Short Papers

Reduced Insertion Loss of X-Band RF Fiber-Optic Links

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Abstract —**Fiber-optic links offer the promise of providing the microwave system designer with new flexibility and capabilities for use in radar and avionics systems. Results presented in this paper show a significant reduction in link RF insertion loss from the typical 40 dB at X-band (9 GHz) to 7 dB with a 3 dB bandwidth of 800 MHz while maintaining a signal-to-noise ratio (SNR) greater than 125 dBc/Hz. This 33 dB improvement can lead the way to many uses of fiber optics in microwave designs, especially for short-distance applications, where currently used waveguide or coax cables have low insertion loss.**

I. Introduction

A microwave X-band fiber-optic link with a typical insertion loss of about 40 dB was optimized in an experimental research project to obtain a less than 10 dB RF insertion loss while maintaining an SNR greater than 125 dBc/Hz (dB relative to the RF carrier in a 1 Hz bandwidth). This large reduction in link loss is a significant step in achieving many system applications for fiber-optic links at microwave frequencies, in which fiber-optic links of less than 100 ft might find it difficult to compete with coax cable or waveguide. The result indicates what might be possible for fiber-optic links.

To meet the full potential of future advanced radar systems, with their vast data collections and processing capabilities, will require a superfast, highly efficient data communication and transfer system. Fiber-optic links offer the promise of meeting those requirements. They are not susceptible to radio frequency noise and are capable of operating at very high data rates and at high radio frequencies without creating opportunities for interception and detection. The light weight and small size of fiber-optic cables may allow the use of highly redundant paths between units, thus improving reliability and damage tolerance. Finally, the EMI immunity of fiber-optic cables will reduce equipment failures caused by electrical power transients and could also improve the capabilities and reduce the size and weight of radars and other avionics systems.

While optical fibers and associated components such as high-frequency laser transmitters and photodiode detector receivers, optical connectors and splices, and multiplexing circuits based on silicon and gallium arsenide devices are now available, the technology for applying, interfacing, and packaging the components for use in avionics systems is very new. Realizing the potential of this technology will require a higher level of understanding of its capabilities and limitations than presently exists, particularly as it would be applied in the microwave spectrum. The reduction of link RF insertion loss will be a key factor in speeding up the near-term use of fiber-optic links in microwave systems.

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II. Fiber-Optic Link with Low Insertion Loss

Fiber-optic links for use in microwave systems will provide to the microwave system engineer the expanded design capability necessary to realize the full potential of future advanced systems. But they also can add a sizable RF insertion loss to the system. Reduction in the typical fiber-optic link RF insertion loss at microwave frequencies can be obtained by improving the typically configured, directly modulated link optical performance and by using RF impedance matching. The optical throughput can be increased by selecting efficient link optical components and increasing the optical coupling into and out of the connecting fiber-optic cable. The RF insertion loss can be reduced by matching techniques at the input and output terminals of the fiber-optic link. Both optical and RF improvements can be accomplished while retaining good link system performance, i.e., SNR, intermodulation (IM) distortion, etc.

A fiber-optic link includes a semiconductor laser transmitter, a single-mode fiber-optic cable, and a semiconductor photodiode detector receiver. The RF signal input and output terminals are isolated, respectively, from the laser input dc drive current and the photodetector output diode current by a bias network consisting of a capacitor and an inductor. The dc current into the laser causes the laser to produce a light intensity output once the current is above the laser threshold current, and the RF input amplitude modulates the laser light intensity. The photodetector converts the light intensity back to a current whose amplitude varies coherently with the input RF modulation. Because both the laser and the photodiode are active devices, they can add noise. Also, because they have some nonlinearity, they can cause intermodulation signal products in a system. Typically, these additions are relatively small, so the fiber-optic link has many useful microwave applications.

The potential of reduced insertion loss by RF passive reactive narrow-bandwidth matching and improved optical performance should be traded off against the potential degradation of other link performance parameters. In many RF applications, this trade-off is an acceptable one.

III. Minimization of Loss of Contributors to Link Insertion Loss

The major contributors to the RF insertion loss, the loss from RF link input to RF output, are shown along with a fiber-optic link diagram [1] in Fig. 1. There are seven major sources of loss in the fiber-optic link, which account for the typical RF insertion loss of about 40 dB at X-band. These sources of loss are also shown in Fig. 1, along with an equation that shows their contribution on the link output power. For other than very long links (many kilometers), the fiber cable loss (typically about 1 dB per kilometer) and connector loss (typically about 1 dB per connec-

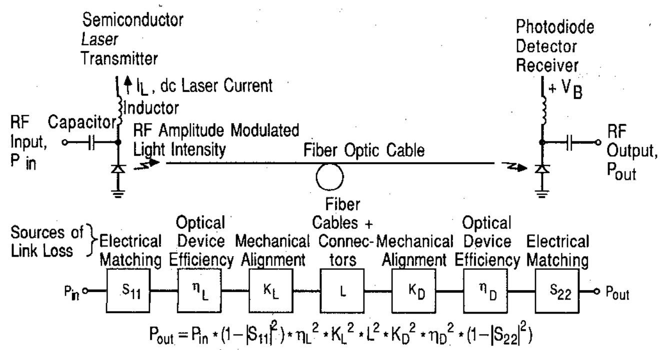

Fig. 1. Directly modulated microwave fiber-optic link and contributors to insertion loss.

tor) are by far the smallest contributors. The other six losses, as shown in Fig. 1, are all major losses for microwave links that use single-mode fiber and operate at a 1.3 μm optical wavelength. All of these losses were minimized to obtain the net 7 dB link insertion loss.

To minimize these losses, we have developed a 1.3-μm-wavelength optical transmitter (laser) and receiver (photodiode) and fusion spliced their single-mode fiber pigtails together to produce a fiber-optic link with about 5 m of fiber and with low insertion loss for X-band (9 GHz) range of RF signals. We have improved the optical performance and made provision for the insertion of RF impedance matching circuits for a fiber-optic link that is a modification of a typical Ortel high-frequency link. First, we obtained about 11 dB of link insertion loss improvement, when compared to a typical link, by removing the "standard" broad-band 50 Ω resistive RF matching at the input and output of the links. This typical 50 Ω broad-band matching of a fiber-optic link does minimize link RF reflections but does not obtain maximum power transfer to the low-impedance laser and output from the high-impedance photodiode detector. Next, we optimized the optical performance of the link to reduce its RF insertion loss by about 13 dB. We accomplished that by selecting lasers and photodiodes with better device optical efficiency and by optimizing the mechanical alignment for increased light coupling of both while maintaining low reflections. Finally, we used RF passive reactive narrow-bandwidth matching circuits to obtain maximum power transfer, which further reduced the link insertion loss by about 9 dB at 9 GHz with an 800 MHz (about 9%) 3 dB bandwidth. Each of these are large reductions in link insertion loss and the total is a significant improvement of about 33 dB, which will allow fiber-optic links to be considered for many radar and avionic systems applications.

IV. Modified Laser and Photodiode Package

In accomplishing the low RF insertion loss, we modified the standard Ortel laser and photodiode detector high-frequency packages so that RF substrates for RF matching circuits could be inserted into each package. Fig. 2, an exploded drawing of the laser package concept, shows the RF substrate, which is interchangeable, and also shows the laser on its submount. The photodiode package modifications were similar, and a picture of this package with the passive RF matching is shown in Fig. 3.

The modified packages allow for insertion of different RF substrates; thus, different matching circuits can be exchanged and tested. Moreover, by exchanging the matching circuits in the same link, we can compare them directly by separating matching circuit improvements from the link optical performance. All matching circuit improvements are evaluated by comparison with

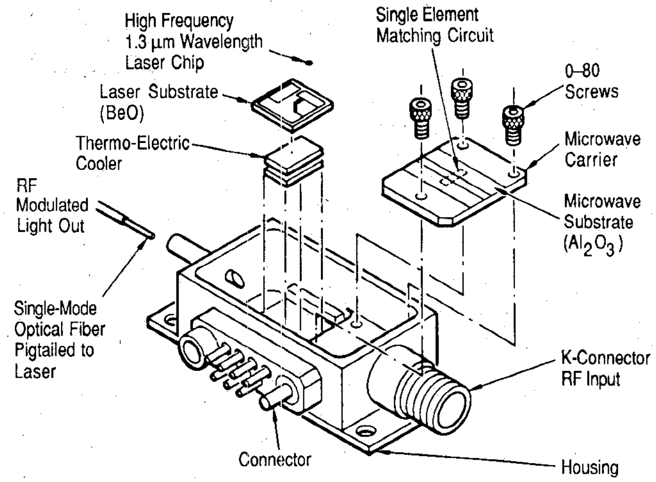

Fig. 2. Improved transmitter package for reduced insertion loss.

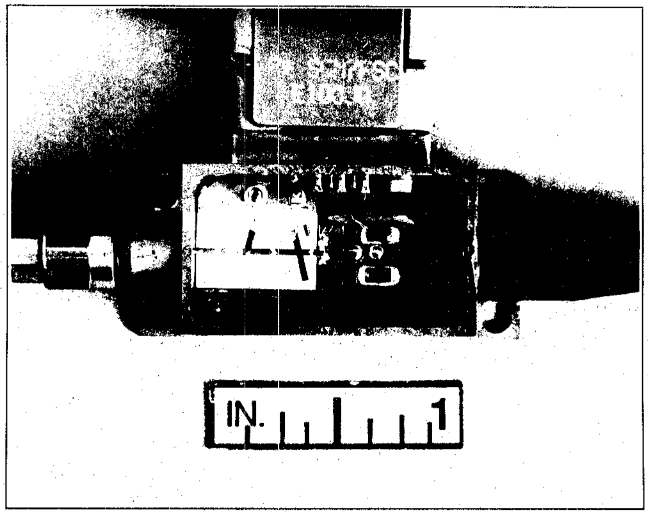

Fig. 3. Picture of modified photodiode package with two-element passive RF reactive narrow-bandwidth matching.

a standard (typical commercial practice) 50 Ω resistive broad-band RF laser input and photodiode output matching circuit. The replaceable RF substrate technique provides a concept that can be used for making impedance matching link comparisons while maintaining the same optical component configuration.

V. Test Data

The improved insertion loss link test data were taken using a network analyzer, and the link throughput (S_{21}) amplitude, in relative dB, was plotted versus frequency in GHz. Fig. 4 shows a network analyzer plot of a typical Ortel high-frequency link throughput along with the input return loss (S_{11}). For this link the RF insertion loss at 9 GHz is about 36 dB. This link did have optical connectors rather than a fusion splice, but it did not have a 50 Ω RF output broad-band matching resistor in the photodiode output. Thus, its insertion loss of 36 dB is several dB less than the typical value, approximately 40 dB, expected at 9 GHz. Fig. 5 shows a plot of throughput, or insertion loss (S_{21}), for the specially modified fiber-optic link, for the link with only the optical improvements (curve *1*) and no broad-band 50 Ω input or output RF matching resistors. Curve *2*, in Fig. 5, shows the link with both optical and RF narrow-bandwidth reactive matching improvements. The link SNR was measured and found to be

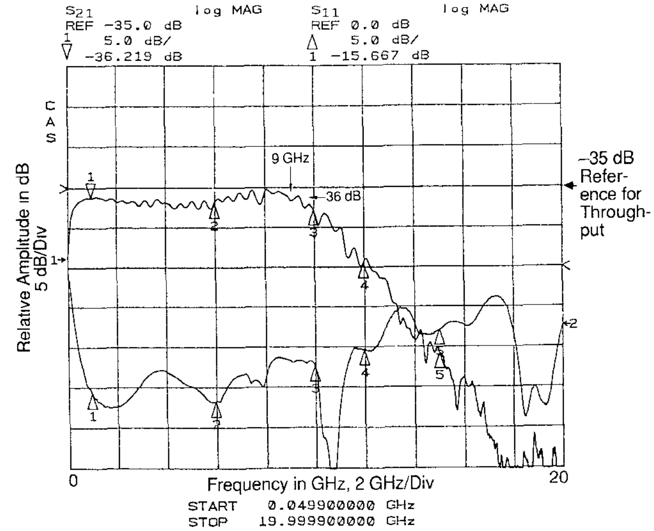

Fig. 4. Typical high-frequency fiber-optic link RF insertion loss characteristics.

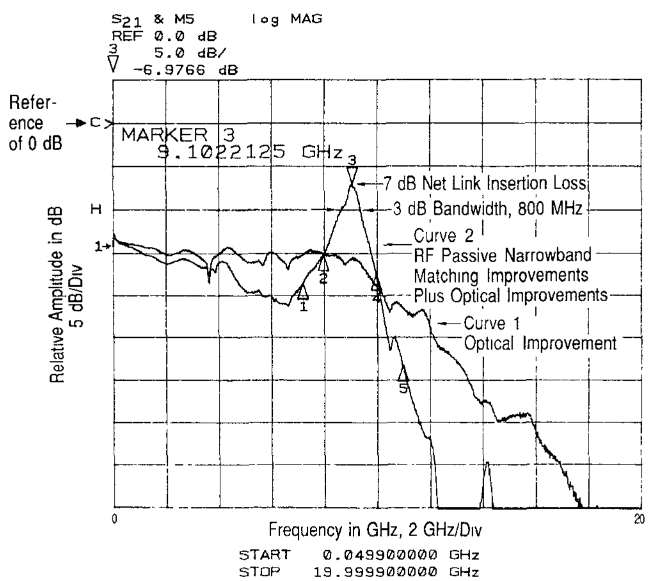

Fig. 5. Modified fiber-optic link RF insertion loss with optical and RF matching improvements.

about 125 dBc/Hz over the 800 MHz bandwidth. This value will meet most modern high-performance radar SNR requirements. Link IM measurements were also made and they showed an input IM third-order intercept point of 18 dBm. This value of IM is about the number for a typical fiber-optic link and also for a low-noise RF amplifier.

VI. Summary

We have reduced the insertion loss of an experimental high-frequency fiber-optic link to 7 dB with an 800 MHz (9%) 3 dB bandwidth at 9 GHz by improving the link optical performance and by using reactive passive RF impedance matching. This is a significant improvement from the typical X-band RF 40 dB link insertion loss and could help to open the way to many microwave applications of fiber-optic links in radar and avionics systems.

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Long Microwave Delay Fiber-Optic Link for Radar Testing

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Abstract —**A long fiber-optic delay line is used as a radar repeater to improve radar testing capabilities. The first known generation of 152 μs delayed ideal target at X-band (10 GHz) frequencies having the phase stability and signal-to-noise ratio (SNR) needed for testing modern high-resolution Doppler radars is demonstrated with a 31.6 km experimental externally modulated fiber-optic link with a distributed-feedback (DFB) laser.**

I. Introduction

Fiber-optic (FO) links are potentially important for many applications in current and future radar and avionic systems [1]. Fiber optics offer many advantages for microwave and high-speed digital signal transmission, including wide bandwidth, low loss in fiber, light weight, small size, and EMI resistance. Furthermore, fiber optics can provide RF delays much longer than practical with coaxial cable or waveguide at X-band (10 GHz) frequencies. In this paper, we present a new and unique application of a fiber-optic link in a radar test set. Using a 31.6 km length of fiber to obtain a 152 μs delay line in a radar repeater test set, we generated an ideal target for testing radars with very long RF transmitter pulses. The experimental fiber-optic link included an external modulator operated with a DFB laser and a specially selected low-loss, single-mode fiber matched to the laser wavelength to obtain very low dispersion for achieving large bandwidth–length performance. Present radar systems that use an external test target repeater must operate with a long-distance separation between the test target repeater and the radar and with the competing external environmental interference. This is the first known implementation of X-band modulated fiber-optic links with radar systems that utilize transmitted waveforms with very long RF pulses needed for long-range, high-performance operation. The successful tests, in which pulse compression peak side lobe measurements were used to confirm the link RF phase

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