Limitation Due to Signal-Clipping in Linearized Microwave-Photonic Links

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***Abstract*—Microwave-photonic links with ideally linear transfer functions (Class A or B) are limited by distortion due to signal clipping. This limitation is investigated theoretically and through numerical simulation, with results for up to 50 input carriers confirming analytic results based on a Gaussian input distribution. An ultimate clipping-free dynamic range of 183.5 dB · Hz is predicted for an ideal Class-B link, up to 70 dB greater than achieved with conventional links.**

***Index Terms*—Class-B links, fiber Bragg grating (FBG), frequency discriminator, microwave-photonic links (MPLs), phase modulation, signal clipping, spurious-free dynamic range (SFDR).**

I. Introduction

MICROWAVE-PHOTONIC links (MPLs) have been used in a wide range of commercial systems, including video distribution, antenna-remoting, and radio-over-fiber (RoF) systems [1]. The performance of an MPL, quantified by the spurious-free dynamic range (SFDR), is bounded by intermodulation distortion (IMD) at high signal power and noise at low signal power, including intensity noise (IN), receiver noise (RN), and shot noise (SN). Due to generation of in-band distortion products, the third-order IMD (IM3) is the most detrimental distortion in most applications. For most conventional links, SFDR is limited by IMD from the far-from-ideal transfer function of the Mach–Zehnder (MZ) or electroabsorption intensity modulator, and by the high IN associated with optical carrier power that is the direct result of biasing the modulator at a linear operating point.

To improve the SFDR, extensive effort has been applied to linearize the transfer function or mitigate carrier-induced IN [2], summarized in [3]. However, these carrier-suppression and linearization techniques achieve moderate performance improvement with expense of complexity. Thus, the external intensity modulator that can be operated with high linearity at low residual optical carrier power has not been realized. Theoretically, a directly modulated laser diode has fairly good linearity at low output power, but its practical performance is limited by nonlinear carrier dynamics.

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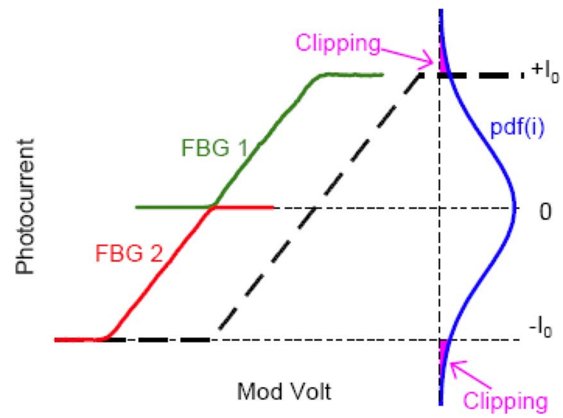

Fig. 1. Illustration of ideal Class B transfer function (dashed line) and signal clipping. Measured transfer functions of two zero-biased complementary linearized-Class-A modulators are also show as FBG 1 and FBG 2, whose superposition creates a Class-B transfer function [5].

We previously reported an alternative approach for high-SFDR MPLs employing optical frequency modulation followed by novel fiber-Bragg-grating (FBG) discriminators with nearly linear transfer functions (transmission versus optical frequency). These allow low- or even near-zero-bias operation, reducing the optical carrier without increasing nonlinear distortions, with bias and modulation index control [4], [5]. In [5], a Class-B link is realized using a phase modulator, a pair of zero-biased complementary FBGs (shown in Fig. 1), and a balanced photodetector. Although using frequency discriminators to recover phase-modulated signals induces, for narrowband applications such as RoF systems, a linear frequency dependence in response, this response is less problematic than distortion. In a practical narrowband system, the RF signals can be integrated before input of the phase modulator or after detection to compensate the differentiation by the frequency discriminator. Results in [5] show a high SFDR of 110.4 dB $\cdot$ Hz$^{2/3}$ with less than 880 μA of total received photocurrent, even with high system relative intensity noise (-146.5 dB/Hz). The value of carrier suppression is clear, in that the maximum SFDR that could be achieved with this RIN using a quadrature (Q)-biased MZ, at any received photocurrent, would be approximately 100 dB/Hz$^{2/3}$.

Also, the advantage of Class-B in improving link dynamic range has been explored theoretically relative to conventional links. The calculation of a theoretically ideal Class-B link with 10% modulation shows that reductions in SN and IN of 11 and 20 dB, respectively, can be achieved, relative to a link using a Q-biased MZ [6]. It has also been predicted that a perfectly linear Class-B optical link, limited only by signal-clipping and driven by an input RF signal voltage with Gaussian probability distribution function (G-pdf), can provide a clipping-free dynamic range (CFDR) that is more than 70 dB larger than that of conventional links with Q-biased MZ modulators [3].

In this letter, we extend the study of clipping-limited links from the theoretically convenient G-pdf input to more practical multicarrier input signals. A numerical model (VPITransmissionMaker) of an ideal Class-B link is presented that can accept arbitrary input signals. Clipping-induced distortion is calculated for multiple examples of input conditions and compared with the theoretical (G-pdf) results for Class B and a conventional Q-biased Mach–Zehnder modulator (MZM). Numerical results confirm the utility of the G-pdf-based theory, and the potential of Class-B techniques to dramatically improve link performance.

II. Theory of Signal Clipping

As shown in Fig. 1, the transfer function (dashed line) of an ideal system has the output photocurrent being linearly proportional to modulation voltage within a response range and flat otherwise. The output photocurrent range is $-I_0$ to I_0 for Class-B (shown in Fig. 1) and 0 to $2I_0$ for a perfect Class-A modulator. A Class-B modulator is realized by two zero-biased complementary linear modulators such that each half-wave rectifies the input signal. A balanced detector differences two photocurrents to regenerate the RF signal i_o with zero mean

$$i_o = I_0(\text{if } i \geq I_0);\; i_o = i\,(\text{if} |i| < I_0);\;\; i_o = -I_0(\text{if } i \leq -I_0) \tag{1}$$

where I_0 is the maximum transmitted photocurrent and i is nondistorted signal photocurrent (without clipping) that is linearly proportional to modulation voltage from $-\infty$V to $+\infty$V.

For Class-B, if the instantaneous value of the nondistorted signal photocurrent is within the allowed output range $\pm I_0$, there is no distortion. With an increase of modulation, however, the output photocurrent is clipped at $\pm I_0$, denoted in Fig. 1 by the filled area as $|i| > I_0$, which induces distortion. In contrast, the characteristic nonlinearity of the transfer function of an MZM-based MPL always causes distortion in the output even with small modulation and the MZM is biased at quadrature. For Class A operation, the discussion is identical, but with a dc current offset of I_0, corresponding to the bias offset.

Although link linearity is generally characterized by two-tone tests, actual input signal voltages depend on the specific application. The G-pdf approximation is appropriate for an input signal that is the sum of a large number of independent processes, such as multichannel CATV systems [7]. Thus, after application to ideal Class-B link (Fig. 1), the nondistorted signal photocurrent is also a stationary Gaussian random process, as illustrated in Fig. 1, whose pdf is given by

$$\text{pdf}(i) = (\sqrt{2\pi}\mu I_0)^{-1} \exp\left[-i^2/\left(2\mu^2 I_0^2\right)\right] \tag{2}$$

where μ is root-mean-square modulation depth. For Class A, i in exponential becomes $i - I_0$.

It has been shown that in the output of an ideal Class-B system with a G-pdf signal, clipping distortion can be treated as noise, called clipping noise (CN) [3]. Its mean-square current density and power of signal photocurrent (A^2) are, respectively,

$$\overline{i_{cn}^2} = \left(\Gamma I_0^2/B_s\right) \cdot \left\{\left[1 + \mu^2 \text{erf}\left(1/(\sqrt{2}\mu)\right)\right] \text{erfc}\left[1/(\sqrt{2}\mu)\right] - \sqrt{2/\pi}\mu \exp\left[-1/(2\mu^2)\right]\right\} \tag{3}$$

and

$$\overline{i_s^2} = I_0^2 \mu^2 \text{erf}^2\left[1/(\sqrt{2}\mu)\right] \tag{4}$$

where B_s is the bandwidth of signal band, $\text{erf}(t)$ is the error function; and $\text{erfc}(t)$ is the complementary error function. Γ is the distortion overlay factor given in [3].

Since signal and clipping are the same for Class A and B, (3) and (4) apply also for Class A. However, IN and SN are fixed in Class A due to the bias-dependent photocurrent, while in Class B, where the output photocurrent is entirely from the signal, the powers of IN and SN are functions of μ.

III. Numerical Simulation and Discussion

To determine the impact of clipping for realistic modulation conditions, a numerical model of an idea Class-B system was constructed using VPItransmissionMaker. Two zero-biased complementary linear intensity modulators and a balanced detector are used to generate the ideal Class-B transfer function. Systems with 5, 10, 20, and 50 electrical input tones with random phase within 9–11 GHz are compared. Clipping is performed on the amplitude envelope of the optical electric field at a level corresponding to $\pm$50-mA maximum photocurrent I_0. A simple distributed feedback laser model is used, operating at 193.1 THz with 1-MHz linewidth and RIN of -155 dB/Hz. No fiber is included in the simulation and noiseless photodiodes are used for detection. The power spectral density of the detected electrical signal is summed from 9 to 11 GHz, while omitting signal frequencies, to measure total in-band noise power. Note that this system allows for canceling common-mode IN by balanced photodetection.

Fig. 2 shows the simulation results for CN compared with the theoretical calculation that assumes G-pdf. The simulation shows that for a given number of input signals, the noise level rises sharply from zero and then levels off. Increasing the number of input signals decreases the modulation depth at which this sudden increase occurs, as expected, since for more signal tones, lower modulation depth is required to prevent the maximum of the total signal voltage from extending beyond the linear response range.

Comparing theoretical prediction with simulation, the signal powers for all numbers of tones are in excellent agreement. The CN for N-channel approaches to theoretical prediction for a G-pdf signal as the N is increased. This is expected since for more tones, the signal more closely approximates a Gaussian distribution. For low levels of CN, the onset of CN is more abrupt for the N-channels than for the G-pdf. CN at these low levels is dominated by infrequent clipping events, and these are overestimated with the G-pdf approximation.

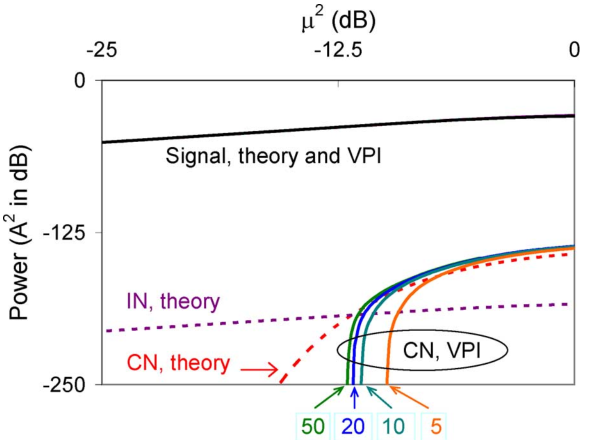

Fig. 2. Comparison of theoretically calculated and numerical simulated CN (1-Hz bandwidth) and total signal powers. The simulation is performed in VPI-transmissionMaker with 5, 10, 20, 50 input RF tones. Theoretically calculated IN is also shown.

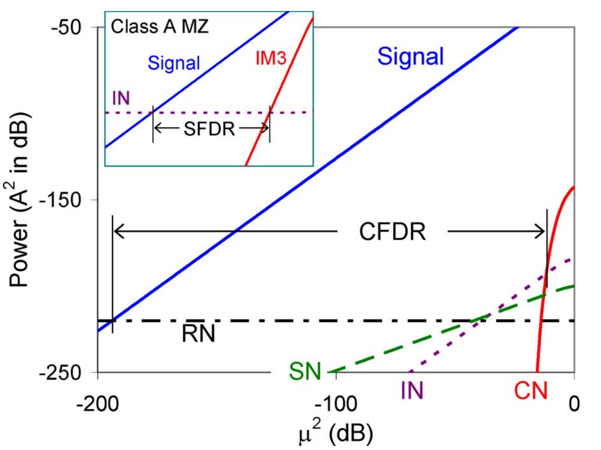

Fig. 3. CFDR of Class-B showing output RF powers of signal, RN, SN, IN, and CN versus square of effective modulation depth (μ^2). The 1-Hz bandwidth for noise powers. For comparison, inset shows SFDR (IM3-free) of conventional Class-A MZ with a signal of 50 channels. The axis ranges in inset is the as same as those of Class-B plot.

We are interested in finding the upper boundary of system CFDR which is the intercrossing between IN and CN. The curve of CN crosses IN (with RIN of -155 dB/Hz) at about $\mu^2 = -11.5$ dB for 50 channels, about same as that for theoretical calculation. For five channels, the G-pdf underestimates the CFDR by 2.2 dB. Also note that the change of IN has less effect on the upper limit of system dynamic range in N-channel numerical model due to sharp rise of CN with μ than for the G-pdf. However, the divergence for lower input levels is below the IN. Therefore, although the G-pdf overestimates the lower level CN, it provides a reasonable approximation to the CFDR (for $N > 10$).

Fig. 3 shows the graphical illustration of the dynamic range for Class-B, CFDR calculated by G-pdf model, in terms of each noise component and total signal power. The parameters used are the same as those in Fig. 2, with $I_0 = 50$ mA. The performance of ideal Class-B links is bounded by RN (10 pA/Hz$^{1/2}$) at low modulation and CN at high modulation. The CFDR, calculated using the total signal power of all 50 channels, is 183.5 dB $\cdot$ Hz.

For comparison, the SFDR (IM3 free) of conventional Class-A MZ with the same available optical power and 50 RF input channels is plotted as inset. Although, in multichannel MZ-based systems, IM3 varies in different channels, the ratio of IM3 power to signal power per channel is no less than $\mu^4/16$ [8], the value used in calculation for inset. The SFDR for the conventional Class-A MZ, limited by IN at low signal power and IM3 at high signal power, is 113 dB $\cdot$ Hz$^{2/3}$.

The dramatic 70 dB (1 Hz) increase of dynamic range in ideal Class B is caused by the improvement at both high and low signal levels. At low levels, carrier suppression by Class-B operation reduces IN and SN to improve the dynamic range by 35 dB. At high levels, achieving perfect linearity (clipping limit) extends the dynamic range by 35 dB, relative to the MZ. Note that a perfectly linear intensity modulator would achieve this improvement. Class-B techniques offer large noise reductions for small modulation while linear modulation methods offer similar gains at large modulation.

IV. Conclusion

Linearization of modulator transfer functions significantly improves the performance of MPLs, but the improvement is fundamentally limited by signal-clipping. We have studied signal clipping theoretically and through numerical simulation, for both conventional Class-A and recently proposed Class-B links. It is shown that the model based on a Gaussian distribution of RF input provides a reasonable prediction of CN. It is shown that in an ideally linearized Class-B system, by combining transfer function linearization with carrier suppression, dramatic increases (70 dB) in dynamic range are possible. The possibility of such dramatic improvements in performance serves as strong motivation for continued advancement of MPLs.

References

[1] C. H. Cox, III, *Analog Optical Links: Theory and Practice*. Cambridge, U.K.: Cambridge Univ. Press, 2004.
[2] R. D. Esman and K. J. Williams, "Wideband efficiency improvement of fiber optic systems by carrier subtraction," *IEEE Photon. Technol. Lett.*, vol. 7, no. 2, pp. 218–220, Feb. 1995.
[3] J. Zhang and T. E. Darcie, "Clipping free dynamic range: The fundamental limit for class-B microwave-photonic links," in *Proc. Tech. Dig. Int. Topical Meeting on Microwave Photonics 2006*, Grenoble, France, Oct. 3–6, 2006, Paper P39.
[4] J. Zhang and T. E. Darcie, "Low-biased microwave-photonic link using optical frequency or phase modulation and fiber-Bragg-grating discriminator," in *Proc. OFC/NFOEC 2006*, Anaheim, CA, Mar. 6–10, 2006, Paper OWG1.
[5] T. E. Darcie, J. Zhang, P. F. Driessen, and J. J. Eun, "Class-B microwave-photonic link using optical frequency modulation and linear frequency discriminators," *J. Lightw. Technol.*, vol. 25, no. 1, pp. 157–164, Jan. 2007.
[6] T. E. Darcie and P. F. Driessen, "Class-AB techniques for high-dynamic-range microwave-photonic links," *IEEE Photon. Technol. Lett.*, vol. 18, no. 8, pp. 929–931, Apr. 15, 2006.
[7] A. A. M. Saleh, "Fundamental limit on number of channels in subcarrier-multiplexed lightwave CATV system," *Electron. Lett.*, vol. 25, no. 12, pp. 776–777, Jun. 1989.
[8] M. T. Abuelma'atti, "Carrier-to intermodulation performance of multiple FM/FDM carrier through a GaAlAs heterojunction laser diode," *IEEE Trans. Commun.*, vol. COM-33, no. 3, pp. 246–248, Mar. 1985.