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0.83- AND 1.3-MICRON MICROWAVE (2-18 GHz) FIBER-OPTIC LINKS USING DIRECTLY MODULATED LASER SOURCES

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ABSTRACT

Loss and noise characteristics of 0.83-µm and 1.3-µm directly modulated laser fiber optic links were measured from 2 to 18 GHz. The 1.3-µm system exhibited lower loss (46 dB at 18 GHz) and noise figure (64 dB at 18 GHz) than the 0.83-µm version for frequencies above 10 GHz. Deleterious feedback induced effects were observed in the 0.83-µm link, including sporadic 45 dB RF signal dropouts.

INTRODUCTION

Transmission of RF signals by a fiber-optic link (FOL) remains an attractive alternative to free-space or coaxial cable methods. Advances in fabrication of high-speed lasers and photodetectors, at both 0.83 and 1.3-µm wavelengths, now allow convenient direct laser modulation and detection to frequencies to J-band (10-20 GHz). Applications of FOLs include radar, communications, signal processing, and remote sensing.

Previous reports of direct-modulation FOLs are limited to about 10 GHz [1]. Here we report for the first time the transmission characteristics of FOLs in the extended frequency range of 2-18 GHz. Comparison of noise and transmission loss characteristics between 0.83-µm and 1.3-µm systems is made. In addition, new limitations of FOL performance, due to optical feedback effects, were observed and are described. The feedback induced degradation of the FOL characteristics include sporadic RF power dropouts of more than 45 dB, which are caused by feedback induced laser mode hopping. Also, for pulsed microwave FOLs, trailing pulses were observed and are caused by Rayleigh scattering in the single-mode fiber.

Since the FOL is typically embedded in a more complex microwave system, its performance characteristics are best described by cascadable measure of loss and noise. We therefore choose to represent these in the form of insertion loss (negative of the available gain in dB) and noise figure, both as a function of frequency. These were measured using the experimental arrangement in Figure 1.

EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUE

The experimental setup for measuring the FOL loss and noise figure is essentially a versatile computer-controlled spectrum analyzer and tracking synthesized sweeper. Measurements of FOL loss L were carried out at 100 MHz intervals. All measurements are corrected for cable, bias tee, and amplifier losses and gains by subtracting (in dB) the calibration measurement, which was taken by connecting the laser bias tee directly to the photodetector bias tee.

Noise measurements are made in a similar manner but the output of the synthesized sweeper is shut off. Noise figure F is given by

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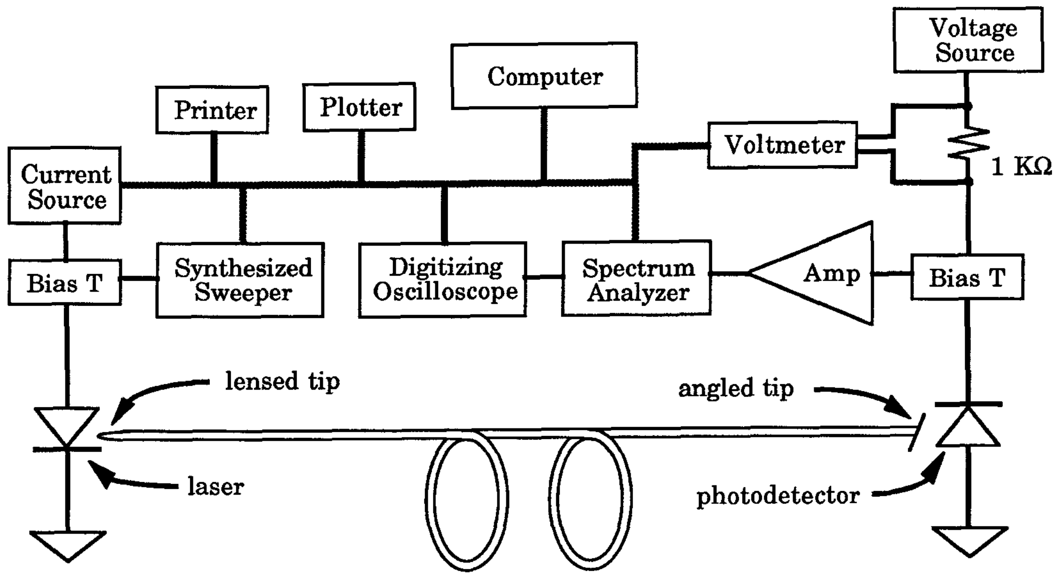

Figure 1. Experimental Setup.

$$F = \frac{(S/N)_{in}}{(S/N)_{out}} = \left(\frac{S_{in}}{S_{out}}\right)\left(\frac{N_{out}}{N_{in}}\right) = \frac{LN_{out}}{kT} \qquad (1)$$

where S_{in}, S_{out} are the available signal power levels. Here we have assumed the input noise power spectral density N_{in} to be due to thermal noise only, $N_{in} = kT = -174$ dBm/Hz and the laser intrinsic intensity noise to dominate the output noise power spectral density N_{out}.

LOSS AND NOISE CHARACTERISTICS

The laser sources and photodetectors in these experiments are as follows; at 0.83-µm we used GaAlAs BH window-structure lasers [2] and GaAlAs/GaAs *p-i-n* photodiodes [3], while at 1.3-µm we used InGaAsP VPR-BH lasers [4] and mesa-geometry InGaAs/InP photodiodes [5]. All of these devices were fabricated and mounted for high-speed operation. Photodetector responsivities were 0.45 and 0.55 A/W for the 0.83 and the 1.3 µm devices, respectively.

In order to determine FOL limitations attributable to the inherent performance of the lasers and photodetectors, initially, short (10 m) lengths of lensed single-mode fiber were used. As discussed below, longer lengths introduce optical feedback due to Rayleigh scattering and are especially deleterious to the 0.83-µm FOL. The laser to fiber coupling efficiency was 23% (-6.4 dB) for the 0.83-µm FOL and 18% (-7.4 dB) for the 1.3-µm FOL.

Typical microwave losses for both types of FOLs are shown in Figure 2. For modulation frequencies less than the crossover frequency of 10 GHz, the 0.83-µm system has approximately 10 dB less loss than the 1.3-µm counterpart. For frequencies above the crossover, the 1.3-µm FOL loss is less, reaching a value of 10 dB below that of the 0.83-µm FOL at frequencies greater than 15 GHz. Since for both wavelengths the photodetector response is relatively flat over the frequency region of interest, the difference in the FOL loss for the two wavelengths is primarily due to lower overall quantum efficiency and higher rolloff frequency of the 1.3-µm laser.

The FOL noise figures, Figure 3, reveal approximate equal noise figures near 2 GHz. However, at 18 GHz the 1.3-µm FOL has a noise figure of about 65 dB which is 9 dB less than the 74 dB noise figure of the 0.83-µm FOL. Note that since $(S/N)_{out} = (S/N)_{in}/F$ and assuming S_{in}

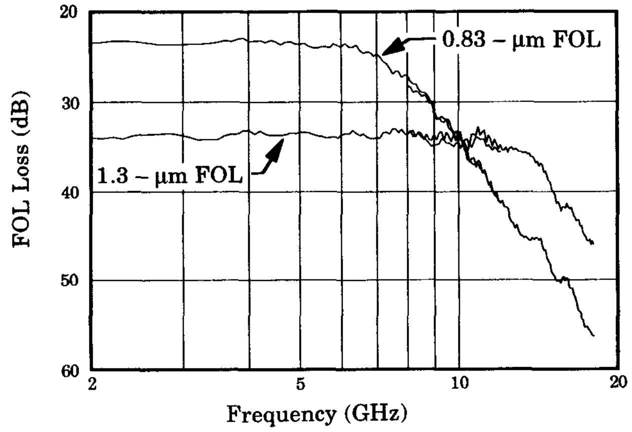

Figure 2. Frequency dependence of FOL loss.

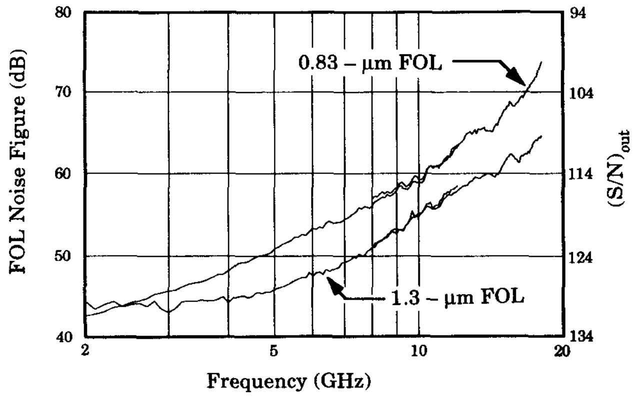

Figure 3. Frequency dependence of FOL noise figure and signal-to-noise ratio.

= 0 dBm, the output signal-to-noise can be written as $(S/N)_{out}$ (in dB/Hz) = (174 - F) (F in dB). Signal-to-noise ratios in these experiments ranged from 132 dB/Hz near 2 GHz to 110 dB/Hz (101 dB/Hz) at 18 GHz for the 1.3-μm (0.83-μm) FOL. At high frequencies the noise figure follows a f^2 dependence which is predicted by using Equation (1) and theoretical expressions for the frequency dependence of the laser loss and noise spectral density [6].

Similar experiments at 1.3-μm with 2.2 Km of single-mode fiber have similar results but with slightly increased loss and noise figure corresponding to additional losses (0.4 dB/Km) in the fiber. However, accurate measurements at 0.83-μm with fiber lengths of more than several hundred meters were not possible due to instability of the RF signal as discussed below.

OPTICAL FEEDBACK EFFECTS

Without the use of an optical isolator, optical feedback from both the fiber entrance facet and from Rayleigh scattering indirectly cause large momentary RF losses or "dropouts." The RF dropouts are caused by laser longitudinal mode instabilities which are induced by optical feedback. Together with the fiber dispersion at 0.83 μm, the presence of more than one longitudinal mode in the laser emission spectrum (3.5 Å mode separation) will result in post-detection microwave destructive interference. Although the 0.83-μm laser was single mode without feedback, multimode operation of the laser was observed to occur as a result of optical feedback from the fiber end closest to the laser. RF dropouts of more than 45 dB were observed when the laser was operating multimode.

Another type of multimode operation occurred when the laser underwent a mode hop, where *during* the mode hop, two modes are present simultaneously. The effect of mode hopping on RF power dropout is shown in Figure 4 where 1.6 Km of fiber was used. The minima of the observed drops in the RF power correspond to the simultaneous presence of two adjacent modes of equal power, occurring during the mode hop, as directly observed on a Fabry-Perot interferometer [7]. The amplitude of the dropout is a function of modulation frequency and was approximately 14 dB for f = 12 GHz shown in Figure 4, and increased to a maximum of more than 45 dB at 10 GHz. A more detailed characterization of the pulse

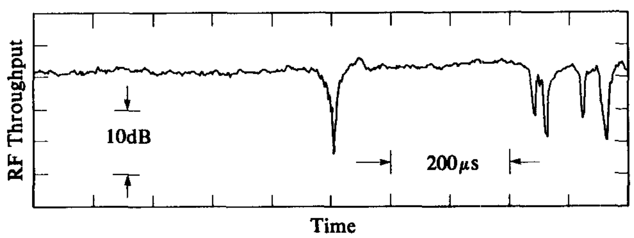

Figure 4. RF throughput power dropouts caused by optical feedback.

dropout magnitude will be presented. Mode hops were observed to be caused by Rayleigh scattering from the single mode fiber, and their frequency of occurrence was dependent on the backscattered power.

Lastly, pulse microwave measurements on the FOLs revealed that in addition to RF dropout another degradation phenomenon in 0.83-μm systems occurs as a result of Rayleigh scattering. The optical feedback is reinjected into the laser cavity, amplified, and retransmitted. The net result can be seen in the received pulsed microwave signal traces as an overlapping trailing pulse, Figure 5. RF dropout is not apparent in Figure 5 due to averaging over 128 traces. The trailing pulse can significantly decrease (by more than 20 dB) the pulse signal to inter-pulse noise ratio and thereby degrade system performance.

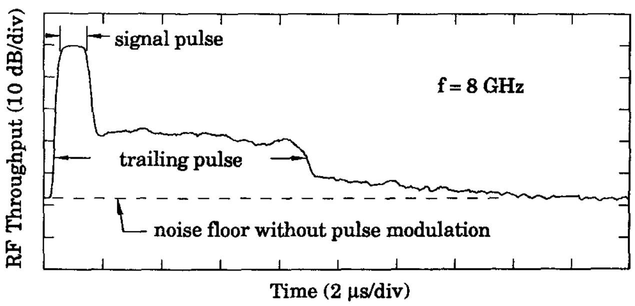

Figure 5. Received signal for a pulsed microwave system, showing the signal pulse and the spurious trailing pulse caused by Rayleigh scattering.

SUMMARY

Wideband fiber-optic links have been demonstrated to 18 GHz. The 0.83-μm FOL exhibited a low frequency loss of 24 dB and a -3 dB frequency of 8 GHz. Whereas, the 1.3-μm FOL has a -3dB frequency of ~ 14.5 GHz, and low frequency loss of 34 dB. Throughout the frequency range the noise figure of the 1.3-μm FOL was less than the 0.83-μm FOL, up to 10 dB (at 18 GHz).

For the first time, severe performance degradation of FOLs associated with optical feedback in 0.83-μm FOLs has been observed and characterized. More than 45 dB of momentary RF signal loss in CW signals, as well as occurrence of trailing pulses, which were more than 20 dB above the background noise floor, in pulsed microwave systems are attributed to optical feedback and fiber dispersion.

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