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FIBER OPTIC SONOBUOY CABLE DEVELOPMENT FY77

Electro-optical components for data transfer between deep submerged acoustic sensors and surface buoys

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10 RA Eastley
WH Putnam

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RR GAVAZZI, CAPT USN
Commander

HL BLOOD
Technical Director

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WE Richards, Head
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This document provides a summary of fiber optic sonobuoy development in FY 1977. An improved sonobuoy cable was fabricated; techniques for producing long, high-strength optical fibers were developed; means of providing duplex communication over the same fiber were explored; and commercially-available optical sources and receivers were surveyed and analyzed.

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OBJECTIVE

Develop the optical components for a 5-km depth sonobuoy which uses optical fibers for signal transmission between the deep sensors and the surface transmitter.

RESULTS

1. A Kevlar-49 strengthened sonobuoy cable was developed on contract at ITT. The optical fiber attenuation did not increase more than 1 dB/km when incorporated into the cable and wound in a simulated sonobuoy coil configuration.

2. Good progress was made at ITT in the fabrication of long, high-strength fibers. When delivered in FY 78, these fibers will have initial strengths at least four times greater than any other 5-km length fiber to date (proof test strain to be increased from 0.25% to 1%). Strength of research fibers (in a related effort funded by the Defense Advanced Research Projects Agency) in 1-km lengths has been increased from 1%-strain to 5%-strain proof test loads. Commercially-available fibers from other manufacturers remain at the 0.25% to 1% strain levels in 1-km lengths.

3. A three-core optical fiber was fabricated and cabled. The fiber may be used for duplex transmission.

4. The best compromise of performance and cost in optical sources is the GaAlAs edge emitter LED. The best choice for an optical receiver is a silicon PIN photodiode and preamplifier optimized for the low data rate of the sonobuoy transmitters. Receivers optimized for sonobuoy data rates 50 kb/s were developed. A link for the 5-km sonobuoy cable having 6-dB/km cabled attenuation and the recommended LED and photodiode will operate with satisfactory margin (19 dB optical power margin over that required to achieve 10^{-9} bit error rate).

RECOMMENDATIONS

1. Determine the effects of tension, pressure, temperature, and coiling on the attenuation of the sonobuoy cable.
2. Conduct mechanical tests on the sonobuoy cable.
3. Conduct winding and payout test on the sonobuoy cable.
4. Develop a reliable fiber optic pressure feedthrough.
5. Conduct a 5-km link test to verify performance estimates.
6. Continue to improve fiber strength and durability.

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ILLUSTRATIONS

TABLES

INTRODUCTION

This report describes the FY 1977 efforts in the development of a fiber optic transmission link for a 5-km depth sonobuoy cable. In 1975, the Naval Air Development Center tasked the Naval Ocean Systems Center (NOSC), to initiate this development. Progress in the project through FY 1976 is detailed in reference 1.

Fiber optic communication technology has advanced to the point that the severe systems requirements of sonobuoys and other undersea systems can be addressed. Optical attenuations as low as 0.5 dB/km at a wavelength of 1.2 μm (1 dB/km at 0.85 μm) have been reported(2) and a 4.5-km, 1.5 Mb/s link has been demonstrated in the field.(3) Exploratory development at NOSC is directed toward the feasibility of a low-cost expendable 5-km, 50 kb/s link for sonobuoys having requirements as indicated in table 1.

Table 1. Sonobuoy system requirements.

Sensor depth (km)		5
Cable operating load, N* (lb)		330 (75)
Cable peak dynamic load, N (lb)		550 (125)
Cable breaking strength, N (lb)		1550 (350)
Cable diameter, mm		1.47
Signal bandwidth	up	50 kb/s
	down	4 kb/s
Duplex		Yes
Electrical power conductor		No
Cable torque balanced		Yes
Cable pack size	outer dia, cm	16.7
	inner dia, cm	3.8 to 4.4 tapered
	length, cm	61.6
Canister configuration		"B"
Storage temperature, °C		–50 to +70
Storage life, year		7
Operating temperature, °C		0 to 30
Operating life, hours		3
Hydrostatic pressure MPa** (kpsi)		48 (7)

* newtons

** megapascals

During FY 77 an improved sonobuoy cable was fabricated; techniques for producing long, high-strength optical fibers were developed; means of providing duplex communication over the same fiber were explored; and commercially-available optical sources and receivers were surveyed and analyzed. Details of these efforts are presented in the following sections.

FIBER OPTIC CABLE

In FY 76, three prototype fiber optic sonobuoy cables were tested.(1) Based on the results of these tests, ITT was awarded a contract to develop an improved cable having the following specifications:

	Design Goals
Length, km	1
Number of fibers	1, on-axis
Diameter, mm	1.47
Strength, N @ 1% strain	1550
Torque, @ 330 N operating load	Minimum
Cable attenuation, dB/km @ 0.82 μm	
Strung	8
Buoy configuration (3.8 cm dia)	8
Excess cabling loss, dB/km, relative to uncabled fiber attenuation	1
Pressure, MPa (kpsi)	48 (7)

The 1550 N cable strength goal provides a 5:1 safety margin over the static weight of the deep sensor package (310 N) and a 2.8:1 margin over the measured dynamic load (550 N) during deceleration to program depth.

During FY 77, the cable strength goal was achieved at 2.5% strain, which is the upper limit for the Kevlar-49 strength member. The fiber, which limits the cable strength, was proof-tested* to 2% strain, providing 4:1 static- and 2.2:1 dynamic operational margins. Because of the relatively low strains on the fiber during storage (0.3%) and operation (0.5%), stress corrosion is not anticipated to be a problem (Appendix A).

Four cable designs were investigated, including impregnated vs nonimpregnated Kevlar, and void-filled *vs* free-flooding. The final design selected was a nonimpregnated, free-flooding design, shown in figure 1.

The fiber fabricated for the cable was measured by the contractor to have the following characteristics prior to cabling:

Length, m	1012
Proof test strain, %	2

* During a proof test, the entire length of fiber is progressively subjected to a known tensile load between capstans for 5 seconds.

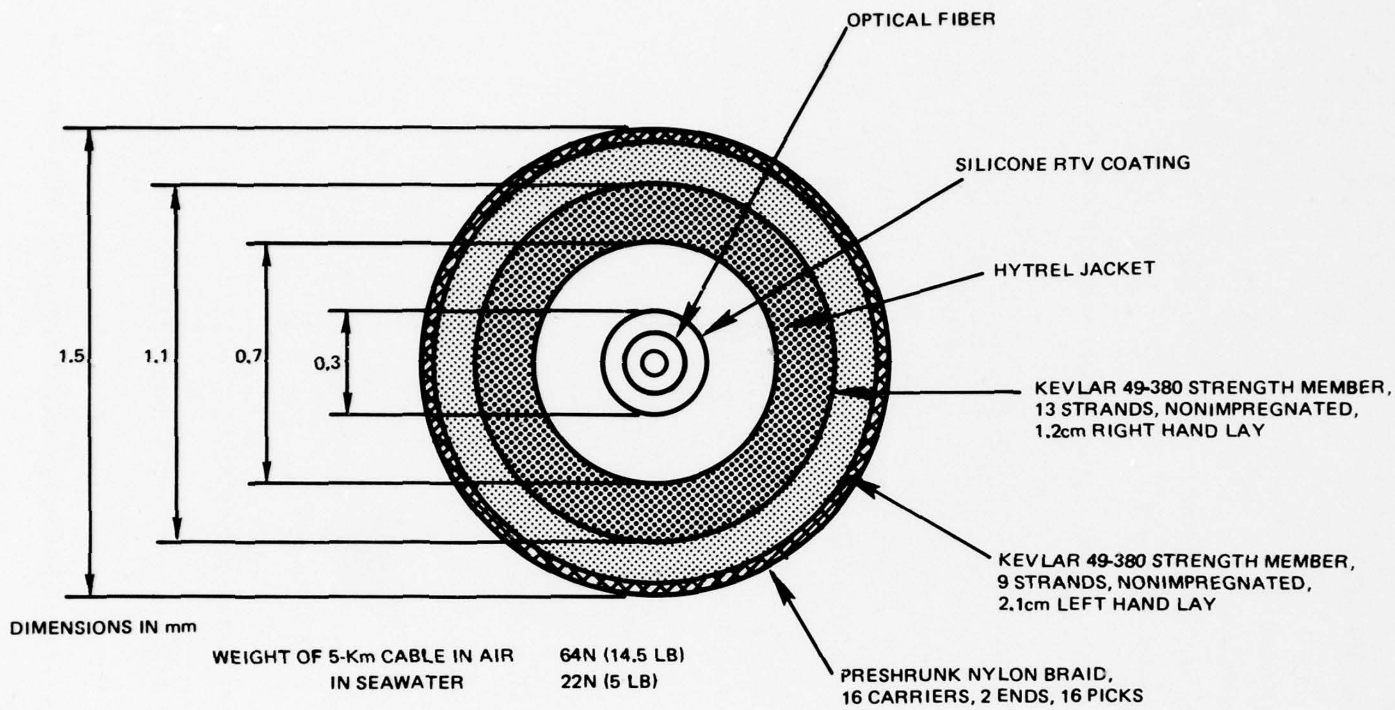

Figure 1. Fiber optic sonobuoy cable design.(4)

Attenuation, dB/km @ 0.82 μm*	
Spooled	6.6
Strung	6.8
Dispersion @ 3 dB, ns/km	8.9
NA	0.34
Core diameter, μm	53
Fiber diameter, μm	125
Nominal buffer diameter, μm	300
Nominal jacket diameter, μm	680

The fiber, when incorporated into a cable, was measured by the contractor to have the following characteristics.(4)

Attenuation, dB/km @ 0.82 μm	
Spooled (15 cm dia)	8.2
Strung	8.9
Buoy configuration	10.2
Specification	8 max

The cable was shipped to NOSC for evaluation. A second cable was fabricated having longer lay lengths and less tension on the strength members. It is expected to be delivered in early FY 78. Some results of tests conducted by ITT on the second cable are shown in table 2.(4)

Table 2. Results of ITT tests on sonobuoy cable.

Strength (cable only), 2.5% strain, N	1550
Strength (fiber limit), 2% strain, N	1250
Fiber proof test strain, %	2
Cable diameter, mm	1.50
Optical attenuation, dB/km at 0.82 μm	
Before cabling	5.9
After cabling	6.0
Buoy configuration	7.1

This cable will be optically, mechanically, and environmentally tested at NOSC during FY 78.

* Measured as the ratio of light intensities through two lengths of fiber, using a filtered tungsten lamp apertured to 0.12 NA.

OPTICAL FIBERS

STEP-INDEX AND GRADED-INDEX 5-km FIBER DEVELOPMENT[5]

NOSC is funding development of long, high-strength optical fibers at ITT/Electro-Optical Products Division, Roanoke, VA, under contract N66001-77-C-0137. This effort is the first known attempt to produce 5-km length, high-strength fibers for any application. The longest high-strength fiber produced prior to this development was 2.3 km.[6] The delivered optical fibers will have the characteristics listed in table 3.

Table 3. Optical fiber specifications.

	Step	Graded
Length, km	5	5
Proof Strain, %	1	1
Attenuation, dB/km at 0.82 μm	7	6
Numerical Aperture	0.23	0.23
Min. Core diameter, μm	40	40
Dispersion, @ 3 dB, ns/km	n/a*	1

* Not specified.

Development areas include: (a) maintenance of high strength using 25 mm, rather than 15 mm, preform tubes, (b) tube-collapsing methods, and (c) achievement of desired refractive index profiles. The fibers will be delivered in early FY 78. By September 1977, ITT had fabricated under contract a 3.6 km step-index fiber which surpassed all specifications.

This development removes fiber length as a pacing item in the fabrication of high-strength 5-km length sonobuoy cables. The step-index fiber, except for strength, is typical of the type of fiber to be incorporated in the sonobuoy cables presently under development. During FY 78, the fibers will be used in the laboratory for 5-km transmission tests. The 1% strain characteristic yields a sonobuoy cable strength of 620 N (140 lbs), which leaves little safety margin over the expected 550 N (125 lb) dynamic load. However, when 2–3% strain fibers become available in the future,* they will permit the full 1550 N (350 lb) cable strength. The numerical aperture (0.23) of the fibers is much higher than the normal 0.14-0.19 NA fibers generally available. The advantage of the high NA is that 2–5 dB more light is coupled into the fiber from LED sources and the fiber attenuation is expected to be less affected by environmental and tension stresses.[1]

TRIPLE-CORE FIBER CABLE

A 614-m triple-core fiber was fabricated under ITT contract N00123-77-C-0079[4] (figure 2). The cores were measured by ITT to have 4.0, 4.3, and 6.4 dB/km attenuation at

* Fiber strength is being improved in a program funded by Defense Advanced Research Projects Agency.[7-9]

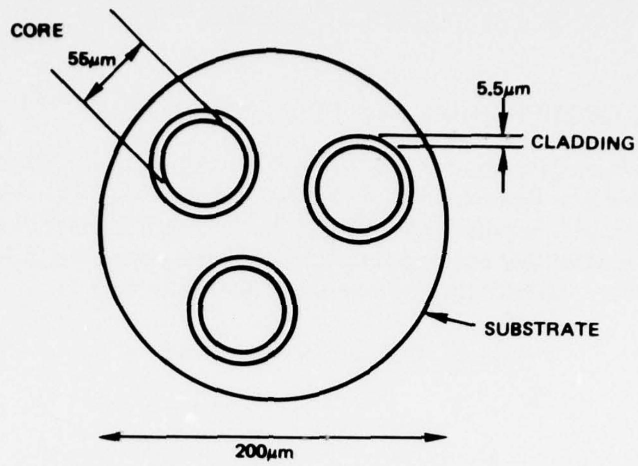

Figure 2. Triple-core optical fiber design.[4]

0.82 μm. Crosstalk between cores was –44 dB (near end) and –31 dB (far end). The fiber was fabricated using the same techniques as the other high-strength fibers at ITT: it passed a proof test load equivalent to 2% strain.

In a duplex link, such as that required of the sonobuoy, the near-end crosstalk should be at least 11 dB less than the signal to be detected. Since equal amounts of power are injected at either end, the signals should be attenuated no more than 33 dB (44 dB near end crosstalk minus 11 dB margin). To meet this condition in a 5-km link, this amounts to a maximum cable attenuation of 6.6 dB/km.

A 100-m section of the triple-core fiber was cabled using the same design as the follow-on sonobuoy cable. Excess cabling losses for the three cores were within the ±2 dB/km precision of measurements.

During FY 1978, the delivered triple-core fiber will be tested at NOSC to verify the optical attenuation and crosstalk.

CATHOLIC UNIVERSITY PHASIL PROCESS PROGRESS

An approach to development of low-cost optical fibers was initiated in 1974 and sponsored with sonobuoy funds in 1975 at Catholic University of America. In FY 1976-77 this work was discontinued under sonobuoy sponsorship because of the difficulty experienced in producing suitable low-loss fibers and the uncertainties in projecting cost benefits relative to the chemical vapor deposition process. During FY 77, CUA reportedly reduced attenuation from 37 dB/km to 13 dB/km in 100 m lengths.[9] This is still at least 7 dB/km above that needed for the sonobuoy cable. To date, CUA research in compressive claddings has yielded 0.3 GPa of compression (equivalent to 0.45% strain). The CUA facility is capable of producing fibers up to approximately 0.1 km in length.[9] In order to be a candidate for sonobuoy applications, the Phasil process requires further research in attenuation (6 dB/km), strength (2.5%), and length (5 km). This development will continue to be monitored by NOSC for appropriateness to sonobuoy use.

FIBER STRENGTH IMPROVEMENT

The severe loading and stowage constraints imposed on sonobuoy cables require that optical fibers be capable of straining at least as much as the strength member. For 5 to 7 km sonobuoy cables which use Kevlar-49 as strength members, fibers must strain at least 2.5% of length to provide the same safety margin as the other cable components. Additional strain allowance must be provided for any degradation in strength during storage or operation. Means of increasing fiber initial strength and preserving strength are currently under investigation in a strength-improvement program, funded primarily by the Defense Advanced Research Projects Agency (DARPA) Material Sciences Office.

In FY 1975, initial maximum fiber strain was increased from 0.25% to 1% in 1-km lengths under the NOSC fiber optic sonobuoy cable contract at ITT.[12] The DARPA fiber strength improvement program was initiated in FY 76 with the goal of developing fibers which can strain 2% continuously over 10-km lengths for 5 years. DARPA contracts were awarded to ITT/Electro-Optical Products Division, Roanoke VA; Hughes Research Laboratories (HRL), Malibu, CA; and The Catholic University of America (CUA), Washington, DC (table 4). NOSC was tasked to develop reliable characterization methods and to evaluate contract deliverables.

Table 4. DARPA fiber strength contracts.

Contractor	Contract No
ITT	12720 (62-657-60131) 76R
HRL	10051 (62-027-60147) 76WR 77G-102280-000
CUA	F19628-77-C-0084

The basic approaches of the contractors to meet the stated goal were:

ITT	Eliminate large flaws to create high-strength, plastic-coated optical fibers and develop quality assurance methods to guarantee the 2% strain goal during 5 years service life
HRL	Develop methods of hermetically sealing fibers with metal coatings to preserve initial strength against attack by moisture
CUA	Develop a compressive cladding which provides an effective 1% strain reduction. The cladding is expected to eliminate fatigue at strains less than 1% and greatly reduce it at strains greater than 1%.

ITT PROGRESS[7]

ITT has made major strides in developing high strength fibers. Table 5 illustrates the progressively higher proof-test loads and lengths for their optical fibers.

ITT's approach is to produce high-priority preforms, draw fibers in a dust-free atmosphere, control the length and temperature of the heat zone, remove dust from the plastic coating liquid, and use a flexible orifice during coating. The overall effect is to reduce the number of abrasion-and thermally-induced flaws. Further development is required to increase the initial strength, length, and fatigue life to meet DARPA strength goals.

Table 5. ITT fiber strength improvement progress.

	FY 75[12]	FY 76[7]	FY 77[5,7]
Proof-test strain over length (5 sec duration)	1%, 1 km	2%, 1.6 km	1%, 3.6 km 3%, 2.0 km 5%, 0.8 km

HRL PROGRESS[8]

The HRL approach attempts to coat the fibers with a tight, durable, hermetic layer of metal by dip-coating the fiber in molten aluminum during drawing. The metal coating protects the fiber from abrasion and attack by moisture. HRL concluded that a continuous metal sheath imparts an improvement in the static fatigue strength of silica fibers in humid environments and that ability to withstand continued tensile loading under such environmental conditions is orders of magnitude better than for fibers protected by plastic coatings. Problem areas to be addressed are (a) pinholes in the aluminum sheath which allow moisture to penetrate to the fiber, (b) corrosion of the aluminum in water, (c) possible fracture of the sheath in cyclic loading past a few cycles, and (d) excess optical loss due to the metal coating. At present, HRL produces fibers of approximately 1 km length.

CATHOLIC UNIVERSITY PROGRESS[9]

The approach to fiber strengthening pursued by CUA is to apply a compressive cladding to the fiber using dopants in the molecular stuffing (Phasil) process.[10] If the fiber surface is under compression, the initial strength is preserved for static loads less than the compression and the time-to-failure is greatly extended for larger loads. CUA evaluated a number of dopant systems. Cs-K-Bi is the most promising to date, yielding fibers with 310 MPa (45 kpsi) compression. The Young's modulus of Phasil glass is approximately the same as for silica glass, 70 GPa (10^7 psi); the 310 MPa surface compression is equivalent to a strain reduction of 0.45%. Fibers from prestressed preforms have been successfully drawn such that the preform stress profile was not only preserved, but enhanced. Strength measurements on prestressed fibers demonstrated the predicted increase in strength due to surface compression. Preliminary measurements also indicate an improvement in static fatigue life. At present, CUA is limited to 100 m length fibers having approximately 13 dB/km attenuation. Proof tests of strength have not been performed.[11]

FIBER STRENGTH EVALUATION TECHNIQUES

The NOSC Optical Fiber Strength Testing Facility was established to independently verify vendor claims of fiber strength as part of the DARPA effort. The task includes basic and applied research on factors affecting fiber strength and static fatigue in the corrosive marine environment. Optical properties are examined under mechanical stress. Tests are performed primarily on the DARPA program deliverables. Other fibers are evaluated on a no-cost-to-the-government basis. Test results are published in the open literature.

The facility will contain the following capabilities:

Short-Length Strength Tester	Dynamic tests of 0.6–2 m fibers
Proof Tester	Proof tests of 3–10 km fibers to assure minimum strength
Static-Fatigue	Test fatigue life of short samples under varied temperature and humidity
High Pressure Chamber	Pressure tests to 70 MPa (10 kpsi) to determine optical properties in seawater
Optical Evaluation Equipment	Determine spectral attenuation, numerical aperture, and pulse dispersion
Scanning Electron Microscope (SEM)	Identify primary and secondary sources of failure in low-strength fiber breaks
Auger Spectroscope	Determine composition of particulate matter at source of failure
Polarizing Microscope	Measure compressive stress in optical fibers

In addition, during FY 77, the Naval Research Laboratory was tasked to develop methods to apply SEM analysis to fiber breaks of the DARPA fibers. In many cases, fiber breaks were caused by bulk flaws and particulate matter (dust).(13)

The results to date in the strength improvement program are encouraging, but incomplete. ITT has made major strides in reducing abrasion- and thermally-induced flaws which were the primary contributors to weak fiber strength. Further development is required to increase initial strength, length, and fatigue life of the fiber to meet DARPA strength goals. HRL has made good progress toward demonstrating the strength-preserving properties of metal coatings. Further work is required to produce fibers of good optical properties having high initial strengths which are preserved by pinhole-free, corrosion-resistant metal coatings. CUA has demonstrated a means of providing 310 MPa (45 kpsi) of compression to a fiber in order to greatly extend service life of fibers operating at high loads. Further development is required to increase the surface compressive stress (150 kpsi theoretical).

LINK DEVELOPMENT

OPTICAL SOURCE

Several candidate optical sources are available commercially which, when packaged for optical fiber use, may be acceptable for fiber optic sonobuoy applications. Selection will depend on the cost and performance of the total link, including the cable and receiver. Because of the projected high price of double-heterostructure continuous injection lasers, only LEDs are presently considered suitable. LEDs can be classified by the geometry of the emitting area: (1) edge, (2) surface, (3) etched-well, and (4) dome. A survey of commercially-available devices was conducted. The results, calculated from data sheets, are listed in table 6, which is organized by geometry and peak wavelength. In general, the surface emitters are calculated to couple the least power into a hypothetical 0.28 NA,

Table 6. Commercially-available LEDS.

Type	λ Peak μm	Material[a]		Radiance $W/cm^2 \cdot sr$	P_{in}[b] dBm	Large Quant. Cost $
Edge	0.79-0.89	GaAlAs	min	28	-17	40[c]
			max	140	-10	100[c]
	0.90	GaAs	min	0.8	-24	6
			max[d]	21	-18	16
Surface	0.79-0.89	GaAlAs	typ	0.4	-27	24[c]
	0.90	GaAs	min	1.2	-22	1
			max	1.6	-21	16
	0.94	GaAs	min	0.3	-28	1
			max	1.2	-22	1
	1.06	GaInAs	min	0.04	-37	250[c]
			max	0.06	-35	600[c]
Etched well	0.79-0.89	GaAlAs	min	6	-15	200[c]
			max	132	-2	385[c]
	0.90	GaAs	min	3	-18	90[c]
			max	35	-8	534[c]
	1.06	GaInAs	typ	10	-13	600[c]
Dome	0.79-0.89	GaAlAs	typ	2.5	-19	550[c]
	0.90	GaAs	typ	0.25	-29	12

a. The "min" and "max" values refer to the lowest- and highest-radiance devices encountered in the survey.

b. The power, P_{in}, coupled into the assumed 0.28 NA, 50-μm core fiber is

$$P_{in} = \pi N \Omega A$$

where

N = radiance
Ω = fiber acceptance solid angle = (numerical aperture)^2
A = area of junction intercepted by fiber core

For example, the first LED in table 6 has a radiance of 28 $W/cm^2 \cdot sr$, and a total emitting area of 6×150 μm: the area available to the fiber core is 6×50 μm^2. The coupled power is

$$P_{in} = \pi (28\ W/cm^2 \cdot sr)(0.28)^2\ sr(6 \times 50)\ \mu m^2 = 2 \times 10^{-5} W \text{ or } -17\ dBm$$

c. Present cost of developmental devices. The order-of-magnitude cost estimated by manufacturers is in the $10 range for the edge emitters, $1 for the surface emitters, and $50 for the etched-well and dome emitters when a large-volume commercial market appears.

d. Broad-area injection laser diode operated below threshold as an LED with 100 mA drive current.

50 μm-core fiber, but cost the least. Their use depends on the availability of a low-cost, high sensitivity receiver. Etched-well devices couple the most power and are the most expensive. The GaAlAs dome emitter couples less power than the lowest-radiance GaAlAs edge emitter. The edge emitters appear to be a good compromise: the best devices couple nearly as much power as the etched-well LED and the order of magnitude cost estimated by manufacturers of the developmental edge emitters is in the $10 range when a high-volume market becomes established, compared to $50 for the etched-well LEDs. In addition, research edge emitters have been reported having much higher radiance than the best etched-well devices. When such a device was used with a fiber having a fused lens on the end and was driven at 500 mA, rather than the rated 200 mA, the radiance exceeded 1,000 W/cm^2-sr and the coupled power was –1 dBm into a 0.16 NA, 90 μm core fiber.(14) For the assumed 0.28 NA, 50 μm core fiber, the estimated coupled power is also approximately –1 dBm, which is more than 2 orders of magnitude more power than the surface emitters.

WAVELENGTH DUPLEXING

The fiber optic link for a sonobuoy is required to transmit information in both directions simultaneously (table 1). It is important to minimize near-end "crosstalk", in which signals transmitted in one direction are detected by the receiver receiving signals from the other direction. One means of separating the two channels is to use one fiber with a core for each channel. The crosstalk in the triple-core fiber, described in the section on fiber development, was –44 dB. Another means of achieving duplex operation is by wavelength duplexing (applicable to single- and multiple-core fibers). For instance, one channel could use a 0.82–0.85 μm source and the other 0.90–0.94 μm or 1.0–1.3 μm source.(15)

Figure 3 is the attenuation of two fiber types, manufactured using the "inside" and "outside" processes.(16) The strong OH^- attenuation peak for outside-process fibers excludes the 0.90–0.94 μm sources, whereas the lack of the OH^- peak in the inside-process

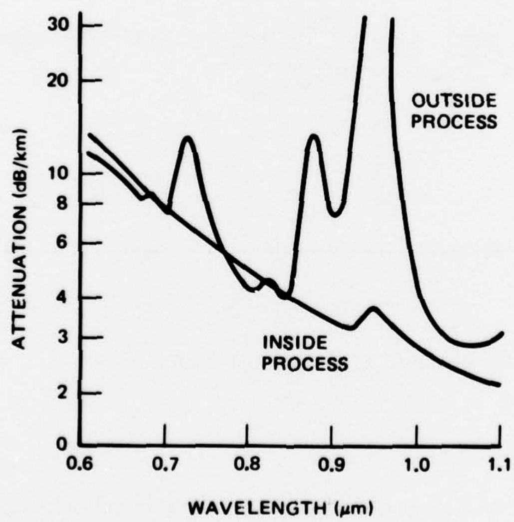

Figure 3. Typical optical fiber spectral attenuation.(16)

fibers tends to favor the 0.90–0.94 μm sources over the 0.82–0.85 μm sources. This difference in fiber attenuation, approximately 1 dB/km, reduces the coupled power advantage of the "max" 0.82 μm edge emitter over the "max" 0.9 μm edge emitter (table 6). Whether the $1 low-radiance surface (0.90 or 0.94 μm) emitters can be used, given the wavelength advantage, requires further discussion of realizable fiber attenuation and receiver sensitivity (see table 7).

The lowest attenuation region is between 1.0 and 1.3 μm.(2) Only three LEDs are commercially available at 1.06 μm, and all are expensive. When the longer-wavelength devices are developed and a suitable market appears, the present high prices can be expected to drop to the same price range as present LEDs.

DRIVER

Drivers for LEDs have been previously developed which are directly applicable to sonobuoy systems. LEDs are modulated by switching the bias current using, for instance, a switching transistor or a hex inverter. Figure 4 is a transmitter circuit typical of those in use at NOSC. This circuit was fabricated using the RCA C30133 pigtail LED edge emitter for use in laboratory evaluation of the 5 km optical fiber.

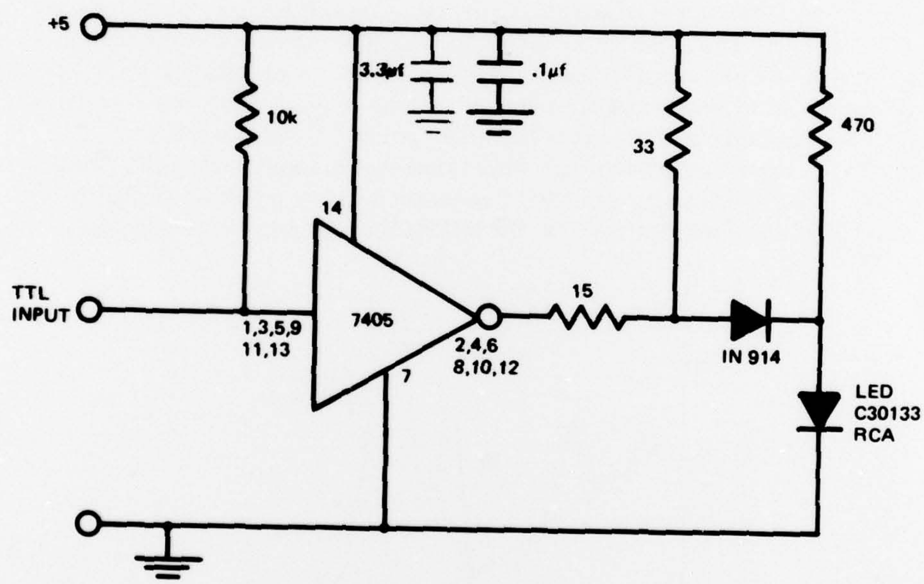

Figure 4. Transmitter schematic.(27)

OPTICAL RECEIVER

Receivers using silicon PIN and silicon avalanche photodiodes have been given considerable theoretical and experimental attention as the optical-to-electrical conversion elements in fiber optic systems. Results of experiments with the best of the receivers are plotted in figure 5. At 50 kb/s, the APD receiver performance is calculated to be 5 dB better

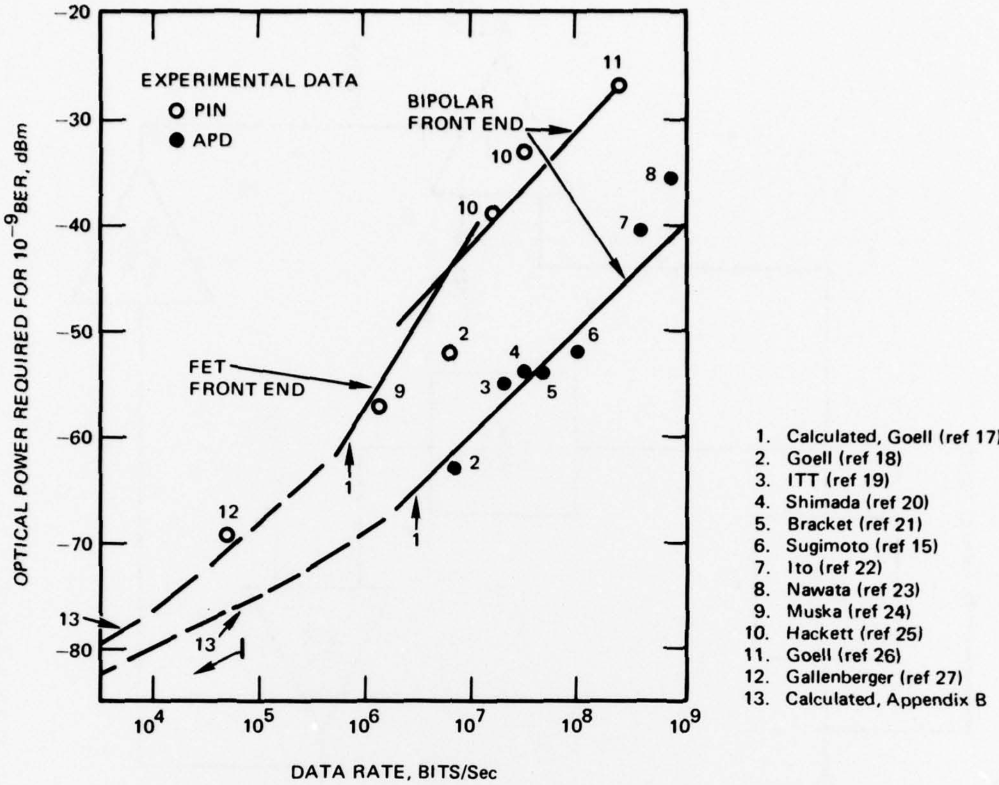

Figure 5. Laboratory receiver performance data.

than the PIN receiver. However, APDs have characteristics, such as the need for a temperature-compensated 200–400V bias and the present high price ($200), which are not desired in expendable sonobuoys. A PIN-diode digital receiver was fabricated at NOSC for laboratory use. Its performance, which is –69 dBm optical power required to achieve 10^{-9} BER, is indicated as data point #12 on figure 5 (calculated in Appendix B). The block diagram of this receiver is shown in figure 6. Since it was designed for high sensitivity to extract the maximum performance from the various detectors to be used in a 5-km link, the receiver was designed without consideration of very low cost. It will serve as a reference for development of simpler, lower-cost receivers for sonobuoy use. Commercially-available receivers, which are typically optimized for (5–20 Mb/s), have wider noise bandwidths and consequently require more optical power for reliable detection; the simplest versions of the commercial PIN diode receivers require approximately –33 dBm. At present, the simple receivers cost in the $400 range, compared to $2500 for receivers similar (in complexity, but at higher bandwidth) to the NOSC receiver.

Future price projections for receivers are highly dependent on the market. The present parts-cost for the NOSC receiver, for instance, is $100. If a market emerges for a sensitive, low-data-rate receiver for commercial applications such as digitized voice, then the sonobuoy receiver may perform as well as the NOSC receiver, yet be priced in the $20 range.

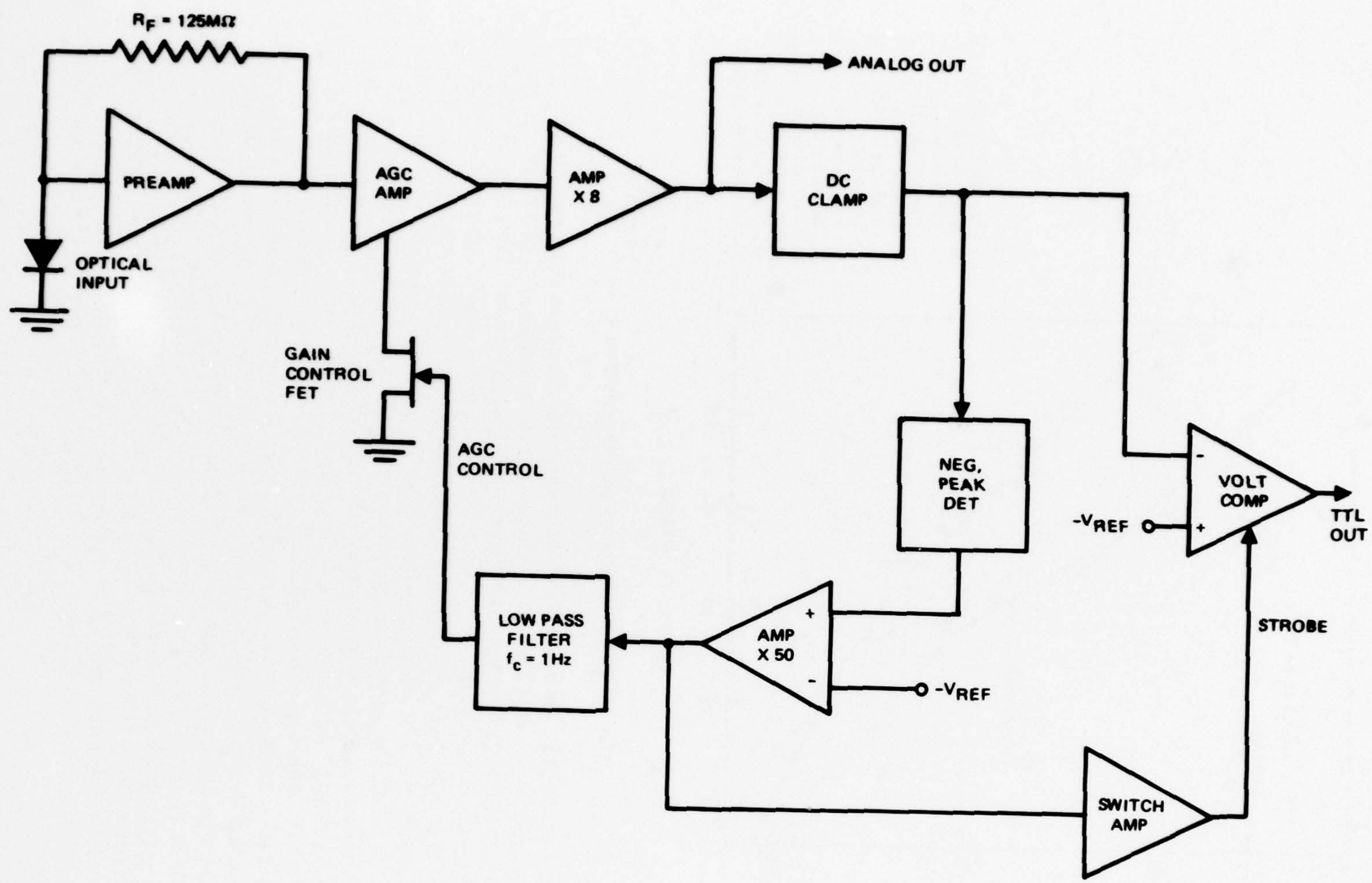

Figure 6. Optical receiver block diagram.[27]

PERFORMANCE ESTIMATE

The important factors to be considered in estimating link performance are:

1. Coupled power (P_{in}). Depends strongly on source geometry, as indicated previously in table 6.

2. Fiber attenuation. Based on development experience obtained in the sonobuoy cable effort, an operational attenuation of 6 dB/km at 0.82 μm appears feasible.

3. Detector end losses. A conservative estimate of 2 dB allows margin for "dry" connections (no index-matching fluid) to the detector via a pigtail.

4. Receiver required optical power. Optimized receivers, such as the NOSC device, require –69 dBm to achieve 10^{-9} BER at the assumed 50 kb/s. Table 7 is an example of five component groupings, each of which operates at a different wavelength and optical fiber attenuation.

Table 7. Examples of sonobuoy links.

	A	B	C	D	E
Wavelength, μm	.82	.83	.90	.94	1.06
LED type	Etched well	Edge	Edge	Surface	Etched well
Drive Current, mA	300	200	100	100	300
1. Coupled power, dBm	–2	–10	–18	–22	–13
2. Duplex coupler, dB	–6	–6	–6	–6	–6
3. Splices (if required), dB	–1	–1	–1	–1	–1
4. Connectors (if required), dB	–2	–2	–2	–2	–2
5. Detector coupler, dB	–2	–2	–2	–2	–2
6. Fiber attenuation (5-km) dB	–30	–29	–25	–23	–15
7. Detector req. opt. power, dBm	–69	–69	–69	–69	–66
margin, dB	26	19	15	13	27

The table does not exhaust the possible combinations of components: several trades of link performance and cost are possible, including the potential for further reduction in fiber attenuation and the emergence of components operating in the 1.0 to 1.3 μm region. In this region, cable attenuations of 2 dB/km or less are feasible and components are under development.

CONCLUSIONS

1. CABLES. A 1-km Kevlar-49 strengthened cable was fabricated which meets the diameter and strength goals. The fiber strength state of the art in 5-km length presently limits the allowable load to 40% of the cable strength. The 1-km fiber incorporated in this cable passed a proof test load equivalent to 2% strain, or 80% of the full cable break strength. When the fiber strength improvement effort (a related program at NOSC) is complete, the full strength of the cable will be realized. The optical attenuation characteristics of the cable are good: 6 dB/km fiber did not increase more than 1 dB/km when incorporated into the cable and wound in a simulated sonobuoy coil configuration. The contract specification was 8 dB/km, max. Optical, mechanical, and environmental tests of the cable will be conducted at NOSC during FY 78.

2. LONG HIGH-STRENGTH FIBERS. Two 5-km optical fibers, one step-index and one graded-index, are being fabricated at ITT. Good progress was made toward meeting contract goals during FY 77. The fibers to be developed will be at least four times stronger than any other comparable-length fiber to date. The attenuation and numerical aperture will be optimized to assure good optical performance in a sonobuoy cable; the attenuation is specified to be less than 7 dB/km for the step-index fiber (6 dB/km for the graded-index fiber) and the NA is 0.23 to minimize coupling loss and stress-induced attenuation increases. Delivery is expected in early FY 78.

3. DUPLEX TRANSMISSION. A 600 m fiber was fabricated having three 55-μm optical cores in a 200 μm diameter fiber. The fiber was buffered to the same 680 μm diameter as the single-core fiber in the sonobuoy cable. The cores had attenuations of 4.0, 4.3 and 6.4 dB/km and near-end crosstalk of −44 dB as measured by ITT. The fiber passed a 2%-strain proof test indicating the potential for high strength in the required 5-km length. 100 m of the new sonobuoy cable design was fabricated incorporating the triple-core fiber.

4. LOW COST FIBER DEVELOPMENT. Catholic University of America was able to reduce attenuation of their Phasil process fibers from 37 dB/km to 13 dB/km, in 100 m lengths, but still require considerable development to approach the length, strength and attenuation specifications of fibers for sonobuoys – under other contracts/programs.

5. FIBER STRENGTH IMPROVEMENT. The Defense Advanced Research Projects Agency funded efforts in FY 76 and FY 77 to increase fiber strength for military systems. Results to date are encouraging, but incomplete. Abrasion and thermally-induced flaws, which are the primary contributors to weak fiber strength, have been reduced and progress has been made in preserving fiber strength by application of metal coatings and compressive claddings. Strength of research fibers in 1-km lengths has been increased from 1%-strain to 5%-strain proof test loads and length at 1%-strain proof test loads has been increased from 1 km to 5 km (sonobuoy contract). By comparison, the commercially-available fibers from other fiber manufacturers remain at 0.25%- to 1%-strain proof-test loads in 1 km lengths.

6. LINK DEVELOPMENT. Of the four general classes of commercially available LEDs surveyed, the best compromise in performance with potential for low cost is the GaAlAs edge emitter. Considerable research has been performed on these devices to optimize them for single fiber use and some are now available commercially. Because of the anticipated demand for the high-speed, high-radiance edge emitters, the future order-of-magnitude high-volume market price is estimated by the manufacturers to be in the $10

range. Other high-radiance devices, such as the etched-well or injection laser, are strong candidates if they become competitive in price. Optical receivers optimized for the relatively low-speed sonobuoy data reception requirements are not available commercially. A laboratory receiver optimized for sonobuoy data rate (but not for cost) performed within 1.5 dB of the theoretical prediction for the low-noise detector used and 12 dB better than the best known laboratory receiver. A link for the 5 km sonobuoy cable having 6 dB/km cabled attenuation at 0.82 μm recommended GaAlAs edge-emitter LED output power, and a receiver equivalent to the NOSC laboratory version will operate with satisfactory margin (19 dB optical power margin over that required to achieve 10^{-9} BER).

RECOMMENDATIONS

1. Test the prototype fiber optic cable and recommend any necessary design improvements to meet operational sonobuoy cable specifications. Test for optical performance under a variety of stress conditions, including hydrostatic pressure, tension, temperature, and small-bend-radius coiling. Test mechanical performance such as tensile strength, torque, rotation, and flexure.

2. Purchase additional cable (1–2 km) and conduct winding and payout tests to devise means of assuring minimum optical attenuation in the coiled configuration and to payout the cable without fouling or breaking.

3. Develop a fiber optic feedthrough technique to reliably penetrate the pressure interface. Exploratory feedthroughs have been fabricated at NOSC and ITT, but further development and testing are required.

4. Conduct 5-km link tests to verify performance estimates. Characterize available sources and detectors and develop a low-cost link. Package fiber optic sources and detectors to efficiently operate with single optical fibers.

5. Continue to improve fiber strength in long lengths. A near term goal should be to increase proof test loads of 5-km length fibers from 1% strain to 2.5% strain. This will allow the cable to achieve its full breakstrength.

6. Continue monitoring the Catholic University glass research.

7. Test the three-core optical fiber for near-end crosstalk and develop an appropriate duplex coupler. Investigate alternate duplexing techniques.

8. Develop optical sources and detectors which operate in the 1.0 to 1.3 μm region to make use of the lower attenuation of optical fibers.

9. Modify NOSC test equipment to measure optical attenuation in the 1.0 to 1.3 μm region.

10. Develop cables and components appropriate to a sonobuoy system which requires a 7-km, 0.66 mm cable having optical attenuation of 6 dB/km.

11. As fiber strength improves, study the feasibility of developing miniature sonobuoys which use optical fibers without loadbearing members. The present state of the art allows 1 km-length 125 μm diameter fibers to support loads of up to 45 N (10 lbs) for a 5%-strain proof test. When the DARPA/Navy fiber strength improvement goals are reached and 2% proof-tested, 10 km length fibers are available, then 7 km-length 250 μm-diameter fibers may be able to support 70 N (16 lb) loads; shorter (up to approximately 300 m), 250 μm diameter fibers, proof tested to 5%, may be able to support 180 N (40 lbs).

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APPENDIX A: FIBER STRESS CORROSION

The relationship between time, proof stress, and applied stress is theoretically described by the following equation (23°C, 55% RH).[28]

$$t_{min}\,\sigma_a^2 = B(\sigma_p/\sigma_a)^{N-2}$$

where:

t_{min} = minimum time to failure, sec

σ_a = applied stress, MPa

σ_p = proof stress, MPa

$B = 1.56 \times 10^6\ \mathrm{MPa}^2\ \mathrm{sec}$

$N = 22.23$

B and N are constants for a given environment and material composition. Thus, for a fiber proof-tested to 1,400 MPa (2% strain) the maximum applied stress over a storage life of 7 years (2.2×10^8 sec) is

$$\sigma_a = \left[\frac{B}{t_{min}}\,\sigma_p^{\,N-2}\right]^{1/N}$$

$$= \left[\frac{(1.56 \times 10^6) \times (1400)^{20.23}}{(2.2 \times 10^8)}\right]^{1/22.23} = 583\ \mathrm{MPa}$$

The equivalent strain is

$$\frac{583 \times 10^6\ \mathrm{Pa}}{70 \times 10^9\ \mathrm{Pa}} = 0.83\%$$

Therefore, we conclude that both the storage strain (0.3%) and operating strain (0.5%) will not cause the fiber to break during the 7-year storage or 3-hour operating periods.

APPENDIX B: NOSC RECEIVER PERFORMANCE

Receiver noise performance is determined within the preamp input stage.[18] Three significant noise sources must be considered:

a. Shot noise due to photodiode dark current and FET gate leakage current,

b. Thermal noise associated with feedback resistor, and

c. FET channel thermal noise.

The equivalent input noise current of the preamp is given by:[18]

$$i_{ni} = \left[2q\, I_L B + \frac{4\,KTB}{R_f} + \frac{4\pi^2\, \epsilon_i^2\, B^3\, e_n^2}{3} \right]^{1/2} \qquad (1)$$

where

q = charge on electron = 1.6×10^{-19} coul

I_L = sum of photodiode dark current plus gate leakage current

K = Boltzmann's constant = 1.37×10^{-23} J/deg

T = Absolute temperature

e_n = channel noise voltage of FET, $V/\sqrt{Hz}$

C_i = total input capacitance of preamp

R_f = feedback resistor

B = equivalent noise bandwidth

The relevant preamp characteristics are summarized below:

C = 13 pF

R_f = 125 MΩ

B = 30 kHz

e (2N4416) = 4×10^{-9} $V/\sqrt{Hz}$

I = 20 pA (gate leakage current at 25°C)

I = 75 – 250 pA, PIN-020A at –10 V bias
1000 pA (max), PIN-020B at –10 V bias

The values given above for dark current are data sheet values. The dark currents were measured for the two photodiodes used in the receiver preamps and were found to be 110 pA for the PIN 020A and 850 pA for the PIN 020B at 10 V reverse bias. Substituting the above values into (1) gives

i_{ni} = 2.5 pA (PIN 020A)

i_{ni} = 3.6 pA (PIN 020B)

The photodiode responsivity is about 0.4 at 850 nm. Thus, the calculated receiver noise equivalent powers (NEP) are 6.3 pW and 9 pW for the 020A and 020B, respectively.

The NEP was measured for each of the two receivers. The measurement was made by first disabling the AGC, measuring total receiver gain, and output noise voltage at the "ANALOG" test point. The NEP is given by:

$$NEP = \frac{V_N}{G_r}$$

where:

V_N = output rms noise voltage
r = photodiode responsivity
G = receiver gain

The measured values of NEP were almost identical for the two receivers; 9.9 pW for the PIN 020B and 9.7 pW for the PIN 020A. Both closely agree with the theoretical values previously calculated.

To achieve a 1×10^{-9} BER, a peak-to-peak signal to rms noise voltage ratio of 12.0 (21.6 dB) is required at the input to the threshold detector.(29) This corresponds to a minimum peak optical power 10.8 dB above the receiver NEP. The required peak optical power is therefore $10 \log (9.7 \times 10^{-9}$ mW) + 10.8 dB = –69.1 dBm, which was plotted as data point #12 in figure 5. The dotted line labeled #13 was calculated by extrapolating equation A1 to lower data rates for the PIN detector. The APD calculation was derived from the assumed NEP of 1×10^{-14} W/Hz$^{1/2}$ which was extended to intersect the curve calculated by Goell (reference 16).