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Figures of merit and performance analysis of photonic microwave links

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1.1 Introduction

Microwave links serve important communication, signal processing and radar functions in many commerical and military applications. However, the attenuation of microwave RF signals in cables and waveguides increases rapidly as the frequency of the signal increases, and it is specially high in the millimeter wave range. Optical fibers offer the potential for avoiding these limitations for the transmission of RF signals.

Photonic microwave links employ optical carriers that are intensity modulated by the microwave signals[1] and transmitted or distributed to optical receivers via optical fibers. Since the optical loss for fibers is very low, the distance for photonic transmission and distribution of microwaves can be very long. When the modulation of an optical carrier is detected at a receiver, the RF signal is regenerated. Figure 1.1 illustrates the basic components of a simple photonic microwave link.

Since the objective of a photonic microwave link is to reproduce the RF signal at the receiver, the link can convey a wide variety of signal formats. In some applications the RF signal is an unmodulated carrier – as for example in the distribution of local oscillator signals in a radar or communication system. In other applications the RF signal consists of a carrier modulated with an analog or digital signal.

From the point of view of input and output ports, photonic microwave links function just like conventional microwave links. A common example is to transmit or to distribute microwave signals to or from remotely located transmitting or receiving antennas via optical fibers. Another common example is to distribute cable TV signals via optical fibers. Not only RF signals can be transmitted in this manner; microwave functions such as mixing (up-conversion or down-conversion) of signal frequencies can also be carried out photonically. We will discuss the

[1] Intensity modulation is in universal use today. Modulation of other parameters of the optical wave, such as its frequency, is in the research stage.

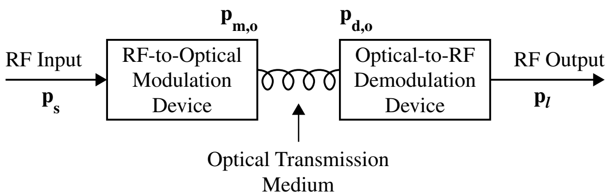

Figure 1.1. Basic components of a fiber optic link: modulation device, optical fiber and photodetection device.

figures of merit and performance measures of photonic RF transmission links in this chapter. The details of devices for the conversion between the RF and optical domains are discussed in other chapters of this book.

The objective of RF photonic links is clearly to achieve the same functions as conventional microwave links with longer distance of transmission, reduced cost, better performance, higher operating frequency, or reduced complexity and size. For this reason, their performance will be evaluated in terms of the criteria for microwave links. For microwave links – which are passive – typical performance criteria include just RF loss and frequency response. There is no nonlinear distortion or additional noise unless the signal is amplified. In photonic microwave links however, additional noise, such as the laser noise, can degrade the noise figure, and nonlinearity of the modulation process can reduce the spurious free dynamic range. Therefore, for microwave transmission and distribution using photonic links, which are more like active RF components, the important performance criteria are: (1) the RF gain and frequency response, (2) the noise figure (*NF*), and (3) the spurious free dynamic range (*SFDR*). These topics will be discussed in Sections 1.2, 1.3, and 1.4, respectively. For systems involving frequency mixing the figures of merit and the performance will be discussed in chapters presenting these techniques.

From the optical point of view, the magnitude of the RF intensity modulation is much less than the intensity of the unmodulated optical carrier. For this reason, one can analyze the link in the small signal approximation. Consequently, at a given DC bias operation point, the time variation of the optical intensity can be expressed as a Taylor series expansion about this DC bias point as a function of the RF signal magnitude.

To demonstrate clearly the system impact of such photonic link parameters as the CW optical carrier intensity, the noise, and the nonlinear distortion, we have chosen to discuss in this chapter the properties of just an *intrinsic* RF photonic link. In an intrinsic link no electronic or optical amplification is employed. An RF signal, at frequency ω, is applied to a modulation device to create intensity modulation of an optical carrier. The modulated carrier is transmitted to the receiver by a single fiber. The RF signals generated by the photodetector receiver constitute the RF output of the link. Only direct detection of the optical intensity (without amplification or any noise compensation scheme such as coherent detection) is considered for our discussion. Distribution of the optical carrier is limited to a single optical receiver. RF gain, *NF* and *SFDR* of such a basic link are analyzed in this chapter. Analysis of complex links involving amplification, distribution, and schemes for noise or distortion reduction, can be extended from the analysis of the intrinsic link.

There are two commonly used methods to create an RF intensity modulation of the CW optical carrier; one is by direct RF modulation of the laser and the second one is by RF modulation of the CW optical carrier via an external modulator. When the distinction between these two modulation methods is not germane to the discussion, we refer to them collectively as the modulation device. The RF gain, the *NF*, and the *SFDR* for both methods are discussed here.

1.2 Gain and frequency response

Conversion efficiencies, especially of the modulation device, are typically less than 10%, which leads immediately to photonic link losses of greater than 20 dB! This situation has motivated considerable work on efficiency improvement techniques. Conceptually there are two routes one can pursue: (1) improve the modulation device, and (2) improve the circuit that interfaces the modulation signal source to the modulation device. In this chapter we set up the analytical framework that shows how each of these approaches affects the solution. We also present an introductory investigation of how the interface circuit can improve performance.

The linear RF gain (or loss) of the link, g_t, is defined as the ratio of "the RF power, p_l, at frequency ω delivered to a matched load at the photodetector output" to "the available RF power at the input, p_s, at a single frequency ω and delivered to the modulation device." That is,

$$g_t = \frac{p_l}{p_s}. \tag{1.1}$$

Frequently the RF gain is expressed in the dB scale as G_t, where $G_t = 10\log_{10} g_t$. If G_t is negative, it represents a loss.

The RF gain of a photonic link is frequency dependent. For links using simple input and output electrical circuits consisting of resistances and capacitances, their RF gain generally decreases as the frequency is increased. To quantify the *low pass* frequency response, the RF bandwidth f_B is defined as the frequency range from its peak value at DC to the frequency at which G_t drops by 3 dB. For a *bandpass* frequency response, which requires a more complex driving circuit, the G_t peaks at a center frequency. In this case, the bandwidth is the frequency range around the center frequency within which G_t drops less than 3 dB from its peak value.

There are three major causes of frequency dependence. (1) The directly modulated laser or the external modulator for the CW laser may have frequency dependent characteristics. (2) The voltage or current delivered to the modulation device may vary as a function of frequency due to the electrical characteristics of the input circuit. (3) The receiver and the detector may have frequency dependent responses.

Let $p_{\mathrm{m,o}}$ be the rms magnitude of the time varying optical power at frequency ω (immediately after the modulation device) in the fiber. Let $p_{\mathrm{d,o}}$ be the rms magnitude of the optical power at ω incident on the detector. Here, the subscript o denotes optical quantities, subscript m designates modulated optical carrier at ω at the beginning of the fiber and subscript d designates modulated optical carrier at ω incident on the detector. Quantities that do not have the o subscript apply to the RF. Then

$$p_{\mathrm{d,o}} = T_{\mathrm{M-D}}\, p_{\mathrm{m,o}}, \tag{1.2}$$

where $T_{\mathrm{M-D}}$ is the total optical loss incurred when transmitting the optical modulation from the modulation device to the detector. This quantity includes the propagation loss of the fiber and the coupling loss to and from the fiber. Since $p_{\mathrm{m,o}}$ is proportional to the current or the voltage of the RF input, $p^2_{\mathrm{m,o}}$ is proportional to p_{s}. Since the RF photocurrent at ω generated by the detector is proportional to $p_{\mathrm{d,o}}$ and since the RF power at the link output is proportional to the square of the photocurrent, $p^2_{\mathrm{d,o}}$ is proportional to p_{load}. Substituting the above relations into Eqs. (1.1) and (1.2) we obtain:

$$g_{\mathrm{t}} = \left(\frac{p^2_{\mathrm{m,o}}}{p_{\mathrm{s}}}\right) T^2_{\mathrm{M-D}} \left(\frac{p_{\mathrm{load}}}{p^2_{\mathrm{d,o}}}\right) \tag{1.3a}$$

or

$$G_{\mathrm{t}} = 10\log_{10}\left(\frac{p^2_{\mathrm{m,o}}}{p_{\mathrm{s}}}\right) + 20\log_{10} T_{\mathrm{M-D}} + 10\log_{10}\left(\frac{p_{\mathrm{load}}}{p^2_{\mathrm{d,o}}}\right). \tag{1.3b}$$

Strictly speaking, the definition of gain requires an impedance match between the modulation source and the modulation device. A typical RF source can be represented by a voltage source with rms voltage v_{s} at a frequency ω in series with an internal resistance R_{S}. As we will see below few, if any, modulation devices have an impedance equal to R_{S}. There are clearly myriad circuits that can accomplish the impedance matching function. The selection for any particular application depends upon many criteria – primary among them are cost, bandwidth and efficiency. We have chosen a few illustrative examples below; a more comprehensive discussion is included in the book by Cox [1].

The simplest – and least expensive – form of matching is to use a resistor. However a resistor is a lossy device, so this form of matching is not very efficient. Thus lossless impedance matching (an ideal situation that can only be approximated in practice) offers greater efficiency but at increased circuit complexity, and hence cost. We will present one example from both categories in the discussion below.

As will become clearer in the sections to follow, $p_{\mathrm{m,o}}^2/p_{\mathrm{s}}$ is an important figure of merit because it contains the combined effects of the modulation device impedance and slope efficiency. To get a feel for $p_{\mathrm{m,o}}^2/p_{\mathrm{s}}$, we will present explicit formulations for several representative cases. In each case we will need to derive two expressions: one for the relationship between the modulation source power, p_{s}, and the modulation voltage or current; and one relating the modulation voltage or current to the modulated optical power, $p_{\mathrm{m,o}}$. Thus the defining equation for $p_{\mathrm{m,o}}^2/p_{\mathrm{s}}$ will be different for different methods used to obtain the RF modulation of the optical carrier.

1.2.1 The $p_{\mathrm{m,o}}^2/p_{\mathrm{s}}$ of directly modulated laser links

The optical power output of a semiconductor laser is produced from the forward biased current injected into its active region. Figure 1.2 illustrates the instantaneous optical power $p_{\mathrm{L}}(t)$ ($p_{\mathrm{L}}(t) = p_{\mathrm{L}} + p_{\mathrm{l,o}}$) as a function of the total injected current $i_{\mathrm{L}}(t)$, ($i_{\mathrm{L}}(t) = I_{\mathrm{L}} + i_{\mathrm{l}}$). Here, the bias current is I_{L}, and i_{l} is the small-signal RF modulation, i.e., $i_{\mathrm{l}} \ll I_{\mathrm{L}}$. If the modulation current is $\sqrt{2} i_{\mathrm{s}} \cos \omega t$ where i_{s} is the rms magnitude of the RF current, then $p_{\mathrm{l,o}}$ is the rms magnitude of the laser power

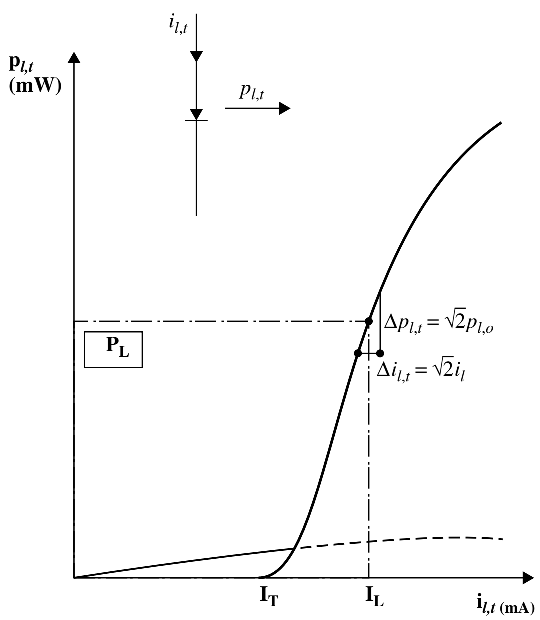

Figure 1.2. Representative plot of a diode laser's optical power, $p_{\mathrm{l,t}}$, vs. the current through the laser, $i_{\mathrm{l,t}}$, with the threshold current, I_{T}, and a typical bias current, i_{L}, for analog modulation.

at ω. Clearly, there is an approximately linear dependence of the change of $p_L(t)$ on the change of $i_L(t)$ in the range from the lasing threshold to the saturation of the laser output.

Direct modulation of semiconductor lasers (i.e., direct modulation of $i_L(t)$) is simpler to implement than external modulation. Hence it is the most commonly used method to achieve intensity modulation of the optical carrier, primarily because it is less expensive. However, the useful bandwidth of modulation is limited to the range from DC to the laser relaxation reasonance, which is typically a few tens of GHz. There is a detailed discussion of the modulation bandwidth, the noise, the nonlinearity, and the modulation efficiency of semiconductor lasers in Chapter 3 of this book.

The slope efficiency of the laser s_l is defined as the slope of the $p_L(t)$ vs. $i_L(t)$ curve at a given laser bias current I_L in Fig. 1.2,

$$s_l = dp_L(t)/di_L(t)|_{I_L} = p_{l,o}/i_l. \tag{1.4}$$

Here, s_l includes the power coupling efficiency of the laser output to the guided wave mode in the fiber.

The i_l is determined from the analysis of the circuit driving the laser. The laser can be represented electrically by an input impedance consisting of a resistance R_L in parallel with a capacitance C_L.

It is well known in circuit theory that the maximum RF power is transferred from the source at voltage v_s to the load impedance when the load impedance is matched to the source impedance, R_S. This maximum available power, p_s, is $v_s^2/(4R_S)$. Therefore the design goal of any RF circuit driving the laser is to provide an impedance match from R_L and C_L to R_S.

Let us consider first a simple resistively matched driving circuit illustrated in Fig. 1.3. This is applicable for frequencies where the reactance of the capacitance, $X_L = 1/j\omega C_L \gg R_L$. For in-plane lasers, typically $R_S \gg R_L$; thus a simple way to satisfy the matching condition at low frequencies is to add a resistance R_{MATCH}

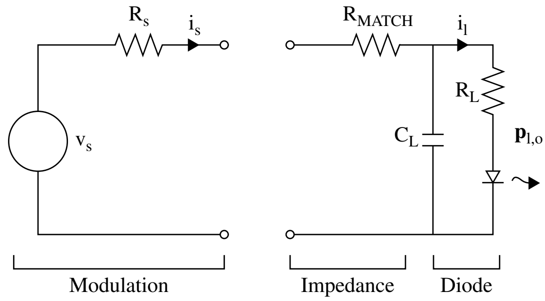

Figure 1.3. Circuit for a resistive magnitude match between a source and a diode laser whose impedance is represented by the parallel connection of a capacitor and a resistor.

in series with the laser so that

$$R_L + R_{MATCH} = R_S. \tag{1.5}$$

Ohm's law permits us to write the expression for the laser current, which in conjunction with Eq. (1.4) yields an expression for the modulated laser power, viz.:

$$i_l = \frac{v_s/2}{(R_L + R_{MATCH})}, \qquad p_{l,o}^2 = \frac{s_l^2}{R_L + R_{MATCH}} \cdot \frac{(v_s/2)^2}{R_s}. \tag{1.6}$$

Dividing the second equation in (1.6) by the maximum power available to the laser at this terminal, p_s, $(v_s/2)^2/R_s$, yields an expression for $p_{l,o}^2/p_s$:

$$\frac{p_{l,o}^2}{p_s} = \frac{s_l^2}{R_s}. \tag{1.7}$$

The frequency variation of $p_{l,o}^2/p_s$ depends on the frequency dependencies of both i_l and s_l. The frequency dependency of s_l will be discussed in Chapter 3; for the purposes of the present discussion it will be assumed to be a constant, independent of frequency.

We can get a feel for the frequency dependency of i_l from the simple circuit of Fig. 1.3. At frequencies higher than DC, i_l drops because of C_L. From the analysis of the circuit shown in Fig. 1.3, we obtain

$$i_s = \frac{v_s}{R_S + R_{MATCH} + \dfrac{R_L}{1 + R_L(j\omega C_L)}},$$

$$i_l = \frac{i_s}{1 + R_L(j\omega C_L)},$$

$$|p_{l,o}| = s_l|i_l| = s_l v_s \left| \frac{1}{2R_S + (R_S + R_{MATCH})(j\omega C_L)R_L} \right|,$$

$$\frac{|p_{l,o}|^2}{p_s} = \frac{s_l^2}{R_S}\left[\frac{1}{1 + \left(2 - \dfrac{R_L}{R_S}\right)^2 \left(\dfrac{R_L \omega C_L}{2}\right)^2}\right]. \tag{1.8}$$

In addition to the frequency variation of s_l, this matching circuit will cause a 3 dB drop of $|p_{l,o}|^2/p_s$ whenever

$$\frac{R_L \omega C_L}{2} = \frac{1}{2 - \dfrac{R_L}{R_S}}. \tag{1.9}$$

The simple circuit illustrated in Fig. 1.3 may be replaced by any one of a number of more sophisticated circuits that matches R_L and C_L more efficiently to R_S.

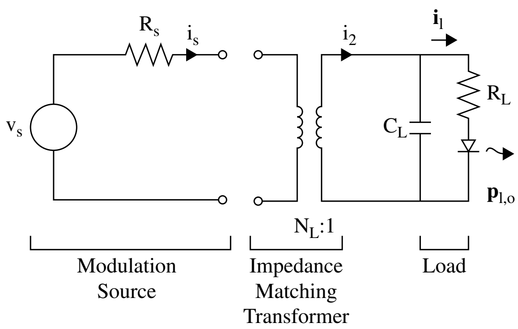

Figure 1.4. Circuit for an ideal transformer magnitude match between a source and a diode laser whose impedance is represented by the parallel connection of a capacitor and a resistor.

Consider here a matching circuit that can be represented symbolically as an ideal transformer as shown in Fig. 1.4. To achieve the desired match, the turns ratio of the transformer is chosen such that

$$N_L^2 R_L = R_s, \qquad \text{and} \quad i_2 = N_L i_s. \tag{1.10}$$

We obtain from conventional circuit analysis:

$$i_l = \frac{v_s N_L}{2R_s + R_s R_L (j\omega C_L)},$$

$$\frac{|p_{l,o}|^2}{p_s} = \frac{s_l^2 N_l^2}{R_s \left[1 + \left(\frac{R_L(\omega C_L)}{2}\right)^2\right]}. \tag{1.11}$$

At low frequencies, $j\omega C_L$ is negligible, and we obtain

$$\frac{p_{l,o}^2}{p_s} = \frac{s_l^2}{R_s} N_L^2. \tag{1.12}$$

Thus transformer (lossless) matching, as show by Eq. (1.12), provides a $p_{l,o}^2/p_s$ that is N_L^2 times larger than the value obtained from resistive (lossy) matching, as shown by Eq. (1.7). The frequency response of this driving circuit will cause a 3 dB drop in $p_{l,o}^2/p_s$ when

$$\frac{R_L \omega C_L}{2} = 1. \tag{1.13}$$

Comparing Eq. (1.13) with Eq. (1.9), we see that the 3 dB bandwidth of the transformer match is a factor of $2 - \frac{R_L}{R_s}$ larger than for the resistively matched circuit. This is an unusual result in that normally one trades increased response for decreased bandwidth.

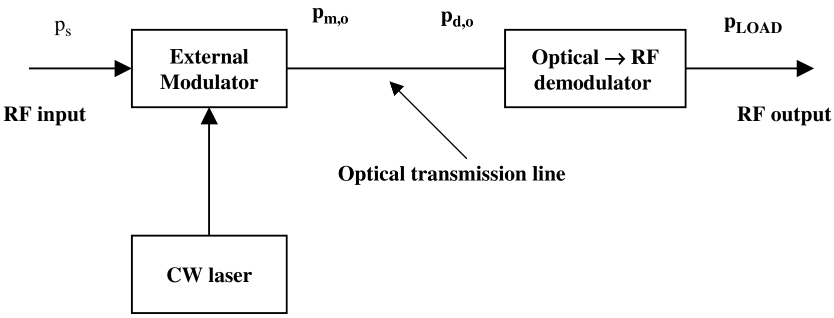

Figure 1.5. Illustration of an externally modulated fiber optic link.

Given the improvement in gain and bandwidth that is obtained in going from a resistive to a transformer match, it is natural to ask: how much further improvement is possible with some other form of matching circuit? Alternatively, one may be interested in using a matching circuit to provide a large i_1, i.e., a large gain g_t, over only a narrow band. The answers to these questions are provided by the Bode–Fano limit. A companion book, *Analog Optical Links*, by Cox [1], also published by Cambridge University Press, discusses such topics extensively.

The discussion in this subsection is applicable to different types of lasers including edge emitting and vertical cavity surface emitting lasers.

1.2.2 The $p_{m,o}^2/p_s$ of external modulation links

For external modulation, the laser operates CW and the desired intensity modulation of the optical carrier is obtained via a modulator connected in series optically with the laser. Figure 1.5 illustrates such an external modulation link. Similar to the case in directly modulated lasers, in external modulation links the frequency variation of $p_{m,o}$ depends on the specific modulator used and on the RF circuit driving the modulator. Different from directly modulated lasers, the bandwidth of state-of-the-art external modulators is approximately five times that of diode lasers. Consequently, the bandwidth of $p_{m,o}^2/p_s$, even when a broadband matching circuit is used, is determined in most applications primarily by the properties of the circuit driving the modulator.

In comparison with directly modulated laser links, the major advantages of external modulation links include (1) the wider bandwidth, (2) higher $p_{m,o}^2/p_s$, (3) lower noise figure and (4) larger *SFDR*. The disadvantages of external modulation links include (1) the additional complexity and cost of optical connections, (2) the necessity of maintaining and matching the optical polarization between the laser and the modulator,[2] and (3) the nonlinear distortions induced by external modulators.

[2] Although polarization independent modulators have been investigated, to date all these modulators have a significant reduction in sensitivity. Thus they are rarely (never?) used in practice.

For more than 10 years the most common type of external modulator that has been considered for RF photonic links is the Mach–Zehnder modulator fabricated in $LiNbO_3$. More recently the polymer Mach–Zehnder modulator as well as the semiconductor Mach–Zehnder and electroabsorption modulators have all also received some consideration for these applications. Each of these modulator types can have one of two types of electrodes: lumped element for lower modulation frequencies and traveling wave for higher frequencies. These different types of modulators are discussed in detail in Chapters 4, 5, 6, and 7 of this book.

The early dominance of the lithium niobate Mach–Zehnder modulator led to the use of the switching voltage for this type of modulator, V_π (to be defined below), as the standard measure of modulator sensitivity. However, with the increasing popularity of alternative types of external modulators – primary among them at present is the electroabsorption (EA) modulator – there is the need to compare the effectiveness of completely different types of modulators. Further, there is also the issue of how to compare the effectiveness of external modulation with direct.

One way to meet these needs, that has proved quite useful from a link perspective, is to extend the concept of slope efficiency – discussed above for direct modulation – to external modulation. This is readily done by starting with the external modulator transfer function, which is often represented in the literature by an optical transmission T of the CW laser power as a function of the voltage ν_M across the modulator, $T(\nu_M)$. To incorporate $T(\nu_M)$ into the external modulation slope efficiency we need two changes in units: modulation voltage to current and optical transmission to power. When these conversions are substituted into Eq. (1.4) we obtain

$$s_m \triangleq \left.\frac{dp(i_L)}{di_L}\right|_{I_M} = R\left.\frac{dp(i_L)}{d\nu_M}\right|_{V_M} = RP_L\left.\frac{dT(\nu_M)}{d\nu_M}\right|_{V_M}. \tag{1.14}$$

Here R is the modulator impedance, P_L is the CW laser power at the input to the modulator and V_M is the modulator bias point.

Let us assume first that, within a given bandwidth of ω, T responds instantaneously to ν_M. In other words, T is a function of the instantaneous V, independent of the time variation of ν_M (this compares to the lumped element electrode case). For example, in Mach–Zehnder modulators whether fabricated in $LiNbO_3$ or polymers, it is well known that

$$T = \frac{T_{FF}}{2}\left[1 + \cos\left(\frac{\pi \nu_M}{V_\pi}\right)\right], \tag{1.15}$$

where T_{FF} is the fraction of the total laser power in the modulator input fiber that is coupled into the modulator output fiber when the modulator is biased for maximum transmission. In a balanced modulator, one of the transmission maxima occurs