WIDEBAND FIBEROPTIC ANALOG INFORMATION LINK

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Summary A high frequency data transmission system which is unaffected by high energy electromagnetic fields is described. The system utilizes a gallium arsenide (GaAs) infrared light emitting diode as the transmitting source, a glass fiber optic light guide as the transmitting medium, and a photomultiplier tube (PMT) as the optical receiving sensor. The photomultiplier output is displayed on a real-time wideband oscilloscope where it is permanently recorded on film.

The overall system concept was chosen and each major component type was evaluated for optimum performance in this application. It was determined during the feasibility phase of the program that cryogenic cooling of the GaAs diode would be necessary to obtain high frequency response and high signal to noise ratio (SNR). Liquid nitrogen (LN_2) was chosen as the cryogen due to its low temperature, low cost, availability, and relatively long holding time.

The described system results in a 40-ft fiber optic, analog data link with a frequency response of 80 MHz and a dynamic range of 32 db. The system is not susceptible to electromagnetic fields.

Introduction Many electronic systems require testing in an electromagnetic pulse environment. The induced current data which result from this type of testing must be monitored, processed, and recorded for subsequent data reduction and analysis. The data must be of high quality, requiring the use of a data transmission system which is impervious to the applied electromagnetic field, has high frequency response, and wide dynamic range.

Alternative Solutions There are several methods by which data may be transmitted through an electromagnetic field. Each method exhibits unique problems, depending upon the particular application. One method employs an RF transmission link which may be limited in the quantity of data channels processed on a given test due to bandwidth vs. inter-channel crosstalk considerations. An RF transmission link is also susceptable to external noise disturbances which may enter the system at the transmitting or receiving antenna; and a line-of-sight must be maintained between the transmitting and receiving antennas.

Another possible method would be the use of a continuous-wave laser, amplitude modulated by the analog data signal. Although this method shows great promise, based on the results of laboratory tests, it requires the development of a modulator for the laser beam to meet the requirements of the system with respect to SNR and dynamic range.

The Solution The third method would make use of electro-luminescent GaAs diodes and fiber optic light guides to transmit the data to an optical receiver. This method was chosen because it was believed that the technology for a system of this type was sufficiently advanced to enable production of a data transmission link which would not require extensive research. Also, this system would not be limited in channel quantity and does not require line-of-sight provisions between transmitter and receiver.

An attempt will be made in this paper to show some of the refinements that may be applied to an optical system of this type and how the refinements result in system performance characteristics exceeding those of previously reported work. The basic system block diagram is shown in Figure 1. A photograph of an operWe laboratory model is provided in Figure 2. The cryostat and diode array shown will accommodate 12 GaAs diodes and fiber light guides. A delay line is mounted beneath the chassis.

System Description Upon application of an external EMP field, signal current will flow in the primary of the transducer, which is a current probe. The primary current varies from ma to hundreds of amperes, depending upon the level of the EM field. The transfer impedance of the current probe is approximately 1Ω, or a 1-a current in the primary results in a secondary voltage of 1v across 50Ω. The applied EM field is simultaneously sensed by the detector antenna, which energizes the bias insertion network. This network generates a bias pulse 10 μsec long and of sufficient amplitude to inject a 500-ma current pulse into the light emitting diode. The probe input signal passes through the coax switch and a 50 nsec delay line to an attenuator. The delay line is required to enable the GaAs diode to become fully forward biased by the step from the bias insertion network. The attenuator is required because of the approximately 120-db range of inputs which may be obtained as a result of the amplitude of the applied EM field. The signal will be attenuated if required and applied to the amplifier system, which will be described in detail later. The outputs of the two power amplifiers are impedance matched and applied to the GaAs diode, which is cooled to liquid nitrogen temperature

(77°K). The infrared light output fromth6 diode is directed into a 40-ft glass fiber, optic light guide. The output from the light guide is collected by a photomultiplier tube and terminated at a wideband real time oscilloscope.

The system includes calibration provisions consisting of a fast rise, repetitive pulse train which is used as the calibration signal, and also as the applied EM field simulator which energizes the bias insertion network. The calibration pulse train is attenuated in the "calibrator attenuator" according to the voltage amplitude that is required to closely simulate a given current probe input. The system end-to-end gain, frequency response, linearity, dynamic range, and SNR may be determined by monitoring the pulse train at the oscilloscope.

The data of interest contain frequencies as high as 80 MHz and the duration of the data may be as long as 10 μsec. The current probe used to monitor these data has a frequency range of 80 kHz to 100 MHz for a ±2-db maximum variation in transfer impedance. The primary RIP current range of the probe is limited to a maximum of 100 a at a 0.001-pulse duty cycle.

The link will be discussed in terms of the components which comprise the overall system, and they will be arranged in the sequence of signal flow as follows: transmitter, fiber optic link, receiver, and data recorder, followed by a discussion of system performance.

Transmitter Two of the basic requirements for the amplifier system are high frequency response and current drive capabilities. It was determined that the optimum GaAs diode response time is obtained when a resistor is placed in series with the diode to reduce the effect of the diode's dynamic impedance. This will be discussed in detail later in this section. The preamplifier has a frequency response from 5 KHz to 400 MHz, a noise figure of 6 db and a gain of 36 db; a 50-Ω power splitter to enable use of two power amplifiers operating in parallel; and two pulse-optimized power amplifiers with a rise time at full power output of 1.6 nsec, a gain of 30 db, and a noise equivalent input of 25 μv. The combined amplifier system results in a net gain of 60 db and a rise time response of 1.7 nsec. Each of the two output amplifiers has an output impedance of 50 Ω.

The amplifier system described has a maximum output drive capability of 20v peak-to-peak and 800 ma peak-to-peak. The amplifiers are produced by Avantek, Inc.

The transient data to be telemetered are bi-polar and analog in nature. Therefore, the GaAs diode, which emits radiation when biased in the forward direction, must be biased "on" previous to the time the data appear so that the negative-going portions of the waveform are not clipped. The diode must also be sufficiently biased in the forward direction so that the maximum excursion of the data waveform in the negative, -or in the direction to decrease the current through the diode, does not drive it into or near the cutoff region, because of the nonlinear optical characteristic in this region.

The method by which the bias step is generated and applied to the GaAs diode has been described. The higher the level of this bias step, the greater the available system dynamic range will be. However, two factors limit the level of bias that can be used. The first limit is the heating effect in the GaAs diode, which is a function of bias step width as well as the amplitude. The second and limiting factor was found to be the maximum driving current output capability of the power amplifiers.

In order to accommodate the longest expected data duration a 10 μsec bias step is necessary. The output radiation of the GaAs diode is a function of temperature, as shown in Figure 3. Various GaAs diodes differ greatly irk the character of this relation, and the curve shown is typical of the type used in this system. If the diode warmed excessively during the bias step, a non-linear effect would be introduced into the data. A bias step of 1.0 a was applied to the diode and its width increased while observing the optical power output. It was found that the emission level did not drop due to heating until the bias step width exceeded 100 μsec. Therefore, heating during the 10 μsec, 500 ma bias step used in the system is not sufficient to affect the optical output of the diode.

It will be shown that the optimum load, in the form of a resistance in series with the GaAs diode, is 25 Ω . A wideband amplifier capable of driving a 25-Ω load was desired and the amplifier system which was used to perform this function has been described. The maximum current-driving capability of the amplifier system working into 25 Ω is 800 ma peak-to-peak or the maximum output signal range from the amplifier system is from +400 ma to -400 ma. Therefore, the bias insertion network must supply a forward current bias step to the diode in excess of 400 ma to ensure that the data signal does not cause the diode to become reverse biased. It was found that a bias step of 500 ma from the bias insertion network is sufficient to keep the diode operating in the linear region at all times. Under these conditions the maximum dynamic current through the diode will range from 100 ma to 900 ma resulting from an 800 ma peak-to-peak input signal.

Because the optical power output of a GaAs diode is proportional to the current through the diode, it would be appropriate to use the lowest possible matching impedance in series with the diode. In order to obtain a given current through the diode, less voltage and output power would be required of the amplifier. Initial attempts, therefore, used an amplifier with an output impedance of less than two ohms, which was capable of driving directly into the GaAs diode. In these early experiments, the diode was connected directly to the amplifier so that the problem of matching the transmission cable to the load could be temporarily circumvented.

Operating directly into the GaAs diode was found to be impractical because the dynamic impedance of the diode is not constant in the required operating range. The effect of this changing dynamic impedance was an increase in rise time and system non-linearity. The dynamic impedance of the diode was measured to be 0.5 Ω at a forward current of 100 ma. If the amplifier driving the diode is not a true current source, the change in dynamic impedance of the diode due to the varying signal amplitude results in system non-linearity. Amplifiers with the required bandwidth and power output are generally not current sources but are either voltage or power sources; therefore, if the load varies about a nominal 0.5 Ω, both the voltage across it and the current through it change. If a resistance is placed in series with a GaAs diode, the changing dynamic impedance of the diode will have less affect on the total effective load and, consequently, the current through the load. In addition to these considerations, amplifiers evaluated for this application showed undesirable distortion and frequency response degradation when working into loads of much less than 25 Ω. The amplifiers selected for use in the system, used two in parallel per channel, are limited in output to ±10 v and +400 ma. Under these constraints 25 Ω is the obvious choice since a standard 50-Ω coaxial cable from each amplifier summed together at the load provides maximum power transfer to the load. Therefore, 25 Ω was selected as the most suitable matching load resistance.

Cooling the GaAs diode to LN_2 temperature has three significant advantages over room temperature operation:

1) The efficiency of the diode increases greatly (see Figure 3). This increased efficiency results in greater signal-to-noise ratio and greater system dynamic range.

2) The rise time of a GaAs diode improves as the diode is cooled. Diodes of the type used in the system provide a system rise time of 4. 5 nsec when at LN_2 temperature and a rise time of only 15 nsec at room temperature.

3) The wavelength emitted shifts from 9100 A at room temperature to 8400 A at 77°K. The spectral response of an S-1 PMT is generally peaked near 8000 A (see Figure 4). Therefore, the GaAs emission is more closely matched to the peak response of the PMT when operated at 77°K.

A relatively simple LN_2 cryostat (see Figure 5) capable of maintaining an array of 12 GaAs diodes within 3°K of LN_2 temperature for 4 hr, on a single filling, was constructed. The cryostat has a volume of 3 liters and is shaped for efficient use of the space allotted for the transmitter section. The basic structure is fabricated from stainless steel and the entire container is insulated with a 1-in. thick layer of polyurethane rigid foam. A cold finger extends from the cryostat cold mounting surface internally approximately 5 in. to provide maximum temperature stability at the diode array interface. The cold finger is made of 1-in. diameter oxygen-free high conductivity copper and is terminated at the exterior cold mounting surface which is finished to a flatness of better than 0.001 in. TIR and a maximum surface roughness of 0.00016 in. to provide a high thermal conductivity mounting surface for the GaAs array. The components described, and their relation to the fiber optic light guides and light guide retainer, are shown in Figure 5.

Vacuum-type cryostats may be used in this application to provide longer operating times while remaining within the same physical volume. However, the much greater cost for a vacuum cryostat was not justified because a holding time of 4 hr. was adequate to meet the system requirements; the additional LN_2 dissipated in the polyurethane-insulated cryostat is relatively inexpensive.

The GaAs diodes must be protected from the atmosphere when they are cooled to prevent condensation of water which may cause damage to the diodes. To accomplish this, the copper fixture on which the diodes are mounted and the stainless steel fiber light guide retainer are separated by a nylon insulating spacer which provides a channel through which dry nitrogen gas may flow (see Figure 5). The gas is obtained from boil-off of the liquid nitrogen within the cryostat. As the cryostat is being filled the boil-off occurs very rapidly until the cryostat has cooled appreciably. Therefore, the channel is automatically purged of air before the diodes cool to the dew point. When the cryostat has been depleted of LN_2, a dry nitrogen source is connected to the fill input to keep the diodes free of frost as the unit warms to ambient temperature. This dry nitrogen flow is required for approximately 1 hr after LN_2 exhaustion. If use of the system is required for longer than 4 hr, liquid nitrogen may be added to the cryostat. The nylon insulating spacer described above also provides thermal isolation between the diode array and the ambient atmosphere.

The heart of the transmitter in this system is the GaAs infrared light emitting diode. Literature on the fabrication, electrical properties, and optical properties of this type semiconductor device is quite extensive(2), (3). Several different techniques are employed in the fabrication of these electro-luminescent diodes. GaAs diodes can be fabricated in the form of coherent light sources (injection lasers) or non-coherent sources. The techniques involved in the fabrication of these two types result in differences in their properties even at low currents where both are non-coherent emitters. The laser diodes do not begin to lase, or produce light by stimulated emission, until a threshold peak current of 1 a or more is reached when the diode is operated at 77°K. The lasing threshold is even greater at room with faster response times are available, but the active area of these devices is so small that efficient coupling of the radiation out of the fiber optic light guide is very difficult. These considerations lead to the choice of a PMT as the most suitable detector for this application. Avalanche solid-state photodiodes are becoming available which may offer a superior detector, but for the present application they are not considered reliable or stable enough for field use.

The PMT used in the system is the RCA 7102. This is a 10-stage S-1 PMT. The spectral response characteristic of the S-1 photocathode surface is shown in Figure 4. The diameter of the active photocathode is 1.24 in. The fiber optic light guide is easily coupled to this PMT by positioning the light guide termination against the PMT window. Although the GaAs emitters could operate at 500-ma forward current continuously, the background radiation level produced would cause the maximum average anode current rating of the PMT to be exceeded. It is for this reason that the bias step is provided for only 10 μsec during which time the data are transmitted.

As the system was being developed, greater signal levels were delivered to the PMT, and it became necessary to decrease the number of PMT dynodes used in order to remain in the linear region and avoid saturation. In the final configuration, only 5 dynodes are used as gain stages. Dynodes Nos. 6 through 10 and the anode are connected together and act as the electron collector for dynode No. 5. The voltage between dynode No. 1 and the cathode is set at the maximum rating of 400 v to reduce noise caused by the statistical fluctuation of secondary emission(8). The total voltage across the divider network is nominally 1 kv. A potentiometer is used to adjust this total voltage to vary the PMT gain so that the individual channels of the system may be balanced. Capacitors shunt the divider resistors on the last three PMT dynode stages to provide additional pulse current surge capacity. A magnetic shield surrounds the PMT.

The lead from the dynode No. 6 collector to the output connector is as short as possible to minimize output reactance and maintain high frequency response. The output of the PMT is coupled to the oscilloscope through low-loss coaxial cable where it is terminated in its characteristic impedance.

Data Recorder One of the significant limitations on the frequency response of this system is the data recording device which is a real time oscilloscope. The current probe data obtained from electromagnetic pulse tests is usually of a nonrepetitive nature; therefore, a sampling oscilloscope which has much higher frequency response is not useable. The oscilloscope used in this system is a Tektronix Type 454 in conjunction with a C31 trace recording camera and Polaroid 10,000 speed film. The oscilloscope has a 150 mHz bandwidth and a rise time of 2.4 nsec when used with a minimum sensitivity of 20 mv/div.

Oscilloscopes with bandwidths from dc to 1 GHz are available, but the signal resolution is very poor due to the small CRT display (2 cm x 6 cm). Instruments in this frequency range generally exhibit vertical deflection factors of approximately 10 v/cm whereas the output voltage of the photomultiplier in this system is on the order of 100 mv. The use of an amplifier would provide a full scale deflection, but the poor resolution and dynamic range would still exist making the system unacceptable.

System Performance The system performance characteristics discussed in the following paragraphs refer to the system from the pre-amplifier input to the oscilloscope display. The measured characteristics are:

System input sensitivity:	240 μv (input signal required to produce a SNR of 1:1, where SNR is the peak signal to peak-peak noise ratio)
Output noise level:	3 mv p-p
Maximum output signal:	120 mv peak
Maximum SNR:	40:1
Dynamic range:	32 db
Linearity:	±5% over entire dynamic range
Response time (t_r):	4. 5 nsec to input step with 1 nsec rise time. Figure 8 shows an oscilloscope photograph of the system response to the 1-nsec step input.

The upper 3-db frequency (f_2) for the system, excluding the current probe, can be calculated from the 10 percent to 90 percent rise time and is given by $f_2 = 0.35/t_r = 78$ MHz. The current probe used with the system has a 1-Ω transfer impedance, which is flat to within ±1 db at the high frequency end out to 80 MHz, where the transfer impedance is +1 db. This increases to +3 db at 110 MHz. Therefore, when this current probe is used in the system the upper 3 db frequency of the system is greater than 80 MHz.

The theoretical performance of the system based on the individual component specifications will now be calculated. In particular, the system rise time and maximum SNR will be calculated. The rise time capabilities of the individual components are:

Amplifier:	1.7 nsec (measured with 0.25 nsec rise time step input and an HP 185 sampling oscilloscope)
GaAs diode:	2.0 nsec (specified typical value)
PMT:	2.4 nsec (specified typical value)
Oscilloscope:	2.4 nsec (Tektronix 454)
Input step rise time:	1. 0 nsec (HP 215 pulse generator)

The rise time of the system (t_r) is given by the square root of the sum of the squares of the individual components rise times, or $t_r = [(1.7)^2 + (2.0)^2 + (2.4)^2 + (2.4)^2 (1.0)^2]^{1/2} =$ 4.6 nsec, which is in close agreement with the measured value.

In order to calculate the theoretical maximum SNR, several PMT parameters must be determined. The photocathode radiant sensitivity (q) at 8400 A is 3 x 10^{-3} a/w for the RCA 7102 PMT, which was selected for high q. The current gain (μ) of the PMT using 5-dynode gain stages as described in the receiver section can be determined from the secondary electron emission coefficient as a function of dynode voltage(8). The first dynode was operated at 400 v, and the remaining 4 dynodes at 120 v. The secondary electron emission coefficient of the Ag-MgO-Cs dynode at 400 v is 7.4 and is 4.0 at 120 v. Therefore, the PMT current gain is $\mu = 7.4 \times (4)^4 = 1900$. The P MT total radiant sensitivity (p) is $p = \mu q = 5.7$ a/w. The measured light guide transmission is 2.5 x 10^{-2}, and the measured GaAs power output at a forward current of 400 ma is 14 mw. The mirror configuration used with the GaAs diode insures that very nearly all of the emitted radiation is directed into the fiber optic light guide within the acceptance angle. The peak power incident on the PMT, when the maximum input signal is applied to the transmitter pre-amplifier is, therefore,

$$(14 \times 10^{-3}\ \mathrm{w})(2.5 \times 10^{-2}) = 3.5 \times 10^{-4}\ \mathrm{w}$$

and the PMT output current is

$$(3.5 \times 10^{-4}\ \mathrm{w})(5.7\ \mathrm{a/w}) = 2.0 \times 10^{-3}\ \mathrm{a}.$$

Since the PMT is working into 50 Ω, the maximum output signal would be (2.0 x 10^{-3} a) (50 Ω) = 100 mv. The measured value was 120 mv.

The theoretical noise is calculated from the rms shot noise current formula,

$$i_n = u\left[2eI_d\left(1 + \frac{B}{m - 1}\right)\Delta f\right]^{1/2}$$

temperature. Since the peak current used in this system does not exceed 90 ma (500 ma step plus 400 ma signal), the diode does not operate in the coherent mode although it is a laser type GaAs diode. The laser diode was selected after extensive evaluation of many diodes of each type because these diodes were found to have faster response times and about equal conversion efficiency at the low peak currents used in the system.

The dimensions of the diode selected for use in the system are 0.004 x 0.004 x 0.020 in. The radiation is emitted from the junction of the diode which approximately bisects the 0.004 x 0.004 face, and runs the length of the diode. The diode is mounted so that the 0.004-in. junction length is directing the radiation outward to be collected by the fiber optic light guide. A small mirror constructed of polished gold ribbon is mounted on each side of the diode to collect the radiation emitted from the sides. The resulting diode configuration is shown in Figure 6.

The peak wavelength emitted at room temperature is 9100 A, and decreases to 8400 A at 77°K. The spectral line width is typically 400 A at room temperature and 150 A at 77°K. It was found that the addition of the gold mirrors typically increased the quantity of radiation collected by the fiber optic light guide by a factor of two. The output power of the diode is directly proportional to the current through the diode for peak currents up to 80 a in pulsed operation at 77°K. This is true for pulse widths on the order of 10 μsec and at low repetition rates. The peak output power of the diode type used in the system was measured to be 35 mw at 77°K, with a 1.0-amp, 1.0-μsec pulse input. These laser diodes are produced by Electro-Nuclear Laboratories.

Fiber Optic Link The distance over which the data are to be transmitted is 40 ft. Two mediums of transmission of the optical information to the receiver locations were evaluated, i.e. , a collimated beam and a fiber optic light guide. The geographic location of the transmitter and receiver stations are such that the collimated beam technique is impractical. That is, several accurately-aligned mirrors would be required to guide the beam and the vibration environment associated with the test facility would not allow maintenance of the required optical alignment. Therefore, fiber optic light guides were selected over a lens and collimated beam system, even though the optical losses are greater. In this way alignment problems are completely eliminated.

Fiber optic light guides conduct light, including infrared, by the phenomena of total internal reflection. The individual glass fibers making up the light guide are of refractive index n_1. A thin glass cladding of lower index n_2 surrounds each fiber and causes light to be completely reflected at the interface over a certain range of incidence angles. (See Figure 7.) If the ray is incident from a medium of refractive index n_0, then

$$n_0 \sin \alpha_m = \left(n_1^2 - n_2^2\right)^{1/2}$$

The term $n_0 \sin \alpha_m$ is the numerical aperture (NA), and is measure of the light gathering power of the light guide. For the light guide used in this system, $n_1 = 1.62$ and $n_2 = 1.52$, therefore, $n_0 \sin \alpha_m = 0.56$, and since the light enters the light guide from an atmosphere of dry nitrogen gas, $n_0 = 1.0$, the maximum acceptance angle is 35 degrees.

Another important parameter of the light guide is the transmission. The transmission losses within the fiber are due to reflection, scattering, and absorption. The transmitted intensity (I) is related to the incident intensity (I_O) by

$$I = I_O e^{-\beta L}$$

where β is the attenuation coefficient and L is the length of the fiber. β is both incidence angle and wavelength dependent. A typical value for β is 2.5×10^{-3} cm^{-1} at 8400 A. For the 40 ft fiber the transmitted intensity is

$$I = I_O(4.8 \times 10^{-2})$$

This accounts for the losses in the fiber only. There are also reflection and packing fraction losses at the insertion end, and reflection losses at the exit. Nominal values for these are 30 percent and 10 percent, respectively. Therefore, the total transmission is (0.048) (0.7) (0.9) = 0.030, or 3 percent. The measured transmission was 2.5 percent at 8400 A. The diameter of the light guide is 0.125 in. and the nominal individual fiber diameter is 0.003 in.

Additional theory and characteristics of fiber optics may be found in the literature(4).

Receiver The function of the receiver is to convert the amplitude- modulated, infrared radiation signal to an electrical signal which can be displayed on the recording oscilloscope. The receiver output signal is a reproduction of the current waveform monitored by the current probe. The transfer function of the system is determined by the amplifier gain, GaAs diode conversion efficiency, light guide transmission, photomultiplier (PMT) sensitivity, and PMT gain. The system transfer function (current probe to oscilloscope) is nominally set at 12.5 mv/ma and is controlled by adjusting the photomultiplier gain.

The sensor selected for the receiver is an S-1 PMT. The only other detector capable of competing with the PMT at 8400 A and responding in the low nsec region is the solid-state silicon photodiode. The PMT has a clear SNR advantage in the direct detection of amplitude modulated low level signals at frequencies above a few MHz when operating under low background conditions(5), (6). A wideband amplifier must be used with a solid-state photodiode because of its low level output. In order for a solid-state photodiode to respond at high frequencies it is necessary for it to work into a small load resistance. This makes the RC time constant of the circuit short enough to pass the desired high frequencies, where R is the amplifier input resistance and C is the photodiode junction capacitance, plus the input capacitance to the amplifier. For very low values of amplifier input impedance, the photodiode internal resistance must also be considered. With a small load resistance, the Johnson noise current becomes the predominant noise source. The rms Johnson noise current is given by $i_j = [4k\ T\ \Delta f/R]^{1/2}$, where k is Boltzmann's constant, T is the temperature in °K, and Δf is the bandwidth. The PMT is shot-noise limited, therefore, as the background radiation increases, the noise in the PMT increases. The noise in the solid-state photodiode does not increase until the shot noise component approaches the Johnson noise level. As the system is operated, the 500-ma bias step to the GaAs infrared emitter produces a strong background level out of which the signal must be detected. Under these conditions, it was found experimentally that the solid-state photodiode was capable of providing a somewhat greater SNR. Considerable care was required to couple the light from the light guide to the small area photodiode. The photodiode must necessarily be of small area to keep the junction capacitance low.

The system response time using the PMT is 4.5 nsec. Since the PMT alone has a rise time of 2.4 nsec, (7) it can be shown that the other system components together have a rise time capability of 3.8 nsec. The system response time using a photodiode detector and wideband amplifier was measured to be 7.0 nsec; therefore, the response time of the photodiode/amplifier combination must be 5.8 nsec. The receiver amplifier used with the photodiode has a measured rise time of 2.0 nsec; therefore, the photodiode rise time is 5.4 nsec. Two types of solidstate photodiodes were evaluated with approximately the same result. The manufacturer's specified rise times of these photodiodes are 3 and 4 nsec. Photodiodes

where

- e = electron charge (1.6×10^{-19} coulombs)
- Δf = system bandwidth (78×10^{6} hz)
- B = statistical factor (1.54) (Ref. 8, p. 56)
- m = secondary emission ratio of first dynode (7.4)
- I_d = dc background current of photocathode.

The background current (I_d) at the photocathode is caused by the 500-ma GaAs bias step. This current can be calculated from the previously given parameters and is

$$I_d = (17.5 \times 10^{-3}\ \text{w})(2.5 \times 10^{-2})(3 \times 10^{-3}\ \text{a/w}) = 1.31 \times 10^{-6}\ \text{a}$$

with these parameter values, $i_n = 1.2 \times 10^{-5}$ amp rms, and the rms shot noise voltage at the oscilloscope is $e_n = i_n \times (50\ \text{ohms}) = 0.6$ mv rms. The noise voltage of the system, as observed on an oscilloscope, is approximately 3 mv p-p. Measuring noise on an oscilloscope is a qualitative procedure and it has been found in working with this type of noise measurement that what is measured on an oscilloscope as p-p noise is typically 5 times the actual rms noise as measured by a wideband true rms voltmeter. Therefore, the theoretical and measured system noises are in reasonably close agreement.

Conclusions This system provides for the transmission of analog or digital data through an electromagnetic field without introducing a disturbing element into the applied field and without experiencing system interference due to the applied field. Although the fiber optic link is not susceptible to the field, the electronics required for the transmitter and receiver must be adequately shielded to prevent interference from the applied field.

A system of this type provides a completely private communication link which can be operated without an FCC license. The quantity of channels is not limited by carrier frequency or crosstalk considerations. The number of channels used in a given system is basically a function of the space available for the total system because the only major components shared by all channels is the cryostat and power supply. Inasmuch as each datum channel is essentially a separate system, virtually no interchannel crosstalk exists provided normal precautions are taken regarding the power supply filtering and grounding schemes.

This system was designed to transmit a distance of forty feet and system performance in the areas of SNR and dynamic range improves appreciably as the transmission distance is decreased. Conversely, as the length of the fiber optic light guide is increased, the SNR and dynamic range are degraded.

The system performance can, in theory, be improved several ways. First, the amplifier system's output power could be increased in conjunction with the bias step level. This would improve SNR and dynamic range by an amount equal to the square root of the increase factor of the bias step amplitude as observed on the oscilloscope. The use of a diode with a lasing threshold low enough to permit operation of the system in the lasing mode would improve SNR, dynamic range, and possibly frequency response. A fiber optic light guide with improved transmission characteristics would also result in improvements in SNR and dynamic range.

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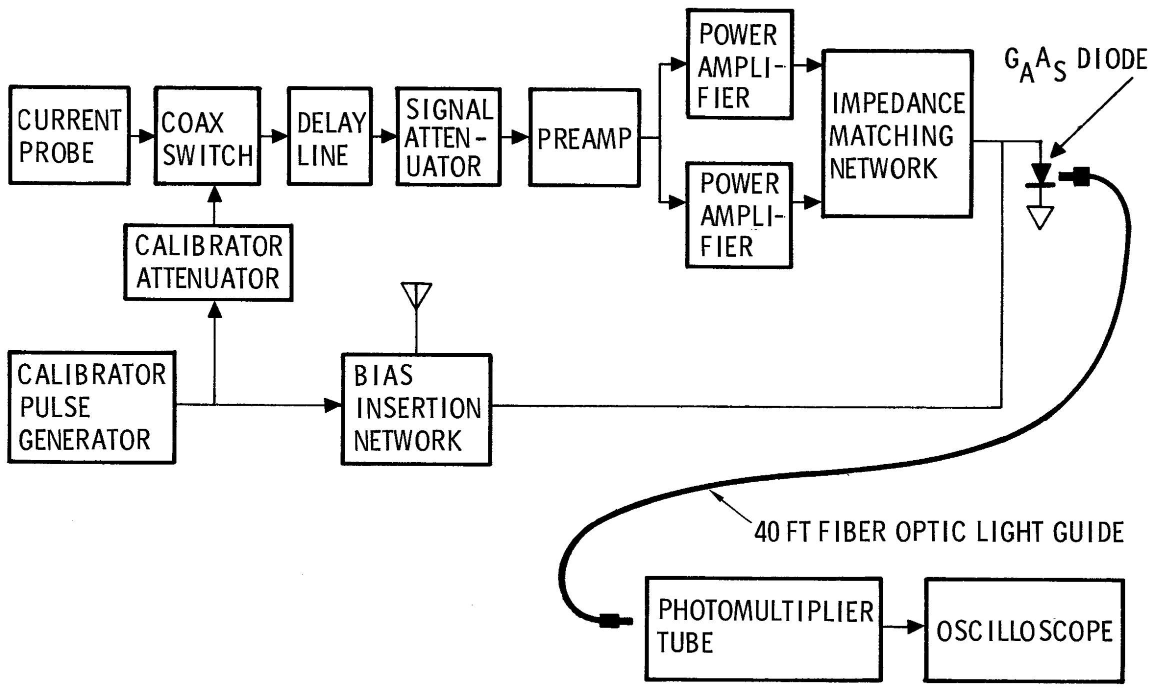

Figure 1. System Block Diagram

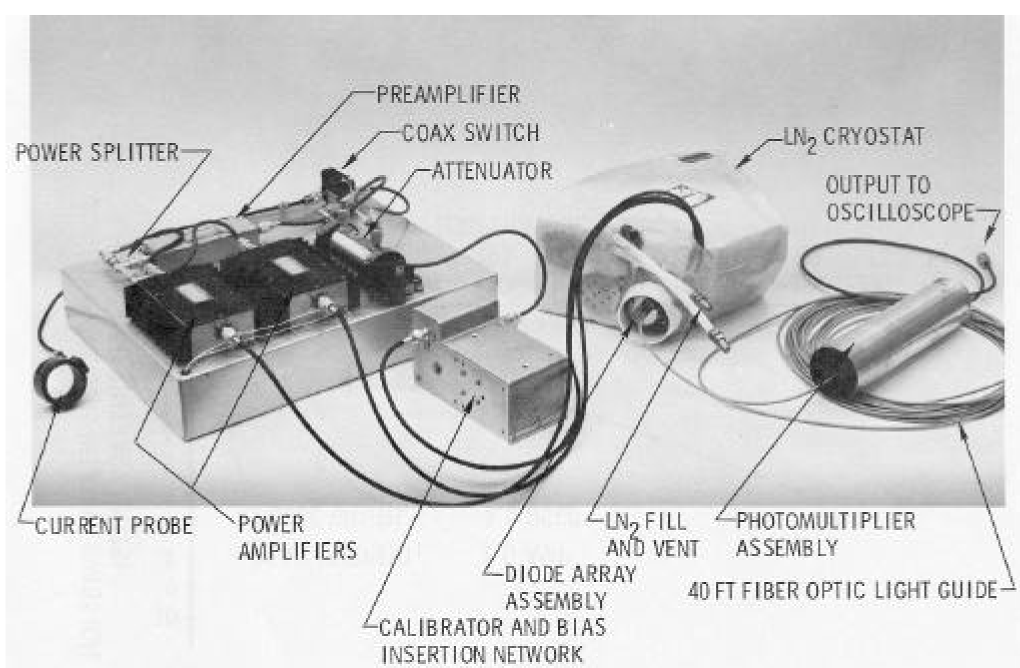

Figure 2. System Assembly

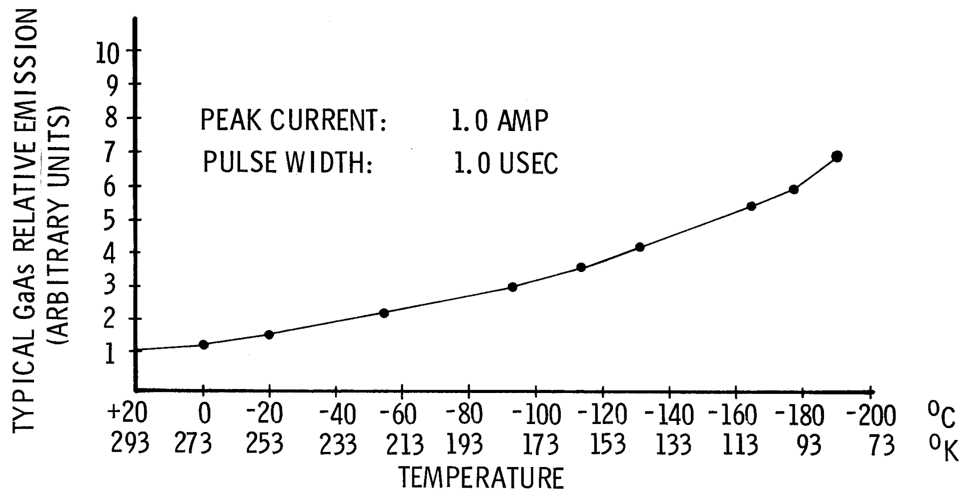

Figure 3. GaAs Relative Emission vs Temperature

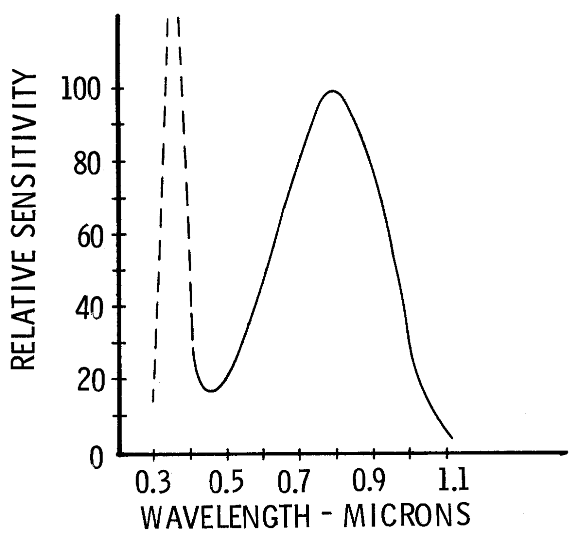

Figure 4. S-1 Spectral Response

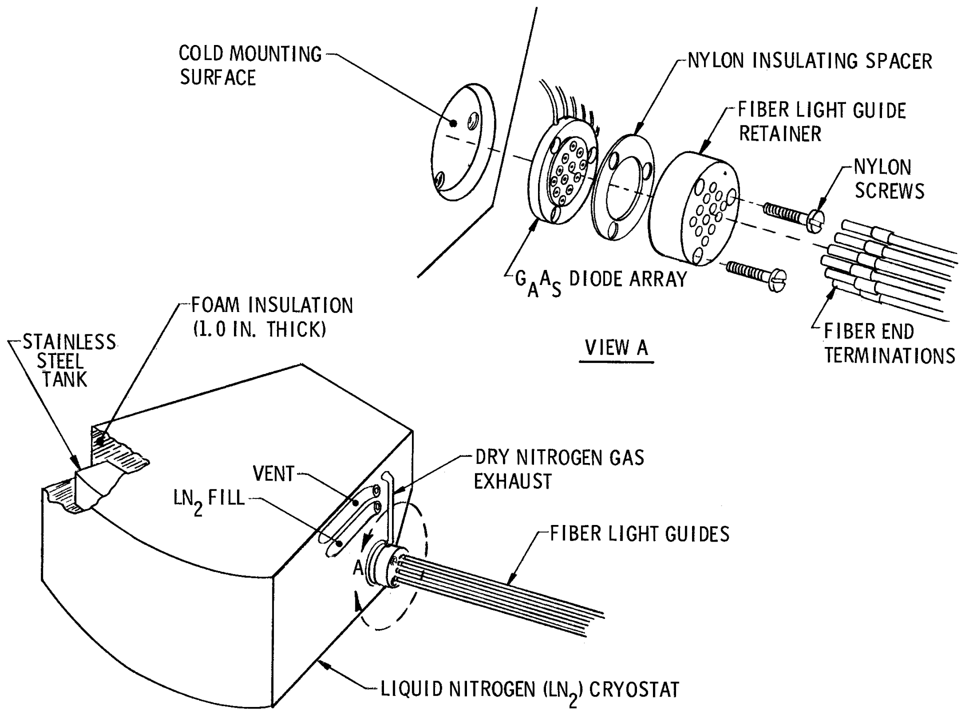

Figure 5. Relation of Components to Fiber Optic Light Guides and Light Guide Retainer

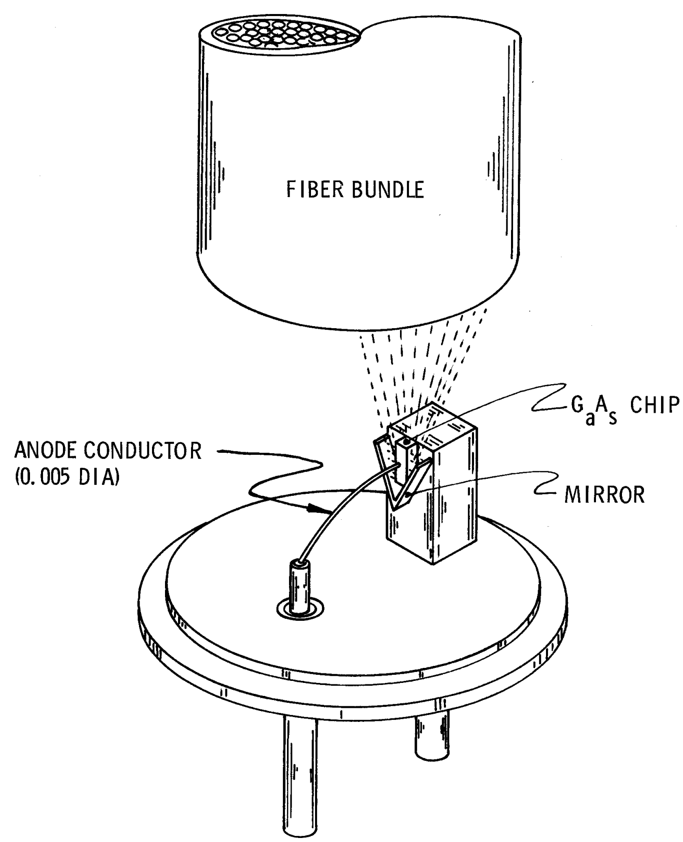

Figure 6. GaAs Diode Configuration

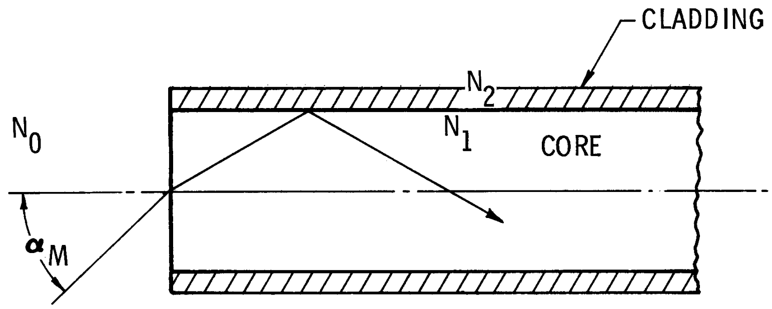

Figure 7. Light Ray Entering Fiber

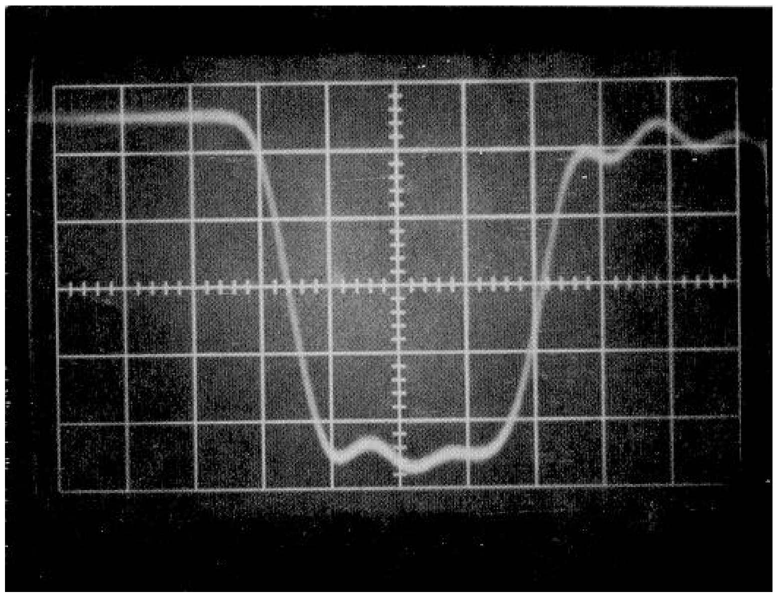

Figure 8. System Rise Time (Horizontal = 5 nsec/div)