NAVAL RESEARCH REVIEWS

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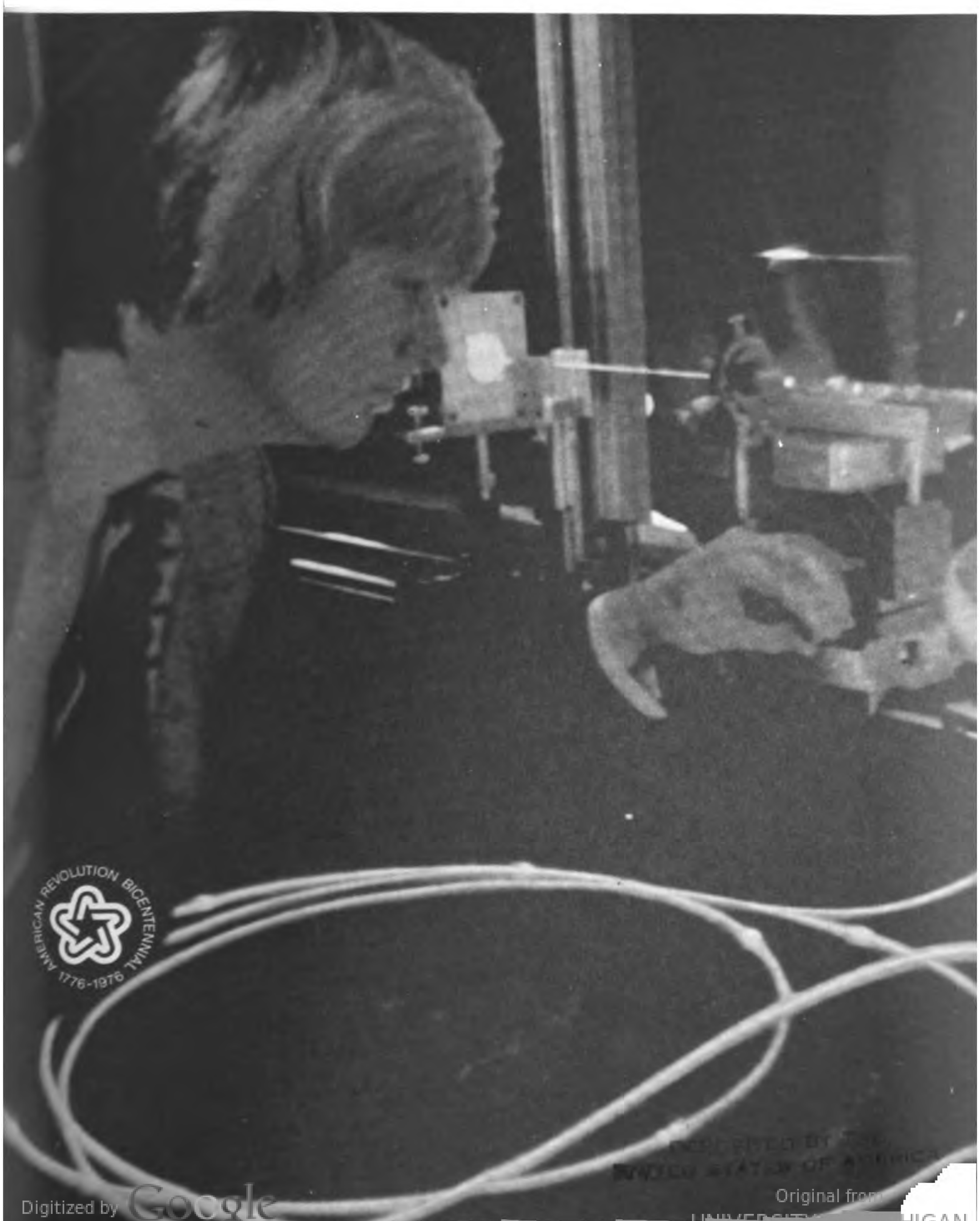

PROFILES IN SCIENCE

Nicolass Bloembergen

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Monolithic Integrated Optical Circuits

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The invention of the laser has given an enormous stimulus to the entire field of optics. Many traditional domains of optics, such as Raman spectroscopy, have benefited from the availability of a powerful, coherent light source. Dormant applications, like holography, have been brought to life, and many entirely new fields have been opened up. One of these new offspring of an old art is integrated optics. Like integrated electronics, integrated optics does not really provide new possibilities in principle, but it makes practical many well-known applications that without this technique would remain too cumbersome or expensive to be utilized.

Traditional optical apparatus must be aligned with extreme accuracy and is thus susceptible to the smallest amount of vibration and temperature change. Integrated optics concentrates light in thin-film waveguides that are deposited on the surface or inside a substrate. Because of the short wavelength of light, dielectric light waveguides can be extremely small in their dimensions. The reduced size of integrated optics circuits thus makes it possible to achieve a much higher density of components compared to conventional optical equipment aligned on steel rails or on heavy optical benches. An additional advantage of the small size and rugged construction of dielectric light waveguides is their insensitivity to vibrations and temperature changes in their environment.

Introduction

Optical communications involving optical fibers and integrated optical circuits is an emerging new technology which may leapfrog conventional communications technology in many high data rate applications. Realizing the ultimate potential of this new technology for the rapid processing and transmission of information requires

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development of integrated optical circuits (IOC's). Reliable, low cost techniques for making transmitters and receivers containing lasers, waveguides, modulators, switches, couplers, and photodetectors must be developed. The most promising emerging technology for IOC's is the formation of optical microcircuitry in the III-V semiconductor materials system (GaAs and its ternary alloys with Aℓ and In). A program for the development of a GaAs IOC transmitter is being carried out in the Central Research Laboratories at Texas Instruments Incorporated. An artist's schematic of such an IOC transmitter is shown in Figure 1. This IOC transmitter is to consist of a monolithic surface laser whose output is coupled into patterned channel waveguides. In this case monolithic means unity of structure. When the transmitter is epitaxially fabricated its components (laser and waveguide) are formed into the structure at the same time. Modulation and switching of the radiation occur in the waveguide circuits and are controlled separately. These structures are to be fabricated monolithically on a single semiconductor chip with each device amenable to integrated, low-cost manufacture. The waveguide outputs of the IOC transmitter will be coupled to single mode optical fibers which form a transmission cable.

The properties of the semiconductors (Ga,Aℓ) As and (Ga,In) As permit performance, in principle, of each of the basic functions included in the device shown in Figure 1: coherent optical emission, passive optical coupling, optical waveguiding, and electrooptic modulation/switching. The emission wavelength of the surface laser can be tailored to match regions of low fiber loss by changing the alloy composition.

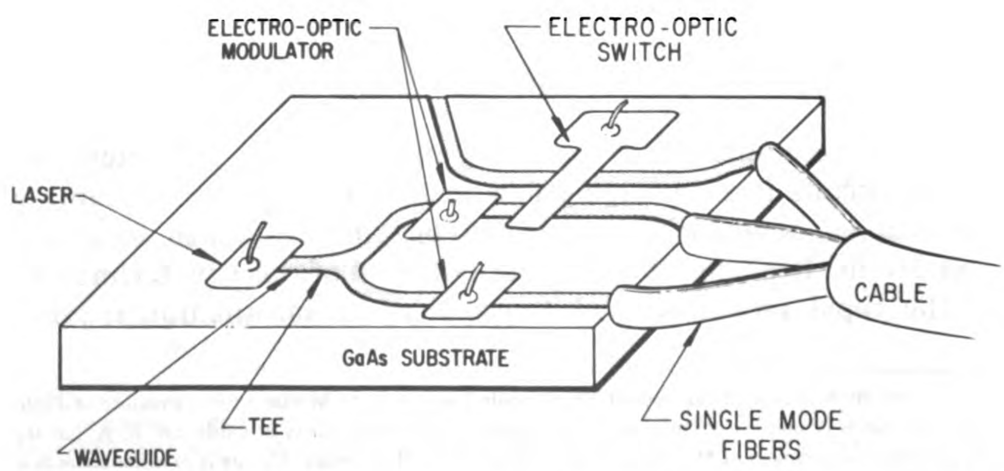

Figure 1 – Artist's schematic of a monolithic GaAs IOC transmitter with its output coupled to single-mode optical fibers

Two necessary circuit functions for a prototype transmitter have been achieved individually in the form of a monolithic surface laser and channel waveguide. Selective epitaxial deposition was used to grow vertical $Ga_{1-x}In_xAs$ mesa laser optical cavities that occupy a small portion of a large chip.(1) Diffusion of Zn into the top face of the mesas was used to form p-n junctions. Electrical pumping (2) of these diodes has yielded the first semiconductor diode lasers with as-grown, crystalline facets. These lasers are the first monolithic, non-discrete diode lasers ever fabricated using conventional photolithography. Also, double epitaxial layers of GaAs were etched to form channel optical waveguides that are the optical analog of the microwave stripline (3). These optical striplines consist of a planar propagating (high-index) epitaxial layer overlaid by a lower-index epitaxial strip. Lateral confinement under the strip in this structure does not involve an index discontinuity in the planar propagating layer, where the light beam is trapped. Thus, the propagation loss should be less sensitive to imperfections in the surface of the overlaid strip. In single-mode waveguides we have measured a loss coefficient of approximately 1 cm^{-1}, the lowest reported to date for III-V semiconductor channel waveguides.

Mesa Structures

The $Ga_{1-x}In_xAs$ mesa structures were grown using a method of selective vapor phase epitaxy previously reported by Shaw (4). By this technique, epitaxial growth on a substrate is restricted to areas which are exposed by holes in an oxide mask. Growth of these mesa lasers was accomplished in a vapor phase epitaxial reactor using arsine, hydrogen chloride gas, and liquid gallium in a hydrogen ambient as the sources. Growth was restricted to diamond-shaped holes in a thin (1500 Å) plasma-deposited silicon dioxide film on the $\{110\}$ surface of a GaAs substrate (Te doped, $n \simeq 2 \times 10^{18}$ cm^{-3}). The diamonds were repetitively patterned on the oxide growth mask using photolithographic techniques. The diamond angles were chosen so that all sides were $\{111\}$ planes, making the long dimension of the diamond lie along a $\{110\}$ cleavage plane. The mesas are n-type, and doping levels of 10^{16} to 10^{18} cm^{-3} were obtained by introduction of sulfur into the reactor vapor. A scanning electron microscope picture of a GaAs mesa is shown in Figure 2. The mesas are 300 μm tip to tip (longest dimension) and can be grown with heights between 5 and 25 μm. The oblique planes at the diamond corners are non-vertical $\{100\}$ and $\{111\}$ planes. The opposite diamond faces are parallel $\{111\}$ crystalline planes which are perpendicular to the substrate. The vertical mesa structure is realized by virtue of the very

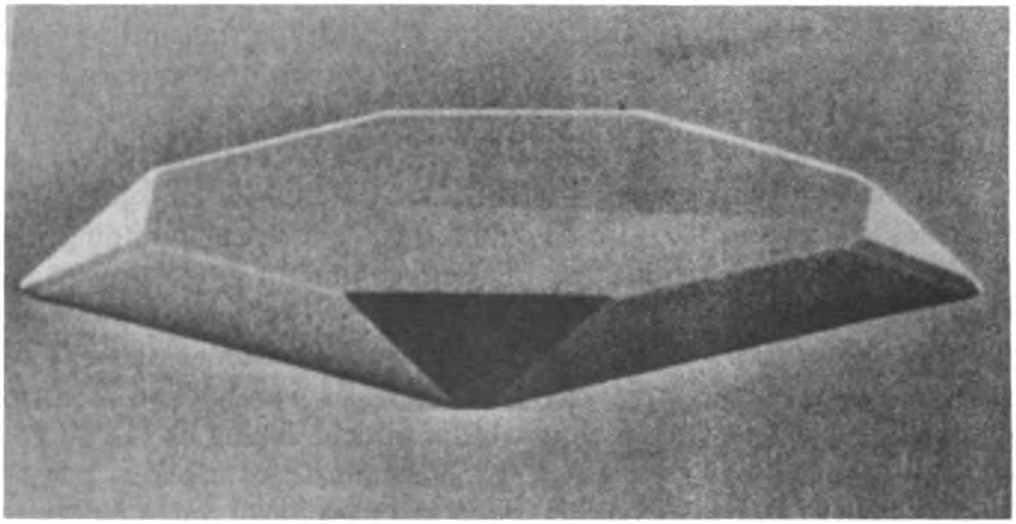

Figure 2 – Scanning electron photomicrograph of a GaAs mesa

slow growth rate of the {111} planes (4). The result is a pedestal structure with opposing parallel crystalline sides forming the laser optical cavity. Geometrical perfection of the mesas is excellent. Interferometric measurements on the top {110} surfaces indicated that the best mesas are flat to within 0.05 μm, and the edges are very sharp and well defined. A photograph of a full slice of several hundred mesas is shown in Figure 3. The yield of geometrically well-formed mesas on a good slice of several square centimeters in area was 80 to 90%. The ability to grow hundreds of lasers at will on a single slice is crucial to eventual low-cost manufacture.

Mesas of (Ga,In) As alloys have also been prepared. To accomplish this, a ratio of In to Ga of about two in the gas phase results in mesa compositions of about $Ga_{0.95}In_{0.05}As$. No grading of the In As content as a function of growth height was used. Mesas with as much as 20% InAs have been grown, but the perfection of these mesas is not as good as that of GaAs ones. The top surfaces of the best mesas were flat to ~ 0.1 μm and the edge definition was good. The most common flaws were microscopic pits and hillocks in the top surface and lateral overgrowth on one set of common polarity faces.

Homojunction injection mesa lasers were fabricated by forming a p-n junction in the mesas and electroplating gold electrical contacts. The p-n junction was formed in the mesa lasers by converting the upper portion of the n-type mesas to p-type. The most apparent techniques for doing this involve the diffusion or implantation of a p-type dopant in the mesas. One immediately faces two difficulties: (1) prevention of type conversion on the optical faces (the sides) of

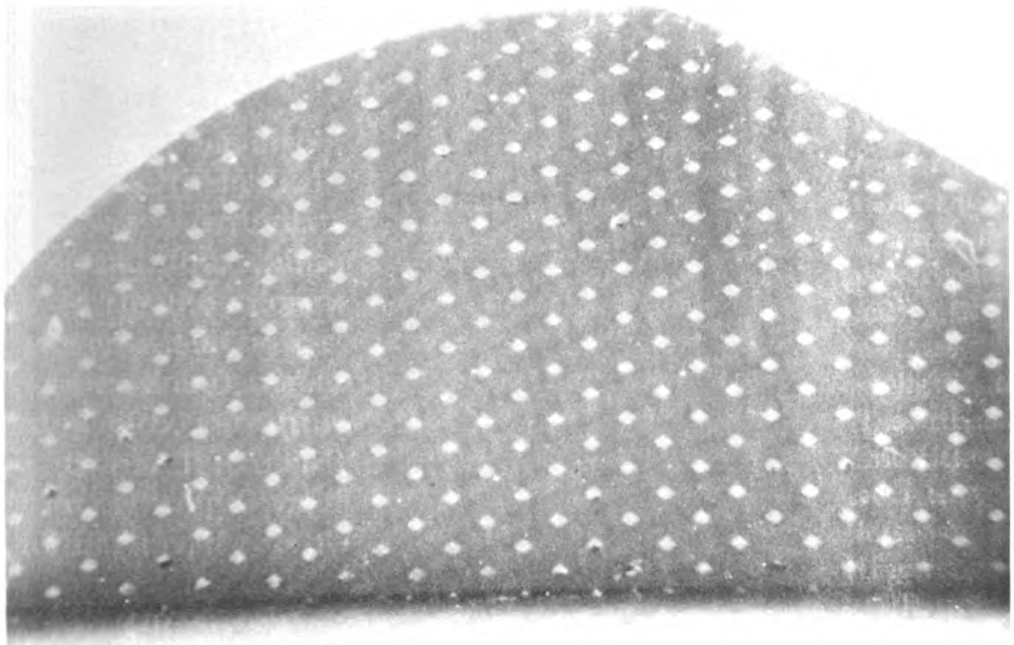

Figure 3 – Photograph of a slice containing several hundred GaAs mesas

the mesa, and (2) the formation of a completely flat junction with the p-type region extending completely to the cavity walls. The technique chosen to avoid these difficulties was diffusion of Zn from Zn-doped SiO_2 layers positioned on the tops of the mesas only. Diffusion of Zn into the slice was accomplished by heating the slice in a nitrogen atmosphere at 800 to 850° C for periods of 10 to 40 minutes. Junction depths of 1 to 6 μm were obtained with a surface Zn concentration of $\sim 10^{20}$ cm^{-3}.

After removal of the SiO_2 layers, electrical contacts were formed by (1) selectively electroplating gold to the mesa tops and back of the slice, (2) alloying the gold at ~ 450° C in a forming gas atmosphere, and (3) again electroplating gold on the mesa tops and back of the slice. Photomasking was used to prevent plating on other parts of the slice. Both full surface and 2.5 mil stripe contacts were used. Diced chips containing two mesa devices each were then soldered to a TO-46 header (mesa up). The individual mesas were contacted with 1 mil gold wire using a thermocompression ball bonder. A photograph of two bonded lasers is shown in Figure 4.

The mounted diode mesa lasers were tested in vacuum on the cold finger of a liquid nitrogen dewar. The lasers were driven by forward bias current pulses about 100 ns in width with a repetition rate of 100 Hz. The lowest threshold current density observed for GaAs lasers was 4 kA/cm^2. The emission spectrum of one of the diode

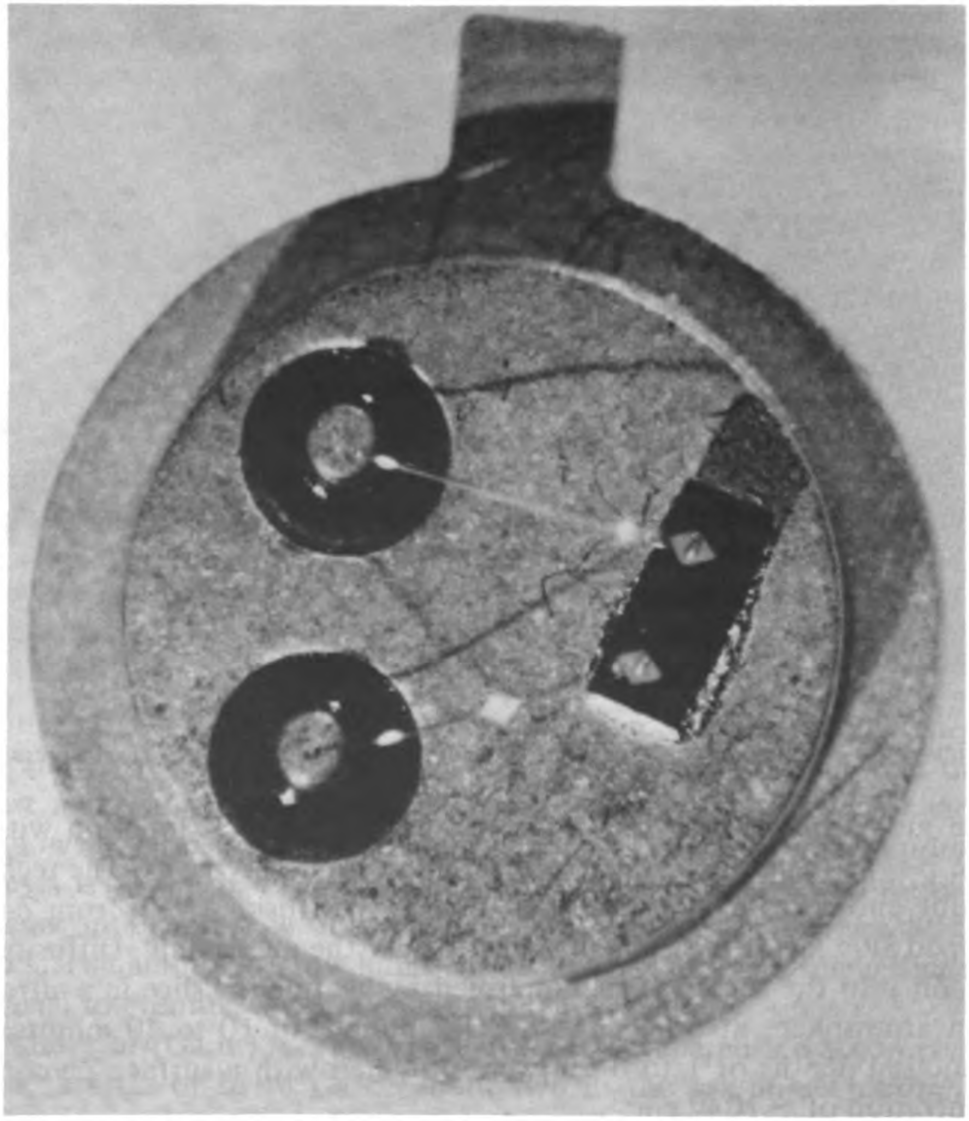

Figure 4 – Photograph of two monolithic injection mesa lasers mounted on a TO-46 header

mesa lasers is shown in Figure 5. Note that the emission is centered near 8390 Å showing strong longitudinal mode structure with a peak separation of ≈ 4.5 Å. Peak power outputs ranged from a few tenths of a watt to 3 watts for the best GaAs devices. For lasers with full surface contacts, emission was found to occur predominantly from two of the four optical facets. Such behavior suggests that the lasers were not oscillating in circulatory bounce modes. Selected lasers with low threshold current densities were also successfully operated at ~ 200 K (dry ice temperature).

$Ga_{1-x}In_xAs$ injection mesa lasers were fabricated with $0 < X < 0.06$. Threshold current densities were in the 20 to 30 kA/cm^2 range

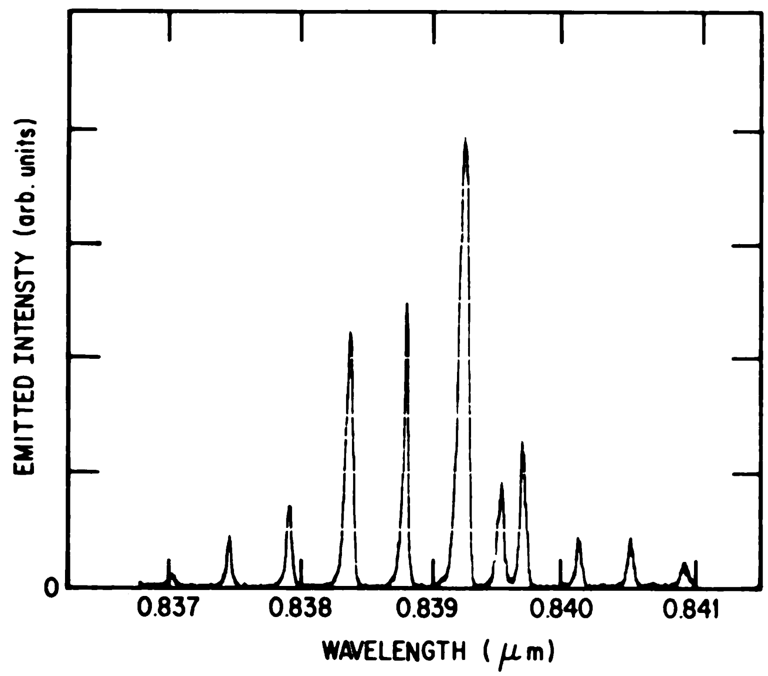

Figure 5 – Emission spectrum of a GaAs diode mesa laser at 77 K driven with a bias current of 10 A

and the highest peak power output observed was 0.9 W. The emission/spectrum of a $Ga_{0.95}In_{0.05}As$ mesa laser is shown in Figure 6. The output is centered near 9050 Å, a substantial shift from the GaAs wavelength of Figure 5. The wavelength tunability of the monolithic $Ga_{1-x}In_xAs$ laser is important for (1) matching wavelengths of low-cost for optical fibers, and (2) shifting the source wavelength in IOC applications so that optical waveguides are transparent to the emitted radiation.

Waveguides for IOC's

Channel optical waveguides generally proposed for semiconductor IOC's consist of either raised ridges (5) or imbedded strips (6,7) in which optical confinement results from abrupt refractive index steps at all waveguide boundaries. The propagation loss in such waveguides is very sensitive to edge roughness, and the fabrication of sufficiently smooth waveguides can tax current pattern definition techniques. We have observed optical confinement in a GaAs channel waveguide structure which is the optical analog of a microwave stripline (8). These waveguides consist of a two-dimensional propagating (high-index) epitaxial layer overlayed by a lower-index epitaxial strip [see Figure 7(a)]. Lateral confinement under the strip in this structure does not involve an index discontinuity in the full-surface propagating

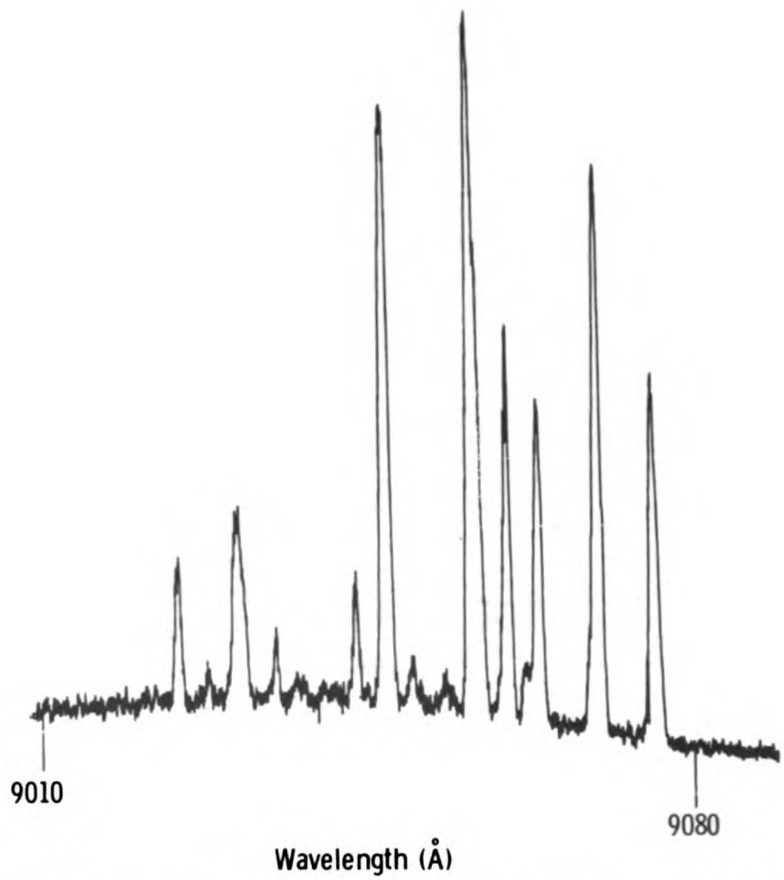

Figure 6 – Emission spectrum of a $Ga_{0.95}In_{0.05}As$ diode mesa laser at 77 K driven with a bias current of 12 A

layer, where the light beam is trapped. Thus, the propagation loss should be less sensitive to imperfections in the surface of the over-layed strip.

The principle of the optical stripline is most easily understood by comparing (a) a single layer asymmetric planar waveguide (a single high index film overlaid by air) with (b) the near-symmetric two-layer planar waveguide. The region outside the stripline ridge is like (a) above. The region at the ridge is like (b) above. From simple planar waveguide theory one immediately sees that a wave guided in the near-symmetric case has a lower phase velocity than that for the asymmetric case. A lower phase velocity implies a higher effective refractive index. This higher effective refractive index exists only *under* the defining strip and traps the wave, much as a conventional channel waveguide. For the GaAs structure of Figure 4, we estimate the effective lateral index step to be $\sim 3.5 \times 10^{-4}$.

The n-type GaAs epitaxial structures were grown on heavily doped ($n^+ \sim 1 \times 10^{18}$ cm^{-3}) $\{100\}$ substrates in an open-tube vapor deposition system using the $AsCl_3/Ga/H_2$ process. By changing the gas phase dopant (S) concentration, two distinct layers of different refractive index were formed during the same deposition run. Higher doping levels produce lower refractive indicies. The first layer had the highest refractive index with a doping level of $n \sim 1 \times 10^{16}$ cm^{-3}, whereas the second layer was of lower indes with $n^{+} \sim 6 \times 10^{17}$ cm^{-3}. To form the stripline the n^{+} layer was selectively etched using a 1.0 M NaOH - 0.7 M H_2O_2 solution in conjunction with an oxide mask formed by plasma deposition and photoresist techniques. Pilot slices were etched just prior to etching the actual samples in order to accurately ascertain the etch rate and permit precision removal of of the n^{+} layer. The result was a series of n^{+} strips of varying width (5-30 μm) on the top of the fullsurface n epitaxial layer. A schematic of the resulting structure is shown in Figure 7(a). Region 1 is the crystalline substrate, while regions 2 and 3 are epitaxial layers. Because of doping level changes, region 2 has the highest refractive index [as shown in Figure 7(a)] and forms the optical waveguide. The thickness of region 2 (n layer) was chosen to yield the lowest-order single vertical mode propagation.

Optical waveguiding was observed using a 1.15 μm He-Ne laser and an infrared vidicon. The input laser beam was focused by a microscope objective onto the cleaved edge of the waveguide to a spot diameter of approximately 2 μm. The input beam was polarized so as to excite the TE modes of the waveguides. The near-field intensity pattern of the radiating waveguide was observed by viewing the magnified image of the opposite cleaved face with the vidicon and a TV monitor. The intensity pattern of a $TE_{1,1}$ mode of an approximately 14 μm-wide waveguide is shown in Figure 7(b). The output beam was linearly polarized with a ratio > 100:1, indicating a conversion to TM modes of < -20 dB. The crystal face was back-illuminated with a lamp to reveal the actual waveguide cross section. The epitaxial strip has sloped edges due to lateral etching under the oxide mask. The laser beam is clearly trapped beneath the overlying strip; there is essentially no light intensity in the etched ridge. For this waveguide, region 2 is 5 μm thick and region 3 is 2 μm thick. The losses in these waveguides were determined by measuring the transmission of several lengths of the same sample. The lowest loss coefficient measured for the $TE_{1,1}$ mode was 1.0 ± 0.2 cm^{-1}, yielding a loss of 4.3 ± 0.9 dB/cm, the lowest ever measured for a III-V channel optical waveguide.

While the monolithic $Ga_{1-x}In_xAs$ injection lasers and GaAs optical striplines described above are important developments, the next important step is to couple the two devices in a single monolithic optical circuit. The laser-waveguide coupling problem is a significant

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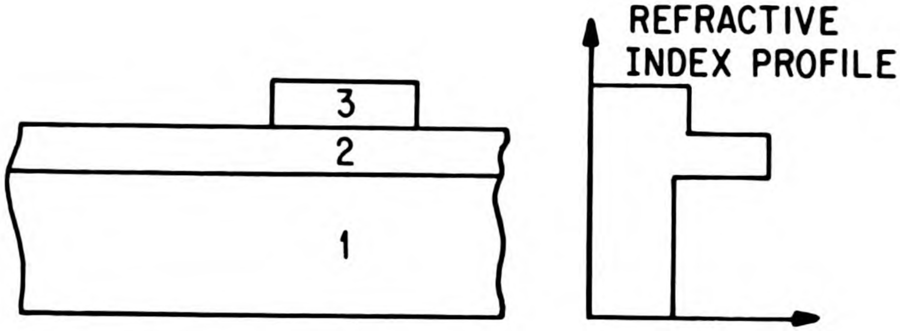
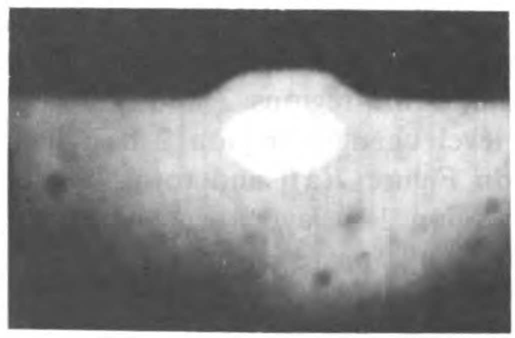


(a)



(b)

Figure 7 – (a) Schematic diagram of the cross section of an optical stripline waveguide and its index profile; (b) photomicrograph of the near-field intensity pattern of the end of a stripline which has trapped a 1.15 μm laser beam

and crucial one for the development of IOC's. The simplest technique for coupling the output of a mesa laser to an epitaxial waveguide is to use the evanescent or "leaky" field character of dielectric waveguides. This can be done by growing a junction mesa laser above a planar epitaxial waveguide. If the active junction region and the passive waveguide are sufficiently close to each other, the decaying (or evanescent) field of one extends into the other, yeilding direct coupling of the two. The radiation is then "leaked" into the passive waveguide and carried away. Epitaxial layers outside the mesa can be used to form channel waveguides, switches, and modulators as shown schematically in Figure 1. Active modulator/switch devices can be made using the stripline waveguides by applying metal Schottky barriers on or near them. The metal-semiconductor junction creates a high electric field directly under the metal due to depletion of mobile carriers. When a reverse bias is applied, the field increases and can be as high at 10^5 to 10^6 V/cm. Such high electric fields change the refractive index of the GaAs. By proper choice of geometry, it is possible to significantly change the guiding properties of the channel waveguides, modulating the light intensity. Preliminary experiments on such devices have been performed in our laboratory.

Summary

Finally, it should be noted that while the devices discussed above were made from $Ga_{1-x}In_xAs$ alloys, this is not an essential requirement. The concept described above applies equally well to $Ga_{1-x}Al_x$ As alloys. Rather than having a $Ga_{0.95}In_{0.05}As$ mesa laser coupled to a GaAs stripline, one could equally well imagine having a GaAs mesa laser coupled to a $Ga_{0.95}Al_{0.05}As$ stripline. One can also imagine schemes to develop heterostructure mesa lasers which would operate at room temperature. The purpose of our research to date has been to develop techniques and workable concepts for a monolithic laser source and low loss channel optical waveguides. The injection mesa laser concept is in itself a much needed development proving the capability of making a localized nondiscrete laser, a feat never before accomplished. Having made this first step, the tasks remaining are to (1) integrate the device functions, (2) improve the performance of the individual devices, and (3) evolve an IOC design which allows efficient room temperature operation. At our current level of technology, we are clearly limited by the commitment of resources to the development of this exciting new technology.

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Data Busing with Fiber Optics

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Introduction

The concept of the data bus (a single transmission line which carries many different multiplexed signals and serves a number of spatially distributed terminals) is becoming increasingly evident in the design of new military aircraft, such as the F-14, F-15, and B-1 generations. A data bus system can be less expensive to install and maintain, lighter in weight and smaller in size, more reliable, easier to modify and expand, and less vulnerable to damage than systems based on point-to-point links. The realization of practical data busses is largely a result of recent advances in solid state electronics, which have made it possible to engineer reliable, compact, and inexpensive multiplexers and demultiplexers. Inadequacies of the transmission line, an electrical wire-pair or coaxial cable in present-day data bus systems, can limit the number of terminals, bandwidth, reliability, and error immunity of the system. Susceptibility to reflections and ringing, crosstalk, Radio Frequency Interference, Electro Magnetic Interference, Electro Magnetic Propagation, ground-level voltage shifts, and fire damage, as well as bandwidth limitations, are shortcomings of electrical cable which are aggravated by the stringent requirements of the data bus system. Furthermore, the technology of electrical transmission lines reached maturity decades ago; the coaxial cable of today is not much different from that of 1950, and there is little chance of major improvement in this area.

The fiber optics transmission line is a strong candidate to replace electrical lines in data bus systems of the future (1). The bandwidth of multimode fiber optics lines is orders of magnitude higher than that of a coaxial cable of comparable size and weight. Properly designed couplers, junctions, and terminations should negate the effects of reflection and ringing in fiber optics lines. The use of opaque jacketing will eliminate electromagnetic pickup and crosstalk. Ground shifts

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cannot occur because the terminals are electrically isolated from each other. Fiber optics lines will operate satisfactorily at temperatures considerably above the 250° C rating of high-temperature electrical cable.

A number of fiber optics links for transmitting analog and digital signals have been successfully demonstrated at Naval Electronics Laboratory Center and elsewhere. Much of this work was described at the Second DoD Conference on Integrated Optics and Fiber Optics Communications held in San Diego in May, 1974. In the avionics area, a major effort to refit the navigation and weapons delivery system of an A-7 aircraft with point-to-point fiber optics links began in early 1974 under NELC management. Flight testing of the aircraft is scheduled for 1976. The flight demonstration of a multi-terminal fiber optics data bus would represent the next logical step beyond the A-7 program in proving the feasibility of utilizing this new technology in military aircraft.

Since February 1973, NELC has participated in an Office of Naval Research sponsored program to develop a multi-terminal fiber optics data bus capable of handling the information flow requirements of a modern military aircraft. A five-terminal, unidirectional system has been demonstrated in the laboratory at a 5 Mb/s data rate, and work is underway to extend the number of terminals to eight and to provide for bidirectional operation. This paper describes the five-terminal bus, with emphasis on the optical and electro-optic components, and discusses possibilities for further component and system improvement. Additional information is contained in NELC Technical Report 1930, "Fiber Optics Data Bus System," August 1974.

Components for Five-Terminal System

A five-terminal data bus system using access ("T") couplers was demonstrated in May 1974. Principal considerations in the choice of components for this demonstration were simplicity and low cost. Commercial light-emitting diode (LED) sources, silicon PIN photodiode detectors, and multimode fiber optics bundles were used. Access couplers, connectors for the fiber optics bundles, and optical transmitters and receivers (incorporating the commercial sources and detectors) were designed and fabricated at NELC.

Fiber Optics Transmission Lines

Two basic types of glass fiber are available for optical communications applications (2). These fiber types are illustrated in Figure 1.

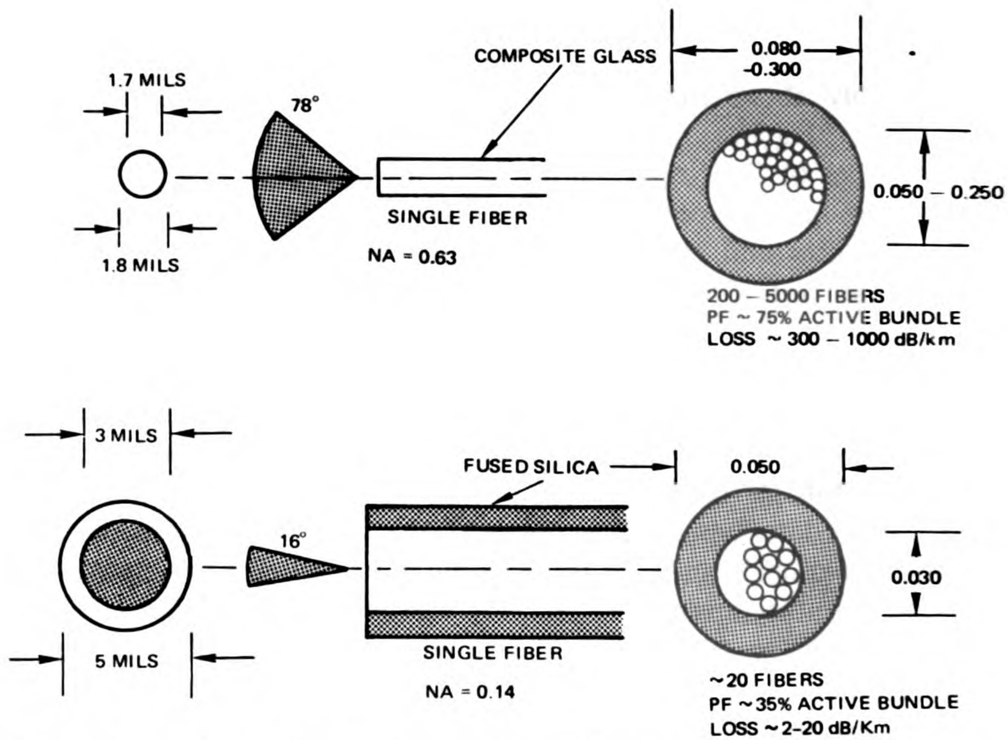

Figure 1 – Comparison of composite and fused silica fibers and bundles

The fused silica fibers are characterized by low optical attenuation, small acceptance angle, and low ratio of the area of the core to the total cross-sectional area of the fibers. The composite (silicate) glass fibers have moderate to high optical attenuation, large acceptance angle, and high ratio of the area of the core to the total area of the fiber. Fused silica fibers are presently much more expensive than the composite fibers.

The composite glass fiber was used in the avionics data bus demonstration described in this paper, because of its substantially lower cost and because the high numerical aperture and packing fraction lead to lower optical input and throughput losses at the fiber bundle-to-coupler interfaces.

A fiber bundle with a total fiber diameter of .125″ was procured from Galileo Electro-Optics for use as the data bus transmission line. The relatively large optical area was considered desirable to facilitate the coupling of light from the low-radiance commercial sources into the main bus. The loss of the bundle was measured to be 700 dB/km, using an LED source with maximum emission near 9000 Å. This attenuation factor would give an unacceptably high loss of 35 dB for a 50 meter bus. However, losses of 350 dB/km have reportedly been achieved recently on a production basis, and, if recent trends continue, losses in the neighborhood of 100 dB/km can be anticipated within the next one to two years. This would reduce the fiber length attenuation for a 50 meter bus to an acceptable value of 5 dB.

Metal end fittings for fiber optic bundles are usually circular in cross-section. The design of the access ("T") couplers, described in the next section, required the use of end fittings with a rectangular aperture. They were fabricated by milling a groove in a brass block, and silver soldering a flat brass plate over the groove to form a .190" X .065" slot into which the fibers could be inserted.

A smooth optical surface at the ends of the fibers is necessary to obtain low losses at the fiber bundle-to-coupler interfaces. To prepare the ends of the fibers, a portion of the PVC jacket near the ends of the bundle was stripped off and epoxy was applied to the exposed fibers. The ends of the fibers were inserted through the rectangular aperture in the end fitting, and the apoxy was allowed to harden. Excess fibers were then clipped off, and the fibers were ground and polished with successively finer grit. The final polish was done with a 2 micron grit on a cloth lap.

Access Couplers

The basic design for the access coupler used in the data bus demonstration is illustrated in Figure 2. The coupler consists of a glass block with an internal, fully reflecting mirror, mounted in a plastic holder. The mirror is oriented at an angle of 45° to the axis of the block, and extends only part of the way across. Some of the light entering the block from the main transmission line is reflected out the side, while the rest propagates through the block and into the next section of the fiber optics. Light injected into the block from the side is reflected by the internal mirror and also enters the next section of the line. This device therefore performs the functions of input, output, and throughput coupling of light signals in a fashion somewhat analogous to the electrical "T" coupler. A photograph of one of the couplers is given in Figure 3.

Previously reported data bus access couplers have used bifurcated fiber bundles in conjunction with glass mixing rods (3-5). Desirable features of the present design include simplicity, ease of manufacture, and mechanical ruggedness, as well as low optical loss. An additional advantage is the ease with which the design can be modified for use in color multiplexing systems, which will be discussed later.

The glass blocks used in the couplers manufactured to date were .190" X .065" X 2" in dimension, and the mirror extended 1/3 of the way across the total width of the block. The aperture dimensions

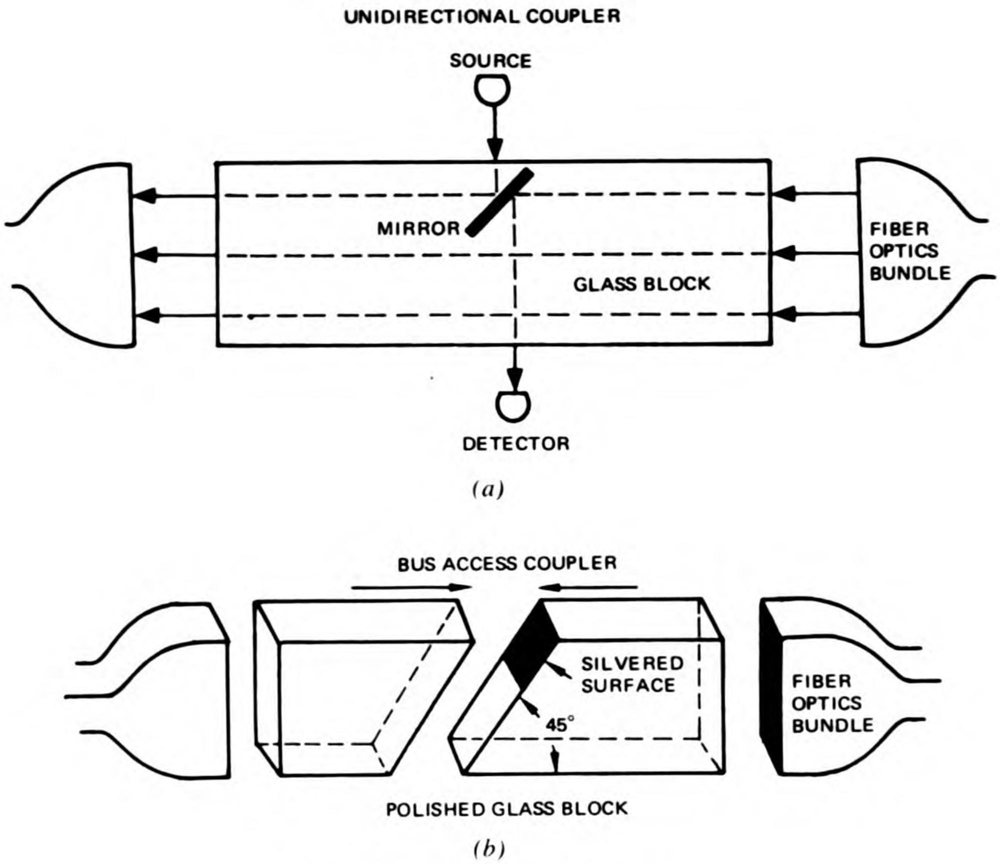

Figure 2 – Access Coupler design

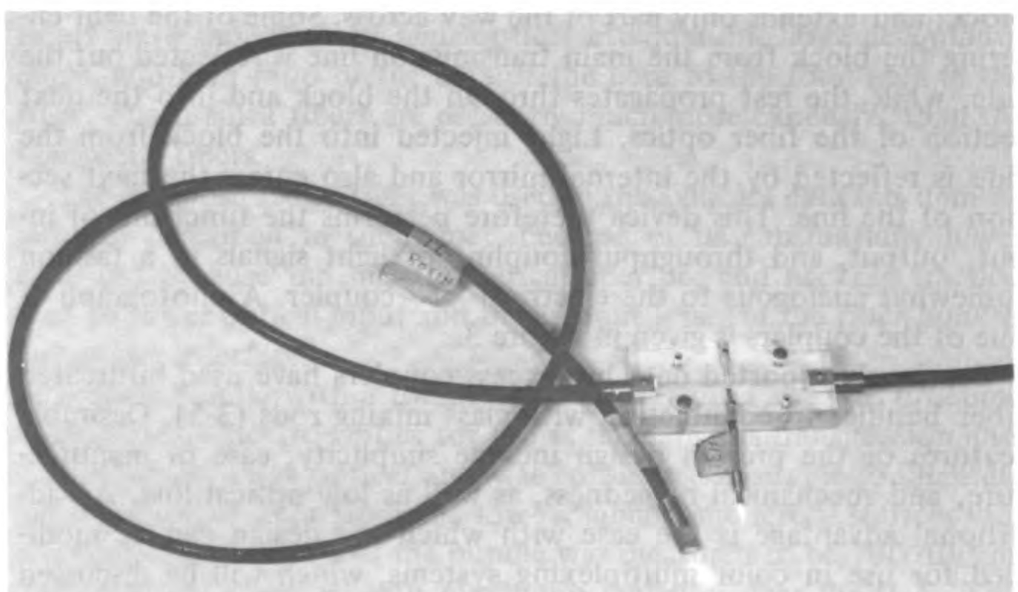

Figure 3 – Photograph of access coupler. Light is incident on the coupler from the right-hand fiber bundle. Part of the light is reflected out the side port, and part is transmitted into the next section of fiber bundle.

of .190″ X .065″ were chosen to match those of the end fitting for the bus transmission line. The acrylic plastic holder (refractive index = 1.48) in which the glass block was mounted was provided with four connector ports: two at the ends for the main bus transmission line, and two at the sides for smaller (.050″ optical diameter) fiber bundles which joined the coupler to the transmitter and receiver at that terminal. Standard, circular metal end fittings were used for those smaller bundles.

Considerable care was taken in polishing the glass blocks used in the couplers. Twelve blocks were cut to size from a single piece of glass stock, and they were taken as a group through successive polishing of all six surfaces. Each block was then cut at a 45° angle, and the angled surfaces were polished. The flatness achieved on those surfaces was approximately 1/10 of a fringe. Smoothness of all the surfaces was important to minimize optical scattering loss at surface reflections. Flatness of the angled surfaces was necessary to insure a low-loss optical joint when the blocks were cemented back together.

Following the polishing, a 200 Å thick aluminum coating extending 1/3 of the way across the angled surface was deposited on the glass blocks. Then, the blocks were cemented back together. The index of the glass had been measured on a refractometer to be 1.570, and that of the cement was 1.563. The closeness of these values insured that Fresnel losses at the cemented interface would be negligible.

Measured values for the optical loss were 4.3 dB for throughput, 5.8 Db for input, and 6.7 dB for output in the best coupler. The throughput loss for the glass blocks was only 3.0 dB before mounting them in the plastic holders, indicating that the mounting causes an increase in loss. This increase is probably due to scattering at the imperfect optical interface between the glass and plastic, and may be reduced or eliminated in future designs by coating the glass with a low refractive index buffer layer.

Transmitter

Signals were sent over the bus by a commercial LED driven with five parallel TTL logic gates. The logic gates used were TTL inverters with open collector circuits. The maximum output current for each logic gate equals 20 ma. Five gates only were required to drive the LED at its current maximum of 100 ma at a 50% duty cycle. The sixth *nor* gate was used as a buffer or isolator between the input and the five circuits driving the LED. The output transistor of each gate was driven into saturation and a series limiting resistor used to set the magnitude of the on current.

Since the series limiting resistor is much greater in magnitude than the series resistance of the light emitting diode, the diode is driven from essentially a current source. The transistion times for light turn on, turn off were measured for this configuration and found to be a 50 ns rise time and a 150 ns fall time. With such short fall times the intersymbol interference at a 5 Mb/s data rate resulting from the speed of the light emitting diode was slight.

The LED was partially coupled to the fiber by a pair of lenses. One lens serves to collimate the light exiting from the LED while the second lens focuses the collimated light upon the bundle of fibers.

Receivers

The receiver can conceptually be divided into three sequential functional units; the input stage, the amplification stages, and the decision circuits at the output. The input stage serves to sense the optical signal and amplify it to the extent that the signal to noise ratio is established. The amplifier chain that follows the input amplifies the signal to the level required by the decision circuits.

The input stage of the receiver must be designed for maximum signal to noise ratio. Two types of detector amplifier were designed and built. Both employed a PIN photodiode rather than an avalanche photodiode on the basis that the PIN photodiode requires simpler bias circuitry and is inherently an electrically more rugged unit.

The first detector amplifier design employed a bipolar transistor in the common emitter configuration. The photodiode load resistance was chosen such that the parallel combination of this resistance and the photodiode capacitance, the transistor input capacitance, and the stray input capacitance provided a 5 MHz upper cut-off frequency for the input circuit. The minimum detectable signal for this detector amplifier was measured to be 10^{-7} watts.

The second detector amplifier design employed a Field Effect transistor amplifier. This transistor and the photodiode were used in a charge integration mode. The photodiode load resistance in association with the diode, the stray, and the FET input capacitance determined an upper cut-off of frequency which is much less than 5 MHz. The input circuitry then essentially forms a lag network. Two stages of gain were employed to establish the signal to noise ratio before the lead network was inserted to compensate the input lag network. The sensitivity was 2×10^{-8} watts.

The amplification following the input stage was provided by a single integrated circuit. This stage has a maximum gain of 2000 and the output is designed to saturate at half a volt. The saturation feature eliminates the need for Automatic Gain Control. The decision circuit was a level detector, and its output is a logic gate.

Description of Five-Terminal System

A five-terminal system was assembled and tested at data rates to 5 Mb/s. A schematic diagram for the system is given in Figure 4. Signals transmitted from any of the four input ports could be received by any of the "downstream" output ports. Three of the terminals were provided with access couplers for both input and output capability; the other two terminals were located at the ends of the main transmission line. Figure 5 is a photograph of the system with two transmitters and two receivers connected to couplers.

The maximum attenuation from one terminal to another was 36 dB, measured with respect to an LED source uniformly illuminating a .050" circular aperture.

Criteria for Data Bus Design Improvement

The five-terminal system can be regarded as a step towards demonstrating the feasibility of fiber optics data bussing for avionics applications. However, this system falls short of meeting present aircraft requirements, not to mention anticipated future needs (6). To meet these requirements, bidirectional operation and more than five terminals will be needed. This section discusses various possible changes to improve the system, some of which are already being implemented.

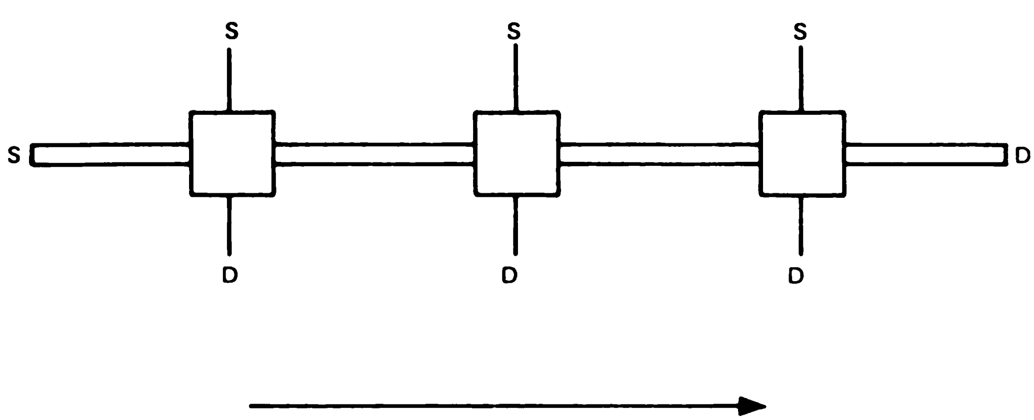

Figure 4 – Schematic of five-terminal system

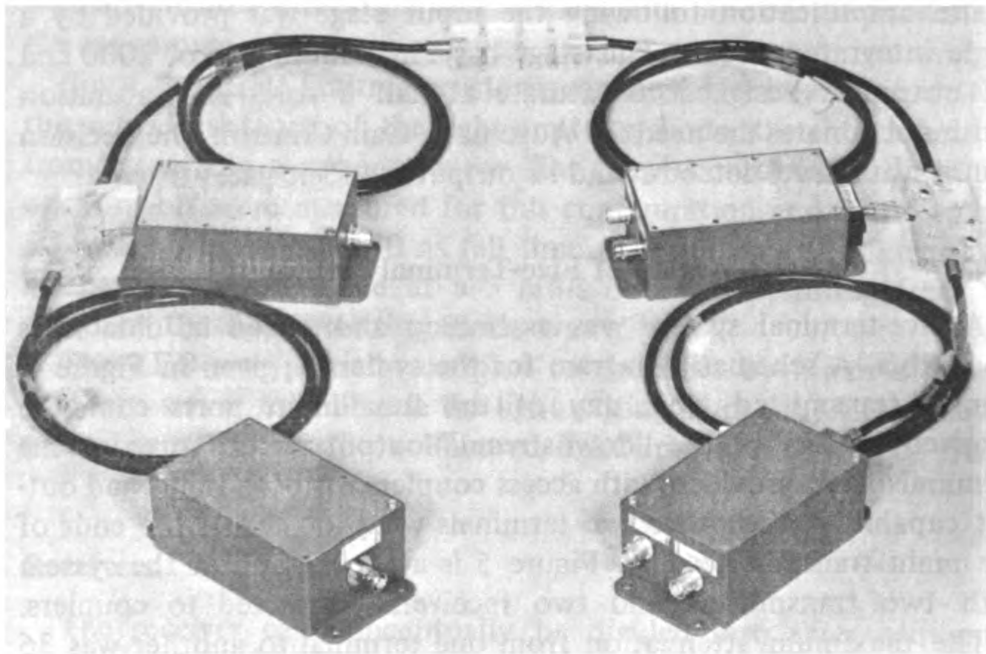

Figure 5 – Photograph of five-terminal system

Star vs. Access Coupler

An alternative to providing access couplers at each terminal in a bus system is to use a single optical mixer, known as a star coupler (7). Each terminal in a star bus system is linked to the coupler by two fiber optics lines, one for transmitting signals to the coupler and one for carrying signals back to the terminal. The coupler performs the function of spatially mixing the light transmitted from each terminal, so that the light carried by each return line is a mixture of the signals from every terminal. One design for a star coupler is illustrated in Figure 6.

The star coupler makes it possible to implement a data bus with a large number of terminals without a repeater. This is true because the terminal-to-terminal loss (in dB) for the star coupler system depends logarithimically on the number of terminals. By contrast, the worst case loss (in dB) for the access coupler system depends linearly on the number of terminals. It turns out that the number of terminals which can be implemented with a star system is therefore a hundred or more, while a repeater must be used for more than about ten terminals in an access coupler system.

Star and access couplers can also be compared with respect to the total length of cable required to connect N terminals together via a data bus. It is desirable to minimize cable length to save weight and space in an aircraft and to lower installation cost, which is

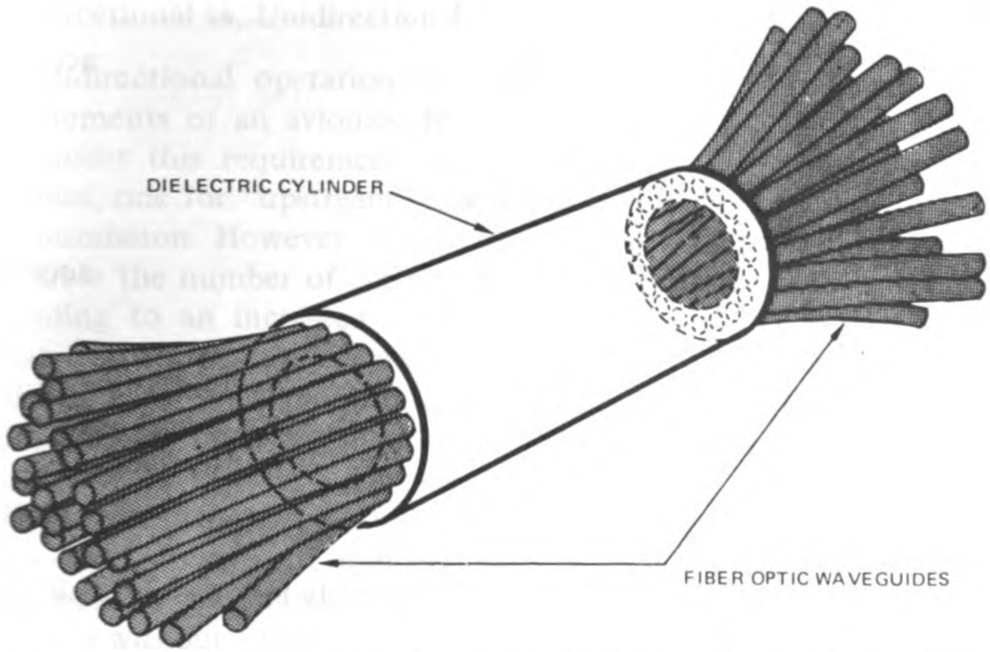

Figure 6 – Star coupler. Signals incident on the coupler in a fiber bundle are shared among all the "output" bundles as a result of spatial mixing in the cylinder

roughly proportional to cable length. The spatial distribution of terminals determines which type of coupler allows a shorter length of cable to be deployed. This is best illustrated by example. First, we assume that the terminals are located at the corners of a hypothetical cube of side a. In this case, if we use a star coupler located at the center of the cube, the total cable length L is

$$L = 4\sqrt{3a} = 6.9a. \qquad \text{(star)}$$

The length for the access type bus which joins all the corners of the cube in sequential fashion is

$$L = 7a \qquad \text{(access)}$$

The lengths are almost the same for this configuration. On the other hand, if the terminals are located on a straight line, a distance apart, the total lengths are

$$L = \frac{N^2 a}{4}, N \text{ even}$$

$$= \frac{(N^2\text{-}1)}{4}, N \text{ odd} \qquad \text{star}$$

and

$$L = (N\text{-}1)a \qquad \text{access}$$

For eight terminals, we have

$$L = 16a \qquad \text{star}$$

$$L = 7a \qquad \text{access}$$

For sixteen terminals

$$L = 64a \qquad \text{star}$$

$$L = 15a \qquad \text{access}$$

The access coupler would therefore considerably reduce the required cable length for a many-terminal system.

The cable length problem could be alleviated in a star system by incorporating the $2N$ access cables servicing the N individual terminals into a single large cable, which would then be deployed serially to each terminal like an access bus cable. However, this would result in a more complex cable with new installation and maintenance problems. Each of the small cables would have to be coded, and installation of a terminal would require that the outer jacket of the large cable be opened. If the large cable were damaged or broken, each of the $2N$ small cables would have to be spliced on an individual basis. The repair of an access coupler bus cable would require only one cable splice, or the replacement of the relatively short length of cable between two terminals with a factory-terminated section.

Similarly, the expansion of a system by adding more terminals would seem to be easier with an access-coupler system. The main bus line could simply be cut and optically terminated at the desired location, and a new access coupler installed. With a star system, a new cable would have to be installed from the coupler to the terminal location. A better arrangement for a star system might be to provide spare cables in a large cable, but adding the new terminal would again require breaking into the large cable. If the location of the new terminal required rerouting of the main bus cable, this would also be more difficult with the star approach.

We conclude with the observation that the information flow requirements of a modern military aircraft can be met using either access couplers or star couplers. If the number of terminals is large, a repeater would be required in an access-coupler system.

Bidirectional vs. Unidirectional

Bidirectional operation is needed to meet the data transfer requirements of an avionics fiber optics data bus (6). A simple way to meet this requirement would be to provide two unidirectional cables, one for "upstream" transmission, and one for "downstream" transmission. However, this would increase the total cable size, and double the number of couplers and optical interfaces in the system, leading to an increased installation and maintenance cost. Fortunately, the coupler design illustrated in Figure 2 can be modified by the addition of a second internal mirror, oriented at right angles to the original one, to provide bidirectional transmission. Bidirectional couplers of this type are now being fabricated for use in a second generation data bus. By reducing optical losses and taking advantage of other component improvements, it is estimated that it should be possible to achieve bidirectional operation with up to eight terminals without a repeater.

Sources and Detectors

It has been mentioned that input coupling for the five-terminal system is radiance-limited, meaning that the input power is proportional to the fraction of the coupler area subtended by the mirror. High-radiance sources would make it possible to couple more power into a fiber optics data bus or to use a smaller fiber bundle for the transmission line. Light from high-radiance LED's which emit through the surface of a well etched into the surface of a double-heterostructure (Ga,A1)As chip has been coupled effectively into very small (60 μm) fiber cores (8). The light from a number of those LED's could be combined at a data bus terminal using a single fiber for each LED. This could improve input coupling for the bus by 10 dB.or more. The injection laser can give even greater improvement in radiance, and the relatively narrow spectral width of the emission would allow for a large number of channels for colo. multiplexing. Operating life for the cw injection laser at room temperature has improved steadily over the past few years to the present record in excess of 10,000 hours. Unfortunately, neither the high-radiance LED nor the cw, room temperature injection laser is commercially available at the present time.

The silicon PIN photodiodes used in the receivers have a quantum efficiency of about 50%. Commercial devices with a higher quantum efficiency (near 90%) are available, which would improve receiver sensitivity by about 2 dB. An additional 10 dB improvement might be realized by using an avalanche photodiode. However, the avalanche detector requires high voltage (100-1000 V), is expensive, and may not be as reliable as the PIN device. For these reasons, it does not appear desirable to use the avalanche photodiode in this application.

Color Multiplexing

Carrier-frequency multiplexing has been used for many decades to increase the information capacity of electrical wire-pair and coaxial transmission lines. This technique can also be considered for use with fiber optics (9). Since the "color" of light is determined by its frequency, we can use the term "color multiplexing" to denote carrier-frequency multiplexing in the optical region of the spectrum. Light sources which emit in different spectral ranges and couplers for combining and separating the different colors will be needed. The number of channels is limited by the spectral width of the light sources and by the color selectivity of the couplers. For light-emitting diodes, 90% of the emitted power is typically contained within a 500 Å wavelength range. The Ga(As,P) and Ga(Al,As) systems can provide emission between 6500 Å and 9500 Å, for a maximum of six channels for color multiplexing.

The access couplers described previously can be modified for color multiplexing by replacing the internal, fully reflecting mirror with a multilayer interference coating. The coating would be designed to reflect light of one color and transmit other colors, making it possible to combine and separate different colors in a single transmission line. Two colors could be used to provide bidirectional transmission, one color for each direction. Alternatively, several different colors could be used for transmission in each direction.

Conclusions

The use of access couplers in a fiber optic data bus for military aircraft is feasible. A five-terminal, unidirectional, 5 Mb/s system has been demonstrated. By lowering the losses in optical couplers and fiber optic cables, and optimizing the transmitters, receivers, and coupler design, it is projected that bidirectional operation can be achieved in an eight terminal system.

If a larger number of terminals is needed, data transmission requirements can be met using access couplers with repeaters, or using star couplers. Color multiplexing offers the possibility of increasing the bandwidth and number of multiplexed channels in a fiber optics data bus.

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Novel Voice Digitizers

The Naval Research Laboratory (NRL) has developed two linear predictive narrowband voice digitizer units which can be used for high frequency communications.

Numerous computer simulation tests, based on various speakers and different input speech conditions, indicate that these units will be superior to the channel vocoder presently in use in voice quality and intelligibility.

Recent intelligibility tests of the new digitizer units scored 93 percent, whereas the channel vocoders tested averaged around 85 percent.

G.S. Kang, principal investigator for NRL in the new development, said that, until now, the channel vocoder has been the most popular narrowband voice digitizer used by the Navy in converting a speech signal into a binary form for secure transmission over high frequency or wire links.

Although the channel vocoder is intelligible, it produces poor speech quality, an unnatural sound that makes speaker recognition difficult.

Research Notes

Protecting the Marine Environment

-- Increased awareness of the importance of the marine environment and the necessity for preserving it has led to a joint research program between the Hawaii Laboratory of the Naval Undersea Center (NUC) and the Hawaii Institute of Marine Biology (HIMB).

NUC with support from the Naval Facilities Engineering Command and the Office of Naval Research and HIMB with funds from the Environmental Protection Agency have initiated a program to determine the environmental effects of siltation, dredging, sewage disposal and ship movements on communities of marine organisms characteristic of Hawaii's harbors and reefs. The results of this research will be further tested on a series of four "environmental ranges" which are being established in Pearl Harbor and Kaneohe Bay, Hawaii; in San Diego Bay, California; and Apra Harbor, Guam.

These tests will be utilized to develop guidelines and techniques for quantifying the marine environmental status of a given water body through the use of "bio-indicator systems", selected marine organisms whose response to various environmental conditions can be "read" by trained personnel. The ultimate product will be a rapid and reliable survey procedure for assessing and subsequently protecting the marine environment of harbors used by the Navy.

Dr. Evan C. Evans, III, who has been directing this research, said that there are a multitude of potential bio-indicator organisms awaiting evaluation and "calibration." One of the objectives of the research at Ulupau will be the selection and lab-testing of the best organisms for general survey purposes.

Under controlled conditions, various natural marine communities will be subjected to known environmental stresses in the Ulupau holding facility. Their responses as a function of intensity of stress will be investigated and component organisms showing the best potential as bio-indicators in the field will be selected.

Over the past four years, HIMB has pioneered in the development of these continuous-flow holding systems at their laboratory on Coconut Island in Kaneohe Bay. Among other things, they have used these systems to test the effects of thermal stress on coral reef communities.

However, the usually high and variable nutrient status of Kaneohe Bay waters have caused increasing deviations from the clean-water conditions required for many of these controlled experiments. Therefore NUC is setting up a second holding tank facility patterned after that at HIMB but drawing low-nutrient, oceanic waters from a surge channel off Mokapu Peninsula. The facility is well under construction at the foot of the extinct Ulupau Volcano on the ocean side of Mokapu Peninsula which is located on the Kaneohe Marine Corps Air Station. Design and construction of this facility has been under the direction of NUC's Scott Henderson, who has been assisted by a number of scientists from HIMB.

Silicon, nitrogen, phosphorous and other elements and vitamins are essential for the normal growth and reproduction of marine organisms. These are present in low amounts in mid-Pacific oceanic sea water. Sea water altered by man-introduced additions exhibits complex and little understood changes in the relationship between its chemical constituents and living marine organisms. The addition of silt can further complicate the situation in many ways.

The combination of the two facilities, one operating on high-nutrient and the other on low-nutrient waters, is expected to be a powerful experimental tool for the better understanding of these complex processes. Testing on the environmental ranges will further enhance the power of this experimental approach.

The NUC holding tank facility at Ulupau is scheduled to become operational in October 1974. Both the Ulupau facility and that at HIMB will be used in concert by scientists from the two institutions.

In addition to the determination of appropriate bio-indicator organisms, one of NUC's goals is to obtain basic information on the efficiency of silts and ship-stirred bottom sediments as a mechanism for removing heavy metals from the water column in shallow harbors. Past survey results from Pearl and Apra Harbors have suggested that the process may result in the reduction of heavy-metal body burdens in certain marine organisms.

Dr. Evan's research team has already shown that ship movements are an important factor in vertical mixing in Pearl Harbor, thus ships may be said to have environmentally beneficial as well as detrimental effects in that harbor. Further research at Ulupau is expected to determine the full extent of these effects for possible utilization in improved harbor management.

For the next ten months, work at Ulupau will center on calibrating the facility with respect to the Coconut Island system, beginning research on the effects of heavy metals and suspended sediments, and providing laboratory support for test and evaluation of specific bio-indicator systems.

NRL Chemical Process Promises Conversion of Sunlight to Electricity

– A solar physicist at the Naval Research Laboratory (NRL) says he has devised a system to harness sunlight chemically and convert it into electricity on a large scale. This design is a spinoff of solar research conducted at the Laboratory over the past 25 years.

Dr. Talbot A. Chubb is the inventor of the proposed system which he calls Project SOLCHEM. The system is designed to convert solar energy (light) into chemical energy through use of high temperature endothermic (heat-absorbing) gas phase reactions in an energy transfer fluid. This gas, for example, sulfur trioxide (SO_3), is passed through a reaction chamber in a solar furnace, where the energy is collected. At a central generating station, the collected energy is used to produce electricity. And, reports Dr. Chubb, the system is closed and would not cause any type of air pollution or side effects which may endanger man or the ecology.

The NRL "sun farm" would provide a continuous 24-hour, 100-megawatt electrical output, and is concerned primarily with harvesting solar energy in favorable clear sky areas of the West and South, where substantial areas of sunny land could be effectively devoted to energy collection.

SOLCHEM also would provide massive quantities of heat energy at temperatures in the range of 450 to 600 degrees centigrade (C). This energy is usable chemical processing; in particular, the heat energy is available at a high enough temperature for the processing of oil shale, and could save the burning of substantial quantities of product fuel to provide the processing heat.

Specifically, SOLCHEM is a gas dissociation high temperature solar thermal power system consisting of a set of solar furnaces dispersed over three square miles of land. Each of the furnaces consists of a reaction chamber mounted at the focus of a scoop (paraboloidal) light collector, at which point concentrated sunlight is capable of heating the reaction chamber to a very high temperature. These chambers, however, are temperature limited by gas flow during the gas dissociation (molecular separation) reaction, thus keeping the reaction chambers at a temperature below about 900 degrees C. Radiative and convective heat losses are relatively small because of the small sized reaction chambers. (Figures 1 and 2).

The dissociated gas mix is then delivered to the central facility by a network of near-ambient temperature low pressure pipes. At the central facility, the collected gas is passed into a central gas recombination reactor where the gas is recombined, giving up the heat absorbed in the solar furnace.

The heat is delivered to the bottom of a molten-frozen salt reservoir resulting in melting of the salt solids at the bottom of the reservoir. The top of the reservoir is maintained in contact with water-boiler tubes, where superheated steam is produced for the production of electricity in a conventional high pressure steam power plant.

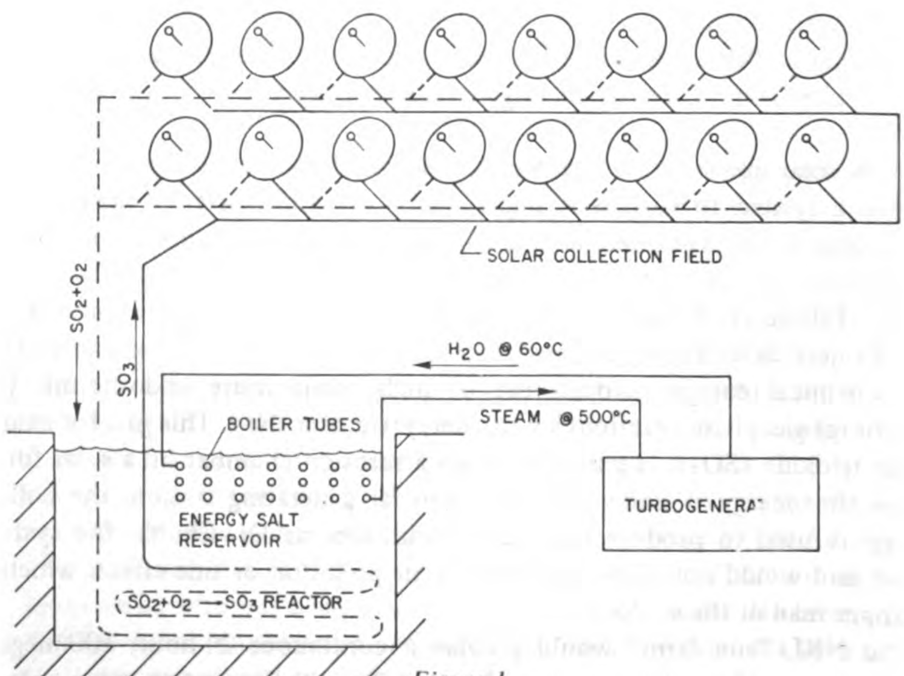


Figure 1

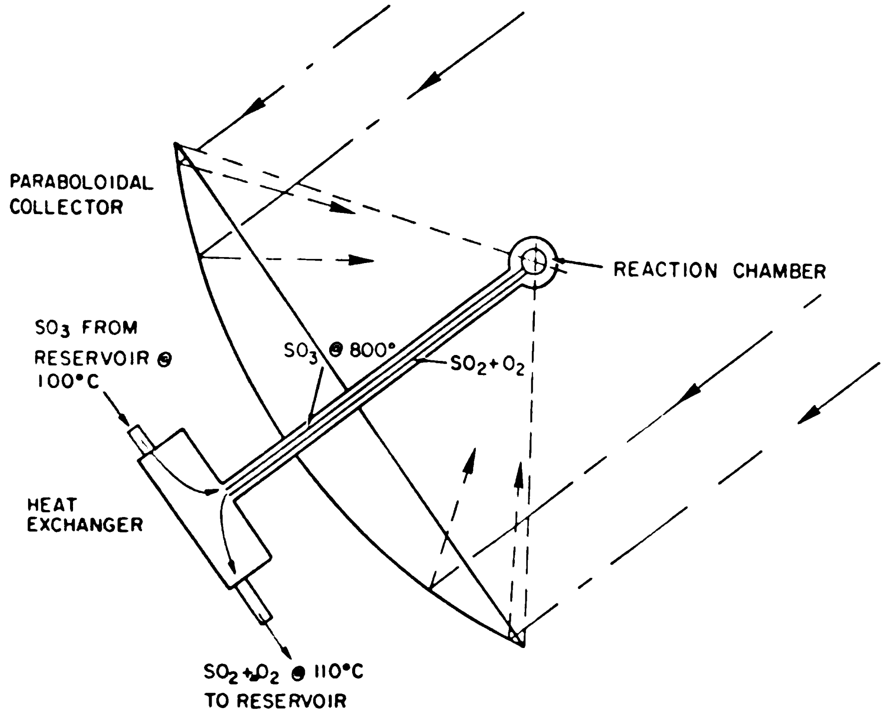


Figure 2

New Method for Surveying the Ocean Floor

The Navy's Civil Engineering Laboratory (CEL), Port Hueneme, California has deveolped a more reliable method of mapping the seafloor and underlying bedrock in a difficult environment.

This improved system of surveying the ocean floor and the subbottom topography reduces the uncertainty in determining underwater cable routes. CEL engineers, adapting a subbottom profiling system for use in shallow water, utilized two transducers instead of the conventional single transceiver used in deep water surveying operations.

During two weeks of testing equipment and evaluating procedures off Santa Barbara County, Laboratory personnel were assisted by the Navy's Underwater Construction Team 2 (UCT2) attached to the Seabee Center, Port Hueneme. The team handled diving assignments and boat operations and used its 35-foot amphibious craft LARC to conduct the surveys.

Since the first submarine telegraph cable was laid in 1851, the constant turbulence of the sea in the shallow waters of the surf zone has endangered cable installations. Bottom-laid cables are shifted against rocks lying on the ocean bottom, or the seafloor sediment that buffers the cable from buried bedrock (perhaps only a few feet below the ocean bottom) is washed away. Exposure to subsequent abrasion often results in cable failure and disruption of service; costly repair and maintenance are common.

In the new survey method two transducers are lowered into the ocean about two feet below the water line. One emits an acoustical signal of low frequency

(3.5 KHz) and the other transducer receives the return signal. It and other electrical data are entered into a recorder.

To record the surface of the seafloor the Laboratory found that a 200 KHz fathometer proved acceptable. The single transducer fathometer and the lower frequency subbottom profiler provided sonic profiles of both the ocean's bottom and subbottom.

CEL evaluated the utility and accuracy of the sonic methods in the ocean off Carpinteria, California because it is the nearest coastal area to the Laboratory with a surf zone dominated by shallow bedrock capable of abrading bottom-laid cables.

To assure precise positioning over a given route, the engineers relied upon range markers and an offset transit on the beach. As the LARC steered a course guided by markers, the transit read bearings relative to points marked on recorders aboard the ship.

Space X-Ray Detector For Apollo-Soyuz Mission

A team of Naval Research Laboratory (NRL) scientists is preparing equipment for X-ray observations experiments on board the Apollo-Soyuz spacecraft.

After the history-making linkup, set for early next year, Russian and American spacemen aboard the satellite-laboratory will conduct a series of cooperative experiments and observations. Among the many scheduled tests is the NRL experiment, which has two major objectives.

The first is to produce a detailed map of celestial X-ray emissions, particularly in the region of the spectrum 0.1 - 2.0 kiloelectron Volts (keV), where no satellite observations have yet been made.

Scientists for the X-ray mapping experiment are Dr. Seth Shulman and Mr. Gilbert Fritz of NRL's Space Science Division. They say the resultant map will make it possible for scientists to pinpoint and examine new X-ray sources and compare them with known sources, such as radio loops and supernova remnants. Further studies may reveal the origin of the emission to be either within or outside of the Milky Way galaxy, of which our solar system is a part.

During the second phase of the mission, the astronauts will point the detector toward predetermined X-ray sources. The objective is to obtain data in the 0.1 to 10.0 keV range for further spectral analysis.

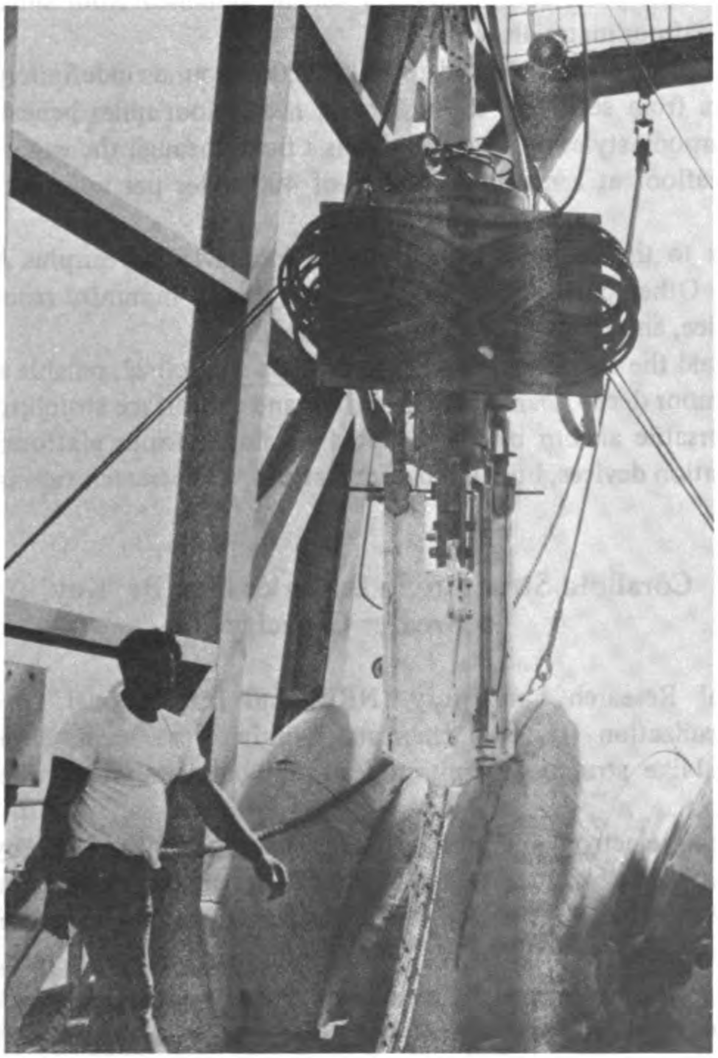
The X-ray detector will also be used to observe the earth, in addition to scanning the sky. These terrestrial observations should enable the astronauts to detect atmospheric X-ray emissions connected with the earth's auroral activity (Northern lights) and particle precipitation, during times when the earth's magnetic field is disturbed by particles ejected from the sun toward the earth.

These studies may provide a wealth of new information on the emission mechanisms which produce some of the most exciting phenomena in high energy astrophysics. Previously, these X-ray studies have been flown only briefly on small sounding rockets.

Deep Water Anchor

In the latest of a continuous series of deep ocean tests, the Deep Water Anchor, developed by the Civil Engineering Laboratory (CEL), Naval Construction Battalion Center, Port Hueneme, Calif., has been successfully tested three times at depths between 8,000 feet and 12,200 feet.

At the maximum depth, the propellant-actuated anchor held 48,000 pounds, more than twice its design capacity.



THE DEEP WATER ANCHOR, developed by the Navy's Civil Engineering Laboratory, is guided over bow shives as it is placed into the ocean during recent deep sea trials. The 1,800-pound propellant-actuated anchor consists of a sediment fluke (plate-like projectile) and an upper launch vehicle which includes a gun barrel, reaction vessel, and 100 feet of down-hand cable placed on the board. The anchor held 48,000 pounds at 12,200 feet, more than twice its design capacity. Additional deep water tests are planned.

Several operational advantages over conventional anchors were obvious during recent tests off the coast of Norfolk. The Deep Water Anchor outperformed a conventional anchor which weighed four times as much and needed several thousand pounds of chain and line. The CEL anchor does not require connective gear or long lengths of mooring lines. Its operation greatly simplified anchor installation which leads to substantial savings.

Although the anchor is functional, additional reliability data are required. The anchor has undergone only 20 deep sea trials but another series is scheduled early this fall at water depths between 18,000 and 20,000 feet off Hawaii. During the next year, additional data will be obtained from similar tests in a variety of seafloor materials.

The CEL device was designed to hold 20,000 pounds indefinitely in all types of seafloors from soft clay to hard rock, nearly four miles beneath the ocean surface. Harpoon style, the system propels a fluke through the water column and into the seafloor at a maximum speed of 400 miles per hour or 590 feet per second.

The key to the anchor's launch system is a sawed-off surplus Army 90mm gun barrel. Other components include steel pipe to minimize recoil action, an arming device, and electronics to fire the propellant.

Taylor said the overall objective is to develop a practical, reliable and efficient anchor to moor deep ocean systems, surface and subsurface structures. He added that the versatile anchor can be adapted to moor various platforms, including instrumentation devices, buoys, weather stations, and research vessels.

Coralloid Structure in Batteries May Be 'Key' to Greater Capacity

--- Naval Research Laboratory (NRL) and International Lead Zinc Research Organization (ILZRO) chemists, working as a team, have discovered that a coral-like structure forms in lead-acid batteries which directly affects their strength.

A scanning electron microscope (SEM) investigation at NRL by the scientists has revealed an unusual coral-like structure in the charged positive, lead dioxide (PbO_2) electrode of lead-acid batteries, which they have termed a coralloid. The scientists report that it's this structure that accounts for the strength, high porosity and stable capacity in the lead-acid batteries.

The research is important to the Navy, where batteries are widely used in propulsion and other ship systems, in emergency power sources, and in remote weather buoys and stations.

Now that they are aware of the coralloid phenomenon, scientists believe that further research should lead to a greater battery capacity, longer life and possibly a lower cost for lead-acid batteries, as well as other battery systems using porous electrodes.

In present batteries, the full benefit of the coralloid structure is not obtained, because of a partial passivation which is brought about by the close packed

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deposition of lead sulfate ($PbSO_4$) crystals on the surface of the coralloid structure during discharge.

Investigations of the lead sulfate crystal growth in the negative electrode have revealed how, in that electrode, the crystal growth may be modified by organic additives, so that passivation is prevented. It is expected that the partial passivation of the coralloid structure in the positive electrode can also be overcome by the further use of organic additives, thus enhancing the use of such batteries.

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Cover Caption

Demonstration of a laser beam going through a fiber bundle. See page 12.

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