OPTICAL AMPLIFICATION IN AVIONIC ANALOG PHOTONIC LINKS

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Introduction

Analog photonic links are a promising technology for the avionic platform. Fiber-optic cabling is invulnerable to electromagnetic interference and is capable of carrying essentially any range of radio, microwave or millimeter-wave frequencies. In addition, fiber-optic cables offer reduced size and increased flexibility as compared to typical RF cabling. While the fiber-optic cabling itself has low loss, typically 0.0005 dB/m for the signal, the electrical-optical-electrical conversion can be quite lossy. However, high-performance analog links have been demonstrated with net electronic gain and acceptable electronic noise figure [1],[2]. Such links require a combination of high-power low-noise optical sources, low- V_π modulators and high-current photodetectors. These high-optical-power links are particularly attractive for avionic platforms that consist of short transmission spans on the order of 10's or 100's of meters where fiber nonlinearities are negligible. High-current photo-detectors [3] and low- V_π modulators [4] have been demonstrated and are available in relatively small packages. However, high-power lasers have yet to be demonstrated in a size acceptable for avionics applications. Here we report on the use of highly saturated erbium-doped fiber amplifiers (EDFAs) and moderate-power low-noise lasers in short analog photonic links to replace high-power low-noise lasers. Using the concepts of generalized relative intensity noise and noise penalty [5], we calculate system performance capabilities and demonstrate them experimentally. It is shown that an amplified link can achieve near-shot-noise-limited performance.

Noise Penalty in IMDD Systems

For an analog photonic link, we cite the four most important performance metrics as electronic gain (G_{rf}), electronic noise figure (NF_{rf}), spurious-free dynamic range ($SFDR$) and 1-dB compression dynamic range (CDR). For an intensity-modulation direct-detection (IMDD) link these metrics are

$$G_{rf} = (I_{dc}\pi/V_\pi)^2 Z_{in} Z_{out} \quad (1)$$

Figure 1. Optically-Amplified Avionic Photonic Link

$$NF_{rf} = RIN_{total} V_\pi^2 / (\pi^2 k_B T Z_{in}) \quad (2)$$

$$SFDR = (4/RIN_{total})^{2/3} \quad (3)$$

$$CDR = \phi_{1dB}^2 / (2RIN_{total}) \quad (4)$$

where I_{dc} is the DC photocurrent, Z_{in} and Z_{out} the input and output impedances, k_B Boltzmann's constant, T the temperature, ϕ_{1dB} the phase-shift amplitude for 1-dB of compression and RIN_{total} the total output-referenced generalized relative intensity noise. Here $RIN_{total} \equiv N_{out} / (I_{dc}^2 Z_{out})$ where N_{out} is the output-reference noise power spectral density. In an optically-amplified short-length analog photonic link, such as shown in Fig. 1, the noise penalty incurred (NP) by employing an EDFA as compared to an unamplified system can be written as

$$NP \equiv 1 + \frac{RIN_{sig-sp} + RIN_{sp-sp}}{RIN_{shot} + RIN_{ith} + RIN_{oth} + RIN_{laser}} \quad (5)$$

where RIN associated with signal-spontaneous beating (RIN_{sig-sp}), spontaneous-spontaneous beating (RIN_{sp-sp}), shot noise (RIN_{shot}), input (RIN_{ith}) and output (RIN_{oth}) thermal noise, and laser noise (RIN_{laser}) are considered. It can be seen that the penalties in NF_{rf} , $SFDR$ and CDR are equal to NP , $(2/3)NP$ [dB] and NP , respectively.

Except for RIN_{laser} , which we treat as a measurable quantity, we have for the terms in (5),

$$RIN_{sig-sp} = 2h\nu NF_{opt} / P_{in} \quad (6)$$

Figure 2. Calculated IMDD Link Performance

$$RIN_{sp-sp} = (h\nu NF_{opt}/P_{in})^2 B_{opt} \quad (7)$$

$$RIN_{shot} = 2h\nu/(\eta G_{opt} l_{opt} P_{in}) \quad (8)$$

$$RIN_{ith} = \pi^2 k_B T Z_{in} / V_{\pi}^2 \quad (9)$$

$$RIN_{oth} = k_B T / (I_{dc}^2 Z_{out}) \quad (10)$$

where h is Planck's constant, ν is the optical frequency, NF_{opt} is the EDFA noise figure, P_{in} is the input power to the EDFA, B_{opt} is the optical bandwidth, η is the detector quantum efficiency, G_{opt} is the EDFA optical gain (assumed to be much larger than unity), and l_{opt} is the post-EDFA optical loss. In deriving (7), it was assumed that $B_{rf} B_{opt} \gg f_{rf}$ where B_{rf} is the RF bandwidth and f_{rf} is the RF frequency of interest.

The calculated performance of an amplified (dashed) and unamplified (solid) IMDD analog link is shown in Fig. 2. Equations (1)-(4) and (6)-(10) were used with $\nu = 193$ THz, $NF_{opt} = 3$ dB, $P_{in} = 50$ mW, $B_{opt} = 3$ THz (25 nm in wavelength), $T = 300$ K, $V_{\pi} = 2$ V, $Z_{in} = Z_{out} = 50 \Omega$ and $RIN_{laser} = -190$ dBc/Hz. At high photocurrents the unamplified link performance is limited by shot noise whereas the amplified link is limited by signal-spontaneous beating. In these limits $NP \rightarrow 0$ dB when $l_{opt} \ll (1/\eta G_{opt} NF_{opt})$, which describes cases where EDFAs can be used without any performance penalties.

In practice NF_{opt} is a function of P_{in} and we show in Fig. 3 the measured performance of a particular EDFA (Avanex Model 03-0905-00-01) in

Figure 3. Measured IMDD Link Performance

a link similar to that in Fig. 1. For these data an optical attenuator was employed to simulate avionic network loss. A low-noise laser (CLR Photonics METEOR[®]) was used as the seed, which has a measured $RIN_{laser} = -190$ dBc/Hz at $f_{rf} = 1$ GHz where the measurements were made. Note that NP can be quite low even at high I_{dc} as long as the EDFA is adequately saturated.

Conclusions

We have described cases where the penalties incurred in IMDD links by utilizing EDFAs can be quite small or negligible. These conclusions are particularly important for short-length high-optical-power links, such as can be used in an avionic platform. These results relax the output-power requirements on low-noise lasers. In addition, this work demonstrates the significance of a new class of EDFAs, namely, EDFAs in compact flight-qualified packages having low noise figure in deep saturation.

References

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