EigenLight
Power Monitor Basics

INTRODUCTION

Conceptually, Fiber Optic Power Monitors are simple devices. Power monitors measure the optical power carried by an optical fiber. Unlike power *meters*, which are terminal devices (i.e. light enters but does not exit), Power *Monitors* are "in-line" devices, allowing the majority of optical power to pass through to a fiber output. Since the light passes through, Power Monitors can be placed in-line to measure optical power while a fiber optic system is operating. Power Monitors are typically used for feedback and control applications, or for dynamic testing of live systems.

In many ways, measuring optical power in a fiber is more like measuring water flowing through a pipe than measuring voltage in an electronic circuit. Measuring the power in a live fiber optic "circuit" requires access to the photons flowing in the core of the fiber. By contrast, voltages in an electronic circuit can be accessed by simply touching a wire or pin with a voltage probe. Thus, a Power Monitor is much like a water gauge on a water pipe, providing information on the flow rate. Instead of liters or gallons per minute, the units of measurement are milliwatts or dBm of optical power.

As with any device imbedded in a live system, it is important for the user to know the device characteristics that can affect system performance once installed. A Power Monitor should ideally have negligible impact on the fiber optic system being monitored, while providing reliable and accurate power measurement over time. The purpose of this tutorial is to discuss the basic optical and electrical parameters that affect performance and system impact of Fiber Optic Power Monitors.

BASIC DESIGNS

As shown in Figure 1, In-line Power Monitors include at least two elements; (1) an optical tap for extracting a small amount of light from the fiber core; and (2) a detector for converting the light tapped out of the fiber core into an electrical current (I_p). This current is typically used to control other optoelectronic components, or to generate digital representations of optical power (for example, for an LCD display).

InGaAs PIN photodiodes are the most common detectors used for telecommunications applications. They cover the wavelength range from approximately 900 nm to 1620 nm. For shorter wavelength applications Silicon PIN photodiodes are preferred.

Historically, power monitoring in lightwave systems was done using a discrete fused fiber optic tap in which the tapped optical power (P_{tap} shown in Figure 1) was carried by a separate optical fiber to a discrete optical detector. In this approach, both the fused-fiber tap and detector were separately packaged devices.

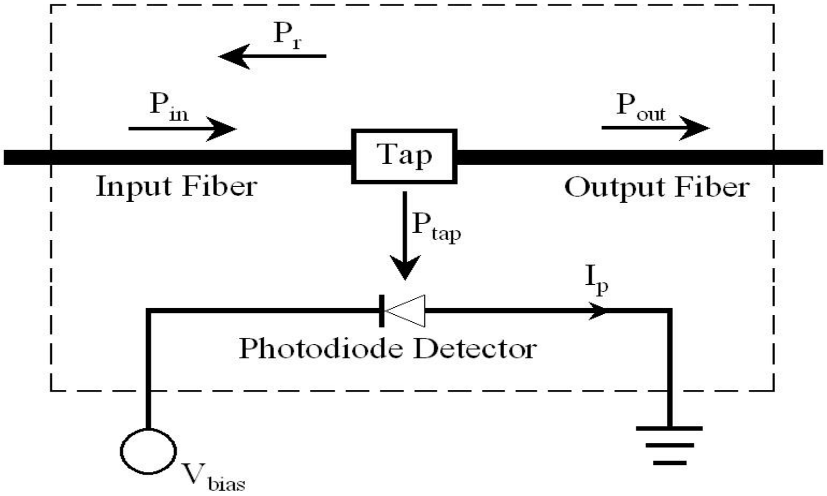

FIGURE 1 – FUNCTIONAL DIAGRAM

To reduce part counts and board space requirements, as well as manufacturing costs, the two functions of the optical tap and detector are now often integrated into a single package.

A variety of technologies are used to integrate optical taps and detectors for Power Monitor applications. One of the most common designs is shown in Figure 2. Here, a lens directs light emerging from the input fiber end onto a partial reflector that reflects the majority of light back into an output fiber, while letting a small amount of light pass through to a detector. The lens and partial reflector form the “tap”.

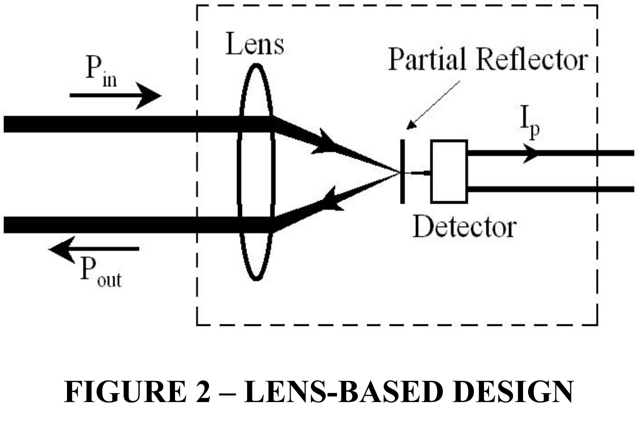

FIGURE 2 – LENS-BASED DESIGN

An alternative approach is to maintain fiber continuity and create an optical tap in the fiber itself, as shown in Figure 3. Here, light is scattered out of the fiber core onto the surface of a detector. Methods for scattering light out of the fiber include: laser induced index changes in the core, microbending of the fiber, laser induced ablation of the fiber cladding to create a reflecting surface, or removal of fiber cladding to produce evanescent coupling of light out of the core.

Depending on the implementation, the advantages of maintaining fiber continuity over the lens design include: lower insertion loss, lower back-reflection (because of the lack of lens interfaces), and better directivity (preferential detection of light flowing in one direction, defined below). In the case of polarization maintaining fiber devices, maintaining fiber continuity has the added advantage of eliminating the need for aligning fiber axes as required with the lens design. This typically results in better polarization extinction ratios.

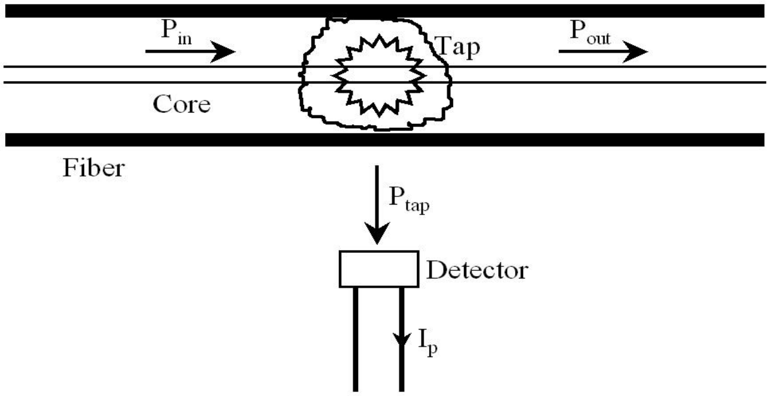

FIGURE 3 – IN-FIBER TAP

At a minimum, good stability over time of both optical tap and detector performance is critical to accurate optical power measurement using a Power Monitor. However, there are other performance parameters that are also important for accurate measurement of optical power. These parameters are common to all Power Monitors regardless of design. In general, they can be divided into **optical parameters** associated with performance of the optical tap, and **electrical parameters** associated with the performance of the detector.

OPTICAL PARAMETERS

Optical parameters associated with Power Monitors can be defined with reference to the functional diagram in Figure 1.

Insertion Loss (L) is the difference between the optical power entering the device and the power exiting the device. This is usually expressed either as a fractional change in power between input and output, or a loss in dB units

(1) $$\mathrm{L} = \frac{(P_{in} - P_{out})}{P_{in}} \qquad (0 \leq \mathrm{L} \leq 1)$$

(2) $$\mathrm{L}_{\mathrm{dB}} = -10\ \mathrm{Log}_{10}\left(\frac{P_{out}}{P_{in}}\right) = -10\ \mathrm{Log}_{10}\ (1 - \mathrm{L}).$$

Note that P_{in} and P_{out} refer to the powers in the input and output fibers and do not include the effects of coupling losses at the fiber ends. As discussed below in the "Calibration " section, such coupling losses become important when calibrating power monitors.

Responsivity (R) is the amount of photocurrent generated by the detector for a given optical power in the fiber

(3) $$R = \frac{I_p}{P_{out}}.$$

Common units for Responsivity in Power Monitors are mA/Watt or µA/milliwatt.

In an ideal device with no excess losses, the responsivity of Eq. (3) can be expressed in terms of the tapped power (P_{tap}) and the responsivity of the detector (R_d)

(4) $$R^{ideal} = \frac{I_p}{P_{out}} = \frac{R_d \cdot P_{tap}}{P_{out}}.$$

The parameter R_d represents the amount of current generated by the detector for a given amount of optical power incident on the detector surface.

Since there are no excess losses in the ideal device, $P_{tap} = P_{in} - P_{out}$ and the ideal responsivity can be expressed in terms of the insertion loss L of Eq. (1)

(5) $$R^{ideal} = \frac{R_d (P_{in} - P_{out})}{P_{out}} = \frac{R_d \cdot L}{(1 - L)}.$$

Real Power Monitors exhibit excess losses associated with incomplete coupling of the tapped power to the detector, as well as excess losses in the optical tap itself. In order to quantify the efficiency of a Power Monitor relative to the ideal, one can define a **Figure of Merit** using Eq. 5**.**, as the ratio of the *real* responsivity to the ideal responsivity

(6) $$\mathbf{F} = \frac{R}{R^{ideal}} = \frac{R}{R_d \cdot L} = \frac{R \cdot (1-L)}{R_d \cdot L} \qquad (0 \le \mathbf{F} \le 1).$$

Note that higher Monitor efficiency is associated with a higher Figure of Merit.

Tap Ratio (T) is a term often applied to fused fiber taps to describe the relative amount of optical power sent to the two output legs. In the context of Integrated Tap/Monitors it is not usually a measurable quantity because the optical power that is in the "tap" leg (shown in Figure 1) goes to the detector and is not available to the user. To compare it to fused fiber taps, the tap ratio of the device in Figure 1 can be expressed as

(7) $$\mathrm{T} = \frac{P_{tap}}{P_{out}}.$$

Under the assumption of no excess losses, the tap power (P_{tap}) is simply the difference $P_{in} - P_{out}$. The tap ratio is then given by the device loss L

(8) $$\mathrm{T} = \frac{P_{tap}}{P_{out}} = \frac{(P_{in} - P_{out})}{P_{out}} = \frac{L}{(1-L)}.$$

Using Eq. 8, the ideal responsivity in Eq. (5) can be expressed in terms of the "effective" tap ratio

(9) $$\mathrm{R}^{\mathrm{ideal}} = R_d \mathrm{T}$$

Polarization-Dependent Loss (PDL) is the *maximum change* in insertion loss when the input state of polarization is varied randomly over all possible states of polarization. This parameter is typically expressed in dB units

(10) $$\mathrm{PDL} = -10\mathrm{Log}_{10}(L_{max} - L_{min}).$$

Polarization Stability (PS) is a measure of the polarization dependence of the responsivity of the device. This is typically expressed as the ratio of the minimum ($\mathrm{R}_{\mathrm{min}}$) and maximum ($\mathrm{R}_{\mathrm{max}}$) responsivity measured when the input state of polarization is randomly varied over all possible states of polarization. This parameter is usually expressed in dB units

(11) $$\mathrm{PS} = -10\mathrm{Log}_{10}\left(\frac{R_{\min}}{R_{\max}}\right).$$

Depending on Power Monitor design, the PDL and polarization stability of a device may be related, but are not necessarily equivalent in expressing the polarization dependence of device performance. Thus, they should be considered separately.

Reflectance (RF) is the relative amount of optical power that is reflected back from the device (P_r in Figure 1). Reflectance is usually expressed as a fraction (or percent) of the incident power, or in dB units

$$\mathbf{RF} = \frac{P_r}{P_{in}}. \tag{12}$$

$$\mathrm{RF_{dB}} = 10\mathrm{Log}_{10}\left(\frac{P_r}{P_{in}}\right) = 10\mathrm{Log}_{10}(\mathrm{RF}). \tag{13}$$

Return Loss (RL) is an alternative to reflectance as an expression of the relative optical power reflected by a device. It is defined as the "loss" induced on an optical signal entering a device and returning to the input. When expressed in dB units it is given by

$$\mathrm{RL} = -10\mathrm{Log}_{10}\left(\frac{P_r}{P_{in}}\right). \tag{14}$$

Note that return loss and reflectance are of equal magnitude but opposite sign when expressed in dB units.

In most fiber optic system designs, a high return loss (low reflectance) is desirable in order to avoid stray optical signals that might affect other system elements.

Directivity (D) is defined as the difference in responsivity between forward and backward directed light. Denoting the forward and backward responsivities by R_F and R_B, the directivity in dB units is given by

$$\mathrm{D} = -10\mathrm{Log}_{10}\left(\frac{R_B}{R_F}\right) \qquad (\mathrm{D} > 0). \tag{15}$$

Often in system design, it is desirable to separately monitor the optical power of upstream or downstream signals. In this situation, a Power Monitor with high directivity is desirable. Directivity may also influence calibration as described further in the **Calibration** section below.

Wavelength and Temperature Dependence: Other device parameters that may be important for the system designer are wavelength dependence and temperature dependence of insertion loss and responsivity. Wavelength dependence is often expressed by a maximum change of the particular parameter over a specified wavelength. Temperature dependence is a maximum change of a parameter over temperature range. Apart from the temperature dependence of insertion loss, which is usually determined by the optical tap, wavelength and temperature dependence are determined by the combined effect of the tap and detector. In an integrated device these two dependencies can be made to compensate each other, in order to produce performance that exceeds the individual components.

ELECTRICAL PARAMETERS

The basic function of the photodetector in a Power Monitor is to convert the optical energy (P_{tap}) of Figure 1 into an electrical current (I_p). Most detectors used in Power Monitors are photodiodes, formed by alternating layers of dissimilar semiconductor material. In the absence of light, these devices behave like diodes in that they tend to conduct electrical current in one direction only. Thus, when biased with a reverse voltage, negligible current is conducted. However, the addition of light in this reversed bias condition causes a photocurrent to be generated.

Electrical parameters that describe the performance of Power Monitors are determined largely by the characteristics of the detector used. These parameters can be understood by considering the equivalent circuit shown in Figure 4.

Real photodiodes can be modeled as an ideal diode in combination with a parallel **Capacitance (C_j), Series Resistance (R_s)**, and parallel **Shunt Resistance (R_{sh})** as shown in Fig. 4. The photocurrent generated by light incident on the detector surface can be modeled as a current generator whose output I_p is directly proportional to the optical energy impinging on the detector. All of these elements are dependent on bias voltage and temperature.

Capacitance (C_j), is largely produced by the photodiode junction and determines the speed or bandwidth of the detector. Generally, the higher the bias voltage the lower the capacitance, which is why in high-speed applications higher bias voltages are employed.

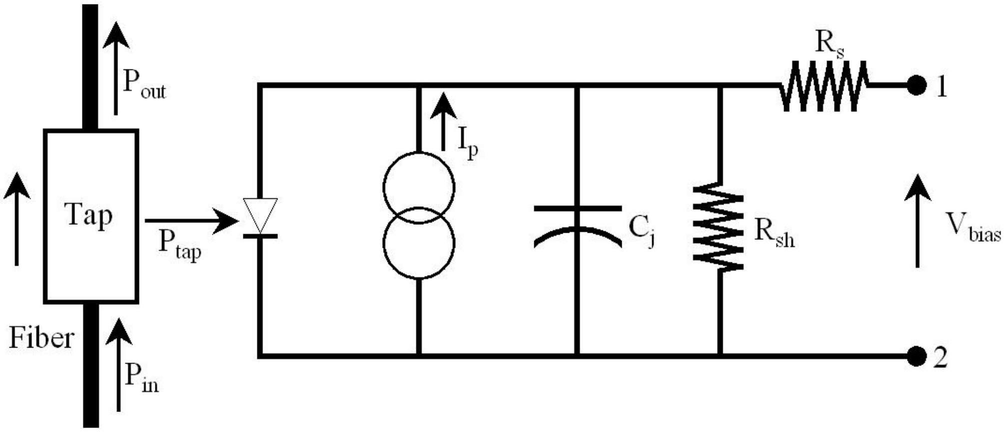

FIGURE 4 – EQUIVALENT CIRCUIT

Shunt resistance (R_{sh}) is defined as the slope of the voltage-current curve at zero voltage.

Dark Current (DC) is the current produced by a photodiode in the absence of optical energy. Typically measured in nanoamps or picoamps, it often determines the lower limit of the useable range for measuring optical power. Since dark current is dependent on a number of factors, including detector size, bias voltage, and temperature, it is usually specified at a specific bias voltage and temperature. For example, dark current is particularly dependent on temperature, increasing by roughly a factor of 10 for every 50°C temperature increase for InGaAs PIN photodiodes.

CALIBRATION

Although calibrating the responsivity of Power Monitors is straight forward, the effect of **reflections from glass-air interfaces** needs to be considered for accurate calibration.

Figure 5 shows a typical set-up for calibrating Power Monitors.

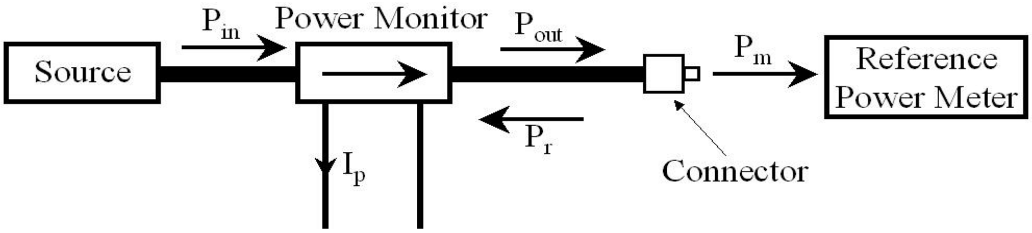

FIGURE 5 – CALIBRATION SET-UP

An optical source transmits light through the device under test. At the output, light is coupled to a reference power meter for measurement of the optical power emerging at the output end. Typically, light is coupled to the power meter using an appropriate connector or cleaved fiber end. Responsivity is determined (see Eq. 3) by the ratio of the photocurrent (I_p) produced by the device under test and the optical power (P_{out}).

The air-gap formed between the connector end-face (or cleaved end) and the power meter detector causes a small fraction of optical power to be reflected at the glass-air interface. The presence of this reflected signal has two consequences for accurate calibration of the device under test. The first is that the optical power (P_m) measured by the power meter is reduced by the reflected power. For typical telecommunications fiber, this results in an error of 3.4% (0.15 dB) between the power measured by the power meter and the power in the fiber upstream of the glass-air interface (shown as P_{out}). Since this error is relatively independent of wavelength, it can be compensated for by adjusting the power measured by the power meter. Note that this error occurs even when using angled interfaces such as with APC connectors.

A second consequence of the reflected power may occur if the connector end face (or the fiber cleave) are flat (for example with PC polish) and the directivity of the device under test is low. In this situation, the reflected light propagates back through the device under test, generating an additional photocurrent. For a device with zero directivity (i.e. sensitivity to forward and backward directed light is the same) the effect is to create a signal 3.5% (0.15 dB) higher than would be measured in the absence of the reflected signal. Note that this error adds to the error caused by the reduced power reaching the power meter, resulting in a total error of 7% (0.32 dB). Thus, it is best to use angled interfaces when calibrating low directivity Power Monitors.

It should be noted that responsivity as defined in Eq. 3, is referenced to the output optical power as opposed to the input power to the device. Thus, Power Monitors are calibrated to indicate the optical power delivered to downstream components. In addition, by defining responsivity in terms of output power, the need to account for device insertion loss and losses associated with coupling power to the input fiber are removed from the calibration procedure.

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