A Low-Loss Ku-Band Directly Modulated Fiber-Optic Link

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Abstract—**The poor insertion loss and dynamic range exhibited by fiber-optic links has, until now, undermined the advantages of using an optical fiber for the transmission of microwave signals. By optimizing electrooptic transducer gains, we have developed the first Ku-band fiber-optic link that suffers only 12.6 dB of insertion loss at 12 GHz with a 3 dB bandwidth of 800 MHz. The broad dynamic range (79.4 dB · MHz) exhibited by the link can be exploited in a number of analog communications applications where the small size, light weight, flexibility, and EMI immunity of optical fibers are most desired.**

Introduction

OPTICAL fiber offers the communications network designer a small, light weight, flexible, and extremely secure means of distributing RF and control signals while suffering very little loss (less than 0.5 dB/km). For this reason, fiber-optic data links are increasingly being considered for a variety of analog communication applications, such as satellite communications, local area networks, and active phased-array harnesses. Until recently, however, the advantages of using optical fiber were offset by the high insertion loss (typically 30 dB or worse) of most of the directly-modulated optical links. By the methodical optimization of electrical and optical coupling efficiencies, an optical link that features 3.7 dB of measured insertion gain at L-band (900 MHz) was realized [1]. Similar optimization efforts at X-band have been shown to result in a low-insertion loss (7 dB at 9 GHz) fiber-optic link [2].

Described here is the first direct-modulation fiber-optic link optimized for low-insertion loss at Ku-band. The link operates at 12 GHz with a minimum loss of 12.6 dB over a 3 dB bandwidth of 800 MHz, and features a dynamic range of 79.4 dB · MHz.

Approach

High-performance link operation at Ku-band requires that both the laser and detector exhibit high electrooptic efficiency at 12 GHz. To this end, GTE has developed a single-mode fiber-pigtailed 1.3 μm-wavelength p–i–n photodiode with a responsivity of $\eta_D = 0.56$ A/W and a 3 dB modulation bandwidth of 15 GHz. The laser in use was an InGaAsP distributed-feedback laser diode manufactured by AT&T. It emits at the 1.3 μm wavelength and features an external differential quantum efficiency of 0.26 W/A and a 3 dB modulation bandwidth in excess of 12 GHz when biased well above its threshold current of 13 mA. The laser and detector were modeled as a forward- and a reverse-biased p–n junction, respectively. The specific element values in the models were derived using Super Compact[1] to fit the models' scattering parameters to those of the actual devices, which had been deembedded from the measured S-parameters of the devices in their packages. The RF insertion gain G of the directly-modulated fiber-optic link shown in Fig. 1 is expressed as follows:

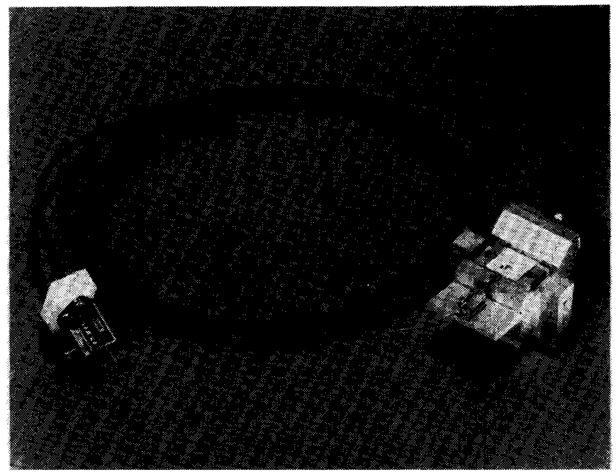

Fig. 1. Directly modulated fiber-optic link optimized for operation at 12 GHz.

$$G = \frac{(1 - |S_{11}|^2)\eta_L^2}{R_L} \eta_{op}^2 \frac{\eta_D^2 (1 - |S_{22}|^2)}{4\omega^2 C_D^2 R_D} \tag{1}$$

where S_{11} and S_{22} are the return losses of the laser and detector, η_L and η_D are their responsivities, η_{op} is the laser-to-detector optical-coupling efficiency, and $\omega = 2\pi f$. The term R_L refers to the resistance of the forward-biased laser diode, and R_D and C_D are the values in the series RC circuit which represents the reverse-biased p–i–n photodiode.

The laser diode had been mounted in a standard microwave test fixture to facilitate deembedding of its intrinsic scattering parameter. Both this fixture and the GTE detector package situate the electrooptic device at the end of a 50 Ω microstrip line, which serves as the RF input or output path. Distributed-element impedance-matching networks were constructed by modifying the microstrip lines in the modules in order to minimize $|S_{11}|^2$ and $|S_{22}|^2$ at $f = 12$ GHz. The circuits fashioned in this manner resulted in 29 and 32 dB measured return losses at 12 GHz for the laser and detector modules, respectively.

Minimization of losses in the optical domain required that the semiconductor laser's diverging output beam be collected and focused into the 8 μm core of the single-mode optical-fiber pigtail of the detector module. Using a planoconvex gradient-index (GRIN) lens with AR-coated facets, a laser-to-fiber coupling efficiency η_{op} of 40% was achieved. This corresponds to a net

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[1] Super Compact is a trademark of Compact Software.

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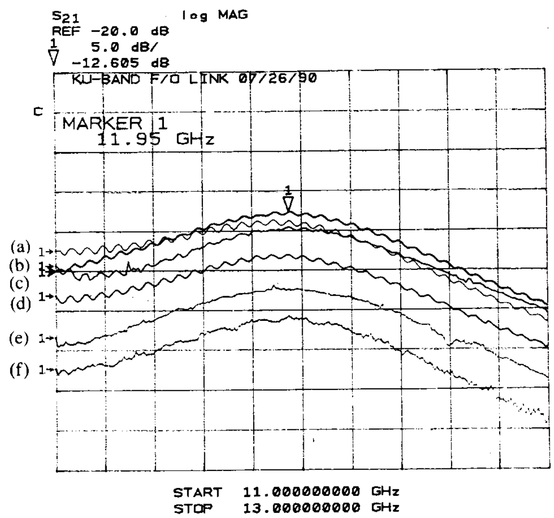

Fig. 2. Measured insertion loss of Ku-band fiber-optic link under various laser diode bias conditions. (a) I_L = 60 mA; (b) 70 mA; (c) 50 mA; (d) 40 mA; (e) 30 mA; and (f) 25 mA.

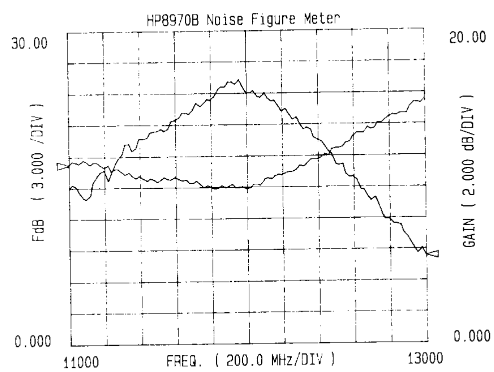

Fig. 3. Measured gain and noise figure of Ku-band fiber-optic link (laser bias current = 70 mA) driven by a 30 dB preamplifier with a noise figure of 4.1 dB at 12 GHz. Preamplifier and link: I_L = 70.0 mA; V_D = -9 V; I_D = 4.40 mA.

current conversion efficiency from laser to detector of 5.8%. Based on this, on the measured return losses of the impedance-matched laser and detector modules, and on the equivalent circuit parameters, (1) predicts a link-insertion loss of 10.7 dB at 12 GHz.

Results

The fiber-optic link is depicted in Fig. 1. At the right is the laser module, in which the GRIN lens and single-mode optical fiber pigtail are visible. Its 50 Ω microstrip-line input, which has been modified as described above to achieve an impedance match at 12 GHz, can also be seen, and the GTE high-frequency detector module and its pigtail are to the left. Fig. 2 shows the measured insertion loss of this fiber-optic link. The different curves in the figure represent the loss versus frequency for several laser-bias current levels. For the lower bias currents (25–50 mA), the laser is inefficient because the relaxation oscillation occurs at a frequency f_r less than 12 GHz. It is likely that $f_r \sim 12$ GHz when I_L = 60 mA, since the insertion loss at 12 GHz is its minimum value of 12.6 dB for this bias level. As the bias is increased further, $f_r > 12$ GHz causing the response at 12 GHz to be lower than the 60 mA response at that frequency. For all of the bias values, the 3 dB bandwidth is approximately 800 MHz. The discrepancy in insertion loss between the predicted and experimental results may be due to parasitics not accounted for in the laser and detector circuit models.

The dynamic range of the fiber-optic link was found to be the greatest for the 70 mA laser bias level, at which the insertion loss is 14 dB. The dynamic range generally increases with laser bias for two reasons: 1) linearity improves because the same input power level corresponds to a smaller modulation depth at a high, rather than low, bias level and 2) the laser's relative intensity noise is maximum at the relaxation oscillation frequency, which is pushed to frequencies greater than 12 GHz as the bias is increased above 60 mA. Fig. 3 shows the measured gain and noise figure of the link (I_L = 70 mA) driven by a 30 dB preamplifier having a noise figure of 4.1 dB. The total noise figure of 15.4 dB corresponds to a noise figure of 45 dB for the link alone. Fig. 4 depicts the results of a two-tone intermodulation distortion measurement performed under the 70 mA laser bias condition. The output power at the third-order intercept is

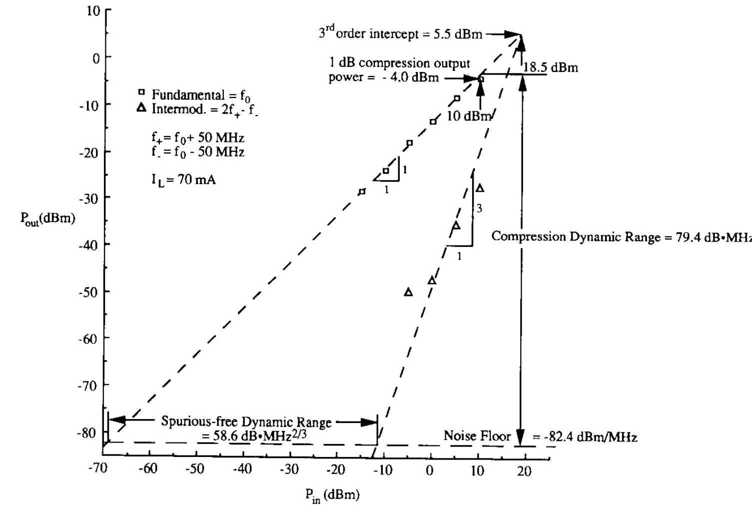

Fig. 4. Results of a two-tone intermodulation distortion measurement, showing the fiber-optic link's third-order intercept and 1 dB compression points. Also shown are the noise floor and the calculated spurious-free and compression dynamic ranges for the link.

5.5 dBm and 1 dB of AM compression occurs at an output power of -4.0 dBm. For a 1 MHz resolution bandwidth, the noise floor at the output of the link is -82.4 dBm. Based on these results, the compression dynamic range and corresponding spurious-free dynamic range of the Ku-band fiber-optic link are 79.4 dB $\cdot$ MHz and 58.6 dB $\cdot$ MHz$^{2/3}$, respectively. This is the highest frequency at which the dynamic range of a fiber-optic link has been characterized.

Summary

Small size, light weight, flexibility, minimal attenuation, and immunity to EMI are all characteristics that make an optical fiber an extremely attractive means of distributing data and control signals among phased array antenna elements. At high microwave frequencies, these advantages have been undermined by the high microwave-optical-microwave conversion losses in the optical link. Optimization of the transducer gains in the laser and detector matching networks at 12 GHz has produced a directly-modulated fiber-optic link with a minimum insertion loss of 12.6 dB over a 3 dB bandwidth of 800 MHz. The wide compression dynamic range (79.4 dB $\cdot$ MHz) exhibited by this Ku-band link affirms its suitability for a variety of analog communications applications, including satellite communications systems, local area networks, and active phased-array harnesses.

References

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[2] H. Blauvelt, D. B. Huff, G. J. Stern, and I. L. Newberg, "Reduced insertion loss of *X*-band RF fiber-optic links," *IEEE Trans. Microwave Theory Tech.*, vol. 38, no. 5, pp. 662–664, 1990.