP transmission system is shown in Fig. 1 where analog signal is modulated onto optical carrier and then detected by optical receiver. A more specific arrangement depends on the detection scheme that is being used. Two types of detection scheme are direct detection and coherent detection. Direct detection is most commonly used due to its simplicity. Light is modulated by changing its intensity and the output signal from photodiode conversion is the result of such varying light intensity. Photodiode response is not sensitive to light frequency and phase change, hence direct detection scheme is only available for intensity modulation. Another detection method is coherent detection (or heterodyne detection) which uses the principle of frequency mixing. The system requires a local oscillator at the receiver to mix with the received signal. Heterodyne detection is more complex but has some advantage in that the signal modulation can either be by amplitude, phase or frequency. Due to the simplicity most MWP systems employ direct detection scheme, especially in practical implementations. Fast PIN photodiodes, made from InGaAsP materials, are commonly used for optical to electrical conversion at the receiver having bandwidth up to hundred GHz.

2.2 Modulation schemes

From the choices of detection schemes, it is preferable to select direct detection, therefore intensity modulation of light is required accordingly. The system is called Intensity Modulated Direct Detection (IMDD). Two methods of intensity modulation are available: direct modulation and external modulation.

For direct modulation, a laser is control by DC bias current and the RF signal to be transmitted. Bias current set the operating condition of the laser on the L-I curve as shown in Fig. 2. A small signal change at this operating point causes the change in output light power. The largest peak-to-peak output is limited by the threshold current and saturation current of the laser as shown. The slope of LI-curve is called Slope Efficiency which is denoted by a symbol s_l with W/A unit.

For external modulation, another device is required to modulate signal onto optical carrier. The light source, usually a DFB laser, is operated by only DC bias current to generate Continuous Wave (CW) light. CW light is input into an external modulator. Mach Zehnder Modulator (MZM) is the most common modulator type for intensity modulation. The operating point of MZM is chosen by DC voltage bias. Slope efficiency of MZM depends on this voltage. As shown in Fig. 3, for highest efficiency the bias voltage v_{bias} gives the largest slope efficiency s_m where the modulator is most linear. In some cases, a different operating point is called for, for example, the null bias v_{null} . Such bias is chosen when one needs to suppress the carrier component to obtain only odd harmonic frequency in the output. This is how we generate two-tone light signal for O/E device characterization as shown in the following sections.

3 COMPONENT REQUIRMENTS

Transmission of microwave photonics system is generally analog. Linear characteristics of components are important. In addition, new applications demand higher frequency of operation such as Radio-over-Fiber systems in millimeter-wave band where carrier frequencies are in tens of GHz range. Frequency characterization of microwave photonic components, such as scattering parameters is also important.

We can classify components into 4 categories according to the types of signal into the input and output ports of the device. We will discuss the general requirements of each component group in the following.

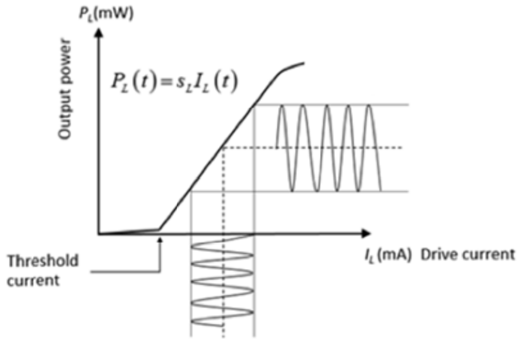

Fig. 2 *Modulation characteristics of a laser diode*

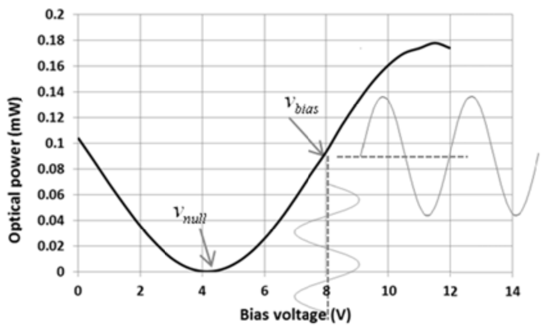

Fig. 3 *Modulation characteristics of an MZM*

3.1 Electronic (E/E) components

E/E components in a MWP system are used between the signal source and optical modulator as well as between the photodetector and the receiver. Three types of components are common consisting of amplifiers, filters and matching networks. We require E/E amplifiers to be wideband and linear. Amplifiers used to drive optical modulators should give large output amplitude, for example, 8Vp-p for Mach Zehnder Modulator. Amplifiers which are used for preamplification before the receiver should have high gain and low noise performance.

Matching networks are required at E-E interfaces throughout the optical link. That is because impedances of E/O or O/E device are usually unmatched to 50Ω. For example, a directly modulated laser diode has impedance typically less than 10 Ω [3]. Several matching networks are therefore essential at E-E interfaces. For O-O interfaces, impedance matching is less problematic. That is because optical connectors can be made to provide maximum transmission and minimum reflection such as Angled Physical Contact (APC) connectors. Optical signal travelling in backward direction can also be minimized by using an optical isolator. In practice we can consider O-O interfaces to be sufficiently matched.

A linear E/E two-port as shown in Fig. 4 can be characterized using S-parameters (scattering parameters) in equations (1) and (2).

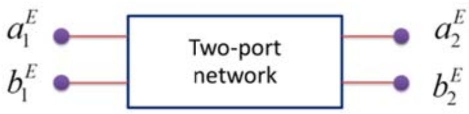

***Fig. 4** An E/E two-port network*

$$b_1^E = S_{11}^{E/E} a_1^E + S_{12}^{E/E} a_2^E \quad (1)$$

$$b_2^E = S_{21}^{E/E} a_1^E + S_{22}^{E/E} a_2^E \quad (2)$$

The variables a_1^E and a_2^E represent incident travelling voltage waves at ports 1 and 2, respectively, while b_1^E and b_2^E represent reflected travelling voltage waves. These variables have the dimensions of $\sqrt{(electrical\ power)}$, i.e. they are directly proportional to the microwave current. $S_{11}^{E/E}$ and $S_{22}^{E/E}$ represent the input and output reflection coefficients, while $S_{21}^{E/E}$ and $S_{12}^{E/E}$ are the forward and reverse transmission coefficients. All 4 parameters of E/E device have non-zero values, which can be measured.

3.2 Electro-optic (E/O) Components

Electro-optic devices have the functions to generate optical signal and modulate electrical signal onto light. In a directly modulation system, an E/O device is usually a directly modulated semiconductor laser such as DFB lasers and VCSEL. These lasers can have bandwidths up to 10s of GHz. In an externally modulated system, E/O devices also include external modulators such as MZM or Electro Absorption Modulator (EAM) which can have higher bandwidths. Therefore frequency characterization is a challenging task.

For an E/O two-port device as shown in Fig. 5, its S parameters can be defined as in equations (3) and (4). The variables a_1^E and b_1^E represent travelling voltage waves at port 1, the variables a_2^O and b_2^O represent optical power waves at port 2. These are also chosen to have the same dimensions of (optical power) or $\sqrt{(electrical\ power)}$. $S_{21}^{E/O}$ represents the electro-optic conversion process, i.e. the conversion of microwave current to modulated optical power.

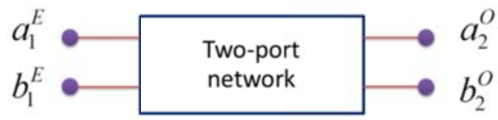

***Fig. 5** An E/O two-port network*

$$b_1^E = S_{11}^{E/O} a_1^E + S_{12}^{E/O} a_2^O \quad (3)$$

$$b_2^O = S_{21}^{E/O} a_1^E + S_{22}^{E/O} a_2^O \quad (4)$$

In the case of a laser diode, provided its peak-to-peak modulation current does not exceed the limits of the linear light–current curve, linearity is guaranteed in the relationship between microwave modulation current and the output modulated optical power. Under these circumstances, $|S_{21}^{E/O}| = \eta$, where η is the slope efficiency of the laser diode (equal to s_l earlier). Most E/O components do not have reverse transmission, therefore $S_{12}^{E/O} = 0$. In other words, laser diodes do not normally convert light back to electrical signal.

3.3 Opto-electronic (O/E) Components

Optical receiver has a function to convert varying light intensity to electrical signal. The most common type is a PIN photodiode which has fast and linear response. Photodiode generates electrical output which varies according to the incident light intensity, this is then converted to voltage signal by a transimpedance circuit. In a MWP system, we require a photodiode with large responsivity over a wide bandwidth as well as fast response time.

For an O/E two-port device as shown in Fig. 6, its S parameters may be defined as in equations (5) and (6). The variables a_1^O and b_1^O represent optical power waves at port 1, the variables a_2^E and b_2^E represent travelling voltage waves at port 2. $S_{21}^{O/E}$ represents the photodetection process, i.e. the conversion of modulated optical power to microwave current.

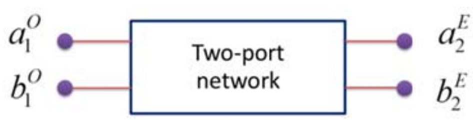

***Fig. 6** An O/E two-port network*

$$b_1^O = S_{11}^{O/E} a_1^O + S_{12}^{O/E} a_2^E \quad (5)$$

$$b_2^E = S_{21}^{O/E} a_1^O + S_{22}^{O/E} a_2^E \quad (6)$$

In the case of a photodiode, provided it obeys a square law relationship, then the photocurrent will be directly proportional to the square of the incoming electric field magnitude. Hence linearity is ensured in the relationship between input modulated optical power and the photogenerated microwave current. Under these circumstances $|S_{21}^{O/E}| = \kappa$, where κ is the photodiode responsivity. Most O/E components also do not have reverse transmission, therefore $S_{12}^{O/E} = 0$. In other words, photodetectors do not act as optical sources.

3.4 Optical (O/O) Components

In the case of O/O two-ports as shown in Fig. 7, the device S parameter can be defined as in equations (7) and (8), the variables a_1^O, a_2^O, b_1^O and b_2^O represent optical power waves modulated at the microwave frequency. These are chosen to have dimensions of (optical power), or they also have dimensions of $\sqrt{(electrical\ power)}$.

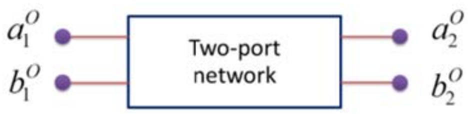

Fig.7 An O/O two-port network

$$b_1^O = S_{11}^{O/O} a_1^O + S_{12}^{O/O} a_2^O \quad (7)$$

$$b_2^O = S_{21}^{O/O} a_1^O + S_{22}^{O/O} a_2^O \quad (8)$$

Characteristics of optical components are less dependent on frequency for O/O components since they are usually wideband. For instance, 1 nm bandwidth of an optical device is equivalent to over 100 GHz electrical bandwidth. Common O/O devices such as fiber coupler, splitters, attenuators and optical amplifiers all have bandwidth of several nm, thus their characteristics such as insertion loss, return loss are valid for all modulating signal frequencies.

4 OPTOELECTRONIC CHARACTERIZATION

Several methods exist to characterize frequency response of MWP components. For E/E components, they can be characterized by a vector network analyzer. Four scattering parameters, $S_{11}^{E/E}$, $S_{12}^{E/E}$, $S_{21}^{E/E}$ and $S_{22}^{E/E}$ can be obtained by this method. For other types of components, network analyzer cannot be used straightforwardly since the instrument only measure between two electrical planes as shown in Fig. 8. The setup as shown measures the characteristic of cascaded E/O-O/O-O/E components but not of each individual device. Therefore scattering parameters of some devices must be calibrated beforehand. Then the frequency characteristics of any device may be measured if pre-calibrated E/O or O/E devices are available, as shown in Fig. 9. Such principle is the operation of a Lightwave Component Analyzer (LCA) [4].

Calibration of O/E or PD has been made standard by the National Institute of Standards and Technology (NIST) as presented in the document titled "Calibration service of optoelectronic frequency response at 1319 nm for combined photodiode/RF power sensor transfer standards" [5]. NIST offers a calibration service of optoelectronic frequency response by a transfer standard over the frequency range of 300 kHz to 55 GHz using light wavelength 1319 nm.

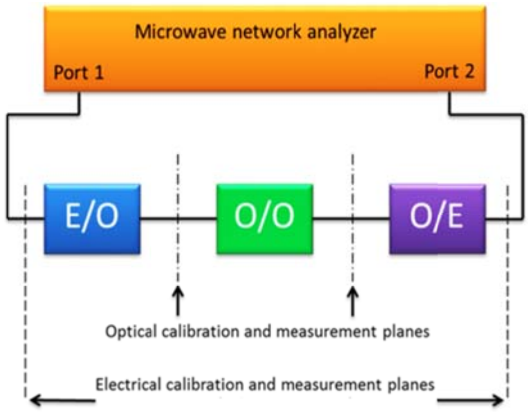

Fig. 8 Network analyzer characterization of cascaded E/O-O/O-O/E components

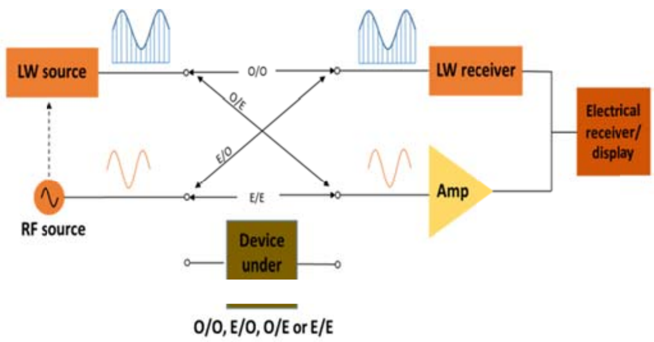

Fig. 9 Component characterization using calibrated E/O and O/E devices [4]

The principle of the NIST transfer standard is based on the heterodyne frequency response measurement. The NIST implements the principle by using two phase locked single frequency Nd:YAG lasers as light source where the excitation of the detector can be calculated from fundamental principles. The system uses two commercially available Nd:YAG lasers operating at 1319 nm. The frequency of each laser can be tuned thermally to give beat frequencies greater than 50 GHz when the beats have a short-term bandwidth of less than 3 kHz. The beat frequency is measured using a microwave counter. As the frequency is scanned, data are acquired automatically. However, the resolution of the system is limited by the scan rate, the frequency jitter, and the time constants of the data acquisition equipment. The highest resolution achievable is about 200 kHz. This measurement system is too complex for a general laboratory. For example, it requires a sophisticated control system for the two phase locked lasers.

Recently, a frequency response heterodyne calibration technique using a high extinction-ratio Mach Zehnder Modulator (MZM) instead of Nd:YAG laser has been proposed [1-2][6]. The method has the same principle as the NIST standard but it is simpler to implement because there is no need for two phase-locked lasers and the only measuring instruments are an optical power meter and an RF power sensor. Thus the method allows an easy photodiode calibration to be performed at most laboratories.

4.1 Principle of two-tone frequency response characterization of an O/E device

An O/E device such as photodiode generally responds to the illumination of the light which may usually form in the sine wave format. The optical signal at the end of optical fiber is usually weak and distorted, photodiode with high responsivity is required. Photodiode requirements in high speed optical communications include high responsivity at the desired wavelength, low noise, fast response time, insensitive to temperature variations, compatible with fiber' physical dimensions and long operating life.

The amount of current flowing in the circuit with a photodiode depends on the incident optical power (or the number of photons) as in the following equation,

$$I_{PD} = \kappa P_{opt} \tag{9}$$

where κ is called the frequency response or the responsivity of the photodiode, that is the ability to respond to variations in the incident intensity. P_{opt} is the incident optical power. The responsivity of the PD, which is the same as $S_{21}^{O/E}$, is a function of light carrier wavelength as well as the modulating signal frequency.

Letting the two-tone frequencies be ω_1 and ω_{-1}, the electric field of the two-tone light incident on the photodiode is

$$E_{opt} = E_1 \cos\omega_1 t + E_{-1} \cos\omega_{-1} t. \tag{10}$$

The optical frequencies are tuned such that $\omega_{+1} - \omega_{-1} = 2\omega_{RF}$ as in figure 1.4 (P_{+1} and P_{-1} tones respectively), which is the frequency at which we want to find the PD responsivity. The instantaneous optical power can be calculated by

$$p_{opt} = \frac{E_{opt}^2}{z}. \tag{11}$$

By substituting (10) into (11) we obtain several frequency components. The components at $2\omega_1$, $2\omega_{-1}$ and $\omega_1 + \omega_{-1}$ are out of the PD band. Only DC component and $\omega_1 - \omega_{-1} = 2\omega_{RF}$ are converted by PD. If $E_1 \cong E_{-1}$ is assumed, the optical power expression, as detected by the PD, reduces to,

$$\begin{aligned} p_{opt} &\approx E_{opt}^2 + E_{opt}^2 \cos(2\omega_{RF} t) \\ &= P_{opt} + P_{opt} \cos(2\omega_{RF} t) \end{aligned} \tag{12}$$

The small signal RF photocurrent i_{RF} to be generated by a photodiode is

$$i_{RF} = \kappa P_{opt} \cos(2\omega_{RF} t) = I_{RF} \cos(2\omega_{RF} t), \tag{13}$$

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

$$P_{RF} = \frac{I_{RF}}{\sqrt{2}} \frac{I_{RF}}{\sqrt{2}} Z_L = 25 I_{RF}^2. \tag{14}$$

Therefore, from (13) and (14), the frequency response κ can be expressed as [2]

$$\kappa = \frac{\sqrt{P_{RF}}}{5 P_{opt}}. \tag{15}$$

P_{RF} is a function of frequency. It includes corrections for sensor calibration factor and mismatch, and is the power that would be delivered to a load R_L (50Ω). The electrical bandwidth of the device is where $20\log(\kappa)$ falls by 3dB from the low frequency level. From the principle, the stimulus signals generated by the light source in the heterodyne measurement system must satisfy a set of requirements as follows [2]: 1) Only two lightwave modes are generated, 2) The frequency difference between two modes is pure and tunable to the desired calibration frequency, 3) The polarizations of the two modes are identical, 4) The powers of the two modes are identical.

4.2 Two-tone characterization using MZM technique

Mach Zehnder Modulator is an E/O device that is able to generate two-tone light as shown in Fig. 10. This is achieved by bias the MZM at null transmission voltage while modulating the MZM with a pure sine wave signal. At this voltage, optical carrier becomes minimum and we obtain double-sideband suppressed carrier (DSB-SC) optical modulation. The frequencies of two tones differ by twice the modulating sine wave frequency. For the frequency response measurement, MZM is used to generate tunable two-tone lightwave signal. Fig. 11 illustrates the proposed measurement system of PD frequency response by using an MZM and Fig. 12 shows the actual testbench at our laboratory. Our testbench is a modified system using commercial standard extinction ratio MZM instead of a high-extinction ratio MZM [6].

In Fig.11, A commercially available MZM with standard extinction ratio performance is used to generate a two-tone light signal whose frequency separation is twice the modulating RF frequency ($2\omega_{RF}$). The optical carrier is generated by a tunable DFB laser at wavelength 1550nm. The RF frequency is generated by a synthesized CW generator and then, is amplified by a wideband RF amplifier.

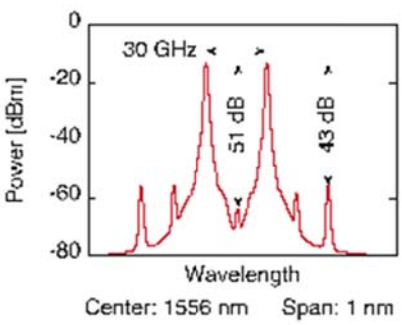

Fig. 10 *Two-tone optical signal generated by MZM [2]*

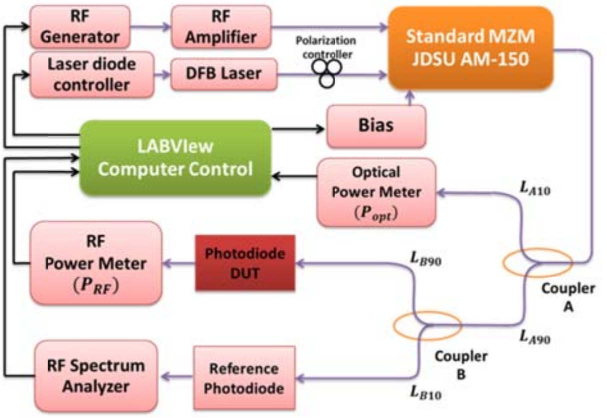

Fig. 11 *Frequency Response measurement system using standard MZM.*

Fig. 12 *Testbench for O/E frequency response characterization using MZM technique*

The polarization controller is used to adjust the polarization of the carrier to obtain low transmission loss through the MZM. The optical carrier ω_0 is suppressed by biasing the MZM at null point ($\phi_B = \pi$) using a programmable power supply. The bias voltage is controlled by computer by considering the different RF frequency components to achieve the optical two-tone signal. The on-off extinction ratio of the MZM is approximately 30dB. The previous study shows that this is sufficiently large for acceptable frequency response error [7]. Optical couplers are used to direct the two-tone signal to either the optical power meter, the photodiode (DUT) or the RF spectrum analyzer.

The measured insertion losses due to fiber couplers through different port pairs are considered, where L_{A90}, L_{B90} and L_{A10} denote the insertion losses in coupler A and B of the 90% and 10% ports as indicated. The RF power sensor is a wideband thermal sensor that has bandwidth 18 GHz and measurement noise level of 10 nW (-50 dBm). The RF spectrum analyzer has bandwidth 22 GHz. PD frequency response values combined with optical coupler insertion loss is obtained [6],

$$\kappa[dBe] = 10\log P_{RF} - 20\log(5P_{opt}) - 2(L_{A10} + L_{B90} - L_{A90}), \quad (16)$$

where L_{A90}, L_{B90} and L_{A10} are the measured insertion losses of couplers.

To obtain the frequency response of the PD across broad frequency range, the frequency of the RF signal generator is swept with the step of 50 MHz step or smaller. At each frequency the optical power before entering the PD is measured, and the RF power after the PD conversion is also measured. The frequency response is calculated using equation (16).

4.3 Two-tone Light Power Control

MZM frequency response characteristic is not constant across frequencies, as the frequency increases the two-tone optical output power of the MZM decreases [8]. Although it does not the frequency response formula theoretically because the response is the ratio of RF power and optical power after MZM, the lower power causes SNR reduction and uncertainty in the detected RF power by an RF power sensor. This can affect to the measurement accuracy, especially in high frequency range. Recently the use of Erbium Doped Fiber Amplifier (EDFA) to control the two-tone power in the new optoelectronic frequency response calibration technique was proposed [8-9].

To control two lightwave power, EDFA is set as a post-amp to amplify the modulated two-tone lightwave from the MZM as shown in Fig. 13 with constant output power mode referred as “gain-controlled EDFA”. A tunable optical band pass filter is also required to reduce ASE noise in frequency outside band of 1 nm. EDFA gain is tunable, where the maximum gain is 25dB. It should be note that the MZM has the insertion loss about 5dB. Therefore, to determine the best constant two-tone optical power level, the EDFA operating mode is set to the constant output power mode which output power level can be adjusted in 1mW step. The converted RF extinction ratio is measured. The best constant two-tone optical power level is also considered by looking for the highest converted RF extinction ratio over the tested frequency range. In this post-amplifying case, the issue of power imbalance of the two-tone light must be considered since both EDFA and optical filter may cause the unequal gains of the light of different wavelengths.

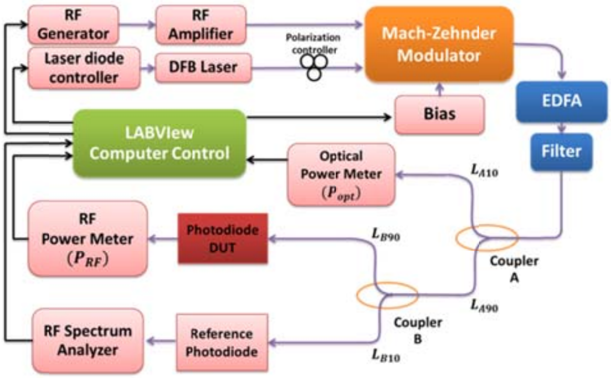

Fig. 13 *Frequency Response measurement system with two-tone light power control using EDFA*

4.4 O/E Characterization Results

The frequency response results of PD bandwidth 19 GHz and a PD bandwidth 15 GHz are plotted in Fig. 14 and Fig. 15 respectively, with 120 points resolution from 100MHz to 12 GHz. The comparisons are made between using gain-controlled EDFA and without gain-controlled EDFA. By using gain-controlled EDFA, frequency response κ is only depending on the two powers (P_{RF} and P_{opt}) without MZM characteristic effect. The power sensor uncertainties are caused by both optical power sensor and RF power sensor. The optical power sensor discrepancies can be limited due to constant optical power and higher input optical power level. The RF power sensor error can also be decreased due to higher PD generated photocurrent level. The typical optical power sensor uncertainty in our system is ±0.15dB, whereas the typical RF power sensor uncertainty is ±0.17dB.

The frequency response falls by 1dB at 12GHz for 19GHz PD and by 3dB above 12GHz for 15 GHz PD. Bandwidths and absolute levels of responses agree with specifications. Further measurement by LCA can be useful to determine the accuracy. By using gain-controlled EDFA, the frequency response curve has lower fluctuation, reduced from around ±0.3dB to ±0.1dB [9].

5 DIRECTLY MODULATED LASER DIODE CHARACTERIZATION

To measure frequency response of a directly modulated laser (E/O component), we may use a pre-calibrated O/E device. Pre-calibration of O/E device may be achieved by the method presented in section 4. The setup is shown in Fig. 16 and 17. From Fig. 17 input impedance of E/O needs to be at 50 Ω, this implies the need for a matching network between bias T and DUT. When the impedance between bias T and E/O DUT is matched the frequency response of the DUT ($S_{21}^{E/O}$) may be found from the difference between RF power meter reading and the signal generator output in dB subtracted by frequency response of the calibrated photodiode ($S_{21}^{O/E}$).

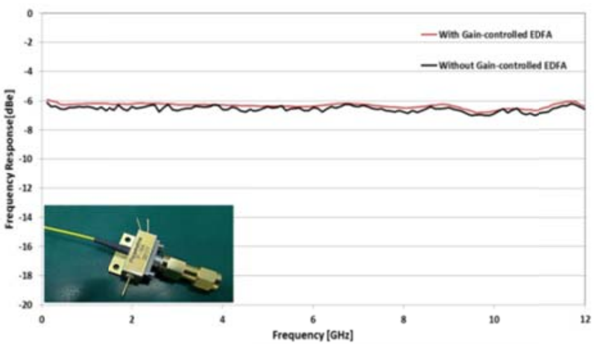

Fig. 14 *Photodiode frequency responses (18GHz PD).*

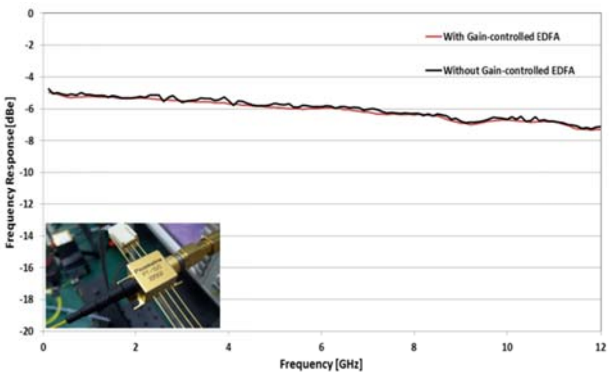

Fig. 15 *Photodiode frequency responses (15 GHz PD).*

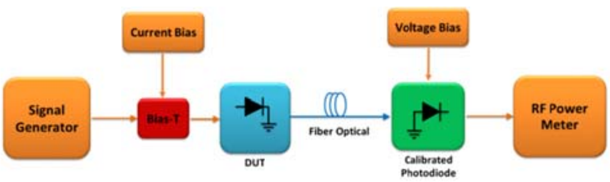

Fig. 16 *Laser diode frequency response measurement using calibrated photodiode.*

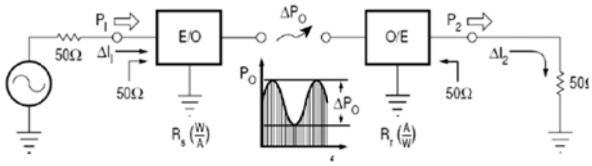

Fig. 17 *E/O frequency response measurement, showing signal and matching condition [6].*

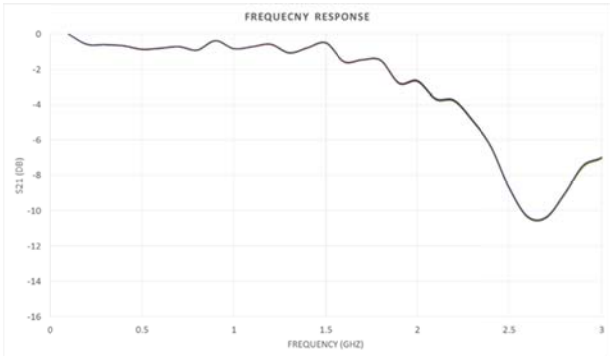

Fig. 18 *Directly modulated laser frequency response.*

The frequency response results of a laser diode DUT may be obtain as in Fig. 18. The laser diode is an InGaAsP/InP multi quantum well TO CAN laser with bandwidth approximately 2 GHz.

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