Linearized Modulators for Analog Photonic Links

by

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Abstract

The potential applications of high dynamic range analog r-f photonic links include antenna remoting, photonic-coupled phased-array antennas, and cable-television transmission. This paper compares the results obtained with a number of different electro-optic modulator types and link configurations assuming an ideal velocity-matched modulator. The degrading effects of velocity mismatching are also presented for some of the modulators studied.

Comparison of Links with Velocity Matched Modulators

The dynamic range of a r-f link is defined as the ratio between the output signal level and the noise level at the point where an undesired intermodulation product just emerges from the noise. The undesired product may be the third-order two-tone intermodulation product (which would likely fall within the passband of even a narrow-band link) or a simple harmonic in the case of a broadband link. High dynamic range may be achieved by (1) reducing the intermodulation products through linearization and (2) reducing the noise level.

In our comparison, we assumed a set of representative values for the components of a simple r-f photonic link, given in Table I, and then used numerical Fourier analysis to find the distortion products and the resulting dynamic range, harmonic content, small-signal gain, and noise figure for the overall link. Numerical integration is necessary since the transfer functions of some modulators do not allow closed-form solutions. We have assumed a specific bandwidth, 1 Hz, for comparisons, rather than express the resulting dynamic range in dB/Hz$^{2/3}$ since the dynamic ranges for some configurations do not vary with a simple power of the bandwidth, and in most cases the exact optimization of the dynamic range depends on all the numerical values assumed in the link. Hence the link results for different values of the parameters are easily recalculated, but not easily scaled. The details of our calculations are given in Ref. 1.

Table II lists the results obtained for links using perfectly velocity-matched Mach-Zehnder modulators (MZM) and directional coupler modulators (DCM) in various configurations. This includes links using (1) a MZM biased to zero even harmonics, (2) two MZM's in parallel optically (but with unequal optical drives), biased as in (1) and modulated out of phase at different r-f levels so that the third-order two tone modulation (IMD) exactly cancels, but the signals do not, (3) three MZM's in parallel with the same strategy as (2), but canceling the IMD to higher order, (4) two MZM's in series optically, not biased to cancel even harmonics, but biased and driven to minimize IMD, (5) a simple DCM biased to zero the second harmonic, (6) a simple DCM biased to minimize IMD, but exhibiting a strong second harmonic, (7) a DCM followed by a d-c bias section (DCB), with both biased to minimize second harmonic and IMD, (8) a DCM followed by two DCB's, with the same strategy as (7), but IMD and second harmonic cancel to higher order.

All modulators have the same half-wave voltage (V_π for MZM's) or crossover voltage (V_s for DCM's) to make the comparison. The parameters varied to maximize dynamic range and minimize harmonics are: the r-f and optical splitting ratios, and the d-c biases applied to the modulator or bias sections. Since all schemes use cancellation in some form, it is not surprising that the link performance depends very critically on the exact values of the parameters, sometimes requiring stabilization of a parameter to better than 0.01% for 1 Hz bandwidth; the dependance is less critical at larger bandwidths. Schemes that employ only d-c voltages as variables rather that optical or r-f splits are likely to be more practical.

In addition to configurations to reduce IMD, we can also consider ways to reduce the noise level. A lower RIN (and likely more expensive) laser reduces one component of the noise. Shot noise can be reduced by lowering the average transmission of the modulator. This idea was originally proposed for the simple MZM by shifting the bias toward the extinction point. This reduces signal, IMD *and* shot noise. Unfortunately, the signal goes to zero at the same bias (V_π) as the IMD, and the second harmonic is greatly increased. This idea works much better for the DCM, since the signal does not go to zero at the bias where the IMD goes to zero. Case (6) in Table II illustrates this mode of operation.

Table I

Parameter	Value
Laser Power	100 mW
Laser RIN	-165 dB
Optical Loss	-10 dB
Mod. Sensitivity	10 V
Mod Impedance	50 Ohm
Det. Responsivity	0.7 A/W
Det. Load Res	50 Ohm
Noise Bandwidth	1 Hz

No electronic preamps or postamps are used.

Table II

Mod. Type	Dyn. R.	Gain	NF
(1) 1xMZM	109.9	-25.2	38
(2) 2xMZM par.	129.7	-36	48.8
(3) 3xMZM par.	134.9	-41.7	54.6
(4) 2xMZM ser.	135.3*	-32.7	37.5
(5) 1xDCM	109.4	-24.8	38
(6) 1xDCM min IMD	135.4*	-31.9	36.7
(7) DCM+1DCB	129.5	-31.7	42.9
(8) DCM+2DCB	129.4	-30.5	43.3
(9) 1xMZM AM het.	115.4	-19.2	35.9

All values in dB
* Second harmonic dynamic range is less.

Others have suggested that the shot noise can be reduced by biasing a simple MZM at its usual $V_\pi/2$ point and then reducing the "carrier" by optical means (interference or filtering). Unfortunately, this does not work, even in principle, because photonic links are *intensity* modulated, not *amplitude* modulated. Reducing the "carrier" lowers the shot noise, but greatly increases harmonic and intermodulation distortion. Such a scheme will work, however, if true optical amplitude modulation is used, for example, by biasing an MZM to its V_π point, where the output is double-sideband, suppressed carrier optical amplitude modulation. Unfortunately, heterodyne detection is now required to recover the signal rather than simple square-law detection. The performance of this link is given in line (9) of Table II. A 10 mW local oscillator laser and the same RIN as Table I was assumed. Heterodyne detection is required even if carrier were re-inserted to yield ordinary amplitude modulation instead of DSSC. Homodyne detection with either optical AM or DSSC yields the same IMD, but a large second harmonic.

Comparison of Links with Velocity Mismatched Modulators

The results stated above ignored the effects of transit time and velocity mismatch. Since linearized modulators typically involve critical cancellations to reduce distortion, it is important to determine how transit-time and velocity mismatch affect the linearization.

We have used a numerical algorithm introduced by Farwell and Chang [2] to analyze the same links as in [1], but with additional representative values of velocity mismatch (microwave velocity = c/4.0, optical velocity = c/2.2, typical of a transmission line on lithium niobate) and a modulator length of 10 mm. As in [2], the modulator structure is divided into many short segments, with a matrix written for each segment. The modulating voltage is assumed uniform in magnitude and phase over the segment, but the phase of successive segments is shifted by an amount appropriate to the velocity mismatch. The program then multiplies all the matrices (typically 128) to relate the output to input. Voltages at two closely-space microwave frequencies f_1 and f_2 are applied and the output FFT-analyzed to find the amplitudes of the signal (f_1), second harmonic ($2f_1$),and intermodulation ($2f_1$ - f_2). The dynamic range (broad band) is determined by finding the input power that makes the intermodulation distortion (IMD) or the second harmonic component equal to the noise level. If only a sub-octive bandwidth link is required, then the dynamic range (narrow band) is limited by the IMD alone.

The results for worst-case velocity mismatch are shown in Fig. 1, which compares the dynamic ranges for four different modulators (see Ref. 1 for modulator and link details): the simple directional coupler modulator biased at its minimum second harmonic point (43% of the transfer voltage) [DCM.43], the same DCM, but biased at its maximum dynamic range point (79% of the transfer voltage) [DCM.79], the directional coupler with two added d-c sections for linearization, from ref. [2], referred to here as the UCSD modulator, considered as limited by intermodulation distortion alone [UCSDw/o2] or limited by intermodulation or second harmonic, whichever is worse [UCSDw2]. In the case of the DCM.43, the limitation switches from IMD below 1GHz to second harmonic above. For DCM.79, the second harmonic is so bad even at very low frequencies, that only the IMD limited (narrow band) dynamic range is shown. Figure 2 shows the gain degradation with frequency for these same three modulators, plus the simple Mach-Zehnder for reference. As suggested by Farwell and Chang, the calculation scales as $f_1 * L * \Delta n$, with L=10 mm and Δn= 1.8 for our calculations, so these curves apply as well to partially velocity-matched modulators [e.g., Ref. 3] by re-scaling the abscissa to the appropriate length and residual velocity mismatch.

The curves in Figs. 1 and 2 show that the second harmonic severely decreases the dynamic range of the UCSD modulator at just a few hundred MHz. The simple DCM dynamic ranges are only slightly less rapidly decreased. We conclude that velocity matching is required to preserve linearization at much lower frequencies than would be required to simply preserve gain.

The program written for this study also easily allows calculations for periodically-rephased modulators [e.g., 4,5] since the modulator is already broken up into a series of incremental matrices. Thus if the modulator is allowed to be mismatched for a few matrices and then rephased for the next few and so on, we have the results shown in Fig. 3 for a four segment modulator (3 rephasings). The same three modulators are considered. With rephasing, the DCM.43 dynamic range is flat to beyond 30 GHz at its d-c value, limited only by IMD, not second harmonic. The DCM.79 (IMD-limited, but with terrible second harmonic) is also greatly improved. The UCSD modulator dynamic range drops off less rapidly, but still seriously. Rephasing more often improves all modulators, as shown in Table III.

We have also added electrode loss to the calculation (requiring only an exponential decrease in amplitude from matrix to matrix), and have compared the effect of loss on perfectly velocity matched modulators. It appears that loss alone reduces the dynamic range of linearized modulators by upsetting the critical distortion-canceling conditions. The effects of loss are less destructive in the rephased modulators, since each segment is "re-amplituded" as well as rephased.

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Fig. 1

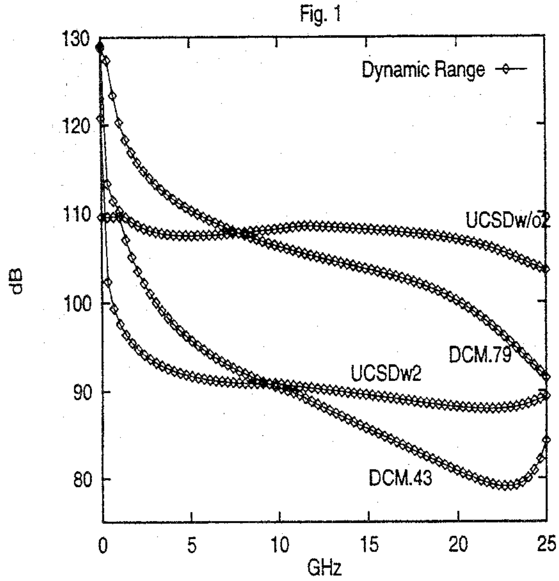

Fig. 2

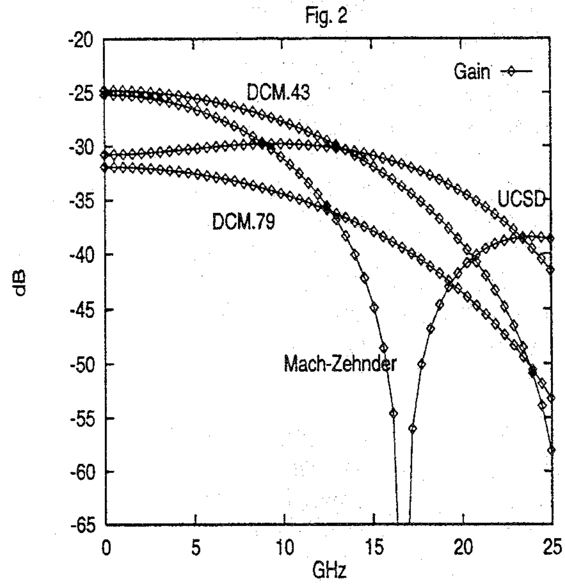

Fig. 3

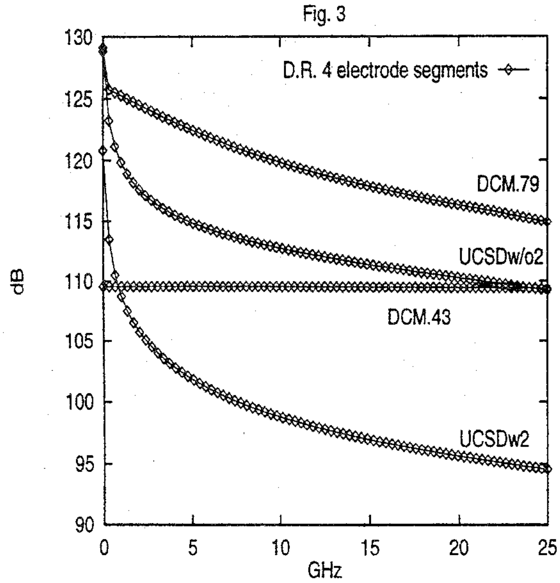

Table III

Modulator	D. R.	3 dB freq. (GHz)			
	DC	1 seg	2 seg	4 seg	8 seg
DCM.43	109.5	1.4	11.5	36	98
DCM.79	128.8	0.42	1.1	5.1	21
UCSDw2	120.8	0.01	0.025	0.12	0.8
UCSDw/o2	129.1	0.02	0.075	0.50	3.0
M-Z	109.8	15.8	31.6	47.4	63.2