Chapter 2

Principle and Theory of Optoelectronic Measurement

2.1 Characterization of Components in Microwave Photonics System

Microwave photonics is the combination of microwaves, ultrafast electronics, and photonic technologies. Today, microwave photonic components are finding an increasing number of applications in the optical generation, distribution and processing of microwave signals, fiber-radio picocellular communication systems, antenna beam forming and optical control of microwave devices. The widely use of photonic systems having microwave modulation bandwidths, coupled with the photonic components in microwave systems, is creating a demand for efficient characterization techniques. In particular, new tools will be required for the accurate measurement of fundamental characteristics such as the microwave frequency response, bandwidth, gain and return loss of microwave photonic components.

A fiber-optic links are usually used to transmit multi-gigabits per second of digital data. Although for such digital systems, Bit Error Ratio (BER) for a given data rate may be a good system performance indicator. However, the BER only gives an indication of the overall system performance whereas the limitations on system performance are due to the individual lightwave components and their interaction with one another [5]. Even within digital optical-fiber systems, components such as laser diodes still behave as analog devices, therefore, microwave scattering parameters are often the more useful component characteristics.

Consider a typical microwave photonic system such as a Radio over Fiber system as in figure 2.1. The two-port components can be classified according to the type of signal present at the input and output ports. These are either electrical (E) signals at microwave frequencies or optical signals (O) whose power is modulated at microwave frequencies. Lightwave components can therefore be identified [5] as E/E, E/O, O/E or O/O and examples of each type are given in Table 2.1

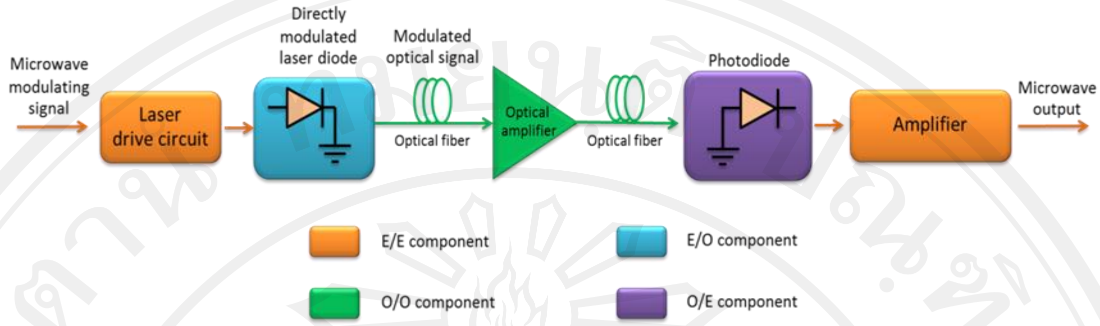


Figure 2.1 A microwave fiber-optic link [5]

Table 2.1 Examples of microwave photonic components [5]

	Electrical output	**Modulated optical output**
Electrical input	E/E components • Microwave amplifiers • Microwave filters • Impedance matching networks • Coaxial cables	E/O components • Laser diodes • Electro-optic modulators
Modulated optical input	O/E components • PIN photodiodes • Avalanche photodiodes • Optically controlled microwave devices	O/O components • Optical fiber • Optical isolators • Optical attenuators • Optical directional couplers • Optical fiber amplifiers

A microwave signal is superimposed on an optical carrier as a pair of sidebands, which are very close to the optical carrier, for a typical optical frequency of the order of 200 THz. Thus, the microwave sidebands are subjected to the same phenomena (e.g. attenuation and dispersion) as the optical carrier. These considerations allow scattering parameters (S-parameters) to be defined for all four types of two-port lightwave component [5].

Scattering parameters of an E/E component [5]

A linear E/E two-port as shown in figure 2.2 can be characterized using S-parameters (scattering parameters) in equations (2.1) and (2.2).

Figure 2.2 An E/E two-port network

$$b_1^E = S_{11}^{E/E} a_1^E + S_{12}^{E/E} a_2^E \tag{2.1}$$

$$b_2^E = S_{21}^{E/E} a_1^E + S_{22}^{E/E} a_2^E \tag{2.2}$$

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.

Scattering parameters of an O/O component **[5]**

In the case of O/O two-ports as shown in figure 2.3, the device S parameter can be defined as in equations (2.3) and (2.4), 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 $\sqrt{(electrical\ power)}$.

Figure 2.3 An O/O two-port network

$$b_1^O = S_{11}^{O/O} a_1^O + S_{12}^{O/O} a_2^O \tag{2.3}$$

$$b_2^O = S_{21}^{O/O} a_1^O + S_{22}^{O/O} a_2^O \tag{2.4}$$

Scattering parameters of an E/O component **[5]**

For an E/O two-port device as shown in figure 2.4, its S parameter can be defined as in equations (2.5) and (2.6). 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.

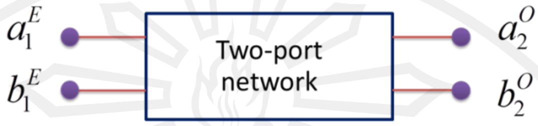


Figure 2.4 An E/O two-port network

$$b_1^E = S_{11}^{E/O} a_1^E + S_{12}^{E/O} a_2^O \tag{2.5}$$

$$b_2^O = S_{21}^{E/O} a_1^E + S_{22}^{E/O} a_2^O \tag{2.6}$$

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 differential efficiency of the laser diode. Most E/O components do not have reverse transmission, it can be seen that $S_{12}^{E/O} = 0$ correspond to electro-optic conversion. In other words, laser diodes do not normally convert light back to electrical signal.

Scattering parameter of an O/E component [5]

For an O/E two-port device as shown in figure 2.5, its S parameter may be defined as in equations (2.7) and (2.8). 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.

Figure 2.5 An O/E two-port network

$$b_1^O = S_{11}^{O/E} a_1^O + S_{12}^{O/E} a_2^E \tag{2.7}$$

$$b_2^E = S_{21}^{O/E} a_1^O + S_{22}^{O/E} a_2^E \tag{2.8}$$

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, it can be seen that $S_{12}^{O/E} = 0$ correspond to photodetection conversion. In other words, photodetectors also do not act as optical sources.

The measurement of the lightwave S-parameter of E/E, E/O, O/E and O/O two-ports as mentioned above allows the small-signal microwave characteristics (such as modulation frequency response, transmission gain/loss and return loss) and a wide variety of other parameters to be obtained. Although the characterization of E/E components is readily carried out with microwave vector network analyzers (VNAs), for which several two-port calibration techniques are available, the corresponding measurement techniques for E/O, O/E and O/O two-port parameters are less developed. Moreover, the lightwave calibrations are simple normalization procedures, which will result in measurement errors unless all parts of a system are well matched [5]. To use a VNA to measure E/O, O/E and O/O components, a cascade of these three components can be regarded as an E/E two-port as in figure 2.6. In this measurement system, the E/O and O/E devices must be calibrated first. The calibration technique of an optoelectronic (O/E) device, such as a photodiode, has been available based on heterodyne detection principle.

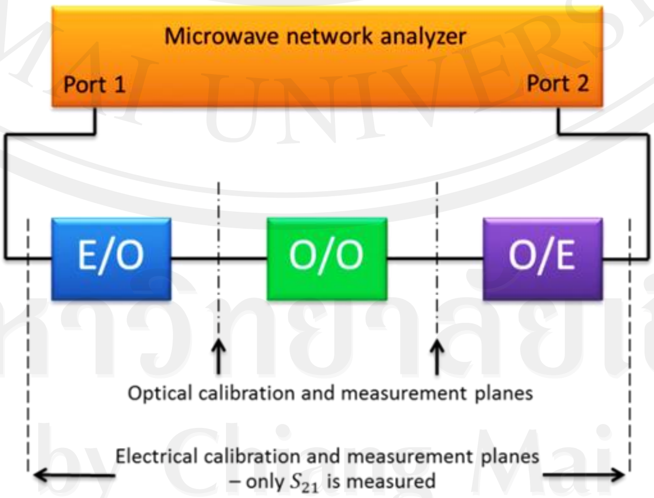


Figure 2.6 Basic lightwave component analyzer configurations
for transmission measurement [5]

2.2 Heterodyne Detection of Photodiodes

The one of the most important component in the optical communication is the receiver with the role to converting the optical signal into the electrical signal, i.e. O/E converter. The photodetector 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, photo detector with high responsivity is required. photodetector 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. Due to above requirements, only kind of photo detector named "photodiodes" is used as photo detectors in optical communication systems.

In heterodyne detection, the interfering between signal and local oscillator waves are applied to a non-linear photodetector. Among the Fourier components of the detector output, these frequencies are not present in the original waves. In particular, the beat frequency is present and serves as the signal. This is referred to the two-tone stimulus signal in this work.

In order to obtain the formula for the frequency response of PD using the two-tone method, first we summarize the PD principle. Then we derive the single-tone detection response, which is subsequently used to derive the PD two-tone response.

2.2.1 Principle of Photodiodes

Photodiode is a device that converts optical power into electrical current. It is essentially a p-n junction device operated under reverse bias. The operation of a photodiode can be explained using a band diagram. Under equilibrium, electrons from n-doped semiconductor and holes from p-dope semiconductor diffuse across the junction. The acceptors become negative charges in the p-side and the donors become positive charges in the n-side. As more carriers diffuse, the these charges cause opposing electric field which prevent further electrons and holes passing across, creating the depletion region as shown in figure 2.7.

When the junction is under reverse bias, the depletion thickness increases and the potential difference of p and n sides also increases as shown in figure 2.8. However when light (a photon) is incident on the depletion region or the area within diffusion length of the region, the electron within the crystal structure becomes stimulated. If the incident light energy is greater than the bandgap energy (Eg), the electrons are pulled up into the conduction band, leaving holes in their place in the valence band. At A, an incoming photon is absorbed in the p-layer creating a hole and free electron. If the photon is absorbed near the n-layer as shown at C, the resulting hole will diffuse to the junction and then drift across it again, given rise to a flow of charge e in the external load. The photon may also be absorbed in the depletion layer as at B, in which case both the hole and electron drift (in opposite directions) under the field until they reach the p- and n-layer. These electron-hole pairs occur throughout the p-layer, depletion layer and n-layer materials. In the depletion layer the electric field accelerated these electrons toward the n-layer and the holes toward the p-layer. As the electron-hole pairs generated in the n-layer, the electrons, along with electrons that have arrived from the p-layer, are left in the n-layer conduction band. The holes at this time are being diffused through the n-layer up to the depletion layer while being accelerated and corrected in the p-layer valence band. In this manner, electron-hole pairs which are generated in proportion to the amount of incident light are collected in the n- and p-layer. This results in a positive charge in the p-layer and a negative charge in the n-layer. If an external circuit is connected between p- and n-layer, electrons will flow away from the n-layer, and holes will flow away from the p-layer toward the opposite respective electrodes. These electrons and holes generating a current flow in a semiconductor are called the carriers.

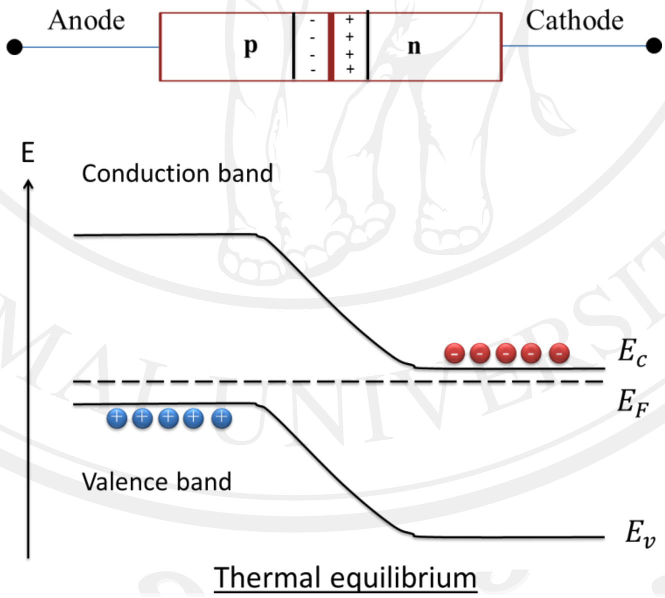


Figure 2.7 Thermal equilibrium

Since the photon is absorbed near the p or n-layer, result in sensitivity decreasing due to long carrier diffusion time outside the depletion region. To minimize the diffusion effect, the junction should be formed very close to its surface. As a result, photodiodes often use a p-i-n structure, where an intrinsic high resistivity

(i) layer is sandwiched between p and n regions. The potential drop occurs mostly across this layer, which can be made long enough to ensure that most of the incident photons are absorbed within it. However, the depletion layer must not be too wide, or transit time effects can limit the frequency response. It also should not be too thin, or excessive capacitance C of the depletion region will result in a large RC time constant. Typical construction of a p-i-n photodiode is shown in figure 2.9 [13].

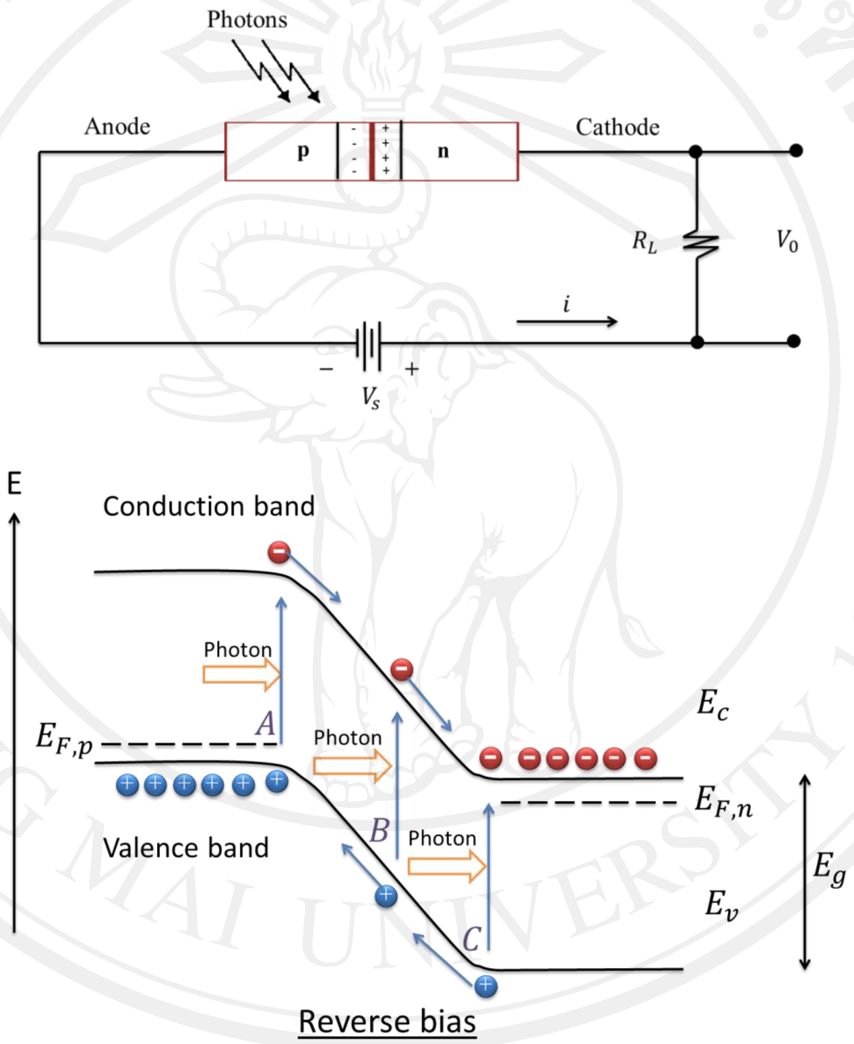


Figure 2.8 Reverse bias

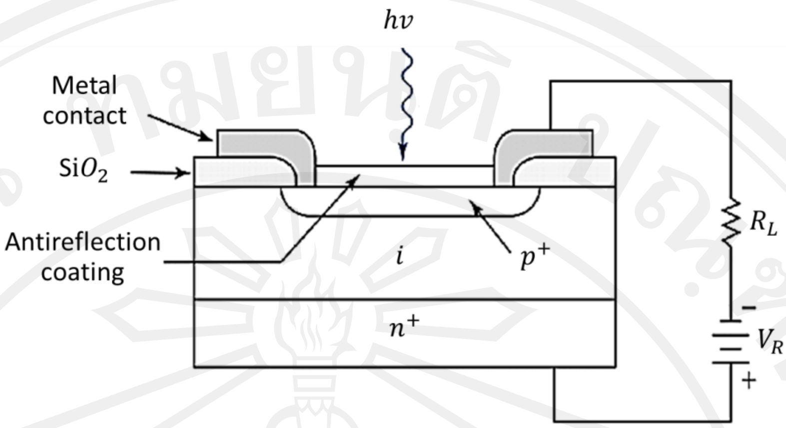


Figure 2.9 Cross section of a p-i-n photodiode

Another type of photodiode is avalanche photodiode where it has an internal gain occurred by the multiplication region inside the depletion region. By increasing the reverse bias across a p-n junction, the field in the depletion layer can increase to a point at which carrier (electrons or holes) that are accerelated across the depletion layer can gain enough kinetic energy to induce new electrons from the valence to the conduction band, while still traversing the layer. This process is referred to as avalanche multiplication. The result is a dramatic increase in junction current that sets in when the electric field becomes high enough. Avalanche photodiode has excellent linearity for various optical power levels in order of nano-watt to several milli-watt. In optical communication system, the optical power at the end of fiber is typically in order of milli-watt, where the p-i-n photodiode can be used with enough responsivity.

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,

$$I_{PD} = \kappa P_{opt} \tag{2.9}$$

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 $S_{21}^{O/E}$ in equation (2.8), is a function of light carrier wavelength as well as the modulating signal frequency. The light carrier wavelength dependence is due to the bandgap energy of the semiconductor materials used to make the PD, whereas the modulating signal frequency dependence is mainly due to the PD device design. For modern PDs, the responsivity bandwidth can be as large as 100 GHz. Typical photodiode bandwidth is in the range 10-20 GHz, for example, the Picometrix P18A photodiode has -3dB bandwidth of almost 20 GHz [14] as shown in figure 2.10.

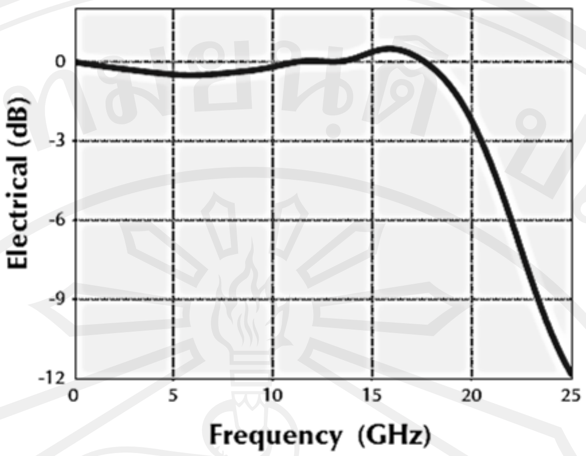


Figure 2.10 Frequency responses (S_{21}) of a Picometrix P18A photodiode, as in datasheet

2.2.2 CW Single-tone Light Detection of Photodiodes

In the case that a photodiode detects optical single tone signal, it results in the photo generated current I_{RF} from the photodiode which has only a DC component, as derived below. The electric field of a single wavelength incident light on the photodiode is

$$E_{opt} = E_0 \cos \omega_0 t. \tag{2.10}$$

where ω_0 is the optical frequency. The optical power can be calculated by

$$\begin{aligned} p_{opt} &= \frac{E_{opt}^2}{z} \\ &= E_0^2 (\frac{1+\cos 2\omega_0 t}{2}) / \mathrm{z} \\ &= (0.5E_0^2 + 0.5E_0^2 \cos 2\omega_0 t) / z \end{aligned} \tag{2.11}$$

From the equation of p_{opt} in (2.11), there are two components of the frequency spectrums. The first term is the DC component (the average power) and the second term is the component at frequency ω_0 in order of 200THz which out of the PD operating range, so only the DC component is present at the PD's output. The wave impedance z can be assumed to 1 to simplify the equations because z is combined into P_{opt} which is measured by the optical power sensor. Then the generated current of the photodiode is

$$I_{RF} = \kappa P_{opt}. \tag{2.12}$$

where P_{opt} is the average optical power equal to $0.5E_0^2 / z$

2.2.3 Two-tone Detection of Photodiodes [3]

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

$$E_{opt} = E_1 \cos \omega_1 t + E_{-1} \cos \omega_{-1} t. \tag{2.13}$$

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

$$\begin{aligned} p_{opt} &= \frac{E_{opt}^2}{z} \\ &= (E_1 \cos \omega_1 t)^2 + (2E_1 E_{-1} \cos \omega_1 t \cos \omega_{-1} t) + (E_{-1} \cos \omega_{-1} t)^2 \\ &= 0.5E_1^2 + 0.5E_1^2 \cos\left(2\omega_1 t\right) + E_1 E_{-1}[\cos(\omega_1 + \omega_{-1})t + \cos(\omega_1 - \omega_{-1})t] \\ &\quad +0.5E_{-1}^2 + 0.5E_{-1}^2 \cos\left(2\omega_{-1} t\right). \end{aligned} \tag{2.14}$$

From the expression of p_{opt} , there are several frequency components. The components at $2\omega_1$, $2\omega_{-1}$ and $\omega_1 + \omega_{-1}$ are out of the PD band. If $E_1 \cong E_{-1}$ is assumed, the optical power expression, as detected by the PD, reduces to,

$$\begin{aligned} p_{opt} &\approx E_{opt}^2 + E_{opt}^2 \cos(2\omega_{RF} t) \\ &= P_{opt} + P_{opt} \cos(2\omega_{RF} t) \end{aligned} \tag{2.15}$$

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

$$i_{RF} = \kappa P_{opt} \cos\left(2\omega_{RF} t\right) = I_{RF} \cos\left(2\omega_{RF} t\right), \tag{2.16}$$

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

$$P_{RF} = \frac{I_{RF}}{\sqrt{2}} \frac{I_{RF}}{\sqrt{2}} Z_L = 25 I_{RF}^2. \tag{2.17}$$

Therefore, from (2.16) and (2.17), the frequency response κ can be expressed as [3]

$$\kappa = \frac{\sqrt{P_{RF}}}{5P_{opt}}. \tag{2.18}$$

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:

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.

2.3 Two-tone Light Amplification

In the PD frequency response measurement system, since the generated two-tone optical power decreases as frequency increases, an optical amplifier with precision level control will be used to improve this problem. Thus this has a potential to increase a measurement bandwidth.

An EDFA is widely used in various microwave photonics applications with its several advantages, high gain, linearity, low noise figure, wide bandwidth and can be used in high data rate systems or Wavelength Division Multiplexing (WDM) systems [15]. However, EDFA adds noise to the system, which is called Amplified Spontaneous Emission (ASE) noise, signal to noise ratio degradation due to ASE noise should be considered.

2.3.1 Structure

The structure of EDFA is shown in figure 2.11. The device consists of erbium doped fiber with suitable doping rate about 100ppm [16], resulting in the light amplification phenomena inside the optical fiber. The 980nm laser is used as a pump laser. An optical coupler is used for combining the pump laser and the input optical signal required to amplify. The pump signal, either 980 or 1480nm [17], is launched into the optical fiber resulting in the decomposition of the erbium elements. If the required input optical signal (1550nm) is launched into the coupler, the stimulated erbium elements will emits the energy equal to the input light, resulting in the amplified output signal at 1550 nm. The advantage of the fiber amplifier is the geometrical structure that is compatible to the optical fiber system, giving low insertion loss. However, the pump power and the fiber length are significantly affected to the maximum gain of the EDFA.

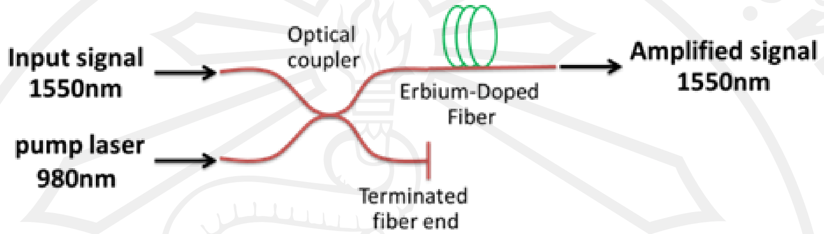


Figure 2.11 Structure of an EDFA

2.3.2 Amplification in Three-Level System of an EDFA [18]

The operation of an EDFA can be characterized by a three-level system as shown in figure 2.12. The erbium ions at the ground state E_1 will be excited to the energy level E_3 by the stimulant light from a semiconductor laser at wavelength 980 nm which is called pump process. At energy level E_3, ions are in unstable state and will be jumped down to the energy level E_2. By pumping more enough power, the population level of ions in E_2 can be made larger than the population of level E_1. Therefore, the population inversion between E_2 and E_1 can be achieved. Any incoming radiation with energy close to E_2-E_1 will be amplified.

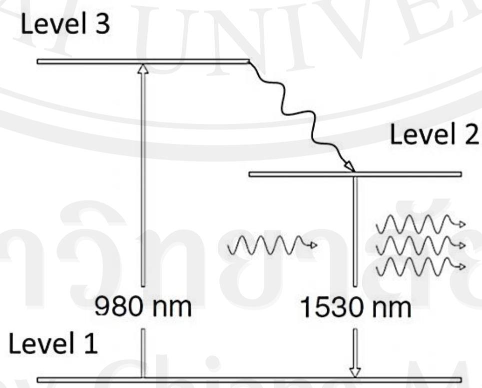


Figure 2.12 Three-level system of EDFA

2.3.3 Amplified Spontaneous Emission [18]

To generate the amplified optical signal, the ions in the E_2 state will jump down to the E_1 state which is called induce emission. Additionally ions in E_2 state also emit spontaneously, which results in the undesired optical power over broad frequency range called ASE noise. Figure 2.13 shows the forward propagating ASE power spectrum as a function of wavelength for a 14 m length of fiber, where the pump powers are 4, 6, 8, 15 and 20 mW at the wavelength of 980 nm. At the wavelength about 1530 nm, an ASE power is at the highest level. In contrast, at the wavelengths near 1550 nm, ASE powers are quite stable.

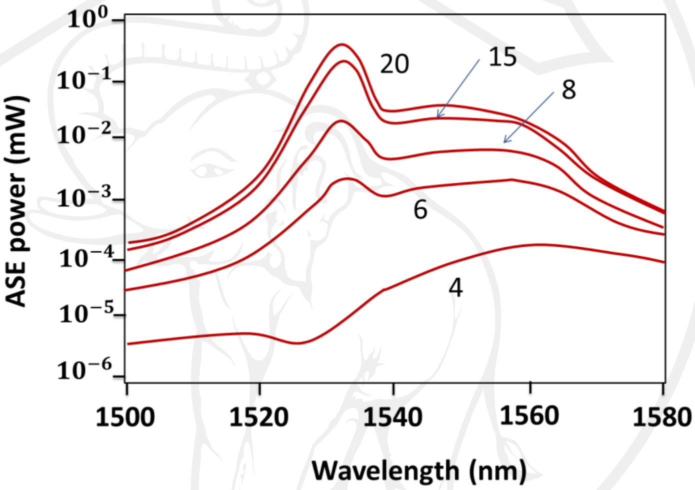


Figure 2.13 ASE power spectrums as a function of wavelength

In this experiment, we use an Amonics AEDFA-PA-25 as the amplifier with maximum 25dB gain [19] as shown in figure 2.14. The gain profile specified in their data sheet is relatively linear.

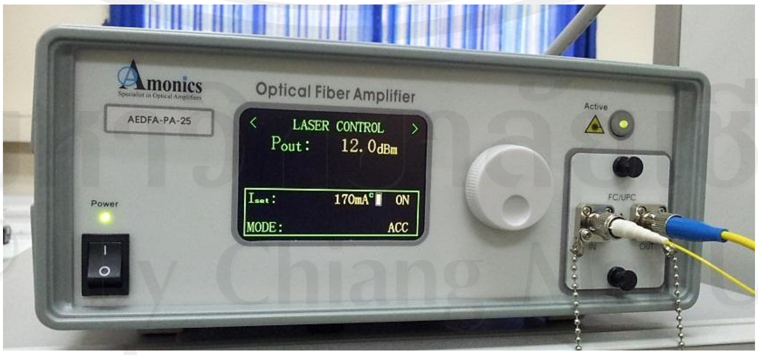
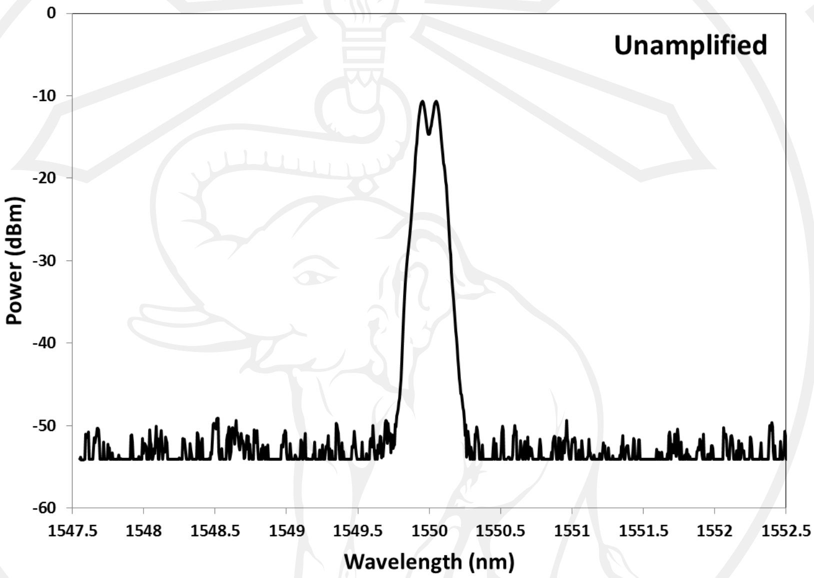
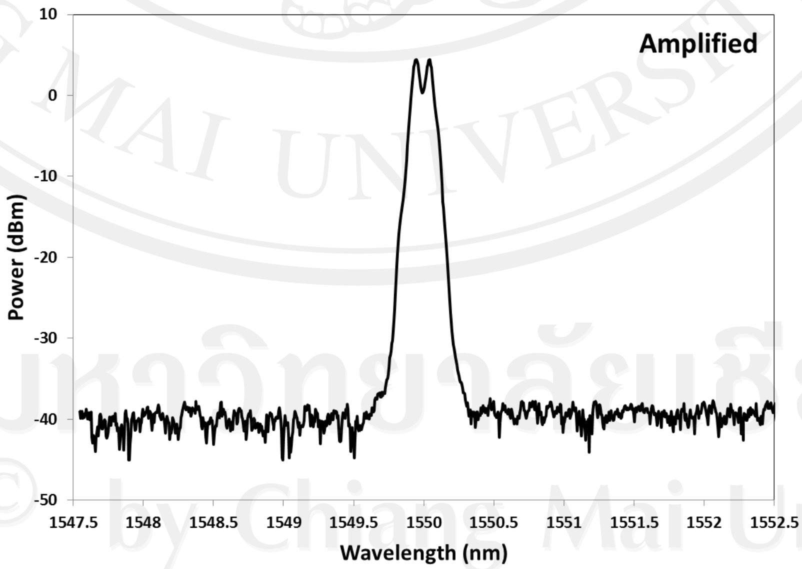


Figure 2.14 Amonics AEDFA-PA-25

In figure 2.15 (a), the generated two-tone optical signal power is about -10 dBm at the center wavelength 1550 nm. In figure 2.15 (b), the two-tone signal in 2.15 (a) is amplified with 15dB gain. The noise floor is also amplified. The two-tone optical signal is detected by an optical spectrum analyzer (Agilent 86142B) with its highest resolution bandwidth of 0.06nm. We can see that the optical spectrum analyzer seems to be unable to resolve the two-tones. In later experiments we instead analyze the two-tone light by the converted RF spectrum.



(a)



(b)

Figure 2.15 (a) Unamplified lightwave and (b) Amplified lightwave