RECIRCULATING FIBEROPTIC LINK FOR MEMORY LOOP

R. Saedi*, X. Zhou*, S. Malone*, A. Daryoush*, P. Herczfeld*, B. Even-Or+

*Center for Microwave-Lightwave Engineering
Dept. of E.C.E., Drexel University, Philadelphia, PA

+ American Electronics Laboratories, Lansdale, PA

ABSTRACT

Fiberoptic links can be used as delay elements in microwave frequency memory loops. This paper presents the analysis and experimental results of a recirculating memory loop operating over 2-4GHz leading to a 100μsec delay. The reactively matched optical transmitter and actively matched optical receiver are designed to achieve optimum loop performance. New gain equalization techniques are discussed permitting a long time delay in the range of milliseconds.

INTRODUCTION

Fiberoptic links can be put to good use in many microwave signal processing applications [1-3]. One potential application is in the recirculating RF memory loop, where the digital RF memory loop is the only other contender. As an integral part of delay line systems in microwave signal processing, fiber optic links offer the clear advantages of particularly small size, light weight, immunity to EMI, and low loss over large distances.

The simplified schematic diagram of a fiber optic based recirculating memory loop is conceptually shown in Fig. 1. This system consists of four basic elements: a switch, an electrical amplifier, a fiberoptic time delay element, and a gain equalizer. The RF input pulse is routed through the switch to the time delay device. The switch closes the loop and thus controls the recirculation. As the signal reenters the microwave circuit, it is amplified and again rerouted through the fiber. As a result, a pulse train which has a pulse repetition interval corresponding to one recirculation time is obtained.

In the design of the Fiber Optic Memory Loop (FOML) our approach is to optimize the performance of the fiber optic delay element so that a flat frequency response over the bandwidth of interest can be assured. In particular, the goal of this paper is to report the development of a low loss, low noise figure fiber optic delay element that is capable of recirculation up to sub-millisecond. Finally we will discuss methods of extending the delays to above the millisecond level.

ANALYSIS

Gain and Noise Figure

This section describes the limiting factors in gain and noise figure of fiberoptic links, which influences the maximum number of recirculations. The gain-bandwidth performance of a fiber optic link[4] is expressed as

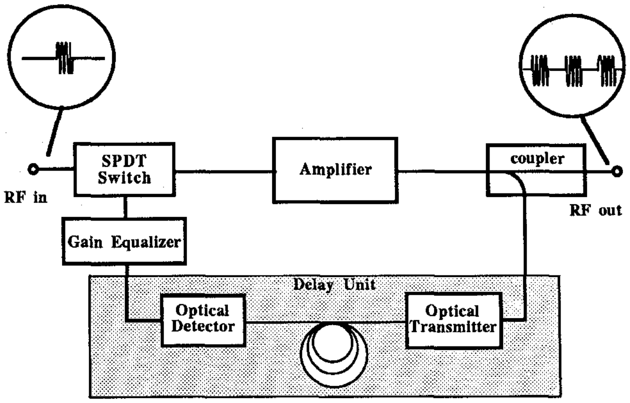

Fig. 1. Conceptual drawing of a fiber optic based recirculating delay line. It is composed of a SPDT switch, electronic amplifier, coupler, optical delay element, and gain equalizer.

$$G = \frac{|S_{21D}|^2 |S_{21L}|^2 \left(1 - |\Gamma_{las}|^2\right) (\eta_L K_L L K_D \eta_D)^2}{\left(|1 - \Gamma_{Las} S_{22L}|^2\right) \times \left(|1 - \Gamma_{SD} S_{11D}|^2\right)}$$

In a well-designed fiberoptic link, the laser and detector are selected so that their bandwidths are larger than the modulation rate and the fiber loss is insignificant. Reactive matching permits the inherent low impedance of the laser diode and high impedance of the photodiode to lead to a transducer gain. Therefore, lower loss fiberoptic links can be realized via reactively or actively matched optical transmitter and receiver modules. However, there is a distinct tradeoff between the minimum acceptable return loss to be realized and the bandwidth over which impedance matching is to be performed [5].

Noise figure is another important parameter that influences performance of the optical memory loop. For a laser diode biased at I_b above the threshold current of I_{th}, the expressions for different noise components are given[4], where the noise figure of the link is dominated by the laser noise, signified by the relative intensity of the laser (RIN). Also, for a reactively matched laser diode, the overall thermal noise contribution from the input is reduced, since the input resistance of a forward biased p-n junction is very small. Furthermore, if insertion loss of fiberoptic link is reduced the shot noise contribution of the photodiode can be minimized.

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The most limiting factor that degrades the output signal of the optical delay element is the noise build-up in the loop over the link bandwidth. In particular, flatness and the noise figure are limiting factors of Fiber Optic Memory Loop.

It can be shown that the maximum number of recirculations, n_{max} is limited to maximum allowable NF by

$$n_{max} = \frac{\log NF_{Tmax} - \log\left[\frac{NF_2-1}{G_1} + C(NF_1 - 1)\right] + \log(C-1)}{\log C}$$

In this expression NF_{Tmax} is defined as maximum $(S/N)_{in}$ to minimum allowable $(S/N)_{out}$ at the output after n recirculations G_1 and NF_1 are gain and noise figure of the RF amplifier, G_2 and NF_2 are gain and noise figure of the fiberoptic link. If we assume that the loop gain for the incoming pulse is unity, then at the other frequencies, the loop gain differs by factor of C from unity. In essence, NF_{Tmax} is the total noise figure that the entire delay system can introduce without degrading the output signal to noise ratio to below acceptable needs.

The implication of non-flat frequency response of the delay unit is that the noise will increase at a faster rate at frequencies where G_1G_2 is greater than unity. Therefore, the nonflat frequency response and high noise figure of the delay element will restrict the maximum time delay attainable by the memory loop. A larger value of recirculations, n, can be achieved by: i) reducing insertion loss and noise figure of the fiber optic link, and ii) flattening the frequency response of the closed loop system, C. Both approaches are pursued here.

To highlight the effect of reactive matching on the overall performance of a 2-4 GHz fiber optic link, three different fiber optic links were simulated. The first link is based on the experimental results of a commercially available AlGaAs FO link from Ortel (SL1020 and PDO50PM). The second link is reactively matched transmitter and the third link has reactive matching for both transmitter and receiver modules, using the same characteristics of AlGaAs lasers and detectors (SL1000H and PDO50C). For the specified $(S/N)_{out}$=10 dB, the calculated results shows that for the flat frequency response the maximum number of recirculations are 1200, 1900, and 2300 for the commercial, reactively matched transmitter, and reactively matched transmitter/receiver links respectively. On the other hand the maximum number of recirculations reduces very rapidly as the open loop gain ripples are increased. With a gain flatness of ±1 dB the maximum number of recirculation reduces to 22, 31, and 32 for the above links respectively.

DESIGN PROCEDURES OF OPTICAL TRANSMITTER AND RECEIVER MODULES

Design steps of optical transmitter and receiver modules are outlined previously [6]. The specific performance characteristics are presented here. First the transmitter, then the receiver, will be discussed.

Transmitter Characteristics

A high-speed AlGaAs laser diode with back facet reflective coating [7] is used as the optical source. Reactive matching can be realized via a three stage network, leading to theoretical return loss of -6 dB. On the 25 mil RT/Duroid substrate, the distributed elements were used to obtain a low loss circuit. The return loss of the transmitter was measured on the network analyzer over the frequency band of 1-6 GHz. Fig. 2 shows the return loss of the transmitter module, where the return loss of $S_{11} \leq -5.3$ dB is measured over the bandwidth of the 2-4 GHz.

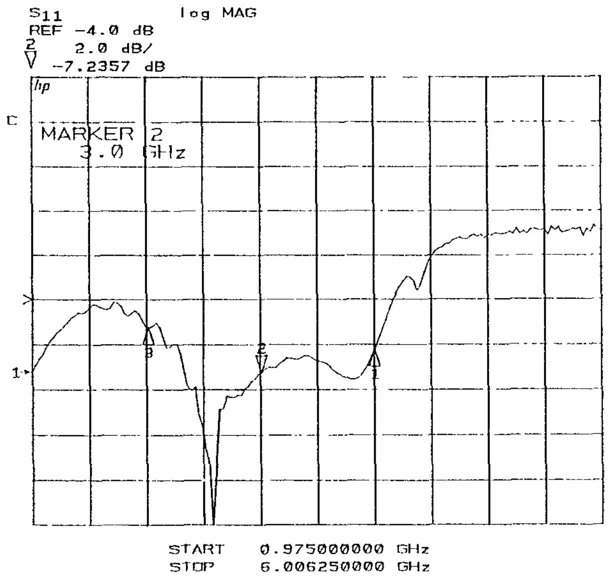

Fig. 2. Return loss ($|S_{11}|$) of the 2-4 GHz reactively matched transmitter module.

The output power of the laser diode is coupled to a custom designed lensed fiber. Optical lenses were fabricated using arc fusion and chemical etching techniques on single-mode and multi-mode optical fibers. The light coupling efficiency of 80% and 35% were achieved on the multi-mode and single-mode fibers respectively.

Light coupling of the laser diode output in to the multi-mode fiber was improved by down-tapering of the fiber end. Tapers are formed by controlled insertion of the fibers into an etching solution of hydrofluoric acid. Light coupling efficiencies as high as 85% have been achieved with the Siecor 50/125μm multi-mode fiber, comparable to results reported by other researchers [8]. This is a significant improvement over the coupling efficiency of 25% achieved with a butt-coupled multimode fiber. The tapered fiber is positioned within the module by an adjustable "V-groove" and secured in place with UV curable epoxy. A lensed fiber is more sensitive to misalignment and imposes greater restriction on the mechanical tolerances.

By establishing a thermistor thermo-electric cooler controller assembly a constant threshold current for laser diode is maintained. To assure a constant laser diode bandwidth, the light output power of the laser diode from the back facet was also monitored through an optical prism as a mirror and a large area photodetector. The photodetector output is used to adjust the laser biasing current.

Receiver Characteristics

Next, the design of a matching network for optical receiver was pursued. In the design of the optical receiver module, our approach is to design an actively matched optical receiver, since over the octave bandwidth the Bode-Fano[5] theoretical limit predicts a $|S_{11}|_{min}$ of -1dB for Q_{ex} of 38. In the case of an actively matched optical receiver, the matching network not only matches the high impedance of the reverse biased PIN photodiode to the amplifier's input, but also amplifies the received signal in the receiver circuitry.

A trans-impedance configuration of a GaAs MESFET, when operated in the common source configuration, has the attractive property of high gate-to-source (input) impedance and low

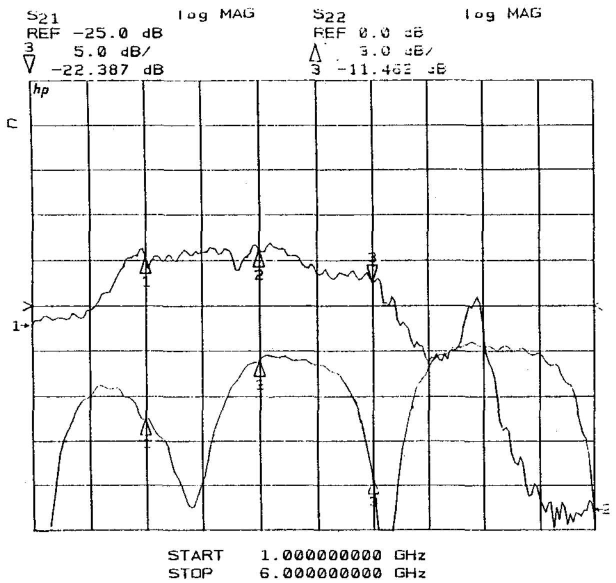

Fig. 3. Return loss ($|S_{22}|$) of the optical receiver module and insertion loss ($|S_{21}|$) of the fiber optic link, using the multi-mode pigtailed 2-4 GHz optical transmitter and receiver.

drain-to-source (output) impedance. Therefore, it is much easier to design a filter with fewer poles to match the PIN detector to the high input impedance of FET. A GaAs MESFET from NEC (NE710) was selected for its low noise figure and high input impedance. The FET was then characterized in terms of S parameters. On the Touchstone CAD program, a design comprising distributed and lumped elements was selected for matching the input impedance to the PIN photodetector and the output impedance to the 50 Ω system. The return loss of the receiver module is shown in Fig. 3. Also shown in Fig. 3 is the insertion loss of link, consisting of the multi-mode pigtailed optical transmitter and receiver, where an insertion loss of 20 dB is measured over the bandwidth.

EXPERIMENTS

Experimental Set-up

The experimental set-up for the performance evaluation of the FOML is shown in Fig. 4. A high speed SPDT PIN switch from NARDA Microwave is used to recirculate the incoming pulse through the memory loop. The fiberoptic delay element consists of the reactively matched optical transmitter, optical fiber delay, and the high-speed PIN photodiode. The delay element is 1km of single mode fiber from Siecor, corresponding to a 5μs unit time delay. The insertion loss of the link is compensated by AC coupled low noise amplifiers from MITEQ. To flatten the loop frequency response, a 13 stage gain equalizer from Sierra Microwave Technology (SM31088) is included in the open loop. A variable attenuator (HP11713A) is also employed to control the gain of the circuit actively over the given frequency range of interest. For recirculation of the RF pulse in the loop, the loop gain should be close to unity. In the absence of the RF pulse, the PIN switch is kept open to prevent the noise build-up in the loop. As shown in Fig. 4, the envelope of the pulse is monitored on an oscilloscope after detection, whereas frequency domain characteristics are observed on a spectrum analyzer.

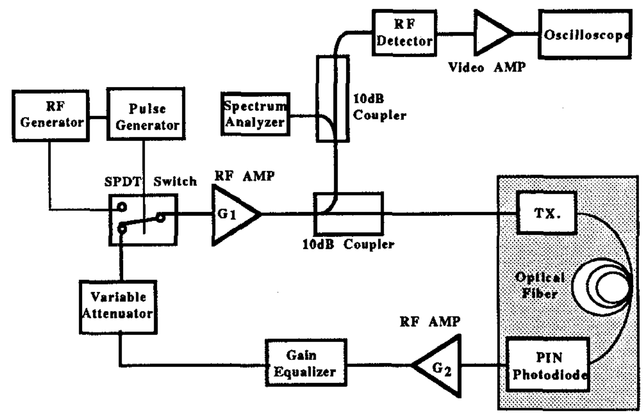

Fig. 4. Experimental set up to study Fiber Optic Recirculating Memory Loop.

Experimental Results

In the experimental set-up, a microwave signal with a pulse repetition rate of 4 kHz was applied to the RF input of the circuit. A TTL logic signal, with the appropriate time delay, switches the SPDT PIN switch from input to the loop circuitry. The RF signal recirculates in the loop for the adjusted time. A pulse signal at frequency of 2.8 GHz was applied to the loop and by adjusting the variable attenuator a loop gain of close to unity was maintained at 2.8 GHz.

One km of single-mode fiber corresponding to 5 μS unit time delay was employed as a delay element. The RF pulse was recirculated for more than 20 times, and the time delay over 100μs was achieved. Fig. 5a shows the train of the detected RF signal recirculating in the loop. For frequencies away from this peak, the loop gain is less than unity and the RF signal decays after few recirculations. On the other hand, when the loop gain is close to unity at a frequency away from the peak of the frequency response, the modulated RF signal does not decay at this frequency. Because of the wide bandwidth of the loop, however, noise at some frequencies has the loop gain of higher than unity, and the circuit leads to a rapid noise build-up, causing oscillation at several frequencies. Once again, for a specified signal to noise ratio, the number of recirculations is limited.

Theoretically, a gain equalizer is capable of flattening the frequency response of the loop over the bandwidth of interest. Even though the gain equalizer reduces the amplitude of the peaks in the open loop frequency response, new harmonically related valleys appeared in the frequency response because of the inter-dependency of each cavity stage.

Train of the decaying signal at 2.7 GHz is depicted in Fig. 5b. The gain of the loop can be increased to unity at 2.7 GHz to compensate for the nonflat open loop gain. For this adjustment, the RF signal at 2.7 GHz does not decay further, and the amplitude of the delayed output signal remains constant. At other frequencies, however, the loop gain will be greater than unity, and noise starts to build-up rapidly. After ten recirculations, noise saturates the amplifier and the signal to noise ratio is so degraded that the signal can not be detected. Fig. 5c shows the train of delayed output at the frequency of 2.7 GHz, where the loop gain was adjusted close to unity for this frequency. As this figure shows, the noise starts to saturate the system after ten recirculations, and the envelope of the RF signal fades in to the background noise.

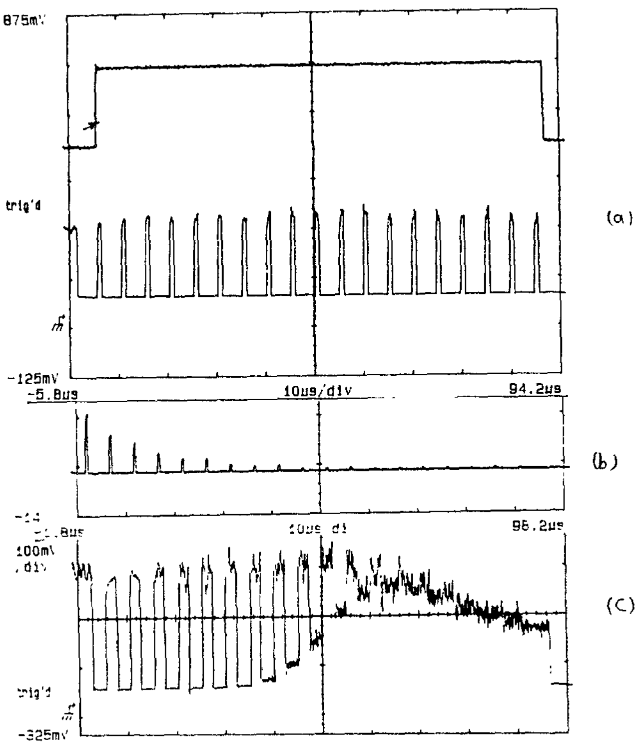

Fig. 5. (a) Train of output pulses for the input pulse at carrier frequency of 2.8 GHz, using the 1 Km of fiber as the delay element. The gain is maximum at this frequency and it is set for unity open loop gain. (b) Train of delayed output at the frequency of 2.7 GHz for loop gain of unity at 2.8 GHz. (c) RF output at the frequency of 2.7 GHz, where the loop gain is unity at 2.7 GHz. (Horizontal scales 10μS/div, the upper trace is switching pulse)

DISCUSSION

The experimental results demonstrate recirculation of pulses at microwave frequencies in the range of sub-milliseconds. Our analytical calculations indicate that, for a fiberoptic based memory loop, the total recirculation times for a flat frequency response reduces from 2300 to only 32 with a gain flatness of ±1dB, where a minimum 10dB S/N is specified.

Our approach is to address the non-flat performance limitation and increase the number of recirculations by: i) reducing insertion loss and noise figure of the fiber optic link, and ii) flattening the frequency response of the closed loop system. Both approaches are currently being pursued. The former requires new structures for laser diodes, which is primarily technology driven, while the second is more realizable with existing technology. We have established two possible techniques: i) an adaptive gain equalization technique, as is presented in another paper in this digest [9], ii) pulse recirculation in both the optical and electrical domains. The optical recirculation would require optical amplifiers in the optical delay path.

For broadband microwave signal processing, pulse recirculation in the optical domain is preferable to the electrical domain. Amplification of the RF pulses in the optical domain can take place either in a fiber amplifier or in a semiconductor optical amplifier. Amplification via an optical fiber takes advantage of the nonlinear property of fiber to amplify the pulsed recirculating signal in the optical domain[10]. Travelling wave laser optical amplifiers offer the advantages of small size and good compatibility with the other elements of the link. For long time delays where dispersion is one of the limiting parameters of the fiber optic links, the 1300nm amplifier is preferable to the others. The polarization dependency of the semiconductor optical amplifier is one of the limiting factors of this amplifier.

REFERENCES

(1) W. Ishak, "4-20 GHz Magnetostatic-Wave Delay-Line Oscillator", *Electronics Lett.,* 83 vol. 19, no.22, pp.930-931.

(2) R. M. Montgomery, "Photorefractive Adaptive Antenna Array Processor", *Proc., SPIE,* vol. 1217, OE. Laser 90, Los Angeles, CA, Jan. 1990.

(3) C.T. Chang, J.a. Cassaboom, and H. Taylor "Fiberoptic Delay Devices for R.F. Signal Processing", *Electronics Lett.* 77 vol. 13, no.22, pp.678-680.

(4) A.S. Daryoush, N. Samant, E. Ackerman, and D. Kasemset,"Interfaces for High Speed Fiberoptic Links," *IEEE MTT International Microwave Symposium Digest,* Boston MA, June 1991.

(5) R.M. Fano, "Technical Limitation on the Broadband Matching Arbitrary Impedances," *J. Franklin Institute,* vol. 249, pp. 57-83 139-154, Jan./Feb. 1950.

(6) A.S. Daryoush, E. Ackerman, R. Saedi, R.R. Kunath and K. Shalkhauser,"High-Speed Fiber Optic Links for Distribution of Satellite Traffic," *IEEE Trans. Microwave Theory Tech.,* vol. MTT 38, May 1990.

(7) P. Hill, R. Olshansky, J. Schlafer, and W. Powazinik, "Reduction of Relative Intensity Noise in 1.3 mm InGaAsP Semiconductor Lasers," *Appl. Phys. Lett.,* vol. 50, no. 20, pp. 1400-1402, May 1987.

(8) G. D. Khoe, et.al "Progress in Monomode Optical fiber Interconnection Devices," *Journal of Lightwave Technology,* vol. LT-2, pp. 217-227 June 1984.

(9) A. Madjar, B. Even-Or, and E. Gertel, "A Novel 2-4 GHz Multi-Passband Tunable and Gain Controlled Miniature Active Equalizer," *IEEE MTT International Microwave Symposium Digest,* Boston MA, June 1991.

(10)D. Desurvire, Michel J. F. Digonnet, and H. J. Shaw, "Theory and Implementation of a Raman Active Fiber Delay Line," *Journal of Lightwave Technology,* vol. LT-4, April 1986.