

# Optically Amplified Downconverting Link with Shot-Noise-Limited Performance

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**Abstract**—Experimental results of a 12-GHz downconverting optical link are presented that demonstrate shot-noise-limited performance at a maximum total photoreceiver current of 72 mA. A balanced photoreceiver is utilized to reject both laser intensity noise and noise added by an erbium-doped fiber amplifier. The receiver was constructed of four commercial 2-GHz photodetectors, each capable of detecting greater than 20 mA of average photocurrent with less than 1-dB compression in received RF power.

## I. INTRODUCTION

THE ABILITY to remote microwave antenna systems with optical fiber offers attractive possibilities for new semi-nonintrusive RF receiving systems. These systems must however compete with electrically mixed RF-to-IF systems which can exhibit noise figures below 10 dB in the multi-gigahertz regime. A simple fiber-optic downconverting technique has achieved low conversion loss (<20 dB) [1]. However, the configuration suffers from high noise figures (~50 dB). Here we propose and demonstrate a configuration based on the same dual in-line modulator approach [2] but that includes optical amplification for reduced loss, lower noise, and distribution capability, and includes a balanced receiver for canceling laser intensity noise [3] and added EDFA noise [4]. The system exhibits a >16 dB improvement in noise figure—with further improvements possible.

The optimized configuration (a) employed here (Fig. 1) comprises a 50-mW single-frequency diode-pumped 1550-nm erbium-doped glass laser<sup>1</sup> coupled to a Mach-Zehnder modulator (MZM) with local oscillator (LO) feed, the output of which is optically amplified with a polarization maintaining erbium-doped fiber amplifier (PM EDFA) [5]. The optical signal can then be distributed remotely to several receive antenna elements. A received RF signal is fed directly to a dual-complementary-output MZM with both outputs connected to a balanced photoreceiver. The dual in-line optical modulation effectively results in the translation of the RF input by the LO signal applied to the first MZM and results in an IF = |RF - LO| signal out of each of the photodetectors (PD's) of the balanced photoreceiver. The complementary MZM outputs provide IF (160 MHz) signals 180° out of phase, whereas the EDFA added noise are common (in phase) to both

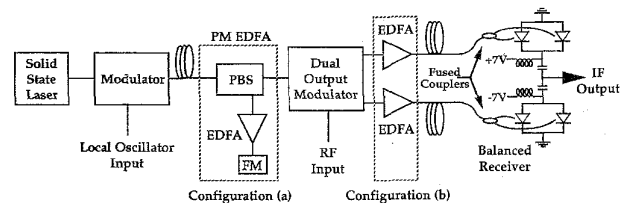


Fig. 1. Dual in-line modulator downconverting link. Configuration (a) utilizes balanced detection and a single polarization-maintaining erbium-doped amplifier (PM EDFA), while configuration (b) replaces the PM EDFA with two post-modulator EDFA's and, hence, rejects laser RIN only, with no EDFA noise rejection. Photodiode impedances are well above 50  $\Omega$ .

outputs and so cancel electrically in the balanced receiver [4]. Additional noise sources include the laser relative intensity noise (RIN), both at the IF frequency and low-frequency RIN (<1 MHz) which is up- and down-converted. However, laser RIN contributions to IF noise are negligible since: 1) solid-state lasers inherently exhibit low-RIN at the IF (for our laser the RIN is < -165 dB/Hz for frequency >10 MHz), 2) IF RIN is canceled in the balanced receiver, and 3) potentially significant RIN levels at low frequencies (<1 MHz) are easily eliminated with simple laser feedback circuits [6]. Thus, with sufficient common-mode noise rejection (amplitude and phase balance), the principal noise contributor—the EDFA added noise—is rejected by the photoreceiver, leaving only shot noise and thermal noise at the IF output. For comparison, configuration (b) in Fig. 1 will be used to show the degradation imposed if the EDFA noise is not balanced out.

To achieve low noise figure, low insertion loss is necessary. Insertion loss is controlled by two mechanisms, modulator  $V_{\pi}$ 's and received photocurrent. The dual-output 12 GHz MZM utilized has a  $V_{\pi}$  of 12 V—although devices [7] with  $V_{\pi}$ 's below 4 V are possible. Within an achievable 3-dB excess MZM loss of each modulator and a 3-dB loss from the first modulator from quadrature biasing, only ~5 mW would remain at the outputs (2.5 mW per output) of the dual modulator if an EDFA is not utilized. Hence, an EDFA is inserted between the modulators which provides a maximum safe input power to the second MZM of ~200 mW. Therefore, 100 mW of total output power is available, or equivalently 50 mW at each modulator output when biased at quadrature. No known PD's are specified with both a maximum input (detection) power of 50 mW and a reasonable (200 MHz) bandwidth. Therefore multiple PD's are used in parallel for high-power performance.

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<sup>1</sup>ATx Model 1535-EHA, ATx Telcom Systems, Naperville IL.

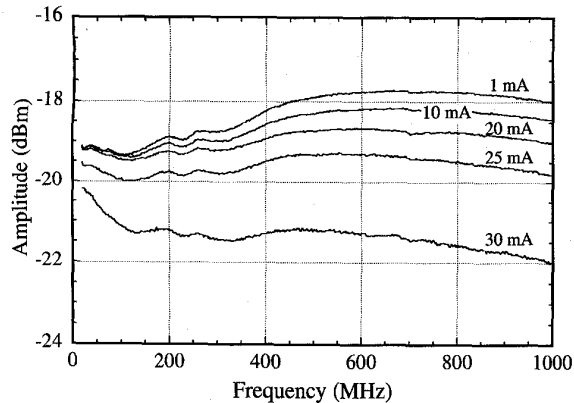


Fig. 2. Small-signal frequency response of a PD at various noted incident power levels. The modulated current is maintained at 1 mA while the PD average current is increased. The PD applied bias was  $-5$  V.

A typical photoresponse of a commercial 2-GHz p-i-n PD<sup>2</sup> is shown in Fig. 2. Frequency response measurements are made with a scanning laser heterodyne system [8] where the scanning laser power is held constant (1.4 mW) and a third 175 mW laser, separated in wavelength, is used to increase the average photocurrent. The photoresponse decreases at high illumination levels due to a buildup of carriers in the depletion region, accompanied by a partial collapse of the intrinsic region electric field [9]. As can be seen in Fig. 2, the photoresponse decreases as the total reverse current increases. Near 20 mA ( $\sim 29$  mW) the photoresponse has decreased by 1 dB between 500 MHz and 1 GHz, here designated as the small-signal 1-dB compression current ( $I_{1\text{-dB}}$ ).

Measurements of  $I_{1\text{-dB}}$  for two samples of this pigtailed commercial p-i-n photodetector are shown in Fig. 3. Parameters that increase  $I_{1\text{-dB}}$  are larger optical spot sizes, higher intrinsic region electric field, and lower intrinsic region background doping densities. The only adjustable parameter available with these devices is the electric field, and as seen in Fig. 3,  $I_{1\text{-dB}}$  generally increases with applied reverse voltage. However, as the voltage increases, the electrical power dissipated in the device also increases. Continued operation at electrical power dissipations above 200–250 mW in this device results in device failure (short circuit). No degradation was observed for short periods of time (hours) at PD power dissipation levels below 200 mW.

To detect the 50 mW from a single MZM output, two devices used in parallel are acceptable. Therefore, a balanced receiver was constructed using four devices, two reversed biased at  $+7$  V and two reverse biased at  $-7$  V through a custom designed bias tee (Fig. 1). The 3-dB bandwidth of the capacitively-coupled balanced photoreceiver (with all four detectors) remained above 500 MHz, well above the desired IF of  $160 \pm 25$  MHz. The PD bias voltage was selected to minimize the power dissipated (140 mW @ 20 mA) in each photodetector while providing the maximum  $I_{1\text{-dB}}$ . All fiber lengths were path matched using an RF network analyzer, resulting in a phase balance of  $\pm 3^\circ$  at 2 GHz for each path. With the output MZM biased at quadrature, sufficient

<sup>2</sup>Epitax Model ETX75-FJ-SLR, Epitax, Inc., Princeton, NJ.

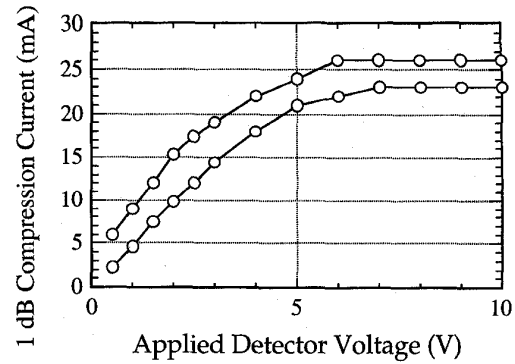


Fig. 3. Compression currents for two samples of a commercial pigtailed 2 GHz p-i-n PD versus applied PD voltage.

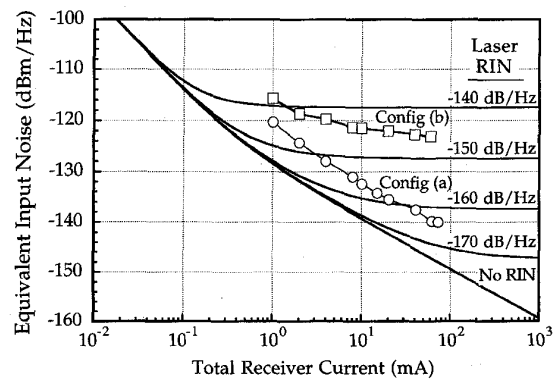


Fig. 4. Equivalent input noise for downconverting link configurations (a) circles and (b) squares. The RF and LO frequencies are 8.00 GHz and 8.16 GHz, respectively. The solid curves correspond to expected EIN of a direct detection (no downconverting) link using  $50\text{-}\Omega$  input and output impedances, a modulator with a  $12\text{-V } V_\pi$ , and various laser RIN levels.

amplitude balance was obtained to yield 22 dB common mode rejection in the receiver so no further fine tuning of the amplitudes was necessary.

Figure 4 shows the resulting equivalent input noise (EIN) obtained from the link configurations (a) and (b) in Fig. 1 as measured with both LO and RF turned on. Also plotted is the direct modulation (no downconversion) EIN that is expected for a 12-V modulator  $V_\pi$  and various laser RIN levels based on an analysis similar to [1]. The EIN of configuration (a) displays a general decrease with increasing current (minus a 7 dB downconverting loss) with a slope equal to the No-RIN curve which displays shot-noise-limited performance. Shot-noise-limited results are obtained with the balanced receiver configuration because laser RIN and EDFA intensity noise are effectively rejected. For comparison, the output of the balanced and unbalanced receiver from configuration (a) is plotted in Fig. 5. The unbalanced receiver is measured by removing either input of the balanced receiver. Note the 15.5 dB noise increase for the unbalanced case, or equivalently a 21.5 dB noise improvement if two outputs were considered. At 72 mA total receiver current (limited by the maximum input optical power to the MZM), the measured receiver common-mode noise rejection is 22 dB. This results in a link EIN of  $-140$  dBm/Hz (34 dB noise figure). By contrast, the EIN for

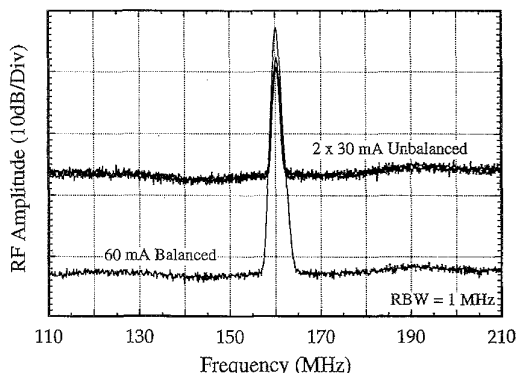


Fig. 5. IF output from photoreceiver. The three curves represent the output in balanced configuration (bottom) (30 mA/detector pair, 60 mA total) and in the unbalanced configuration (top) with one detector pair attenuated (30 mA/detector pair, 30 mA total).

configuration (b) is 6–16 dB higher than configuration (a) over the same range of receiver current, due to the uncorrelated EDFA noise which cannot be balanced out. Despite being driven at different input optical power levels [10 mW for (a) versus 2.5 mW for (b)], the EDFA noise contributions for both configurations is suspected to be nearly equal since both provide only  $\sim 13$  dB maximum saturated gain ( $-4$  dB min) and are, therefore, well into saturation.

The insertion loss (RF to IF) of the downconverting link configuration (a) at 72 mA and 8 GHz was 11.0 dB. Although this is only 9-dB better than the conversion loss previously reported using single-output modulators ( $V_{\pi} = 9$  V), the EIN has been reduced 16 dB from  $-124$  dBm/Hz to  $-140$  dBm/Hz. With present-day technology, a 4-V  $V_{\pi}$  dual-output 18 GHz MZM would result in an EIN of  $-150.5$  dBm/Hz ( $\sim 24.5$  dB

noise figure). Further noise figure improvements are possible with improvements to MZM maximum output optical power, since additional or improved PD's could be used to increase the maximum detectable current.

In conclusion, a 12-GHz downconverting optical link obtaining shot-noise-limited performance has been demonstrated with a maximum total photocurrent of 72 mA. A balanced photoreceiver was utilized to reject laser RIN and the noise generated from an erbium-doped fiber amplifier, resulting in a link EIN of  $-140$  dBm/Hz and a conversion loss of 11 dB at 8 GHz.

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