Intermodulation Distortion in High Dynamic Range Microwave Fiber-Optic Links with Linearized Modulators

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Abstract—A number of techniques have recently been described to linearize integrated optic intensity modulators, and thus significantly reduce the two-tone intermodulation distortion. The resulting intermodulation distortion produced by these extended linearity modulators then varies as the input power to the fifth-order or higher. When these modulators are included in a fiber-optic link system, the overall intermodulation product is a combination of third-order and higher order terms. In this paper we determine the dynamic range of a cascaded microwave network consisting of a preamplifier, a high dynamic range fiber-optic link with a highly linear modulator, and a post-amplifier. An expression is found that relates the intermodulation power at the output to the relative suppression from the signal level. As an example, a hypothetical 10 GHz low distortion fiber-optic link that has a dynamic range of 125 dB in a bandwidth of 1 Hz is cascaded with various preamplifiers, and it is shown that the dynamic range of the system is reduced by as much as 20 dB, depending upon the third-order intercept of the amplifier.

I. INTRODUCTION

A variety of techniques to reduce the two-tone third-order intermodulation distortion in integrated optic amplitude modulators have been published recently. These include polarization-mixing [1], dual parallel modulators [2], and modified directional coupler modulators [3]. In all of these modulators the optical signal is essentially split into two paths where the degree of modulation in each path is determined by the RF power split, optical power split, and modulator biasing conditions. It then is possible to suppress the third-order distortion by summing the two paths with 180° of phase difference so that the third-order products cancel. This process eliminates the third-order term in the Taylor series expansion of the modulator transfer curve of output optical power versus the applied electrode voltage, and thus the transfer curve is more linear around the modulator’s bias point. As a result the residual two-tone third-order intermodulation products vary as the input power to the fifth-order, and consequently the dynamic range of the fiber-optic link is increased. A continuation of this process would then eliminate the fifth-order term in the Taylor series expansion of the transfer curve and thus the intermodulation products would vary as the input power to the fifth-order, and consequently the residual two-tone third-order intermodulation products would vary as the input power to the fifth-order, and consequently the dynamically linear around the modulator’s bias point.

While such extended linear dynamic range modulators have exciting potential applications in CATV and microwave communication systems, the fact remains that these links inevitably need pre- and post-amplification of the signal, and these electronic amplifiers generate their own third-order intermodulation distortion. Thus, it is important for the fiber-optic link designer, when trying to choose the optimum system components, to understand how the intermodulation distortion produced by each of the cascaded network elements contributes to the overall system distortion. Rules for determining the overall dynamic range of cascaded microwave networks where each network has third-order intermodulation distortion are well known [4], [5]. These rules have been applied to determine the dynamic range of analog optical links with conventional Mach-Zehnder interferometric modulators covering frequencies up to 22 GHz [6]. However, in a fiber-optic link containing a linearized modulator the residual third-order intermodulation distortion is now proportional to the input powers to the fifth-order or higher. The overall intermodulation distortion is now a combination of this higher-order term and third-order components from the amplifiers. Thus the previously derived simple formulas for dynamic range no longer apply. A modification of the method developed by Kanagalekar et al. [5] is presented here that allows one to account for the third-order intermodulation power waves generated by each amplifier and the residual third-order intermodulation power generated by the high dynamic range fiber-optic link. This approach is applied specifically to a system with a high dynamic range fiber-optic link that has intermodulation distortion that varies with the fifth-order of the input power, and a new nonlinear expression is obtained for the overall worst-case dynamic range which is still simple enough to program quickly.

II. DYNAMIC RANGE OF THE SYSTEM

The intermodulation performance of a system is usually specified by the intercept point of the linear extrapolated signal and intermodulation power curves as a function of input power as illustrated in Fig. 1. The nth order intercept point $X_n$ (dBm) is related to the relative suppression, $R$ (dB), of the nth order intermodulation power and the output signal power, $P_o$ (dBm), by [4], [5]

$$R = (n - 1) [X_n - P_o] \quad \text{(dBm)}.$$  

(1)
Fig. 1. Output signal power \( P_{\text{out}} \) and nth order intermodulation power \( P_{\text{IM}} \) as a function of input power on a log-log scale. The nth order intercept point, \( X_n \), (dBm), is the intersection of the extrapolated power curves, and the dynamic range, \( \Delta \) (dB), is the difference between the signal power and lowest order intermodulation power (typically third order) when the intermodulation power equals the noise floor in a bandwidth \( B \).

\[
\frac{1}{r_T} = \frac{P_o}{P_n} = \frac{d_1}{p_1} + \frac{d_2}{p_2} + \frac{d_3}{p_3} \\
+ 2 \sqrt{\frac{d_1 d_2}{p_1 p_2}} \cos (\theta_1 - \theta_2 + \phi_1 - \phi_2) \\
+ 2 \sqrt{\frac{d_1 d_3}{p_1 p_3}} \cos (\theta_1 - \theta_3 + \phi_1 - \phi_3) \\
+ 2 \sqrt{\frac{d_2 d_3}{p_2 p_3}} \cos (\theta_2 - \theta_3 + \phi_2 - \phi_3) \quad (4)
\]

where \( \sqrt{G} e^{i\phi} \) is the complex power wave gain from the output of the ith stage to the load, and \( \sqrt{G} e^{i\phi} \) is the intermodulation complex power wave generated in the ith stage. The subscript \( T \) denotes values for the entire cascade.

The relationships between the intercept points of the individual stages and their relative suppressions can be found from (2). Explicitly, they are \( x_1 = r_{11}^1 p_1 \) and \( x_3 = r_{31}^3 p_3 \) for the pre- and post-amplifiers with third-order intercept points, and \( x_2 = r_{21}^2 p_2 \) for the low distortion fiber-optic link with a fifth-order intercept point. Therefore, (4) can be written as

\[
x = \frac{1}{r_T} \left[ \frac{P_o}{x_1^3 g_1} + \frac{P_o}{x_2^3 g_2} + \frac{P_o}{x_3^3 g_3} \right] \\
+ \frac{2p_0}{x_1 x_3 g_1} \cos (\theta_1 - \theta_2 + \phi_1 - \phi_2) \\
+ \frac{2p_0^2}{x_1 x_3^2 g_2} \cos (\theta_1 + \phi_1 - \phi_3) \\
+ \frac{2p_0^3}{x_2 x_3^3 g_3} \cos (\theta_2 + \phi_2 - \phi_3). \quad (5)
\]

In (5) \( p_0 g_1 \) has been substituted for \( p_1 \), and \( g_3 = 1 \) with \( \theta_3 = 0 \) (the gain is unity between the post-amplifier and the load).

The relative suppression \( r_T \) is a minimum when all of the cosine terms are unity, so that a worst-case equation can be written in terms of \( r_T \)

\[
\frac{1}{r_T} = \left( \frac{d_T}{x_1^3 g_1} \right)^3 + 2d_T \left( \frac{1}{x_1 x_2 g_1} + \frac{1}{x_2 x_3 g_2} \right) r_T^3 \\
+ \left( \frac{1}{x_1^3 g_1} + \frac{1}{x_2^3 g_2} + \frac{2}{x_1 x_3 g_1} \right) r_T^3 \quad (6)
\]

where \( p_0 = r_T d_T \) was used. The minimum dynamic range of the overall system is the value of \( r_T \) that is determined from (6) by setting \( d_T = F_T k T_S g_T B \), where \( F_T \) is the system noise figure, \( g_T \) is the system gain, \( k \) is Boltzmann’s constant (J/K), \( T_S \) is the system temperature (K), and \( B \) is the bandwidth (Hz).

### III. EXAMPLES

A hypothetical system was designed for operation up to 10 GHz which included a preamplifier and a low distortion fiber-optic link. A program was written that calculated the
TABLE I
FIBER-OPTIC LINK PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulator switching voltage, $V_s$</td>
<td>8 V</td>
</tr>
<tr>
<td>Modulator insertion loss</td>
<td>7.0 dB</td>
</tr>
<tr>
<td>Traveling wave electrode impedance</td>
<td>25 Ω</td>
</tr>
<tr>
<td>RF power split</td>
<td>2.4:1</td>
</tr>
<tr>
<td>Optical power split</td>
<td>1:13.8</td>
</tr>
<tr>
<td>Optical power out of the laser</td>
<td>50 mW</td>
</tr>
<tr>
<td>Laser RIN</td>
<td>-160 dB/Hz</td>
</tr>
<tr>
<td>Detector Responsivity</td>
<td>0.8</td>
</tr>
<tr>
<td>Detector Load Resistance</td>
<td>50 Ω</td>
</tr>
</tbody>
</table>

output signal power, two-tone intermodulation power, and noise level of the link as a function of the input RF power. The contribution each stage brings to the overall system performance only depends upon the intercept point, gain, and noise figure of that stage and therefore the low distortion link of stage two could contain any linearized modulator that suppresses the third-order products of the third-order distortion. In the example presented in this section, the fiber-optic link was assumed to include a dual parallel modulator [2] in order to obtain a specific dynamic range for stage two. Modulator and amplifier parameters were taken from commercially available components, and the parameters for the link are listed in Table I. It was found that an RF power split between the dual modulators of 2.4:1 and an optical power split of 1:13.8 gave an optimum fiber-optic link dynamic range of 125 dB when the noise power bandwidth was limited to 1 Hz. The link loss was calculated to be 35.7 dB, the fifth-order intercept point was -2.1 dBm, and the noise figure was 51.1 dB. The preamplifier was chosen to be a 6–12 GHz power amplifier with a third-order intercept of 35 dBm; it also had 31 dB of gain and a noise figure of 12 dB.

The dynamic range of the amplifier plus fiber-optic link cascade calculated from (6), was found to be 104.8 dB in a bandwidth of 1 Hz. Fig. 3(a) shows the output signal power, intermodulation power, and noise level as a function of the input power. The slope of the intermodulation power is 3 dBm/dBm until the output power level approaches the intercept point, essentially the slope of the preamplifier distortion. This result is not too surprising because the high fiber-optic link insertion loss means that the amplifier must be driven hard for a specified link output power, thus reducing dynamic range. If the third-order intercept point of the amplifier were increased to 50 dBm, then the dynamic range would increase to 114.8 dB, as shown in Fig. 3(b), where the slope of the intermodulation power is 3 dBm/dBm until the output power level approaches the intercept point, essentially the slope of the preamplifier distortion. A post-amplifier identical to the preamplifier had little effect on the system dynamic range, lowering it by just 1 dB. The dependence of the dynamic range upon the bandwidth for the asymptotic cases of Fig. 3(a) and (c) can be found in (3). However in the transition region of Fig. 3(b), the slope of the intermodulation distortion (in decibels) is not constant and the dynamic range does not vary with bandwidth as either $B^{-2/3}$ or $B^{-4/5}$. In this case (6) must be solved for the dynamic range with the intermodulation distortion equal to the noise level in a bandwidth $B$ (of course, the dynamic range could be estimated from Fig. 3(b) for different bandwidths by sliding the noise level up by $B$ in decibels).
An exact expression that relates the dynamic range of a microwave fiber-optic system including a linearized modulator to the network variables of gain, third- and fifth-order intercept points, and noise figure was derived from power wave analysis. In a fiber-optic link, the system dynamic range can be limited by any one of the cascaded stages, or even a combination of all of the stages. Usually, for fiber-optic links containing conventional Mach–Zehnder modulators, the optical link itself is the limiting factor in the dynamic range of the system, however, for a link with a linearized modulator, it is obvious that the amplifiers should play a bigger role in the dynamic range of the system. This was shown in the simple two-stage example presented above where, for that particular example, the relative importance of each stage in determining the overall dynamic range was seen to depend upon the third-order intercept point of the preamplifier. Equation (6) can be used to perform trade-off studies of various network components to determine the optimum design for a high fidelity fiber-optic system.

Furthermore, the analysis presented here is important, not only for the design of high fidelity fiber-optic systems, but also in the experimental determination of the dynamic range of such systems. This is because in conventional networks the third-order intercept point can be found from a linear extrapolation of the measured output power and two-tone modulation power in decibels; and from (3), the dynamic range can be computed. However, in the high fidelity link, the total intermodulation power may be nonlinear (in decibels) with the input power. Therefore, the dynamic range of the system must be found with the aid of the expressions derived above and the parameters of the individual components. Thus, linearized modulators begin to impact the fiber-optic industry, the systems into which these modulators are placed can be designed confidently.

**IV. DISCUSSION**

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**REFERENCES**


James H. Schaffner was born in Chicago, IL, on April 27, 1955. He received the B.S., M.S., and Ph.D. degrees from the University of California, Los Angeles, in 1978, 1979, and 1988, respectively. His doctoral research centered on the high frequency characterization of field effect transistors. From 1978 to 1988 he was a staff member at Hughes Aircraft Company Missile System Group where he worked on antenna arrays and antenna feed systems for microwave and millimeter wave systems. In addition he was involved with the development of microwave and millimeter wave integrated circuits. Since 1988 he has been with the Hughes Research Laboratories. He is now involved with the development of high frequency and high linearity electrooptic components for analog fiber-optic links.

William B. Bridges (S’53–M’61–F’70) was born in Inglewood, CA, in 1934. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from the University of California, Berkeley, in 1956, 1957, and 1962, respectively, and was an Associate in Electrical Engineering from 1957 to 1959, teaching courses in communication and circuits. His graduate research dealt with noise in microwave tubes and electron-stream instabilities (which later became the basis of the Victorator). Summer jobs at RCA and Varian provided stimulating experience with microwave radar systems, ammonia beam masers, and the early development of the ion vacuum pump.

He joined the Hughes Research Laboratories in 1960 as a member of the Technical Staff and was a Senior Scientist from 1968 to 1977, with a brief tour as Manager of the Laser Department in 1969–70. His research at Hughes involved gas lasers of all types and their application to optical communication, radar, and imaging systems. He is the discoverer of laser oscillation in noble gas ions and spent several years on the engineering development of practical high-power visible and ultraviolet ion lasers for military applications. He joined the faculty of the California Institute of Technology in 1973 as Professor of Electrical Engineering and Applied Physics. He served as Executive Officer for Electrical Engineering from 1979 to 1981. In 1983, he was appointed Carl F. Braun Professor of Engineering and conducts research in optical and millimeter wave devices and their applications. Current studies include the millimeter-wave modulation of light and innovation in waveguide gas lasers.

Dr. Bridges is a member ofEta Kappa Nu, Tau Beta Pi, Phi Beta Kappa, and Sigma Xi, receiving Honorable Mention from Eta Kappa Nu as an "Outstanding Young Electrical Engineer" in 1956. He received the Distinguished Teaching Award in 1980 and 1982 from the Associated Students of Caltech, the Arthur L. Schawlow Medal from the Laser Institute of America in 1986, and the IEEE LEOS Quantum Electronics Award in 1985. He is a member of the National Academy of Engineering and the National Academy of Sciences, and a Fellow of the Optical Society of America and the Laser Institute of America. He was a Sherman Fairchild Distinguished Scholar at Caltech in 1974–1975, and a Visiting Professor at Chalmers Technical University, Göteborg, Sweden in 1989. He is coauthor (with C. K. Birdsell) of Electronic Dynamics of Diode Regions (New York: Academic Press, 1966.) He has served on various committees of both IEEE and OSA, and was formerly Associate Editor of the IEEE Journal of Quantum Electronics and the Journal of the Optical Society of America. He is the President of the Optical Society of America in 1988, and was a member of the U.S. Air Force Scientific Advisory Board 1985–1989.