# A Path to Realizing High-Performance 100-GHz Analog Links

*Charles H. Cox, III and Edward I. Ackerman*
*Photonic Systems, Inc.*
*Billerica, Massachusetts 01821*

## Introduction

Communications and sensor systems on aircraft and other vehicles would benefit from the development of optical fiber links with low noise figure and high dynamic range over broad bandwidths extending to as high as 100 GHz. To date, however, there have been few reports of analog optical links that include their performance at $f > 20$ GHz, and the best unamplified noise figure [1] and dynamic range [2] results have been reported at ≤ 12 GHz. In this paper, we compare several competing link architectures, identify the one with the potential to yield high performance across a broad bandwidth up to 100 GHz, and discuss some of the challenges that must be overcome.

## Selection of the link architecture

At the output end of an analog optical link, adequately efficient and low-noise detection of light modulated at frequencies > 100 GHz has been reported for several types of photodiodes [3 – 5] that all leverage the same physical phenomenon (the photoelectric effect). By contrast, at the input end of the link there exist several techniques for modulating the light. None of these techniques has yet to enable demonstration of a high-performance link at 100 GHz. Because each technique relies on a different physical effect, each has a significantly different potential for enabling such performance in the future.

Light from a diode laser can be *directly* modulated with adequately high efficiency, but only at frequencies below the relaxation resonance frequency at which there is oscillation in the transfer of energy between the photons stored in the laser cavity and the conduction-band electrons injected by the input signal. An even lower limit to the maximum operation frequency of a directly modulated diode laser is imposed by the fact that nonlinear distortion of input signals is maximum at a frequency equal to half of the relaxation resonance frequency [6]; therefore, direct modulation of even the diode laser with the highest reported relaxation resonance frequency of 40 GHz [7] could not yield a broadband link with high performance at > 20 GHz.

Alternatively, light from any laser can be *externally* modulated using any of a number of types of modulators. At the output end of the link, the high-speed photodetector can only recover a signal that modulates the intensity of the light, but this intensity modulation can be accomplished by modulating either (1) the extent to which light is absorbed in the modulator, or (2) the refractive index, with some means to then have this affect the number of photons that couple out of the modulator. It turns out that, although the absorption method is more straightforward and can be accomplished in a small semiconductor modulator that can be monolithically integrated with the diode laser source, it generates photocurrent that interacts with the input circuit in a manner that imposes an upper limit on the link's gain and a lower limit on its noise figure [8]. Therefore, the path to high-performance 100-GHz links is *external modulation in a non-absorptive modulator.*

## Realizing High Performance up to 100 GHz

It has been previously explained and demonstrated [9] that the most important performance parameters – *i.e.*, the gain, noise figure, and dynamic range – of a broadband external modulation link using a non-absorptive external modulator such as a Mach-Zehnder (MZ) interferometric modulator can be expressed in terms of just three quantities: the modulator's on-off voltage (in the case of an MZ this is $V_\pi$), the laser's relative intensity noise (RIN), and the average photocurrent ($I_D$).

**Fig. 1**

Unamplified broadband external modulation link noise figure as a function of MZ modulator $V_\pi$ and laser relative intensity noise (RIN), assuming the average photodetector current = 20 mA. Also shown is the lowest demonstrated broadband NF result of 3.5 – 7.5 dB across 1 – 12 GHz.

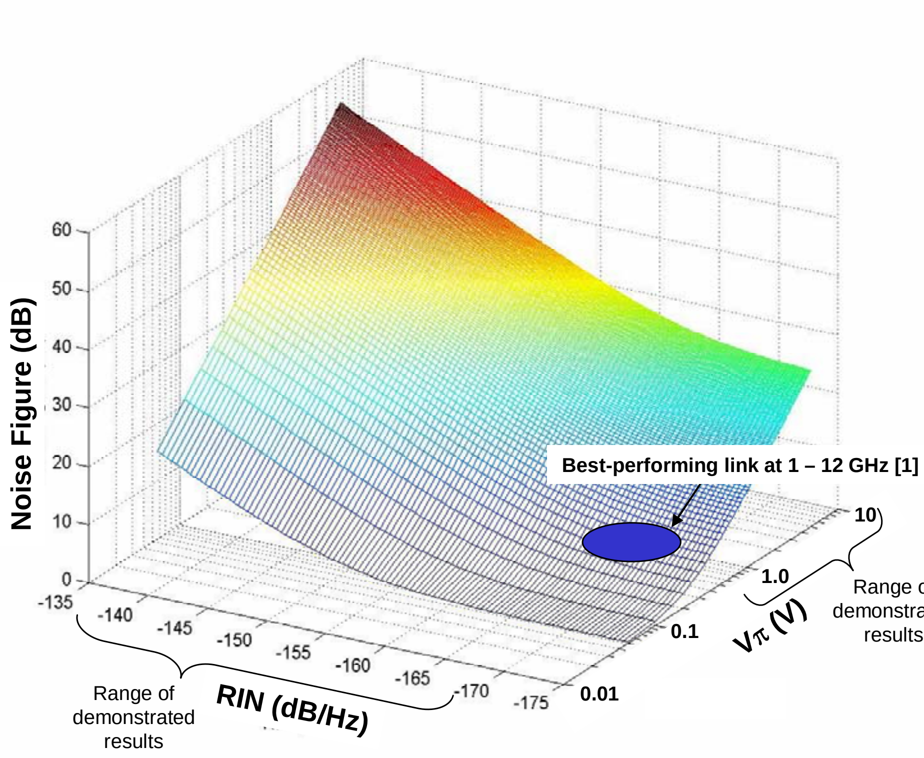


Figure 1 shows how one link performance parameter – noise figure (NF) – varies as a function of laser RIN and MZ modulator $V_\pi$, assuming that $I_D$ = 20 mA. Whereas photodiode current handling capability has been demonstrated to almost 20 mA at frequencies up to 250 GHz [5], the ranges of RINs and $V_\pi$s shown include values that have never been demonstrated. The link NF scales roughly as the inverse of $I_D$, and therefore higher $I_D$ values that have not yet been achieved would push the NF downward everywhere except in the fairly flat region in the right foreground, where it already asymptotically approaches 0 dB.

We can conclude from Fig. 1 that the development of a 100-GHz modulator with sufficiently low on-off voltage (*e.g.*, $V_\pi$ < 0.5 V) would enable unamplified low-NF (~ 5 dB) 100-GHz links without requiring any improvement to presently available laser RIN, and without requiring that the photodetector current handling capability be increased beyond 20 mA. It is likely, however, that high-performance 100-GHz links will be enabled more readily through a combination of $V_\pi$ reduction and an increase in the detector's maximum photocurrent, which may in turn require reduction in laser RIN to ensure shot noise-limited performance even at the new, higher, photocurrent. This path presents laser, modulator, and detector designers with challenges that are significant but not, to our knowledge, precluded by any physical laws.

## References

[1] H. Roussell, *et al.*, *Proc. IEEE Int. Topical Meet. on Microwave Photonics*, pp. 84-87, October 2007.
[2] A. Karim and J. Devenport, *J. Lightwave Technol.*, vol. 26, pp. 2718-2724, August 2008.
[3] Y. Wey, *et al., J. Lightwave Technol.*, vol. 13, pp. 1490-1499, July 1995.
[4] K. Kato, *Proc. IEEE Lasers Electro-Opt. Soc. Annu. Meet. (LEOS'97),* pp. 158-159, November 1997.
[5] J. Shi, *et al.*, *IEEE Photon. Technol. Lett.*, vol. 24, pp. 533-535, April 2012.
[6] T. Darcie, *et al., Electron. Lett.*, vol. 21, pp. 665-666, August 1985.
[7] S. Weisser, *et al., IEEE Photon. Technol. Lett.*, vol. 8, pp. 608-610, May 1996.
[8] G. Betts, *et al.*, *IEEE Photon. Technol. Lett.*, vol. 18, pp. 2065-2067, October 2006.
[9] C. Cox, *Analog Optical Links: Theory and Practice*, Cambridge University Press, 2004.