High Electro-Optic Sensitivity (r_{33}) Polymers: They Are Not Just for Low Voltage Modulators Any More†

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To achieve gain ≥0 dB in an external modulation analogue optical link with modest laser power (∼10 mW), the external modulator needs to have an on−off voltage (V_π) of ∼ 0.3 V, which is more than a factor of 10 smaller than the on−off voltages of most commercially available modulators. Polymeric materials, in which the electrooptic tensor r_{33} has been engineered to have a very large magnitude (>100 pm/V), enable external modulator designers to meet this goal, because the modulator's on−off voltage is inversely proportional to this tensor magnitude. Now that polymer materials have surpassed 100 pm/V, the natural question is: what do we need even higher r_{33} material for? We will show that there are many uses to which a larger r_{33} material can be put, but that, contrary to present perception, even lower V_π is not one of them. The paper concludes by discussing one of the uses for a larger r_{33}: a linearized modulator.

Introduction

Fiber optic links have become ubiquitous for long distance digital communication and are finding increasing application for transporting analogue signals as well. Regardless of whether one is analyzing a distribution link that feeds hundreds or thousands of nodes, such as with cable TV (CATV), all of these link configurations can be decomposed into one or more basic point-to-point optical link(s), as shown in Figure 1a. For the RF-to-optical modulation device, both direct and external modulation have been extensively investigated and are in widespread commercial use.[1] Since the discussion in this paper will center on electrooptic polymers for external modulators, we will limit our consideration to such external modulators in general and to the Mach−Zehnder modulator in particular. The layout of this modulator is shown in Figure 1b and is one of the most common form of such modulators. The modulating voltage is applied to electrodes that are placed above single mode optical waveguides, which have been fabricated in an electrooptic material. The resulting electrical field alters the optical index of refraction in the waveguide to an extent that is largely determined by the material's electrooptic tensor, which is commonly designated by r_{33}. The interferometric combination of two phase modulated optical waves results in an intensity modulated optical wave that corresponds to the original electrical modulation signal.

One of the key parameters of an optical link is its RF loss, which is defined simply as the ratio of the RF power at the link output to the RF power at the link input. In turn it can be shown (see for example ref 1) that one of the most effective techniques for reducing the loss, or even achieving RF gain, from a link is to have a modulator with a low switching voltage. In the case of a Mach−Zehnder modulator, this would mean a low V_π, which is the voltage required to switch the modulator between full on and full off.

In addition to r_{33}, V_π also depends on several geometrical parameters involving the electrodes and their layout relative to the optical waveguide. These parameters are defined in Figure 1b. An expression for the V_π of a Mach−Zehnder modulator can be show to be[2]

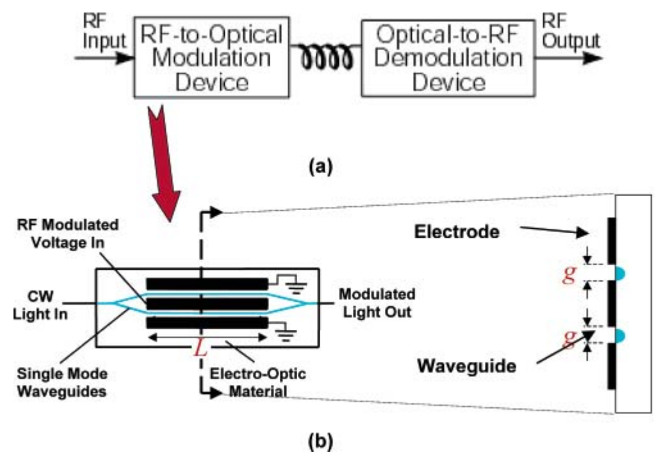

Figure 1. (a) Block diagram of a basic point-to-point optical link; (b) plan (left) and section views of a Mach−Zehnder modulator.

$$V_\pi = \frac{\lambda g}{pn^3|r_{33}|\Gamma L} \tag{1}$$

where g and L are as defined in Figure 1b, λ is the optical wavelength, p is a constant that depends on electrode geometry, Γ is the overlap of the modulating and optical fields, and n is the electrooptic material refractive index. This equation makes clear that once all of the other parameters have been optimized the only remaining option to achieve a low V_π is as large a value of r_{33} as possible. In theory, one might also try reducing V_π by increasing L, but electrical loss will dictate diminishing returns, and large L is also undesirable from a packaging standpoint.

V_π Low but Not Too Low

We begin our investigation of the impacts of lower V_π on link performance by considering the link gain. In Figure 2, we plot the intrinsic link gain (i.e., the link gain without any amplifiers) vs the V_π of the Mach−Zehnder modulator, with

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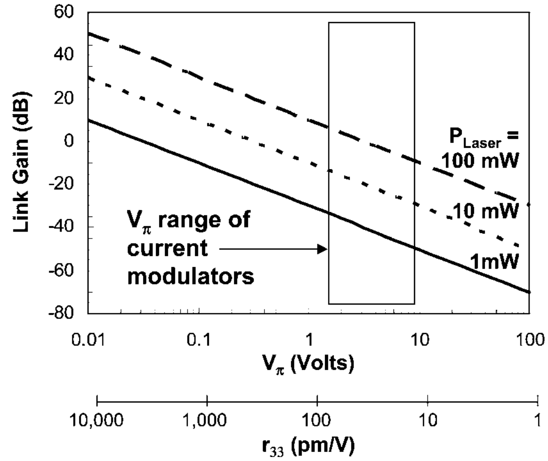

Figure 2. Plot of link gain vs Mach−Zehnder V_π with optical power into the modulator as the parameter. A second abscissa lists the corresponding range of electrooptic material r_{33}, for a common Mach−Zehnder modulator design: $L = 2$ cm, $g = 15$ μm, $\lambda = 1.55$ μm, $p = 2$, $\Gamma = 0.5$, and $n = 2.2$.

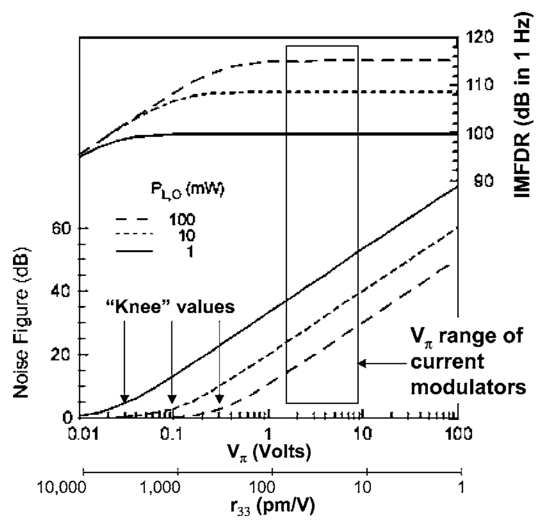

Figure 3. Plot of link noise figure (left vertical axis) and intermodulation-free dynamic range (IMFDR) vs Mach−Zehnder modulator V_π and electrooptic material r_{33}, where the same modulator design parameters as was used for Figure 2 have been used.

the average optical power into the modulator as a parameter. From these curves, it is clear that one can only achieve a lossless link (i.e., one in which the gain = 0 dB) when high optical powers, on the order of 100 mW, are combined with the lowest V_π modulators that are currently commercially available. We have also calculated the corresponding values of r_{33}, assuming common values for the other parameters in eq 1.

However, there is no tradeoff here: the higher the value of r_{33}, the lower the V_π and hence the better the link gain.

Next we consider another important link parameter: noise figure. This parameter is basically a measure of the degradation of the signal-to-noise ratio (SNR) between input and output of an RF component, in this case the optical link. Unlike gain, which has no minimum (or maximum) value, the noise figure has a definite lower bound. At best, there is no degradation of the noise figure, which means that the output SNR equals the input SNR. Consequently, the minimum noise figure, which is 10 times the base-ten logarithm of this ratio, is 0 dB. In Figure 3, we plot the noise figure vs Mach−Zehnder V_π, again with optical power as the parameter. As expected, we see that for high values of V_π the noise figure does decrease as V_π decreases. In this region, the smaller values of V_π result in higher values

TABLE 1: Calculated "Knee" Values of V_π and r_{33} as a Function of CW Laser Power into the Mach−Zehnder Modulator

	"knee" values	
P_{laser} (mW)	V_π (V)	r_{33} (pm/V)
1	0.03	3600
10	0.1	1100
100	0.3	360

of link gain, which in turn are more effective at reducing the impact of noise at the link output on the noise figure.

However, eventually, we reach a region where further decreases in V_π do not result in further decreases in noise figure. In this region, the input noise is amplified by the high-gain link to such a degree that other noise generated by the link is comparatively insignificant. Notice that this constant region has gone largely un-noticed at present because the range of V_π values for current Mach−Zehnder modulators is above the region where one would expect to see this effect. The "knee" value of V_π that signifies the transition between these two regions depends on the average optical power.

A third important link parameter is dynamic range. There are actually several measures of dynamic range. The one we will concentrate on here is the intermodulation-free dynamic range (IMFDR), which is the ratio of the fundamental to distortion powers, when the distortion signal power equals the noise power. The power of the RF signal applied to a modulator at which the power of the output distortion products equals that of the noise depends on the linearity of the modulator, as will be discussed further on in this paper. Basically, the more linear the modulator, the greater the power the input RF signal can have before distortion products exceed the noise and, therefore, the greater the IMFDR. We plot in Figure 3 the IMFDR vs Mach−Zehnder for the same range of optical powers. For high values of V_π, the IMFDR is independent of V_π. The reason is that in this range the distortion is changing at the same rate as the noise; hence, their ratio is independent of V_π. However, once one enters the region where the noise figure ceases to decrease with V_π, then the decrease in IMFDR with further decreases in V_π becomes apparent. Again this region is largely unexplored, because it is below the V_π range of present commercial Mach−Zehnder modulators.

Now by examining both noise figure and IMFDR in Figure 3, it is apparent that V_π introduces a link design tradeoff. Unlike the link gain dependence on V_π, where smaller is always better, we see that when these two additional link parameters are taken into account small values V_π of are not always better. Often one wants the best of both noise figure and IMFDR. To satisfy this requirement, one would want a small enough value of V_π that the noise figure is low, while at the same time remaining on the edge of the constant IMFDR region. To satisfy this tradeoff, we clearly see that the smallest value of V_π is not the best value.

To get a feel for the values of r_{33} where this tradeoff comes into effect, we have summarized in Table 1 the knee values of r_{33} as a function of V_π and laser optical power into the Mach−Zehnder modulator, for the typical modulator design parameters listed in the Figure 1 caption. Although the range of 360−3600 pm/V may seem large to some, it is important to point out that it is projected that within the next few years electrooptic polymers will at least reach the lower end of this range.[3] (For a discussion of the chemical routes to these high r_{33} values, see ref 4 and the articles referenced therein.)

Beyond Low V_π: A Use for Even Higher Values Of r_{33}

It might appear from the preceding section that there is not much utility to attempting to achieve further increases in r_{33}.

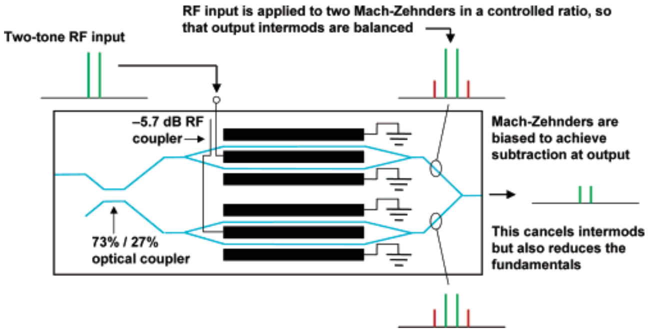

Figure 4. Linearized Mach−Zehnder modulator (after ref 5) in which two standard Mach−Zehnder modulators are connected in parallel and biased such that their distortion cancels.

However, that is not the case if one considers applications of modulators that go beyond the simple, point-to-point link example that was discussed above. Some of the examples of where higher values of r_{33} could be put to good use include:

(1) Linearized modulators
(2) Polarization insensitive modulators
(3) Frequency conversion links

We will discuss only the first example in the following. It turns out that there are a number of applications, antenna remoting of radar signals and distribution of CATV signals prime among them, where greater IMFDR is required than is available from a standard Mach−Zehnder modulator. As mentioned earlier in this paper, the upper end of the IMFDR is dictated by the linearity of the processes by which the RF signal at the input to an analogue link modulates the light and is retrieved from its optical carrier at the detector at the output of the link. In most analogue links, the modulation process is quite nonlinear (especially when compared to the most commonly used detection process, which is very linear over a large range of optical and RF power levels). For example, the depth of optical modulation from a Mach−Zehnder modulator is proportional to the trigonometric sine of a quantity that is proportional to the input signal. For small signals, the small-angle approximation of the sine function tells us that the modulation is quite linear, and therefore, we can expect distortion products to be weak (below noise). However, for larger input signals, the small-angle approximation no longer holds, and the nonlinearity of the modulation results in strong distortion products. Hence, over the years, a number of methods have been proposed, investigated, and commercialized that extend the link IMFDR via "linearization" of the modulation function. An example of one configuration of linearized Mach−Zehnder modulator is shown in Figure 4 (after ref 5). In this linearization method, two Mach−Zehnder modulators are connected in parallel. Both are modulated with the same signal, albeit with different amplitudes. The bias points of the modulators are chosen such that in combination with the modulation amplitudes the distortion produced by each modulator is of equal amplitude but 180° out of phase from the other. Thus, the distortion is canceled.

Unfortunately, the modulation at the fundamental is partially, but not completely, canceled as well. Thus, while linearization eliminates (at least ideally) the distortion, it also reduces the fundamental. Although we have shown this for this particular linearization topology, it turns out that this effect occurs in all other optical linearization methods of which the authors are aware.

If we now repeat Figure 4 for the case of a linearized modulator, we obtain the plot shown in Figure 5. Although the general shape of the noise figure and IMFDR curves is the same

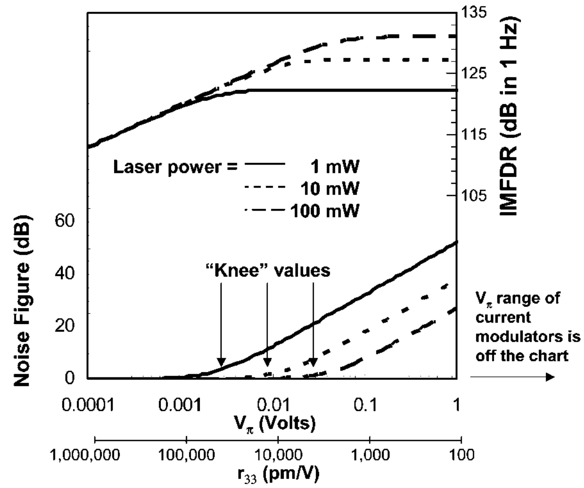

Figure 5. Plot of link noise figure (right vertical axis) and IMFDR vs V_π for the linearized modulator shown in Figure 4. The same modulator design parameters listed in the Figure 2 caption were used to convert the V_π into a corresponding r_{33} scale.

as in the previous plot, we notice that the "knee" values have been shifted to lower values of V_π. In turn, this means that to achieve the same tradeoff point with a linearized modulator is going to require a smaller value of V_π, which in turn will require a higher value of r_{33}.

Conclusions

We have tried to demonstrate that a higher value of electrooptic material r_{33} has many benefits, prime among them are higher link gain and lower noise figure. However, we have also demonstrated that if an additional link parameter, IMFDR, is also included, as it almost invariably is, that the link improvements with increasing r_{33} only go so far. Beyond this value, further increases in r_{33} are actually detrimental to link performance. Hence, a tradeoff exists and the exact value depends on the modulator design parameters as well as the average optical power that will be fed to the modulator.

However, there are definitely uses of higher values of r_{33}. There are many link and modulator configurations in which an improvement in one parameter comes at the expense of another. In these cases higher values of r_{33} would permit one to maintain the improved parameter while simultaneously reducing the degradation of the other. The linearized modulator is but one example of this; other examples include a polarization independent modulator and a frequency converting link.

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References and Notes

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