Chapter 1

Introduction

1.1 Principle and Rationale

Telecommunication infrastructure is a key element in the social and economic development of a country, enabling efficient data transfer for both personal and business purposes. Modern core and mobile backhaul networks are now using high speed baseband as well as Radio-over-Fiber optical links. Optical to Electrical (O/E) conversion devices such as photodiodes (PDs) with bandwidth of several tens of GHz are widely used in various photonics systems. The conversion efficiency and frequency response are their key specifications [1]. The frequency characteristics up to millimeter-wave frequency ranges are required for these photodiodes. National Institute of Standard and Technology (NIST) has developed a PD frequency response measurement standard, based on a heterodyne principle using a pair of Nd:YAG lasers to generate two-tone lightwave signal, which is used to stimulate the PD response [2]. 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, 3]. 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.

Using MZM to generate two-tone lightwave signal in the new measurement method has its limitation. As frequency increases the two-tone optical output power of the MZM decreases due to the MZM response characteristics, causing SNR reduction when RF power is detected by an RF power sensor [4]. We therefore study the use of optical amplifier, Erbium Doped Fiber Amplifier (EDFA), to increase the two-tone lightwave level over frequency measurement range to improve SNR of the RF responses. The experiment is divided into two stages to determine the best measurement setup scheme to control the optical power of the two-tone lightwave. In the first stage, a measurement system is set up to determine the best input optical power level into the MZM by considering the highest output converted RF extinction ratio. In the second stage, we aim to determine the best constant output two-tone stimulus signal power level which is to be amplified by the EDFA by considering the highest converted RF extinction ratio.

1.2 Literature Review

Lightwave components in many applications are operating at microwave frequency. Frequency responses are their key specification to indicate the overall system performance. Lightwave components can be identified as E/E, E/O, O/E, and O/O [5], where “E” refers to electrical domain and “O” refers to optical domain. The scattering parameter of an E/E device can be measured by a Microwave Network Analyzer. Since scattering parameter of lightwave components are defined in electrical domain, the frequency response of O/E, E/O and O/O components are measured against a pre-calibrated O/E device. To measure the frequency response of a photodiode (O/E) device , there are several methods available: NIST standard method, LCAs and the recently proposed technique using MZM. We will review all the available techniques in this section, and also at the end of this section, we will discuss the purpose of the work to be carried out in this thesis.

1.2.1 Currently Available PD Frequency Response Measurement of NIST Standard

The 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 [1]. 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 [6]. A schematic of the heterodyne system is shown in figure 1.1 [5]. 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 [3].

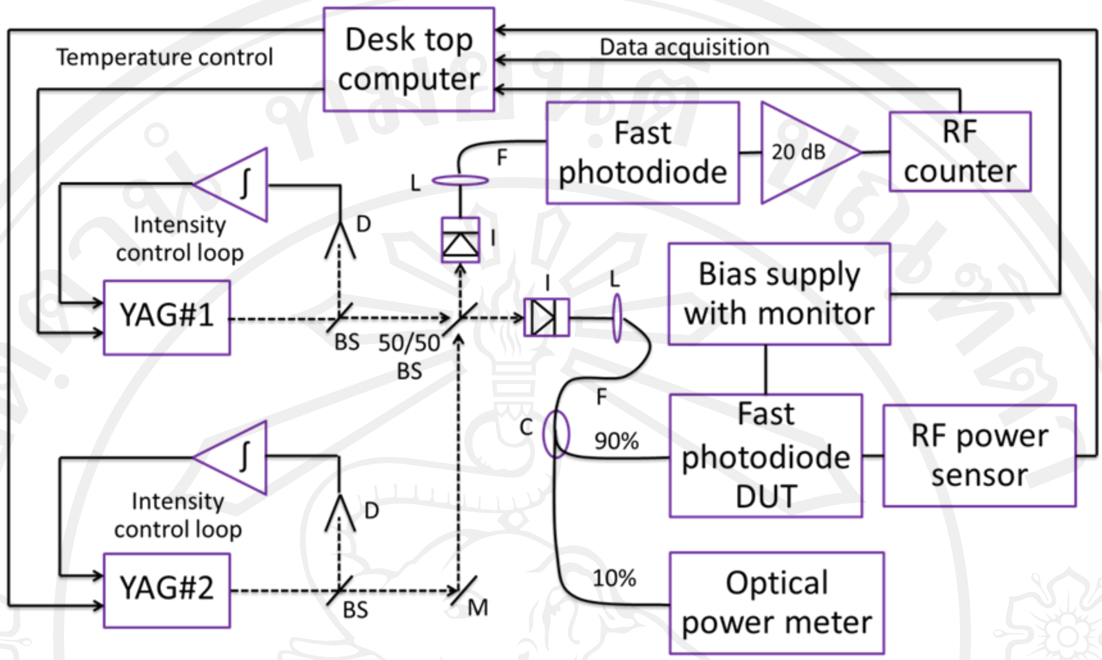


Figure 1.1 NIST Nd:YAG heterodyne system [5], where labeled components are BS(Beam splitter), M(Mirror), L(Lens), F(Single mode fiber), D(Large area detector) and A(Integrating amplifier).

1.2.2 Currently Available PD Frequency Response Measurement Using LCA

Lightwave component analyzer (LCA) is a widely used instrument to measure the scattering parameters of all E/E, E/O, O/E and O/O components. The instrument consists of a Network analyzer and a calibrated O/E and E/O converter as shown in figure 1.2. LCA measurement is traceable to the optoelectronic transfer standards managed by NIST in the United States.

From [1], it has been found that, although LCAs are powerful and flexible to measure the traceable frequency response of O/E and E/O devices, the performance of absolute frequency response uncertainties specified in their data sheets [7, 8] range from ±1.2 dB to ±1.8 dB, still to be rather poor. On the other hand, the "frequency response repeatabilities" ranging from ±0.02 dB to ±0.2 dB are excellent. In reference [9], it is suggested that the large absolute uncertainties could be attributed to the lack of calibration kits at user sites, which results in long calibration intervals between factory calibration services. Due to this reason, a simple calibration method has been proposed based on the NIST standard but using MZM to generate two-tone light.

Figure 1.2 LCA Model N4374C [7]

1.2.3 New PD Frequency Response Measurement Method Using MZM

For the frequency response measurement, a new method to generate tunable two-tone lightwave signal has been proposed by using an MZM instead of two Nd:YAG lasers. The MZM are operated in double-sideband suppressed carrier (DSB-SC) optical modulation which is useful for micro/millimetre-wave fiber links because undesired dispersion effect in a fiber can be suppressed; and the RF-signal frequency at the receiver side are double the modulation frequency at the transmitter side [10]. Figure 1.3 illustrates the proposed measurement system of PD frequency response by using an MZM [1, 3].

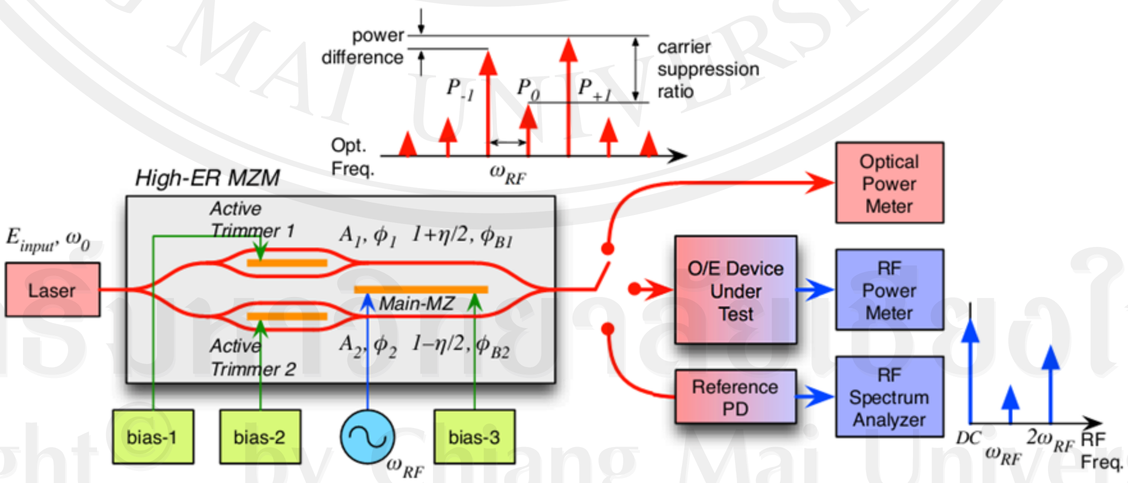
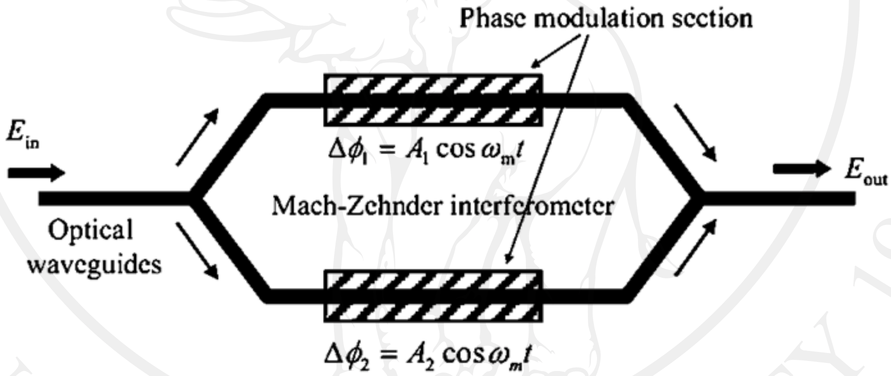


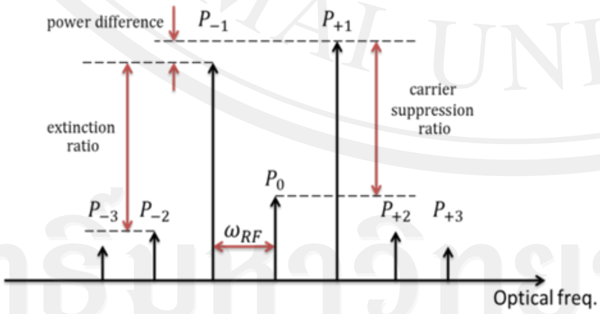
Figure 1.3 Frequency response measurement system using MZM [3]

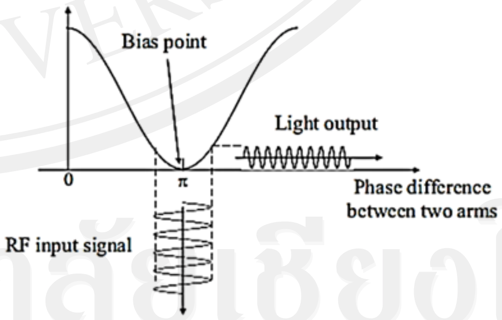
1.2.4 Improving Two-tone Lightwave Signal in MZM Method

An MZM generates two-tone lightwave by interference between two phase-modulated lightwave. Figure 1.4(a) shows a schematic of the general MZ modulator where A_1 and A_2 represent amplitudes of the optical phase modulation in two arms of MZ interferometer [11]. The output light from an MZM generally consists of several undesired harmonics components as in figure 1.4(b) such as the second and third order sideband. The third order components are due to intrinsic nonlinearity of the MZ modulator. On the other hand, the second order components would be zero, if the modulator is perfectly balanced [12]. To obtain a carrier suppressed two-tone lightwave signal with high extinction ratio, the MZM must operate under the minimum transmission bias point (Null point) v_π as in figure 1.4(c). However, the output signal of general MZM still contains unwanted carrier signal and modulation harmonics due to fabrication imperfection.



(a)





(b) (c)

Figure 1.4 (a) Schematic of the MZ modulator, (b) Output spectrum components of an MZM [1, 3], (c) Output lightwave response of MZM at v=v_π [11]

The carrier suppression ratio is dominated by the MZM waveguide structure and limited by fabrication errors in the waveguide structures [10]. Crosstalk between the fundamental waveguide mode and high-order radiative modes also degrades the extinction ratio. An extinction ratio of a general MZ modulator is less than 35dB [10]. In the newly proposed measurement system [1], a high extinction ratio MZM has been used as shown in figure 1.5. Active trimmers are integrated in each arm of the main MZM, which allow adjusting the power of the two arms exactly the same. The carrier suppression ratio is greater than 51dB. In the other hand, the carrier suppression ratio greater than 30dB can be used with acceptable measurement error [9].

The power imbalance in the generated two-tone lightwave signal, such as imbalance of the light splitting ratio, causes redundant optical spectrum components, which may induce undesired harmonics in the obtained RF signals [11]. Therefore the active trimmers can also be used to compensate such that imbalance.

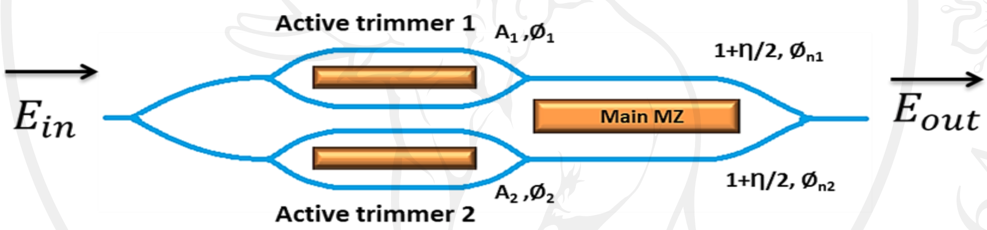


Figure 1.5 A high-extinction ratio MZM

Recently, a dual-parallel MZ modulator (DPMZM) for the two-tone generation has been proposed as shown in figure 1.6 [12]. Each MZ structure has two individual electrodes for balance operation which can achieve the extinction ratio higher than 70dB.

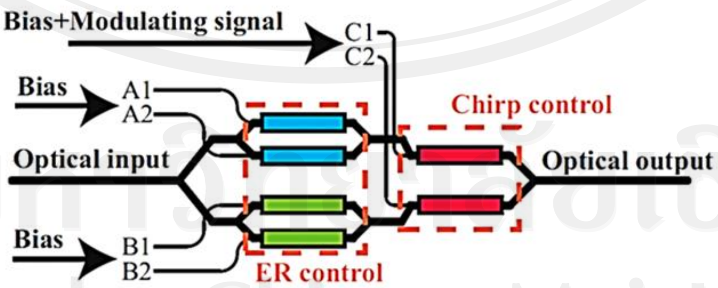


Figure 1.6 Schematic of the DPMZM [12]

The imbalance of electric field intensity induced by modulating signal results in the chirp parameter, which can be suppressed by adjusting the amplitude of modulating signal on each of electrode C_1 and C_2 of the main MZ structure. The chirp parameter corresponds to the imbalance factor in the phase modulation between two arms, and can be expressed as [11],

$$\alpha = (A_1 + A_2)/(A_1 - A_2). \tag{1.1}$$

Figure 1.7 shows the optical spectrum of MZM with various chirp parameters, for α = 0 the second harmonic components can be suppressed [12].

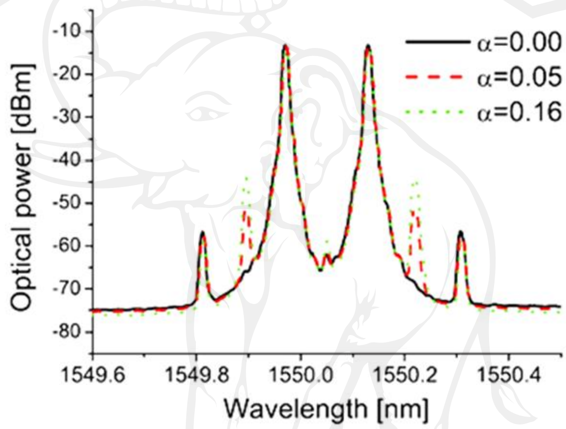


Figure 1.7 MZM output optical spectrums with various chirp parameters [12].

Due to fabrication imperfections, several error factors have been investigated in the proposed measurement system [9]. There are consisting of power difference, spurious tones, third-order modulation harmonics, optical measurement uncertainty, and RF power measurement uncertainty. Therefore, an optimized power budget design is essential to improves several uncertainty factors. An optical amplifier with precision level control can be used for such optimization [4].

1.2.5 Two-tone Power Level Variation with Frequency in MZM Method

From the MZM frequency response characteristic in figure 1.8, as the frequency increases the two-tone optical output power of the MZM decreases (dash line) [13], causing SNR reduction 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 [4]. The constant two-tone light power level (black line) can improve the SNR of the RF response over a broad frequency range. Thus this has a potential to increase the accuracy over a larger bandwidth. However, the study was only a demonstration of how EDFA may be used but its effects were not considered in detail.

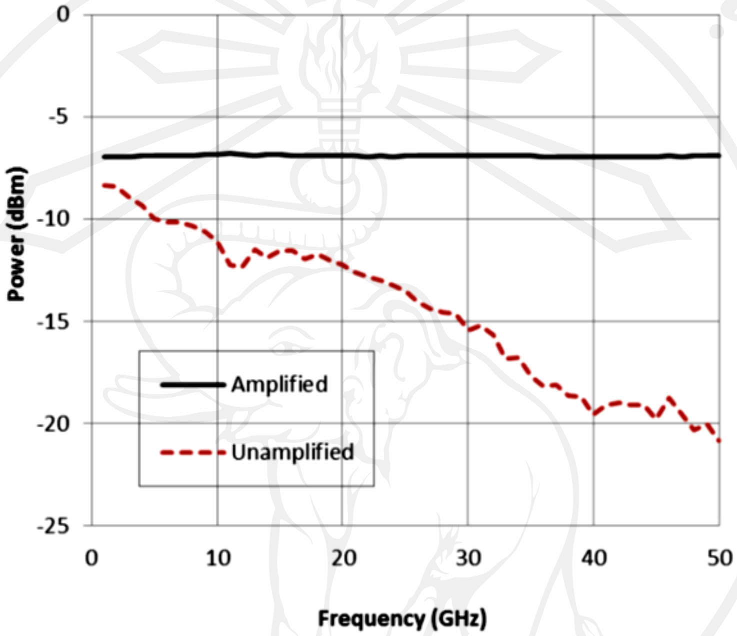


Figure 1.8 Power of the two-tone stimulus signal as frequency changes [4]

1.2.6 Summary of Literature Review and the Expected Contribution of This Thesis

We have reviewed the available techniques for the PD frequency response measurement. These techniques are based on the heterodyne detection principle. The transfer standard for measuring the PD frequency response was first defined by NIST, but the measurement system is too complex with intensity control loop of the two lasers. Another method became commercially available with powerful and flexible performance, which uses an LCA. LCA is traceable to the NIST standard, however, it is expensive and has large absolute uncertainty. In the recently proposed method, an MZM is used to generate the two-tone lightwave signal instead of two lasers. Nevertheless due to fabrication imperfections, the generated two-tone lightwave signal may not satisfy the requirements for the suppression ratio, power imbalance and chirp parameter. In our measurement system, a commercially available MZM will be used with suppression ratio around 30dB.

From this work, photodiode frequency response measurement system based on MZM technique will be set up at the NTC Telecommunications Research Laboratory, Department of Electrical Engineering, Chiang Mai University. It will be the first time that the control of two-tone lightwave power using EDFA is achieved and the effects of EDFA on the PD frequency response measurement are studied. The system will provide an economical solution to the photodiode calibration.

A new algorithm will be developed to control the null bias point of the MZM where the bias point is determined from analyzing the harmonic components of the converted RF spectrum instead of optical spectrum. This method will be more practical for the measurement at low modulating frequencies which are lower than the best resolution of a standard optical spectrum analyzer.

1.3 Objectives

1.3.1 Study the effects of the two-tone lightwave power on the result of the photodiode frequency response measurement.

1.3.2 Determine the best system scheme to control optical power of two-tone lightwave power using Erbium Doped Fiber Amplifier (EDFA).

1.4 Scope of Work

1.4.1 Setup the experiment to measure the characteristics of a photodiodes in frequency range below 12 GHz based on the MZM technique.

1.4.2 The experiment uses conventional commercially available MZM to generate two-tone light instead of a high extinction ratio MZM.

1.4.3 Determine the optimal power budget of an MZM by considering the highest converted RF extinction ratio, by dividing the experiment into two stages , to find the best optical input power level and the best constant two-tone stimulus power level.

1.5 Research Methodology

Setup the experiment system to measure the characteristics of photodiodes based on the Mach Zehnder Modulator method [4]. In this experiment, we use conventional MZM to generate two-tone lightwave signal to be used as the stimulus light source for the photodiode. Input optical power into the MZM is determined first by considering the converted RF extinction ratio. Optical amplifier (EDFA) is used to control the output two-tone stimulus signal power from the MZM. The goal of optical amplifier is to increase the signal to noise ratio of the converted RF signal of the photodiode at high frequencies as pointed out. The drawbacks are that optical amplifier generates ASE noise and it is also nonlinear in the high power region. In this study, we will study the trade-off between the optical power gain of the optical amplifier and the ASE noise caused by the amplifier. The measurement system will be studied both experimentally and analytically.

1.6 Expected Benefits

1.6.1 The use of optical amplifier, Erbium Doped Fiber Amplifier (EDFA) can increase the two-tone lightwave level to improve SNR of the frequency response over a broad frequency range.

1.6.2 Constant two-tone lightwave should enable faster and automated measurement in optoelectronic frequency response measurement system.

1.6.3 The frequency response measurement method may be performed at most laboratory using lower performance MZM and measuring instruments.

1.6.4 The photodiode that is calibrated using this method may be used as a reference to measure the frequency response of an E/O such as a directly modulated laser or an EAM modulator.