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A VERSATILE FIBER-OPTIC SIGNAL LINK FOR EMP TESTING AND GENERAL--ETC(U)

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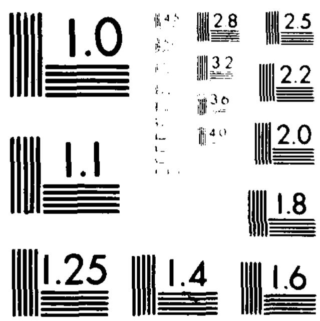

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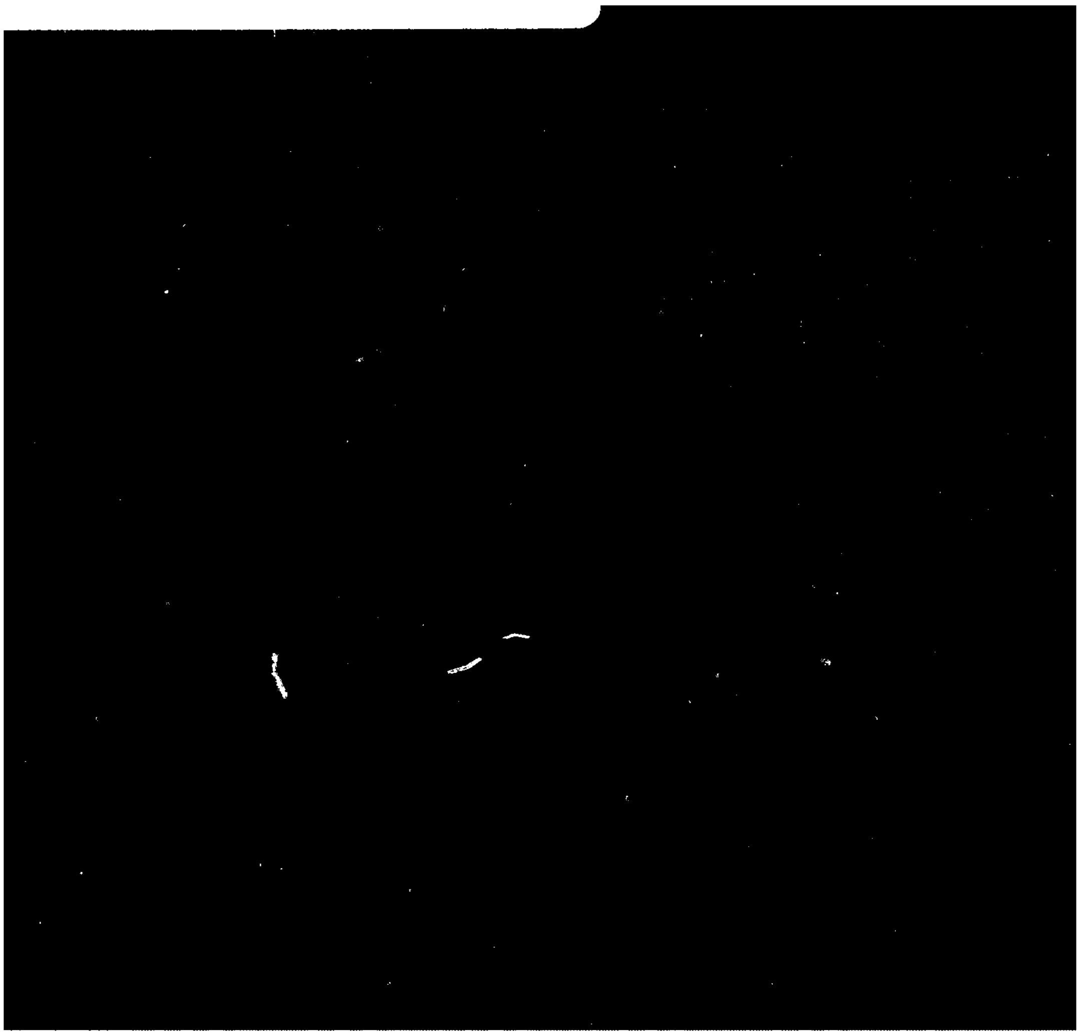

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A fiber-optic analog signal link is described that was designed specifically to be used for EMP measurements. The link accepts electrical inputs in the range from millivolts to volts and converts them to optical signals which are then transmitted by optical fibers to a remote receiver. The unit is unaffected by electric fields up to hundreds of kilovolts/meter, and a bandwidth of about 130 MHz is provided; the unit has a dynamic range of approximately 30 dB.

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20. ABSTRACT (Cont'd)

This dynamic range is extended an additional 45 dB by an internal attenuator which is commanded (by an optical fiber link) to insert a fixed attenuation in the range of 0 to 45 dB between the input connecter and transmitter. A self-calibrator is also commanded by the same link. An unusual circuit feature is the use of a single electro-optic device to perform both light-emitting diode and detector functions.

CONTENTS

FIGURES

1. INTRODUCTION

The optical signal link described here is based on an earlier, less adaptable system.[1] It was built to answer the need for a versatile EMP-resistant conduit that could convey the signals from sensors to a remote location without noise pickup. In addition to having no noise pickup itself, the fiber-optic link also insures that no noise is conveyed into the system under test (as might occur with conducting lines). The optical cable may be less than 1 mm in diameter where necessary and consequently can pass through an opening so small that it provides no significant compromise in shielding, even at the highest EMP frequencies. The system also typically provides a wider bandwidth than is possible with tractable conducting cables. The fiber-optic cable is wideband, mechanically durable, flexible, and resistant to moisture. The transmitter and fiber optics were tested in electric fields as high as several hundred kilovolts/meter, and no significant noise was picked up even though signals as low as 1 mV were being transmitted. A number of these systems have been in use since late 1977, often under field conditions, with no significant failures or instabilities except for some early failures caused by a defective lot of signal light-emitting diodes (LED's).

The optical tansmitter is the cylindrical structure on the right of figure 1 (p 6). It accepts the sensor signals (in the range from millivolts to volts) at its 50-ohm input and converts them to optical signals which are carried to the receiver by an optical fiber (or fiber bundle). Additional circuitry in the transmitter decodes and executes the various commands sent by the front-panel controls of the receiver/control unit. The lower half of the transmitter is a plug-in battery pack which provides more than 12 hours of continuous use. In the application for which this system was built, space was liberally available and thus no attempt was made at miniaturization. Were it necessary, the volume of the transmitter could be reduced to one-third the size of the present unit; only assembly convenience and battery running time would be compromised.

[1] *J. Blackburn, A 120-MHz Bandwidth Linear Signal Transmission System Using Fiber Optics, IEEE Trans. Instrum. Meas. IM-24, 3 (September 1975).*

The optical receiver and control unit (left-hand cabinet of fig. 1) receives the optical signals and converts them to an electrical signal available at the receiver output, which is typically connected directly to an oscilloscope. The controls allow the user to turn the system on and off, insert an attenuation between 0 and 45 dB at the input, and turn the internal 10-mV calibrator on and off. A logical "handshake" confirms proper reception of the attenuation commands. All signals are conveyed between the receiver/control unit and transmitter/remote unit via optical fibers.

The two spools each contain 100 m of optical cable: one is used to transmit the signal from transmitter to receiver and the other to carry controlling commands in both directions between transmitter and control unit. A single cable containing two fibers, one for each function, could equally well have been used. Such a twin-fiber cable would reduce total cable weight to only about 3-kg for the 100-m distance.

2. TRANSMITTER—BLOCK DIAGRAM AND DESCRIPTION

The electronic circuitry of the transmitter/remote unit is summarized by figure 2, and an internal view of the transmitter is shown in figure 3. Proceeding from the optical output back towards the electrical input, the low-impedance LED is driven by a single transistor stage which provides operating bias, modulation current, and some high-frequency pre-emphasis. This stage is driven by a linear 50-ohm amplifier which provides voltage gain. The input of this stage may be connected by remote control either to the input attenuator or to the calibration generator. The input attenuator uses four TO-5-can relays to insert or remove 3-, 6-, 12-, and 24-dB attenuation elements in response to the commands from the control unit.

The remote-control link consists of an LED which is used both as a light-emitting element when forward biased and as a photovoltaic detector when zero biased and operated into a high load impedance. In the control sequence the detector

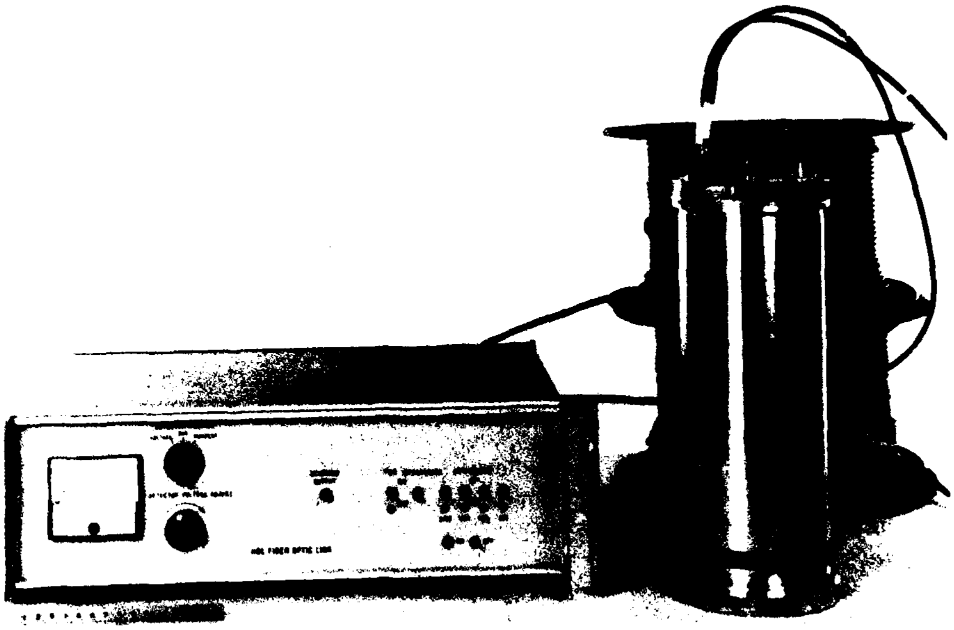


Figure 1. Fiber-optic signal link. Control unit on left, transmitter and cable on right.

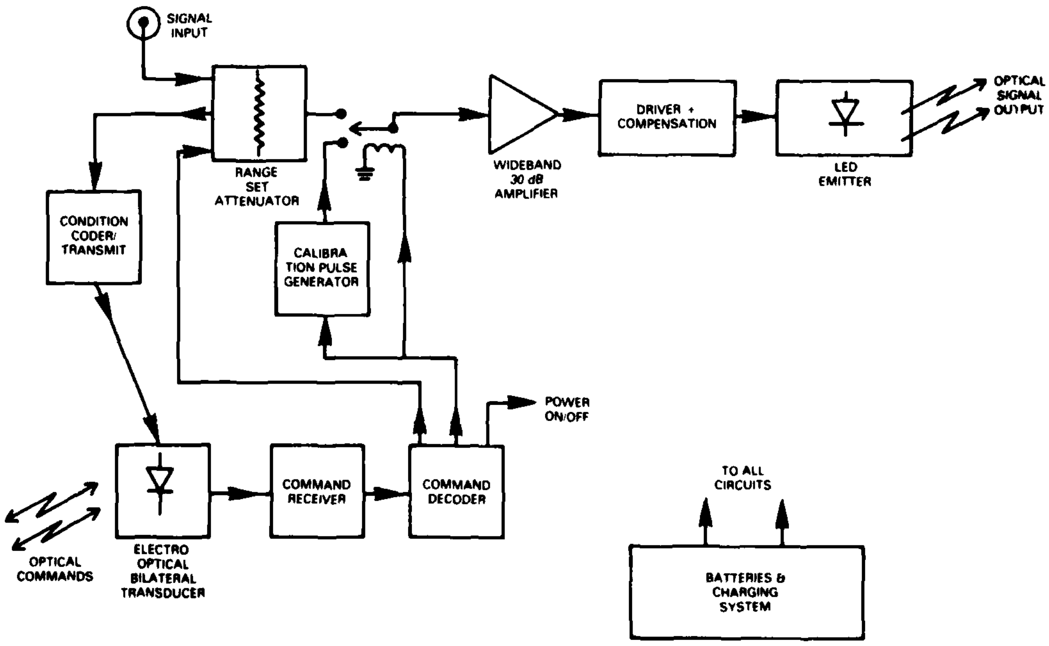


Figure 2. Block diagram of LED transmitter and control system.

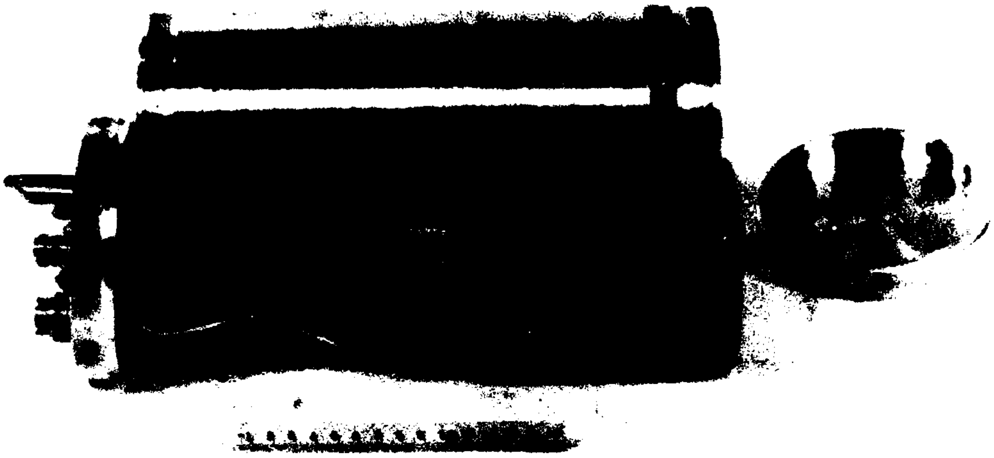


Figure 3. Internal view of transmitter and battery pack.

first receives the pulse-modulated optical commands incoming on the control fiber and then (by time multiplexing) later sends out optical signals to verify proper reception of the attenuation command.

Since the attenuator is a stable and accurate device using precision resistors, and since its proper setting is verified by the control link, it is necessary only to verify the system gain between the input of the wideband amplifier and the output of the receiver in order to know the total system gain from signal input to receiver output. This is accomplished by the calibration generator which, upon command, applies a +10, 0, −10 mV three-state calibration pulse sequence to the input of the 30-dB amplifier.

Such a calibration is essential since the attenuation of the optical fiber, and to a lesser extent the gains of the LED and detector, may change by a decibel or two during a day. The attenuation of the optical fiber also may change by a few decibels when the optical connectors are disconnected and reconnected, or when the fiber cable is spooled and re-layed, etc., in moving from one test situation to another.

In principle, one could apply an automatic gain control (AGC) loop to the receiver and automatically remove most of this variation. Since one would still need a calibration generator to verify this operation, the AGC loop has been left out and calibration has been made completely straightforward.

3. RECEIVER AND CONTROL UNIT — BLOCK DIAGRAM AND DESCRIPTION

The electronic system of the optical receiver/control unit is depicted in figure 4. The commands (system on-off, attenuation, calibrator on-off) are set by the operator on the front panel switches. These commands are coded by the electronics, and the coded signal is applied to the electro-optical transducer, which emits a light pulse sequence into the control optical fiber. After an interval of some milliseconds, during which the remote unit executes the commands, the optical transducer goes into the receive mode and the verification signal from the remote unit is received, decoded, and displayed. Proper attenuation command reception is verified if an LED indicator lights under each "on" attenuator control switch.

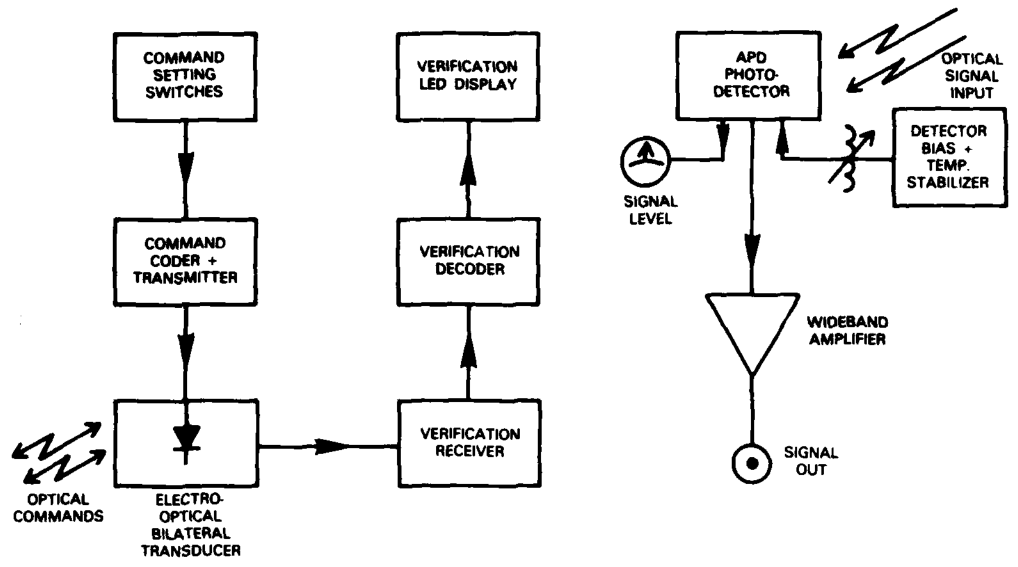


Figure 4. Block diagram of optical receiver and control system.

The attenuation command to the remote unit is sent only once, immediately after the remote unit is commanded to turn on; after this attenuation command has been received, the remote unit locks and will not accept any further attenuation commands until after it has been turned off, and then on again. This prevents any possibility of unexpected attenuation changes due to noise pickup, loose optical control cables, etc. The calibrator, and of course power, may be turned on and off at any time.

The design of the signal receiver is very straightforward, consisting of an avalanche photodetector, (APD), detector bias supply, and wideband ac-coupled amplifier. The bias supply is temperature compensated to nullify detector gain changes in response to environmental temperature changes.

A signal-level meter indicates the detector dc current (and, therefore, optical carrier level). A limited-range detector bias control allows the operator to make fine signal-level adjustments.

4. OPTICAL FIBER CONSIDERATIONS

Fiber optics can be supplied in a variety of physical configurations which meet almost any handling and environmental situation while providing the advantages of optical communication. A fiber with a single-layer coating of plastic is suitable for light duty use, and typically has an outside diameter of less than 1 mm. With additional layers of nonconducting plastic coverings, a fiber cable smaller than RG-58, and much lighter in weight, can withstand a tension of hundreds of Newtons and also foot and vehicle traffic. Most cables will operate over a temperature range of −30 to +60°C and are unaffected by moisture. A much wider temperature range is attainable with special coverings. Multi-fiber cables, providing a number of isolated signal channels, are not much larger than single-fiber units since the fibers themselves are insignificant in size and share the more bulky mechanical protective coatings.

Connectors can be used to join various fiber configurations so that, for instance, a very durable multi-fiber cable of the size of ordinary coaxial cable can be run from instrumentation to a remote point, with each of the fibers joined to an individual strand of submillimeter diameter fiber, and each of these tiny fibers runs into a test object through a small opening which does not compromise the electrical shielding or mechanical properties of the test object.

In addition to the obvious advantages of light weight, small size, and immunity to electric fields and noise, fiber optics also has the advantage of very great bandwidth compared to coaxial cables. A modest-performance optical fiber has a bandwidth of 20 MHz (flat within 3 dB) over a 1-km distance, with a loss of perhaps 15 dB. To this, compare the RG-58, which has a loss of about 55 dB/km at 20 MHz and a loss of over 10 dB at 1 MHz. A 1-km length of high-performance fiber may have a response flat within 3 dB from dc to over 1 GHz with a total loss of 5 dB.

At present, satisfactory connectors are available for all types of optical fibers (this was not true as recently as a year or so ago). As might be expected, the smaller the fiber diameter, the more precise the connector must be. Molded plastic connectors suffice for a wide variety of modest-performance fibers; precision metal connectors are usually required with high-performance (and consequently small-diameter) fibers. The unique connector manufactured by Deutsch Company seems at present to be the most satisfactory for the widely used 63-mm fibers.

For permanent splices between fibers, a fiber-to-fiber welding technique is available which allows low-loss permanent connections without the use of connector hardware.

Optical time-domain reflectometer (TDR) equipment is also now available for use in locating fiber breaks. The optical TDR sends a short, fast-rise pulse of light down the fiber and then views the fiber with a sensitive detector, indicating the time and amplitude history of the reflected light on a scope display.

The choice of fiber to be used in a given application depends on the signal frequency and transmission distance.[2] For the system described, the logic rate of the control link is so low that fiber dispersion is of no consequence; plastic clad silica (PCS) fiber is suitable. The large numerical aperture and core diameter of this fiber allows excellent optical coupling. The signal fiber, because of its >100 MHz bandwidth, must be chosen with attention to dispersion. For distances up to several tens of meters, PCS fiber is suitable; for distances up to 100 m or so, step-index glass is the best choice: it provides a lesser optical coupling than PCS, but has a much reduced dispersion. For long distances, dispersion considerations dominate all others and graded index fibers are required, even though they have the least numerical aperture and core diameter of the three types. The reduced optical coupling available with the graded fiber will produce the least signal-to-noise ratio in the received optical signal, but transmission over more than a kilometer is feasible.

All types of fibers can be supplied with the full range of coverings to provide the required physical properties.

5. RECEIVER CIRCUITRY

5.1 Detector and Voltage Control

The C30884 APD (see fig. 5) requires a rather closely controlled reverse bias voltage between about 270 and 340 V, depending on the individual unit. Further, if the gain of the APD is to be constant, this voltage must be increased as the detector's temperature increases. An AD580 voltage reference, a thermistor, and a CA3130 optical amplifier combine with Q20 to provide the necessary adjustment, regulation, and compensation functions.

The +400 V supply passes through R10 and is dropped to the required voltage by the current

[2] W. B. Allan, *Fiber Optics Theory and Practice*, Plenum Press, New York (197[illegible])

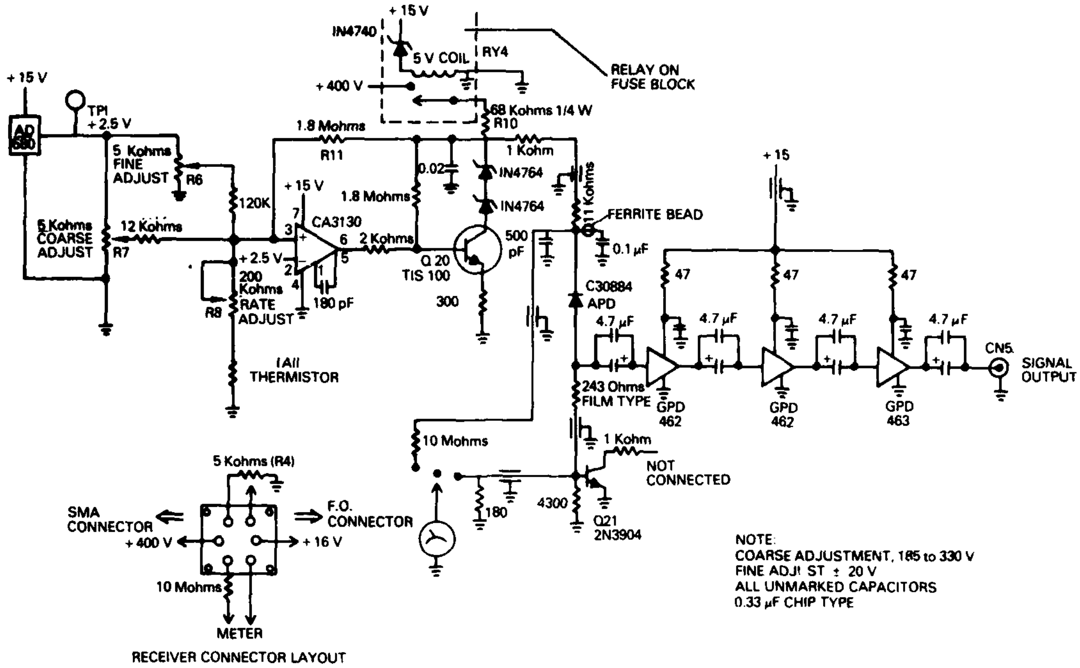


Figure 5. Optical receiver circuit.

through Q20 (and the current through the APD). The voltage is fed back through R11 and compared with the AD580 reference. The result of the comparison is amplified by the CA3130 and drives the TIS 100, thus completing the loop.

The 1A11 thermistor provides temperature compensation. As the temperature rises, the thermistor decreases in resistance and more current flows from the node where R6, R7, and R8 meet to ground. This causes a voltage increase across Q20; consequently, more current flows through R11 into the node. R8 adjusts the rate of this compensation to about 2 V/C as required by the detector.

The relay RY4 is used to turn the +400 V supply off if the +15 V supply drops to a value too low to enable the AD580 and the CA3130 to operate. Without RY4, if the +15 V supply were removed, Q20 would not be driven and the detector voltage would soar to a value which could damage the detector.

The proper detector current is around 200 μA. An excessive detector voltage will cause the APD to draw large self-avalanche currents and injure itself. Such self-avalanche is accompanied by considerable noise, readily visible if the receiver output is displayed on a wideband oscilloscope.

5.2 Amplifiers

The output of the APD is amplified by three GPD-type* amplifier modules to an output of several hundred millivolts (at maximum signal). The GPD units are hybrid circuits containing a signal transistor and the necessary matching and biasing components. Each stage has a gain of about 13 dB.

Although this type of amplifier, with its low input impedance (about 40 ohms) is not generally the optimal choice for use with a current source such as the APD, in this application the optical

*GPD is a product designation of Avantek, Inc., Santa Clara, CA.

signal level is high enough so that amplifier noise is not of critical importance. When analyzing noise performance of an analog AM-modulated system using an APD, one must bear in mind that a weak signal (low-modulation index) produces the situation of a small signal variation superimposed on a high background level; detector excess noise may be considerable.[3]

Examination of the noise output from the receiver shows that it contains a significant number of narrow (~ 1 ns) spikes, occurring at a random rate. Since these spikes are very narrow and occur at a relatively low average rate, they may not be visible on even a wideband scope if it does not have a high writing rate. These spikes can provide false triggering if one is attempting to observe a weak receiver signal output on an internally triggered scope. If the received signal is of reasonable strength, this is not likely to be a problem. One should normally choose the transmitter's front-end attenuation so as to provide a strong signal at the receiver.

6. SIGNAL TRANSMITTER CIRCUITS

The transmitter system (fig. 6) consists of three subdivisions: the front-end attenuator and its logic (described in sect. 7), the waveform generator (calibrator) (Q16 to Q19), and the transmitter itself, which consists of two GPD stages, the driver Q20, and the C30133 LED. A description of the calibrator and transmitter follows.

Transmitter. — The transmitter consists of two GPD stages having a total gain of 26 dB and the common emitter driver, Q20, which has the LED as the collector load. For transmission of sub-millivolt signals, an additional GPD amplifier stage may be added to provide 40 dB of gain. Since the LED has a low dynamic impedance, there is very little Miller effect degradation in the final stage. R3 sets the no-signal bias, typically 30 to 50 mA. This value must be individually adjusted to provide the maximum undistorted modulation swing for the LED. The trimmer capacitors and resistor, R6, are adjusted to provide the best pulse shape response for the link.

Calibrator. — When RY2 is energized (by Q2 of the remote unit logic), the transmitter input is transferred from the signal to the calibrator. The waveform generator consists of two monostable amplifiers (Q16, 17 and Q18, 19) driven by the 10-kHz waveform from IC4F (on the logic board). IC4F triggers Q19, which triggers Q18, causing the collector of Q18 to go negative for the desired period. This constitutes half of the calibrator waveform. When the collector of Q18 returns, this is coupled by the 15-pF capacitor to Q17. The collector of Q16 now goes positive for a period, producing the positive half of the waveform. R5 sets the waveform level and R4 adjusts the symmetry (for equal positive and negative excursions). Time symmetry does not have a convenient control but could be adjusted by a change in the value of the 56-pF capacitors associated with Q16, 17 and Q18, 19. The waveform thus produced goes first negative, then positive, and then back to zero. Since the system inverts all signals, this appears at the receiver output as the desired (positive-first) waveform.

7. CONTROL UNIT LOGIC

When the on-off switch of the control unit (fig. 7) is energized, section 1 of U14 immediately emits a low on its Q output. This low (1) causes U13 to load the data selected by the front-panel attenuation switches and applied to the inputs A through D, (2) disables U12, section 1, by forcing the clear and B inputs low, and (3) clears U11, section 2.

As a result of the clear applied to U11, section 2, Q15 is turned on. The clear applied to U12, section 1, prevents it from triggering U12, section 2; thus, the 2Q output is low: this low state turns Q14 on. Since both Q14 and Q15 are on, the LED D8 is illuminated and this illumination is conveyed to the remote unit by a fiber-optic cable. This in turn, energizes the remote unit.

[3] *H. Melchoir and W. T. Lynch, Signal and Noise Response of High Speed Germanium Avalanche Photodiodes, IEEE Trans. Electron Devices, ED-13, (1966), 829.*

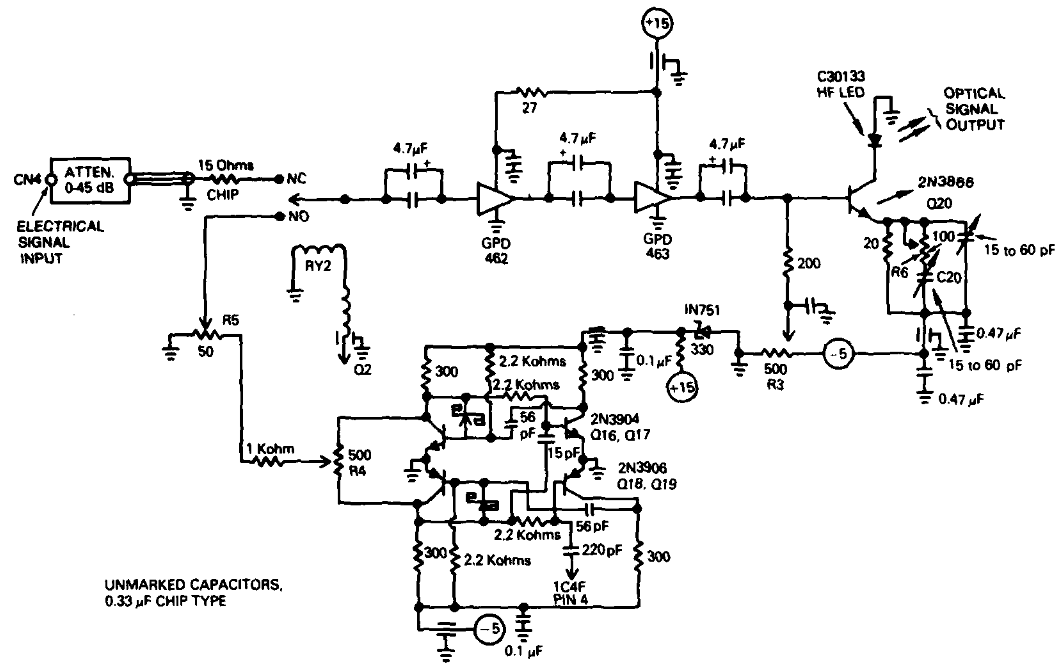


Figure 6. Signal transmitter circuit schematic.

When U14, section 1Q̈ goes high it (1) enables U11, section 2, (2) removes the load signal from U13, and (3) allows U12, section 1, to operate. Section 1 of U12 is an oscillator driving U12, section 2; thus, a series of pulses is produced at the U12, section 2, Q output. This is a square wave of about 500 Hz. This square wave both drives LED D8 (through Q14) and counts U13 down. When U13 is counted down to zero, the borrow input goes low, thus disabling U12, section 2, and terminating the 500-Hz square wave. Meanwhile, the remote unit (fig. 8) has used detector D7, etc., to count the flashes of LED D8.

LED D9 begins in the "on" state and ends up in the "on" state, having made a brief series of "off" excursions. Its duty cycle is such that it is "on" most of the time.

U11, section 2 (which is triggered by the oscillator of U11, section 1), having been enabled by U14, section 1, periodically emits a high on its Q output. The leading edge of this high causes U14, section 2, to emit a short pulse which clears counter U10. During the entire duration of the high, Q15 is turned off, thus removing the drive from D8 and allowing it to serve as a photodetector. The interruption of the light from D8 causes the remote unit to go into its interrogate cycle (as described in sect. 8). When the remote unit replies (via flashes from LED D7), detector D8 and comparator U15 detect the flashes and feed the signal through shaper U9 into counter U10. The count of U10 is displayed via the LEDs on the front panel.

The interrogate cycle can be defeated by a front panel switch which prevents U11, section 2, from becoming triggered.

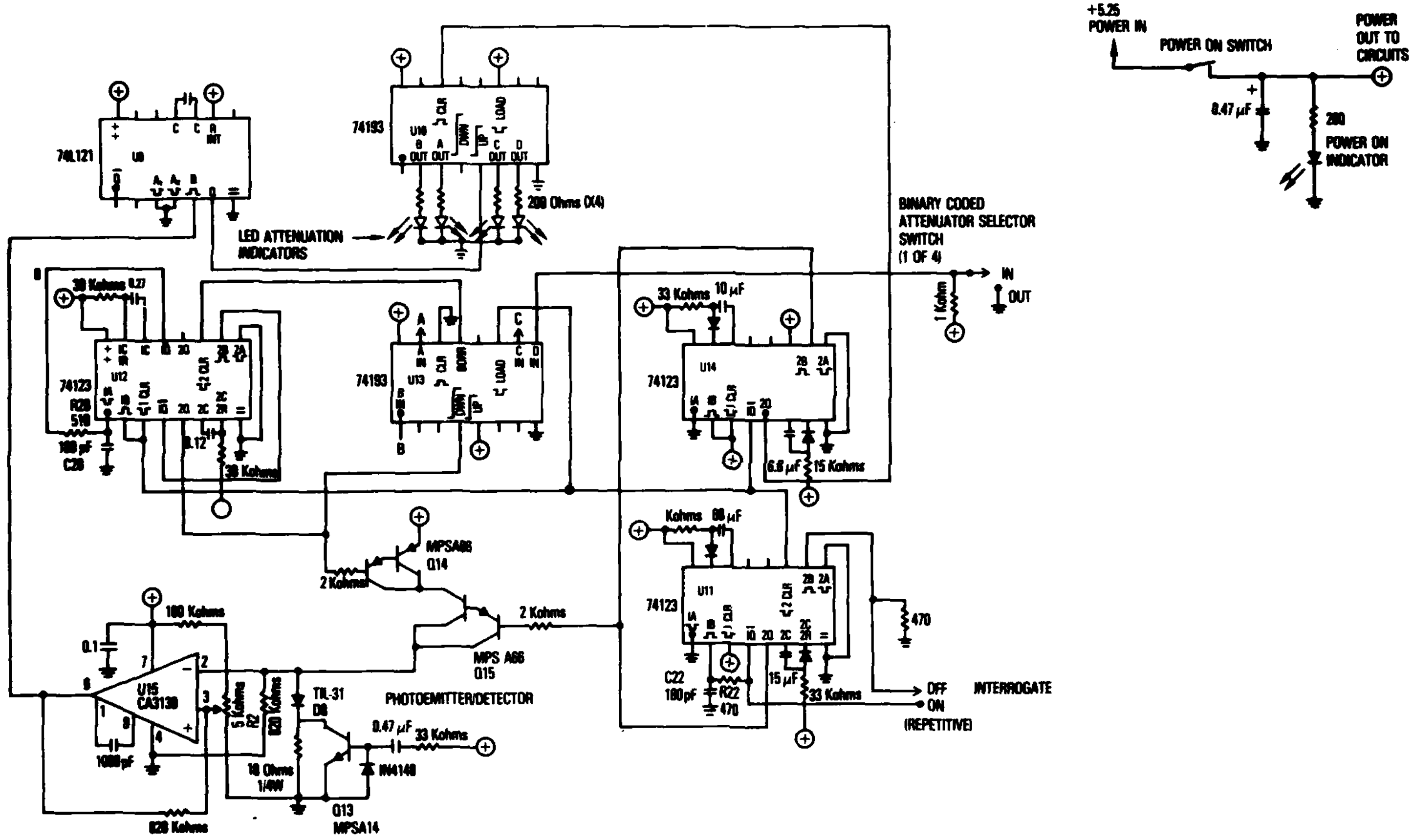
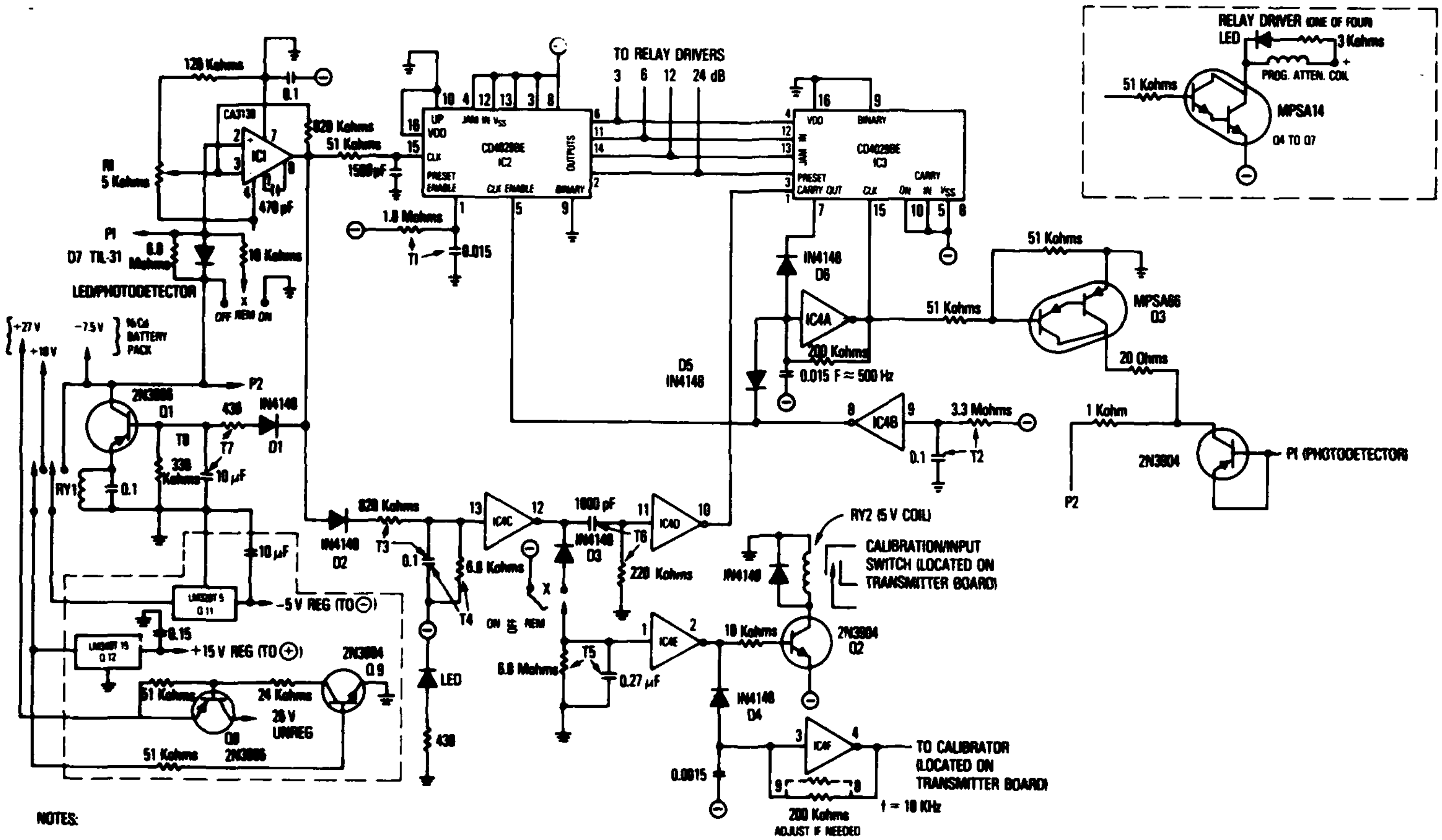


Figure 7. Control unit circuit schematic.



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IC4 CD40106BE
−, + BATTERY TAPS
⊖, ⊕ REGULATED VOLTAGES

PARTS INSIDE DOTTED LINE ON BOARDS SEPARATE FROM OTHER CIRCUITS

Figure 8. Remote-unit control logic schematic.

8. REMOTE-UNIT CONTROL LOGIC

8.1 Input/Output Circuit

The TIL-31 LED (D7 of fig. 8) acts both as a photodetector and as a photoemitter.This eliminates cable alignment difficulties which result from coupling light between a fiber-optic cable and two physically separated electro-optic components. The LED as a photodetector can easily provide several hundred millivolts of usable signal when operated into a high impedance.

When the unit is receiving commands (sent from the controller via the fiber-optic cable), the photodetector output is compared by IC1 to the reference level set by R1.

When the remote unit is sending the attenuator verification pulses back to the controller diode, D7 serves as an emitter, driven by Q3. During send-back, D7 is of course "blind," but at this time there is no requirement for receiving signals.

8.2 Turn On/Off

The input detector (D7) and the comparator (IC1) are always powered. When the controller is turned on, the light from LED D8 (fig. 7) is coupled via the control fiber-optic cable into D7. The light is sensed and the comparator output changes state. This charges the 10-μF capacitor and as the voltage rises the 2N3906 emitter follower (Q1) turns the relay (RY1) on. The relay in turn supplies power to the rest of the unit.

When the controller is turned off, the 10-μF capacitor decays through the 330-kohm resistor, thereby turning the unit off. This turn-off delay is sufficiently long to keep the unit from turning off during interrogate commands.

8.3 Loading of Attenuation Command

When RY1 initially closes at turn-on, the application of the negative supply determines the start of many of the timing signals. For example, at the preset enable of IC2 (Pin 1) the voltage across the capacitor, C1, is 0 V relative to the VDD supply (Pin 16). This is a logical 1, which causes the zeros at the jam inputs to be loaded into the counter. Capacitor T1 now charges to the negative supply through the 1.8 Mohm resistor until the preset enable is at logical zero. The counter is now ready to receive and count pulses.

The controller, having waited an appropriate time after turn-on, now sends out a series of pulses in the form of brief interruptions in the output of D8. These interruptions of light output are too brief to open RY1 (because of the time constant in the base of Q1), but are fed into IC2 Pin 15 and counted. The pulse count is taken from the outputs of IC2, amplified by drivers Q4 through Q7, and closes appropriate relays in the attenuator.

After about 300 ms, the output of IC4B (which is controlled by time constant T1) goes high and counter IC2 is inhibited from receiving further counts. At the same time clamping diode D5 is reverse-biased.

Since the attenuation loading is complete, the remote unit is now ready to be interrogated by the controller.

8.4 Interrogation/Calibration

When the operator commands the control unit to interrogate (by flipping the front-panel switch), the current drive is removed from D8 (by the turning off of Q15) and thus D8 is enabled to act as a photodetector. The remote unit's D7 senses the absence of light, and the output of IC1 switches. This begins the charge of capacitor C2 at the input of IC4C. After approximately 30 ms, IC4C switches. (This 30-ms delay is required to allow the carriers in the controller LED, which had been on, to decay, allowing what was once an LED to now function as a photodetector). When IC4C switches, the output is differentiated and the resultant pulse applied through IC4D to IC3 Pin 1 (preset). This loads IC3 with the output of IC2 (i.e., the actual attenuator setting at this time). Loading IC3 with a nonzero count causes the carryout (Pin 7) line of IC3 to go high. This reverse-biases clamp diode D6 and enables IC4A, which now oscillates at a frequency of 500 Hz. The output of IC4A pulses D7 (via driver Q3) and also pulses the clock input (Pin 1) of IC3. When IC3 has been clocked down to zero by the pulses the carryout (Pin 7) goes low, forward biasing diode D6 and turning the oscillator off. Meanwhile, the light flashes produced by D7 have been received by D8, counted by U10, and displayed on the front-panel LEDs of the controller. After the controller has received these pulses, it turns its LED back on. If it did not turn back on, the remote unit would turn itself off after the expiration of the time constant set by T2.

The remote unit is unable to respond to further interrogations until a time delay set by T4 has passed. This prevents the remote unit from interpreting its own light pulses as requests for interrogation and thus running continuously.

The interrogate command also causes the remote unit to send its calibrate signal. The output of IC4C is coupled to IC4E, which turns on for a period determined by time constant T4 (approximately 2s). The output of IC4E turns transistor Q2 on. This in turn closes the relay RY2 on the fiber-optic transmitter board, shifting the transmitter's signal input from external inputs to the calibrator. The repetition rate of the calibrator is determined by oscillator IC4F. The nominal frequency of the calibrator is 10 kHz, which can be trimmed by adjusting the value of the 200-kohm resistor. The time constant T4 is longer than the repetition rate of the controller interrogate; as a result, the calibration relay is continuously closed and the oscillator runs continuously for as long as the controller is in the interrogate mode.

9. SYSTEM PERFORMANCE

The amplitude and phase response of the system is shown in figure 9. These plots were obtained by feeding the test signal from the analyser into the transmitter, connecting the transmitter to the receiver with a 3-m long optical fiber, and feeding the optical receiver output into the analyser test channel. Although the amplitude data are correct, there is some doubt about the accuracy of the phase information because of the problem of providing equal propagation time delay between reference and test channels when the test channel contains a delay as great as the 3-m optical cable. In any event, phase distortion is reasonable, since square pulses are transmitted with only modest ripple. Low-frequency square waves show a tilt due to the low-frequency 3-dB point of about 5 kHz.

The dynamic range of the system is limited at the upper end by the level at which distortion in the transmitter becomes excessive and at the lower end by the level at which the signal modulation is obscured by noise; the low end is therefore to a great extent determined by the amount of optical signal that reaches the detector. This signal level, in turn, is dependent on the optical losses between the LED and detector. Over modest distances (up to

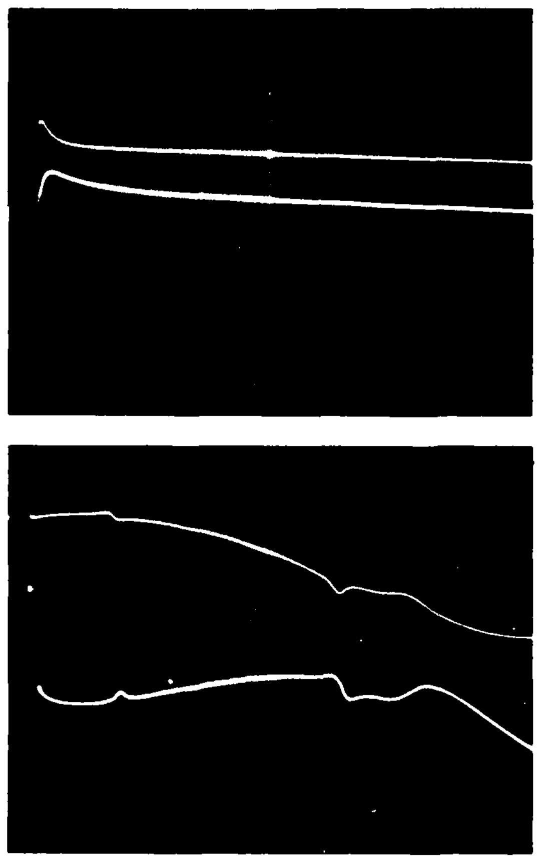

Figure 9. Phase and amplitude plots: upper, 0.1 to 11 MHz; lower, 1 to 110 MHz. Phase, 10 deg/division; amplitude, 1 dB/division.

50 m or so), a high numerical aperture fiber with a large optical transfer coefficient can be used, and the dynamic range should be nearly 40 dB. At greater distances, the dispersion of the high numerical aperture fiber will be excessive, and the required small-core fibers will give a smaller optical transfer and, consequently, a dynamic range near 30 dB.

10. FUTURE PLANS AND SUGGESTIONS

Although the described instrument, made originally in 1977, has worked very successfully and provided much measurement data which would probably have been prohibitively difficult to obtain with more unwieldy dielectric transmission systems (and totally unobtainable with hard-wire) it is, in a sense, obsolete at this time. At present, laser diodes have been developed to the point where their linearity is at least as good as that of an LED, and their lifetimes and stability are certainly adequate for laboratory instrumentation. With threshold currents now as low as about 35 mA, and very high dynamic sensitivity, a laser can be substituted for the LED with very little circuit change, and the resulting system will offer several times the bandwidth of the LED system together with better dynamic range. Such a signal link, incorporating a single-mode laser and highly miniaturized attenuator, has now been essentially completed by the authors. This system has a bandwidth of 500 MHz, and a dynamic range of 35 to 40 dB; it will be contained in a volume of about 35 cubic inches. All the control features of the original system have been retained.

Lest one completely despair that the LED system become outmoded, it should be pointed out that the cost of LEDs is much less than that of lasers and that their lifetimes and temperature stability are superior. Also, the very narrow spectral output of single-mode lasers has produced some knotty optical fiber problems not experienced with LED emitters; interference effects within fibers and at the connector can produce model noise.[4]

A number of experimenters[5] have used predistortion and feed-forward or feed-backward schemes to linearize LED systems, producing second and higher harmonics down 60 or more dB. At present this work has concentrated at video bandwidths, but the possibility of applying it to wideband instrumentation links is certainly attractive.

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[4] R. E. Epworth, *Phenomenon of Modal Noise in Fiber Systems*, OSA/IEEE meeting, Washington, DC (9 March 1979)

[5] I. Straus, *Linearized Transmitters for Analog Fiber Optical Systems*, Paper II GG2, OSA/IEEE meeting, San Diego, CA (7 February 1978)

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5. I. Strauss, *Linearized Transmitters for Analog Fiber Optical Systems*, Paper TUGG2, OSA/IEEE meeting, San Diego, CA (7 February 1978).

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