Analysis of gain, noise figure and dynamic range of an analog photonic link employing a low-biased Mach-Zehnder modulator

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In this paper, an analysis of the important figures of merit (FOM) of an analog photonic link (APL) employing a low-biased Mach-Zehnder modulator (MZM) is presented. These FOM are the link gain, noise figure and the spurious-free dynamic range. The importance of increasing the optical power in the link and the advantage of low biasing the MZM are discussed. Two low-biased APL architectures, one powered with a high power laser diode and the other using an erbium doped fiber amplifier (EDFA) are compared in performance.

Introduction

In APLs radio frequency or microwave signals are transported via optical fibers to a remote location. The low-loss characteristic of the fiber permits a transport of higher frequency signals over a longer distance relative to the case where coaxial cables are used. An externally-modulated APL typically employs a continuous wave (CW) laser source in conjunction with an MZM as the modulation device and a p-i-n photodetector (PD) to restore the RF signal. The analog nature of the RF signals imposes stringent requirements to the APL, notably in terms of signal loss, noise and linearity. Two limiting factors of the APL are the low RF-to-RF transfer efficiency in the link that leads to a low link gain and the high relative intensity noise (RIN) of the laser that leads to a high link noise figure (NF). It has been widely reported that the link gain can be improved by means of increasing the received optical power at the photodetector [1]. In most cases, increasing this optical power is readily available in two options: using a higher power laser source or using an optical amplifier. As for reducing the impact of RIN and subsequently lowering the NF, low biasing the MZM (i.e. off-quadrature biasing) is considered very attractive [2].

In this paper, we analyze the performance of two different low-biased APL architectures with increased optical power, where one is employing a high power laser diode and the other employs an EDFA. Their architectures are depicted in Fig. 1 (a) and 1 (b), respectively.

High Power Laser APL

The schematic of the high power laser APL is shown in Fig. 1 (a). The laser used in this APL is a high power 1560 nm DFB laser (EM4 AA1401). The laser is operated at an

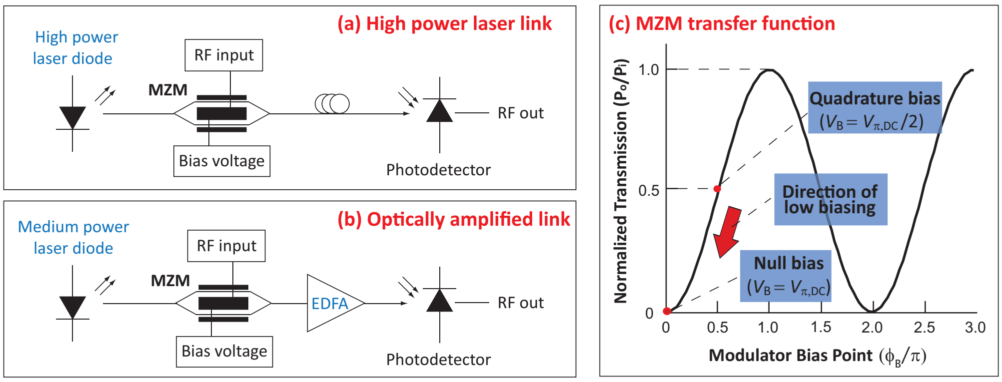


Figure 1: (a) High power laser link, (b) optically amplified link, (c) MZM transfer function.

injection current of 500 mA, yielding an output optical power of 112 mW (20.5 dBm). At this output power, the laser RIN level is measured to be -171 dB/Hz. The laser is then used to illuminate an MZM (Avanex F10) with an insertion loss (L) of 5 dB, a DC half-wave voltage ($V_{\pi,\mathrm{DC}}$) of 5.3 V and an RF half-wave voltage ($V_{\pi,\mathrm{RF}}$) of 3.8 V. Finally, a p-i-n PD (Emcore R2560A) with a responsivity (r_{PD}) of 0.75 A/W is used to restore the RF signal. The PD is impedance matched to a $50\,\Omega$ load resistance (R_{L}). For such a configuration, the link gain of the APL can be expressed as

$$g_{\mathrm{link}} = \left(\frac{\pi R_{\mathrm{L}}\, r_{\mathrm{PD}}\, P_{\mathrm{i}} \sin\phi_{\mathrm{B}}}{4 L\, V_{\pi,\mathrm{RF}}}\right)^2, \tag{1}$$

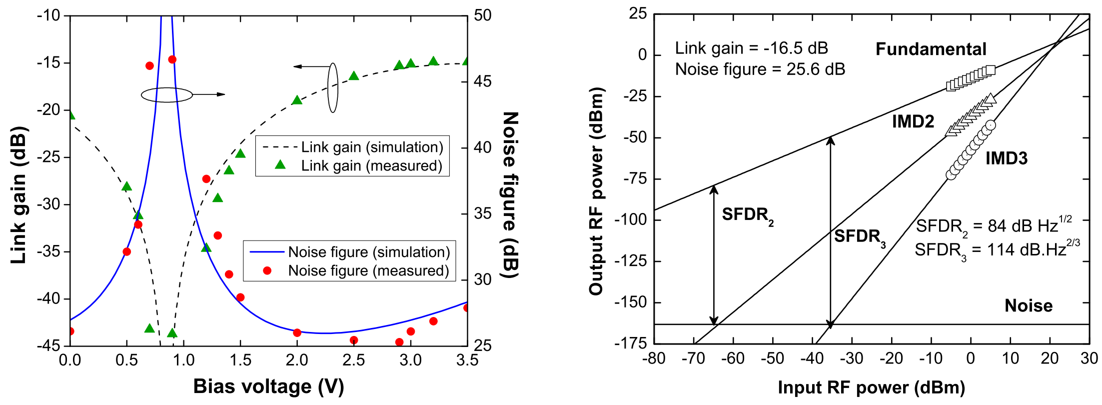
where $\phi_{\mathrm{B}} = \pi V_{\mathrm{B}}/V_{\pi,\mathrm{DC}}$ is the MZM bias angle and V_{B} is the MZM DC bias voltage. From Eq. (1), it is clear that to maximize the link gain, the input optical power to the modulator, P_{i}, should be maximized and the APL should be biased at quadrature, where $\phi_{\mathrm{B}} = \pi/2$ (see Fig. 1 (c)).
The total noise power spectral density (PSD), in W/Hz, can be written as

$$p_{\mathrm{N}} = (1 + g_{\mathrm{link}})\, kT + \frac{1}{4}\left(2q I_{\mathrm{D}} + \mathrm{RIN}\, I_{\mathrm{D}}^2\right) R_{\mathrm{L}} \tag{2}$$

where k is the Boltzmann constant, $T = 298$ K is the room temperature, q is the electron charge and $I_{\mathrm{D}} = r_{\mathrm{PD}} P_{\mathrm{i}} (1 - \cos\phi_{\mathrm{B}}) / (2L)$ is the average detected photocurrent. The first term in Eq. (2) is the thermal noise contribution while the second and the third terms are the shot noise and the RIN contributions, respectively. Finally, the NF of the link can be written as

$$\mathrm{NF} = 10 \log_{10}\left(\frac{p_{\mathrm{N}}}{g_{\mathrm{link}}\, kT}\right). \tag{3}$$

We measure the link gain and the NF of the high power laser APL. A single-tone RF signal with a frequency of 2 GHz and a power of 0 dBm was supplied from the signal generator to the MZM. The MZM bias voltage was varied from 0 to 3.5 V. For each V_{B}, the fundamental signal power at the PD output was measured. The average photocurrent was also measured for every V_{B}. For the noise measurements, the RF signal was removed and an RF amplifier with a gain of 36.5 dB was used to reduce the displayed analyzer noise level of the RF spectrum analyzer. The link gain was then calculated as the ratio of



(a) (b)

Figure 2: Measured figure of merits of the high power laser APL. (a) Link gain and NF (b) SFDR at $V_B = 2.0$ V.

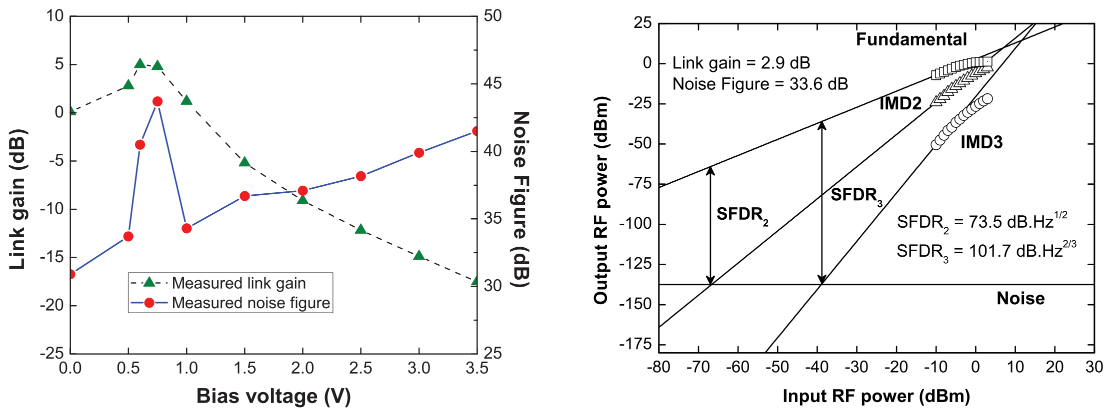
the measured output to the input power RF power. The NF was calculated using Eq. (3) by supplying the measured values of p_N and g_{link}.

The measured link gain and NF of the high power laser APL are depicted in Fig. 2(a), together with the simulation results plotted from Eqs. (1)-(3). The simulation results agree very well with the measurements. As expected the highest link gain is obtained at quadrature bias where $V_B = 3.25$ V. At this bias point, the link gain and NF are -14.9 dB and 26.7 dB, respectively. According to Fig. 2(a), the lowest NF is obtained at $V_B =$ 2.25 V. At this bias point, g_{link} and NF are -16.5 dB and 25.6 dB. Thus, low biasing reduces the link gain but improves the NF. The improvement is limited to about 1 dB because the APL noise is shot noise limited [3].

Furthermore, we characterize the APL spurious-free dynamic range (SFDR) at $V_B =$ 2.25 V. The SFDR is defined as the SNR where the intermodulation distortion (IMD) power is equal to the noise floor [1]. In these SFDR measurements the RF power was varied from -5 dBm to 5 dBm with a step of 1 dB. The measurement results are shown in Fig. 2(b). As expected, low biasing reduces the second-order SFDR ($SFDR_2$). This is in contrast to the quadrature bias APL where the SFDR is limited by $SFDR_3$ instead. The measured $SFDR_2$ and $SFDR_3$ of the APL are 84 dB·Hz$^{1/2}$ and 114 dB·Hz$^{2/3}$, respectively.

Optically Amplified APL

We repeat the APL characterization on the architecture shown in Fig. 1 (b). We replace the high power laser in the previous measurements with a 1550 nm medium power DFB laser from Agere with an output optical power of 11 dBm. The laser RIN is measured to be -160 dB/Hz. The EDFA (from Keopsys) was placed after the MZM and before the PD. It is operated in the automatic power control mode in which the EDFA output optical power is set at a constant value regardless of the input optical power. In all measurements, the EDFA output optical power is set at 12.5 dBm which results in a photocurrent of 12.6 mA. The impact of MZM bias voltage variation to the link gain and NF is depicted in Fig. 3(a). In contrast with the high power laser APL, low biasing the EDFA APL increases the link gain. The improvements stem from the fact that the link gain scales with the optical gain of the EDFA, which depends on the input optical power to the EDFA. By low biasing then



(a) (b)

Figure 3: Measured figure of merits of the optically amplified APL. (a) Link gain and NF (b) SFDR at $V_B = 0.5$ V.

amplifying, a much higher optical gain can be achieved since the EDFA is less saturated. In the low bias link, the average optical power to the EDFA is much lower compared to the quadrature-biased link. In our measurements the optimum link gain of +5 dB has been obtained at the bias voltage of 0.6 V. The quadrature biased link with the same photocurrent has the link gain of -14.9 dB. Thus, by optimizing the MZM bias we have shown a gain improvement of nearly 20 dB. As for the NF, the lowest value is obtained at $V_B = 0.5$ V, where NF $= 33.6$ dB. This is a reduction of 5.9 dB, relative to the NF at quadrature, which amounts to 39.5 dB.

Finally, we characterize the link SFDR at $V_B = 0.5$ V. The results are shown in Fig. 3(b). Although the low bias link shows improved gain and NF relative to the quadrature biased link, these improvements are obtained at the cost of decreased linearity. This reduction primarily comes from the fact that the low bias link generates much more RF photocurrent compared to the quadrature biased link, in which the DC portion is dominant. The increase of this RF current might generate distortion due to the saturation of the photodetector. This saturation effects can be observed in the fundamental, the IMD2 and the IMD3 powers at high input RF power. The measured $SFDR_2$ and $SFDR_3$ are 73.5 dB$\cdot$Hz$^{1/2}$ and 101.7 dB$\cdot$Hz$^{2/3}$, respectively. These values are much lower compared to the ones obtained with the high power laser APL.

Conclusions

The performance of two APL architectures with an increased optical power are investigated. The high power laser APL shows a lower link gain but a better NF and SFDR values compared to the APL with an placed EDFA after the MZM. The latter architecture exhibits a positive link gain when biased away from the quadrature towards the lowest transmission point.

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