A Study of Broadband Microwave Fiber Optic Links with Linearized Integrated-Optic Modulators

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ABSTRACT

A universally accepted figure of merit for analog microwave transmission links is the spur-free dynamic range (SFDR), which is the ratio (usually expressed in dB) of the largest to smallest signal a link can transmit and receive without introducing any measurable distortion. This paper presents the result of a study of broadband, microwave fiber optic links that contain high-linearity integrated-optic modulators. This study focused on two distinct modulator forms, the dual-parallel Mach-Zehnder modulator and the linearized directional-coupler modulator. Computer simulations were performed to determine how the SFDR was affected by variations of modulator parameters. In addition, the dynamic range and noise figure of links that included preamplifiers were calculated. The result of the link analysis was that the linearized directional-coupler modulator provided the highest SFDR for a broadband microwave fiber optic link.

1. INTRODUCTION

One well-established performance measure for microwave analog transmission links is the spur-free dynamic range (SFDR), which is the ratio of the smallest signal a link can transmit and receive without introducing any third-order intermodulation distortion (IMD). Therefore, analog fiber optic links can be characterized by the SFDR to evaluate the expected fidelity of signals as they are transmitted through the link. The lower limit of the SFDR is set by the noise floor of the system, consisting of laser and shot noise of the photonic component and the thermal and excess noise of the electronic amplifiers. The recent arrival of diode-pumped solid-state lasers has resulted in the noise floor being reduced as much as possible for now; the next obvious step toward improving the SFDR would be to address the distortion that defines and limits the high end of the SFDR. Directly-modulated lasers have a large second harmonic component that limits the SFDR to about 80 dB/Hz, and intermodulation distortion that limits the in-band SFDR to about 102 dB/Hz. External modulators of the interferometric type have no second harmonic, and can be used with diode pumped lasers to achieve considerably better values of SFDR [1].

Various linearized modulator schemes have been proposed and in some cases demonstrated with significant reduction in harmonics and intermodulation products [2]-[9]. In all cases, the increase in SFDR is critically dependent upon modulator parameters, which will have to be controlled by active means, especially if the distortion reduction is to be maintained over a large bandwidth. Additionally, the improvement in SFDR can be eroded by the nonlinear behavior of the electronic amplifiers required by the photonic link to realize reasonable gain and noise figure [10].

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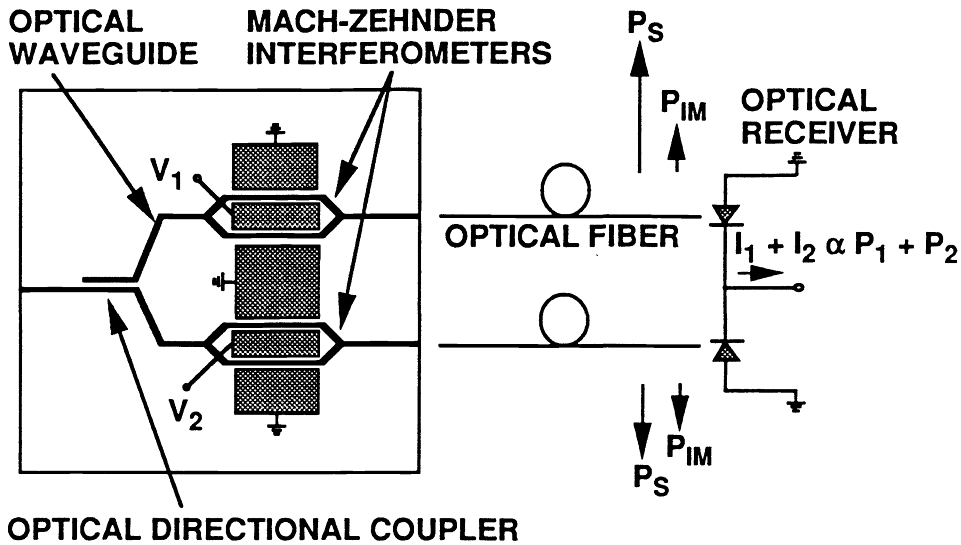
The gain, noise figure, harmonics, intermodulation products, and dynamic range results that are reported in this paper were obtained from a simple photonic link computer model. The objective of this work was to determine what type of linearized modulator would be the best for a high fidelity fiber optic link with up to an octave bandwidth. The study focused on two distinct modulator forms, the dual-parallel Mach-Zehnder modulator (DMZM), and the linearized directional-coupler modulator (LDCM), shown in Fig. 1. Sensitivity analysis of the SFDR to modulator parameters clearly indicated that linearized directional coupler modulator is the best for broadband analog link applications.



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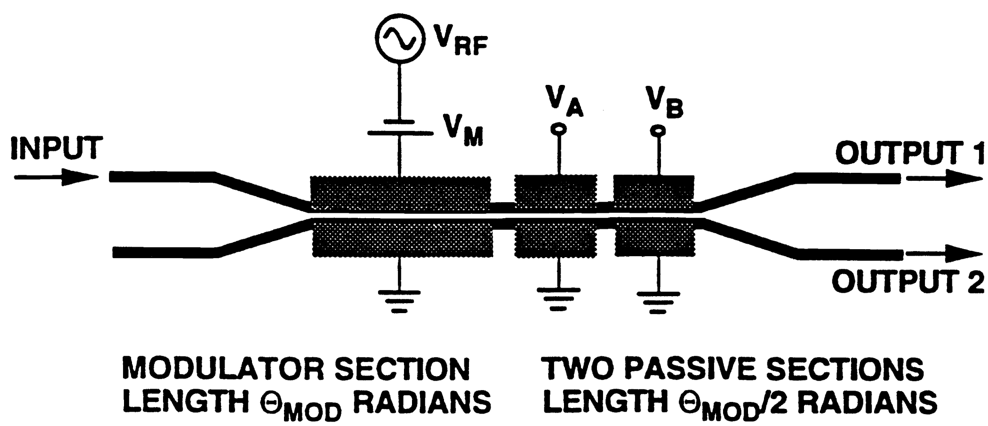

(b)

Fig 1. (a) Dual-parallel Mach-Zehnder modulator and (b) linearized directional coupler modulator.

2. LINK MODEL

In comparing the performance among links with different modulators, it is necessary that the link variables be identical, where possible. Thus, each link had the same laser source power P_L [W], laser relative intensity noise RIN [dB/Hz], modulator characteristic impedance (for traveling wave modulators) R_M [Ω], detector responsivity η [A/W], and detector terminating load impedance R_D [Ω]. The modulator transfer function was characterized by its switching voltage, V_π in the case of Mach-Zehnder based modulators and V_s in the case directional-coupler based modulators, and other bias voltages, optical splits, etc., as necessary. The total optical loss from the laser to the photodetector was L [dB]. The numerical values used in this study are presented in Table I.

The RF power P_{in} [dBm] into the modulator consisted of two equal-amplitude sinusoidal signals at 1.0 and 0.9 Hz. The results obtained from these "normalized" RF frequencies can be scaled up to microwave frequencies if an RF/optical velocity match is maintained in the modulator (i.e., traveling wave), and the photodetector nonlinearity remains insignificant*. The Fourier components 1.0, 2.0, and 1.1 Hz, correspond to signal, second harmonic, and IMD at $2\omega_1$-ω_2. These were calculated by direct numerical integration over the complete period for this signal: 1.0/(1.0-0.9) = 10 sec. (The other intermodulation product $2\omega_2$-ω_1 at 0.8 Hz has the same amplitude as that at 1.1 Hz). Calculation of these specific frequency components rather than using an FFT to obtain a complete output spectral response allowed the link model to be programmed in the user-friendly language MathCad® on personal computers (386 SX and Macintosh II). The output Fourier components were calculated for input signal levels (per tone) ranging from -140 dBm to +40 dBm. The calculated noise included laser RIN, shot noise due to the average photodiode current (assuming no dark current), and thermal noise in the input source and output terminating resistors.

The SFDR was found by solving for the input RF drive level at which the IMD curve intersected the noise level using the MathCad® root-finding routine or by actually plotting the curve. The SFDR was calculated as the difference (in dB) between the intermodulation and the signal power at this level. The link model program was used in a trial-and-error fashion to adjust the various biases, splits, etc., on the linearized modulators to maximize the SFDR. Usually, these values were determined to five significant figures with the root-finding routine, which was required for the sensitivity calculations.

3. LINKS WITH DUAL-PARALLEL MACH-ZEHNDER MODULATORS

The Mach-Zehnder modulator (MZM) is a simple optical interferometer which produces a sine-squared dependence of light output on the drive voltage. The modulator is usually biased to the most linear portion of its transfer curve, which for a perfect modulator, assures no even-harmonic generation. However, the nonlinearity of the transfer curve is responsible for the generation of all odd harmonics and all possible intermodulation products. The dual-parallel Mach-Zehnder modulator (DMZM) scheme uses two MZM's, driven at different RF levels and fed with different optical powers, as illustrated in Fig. 1(a) The RF and optical power splitting ratios are chosen so that the modulator receiving the larger optical power concurrently receives the smaller RF drive power. The modulator that receives most of the optical signal generates some distortion, but the modulator that receives only a little optical power, is driven

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* While the result should be independent of the numerical values chosen for ω_1 and ω_2, it does happen that high-order intermodulation terms can coincidentally fall at frequencies of interest. Thus a "second harmonic" at 2.0 Hz can also arrive from the intermodulation product $11\omega_1$-$10\omega_2$ and would disappear if ω_1 and ω_2 were chosen slightly differently.

much harder, and thus yields a larger IMD. The two optical inputs are combined incoherently, for example, by combining the electrical outputs of two separate detectors, as shown in Fig. 1(a). If the bias points of the two modulators are chosen so that the modulations are out of phase, and the ratios of both optical and RF powers are properly chosen, then the two distortions cancels, while the signals do not completely cancel.

The distorted signal out of each modulator can be expanded in a Fourier series that includes the signal, odd harmonics, and intermodulation products, with the coefficients of expansion represented by products of Bessel functions [11]. If the input signal consists of equal amplitudes, then the coefficient of the third-order IMD contains the product of Bessel functions $J_1(\theta)J_2(\theta)$, where the argument θ is proportional to the RF voltage level. When this term is approximated by a power series expansion for $J_1(\theta)$ and $J_2(\theta)$, for each modulator, then the third-order IMD power is proportional to the RF power cubed. These coefficient may be adjusted to be equal and opposite so they would cancel at the receiver (in the small signal approximation). The condition for this to occur is to have the optical power split be the inverse cube of the RF drive voltage split. Although this particular condition cancels the cubic term, there remains higher-order odd-power terms of the RF modulation. Thus, only the third-order expansion term of the third-order IMD at $2\omega_1-\omega_2$ is cancelled, and the third-order IMD now depends primarily on the fifth order expansion term. Thus, for low input power values, the IMD varies as the input voltage to the fifth power (i.e., 5 dB/dB rather than 3 dB/dB), and the SFDR is increased. For the link parameters of Table I, the SFDR was maximized at 126.2 dB, with an RF voltage split of 2.62 (and an optical split of 1:17.98).

TABLE 1. FIBER OPTIC LINK COMMON PARAMETERS

Laser Power	P_L	0.1	W
Laser Noise	RIN	-165	dB
Total Optical Loss	L	-10.0	dB
Modulator Sensitivity	V_s or V_π	10	V
Modulator Impedance	R_M	50	Ω
Detector Responsivity	η_D	0.7	A/W
Detector Load	R_D	50	Ω

Alternatively, the third-order IMD distortion may be exactly cancelled using a slightly different optical or RF splitting ratio, but cancellation only occurs at a single input power level. As the input power is decreased further, the IMD output power increases to a relative maximum before decreasing again, as shown in Fig. 2 (in fact, multiple relative maximas occur with rapidly decreasing output peaks as the input power is decreased even further). In this case, if the relative maximum peak occurs above the noise floor, it is possible for the IMD curve will have three intersections with the noise line, and the appropriate intersection must be used in the SFDR computation. No ambiguity will exist if the SFDR is calculated at the IMD intersections with noise level at the smallest input level. Now the SFDR will vary

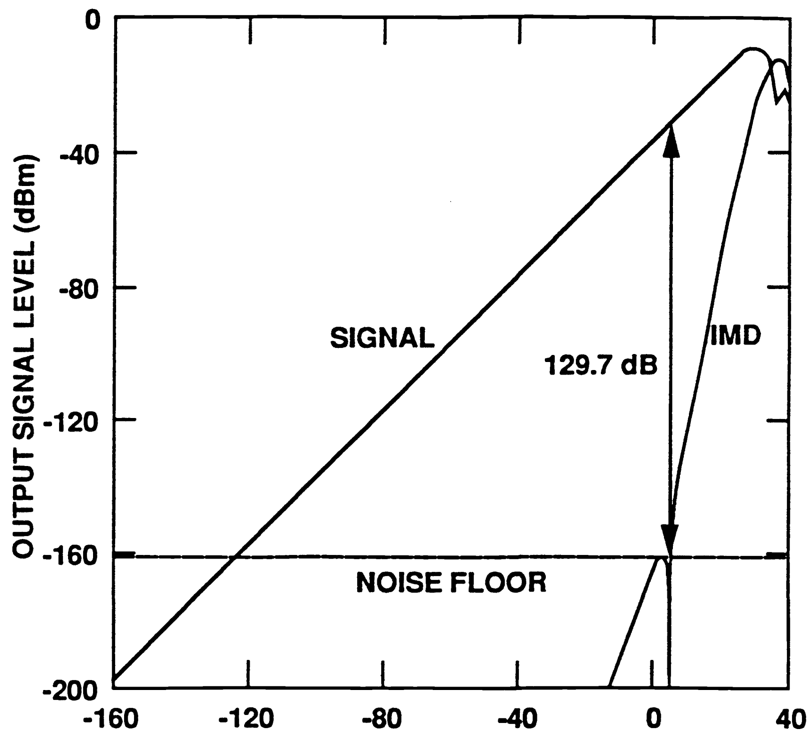
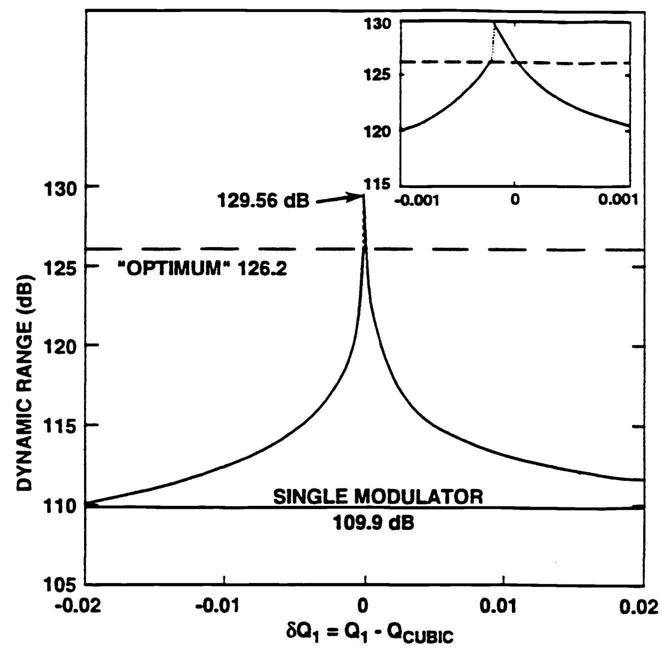


Fig. 2. Output RF signal power and third-order intermodulation power as a function of the input signal for a fiber optic link with a dual-parallel Mach-Zehnder modulator. The splitting ratio has been adjusted for maximum dynamic range.

discontinuously with changing RF or optical split ratios as the auxiliary maximum passes from being below the noise floor (where the "normal" definition of SFDR applies) to being above the noise floor (where the SFDR must be evaluated from the low input power side of the relative maximum). Computations of the SFDR using the link model showed that the maximum dynamic range occurs when the auxiliary maximum is just below the noise level, and that the SFDR drops discontinuously when that maximum increases above the noise level. The maximum SFDR was found to be 129.7 dB compared to 126.2 dB for the "cubic" condition.

The SFDR depends strongly upon the RF and optical splitting ratios. Figure 3(a) shows the sensitivity of the dynamic range to a change in the optical splitting ratio when the RF voltage is held in the "inverse cubic" optimum split of 2.62:1, while Fig. 3(b) shows the sensitivity to change in the RF voltage ratio for the "inverse cubic" optimum optical ratio of 1:17.98. In these figures the total input RF and optical powers are normalized and held constant at 1.0, i.e. $\delta Q_1+\delta Q_2 = 0$ and $\delta W_1+\delta W_2 = 0$. Also shown in those figures is the dynamic range of a link with a single MZM and the parameters of Table I. The conclusion drawn from these curves is that the RF and optical splits must be held to <u>better</u> than 1% across the band for the DMZM link to have any significant improvement in SFDR over that attainable with a single MZM. Even if it was possible to maintain the optical split through the passive coupler with a single frequency laser, it would be difficult, if not impossible, to maintain the required RF power splitting ratio into the two modulators over even a moderately broad bandwidth. Therefore, the use of a DMZM modulator must be reserved for narrow-bandwidth microwave fiber optic links.



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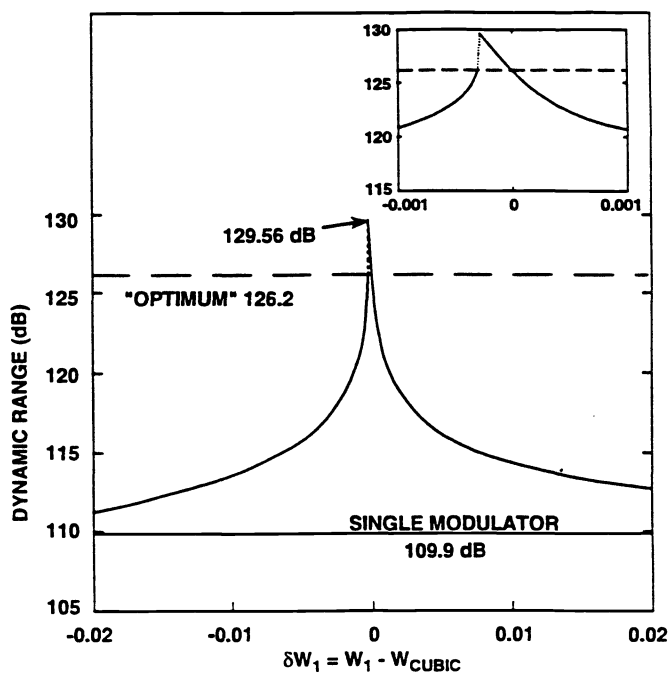

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Fig. 3. Sensitivity of the spur-free dynamic range of a dual-parallel modulator to changes in the (a) optical power split with the RF split held constant at its "optimum" cubic value, and (b) RF power split with the optical split held constant at its "optimum" cubic value. The dynamic range of the link with a single Mach-Zehnder modulator is shown for comparison.

4. LINKS WITH LINEARIZED DIRECTIONAL-COUPLER MODULATORS

Integrated-optic directional couplers fabricated on electro-optic substrates can also be used as optical modulators [12]. Modulating electrodes are applied to the two coupled waveguide channels so that the propagation constants of the guides are changed incrementally in opposite directions when a voltage is applied. Light traveling through one guide will couple across to the neighboring guide, with the fraction of cross-guided light to incident light determined by the length and separation of the directional coupler and the applied voltage on the electrodes. The voltage required to switch the optical signal completely from one channel to the other channel is termed the switching voltage V_s, and is analogous to V_π in MZM. A "simple" directional coupler modulator (DCM) is fabricated with a product of the coupling coefficient and length, κL, equal to $\pi/2$ so that zero bias voltage on the electrode causes complete switching. A bias voltage of $V_s/2$ and application of an RF signal voltage produces optical intensity modulation with nearly the same modulation percentage as for a MZM similarly driven [13]. However, the DCM does produce small even-harmonics at this bias point.

The linearization of the DCM transfer function can be achieved with modulator configurations that have two or three sets of electrodes [4]-[6], as shown in Fig. 1. The linearized directional coupler modulator (LDCM) length is such $\kappa L \sim \pi$. The RF voltage V_{RF} and a DC bias voltage V_M are applied to the first electrode while the second and third electrodes have only DC biases, V_A and V_B. Appropriate bias voltages applied to the modulator allow suppression of the second harmonic as well as the third-order IMD. Computations of signal, IMD, and second harmonic using the link model resulted in the observation that the IMD and second harmonic can be cancelled exactly for particular input power levels, although the input powers for cancellation do not necessarily coincide. Using the parameters in Table I, the calculated link response was a maximum SFDR of 129.4 dB, a gain of -30.5 dB, and a noise figure of 43.3 dB with the modulator biases set to $V_M = 0.509V_s$, $V_A = 0.738045V_s$, and $V_B = 0.770017V_s$. This should be compared to the result of the link calculation with a simple DCM where the SFDR, gain, and noise figure were found to be 109.4 dB, -24.8 dB, and 38.0 dB, respectively. As with exact cancellation of the IMD for the DMZM, distortion "sidelobes" can pop above the noise level with further reduction in the two-tone input power. As a result, curves of the sensitivity of the SFDR to bias voltages also have a discontinuity at the maximized bias point.

The sensitivity of the third-order IMD SFDR to changes in the bias voltages is shown in Fig. 4. Figure 4(a) shows the modulator sensitivity to changes in V_M/V_s, and Fig. 4(b) shows the modulator sensitivity to changes in V_A/V_s; sensitivity to V_B/V_s is similar. The second harmonic is also shown in these curves, as DY2, is the ratio of the signal level to the second harmonic signal just at the point where the third-order IMD ($2\omega_1$-ω_2) curve crosses the noise level, the same point where the SFDR is defined. It can be seen from these curves that the SFDR is relatively insensitive to the active electrode's bias, and is much more sensitive to the passive electrode's bias (as would be expected since the goal is to "linearize" the transfer function of the active electrode). A $\pm 0.01\%$ change in V_A/V_s would reduce the dynamic range by 5 dB. For $V_s = 10$ V, this means that the DC bias voltage must be held to within ± 1 mV. Keeping the second harmonic below the third-order IMD would require tolerances on the order of ± 0.1 mV. While it is apparent that the bias voltage tolerances must be controlled with an active feedback network, it must be emphasized that it is only the DC voltage that must be tightly controlled in the LDCM. Unlike the DMZM, which must control RF and optical power splits, the LDCM could operate over a very broad bandwidth under stable bias control.

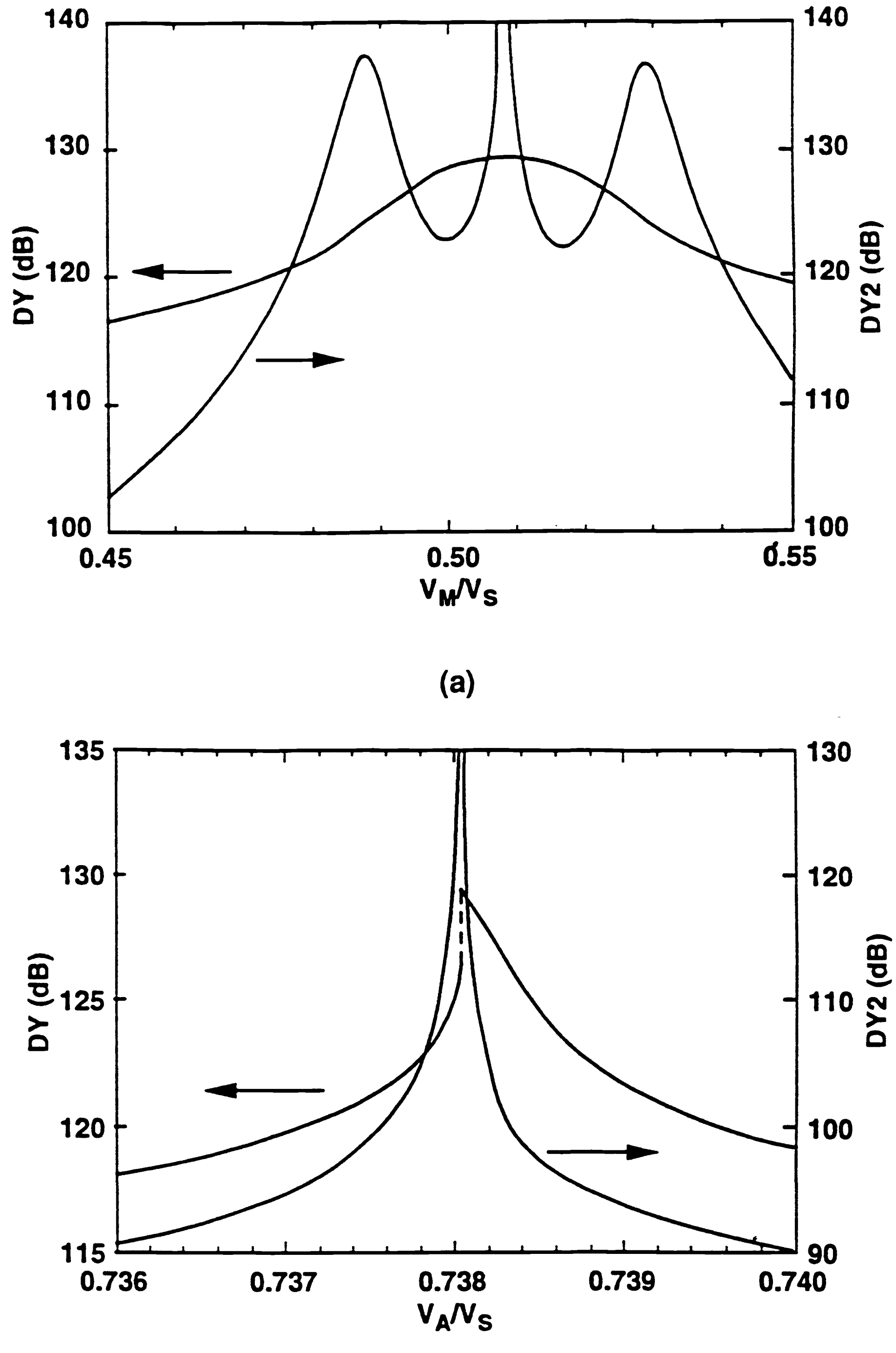

Fig. 4. Dynamic range (left scale) and signal-to-second harmonic ratio at the input power where the $2\omega_1$-ω_2 intermodulation intersects the noise level (right scale) as a function of (a) modulator bias point and (b) first bias section voltage for a photonic link with a linearized directional coupler modulator.

5. HIGH DYNAMIC RANGE LINKS

Up to this point the performance of the high linearity fiber optic link has been determined without any RF pre- or post- amplification. In practice, at least an electronic pre-amplifier would be used to overcome the fiber optic link insertion loss and high noise figure. Electronic amplifiers have their own gain, noise figure, and distortion (indicated by the amplifier's third-order intercept point) and thus the link's overall performance will depend upon these RF amplifier parameters. Thus, while the intrinsic fiber optic link (no amplifiers) with a high linearity modulator can obtain a large SFDR, the overall SFDR of the cascaded amplifier and link could be substantially reduced [10].

The computer link model was modified to include RF amplifiers, and in Figs. 5 and 6, the calculated SFDR and noise figure for a 2-4 GHz fiber optic links with RF pre-amplification (no post-amplification) are shown as a function of the pre-amplifier gain. For these figures, the modulator switching voltage was taken to be 5.5 V, while the other link parameters of Table I remained the same. The 2-4 GHz amplifier was assumed to have a 3 dB noise figure and a 40 dBm output third-order intercept point. The Avantek APG-4004 is such an amplifier with these specified performance values and an average gain of 37 dB.

The links with MZM and DMZM are presented in Fig. 5 and the link with the DCM and LDCM is presented in Fig. 6. In all cases it can be seen that the pre-amplifier gain results in a trade-off between the overall noise figure and the SFDR. As the amplifier gain increases, its own IMD increases and the link SFDR begins to degrade when the amplifier IMD at the output of the link exceeds the IMD generated by the modulator (at the link output). Simultaneously, as the amplifier gain increases, the over noise figure of the link decreases. The curves for the DCM and MZM are almost identical, as expected. However, the link with the LDCM has an insertion loss that is roughly 5 dB less than the link with a DMZM, and as a result, gives the highest SFDR of all of the links considered. Further computations with a post-amplifier did not degrade the SFDR by more than 1 dB.

6. SUMMARY

In summary, a study of the SFDR sensitivity to modulator parameters was conducted for high fidelity fiber optic links with dual-parallel Mach-Zehnder modulators and linearized directional coupler modulators. Comparisons of factors such as RF and optical voltage splits and DC bias have indicated that for broadband operation the LDCM modulator must be chosen over the DMZM. Furthermore, in links with pre-amplification, it was found that with LDCM modulators had higher SFDR than any of the other modulator configurations considered.

7. ACKNOWLEDGMENT

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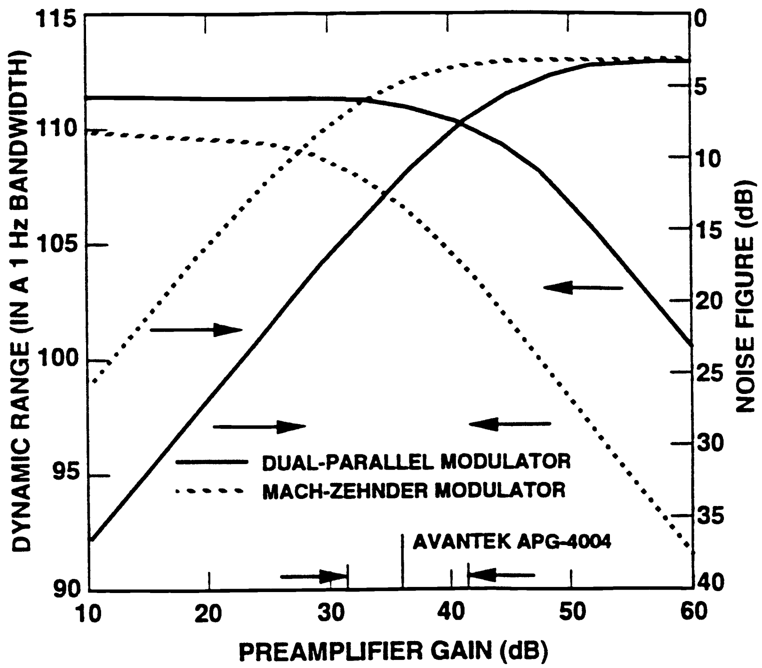

Fig. 5. Performance of a 2-4 GHz link as a function of pre-amplifier gain. The solid curve represents a link with a dual-parallel modulator, and the dashed curve represents a link with a single Mach-Zehnder modulator.

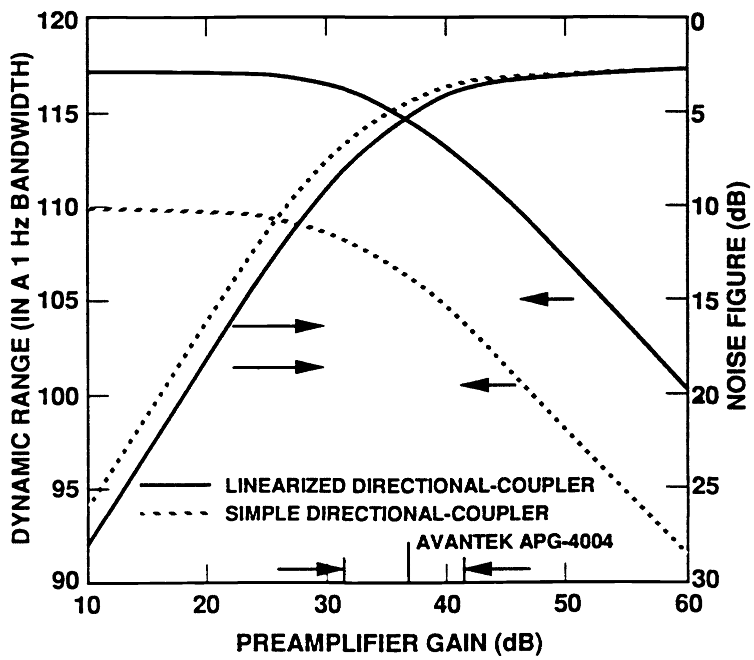

Fig. 6. Performance of a 2-4 GHz link as a function of pre-amplifier gain. The solid curve represents a link with a linearized directional coupler modulator, and the dashed curve represents a link with a simple directional coupler modulator.