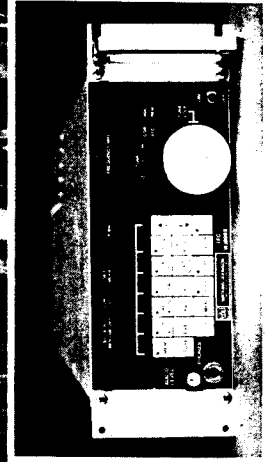
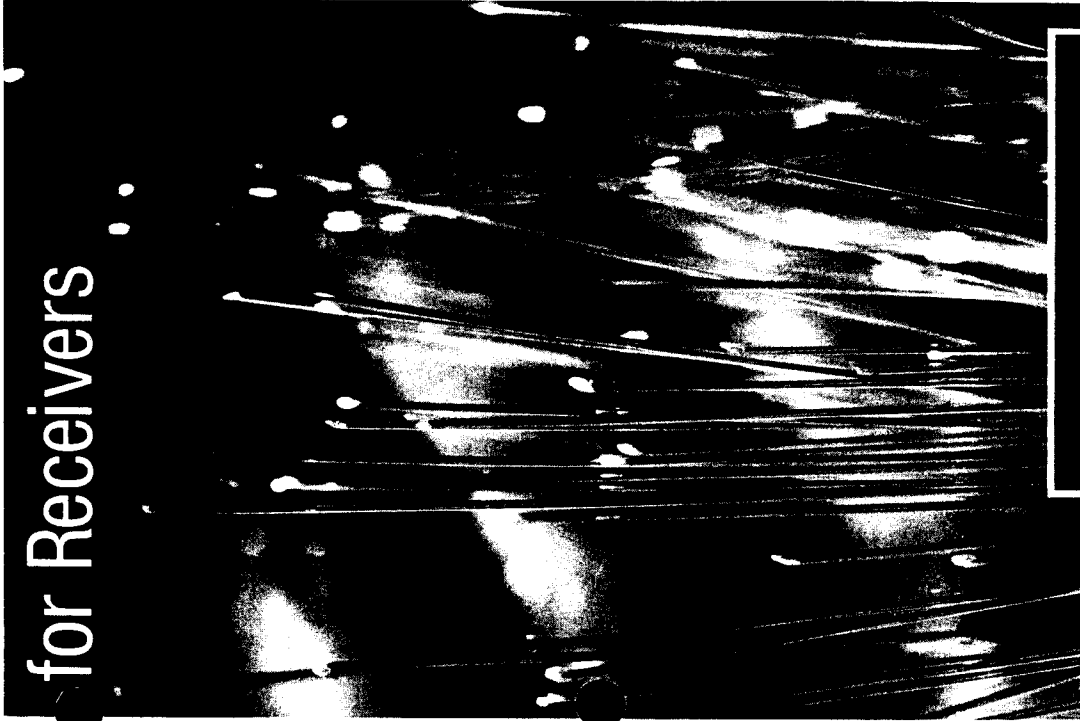


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Fiber-optic links have several qualities which readily lend them to use in situations where transmission security is the major priority. Optical fiber is immune to EMI and it emits no electromagnetic radiation to the surrounding environment. Ground loops, which pose significant problems when using conventional electrical cable, have no equivalent in optics. Crosstalk between adjacent cables is minimized by the coating which surrounds the fiber. Glass fiber, in general, is a low-loss medium; it can support greater bandwidths than metallic conductors, with markedly lower signal attenuation. In addition, fiber-optic cable is small and lightweight; in fact, the protective jackets which support the fiber make up the bulk of the cable.

The above attributes make fiber optics ideally suited for applications in the field of signal intelligence (SIGINT). Information from remote antennas can be relayed several kilometers without repeaters, and a higher data rate can be supported by fiber-optic cable than by conventional cable. Fiber-optic links are unaffected by strong electromagnetic fields or proximity to high-voltage lines. The particular application discussed in this paper draws on the measure of security which fiber optics ensures the user.

Specifically, emissions from a microwave receiving system are highly vulnerable to interception when conducted through cable which emits electromagnetic radiation. Due to the high frequency of the RF input to microwave receivers, typical installations have the tuner remotely located near the antenna to minimize RF cable losses. Thus, in a typical system, a relatively long transmission line is required at the system intermediate frequency (IF). Use of a fiber-optic transmission line for this IF path

greatly improves the system electromagnetic security.

## General Requirements and Definitions

The general requirement which is addressed in this paper is to provide a fiber-optic link which will support receiver IFs of 70 and 140 MHz, provide sufficient dynamic range to support the SIGINT mission requirements, and work over a 100-meter path length.

Critical SIGINT system parameters are phase noise (jitter), dynamic range, group-delay distortion, intermodulation distortion, and passband ripple. The phase noise is determined by the local oscillator used in the microwave sensor, so it will not be discussed regarding fiber optics. Dynamic range is defined throughout this paper as the difference from the minimum discernible signal (MDS) to the 1-dB compression point. MDS is the point where the received signal is equal to the noise in a 1-MHz bandwidth, and the 1-dB compression point is defined as the level where the gain is reduced by 1 dB.

Phase linearity (group-delay distortion) is an important parameter to consider when implementing modulation schemes such as frequency-division multiplexing (FDM) or time-division multiplexing (TDM). In an FDM scheme, the signals in several distinct channels are positioned in non-overlapping frequency bands, allowing the information to be recovered by selective filtering. In a TDM scheme, each signal is sampled, the "samples are interleaved, and a single composite signal consisting of all the interleaved pulses is transmitted over the channel."<sup>[1]</sup>

Older, analog microwave systems employ FDM with a frequency-modulated carrier. Modern digital communication systems use an encoding scheme such as pulse-code modulation (PCM),

which may employ phase-shift keyed (PSK) modulation or quadrature amplitude modulation (QAM). At higher data rates, low group-delay distortion is required to preserve the coded information. Group delay is mathematically defined as the derivative of phase with respect to frequency and, in practice, represents the time required to pass a signal through a device. If the magnitude of the group-delay distortion is not well below that of the pulse width, the transmission error may be unacceptable. Subsequently, to support a tuner with a 5-10 ns group-delay distortion at IF, the fiber-optic link should maintain less than 1 ns of distortion; this yields excellent phase performance in the majority of encoding schemes.

Noise power ratio (NPR) is a comprehensive figure of merit which indicates the performance of the entire transmission path. In the majority of applications, a 40-dB system NPR is considered the benchmark for telecommunication applications, so 40 dB is used here as the NPR specification. NPR testing of an FM/FDM system is achieved by white-noise loading to reproduce the state where all channels are being used; band-reject filters can then be used to remove the noise from a particular channel. Intermodulation distortion products may fill in the channel, limiting the achievable NPR, making a high third-order intercept point desirable. The ratio of the output noise measured with white noise in all channels to the output noise measured with the white noise notched out of the selected channel is the NPR. The highest NPR is achieved when the least amount of noise fills the channel, representing the best system noise performance.

## Optical Source

One of the most significant decisions

to be made when designing a fiber-optic system is selecting the type of optical transmitter. The transmitter converts an electrical signal to an optical signal; a bias current is applied to maintain the optical source in its linear operating region, while the IF signal modulates the intensity of the light. This variation in intensity optically transmits the electrical information contained in the IF signal (see Figure 1).

The optical source can take the form of either a light-emitting diode (LED) or a laser diode, two distinctly different devices. LEDs are semiconductor pn junctions which use the refractive properties of the materials to guide the optical emission. The active area is wedged between two semiconductor layers with higher band gaps and different refractive indices than the active layer. The differing energy levels of the materials limit photon generation to the active zone, and the difference in refractive index then confines the carriers. The overall structure is termed a *double heterojunction*, as shown in Figure 2. The generated light has a fairly large spectral width, and the energy is emitted over a broad solid angle as allowed by the opening to the active layer. A lens is usually added to focus the light, improving the efficiency of this type of transmitter.

Laser diodes are similar to LEDs in that they use a double-heterojunction structure and the light is guided by the properties of the surrounding materials, but the fundamental difference is the emission process. The LED radiates when one excited electron recombines with a hole, causing spontaneous emission of a photon, whereas in a laser diode photons induce more recombinations, stimulating increased numbers of coherent photons (see Figure 3). It is this coherence which results in the laser diode's narrow spectral width. The structural difference which makes

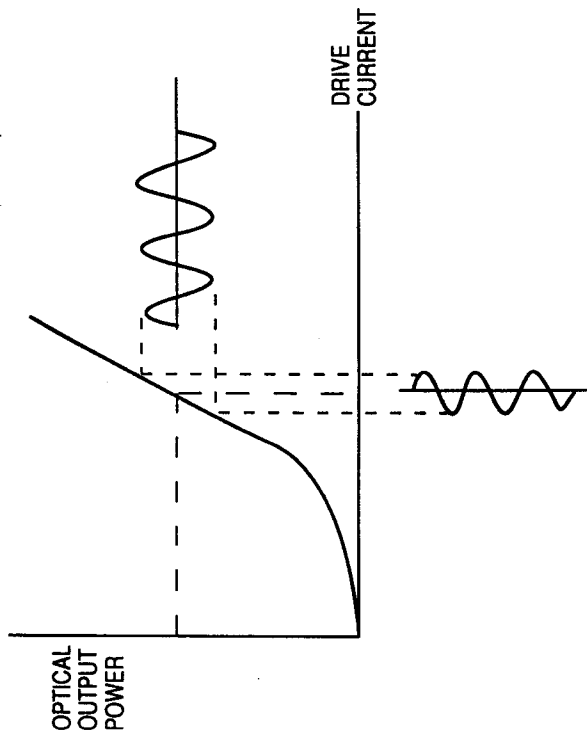
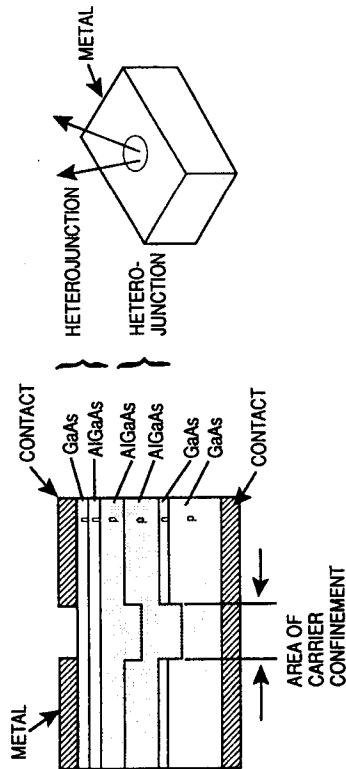


Figure 1. Optical source biased for linear modulation.



Reprinted Courtesy of AMP Incorporated

Figure 2. Typical double-heterojunction LED structure.

stimulated emission possible is the optical cavity formed by highly reflective mirrors or corrugated waveguide which repeatedly reflects the photons through the cavity. These photons

stimulate the emission of more photons, and when a high enough density of excited particles exists, a highly collimated beam of coherent light is emitted (see Figure 4).

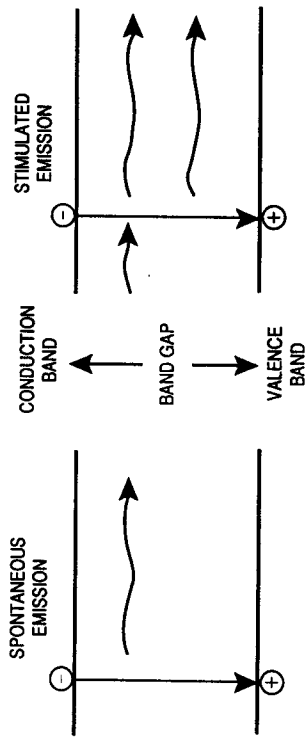


Figure 3. Spontaneous vs. stimulated emission.

Laser diodes offer a great improvement over LEDs in terms of output power, spectral width, and modulation bandwidth, but there are other factors which must be considered when choosing the optical source for a system. A laser diode is much more complex, and can generate enough heat to affect the wavelength of light emitted. It often requires a built-in thermoelectric cooler which, in turn, draws a large amount of current. A photodiode is also included to monitor the output power level, allowing for automatic control. As a result, the laser diode can cost 10 to 100 times more than an LED and consumes significantly more power; the cooler alone typically consumes 1 watt of power. The laser diode offers wider modulation bandwidth capabilities due to a much faster rise time than an LED; the typical limit for the bandwidth of an LED is 100 MHz, while laser diodes commonly operate to 1 GHz. A laser diode generally produces on the order of 1 mW of optical power, while an LED's power is roughly 0.1 - 0.25 mW.

If the intended application involves long-distance digital transmission, the laser diode may be the most appropriate emitter, but for analog signal applications, linearity is the key parameter. LEDs offer better linearity than

laser diodes due to the difference in their structures. A laser diode needs a certain threshold current and must be biased far enough above this value to operate in the linear portion of its characteristic curve. Even in this range, "different portions of the beam exhibit different linearity characteristics. In practical situations, the good linearity is often useless because of strong noise sources such as modal noise and optical feedback noise." [2] The good theoretical linearity of the laser diode, shown in Figure 5, is not achieved in practice.

LEDs, in general, are more linear than laser diodes. One of the sources of non-linearity in a laser diode is optical feedback noise due to reflected light which upsets the oscillation in the optical cavity. An LED has no optical cavity and is, therefore, much less sensitive to reflections than a laser diode. The linearity, low power consumption, ease of operation, and low cost of the LED make it the best optical source for transmission of analog IF signals.

### Wavelength of Operation

Once the type of optical source has been selected, the wavelength of operation remains to be decided. Technology is centered around transmission wave-

lengths of 820 nm, 1300 nm, and 1550 nm. Transmitters at 820 nm are the simplest to manufacture and much of the established technology exists in this region. Transmission at 1300 nm and 1550 nm offers very low attenuation, less than 1 dB/km of fiber, so for long-haul systems of several kilometers, one of the longer operating wavelengths should be selected. Based on these characteristics, an 820 nm LED was chosen to transmit over the 100-meter distance between the tuner and demodulator.

### Mechanical Considerations

A package style with a built-in lens system was selected that would mount easily onto a PC board and provide high repeatability for connections to optical fiber. The connector is part of the LED's package, allowing for very reliable connections with no risk of damaging the lens. The casing is highly resistant to heat and chemical damage, although a sharp impact may damage the lens. The junction sizes of optical transmitters are, in general, very small, increasing their sensitivity to electrostatic damage if standard precautionary measures are not taken. Ambient light, however, will not damage the optical transmitter or receiver, as the fiber-optic components function in the infrared region of the spectrum. When installed in a system, the LED can be treated as a fairly rugged transmitter, since the user only has access to the optical connector.

### Fiber-Optic Cable

Fiber-optic cable is often optimized to transmit a specific wavelength, so it should be selected after the source is known. The primary specifications of fiber are size, acceptance of light, bandwidth, and attenuation. Fiber size is given by two numbers: the diameter of the core and diameter of the clad-

ding. As an example, a 62.5/125 micron cable has a core diameter of 62.5 microns, and a cladding diameter of 125 microns. Light propagates through the core and is confined to this region by the cladding, a material with an index of refraction very slightly different from that of the core, such that it reflects the light back into the core.

Fiber which has a core fixed at one refractive index is called step-index as there is a sharp jump from the core index to the cladding index. Rays of light travelling at different angles in the fiber travel at different speeds, resulting in modal dispersion, which limits the useful bandwidth of a cable. Graded-index fibers were developed to minimize this dispersive effect. In these fibers, the core index increases gradually to that of the cladding, allowing rays travelling a longer distance to have the same average speed as rays at the center. Modal dispersion can be eliminated by using single-mode fiber as opposed to the multi-mode fiber discussed above, but this fiber is expensive and must be aligned exactly, so it is reserved for more exacting laser-based applications (see Figure 6).

System performance depends on the modal dispersion in the cable and the length of cable used. Fiber-optic cable is specified by a length-bandwidth product; for example, the cable can support a 300-MHz modulation bandwidth over 1 km or 3-GHz modulation bandwidth over 100 meters. For the system under consideration, a 100/140 micron cable was selected with a length-bandwidth product of 300 MHz-km. For a 100-meter transmission distance, this cable has more than sufficient bandwidth, and allows negligible degradation of system performance at low cost. With only 0.5-dB loss over the 100-meter distance, this system has a useful range of closer to 500 meters, limited by the optical output power of the LED.

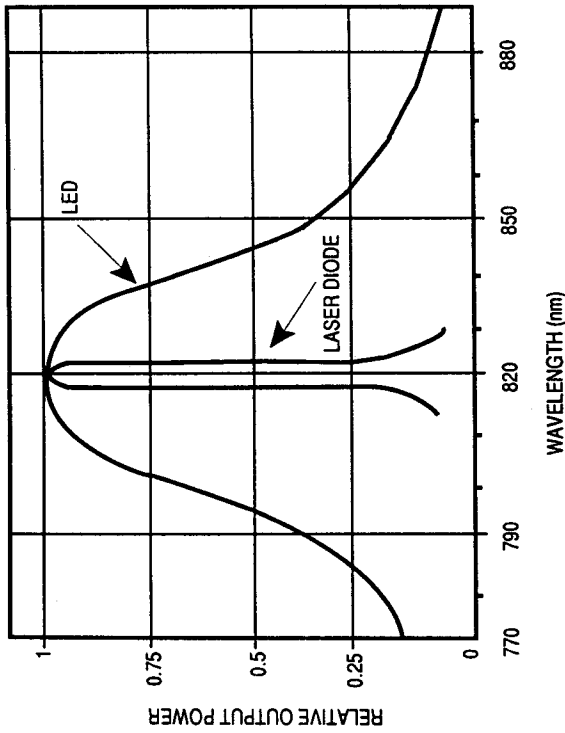


Figure 4. Typical spectral widths.

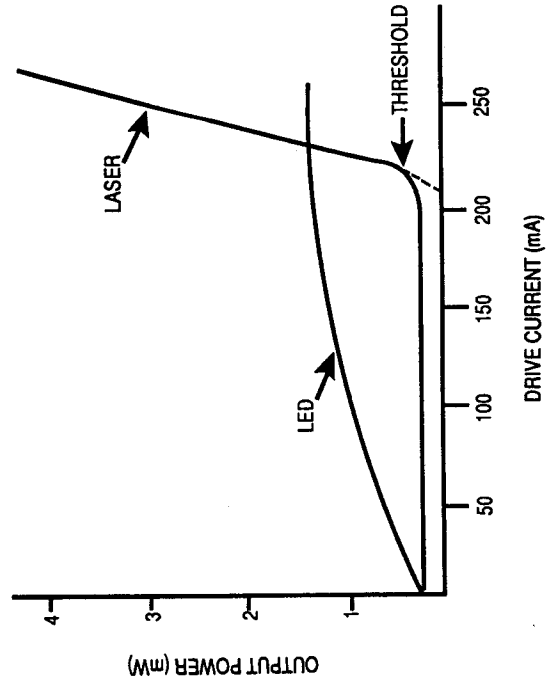


Figure 5. Optical source transfer characteristics.

To illustrate the benefits of fiber-optic cable, let us compare a 100-meter IF path using fiber-optic cable to one using RG-223, which is a popular coaxial cable for such applications. RG-223 is capable of handling modulation bandwidths up to 1 GHz over short transmission distances, has a 5-mm diameter, and costs roughly \$1.30/meter. A general purpose 100/140 micron fiber-optic cable with a bandwidth of 300 MHz-km has a 4-mm diameter and costs roughly \$3.30/meter. RG-223 weighs 5.0 kg/100 meters, and has 15-dB attenuation over 100 meters at 140 MHz. The fiber-optic cable weighs 1.3 kg/100 meters, and has less than 1-dB attenuation over 100 meters at 140 MHz. For short-range applications, fiber-optic transmission is cost-effective only if security is important. For separation of a few hundred meters to a few kilometers, a fiber-optic system has clear economic advantages because a coaxial-based system depends on repeater-amplifiers to boost the attenuated signal and the accompanying noise, over distance. Even for path lengths as short as 100 meters, fiber-optic transmission is a cost-effective alternative to conventional transmission for applications where the security and EMI advantages of fiber optics are important (see Figure 7).

## Connectors

While no single standard has emerged for fiber-optic connectors, a wide range of practical choices are available. Connectors introduce 0.01 to 3 dB loss, depending on the precision of the aligning mechanism, and are priced accordingly. A general purpose, inexpensive connector, based on the SMA connector, has roughly 0.5-dB loss, good repeatability, and high resistance to vibration. The LED

housing chosen earlier utilized an SMA-type optical connector.

## Optical-Receiver Diodes

To complete the fiber-optic link, there is the choice of optical receivers which must take the optical signal from the fiber and convert it to an electrical signal. There are two types of optical receivers: the PIN photodiode and the avalanche photodiode (APD). The PIN photodiode is simply three layers, positive, intrinsic, and negative, such that a photon hitting the diode causes one electron to be added to the current flow at the output. An APD depends on a multiplication factor, where one incident photon produces many electrons at the output. This is achieved by applying a high potential across the APD structure to create a large electric field. An APD needs temperature and voltage stabilization because the multiplication factor is not stable, and the device has non-linearities brought on by any load resistance. A PIN photodiode was selected for our purpose due to its simplicity and linearity.

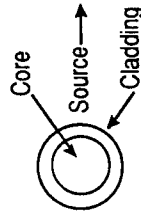
## Buffer Amplifier

In addition to the photodiode, a transimpedance amplifier is necessary to buffer the signal, providing a useful signal source. These are often integrated with the photodiode to reduce stray capacitance; discrete transimpedance amplifiers which can operate above 100 MHz are not commonly available. A standard, integrated PIN detector/amplifier with 125 MHz 3-dB bandwidth was compensated to provide a 0.3-dB bandwidth of greater than 180 MHz.

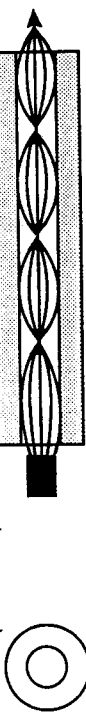
## Link Performance

The complete fiber-optic link was built consisting of an 820 nm LED

Step Index (Multimode)



Graded Index (Multimode)



Single Mode (Monomode)

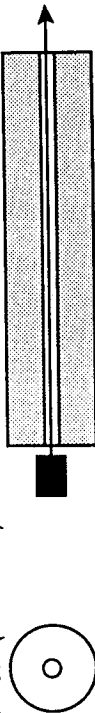


Illustration Courtesy of BELDEN Wire and Cable

Figure 6. Modes of transmission in three types of optical fibers.

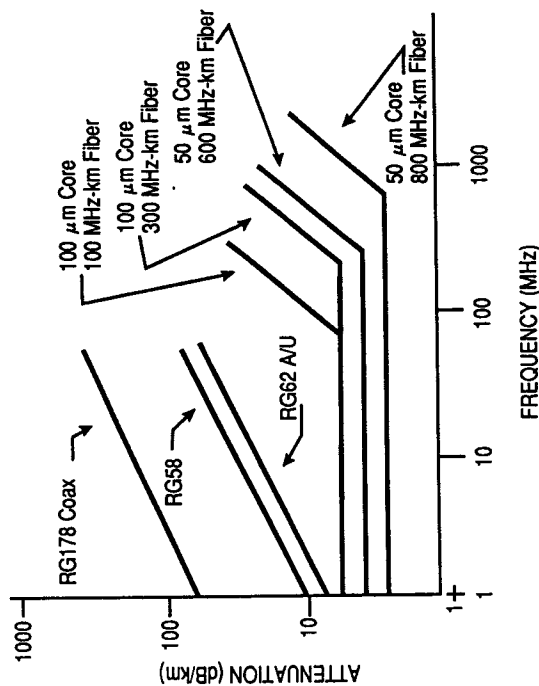


Illustration Courtesy of BELDEN Wire and Cable

Figure 7. Frequency response of typical coaxial and optical cables.

and lens, a wideband driver circuit, 100/140 micron cable with SMA connectors, a PIN photodiode with integrated transimpedance amplifier, an amplifier stage, and frequency-compensation circuitry. The largest expense incurred is the cable and the optical connectors. Considering the advantages of EML/RFI immunity, bandwidth, and signal attenuation, the fiber-optic link is a low-cost solution to secure IF signal transmission.

### Frequency and Phase Response

The link bandwidth is 8 to 240 MHz at the -3 dB points, and is flat to within  $\pm 0.3$  dB from 50 to 180 MHz. The main challenge was achieving this type of frequency performance from components intended for half that frequency range (see Figure 8).

There is a theorem which, in greatly simplified form, states that the less ripple in the passband, the better the group-delay distortion performance. In this case, this principle certainly held true: the variation in group delay was approximately 500 ps for the 70 MHz IF and 600 ps for the 140 MHz IF. These measurements show that very little dispersion exists in the system.

### Dynamic Range and NPR

For the overall system, the input 1-dB compression point is +4 dBm at 70 MHz, and the link loss is 14 dB. The output 1-dB compression point is -10 dBm and the MDS in a 1-MHz bandwidth is -75 dBm. The MDS is set primarily by the efficiency of the detector and the noise figure of the buffer amplifier. The dynamic range of the

link from the 1-dB compression point to MDS is thus 65 dB in a 1-MHz bandwidth. NPR tests show optimum results at an input signal of 0 dBm. The measured NPR for a conventional microwave system with 600 channels of 4 kHz each was 45.1 dB. Using the fiber-optic link to transmit the IF, the measured NPR was 41.6 dB. The design goal of 40 dB NPR was achieved with inexpensive, standard components. Comparable NPR values at wider bandwidths can be achieved with more efficient or lower-noise optical detectors.

### Conclusion

Using these parameters to evaluate the performance of the link as a whole, the fiber-optic link preserves the system specifications. At the highest modulation rates, a higher-performance receiver diode would yield better results. The fiber-optic link is undoubtedly an excellent choice for maintaining the strictest security in transmitting an IF signal. Fiber-optic cable is extremely low loss, small, lightweight, and provides an excellent barrier to electromagnetic interference from the surroundings.

Technological developments in the optical spectrum surrounding 1300 nm will increase the number of available low-cost components. In recent years, applications in the telephone industry, optical computing, and local area networks have forced a dramatic expansion in digital fiber optics. The present trend is towards utilizing analog fiber optics for telecommunications, cable TV, and in the microwave industry. Watkins-Johnson Company has demonstrated the feasibility of using low cost fiber optics in secure reconnaissance applications.

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### Author



### Judith A. Kay

Ms. Kay is a Member of the Technical Staff in the Product Development Department. She is currently developing a phase-locked loop for the resolution LO of the TN-124 microwave tuner. The TN-124 is a synthesized frequency converter that covers the 0.5 to 18 GHz range, and has very low phase jitter.

Ms. Kay is also involved in the design of analog fiber-optic links to improve performance of receiver systems with remotely located sensors or stringent emission specifications.

Ms. Kay received a B.S. in electrical engineering from Cornell University and is a member of the IEEE, Eta Kappa Nu, and the Society of Women Engineers.

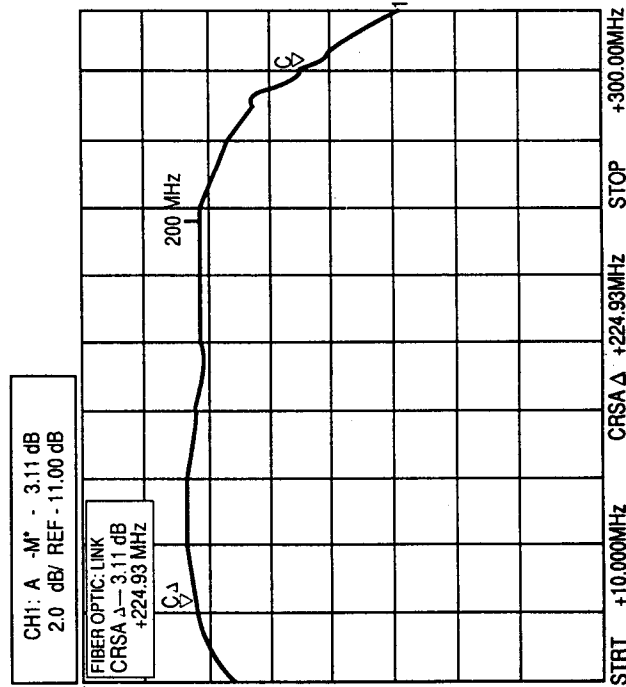


Figure 8. Fiber-optic link frequency response.