Class-AB Techniques for High-Dynamic-Range Microwave-Photonic Links

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***Abstract*—Class-AB techniques are analyzed as a means to minimize the noise associated with the residual carrier in analog optical links. A bound for shot and intensity noise is derived and compared to previously reported measurements. It is found that for an ideal modulator transfer function (Class B), a substantial improvement in shot-noise limited spur-free dynamic range (e.g., 11.7 dB at 10% modulation) can be realized.**

***Index Terms*—Analog link, balanced detector, Class AB (CAB), Class B, intensity-noise suppression, microwave-photonic link (MPL), optical link, radio-over-fiber, spur-free dynamic range.**

I. Introduction

MICROWAVE-PHOTONIC links (MPLs) have become essential components in a wide variety of microwave and RF transmission applications, including cable television networks, remote antennas, and radar links. Although simple direct- or externally modulated links provide long reach, high signal-to-noise ratio (SNR), and high linearity, considerable effort continues to improve link performance. A key measure of link performance is the spurious-free dynamic range (SFDR) [1], which describes the difference between the minimum signal that can be detected above noise and the maximum signal that can be transmitted without interference from distortion.

Several noise sources limit the SFDR. For high-performance links, where optical power levels at the receiver are high (e.g., 100 mW), shot noise and relative-intensity noise (RIN) usually dominate [2]. Total shot-noise and RIN powers exhibit linear and quadratic dependence on average received optical power, respectively. Hence, a priority has been attempting to reduce the total average received optical power associated with biasing the transmitter to a linear operating point. Techniques that have been reported include carrier filtering, dynamic bias modulation, coherent techniques, and low-bias operation. Each of these adds complexity and/or distortion, for limited reduction in noise.

Recently, we reported [3] the use of Class-AB (CAB) techniques as a new means of minimizing the residual carrier, demonstrating a 5.7-dB reduction in shot noise and reduction of RIN to below measurable levels, relative to a conventional quadrature-biased link (Q-biased or Class-A operation). As in electronic amplifiers, CAB refers to Class-B operation, but with the addition of a small prebias to avoid nonlinear distortion introduced during turn-on of the transistors (or modulators in our case). In this letter, we explore the ultimate limits to the performance of CAB optical links relative to previously reported measurements. We show that if an ideal transfer function can be realized (Class B), then shot noise can be reduced by up to 11.7 dB (modulation index of 10%), and the noise associated with RIN can be essentially eliminated.

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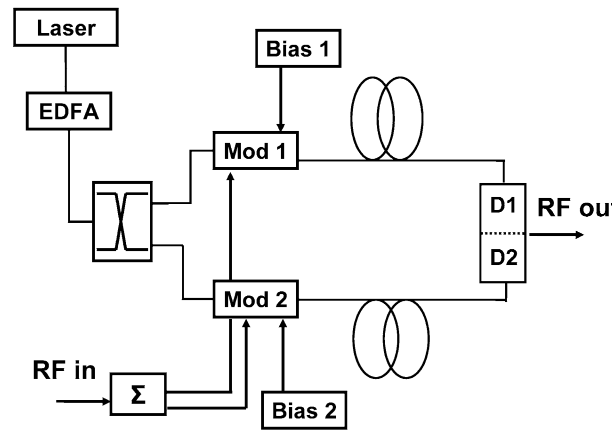

Fig. 1. System configuration for CAB optical link using two complementary modulators (Mod 1 and Mod 2). The output signal is recovered at the output of a balanced photodetector (D1, D2).

II. Analysis and Discussion

CAB transmission has been demonstrated [3] using two identical intensity modulators (Mod 1 and Mod 2) in the configuration shown in Fig. 1. Modulators are biased at complementary low-bias points, typically at offset voltages $\Delta V \sim V_\pi/6$ on opposite sides of extinction. Fig. 2 shows how the balanced detector subtracts current generated in Detector 1 (D1 in Fig. 1) from that generated in D2 creating an effective transfer function that is sinusoidal, but with zero average power (Mod CAB).

While interferometric [Mach–Zehnder (MZ)] modulators with sinusoidal transfer functions are used widely, this transfer function is far from ideal for CAB applications. As described in [3], ΔV must be sufficiently large to maintain a strong signal, but small enough to minimize dc-power at the bias point at which the input signal is approximately half-wave rectified (for large signals). Ideal transfer functions for the electrical-to-optical converters comprising the complementary source pair are shown also in Fig. 2. Each source provides a linear output with a sharp threshold, such that the output of the balanced detector is linear with average current equal to zero. We will refer to a device with this ideal transfer function as an ideal linear threshold device (ILTD). Candidates for ILTDs include directly modulated or injection-locked laser diodes, and modified MZ

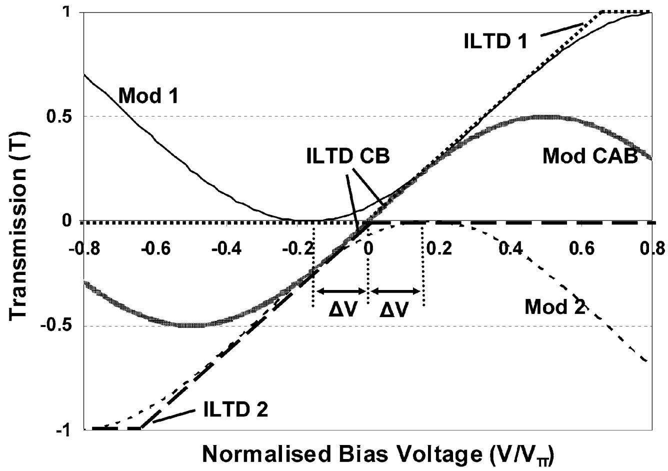

Fig. 2. Effective link transfer function for CAB link using two complementary modulators (Mod 1 and Mod 2) with sinusoidal transfer functions and ideal Class-B link using ideal linear threshold devices (ILTD 1 and ILTD 2). The signal recovered at the output of a balanced photodetector (D1, D2) provides a zero-mean sinusoidal (Mod CAB) for CAB or linear (ILTD CB) for Class B.

or electroabsorption modulators. One goal of this letter is to inspire development of suitable ILTDs, since, as will be shown, the performance gains that can be achieved in CAB or Class-B systems are substantial.

To compare the ultimate performance of the CAB approach with conventional optical links, we consider the ILTD transfer function and derive signal and noise contributions for shot noise and RIN, under single and multichannel modulation conditions. For a single-channel conventional link operating with average detected photocurrent I_o, peak modulation current i_p, and modulation index $m = i_p/I_o$, the SNR is

$$\mathrm{SNR} = \frac{1}{2} i_p^2 \frac{1}{(n_r + n_s + n_{\mathrm{RIN}^*})B} \tag{1}$$

where n_r is the mean-square noise current (per hertz of bandwidth) generated by the receiver, n_s is from shot noise ($n_s = 2qI_o$, where q is the electronic charge), and n_{RIN^*} is from the total effective RIN* [3], which includes laser RIN and signal-spontaneous beat noise from an optical amplifier.

For Q-biased N-channel modulation (random channel frequencies and phases), where Ω_i is the subcarrier frequency of the ith channel

$$i_s(t) = i_p \sum_{i=1}^{N} \cos(\Omega_i t). \tag{2}$$

Composite signals of this form can be described by a zero-mean Gaussian process with variance σ_i^2, and can be normalized to I_o, such that $\mu^2 = \sigma_i^2/I_o^2 = m^2 N/2$, where μ is the well-known normalized modulation index. We can also use μ to describe other arbitrary modulation signals (e.g., unequal channel amplitudes, band-limited noise, etc.).

For single-channel ideal Class-B modulation, we consider modulation with the same peak photocurrent i_p. In this case, opposite halves of the detected modulation are generated in each detector, but with identical i_p. Since the effective I_o approaches zero for Class B, μ becomes less meaningful. However, it is useful to define μ for Class B as the ratio of the ratio of σ_i to the maximum transmission of the one ILTD $I_{\max}$ (normalized to ± 1 on Fig. 2). We assume that the available source power was split equally to serve both Class-B ILTDs. In this case, to compare to a single Q-biased MZ modulator with the same available optical power, $I_o = I_{\max}$.

Shot Noise: For Class B with single-channel modulation, the total shot-noise power generated in each detector arises only from the detected signal, which is present in each detector over only half of the RF cycle. In strong contrast to conventional operation, shot noise is thereby generated only by the detection of optical power that corresponds to signal power. Hence, n_s is determined by averaging $n_s = 2qi_p \cos(\Omega t)$ over a half cycle, leading to

$$n_s = 2qi_p \cdot 2/\pi. \tag{3}$$

Since the signal power i_p is the same as in the conventional case, comparing (1) and (3) shows that shot noise for Class B is less that that of a conventional link by $2m/\pi$. For $m = 10\%$, this is a compelling reduction of 11.7 dB.

For multiple input channels, shot noise also arises from the signal current generated by all other channels. This current can be described by the half-wave rectified Gaussian distribution described by σ_i, which has an expected value

$$E(i_s) = \frac{1}{\sqrt{2\pi}\sigma_i} \int_0^{\infty} i_s e^{-\frac{i_s^2}{2\sigma_i^2}} \, di_s = \frac{\sigma_i}{\sqrt{2\pi}}. \tag{4}$$

This translates into average shot noise, in two detectors

$$n_s = 2 \cdot 2q \frac{\sigma_i}{\sqrt{2\pi}} = 2qi_p \sqrt{\frac{N}{\pi}} = 4qI_{\max} \frac{\mu}{\sqrt{2\pi}}. \tag{5}$$

For $N = 1$, the $2/\sqrt{\pi} (= 1.128)$ factor in (5) is close to the $4/\pi (= 1.273)$ in (3).

It can then be seen that the ratio of shot noise for Class B relative to a conventional link (Class A) with the same detected signal power is

$$\frac{n_s^B}{n_s^A} = \frac{2qi_p\sqrt{N/\pi}}{2qI_o} = \sqrt{\frac{2}{\pi}}\mu = m\sqrt{\frac{N}{\pi}}. \tag{6}$$

This simple result describes a substantial reduction in shot noise, particularly for small modulation depths typically encountered where linearity or SFDR must be high.

Fig. 3 compares the shot noise values for Class B predicted by (5), with those for CAB and Q-biased links, as a function of μ. Since each of the two $I_{\max}$ cases presented (1.7 and 100 mA) result in equal signal powers for the three links, any reduction of noise translates directly into improved SFDR. For Class B, since shot noise results only from signal power, shot noise power increases linearly with increasing μ. For CAB and Q-biased (MZ) links, shot noise is independent of signal power. (These lines are drawn only up to moderate μ, where small signal approximations are valid.) By increasing μ, noise for Q-biased and CAB approaches that of Class B. Comparing CAB with Q-biased operation, for the same μ and maximum received dc photocurrent ($I_o = 1.7$ mA), shows the 5.7-dB improvement (independent of modulation depth) described previously [3] that results from the reduction of total received dc current. Measured shot-noise

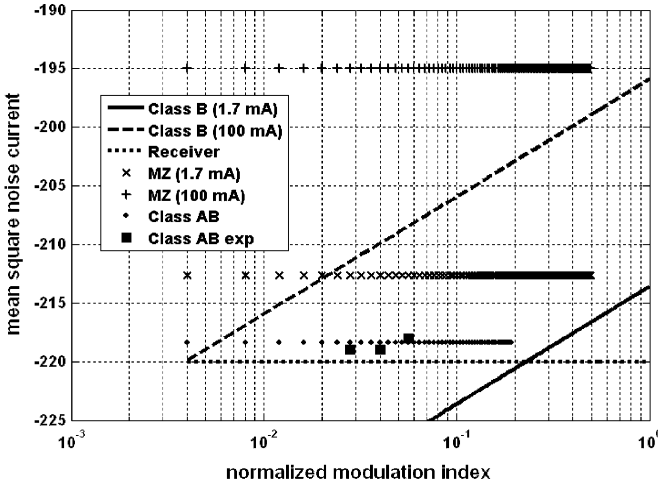

Fig. 3. Shot noise power per ohm (1-Hz bandwidth) in decibels predicted for Class B compared to quadrature-biased MZ for $I_{\max}$ of 100, and 1.7 mA. Also shown is the predicted shot noise for MZ-based CAB that results in the same signal power, and corresponding measurements ([3]). Receiver noise shown corresponds to 10 $\mathrm{pA}/\sqrt{\mathrm{Hz}}$.

power for CAB is in excellent agreement with predictions. Note that for small μ, the improvement for Class B over either CAB or Q-biased operation can be large ($>$10 dB).

Intensity Noise: For a single channel Class-B link, n_{RIN^*} is generated by only the detection of signal power. Therefore, n_{RIN^*} is determined by averaging the sinusoidal signal current over the half cycle (for each detector), resulting in

$$n_{\mathrm{RIN}^*} = \frac{1}{2} i_p^2 \mathrm{RIN}^*. \tag{7}$$

For multiple channels, the average intensity noise in one detector can be determined from the expected value of the square of i_s, or by replacing the i_s term in (4) by i_s^2. This result is then doubled to account for the two detectors, resulting in

$$n_{\mathrm{RIN}^*} = (\mu I_{\max})^2 \mathrm{RIN}^*. \tag{8}$$

For $N = 1$, this equals the single-channel result. Comparing n_{RIN^*} for Class B to a Q-biased link with the same RIN* shows that intensity noise is reduced by μ^2. For $\mu = 0.1$, total intensity noise is reduced by 20 dB.

III. Summary

CAB techniques applied to analog optical links offer an opportunity to realize substantial ($\sim$10 dB) improvements in dynamic range. While CAB operation using the sinusoidal transfer function of popular modulators has been shown to result in a shot-noise reduction of 5.7 dB, we have shown that much larger improvements can be achieved. In the limit of the perfect linear transfer function (Class B), shot noise and intensity noise can be reduced by over 11 and 20 dB, respectively, relative to a conventional link operating with a 10% modulation depth. Class-B operation represents the theoretical limit for link performance, in that all of the detected optical power contributes directly to signal power. This minimizes the optical power required to achieve a particular SNR, reducing substantially the limitations imposed by intensity noise, fiber nonlinearity and detector saturation.

Several practical concerns, such as dependence of noise and distortion on imbalance in optical and RF powers, and the issue of crossover distortion, encountered in electronic Class-B amplifiers, will be the subject of further study. However, it appears that these techniques, along with continued innovation toward more suitable modulator transfer functions, offer an attractive path forward for high-performance MPLs.

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