FIBER-OPTIC ANTENNA REMOTING FOR RADIOASTRONOMY APPLICATIONS

Edward Ackerman[(1)], Charles Cox[(1)], John Dreher[(2)], Mike Davis[(2)], Dave DeBoer[(2)]

[(1)]Photonic Systems, Inc., 103 Terrace Hall Ave., Suite A, Burlington, MA, 01803, USA
Email: eackerman@photonicsinc.com

[(2)]SETI Institute, 2035 Landings Drive, Mountain View, CA, 94043, USA
Email: dreher@seti.org

ABSTRACT

We review the state of the art in analog fiber-optic link technology to assess its potential role in radioastronomy applications. An excellent example of such an application is the Allen Telescope Array, which is a joint effort by the SETI Institute and the University of California, Berkeley. Because of its novel construction—an 350-element array of inexpensive 6-meter antennas spread over a collecting area of approximately one hectare—this radiotelescope can take full advantage of the attractive properties of optical fiber to deliver the individually collected components of the received signals to a single remote station for processing.

INTRODUCTION: HIGH-PERFORMANCE ANALOG FIBER-OPTIC LINKS

Because of its very low attenuation and dispersion properties, telecommunications-grade single-mode optical fiber allows the signals collected by multiple antennas to be processed in one location, which, depending on the signal bandwidth, can be a distance a few or many kilometers away.

Figure 1 shows a block diagram of the components in an analog fiber-optic link. At a minimum, an analog fiber-optic link consists of all the hardware required to impose an analog signal on an optical carrier, the transmission medium (this is the optical fiber itself), and the hardware required to recover the signal from the carrier. The optical carrier's wavelength is usually selected to coincide with either the 1.3 micron window at which standard single-mode fiber has minimum dispersion or the ~1.55 micron window at which its attenuation is minimum (and which is compatible with the best-performing type of optical amplifier). A shorter wavelength, 0.85 micron, was historically the first to receive widespread use, and it has re-emerged recently for short-range digital links, such as in local area networks (LANs). However, when this wavelength band is used it is almost exclusively with multimode fiber, which is generally unsuitable for high-performance analog links because the transmitted RF phase varies with temperature to a much greater extent than in single-mode fiber (the dominant fiber type used for 1.3 micron and 1.55 micron links).

Intensity-modulation/direct-detection (IMDD) links can differ from one another in the method used to modulate the light; however all known methods can be categorized as either *direct* or *external* modulation methods. In a direct modulation link a semiconductor laser serves as both the source of light and the means of modulating it; in an external modulation link a separate modulator device imposes the analog signal on the light supplied by the laser. Either type of IMDD link also includes a photodetector. Table 1 summarizes the best measured efficiencies and bandwidths reported for each of the key components in analog fiber-optic links [1-14].

It is noticeable from Table 1 that the modulation efficiency of a Mach-Zehnder (MZ) interferometric external modulator can be much greater than that of any of the directly modulated semiconductor laser types. This is because an external modulator's slope efficiency is proportional to the CW optical power supplied to the modulator, and the MZ modulator whose efficiency is quoted in Table 1 demonstrated the ability to modulate 400 mW from a high-power 1.3 micron solid-state Nd:YAG laser. This very high external modulation efficiency translated into the highest unamplified RF gain (G = 31 dB) and lowest unamplified noise figure (NF = 2.5 dB) ever demonstrated for an analog link [12].

Whereas the high gain and low noise figure reported for some analog fiber-optic links have proven that they can replace coaxial cables in many antenna remoting applications, an additional figure of merit that needs to be considered is their intermodulation-free dynamic range (IMFDR). In this attribute most direct and external modulation links yield comparable performance: usually 110–115 $\mathrm{dB \cdot Hz^{2/3}}$ (if limited by 3^{rd}-order rather than 2^{nd}-order nonlinear distortion products). When an extremely high-linearity directly modulated laser or a linearized external modulator is used, 10 to 20 dB of additional dynamic range has been demonstrated [15, 16].

FIBER-OPTIC LINKS FOR THE ALLEN TELESCOPE ARRAY

We have investigated the insertion of fiber-optic technology into a specific radioastronomy application: RF signal remoting links in the Allen Telescope Array (ATA). The ATA is a 350-element array of inexpensive 6-meter antennas spread over a collecting area of approximately one hectare. Each of the 350 antennas relays a very broad spectrum of detected energy—500 MHz to 11 GHz—in both polarizations to a single receive station up 1 km distant.

Minimizing the cost of the fiber-optic links is of paramount importance. Fortunately, growth in the telecommunications industry over the past 5 years has spurred an increase in the number of vendors supplying devices suitable for use in 10 Gbit/s digital signal links. To ensure reliable transmission of 10 Gbit/s data over long distances of fiber, most of these components have been designed with 3 dB electrical bandwidths exceeding 10 GHz. Moreover, competition has forced vendors to lower their prices, and has even provided the incentive for developments of new, inherently lower-cost, technologies. A drastic cost reduction is expected to result, for example, from the introduction of directly-modulated vertical-cavity surface-emitting lasers (VCSELs)—a goal towards which several companies are racing one another. It is projected that the cost of a 0.5-11 GHz link will have decreased by a factor of three between the start of our investigation in 2000 and the anticipated availability of 10 Gbit/s VCSELs in 2003. Table 2 is a summary of how, over time, the lowest-cost approach for the ATA links has been affected by the availability of new, lower-cost components.

It may come as a surprise that, until 10 Gbit/s VCSELs become commercially available, the lowest-cost alternative has always been an externally-modulated CW laser rather than a directly-modulated edge-emitting laser. Edge-emitting lasers are inherently expensive to fabricate and test, but obviously no more expensive than edge-emitting lasers combined with external modulators. However a directly-modulated edge-emitter is costly enough that it would never be considered for short-haul applications, and when it is directly intensity-modulated at high data rates the unintentional modulation of its wavelength (called “chirp”) precludes its use in long-haul applications, especially when dense wavelength multiplexing is used to take advantage of the wide transmission bandwidth of the fiber. Therefore the lower cost of 10 Gbit/s external modulation sources up until now has been an example of a demand-drive market situation.

As of this writing, the components chosen for the ATA remoting links—based on their performance and cost—are a Fujitsu integrated InGaAsP laser/electroabsorption (EA) modulator and a Discovery Semiconductor InGaAs p-i-n photodetector. The laser emits 5 mW of optical power at 1.556 micron when biased at 60 mA. The EA modulator integrated in the package with the laser efficiently modulates this wavelength of light when biased between –0.3 V and –0.8 V. Figure 2 summarizes the RF performance parameters that have been measured for a link consisting of this laser/modulator connected to the photodetector via 1 km of standard telecommuncations-grade single-mode fiber.

The link frequency response measurement shown in Figure 2 was performed using a network analyzer. The 3 dB electrical bandwidth of the link is greater than 11 GHz for modulator biases of –0.6 to –0.8 V. At both the –0.8 V and the –0.5 V biases the link was fully characterized in terms of its NF and IMFDR by performing a two-tone intermodulation distortion measurement along with an output noise measurement using a high-gain amplifier and an RF spectrum analyzer. These two bias points were selected because at –0.8 V the measured second-order distortion products were minimized, and at –0.5 V the third-order distortion products were minimized. Figure 2 shows a plot of the distortion product measurement when the two input fundamental tones were both approximately 5 GHz.

The G, NF, and IMFDR results listed in Figure 2 are significantly less impressive than the best analog link results reported in the literature, which is of course a by-product of the cost constraints. (That is, the higher-performance links used lasers that were about a factor of 10 more expensive.) However the performance shown in Figure 2 has been judged to be satisfactory for the remoting links in the ATA. Front-end pre-amplification stages are being designed to counteract the large insertion loss and noise figure of the link without significant adverse impact on its dynamic range.

SUMMARY

The development of high-performance, low-cost components for 10 Gbit/s digital links in the telecommunications market is enabling the inclusion of affordable 0.5-11 GHz antenna remoting links in the Allen Telescope Array being designed by SETI and UC Berkeley. Photonic Systems, Inc. is continuing to test the analog performance—gain, bandwidth, noise figure, and dynamic range—of low-cost fiber-optic components as they are introduced.

The authors thank Harold Roussell of Photonic Systems for performing the measurements shown in Figure 2.

REFERENCES

[1] St. Kollakowski, A. Strittmatter, E. Droge, E. Bottcher, and D. Bimberg, O. Reimann, and K. Janiak, "65 GHz InGaAs/InAlGaAs/InP waveguide-integrated photodetectors for the 1.3-1.55 μm wavelength range," *Appl. Phys. Lett*., vol. 74, pp. 612-614, January 1999.
[2] Y. Chen, S. Williamson, T. Brock, R. Smith, and A. Calawa, "375-GHz-bandwidth photoconductive detector," *Appl. Phys. Lett.*, vol. 59, pp. 1984-1986, October 1991.
[3] J. Bowers and C. Burrus, "Heterojunction waveguide photodetectors," *Proc. SPIE,* vol. 716, p. 109, 1986.
[4] Y. Chiu, S. Fleischer, and J. Bowers, "High-speed low-temperature-grown GaAs p-i-n traveling-wave photodetector," *IEEE Photon. Technol. Lett*., vol. 10, pp. 1012-1014, July 1998.
[5] J. Chiu, S. Fleischer, and J. Bowers, "Low-temperature grown GaAs traveling wave PIN photodetector with high bandwidth," *Proc. IEEE Lasers Electro-Opt. Soc. Annu. Meet. (LEOS'97),* pp. 164-165, November 1997.
[6] D. Young, J. Scott, M. Peters, M. Majewski, B. Thiebeault, S. Corzine, and L. Coldren, "Enhanced performance of offset-gain high-barrier vertical-cavity surface-emitting lasers," *IEEE J. Quantum Electron.*, vol. 29, p. 2013, 1993.
[7] D. Tauber, G. Wang, R. Geels, J. Bowers, and L. Coldren, "Large and small signal dynamics of vertical cavity surface emitting lasers," *Appl. Phys. Lett.*, vol. 62, pp. 325-327, January 1993.
[8] E. Meland, R. Holmstrom, J. Schlafer, R. Lauer, and W. Powazinik, "Extremely high-frequency (24 GHz) InGaAsP diode lasers with excellent modulation efficiency," *Electron. Lett.*, vol. 26, pp. 1827-1829, October 1990.
[9] S. Weisser, *et al.*, "Damping-limited modulation bandwidths up to 40 GHz in undoped short-cavity $In_{0.35}Ga_{0.65}As$–GaAs multiple-quantum-well lasers," *IEEE Photon. Technol. Lett*., vol. 8, pp. 608-610, May 1996.
[10] L. Lester, W. Schaff, X. Song, and L. Eastman, "Optical and RF characteristics of short-cavity-length multiquantum-well strained-layer lasers," *IEEE Photon. Technol. Lett.*, vol. 3, pp. 1049-1051, December 1991.
[11] T. Chen, J. Ungar, X. Yeh, and N. Bar-Chaim, "Very large bandwidth strained MQW DFB laser at 1.3 μm," *IEEE Photon. Technol. Lett.*, vol. 7, pp. 458-460, May 1995.
[12] C. Cox, E. Ackerman, and G. Betts, "Relationship between gain and noise figure of an optical analog link," *IEEE MTT-S Int. Microwave Symp. Dig.*, San Francisco, California, pp. 1551-1554, June 1996.
[13] K. Noguchi, O. Mitomi, and H. Miyazawa, "Millimeter-wave Ti: $LiNbO_3$ optical modulators," *J. Lightwave Tech*., vol. 16, pp. 615-617, April 1998.
[14] W. Bridges and F. Sheehy, "Velocity-matched electro-optic modulator," *Proc. SPIE*, vol. 1371, pp. 68-77, 1990.
[15] S. Pappert, "Photonic links for RF antenna remoting," *ONR MURI on RF Photonics Materials and Devices*, 1997.
[16] G. Betts, "Linearized modulator for suboctave-bandpass optical analog links," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 2642-2649, 1994.

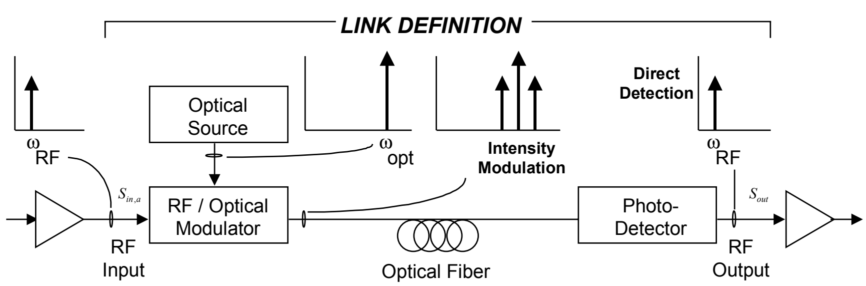


Figure 1 Definition of an intensity-modulation direct-detection (IMDD) analog optical link.

Date	Lowest-cost link approach with satisfactory 0.5-11 GHz performance	Link cost
November 2000	Separate CW semiconductor laser and lithium niobate MZ modulator; p-i-n photodetector	**$ 3,750**
April 2001	Integrated semiconductor laser and electroabsorption modulator; p-i-n photodetector	**$ 2,450**
2003	Directly-modulated semiconductor VCSEL; p-i-n photodetector	**$ 1,250**

Table 2 Evolution of the expected cost of 0.5-11 GHz fiber-optic links for the Allen Telescope Array. Link cost does not include the fiber itself, and assumes component prices quoted in quantities of 1,000.

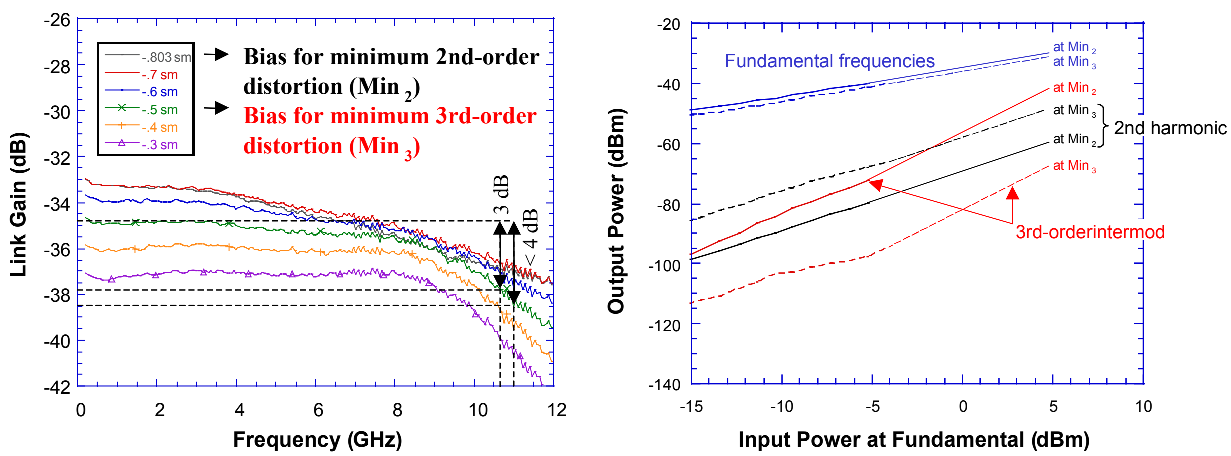
Component	Greatest Efficiency *	Greatest Bandwidth **	Greatest Efficiency × Bandwidth Product
Photodetector			
Surface-Illuminated	0.94 A/W [1]	375 GHz [2]	78 (A/W)·GHz [2]
Edge-Illuminated	0.84 A/W [3]	520 GHz [4]	89 (A/W)·GHz [5]
Directly-Modulated Laser			
Vertical-Cavity Surface Emitter (VCSEL)	0.61 W/A [6]	36 GHz [7]	8.0 (W/A)·GHz [7]
Fabry-Perot (FP) Edge Emitter	0.38 W/A [8]	40 GHz [9]	10 (W/A)·GHz [10]
Distributed Feedback (DFB) Edge Emitter	0.44 W/A [11]	20 GHz [11]	8.8 (W/A)·GHz [11]
External Intensity Modulator			
Mach-Zehnder (MZ)	15 W/A [12]	70 GHz [13]	140 (W/A)·GHz [13]
Electro-Absorption (EA)	***	60 GHz [14]	***

* All measured efficiencies are converted to equivalent efficiencies at λ=1.3 μm.

** Bandwidths are measured 3 dB (electrical) bandwidths.

*** Parameters needed to calculate EA modulator slope efficiency are generally not reported in the literature.

Table 1 Best measured efficiency and 3 dB bandwidth for the components used in analog fiber-optic links.



Min$_2$ Bias Voltage
$G_{11\ GHz}$ ~ – 37 dB
BW_{3dB} ~ 9.5 GHz
$\Delta G_{0.5\text{-}11\ GHz}$ < 4 dB

Min$_3$ Bias Voltage
$G_{11\ GHz}$ ~ – 38.5 dB
BW_{3dB} ~ 10.5 GHz
$\Delta G_{0.5\text{-}11\ GHz}$ < 4 dB

(a)

Min$_2$ Bias Voltage
NF ≤ 42 dB
$IMFDR_3 \geq$ 95 dB·Hz$^{2/3}$
$IMFDR_2 \geq$ 79 dB·Hz$^{1/2}$

Min$_3$ Bias Voltage
NF ≤ 45 dB
$IMFDR_3 \geq$ 102 dB·Hz$^{2/3}$
$IMFDR_2 \geq$ 76 dB·Hz$^{1/2}$

(b)

Figure 2 (a) Measured small-signal response of the fiber-optic link consisting of the integrated laser/electro-absorption modulator, 1-km fiber span, and reverse-biased p-i-n photodetector (bias = –6 V), for several modulator bias voltages.

(b) Measured fundamental, second- and third-order distortion products as a function of input power at two fundamental frequencies at ~5 GHz, and the calculated noise figure (NF) and maximum 2nd- and 3rd-order distortion-limited intermodulation-free dynamic ranges ($IMFDR_2$ and $IMFDR_3$, respectively).