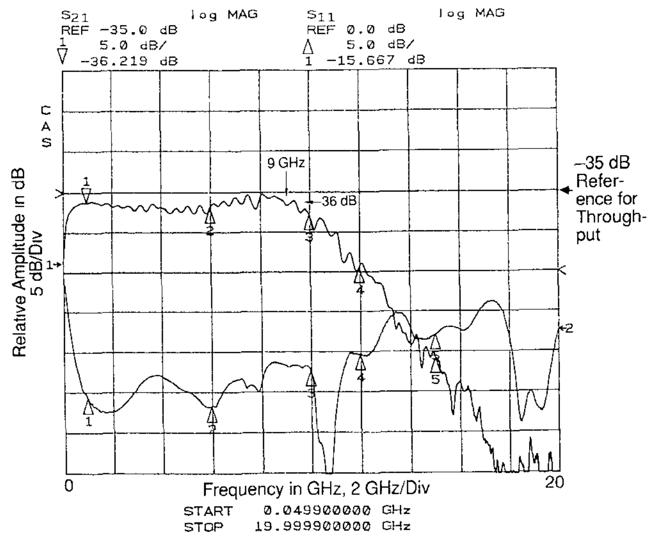


Fig. 4. Typical high-frequency fiber-optic link RF insertion loss characteristics.

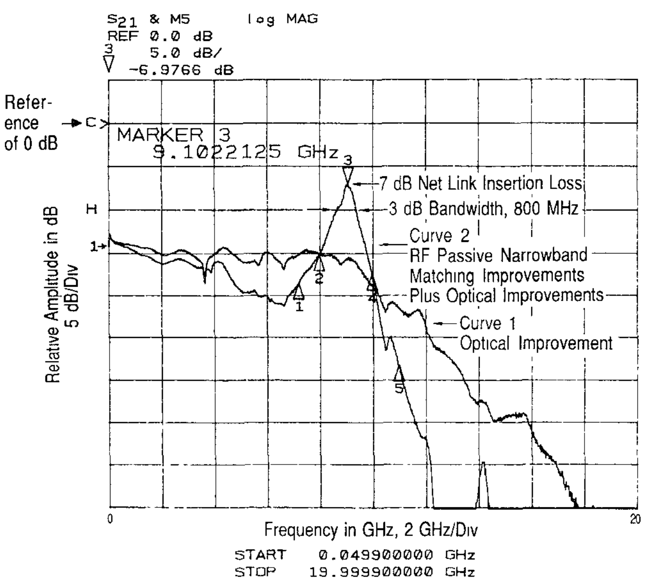


Fig. 5. Modified fiber-optic link RF insertion loss with optical and RF matching improvements.

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.

## Acknowledgment

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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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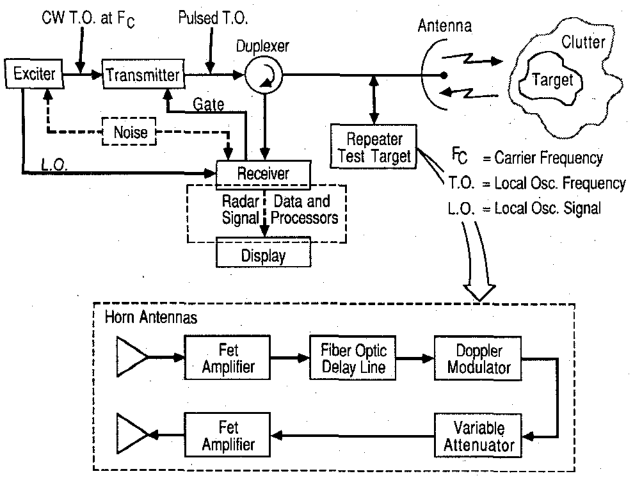


Fig. 1. A radar system with a collocated repeater test set to provide the delay that is generally achieved with a test target located many miles from the radar. A fiber-optic delay line is incorporated in the repeater.

linearity and SNR performance, demonstrate that these fiber-optic links can meet the stringent SNR and phase linearity and stability requirements for Doppler radar systems that use pulse compression waveforms to obtain long-range operation with high resolution.

## II. Test Set Application

The application of high-speed fiber-optic links in a radar repeater test set is shown in Fig. 1, where the fiber-optic repeater test set is collocated with a radar system. The radar system includes an exciter unit that generates a low-noise, coherent CW RF signal with a pulse compression waveform that is amplified in the transmitter and pulsed at a pulse repetition frequency (PRF). The duplexer directs the transmitted energy out of the antenna and the received energy into the receiver while providing isolation between the two of them. The received signal is processed in the radar signal and data processor. During the transmit pulse, the receiver is blanked to prevent damage to the receiver by the transmitter pulse output. Pulse compression waveforms are used to obtain good radar range resolution while achieving high average power output to obtain long-range target detections. The waveform is encoded with phase or frequency coding that allows the return radar signal to be specially processed to "compress" (autocorrelate) it to obtain a very narrow pulse from the long coded pulse (thus the name of pulse compression).

Current repeater test targets are typically located several miles from the radar to achieve sufficient delay for the radar to receive its transmitted pulse. The delay in this case is obtained by the time required for the radar transmitted pulse to reach the repeater and be retransmitted as a target return to the radar. The fiber-optic repeater provides the long delay required for the radar to receive and process its own transmitter pulse with the repeater test set independently operated while being collocated with the radar.

## III. Link Configuration

The long delay and high-frequency specification for this application required a specially designed fiber-optic link. The fiber-optic link, illustrated in Fig. 2 and shown pictorially in Fig. 3, consists of a 1.3 $\mu$m CW DFB laser transmitter, a GRIN (graded index) lens for focusing the light, an optical isolator to minimize reflected light into the laser, a traveling-wave $LiNbO_3$ electro-optic modulator [2], a long (31.6 km) single-mode fiber, and a high-

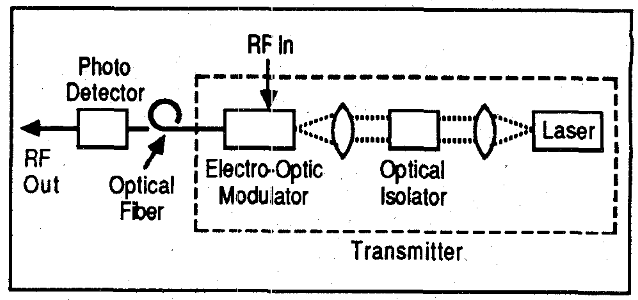


Fig. 2. External modulation fiber-optic link.

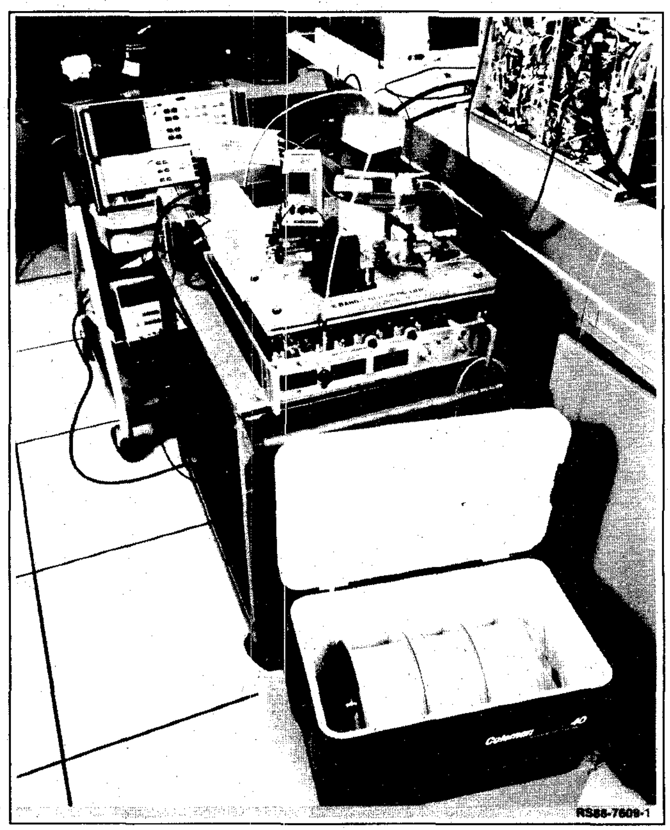

Fig. 3. Fiber-optic link test target with 152 $\mu$s delay.

speed photodiode detector receiver. The major advantages of the external modulation technique over the more typically used direct laser modulation technique for this application are the high microwave frequency operation (currently up to 18 GHz with potential for much higher frequencies in the millimeter waves) of the external modulator and the ability to separately select a DFB (as opposed to a multimode) laser transmitter with a very narrow (light spectrum) line width for low dispersion performance over the long fiber length. The fiber used had its zero dispersion wavelength specially matched to the wavelength of the DFB laser. Because the fiber has a zero dispersion slope [3] of 0.092 ps/(nm$^2$·km) the dispersion of the link was calculated to have a light dispersion through the 31.6 km of fiber of approximately 1 ps. This means that after the 152 $\mu$s fiber delay, a 10 GHz RF signal amplitude modulated on the light would arrive with less than 5° of phase difference caused by dispersion in the fiber. By comparison, a typical 1.3 $\mu$m multimode Fabry–Perot semiconductor laser will have a line spectrum of about 3 nm width, which could cause 50 ps dispersion over 31.6 km of fiber. Because 50 ps

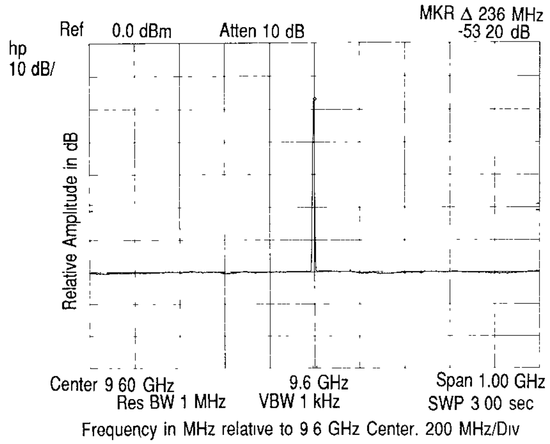


Fig. 4. 113 dBc/Hz (53 dBc/MHz) signal-to-noise ratio curve of fiber-optic link with 31 6 km fiber cable

represents 180° of phase at 10 GHz, this RF spread in delay would cause partial cancellation of the desired signal.

Several other potential error sources, in addition to the above-mentioned dispersion effects, are temperature and vibration effects. Both of these effects can cause phase errors (which result in an amplitude distortion) in the modulated RF signals sent over the long fiber-optic cable. Temperature changes affect the delay in the fiber link in two ways. Both the speed of propagation in the fiber and the overall length of the fiber will change as a function of temperature. The delay variation due to a change in the speed of propagation is about an order of magnitude greater than that due to the change in fiber length. The change in speed of the light propagation in the fiber is proportional to the change in the fiber index of refraction, and has a value of approximately $1\times10^{-5}$ per °C. The change in length of the fiber due to expansion or contraction of the fiber is approximately $6\times10^{-7}$ cm/cm/°C. Thus, for a 1°C change in temperature, the delay change due to the change in speed of propagation in the 31.6 km length of fiber is about 1500 ps or 15 wavelengths (5400° of phase) at a signal frequency of 10 GHz. A 1°C change in temperature will also cause the 31.6 km length of fiber to change by about 1.5 cm. This length change represents about a 180° change in phase at 10 GHz. Vibration effects can cause changes in delay times (and thus phase) in the fiber because of flexing of and pressure on the fiber cable.

Both temperature and vibration effects were minimized in the long length of fiber by placing the fiber delay line in an insulated container. For radar testing, only the short-term effects, i.e., measured in milliseconds intervals, will cause problems. This is because of the way that radar signals are processed in a radar system. The insulated container provided sufficient isolation from both temperature and vibration to minimize those effects on performance.

## IV. Link Testing

The output SNR of the link with the 31.6 km of single-mode fiber was about 113 dBc/Hz (dB below the carrier in a 1 Hz noise bandwidth). Fig. 4 shows a signal-to-noise ratio curve taken using a spectrum analyzer over a 1 GHz frequency range using a low-noise 9.6 GHz CW signal source as input to link. RF FET amplifiers were used to establish usable RF levels at the link input and output. The 31.6 km long fiber had an equivalent electrical loss of about 22 dB (11 dB optical), and the DFB laser and external modulator fiber-optic link connected without the fiber cable had an "electrical" insertion loss (RF in to RF out) of about 60 dB. The SNR of 113 dBc/Hz is more than adequate, and extrapolation of the link SNR to obtain an estimate of potential maximum length of fiber cable that could be put in the fiber-optic link indicates that a 100 km length of fiber could be used to obtain a usable narrow bandwidth SNR. A length of 100 km would provide about a 500 μs delay. The limit on maximum delay is established by both the dispersion effects and fiber attenuation in the long cable. Further improvements in components and cable could extend the 500 μs estimate.

The link performance was tested by installing it in a laboratory area with a radar system requiring the long delay and small phase distortion in its long pulse compressed waveforms. The results of these tests demonstrated the link performance. By measuring radar peak side lobes on the radar processed pulse compressed waveform with and without the fiber-optic link in the radar system, we determined that the fiber-optic link did not degrade the radar performance and that the addition of the fiber-optic link's long delay allowed the radar to evaluate its own performance within the laboratory for the first time.

Radar systems that use long transmitter pulses to obtain high average power for long-range operation and use pulse compression to obtain good range resolution (for separating closely spaced targets) require good phase linearity and SNR for up to several seconds during the processing time of the long radar pulses. Thus, the minimum dispersion achieved with the fiber-optic link is required for modern pulse Doppler radars. The radar itself is the best test set for evaluation of its own overall end-to-end performance, and the fiber-optic delay line repeater test set provides for the first time an "ideal" target return for the radar to process and evaluate.

## V. Conclusions

We have demonstrated that fiber optics can improve the capability of radar test set systems. With the use of a 1.3-μm-wavelength DFB laser and an external modulator connected to a long fiber cable to provide long (152 μs) delays with minimum dispersion at $X$-band (10 GHz) frequencies, performance measurements can be made on modern Doppler radars utilizing long transmitter pulses. The results show that fiber-optic links will meet the stringent phase and noise requirements of modern radars at high microwave frequencies. Thus, fiber optics provides a unique and needed capability for testing many radars that has not been possible before, and in the future, delays of up to 500 μs may be obtained.

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