DESIGN AND PERFORMANCE OF AN UNDERSEA, SINGLE-FIBER MULTI-REPEATER, FULL DUPLEX, ELECTRO-OPTICAL DATA LINK

G. Wilkins, A. Nakagawa & N. Kamikawa
Naval Ocean Systems Center
Hawaii Laboratory
Kailua, HI 96734

D. Baldwin & P. Couch
ITT-EOPD
Roanoke, VA 24019

ABSTRACT

Fiber optics' major contributions to undersea communications should include greater telemetry bandwidth, improved data precision and a decrease of system volume. The last two of these served as primary goals during recent design, fabrication and ocean testing of an undersea, electro-optical (E-O) telemetry system. The system's total length was nearly 70 km. It contained 8 in-line repeaters which were powered through the E-O cable. Data were transmitted full duplex (22 MB/s at 0.83 µm & 43 KB/s at 1.06 µm through a single optical fiber. Power consumption was 1.69 watts for each repeater. Telemetry BER through the 70-km cable path was better than 10^{-9} at 22 MB/s. The repeater housings were designed for 1-km ocean depths. Their dimensions (including bend-limiting cable terminations) were 2.88-cm diameter by 30.5 cm length. Each repeater contained special circuitry so that it would be queried from shore in a fault diagnosis mode. Designs and performance are reported for the E-O telemetry system and for its major components.

INTRODUCTION

In 1977, the Hawaii Laboratory, Naval Ocean Systems Center (NOSC) began[*] the demonstration development of a fiber optic, repeatered, undersea telemetry system. The rationale for this effort was the realization that---no matter how low the attenuation of optical fibers might become---there would still be a growing need for fiber optic telemetry in the ocean over distances greater than one (or even several) inter-repeater spans. One commercial application for such technology is in the transoceanic telephone (or "long haul") system.

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[*] ITT-EOPD served as the principal systems contractor for this effort, which was sponsored by the Navy Exploratory Development Program.

The development goals of the Navy program required a deliberate assault on the state of the art in E-O technology. Most of these performance objectives required E-O components that did not even exist in 1977. Examples of such technology "stretching" include:

(1) The E-O telemetry system must operate in a full-duplex mode; that is, with simultaneous two-way transmission of optical data. As a further design goal, this was to be done through a cable with only one optical fiber. To do this, an optical duplexer (bidirectional optical coupler) would have to be developed. No such device existed in 1977.

(2) Maximum use would be made of hybrid electronic circuits in an attempt to reduce the mass and volume of the E-O repeater. These dimensional goals began to influence our perception of size and shape for the repeater, and it became known as the "banana".

(3) Inter-repeater distance would be at least 8 kilometers---a considerable challenge in 1977 when optical telemetry was constrained to wavelengths less than about 1.1 µm. (This minimum distance was selected because it is also the length required for ship support of cable-tethered vehicles operating at the 6-km depth of the ocean's abyssal plains. Examples of such operations include deep sea search, mapping and recovery tasks.)

(4) Repeater power consumption was also to be minimized. As an early goal, each E-O repeater was to support full-duplex operation of the telemetry system while consuming no more than 1.5 watt. Any power used to support diagnostic circuitry was not counted against this budget.

(5) The repeater structures must be pressure resistant. Each repeater must withstand long-term exposure to ocean depths of at least 1 km---without buckling, leaking, or degrading the telemetry system's power, data or strength functions. Long-term hermeticity was highly desirable, but the initial design objectives required only a capability for several months of submerged operation without measurable degradation of E-O repeater performance due to leakage.

(6) All electrical power to the E-O repeaters (and the cable's sea terminal) must be supplied through the cable. At the same time, the diameter and transport volume of that cable were to be as small as possible.

(7) A system Bit Error Rate (BER) no worse than 10^{-7} was required for the high frequency data channel. (This corresponded to a BER of 10^{-8} for each of the system's 8 repeaters and 2 end terminals.)

(8) The state of the art in telemetry bandwidth was not pushed. A data rate of 22 MB/s at 0.83 µm was chosen for the instrumentation channel, while the control channel operated at approximately 43 KB/s (1.06 µm). The ratio of these two rates is $2^9 = 512$.

AN OVERVIEW OF THE E-O TELEMETRY SYSTEM

Figure (1) schematically describes the demonstration E-O telemetry system as it operated after ocean deployment. The system contained 10 cable sections and 8 repeaters, and had a total length of 69.2 km. Optical characteristics of the assembled E-O cables are summarized in Table (1). Generally, these cables had slight less attenuation than did the ready-for-cabling optical fibers on their storage reels. (No miracles are claimed since, even for precision winding of optical fibers, on-reel storage represents a high stress environment, with many fiber crossovers and microbends.

In addition to its primary role as a cable-powered, two-way, data link, the demonstration system supplied power to an “Ocean Terminal”. Such a terminal could be no more than a ground plane to initiate the seawater-return power circuit. If so, then the system can be considered as a scale model for half of a transoceanic, optical, communications link. In such a context, it would be powered from both ends, and at least one mid-ocean ground plane would be used to support the power return circuit.

The “Laboratory Terminal” for the E-O telemetry system was located at NOSC’s Hawaii Laboratory on Kaneohe Bay, Oahu. The data link was deployed in a long offshore loop to a maximum water depth of about 150 m. The Ocean Terminal was located outside the Kaneohe Bay barrier reef, so that the length of the seawater power return was about 3 km.

The “Junction Box” in Figure (1) was placed adjacent to the Ocean terminal at a depth of approximately 30 m. It served as an interface for make-and-break splicing of the seaward portion of the telemetry system to an armored E-O shore cable[*] (unit 1-A). Location of this junction at a point well clear of the barrier reef allowed NOSC support boats to safely anchor near the end of the shore cable. Divers could then bring the Junction Box aboard, so that electrical- and optical connections could be made and the mated E-O cable sections deployed on the seafloor.

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[*] The shore cable is an example of the impact that an E-O cable’s reduced diameter can have on its deployment complexity and cost. The design of this cable was the same as that of the cable (to be described) in the demonstration system, except that additional armoring and jacketing increased its diameter from 2.54 mm to 6.35 mm. Cable laying started at the Junction Box and led back toward the Laboratory Terminal, and the cable was plowed in over much of the 3.9-km route. The total time required for this operation---from departure of the cable-laying boat from the Hawaii Laboratory quay wall to passing the cable ashore---was less than 4 hours.

System data telemetry achieved the development goal of full-duplex operation over a single optical fiber, and consisted of:

LBR Channel	Control signals were telemetered to the Ocean Terminal through a low-bit-rate (LBR) channel at 42.97 KB/s ($\lambda = 1.06$ µm). A Plessey GAL-103 light-emitting diode (LED) was used for each section of the LBR telemetry path. The detectors were RCA Model C30922F avalanche photo diodes (APD's).
HBR Channel	Data were received at the Laboratory Terminal over a high-bit-rate (HBR) channel at 22 MB/s (0.83 µm). An injection laser diode (LD) was used for all path segments. The LD, which contained hybrid temperature- and voltage-compensating circuitry, was developed for this program by RCA's David Sarnoff Research Center (1). The detector was an RCA C30921E APD.

The data format in the HBR and LBR channels was digital pulse code moulation (PCM), with biphase-M or alternate mark inversion (AMI) data code (2). This code guarantees a high number of transitions, and simplifies timing recovery and fault detection. The relatively high value for its low frequency cut-off permits the use of smaller electronic components in the E-O repeaters. The resulting narrow data bandwidths also help in electrical isolation of the two transmission channels. They do, however, require a clock rate which is twice the bit rate.

Power consumption at each repeater was 1.69 watts (165 mA at 10.25 VDC), and 20 watts were delivered to the Ocean Terminal. This latter level could have been increased to more than 50 watts without overstressing cable insulation.

Each repeater had an overall diameter of 2.88 cm, and a total length of 30.5 cm. (This length included flexible bend limiters at each end of the cylindrical structure.) Each repeater housing was also a pressure vessel. Tests of these housings showed no measurable leakage during a 90-day exposure to a hydrostatic pressure of 105 kg/cm^2 (1000-m equivalent ocean depth). The weight of each repeater was less than 400 grams.

The Laboratory Terminal was operated under computer control, and served as the telemetry's system's primary center for data collection and evaluation. Typical monitoring functions included:

- Measurement of bit error rate for the HBR channel was initiated via an LBR signal to the Ocean Terminal. This activated a generator which began to transmit a $2^{10} - 1$ pseudo-random HBR bit sequence to shore.

- The BER for the LBR channel was measured with a turnaround procedure. The received LBR data were stepped up in frequency by 2^9 (512 times) at the Ocean Terminal, then were transmitted back to shore. Any error bit which occurred during the outbound leg of this 140-km path must stand out in the returning signal as a series of 512 consecutive errors. Any errors which were inherent to the (returning) HBR path occurred singly and, therefore, could be filtered out in data processing.

- The Ocean Terminal was equipped with simple sensors---internal humidity and temperature monitors, plus a current meter and a pressure sensor. On (LBR) command from shore, data from these sensors were digitized and transmitted over the HBR channel back to shore.

- A “ping pong” match could be played on the E-O data link by activating a game chip in the Ocean Terminal. Command signals were sent via the LBR channel, while motions of the game’s paddles and ball were monitored by video signals transmitted over the HBR data channel.

- Each repeater contained a diagnostic circuit which could be commanded by transmitting a uniquely coded LBR signal from shore. On receipt of that signal, the interrogated repeater would (a) interrupt the stream of HBR data from the Ocean Terminal and (b) begin to transmit a unique (known) series of HBR data bits back to shore. This bit stream allowed the performance of that repeater---plus all elements of the E-O system closer to shore---to be measured. Each repeater had a unique address for such performance queries. The sequence ended automatically when a query was sent to an address which did not exist within the link.

TELEMETRY SYSTEM DESIGN

The design of the E-O ocean telemetry system can be naturally separated into three discussion topics---the E-O cable, the repeater structure and its cable terminations, and the repeater electro-optics. These subjects are treated in that order below.

The Electro-Optical Cable

This cable has been extensively discussed in the literature (3, 4), so only design and performance highlights will be reported here. The-cable is shown in cross section in Figure (2). It was designed to protect a single optical fiber during ocean deployment and operating stresses, while simultaneously delivering electrical power to a series of E-O repeaters and an end terminal. Key features of the design included:

- The approach assumed successful development of an optical duplexer. (An alternative design---which required 2 optical fibers---was abandoned as soon as this assumption could be proved correct.)

- The fibers were graded index, multi-mode units. Their attenuation and dispersion levels were low for U.S. industry in 1978/79, but were not outstanding. Table (1) lists cabled values for these parameters.

- However, all fibers used in the demonstration cables were subjected to a 1.0% proof strain during the manufacturing/buffering phases. Today, that proof strain could probably be raised to 1.5% at moderate risk, and to 2.0% with a high rejection rate.

- The optical fibers were buffered with a silicone rubber (Dow RTV 184) to an O.D. of 0.33 mm, then with a polyester elastomer (DuPont HYTREL 7246) to a 1.02-mm O.D. Note the large diameter of this second protective coat. This was done to give the optical fiber more isolation from the somewhat anisotropic stresses which occur when the metal wires (under axial tension) bear down on the fiber's outer buffer.

- The metal wires in the E-O cable have a dual role, as the primary load-bearing structure and as the electrical conductor. To reconcile these conflicting roles, a special copper-clad steel was used.

Ultimate Tensile Stress	7800 kg/cm^2
Ultimate Tensile Strain	0.79%
Yield Strain	No yield (per definition as 0.2% strain offset)
Conductivity	60% (re IACS)

  Note that ultimate wire strain is appreciably less than the fiber proof strain. Copper/steel wires have been reported (5) with 60% conductivity and with an ultimate tensile stress of more than 10,500 kg/cm^2.

For a 6.4° assembly helix angle, the E-O cable's resistance was 38 ohms/km, and ultimate cable strength was nearly 60 kg at 0.79% strain. Jacket voltage stress was less than 1930 V/mm at the maximum operating voltage of 600 VDC. Jacket resistance was 800 megohm-km and cable specific gravity was 2.12.

The E-O cable showed slightly *reduced* optical attenuation (at 0.83 µm) when subjected to tensile loads which were 20% of ultimate cable strength. Even at 50% (relative) loading, the attenuation was no higher than it had been at zero tensile stress. Our model for this behavior assumes that the effect of initial axial loading is to pull the fiber straighter in the cable---i.e., to minimize residual microbends. At higher loadings, bearing pressures for the conductors may cause them to partially embed in the fiber buffer.

The E-O cable's attenuation increase was less than 0.3 dB/km for exposure to a hydrostatic pressure of 100 kg/cm^2. We believe that even this reaction would have disappeared if the channels between the conductor wires and the HYTREL buffer could have been void filled. When these cables were built, ITT did not have the equipment needed to carry out this operation.

The cable's responses to (loaded) flexure and environmental temperature were also measured.

Flexure	During more than a dozen tests, the E-O cable survived at least 460,000 cycles of loaded flexure (± 28° at 20% of ultimate loading over a 5-cm-radius grooved sheave.) Average flexure life was 710,000 cycles. The optical fiber never failed until several copper-clad-steel wires had parted.
Temperature	The maximum attenuation change noted over a temperature range of -55°C to +75°C was 0.23 dB/km (at 0.83 µm. The attenuation of the *uncabled* fiber increased by as much as ±13 dB/km at the lower temperature. (See Ref. *3*.)

The addition of a 1% requirement on fiber proof strain to the attenuation and dispersion goals in Table (1) had an adverse effect on production efficiency (i.e., km of acceptable fiber per km produced). This was one of two reasons for a decision to accept fiber splices in the E-O cable. The second factor was our realization that---ultimately---reductions in fiber attenuation would allow repeater separations so large that production economics would dictate a requirement to have (several?) splices in each inter-repeater cable section.

Therefore, *this* project became a guinea pig to determine the effects of fiber splices on long sections of E-O cable. Of the 10 cables shown in Table (1), Sections (6), (7) and (8) contain an optical splice. The Table shows that these splices have little effect on average fiber attenuation or dispersion.

The most difficult part of the splicing operation is *not* the fusing together of the two fiber ends. Rather, it is the need to immediately and uniformly reestablish the fiber buffer(s) , so that the weakened fiber retains some fair approximation of a hydrostatic (i.e., radially isotropic) stress response.

As a proof test of the quality of the splicing-and-rebuffering operation, all fiber splices were subjected to a proof strain of 2.0%. This strain is much less than the fiber's average ultimate strain (about 5--6%). It is, however, twice as high as the rolling proof strain applied to the rest of the fiber. Therefore, it should ensure that the splice zone is not the weakest link in any spliced fiber or cable. As support for this assumption, all three of the fiber splices survived the stresses of cabling, deployment and operation. No problems have been linked to the use of fiber splices in the E-O cable.

But somewhere there must be a weakest link. For the E-O telemetry system, it has been the cable's electrical jacket. Although the conductor wires give excellent protection to the optical fibers, they are in turn protected only by the cable jacket. Any external action which damages this jacket directly affects the system's ability to supply electrical power to downstream users. Without electrical power, the system is useless---and that power support must depend on the integrity of a thin jacket of high density polyethylene. This jacket has been the telemetry system's Achilles heel.

Repeater Structure And Terminations (6)

The structure of an E-O repeater is shown in Figure (4). Total length for a repeater unit (including bend limiters) is 30.5 cm, and its overall diameter is 2.88 cm. Unit weight is slightly less than 400 grams. These dimensions include all electro-optical circuitry required for operation in a full-duplex mode---including circuits to support system diagnostics.

Beryllium copper (Grade CA 173, 2.5% Be) was used to fabricate the repeater's cylindrical wall and end bulkheads. This alloy can be heat- and work-treated to a yield stress of 12,200 kg/cm^2 at 0.2% strain offset. Equally important, its thermal conductivity is 2.5-times that of steel, and is nearly 8-times greater than that of stainless steel.

Figure (5) shows the cable termination unit designed for the ocean telemetry demonstration. This interface must simultaneously preserve the electrical, optical and physical integrity of the E-O cable. It must also fix a minimum bend radius for the cable during high off-axis loadings. And, it must do all of these while limiting water leakage or diffusion into the repeater's minuscule E-O cavity to an absolute minimum.

The initial step in forming the cable termination is to mold a polyethylene "nosepiece" or interface plug, so that it is both flow-bonded to the cable's jacket and mechanically mated to a beryllium/copper bulkhead. This interface piece, shown in Figure (5), will also serve as a bend limiter and reinforcing element for the E-O cable.

Within the confines of the bulkhead, the cable passes through an epoxy/glass insulation bushing into a steel termination cone. There, the cable jacket is removed and the copper/steel wires are fanned out within the volume of the cone. The optical fiber continues down the cone axis. The fiber and wires are then potted into place.

Any cable-driven leakage must begin beyond the bend limiter(s); and must then pass through the polyethylene flow bond and epoxy termination to enter the repeater cavity. Any other leakage path must contend with the double O-ring seal which joins the repeater's cylindrical wall to each bulkhead piece.

Figure (3) shows the E-O cable termination subjected to a 23-kg load (40% of ultimate) applied at a 45° angle to the repeater axis. For these conditions, the termination withstood a hydrostatic pressure of 105 kg/cm^2 for 1 hour with no leakage. In a relaxed condition, the termination has been soaked at a pressure of 105 kg/cm^2 for 90 days---again with no sign of leakage.

One likely leakage mode for O-ring seals is a failure-to-seat tendency at very low hydrostatic pressures. The repeaters in the completed telemetry system were tested in shallow water baths for a total time of several weeks (each). No operational evidence of leakage could be found.

SYSTEM OPTICS, ELECTRONICS AND ELECTRO-OPTICS

As Figure (6) shows, each E-O repeater must serve as an optical detector, as an amplifier, as a signal reconditioner and as an optical transmitter. This is done in a digital PCM mode, using a BiPhase-M AMI code (2). Each repeater must also operate full duplex---transmitting 22-MB/s (HBR) data to shore at a wavelength of 0.83 µm, while simultaneously transmitting LBR command signals at 43 KB/s and 1.06 µm to the Ocean Terminal.

The Optical Duplexer (7)

Since only one fiber is involved in this telemetry, two optical duplexers are required in each of the E-O repeaters in order to separate (and recombine) the dual-wavelength telemetry signals. The schematic for this operation is shown in Figure (10), and the operation of a duplexer is sketched in Figure (7). A photograph of an operational duplexer from the E-O telemetry system is shown in Figure (8), where a dime establishes the measurement scale.

During duplexer operation (Fig. 7), radiation from a local optical source is led through a pigtail fiber to the Petzval surface of the (left hand) lens, and is collimated by that lens. At wavelength λ_1, the dichroic filter will be highly reflective, so that this optical signal passes back through the lens and is brought to a sharp focus on the core of the cable fiber. Because of these forward-reverse lens passes, first-order image aberrations will be cancelled.

Optical signal (λ_2) from the cable's distant end is also collimated by the lens, but passes through the now highly transparent dichroic filter. An identical (but reversed) lens focuses this second signal into a detector pigtail fiber. Again, first-order aberrations cancel. An optional bulk filter (e.g., AR-coated Si, GaAs or InP) can be inserted into the optical duplexer to further isolate the detector from the intense local optical source.

In the demonstration telemetry system, the optical duplexer was operated at wavelengths of 0.83 µm and 1.06 µm. Each E-O repeater contained two duplexer units which were structurally identical; differing only in the choice of the dichroic mirror. The mirror in one unit transmitted 0.83-µm radiation and reflected the longer wavelength---the roles reversed in the second duplexer. In each case, the dichroic mirror was a multi-layer interference filter. The throughput loss at each duplexer varied from part to part, but generally was less than 2.0 dB. Channel separation was better than 50 dB, as seen without a blocking filter from the 1.06-µm detector. It was better than 60 dB at the 0.83-µm detector.

In practice, the optical duplexer can operate at any wavelength pair within the practical transmission range of fused silica (say, 0.8- to 1.55 µm). The wavelengths should, however, be separated by at least 10%. If either optical source is an LED, the wavelength separation should be greater because of that source's relatively broad emission spectrum.

NOSC Hawaii (8, 9) has used unmodified optical duplexers from this telemetry system to support full duplex operation of an 8.2-km-long optical tether at wavelengths of 1.25 µm (120 MB/s) and 0.83 µm (2.0 KB/s). Optical filtering was the only method used to separate the two telemetry channels.

Repeater Electronics

The operating modes of the optical duplexers are illustrated in the repeater block diagram in Figure (10). Circuit blocks for the HBR receiver and transmitter are shown at the top with signals propagating to the right. The LBR receiver and transmitter are shown near the middle, where the signals travel toward the left. The HBR signals also flow through a data switch, which is associated with the diagnostic (fault location) circuits.

As Figure (10) shows, the supply of electrical power from the cable to the E-O repeater is totally separated from the optical signal. This is a major improvement over a coaxial telemetry system, where large filters are needed to isolate the small AC signal voltage from high levels of (AC/DC) powering voltage on the same conductors).

In this E-O repeater, the electrical power conditioning circuit is in series with the cable's electrical conductor. That circuit includes a filter and a transient suppressor, followed by additional filtering and regulation. The power conditioning circuit converts the constant line current from the cable to the regulated constant voltage required by the repeater electronics.

Fault Location. This circuit is used during system setup, or in case of a subsystem failure, in order to identify the location of a system fault. The circuit can identify the last (most seaward) working repeater---including the Ocean Terminal. In order to locate a fault, the Laboratory Terminal operator interrupts normal LBR traffic and transmits a coded bit sequence or address which is unique to one of the repeaters. This code triggers the appropriate repeater to switch from the HBR receiver to an internal data generator, as shown in Figure (10). That generator produces a continuous series of alternating AMI-coded 1's and 0's. This signal is monitored by the operator, and can be used as a diagnostic tool as well as for fault location. Calling the address of a new repeater activates that unit and allows the previous unit to switch to its normal mode. If a nonexistent repeater address is transmitted, the entire telemetry system will return to normal operation.

The power switch in the fault location circuitry serves to reduce electrical power consumption. The HBR receiver is deactivated during operation of the fault location mode. The power it normally consumes will be used instead to power the internal data generator.

E-O Receiver. The receivers will be the most critical circuit elements in the repeater. Figure (6) shows the circuit block diagram for either the HBR or LBR receiver. The APD signal is amplified by bipolar transistors in a transimpedance front end. Balanced circuit techniques are used throughout that front end. With the filter and the chain of limiting amplifiers, the use of balanced circuits minimizes the effects of various types of noise such as ground loops. It also helps to prevent oscillation.

Limiting amplifiers take the place of the more common integrated circuit (IC) amplifiers and IC comparator. The IC's available for these functions consume considerably more power, and are more sophisticated than necessary. Use of simpler limiting amplifiers is allowed by the choice of AMI coding, because of its 50% duty factor and its restrictions on pulse length variations.

Although the limiting amplifiers have low power consumption, they have high performance. In particular, they allow very large dynamic range, even with no automatic gain control (AGC) feedback loops in the amplifier chain. For even greater dynamic range, signal from the limiting amplifiers is rectified and used to control the APD voltage independently for each receiver. Only one APD power supply is required to support both detector channels.

After the limiting amplifiers, the signal is passed to the data regeneration stage, which restores pulse shape, pulse width and pulse heights. Timing recovery is used to reduce timing jitter accumulation over many repeaters. The timing recovery in both receivers is accomplished with a phase-locked loop (PLL), instead of a more conventional ringing tank circuit. The PLL reduces pattern dependence, simplifies setup procedure, and improves stability with time, temperature and variations of voltage supply. The PLL also requires smaller inductors than the large coils required for a ringing tank. This is especially true for the LBR receiver.

Integrated circuits were used in the data regeneration and timing recovery circuits because of the simplicity with which they can perform these complex functions. Standard IC's available for these tasks have reasonable power consumption, small size and transistor-transistor logic (TTL) compatibility.

The APD power supply shown in Figure (6) steps up the voltage from about 5 V to the level of about 300 V required for high APD gain. This supply is based on a very small hybrid circuit and transformer which was originally developed for use in ITT-EOPD's night vision goggles.

Avalanche Photodiode (APD). The optical detectors chosen for both HBR and LBR channels are APD's. These units are now commercially available from RCA in Canada, and are packaged by that company in a TO-18 can with a light pipe from the detector chip to the surface of the can. Their designations are:

C30921E	0.83-µm (HBR) Channel
C30922F	Enhanced 1.06-µm (LBR) Channel

Volume was at such a premium in the E-O repeater that ITT-EOPD was forced to develop a special fiber pigtail which exited the APD via a right-angle bend. This feature is illustrated in Figure (15). The bend has a well-controlled radius (≥ 2.5 mm), and is formed by an initial careful heating of the fiber. The bent fiber is then potted into an epoxy boot and its end polished. The epoxy protects the pigtail, and also strips off any cladding modes that may propagate light scattered within the optical duplexer.

For the 1.66-µm APD, a small chip of AR-coated GaAs was placed between the detector cane and the fiber as a spectral filter to help reduce cross talk. No filter was required for the 0.85-µm detector, since the 1.06-µm source (an LED) has relatively low output optical power, and because the sensitivity of the 22 MB/s receiver is (relatively) low.

Light-Emitting Diode. The optical source for the LBR channel was an LED with a wavelength centered at 1.06 µm. This unit (Plessey No. GAL 103) is a surface emitter type available in a pill package. ITT-EOPD incorporated the Plessey unit into a slightly larger package which supported the optical fiber pigtail and provided a means to mount the module onto the repeater bulkhead.

Injection Laser Diode. A low-threshold, AlGaAs, injection laser diode (LD) was used as the optical source for the HBR channel. The peak wavelength for this device varied (part to part) between 0.821- and 0.842 µm. The optical power launched into a 55-µm-core-diameter, graded index fiber varied (part to part) between 1.6- and 2.8 mW.

The LD, an electronic drive circuit, a special temperature compensation circuit and a heat sink block were all contained within a hybrid circuit module developed by RCA (1) at that company's David Sarnoff Research Center. This module, with dimensions 14 mm X 18 mm X 10 mm high, is shown in Figure (9). Power consumption varied (part to part) between 415- and 503 mW. Obviously, this is a critically large fraction of the E-O repeater's total power budget of 1690 mW (in a full duplex mode).

Voltage Regulation. Figure (11), a full repeater block diagram, demonstrates the arrangement for power supply and filtering. Note that two supply rails are used; each with its own regulation to about 5 V. The HBR regulator was actually specified at 5.25 V ± 0.25 V in order to improve rise time and to reduce delay for the laser module. For similar reasons, the control section of the laser module bridges across both rails to give 10.25 V ± 0.50 V. As the previous section mentioned, this laser module has its own regulator circuit to provide the very high voltage stabilization needed for response to changes in ambient temperature and/or bias voltage.

Several different voltage conditioning arrangements were evaluated during the design of the E-O repeaters. Early analyses had assumed that a mix of series and shunt voltage regulation would be required. However, initial breadboard circuits proved that use of a single (and better) shunt regulator for each rail would reduce overall power consumption and improve supply regulation.

The optimum repeater voltage drop will vary with the cable's length and its resistance per unit length, with repeater power and with the level of power delivered to any end terminal. It was concluded that, for actual telemetry system conditions, a drop of approximately 10 V would be optimum. The twin requirements for this 10-volt supply and for low repeater power consumption are the main reasons for having two stacked 5-volt supply rails.

Hybrid Circuits. The E-O repeater circuits were extensively hybridized in an attempt to reduce size and volume, while hopefully improving HBR reliability and performance. Each repeater used 6 hybrids---defined below and sketched as numbered, dashed-line groups in Figure (11). Hybrids H1----H4 are also shown in Figure (12) alongside an inch scale.

H-1	LBR receiver.
H-2	HBR receiver.
H-3	LBR transmitter; including timing recovery, fault location & shunt regulation.
H-4	HBR data regeneration, timing recovery, fault location data generator & shunt regulator.
H-5	APD power supply oscillator & regulator.
H-6	RCA HBR laser module.

To make these circuits compatible with hybridization, and to limit the number of parts that must be mounted outside the hybrid packages, the following guidelines were adopted.

(1) Eliminate potentiometers and variable resistors. If variation became necessary, use chip resistors.

(2) Eliminate inductors unless absolutely necessary; and then use low-Q for small size.

(3) Eliminate (or reduce the size of) transformers.

(4) Eliminate variable capacitors.

(5) Reduce capacitor size---the smaller the better, with a preference for a maximum of 10 μf.

(6) Eliminate large voltage-line filters.

(7) Eliminate crystals. If used, they must remain in their original can.

(8) Eliminate the need for heat sinks on transistors by lowering the power consumption.

Electro-Optics Assembly. Only a few electrical components remained outside the hybrid cans. They are the LED, the APD's (actually mounted on the bottom of a hybrid unit), the APD power supply transformers, high voltage capacitors and rectifier diodes, 2 small adjustable inductors (one for each data channel frequency range), and several access terminals for testing.

Two views of the assembled E-O repeater are shown in Figures (13) and (14). The internal dimensions of the circuit assembly are 15.5-cm length by 2.3-cm greatest diameter. This volume contains 2 optical duplexers, 6 hybrid circuits (including 2 APD's and a laser), discrete electronic components on 2 printed circuit boards, an LED, fiber routing and storage space and, finally, 0.15 cm in each direction for tolerance and compliance.

PERFORMANCE OF THE E-O TELEMETRY SYSTEM

A 4.4-km length of armored shore cable (Section 1-A) was delivered to the NOSC Hawaii Laboratory in mid-1978, and was almost immediately installed as an electro-optical "jumper" cable to connect the laboratory with deep water seaward of the Kaneohe Bay barrier reef.

A prototype version of the demonstration E-O telemetry system was installed later that summer. It consisted of the Laboratory Terminal, shore cable 1-A, a 2-km length of the system cable, a prototype repeater, another 2-km length of system cable, and the Ocean Terminal. Appropriate lengths of optical fiber were spliced into the telemetry system at the Laboratory and Ocean Terminals to make the prototype system operate as though it were one repeater between two 8-km lengths of E-O cable.

The prototype telemetry system was operated for two weeks; then was recovered for inspection. During that time, it met all performance goals; according to the test series described in the "Overview" section. Inspection of recovered components showed no evidence of degradation.

The remaining 64.8 km of E-O data link (Sections 1-A---9) were delivered to NOSC Hawaii in mid-summer of 1979. This telemetry system generally met or exceeded all of the program's original performance goals---and met them over the environmental temperature range of 0°C-32°C. Table (2) compares the demonstration system's performance with several of these objectives. Table (3) compares the HBR and LBR optical budgets (for 8-km Cable Section 2) with the original budget predictions.

Both HBR and LBR channels had much higher optical margins than had originally been predicted. This was due to lower than expected levels of attenuation; especially for the 1.06-µm LBR channel. Overload became a more serious problem than optical margin. It became necessary, for example, to install 10-dB attenuators in HBR Sections (3) and (4).

Discovery Of The "Fishbite" Effect

The original deployment plan had been to electrically and optically connect the 64.8-km demonstration system to the 4.4-km E-O shore cable; then deploy the data link in a giant loop along the eastern shore of Oahu (Fig. 1). This plan stalled when it was discovered that exposure samples of the system cable were the subjects of ferocious attacks by local fish.

These attacks varied in intensity from relatively curious nibbles and slashes to full-jaw assaults so vigorous they kinked the copper/steel wires in the cable. Figure (16) shows examples of these extremes. The attacks occurred with a density of several per meter---and generally within minutes of cable entry into the ocean.

Plans to deploy the E-O telemetry system were set aside, and attention was directed to the problem of fishbite. A series of ocean exposure tests were carried out with the results listed below.

(1) From a survey of fish populations and examination of hundreds of cable wounds, we concluded that the primary culprit was the "Triggerfish" or <u>Rhinecanthus Rectangulus</u> (known as the <u>humuhumu</u> <u>nukunuku</u> <u>a</u> <u>pua'a</u> in a popular Hawaiian song).

(2) The attacks appeared to be an expression of territorial defense, rather than a search for food. They occurred only on the seafloor, and within minutes of the cable's arrival there. This fits well with the habits of the Triggerfish. The shape of <u>most</u> of the bites also fit the dentition of that fish.

(3) No statistically valid relationship could be found between intensity or density of attacks and the color or composition of jacketing materials. Materials exposed included polyethylene, polyurethane, polyallomer, nylon and acetal copolymer (the last of these per recommendations in the NOAA Fishbite Manual). Black, white and neutral colors were investigated. All samples were enthusiastically attacked. All samples which had relatively soft and/or thin jackets were damaged. "Protection" was clearly a function primarily of jacket <u>thickness</u> and <u>toughness</u>.

(4) The effect of fishbite on the E-O telemetry system was entirely electrical; i.e., a shorting of the conductor to seawater. Even for samples mauled as badly as the

(lower) example in Figure (16), <u>no optical fiber break has ever been observed</u>.

(5) The conclusion was obvious. If the demonstration E-O telemetry system was to be deployed, then its cable must be given additional protection.

We decided that the least costly (but still effective) approach would be to insert the system cable into a protective plastic tube. Of the materials which had been evaluated, Eastman's Tenite 5121 black polyallomer was chosen as representing the best compromise among available lengths, toughness, cost and workability. The tube's O.D. was 6.35 mm, and its wall thickness was a nominal 1 mm. This concept was tested and verified by successful exposure of several hundred meters of system cable which had been overjacketed with the Tenite tubing. While many areas of fishbite attack on the polyallomer were observed, none penetrated the tubing. A fixture was assembled in the Hawaii Laboratory which:

(1) Passed the system cable through a water bath to check for electrical faults in the jacket. (Three were found in a 64.8-km total length.)

(2) Cut a slit in the side of the Tenite 5121 tubing.

(3) Spread that slit open and inserted the system cable.

(4) Filled the residual void space with a marine grease, then allowed the (springy) Tenite to snap shut.

The reader is invited to contemplate the joys of performing such a task on nearly 65 km of cable. The telemetry system was carefully monitored during this armoring process. No degradation was observed.

System Deployment

Deployment of the E-O ocean telemetry system was relatively straightforward; complicated only by the fact that an electrical short had been discovered in the E-O shore cable a few days before the date set for laying of the cable. An inspection of the Junction Box showed that the fault lay elsewhere, so the armored shore cable was bypassed by running a 4-km length of system cable (Section 1-B) along the same route from the Junction Box to the Laboratory Terminal.

This was done the day before deployment of the E-O telemetry system. The jury-rigged shore cable was monitored overnight, and the TRBR channel's performance remained better than BER = 10^{-9}. At about noon on the second day, the support boat's moorings were cast off and deployment of the telemetry system began. This phase was uneventful, and the performance of the system continued to meet performance standards with no deviations. The laying of the cable, repeaters and Ocean Terminal was completed in less than 5 hours.

Approximately 40 hours later, we began to observe degraded operation of the telemetry system. Characteristics of the fault included:

(1) The supply voltage required to maintain a 165-mA line current dropped by more than half. This current/voltage behavior was consistent with a short in the cable's electrical jacket somewhere between repeaters (4) and (5).

(2) When this occurred, all HBR signals from the Ocean Terminal were lost. Only repeaters (1) through (4) could be interrogated.

(3) Periodically, these defects disappeared, and the entire system would again play in a fault-free mode. System BER would again be better than 10^{-9} for the HBR channel.

In earlier laboratory simulations of E-O cable failures, we had observed electrolysis and formation of bubbles at the site of a jacket flaw when the cable was transmitting current. As these bubbles grew and broke away from the cable, the shunt resistance of the short would fluctuate from nearly a dead short to values so high as to be effectively infinite.

It seemed clear that this was also happening in the telemetry system between repeaters (4) and (5). We continued to operate and monitor the system in this intermittent mode. Eight days after deployment, another short was noted between repeaters (2) and (4). Five days after this event, a third short appeared just beyond repeater (1). At this point it became obvious that very little could be gained from further monitoring of the data link. The system was shut down.

Eight months after deployment, 2 repeaters and approximately 12 km of E-O cable were recovered. The cable showed periodic zones of heavy electrical damage, corresponding to sections where (for reasons not yet known) the E-O cable had been forced out of its polyallomer jacket. Whenever this occurred, the cable suffered extensive fishbite damage. The polyallomer jacket was also severely bitten, but none of the bites penetrated that material.

The 12-km cable section was given extremely rough treatment during recovery. Extensive lengths were so badly battered that the polyethylene insulation was stripped from the copper/steel conductor wires. The conductors occasionally were separated and/or kinked. Yet, the optical fiber in this cable was not broken.

Both of the recovered E-O repeaters appear to be in good condition, and show no evidence of internal leakage or other degradation as a result of 8-months seafloor exposure. One of them has been checked out electro-optically, and has unchanged characteristics. (Such checkouts have barely started, and will continue with further recovery operations and laboratory tests.)

CONCLUSIONS

(1) We have demonstrated that an undersea, repeatered, electro-optical telemetry system can be built which combines very small volume, moderate repeater separations, moderate repeater power and full duplex operation over a single optical fiber. The BER of this system is better than 10^{-9} over a total attenuation level of 360 dB (280 dB of cable attenuation at 0.83 µm).

(2) The electro-optic capabilities demonstrated here can be applied almost as readily at the "long haul" wavelengths of 1.3 µm and 1.55 µm. Where we achieved 8-km maximum repeater separations, the use of these longer wavelengths will allow repeater spacings of 50---100 km.

(3) Per-repeater power consumption was less than 1.7 watts for full duplex operation. This level can be reduced to less than 1 watt with today's low-threshold lasers.

(4) Any requirement for power supply through the cable imposes very severe constraints on the data link. It adds a failure mode which is extraordinarily intolerant of faults, <u>and</u> almost completely independent of failure modes for the optical fiber.

(5) If the cable must supply power to repeaters and end systems, then it must be carefully designed to protect that power line. The associated challenge may be appreciably more difficult than the task of protecting the optical fiber. A design technique discussed elsewhere in these procedings (10) is offered as an example of an approach which emphasizes physical protection of an E-O cable's electrical section.

ACKNOWLEDGEMENTS

Many competent and dedicated people contributed to the accomplishments which are described in this paper. Space allows mention only of a few.

ITT-EOPD. Robert Thompson (cables & management); Xenophon Glavas (mechanical design; John Keller (electronics); Fred McDuffey & Tom Osborne (optical assembly & splicing); George Gasparian, Art Nelson & Gary Bickel (duplexer and optical measurements); Larry Ptaschek, Dorothy Rowe, Don Taylor & John Smith (cable

development); Frank Akers & Les Hodges (development of strong, low loss optical fibers).

ITT-AVIONICS. Steve Reiss, who led the layout and fabrication effort for the hybrid circuits.

ITT-CHD. Dave Hibbs & Hans Heinzer, who perfected and verified the design of the repeater structure.

RCA. Mike Ettenberg for development of the hybrid laser module; but also for consistently performing beyond our expectations.

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And, most of all, Donna LaRue who kept the program's myriad loose ends from unraveling, and who also kept her sanity when any reasonable person would have lost his.

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3. Wilkins, G.A., “Recent Experience With Small, Undersea, Optical Cables”, Proceedings Of IEEE-EASCON, Vol. 3, (pp. 581--594), Washington, D.C., October, 1979.

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5. Jones, Donald T. personal communication, Copperweld Corporation, Bimetallics Group, Robinson Plaza 2, Pittsburgh, PA 15205.

6. Hibbs, D.A., “Development Of Repeater Housing And Cable Termination For Fiber Optic Cable”, ITT Cable-Hydrospace Report of 7 March, 1978.

7. Optical “glassboards” of these duplexers were first demonstrated at the Hawaii Laboratory of NOSC. Ransom Physics Laboratory (Camarillo, CA) suggested improvements to the original laboratory model, then fabricated the lenses and structural hardware. Optical Coating Laboratory, Inc. (Santa Rosa, CA) built the interference filters. ITT-EOPD assembled the optical duplexers and developed checkout- and alignment procedures.

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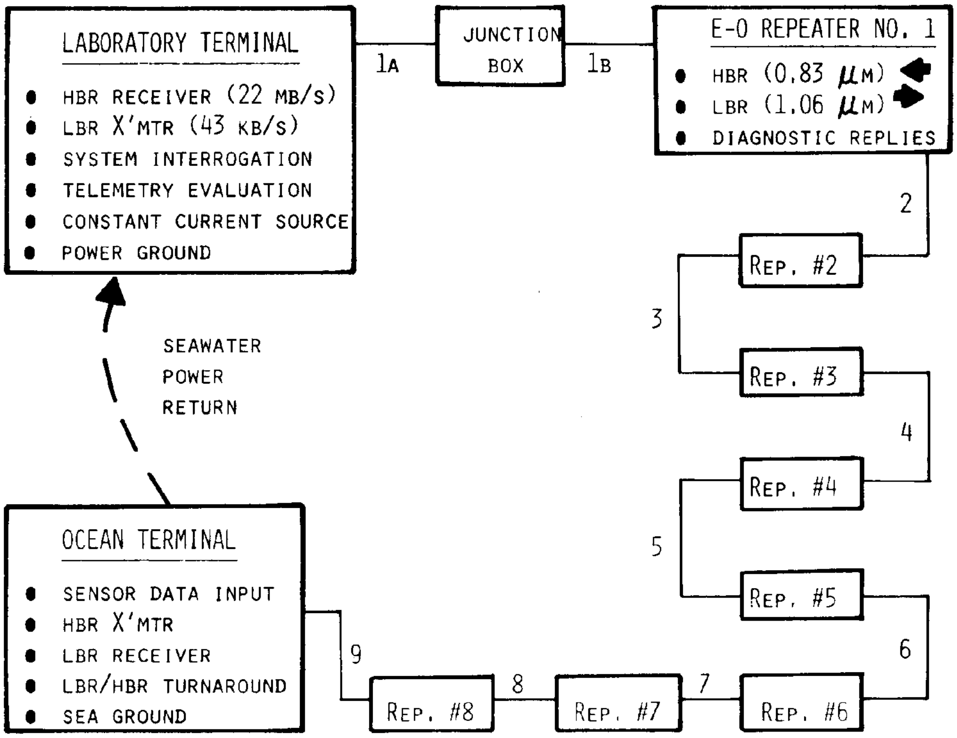

FIG. (1). ELECTRO-OPTICAL, OCEAN, TELEMETRY SYSTEM.

CABLE SECTION	SECTION LENGTH (KM)	ATTENUATION (DB/KM)		DISPERSION AT 0.83 µm (NS/KM)	FIBER NA (WHITE LIGHT)
		0.83 µm	1.06 µm		
1A	4.4	3.73	1.57	0.41	0.27
1B	3.8	4.64	2.10	0.69	0.25
2	8.0	4.04	1.81	0.79	0.25
3	7.7	3.74	1.59	0.83	0.26
4	7.7	3.73	1.59	0.47	0.23
5	7.7	3.95	1.79	0.46	0.23
6	7.7	4.00	1.80	0.61	0.24
7	7.7	3.93	1.72	0.37	0.26
8	7.7	4.49	2.03	0.67	0.25
9	6.8	4.63	2.17	0.85	0.22
GOALS	≥8.0	≤5.0	≤3.5	≤1.3	0.24 ± 0.02

TABLE (1). CHARACTERISTICS OF E-O CABLES.

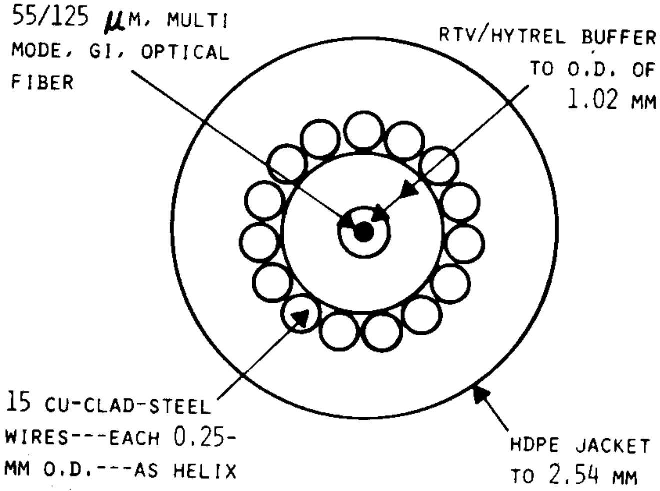

FIG. (2). E-O CABLE.

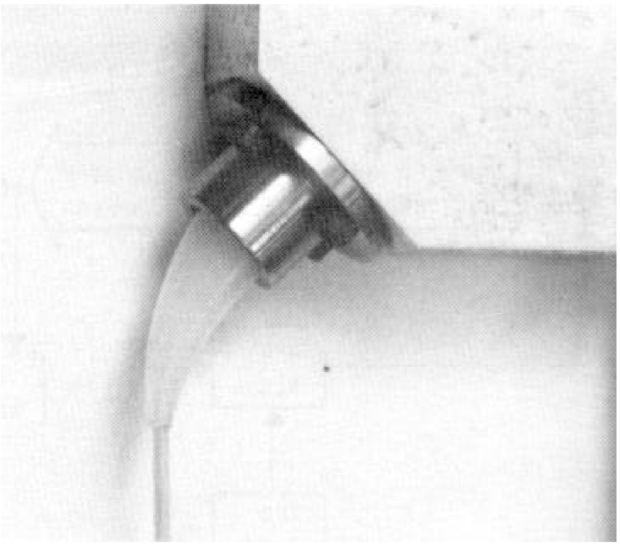

FIG. (3). CABLE BEND LIMITER.

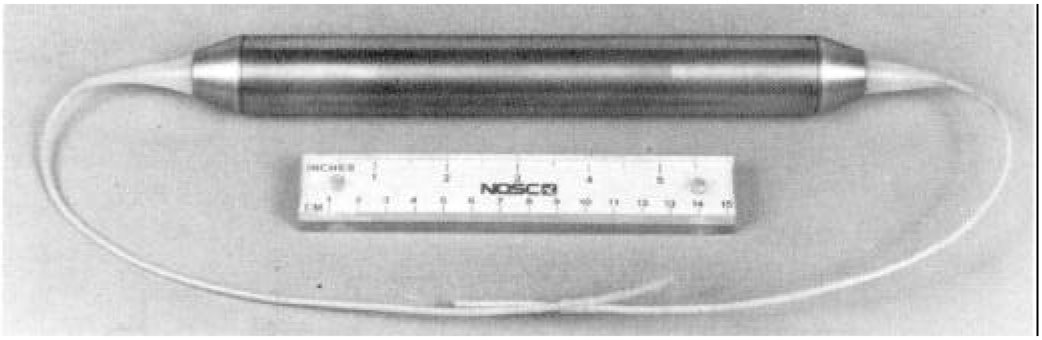

FIG. (4). COMPLETE E-O REPEATER UNIT.

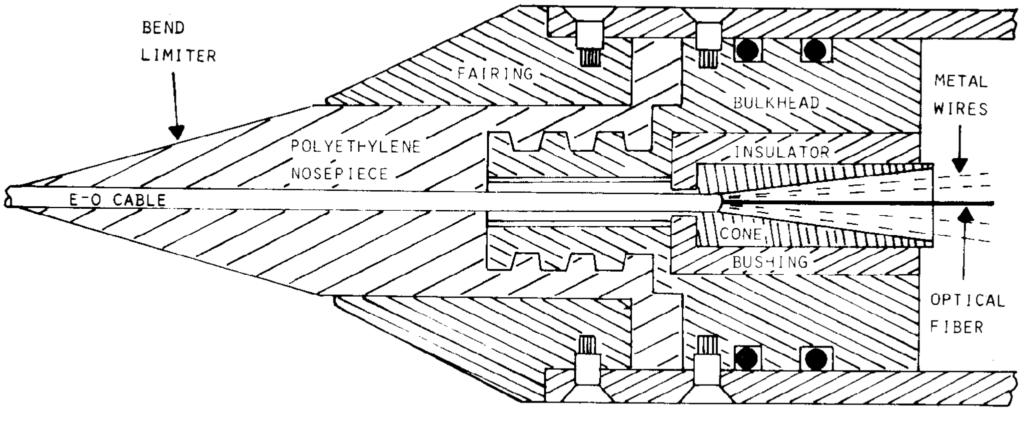

FIG. (5) CABLE/REPEATER TERMINATION INTERFACE.

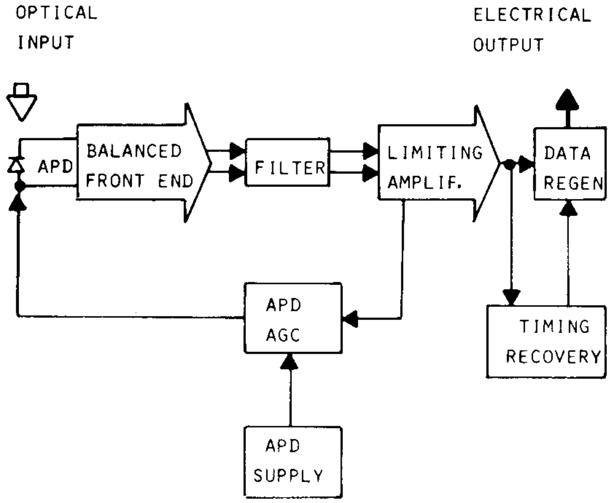

FIG. (6). REPEATER CIRCUIT.

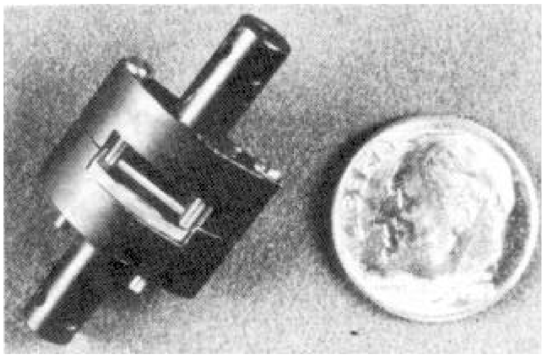

FIG. (8). OPTICAL DUPLEXER.

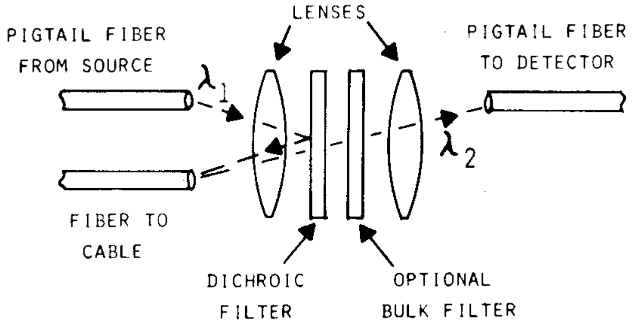

FIG. (7). DUPLEXER SCHEMATIC.

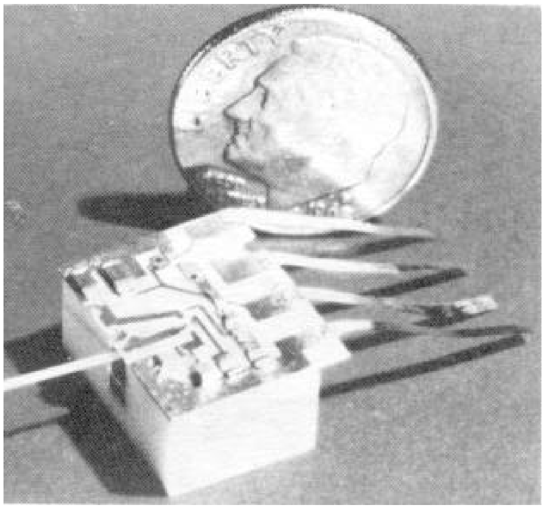

FIG. (9). LASER MODULE.

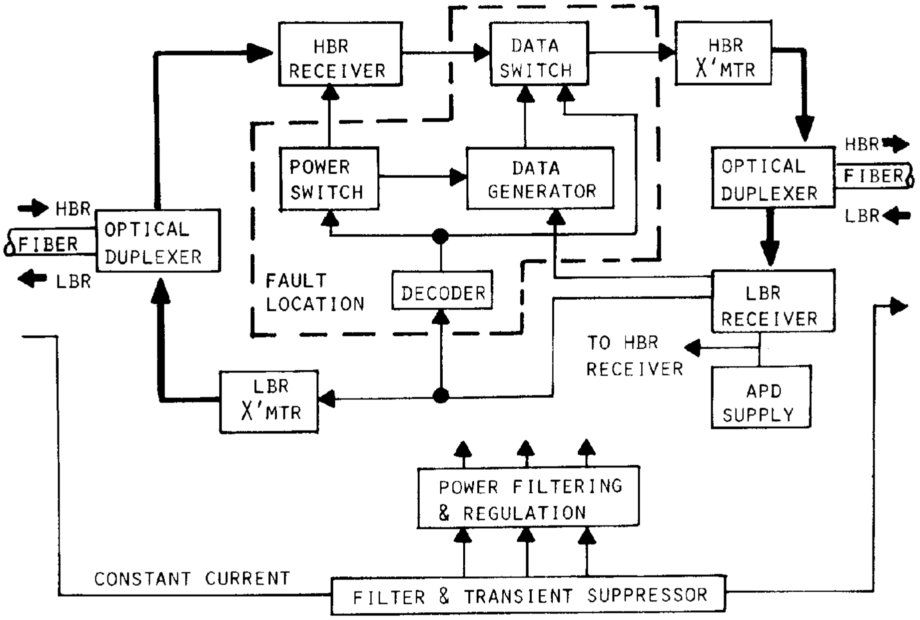

FIG. (10). BLOCK DIAGRAM OF REPEATER E-O CIRCUIT.

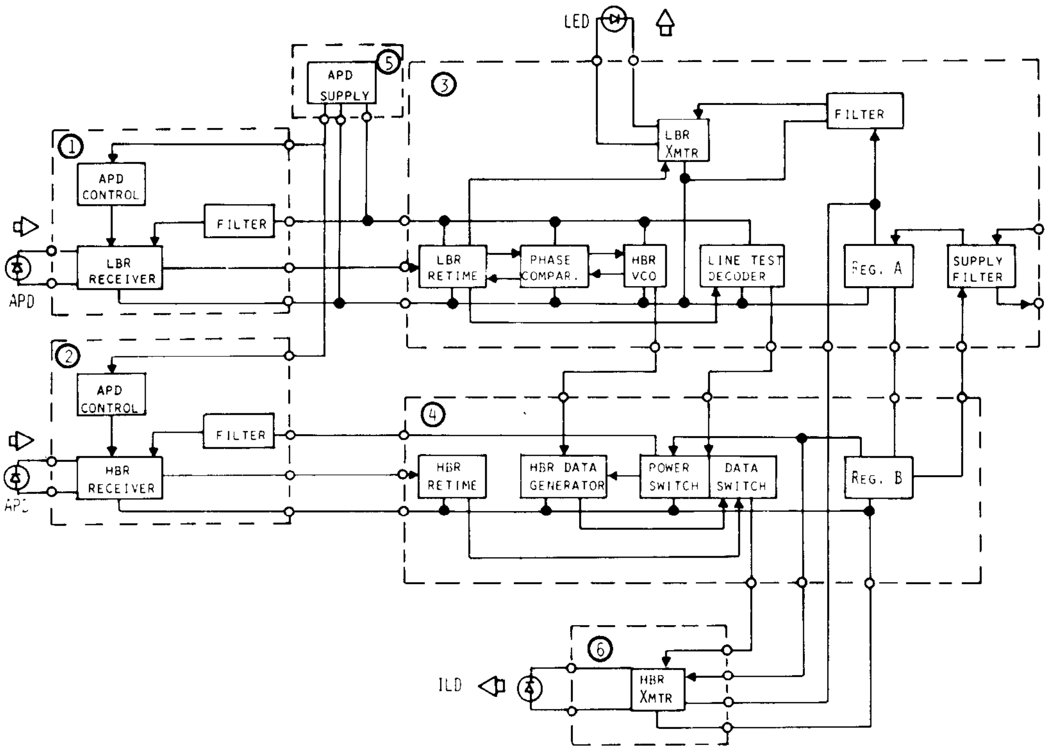

FIG. (11). SCHEMATIC OF REPEATER E-O CIRCUIT.

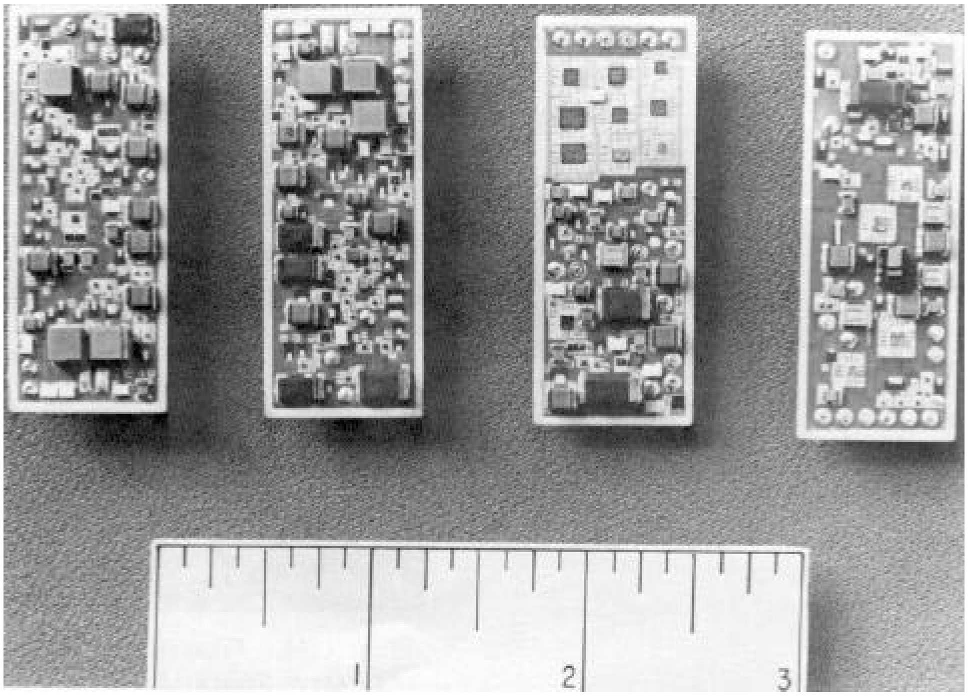

FIG. (12). FROM LEFT; HYBRIDS H-2, H-1, H-3 & H-4.

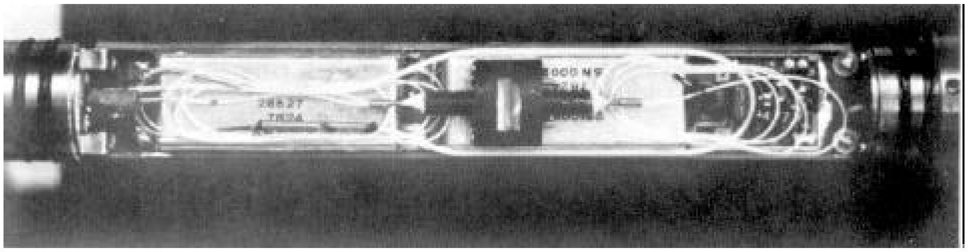

FIG. (13). TOP VIEW OF E-O REPEATER ELECTRONICS ASSEMBLY.

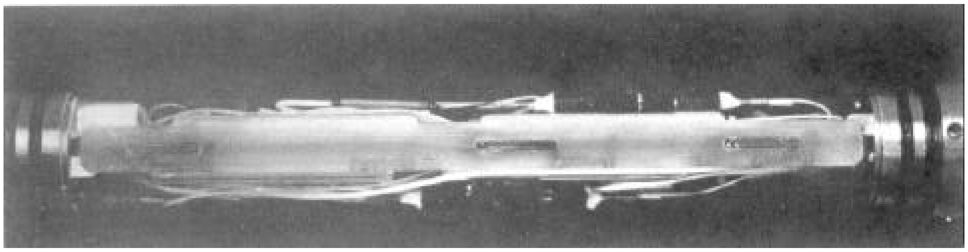

FIG. (14). SIDE VIEW OF E-O REPEATER ELECTRONICS ASSEMBLY.

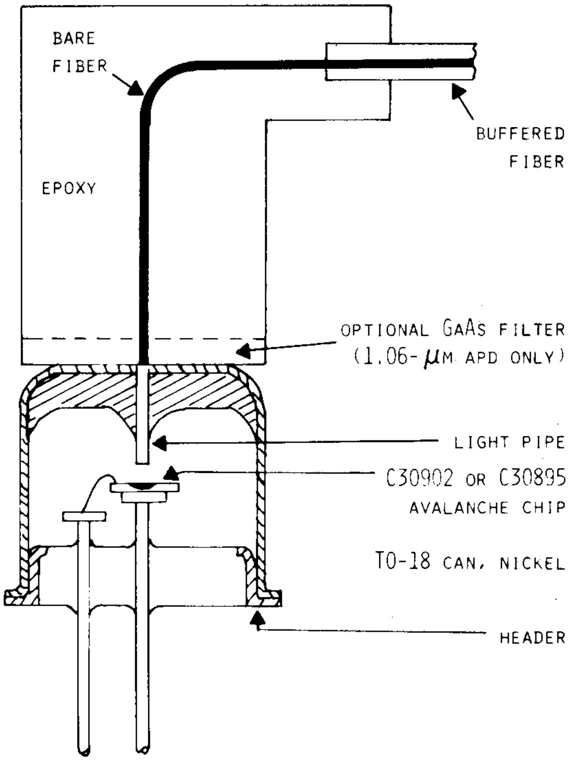

FIG. (15). MODIFIED APD.

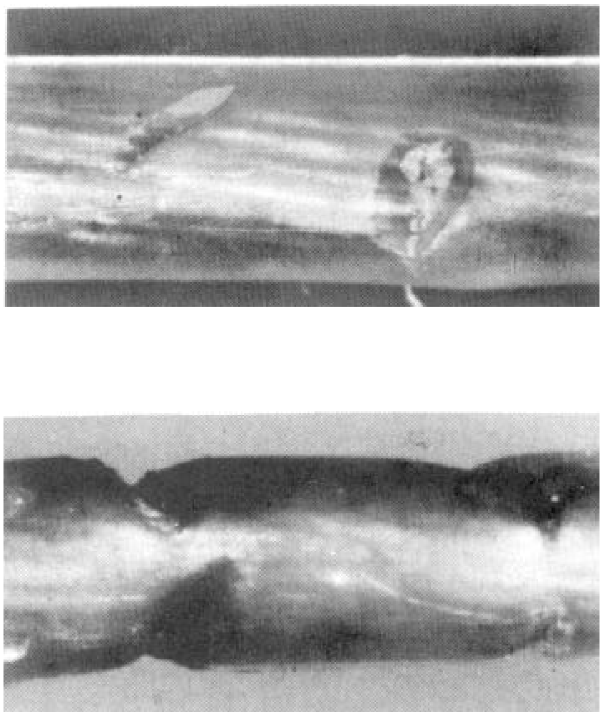

FIG. (16). FISHBITE EXAMPLES; TENTATIVE NIBBLES AT TOP AND DETERMINED ATTACK AT BOTTOM.

PERFORMANCE PARAMETER	GOAL	ACHIEVED:
1. SYSTEM LENGTH (KM)	55----74	69.3
2. REPEATER SPACING (KM)	8-----10	6.8----8.0
3. NUMBER OF REPEATERS	8	8
4. PER-REPEATER POWER (W)	≤1.5 (DUPLEX)	1.69 (AT 165 MA)
5. REPEATER STRUCTURE		
DIAMETER (CM)	≤2.5	2.88
LENGTH (CM)	≤30.0	30.5
WEIGHT (GRAMS)	≤500	< 400
OPERATING DEPTH (M)	≥1000	1000 (TEST)
6. CABLE		
DIAMETER (MM)	≤2.5	2.54
STRENGTH (KG)	100 (2% STRAIN)	60 (0.8% STRAIN)
SPECIFIC GRAVITY	1.5----2.5	2.12
MAXIMUM VOLTAGE (V)	NOT SPEC.	750
7. TELEMETRY		
DATA FORMAT	DIGITAL PCM	BIPHASE-M; AMI
FULL DUPLEX, 1 FIBER?	GOAL	ACHIEVED
WAVELENGTHS	0.85- & 1.06 μm	0.83 & 1.06 μm
HBR CHANNEL		
BIT RATE	22 MB/s	22 MB/s
BER	10^{-7}	$< 10^{-9}$
LOCK-IN RANGE	± 0.5%	+1.2%; -0.7%
LBR CHANNEL		
BIT RATE	5---200 KB/s	42.9 KB/s
BER	10^{-7}	$< 10^{-7}$
LOCK-IN RANGE	± 0.5%	+1.2%; -1.4%
8. FAULT LOCATION CAPABILITY?	AS GOAL	YES (WITH ACCESS VIA LBR CHANNEL)
9. OPERATING LIFE	MONTHS	DAYS

TABLE (2). GOALS AND ACHIEVEMENTS FOR THE E-O OCEAN TELEMETRY SYSTEM.

PARAMETER	HBR CHANNEL		LBR CHANNEL	
	BUDGET	ACTUAL	BUDGET	ACTUAL
SOURCE POWER (DBM)	2.0	3.0	-25.0	-25.4
LOSSES (DB)				
CABLE (8 KM)	42.0	32.3	30.0	14.5
SPLICES (2)	2.0	2.0	2.0	2.0
COUPLERS (2)	4.0	2.9	4.0	4.2
CONNECTOR	0.	0.	0.	0.
FILTER*	0.	0.	0.	0.
SUBTOTAL LOSSES	48.0	37.2	36.0	20.7
RECEIVED POWER (DBM)	-46.0	-34.2	-61.0	-46.1
SENSITIVITY (DBM)	-51.0	-50.5	-66.0	-65.0
POWER MARGIN (DB)	+ 5.0	+16.3	+5.0	+18.9
OVERLOAD POWER (DBM)	-26.0	-20.6	-30.0	-25.7
OVERLOAD MARGIN (DB)	+20.0	+13.6	+31.0	+20.4

* ALTERNATIVE USES ARE AS BLOCKING FILTER FOR OPTICAL DUPLEXER OR AS ATTENUATOR TO PREVENT CHANNEL OVERLOAD.

TABLE (3). OPTICAL POWER BUDGET FOR (8 KM) TELEMETRY SECTION TWO.