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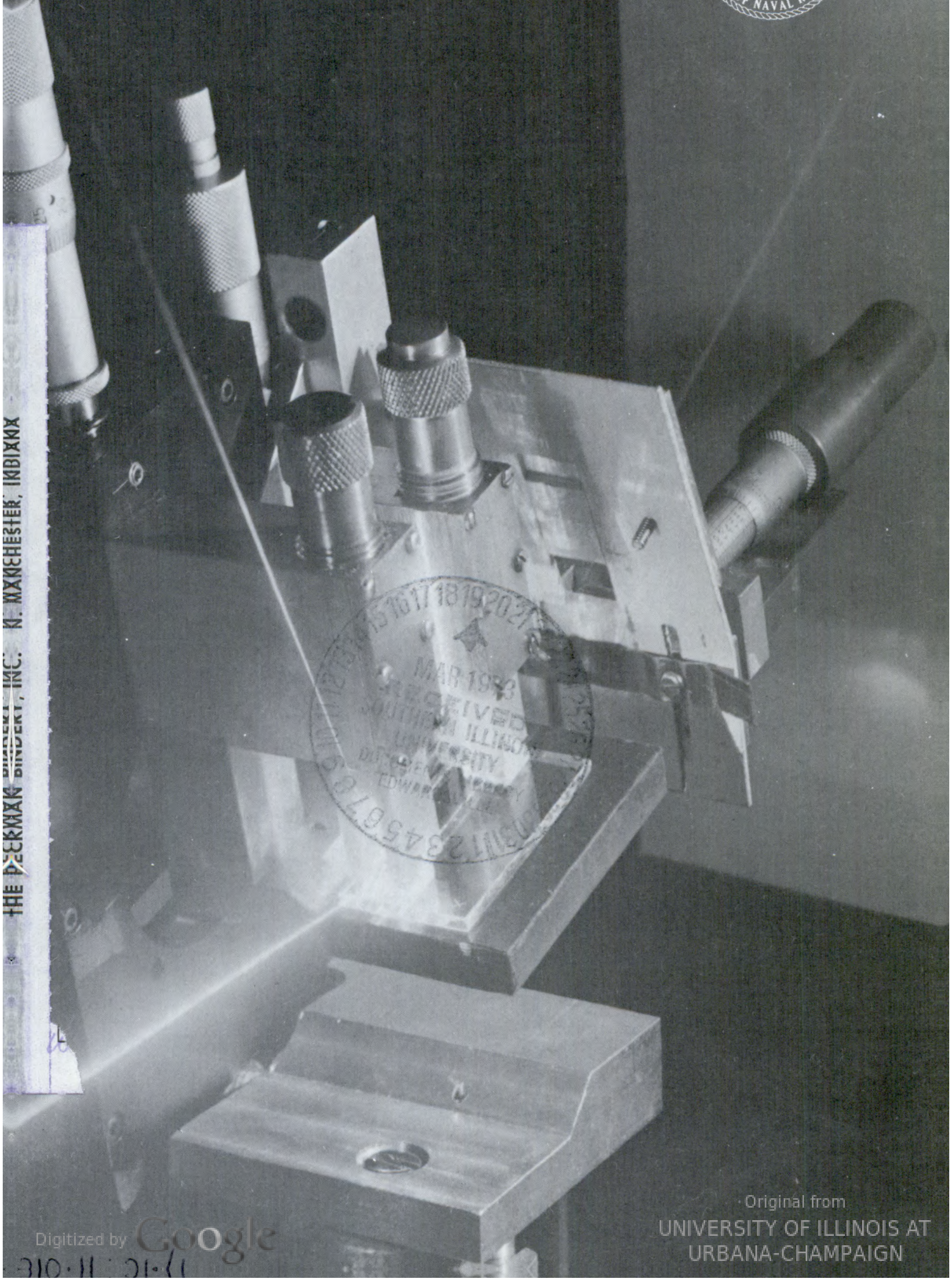
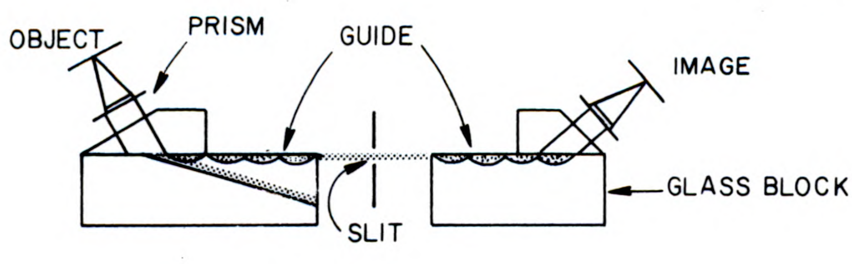


PROFILES IN SCIENCE

Dr. Osterberg



Dr. Harold Osterberg is the 'Father of Integrated Optics.' In experiments carried out together with L. W. Smith in 1964 Osterberg used incoherent light to transmit a visible image along the surface of a sheet of glass, through a gap and into another sheet, prism and focusing apparatus. The surface effect was detectable in most glasses, but was enhanced in Pilkington float glass, which had a graded increase in the index of refraction near the surface and thus served as an excellent optical waveguide. Dr. Osterberg was Research Physicist and Head of Physical Optics from 1937-1972 at the American Optical Co., Southbridge, Massachusetts. He is renown for his work in the fields of Elasticity, Piezoelectricity, Diffraction, Interface, and Microscopy.

Organization of the Electrooptics Project at the Office of Naval Research

Robert G. Morris*
Office of Naval Research

A committee for discussing projects in electrooptics† which cut across disciplinary lines at the Office of Naval Research was set up informally in the spring of 1972 mainly due to the efforts of CDR H. B. Lyon, Jr., then a scientific officer in the Aeronautics Program. Several programs at ONR had been supporting work in electrooptics, but interest in the field was intensified by a special meeting of the Optical Society of America on Integrated Optical Circuits in February and by a Defense Department meeting on Fiber Optics Communications held at the Naval Electronics Laboratory Center at San Diego in March. (An integrated optical circuit is analogous to a microwave circuit but is much smaller in size; in it light serves as the signal carrier. Optical fibers serve as transmission lines for such carriers).

The Committee was called the Electrooptics Coordinating Committee (EOCC) and after a few irregular sessions began meeting monthly in July. The idea from the first was to make interested parties at ONR aware of work related to their own supported projects in electrooptics and to discuss both applications of importance to the Navy and the research necessary for the development of components and systems for such applications. The group had a strong commitment to research, but research with a special significance and importance.

It was agreed that initial emphasis would be on integrated optical circuits, which seem to offer such great advantages for military communications, control and information systems in terms of reduced size and weight, increased bandwidth and rejection of electromagnetic interference.

The Committee seeks ways to take timely advantage of these circuits and to show the Navy where they may be used effectively. The special nature of the Committee and its charter seemed to be dictated by the rapid development of the field and the long lead time between Naval design and fleet use.

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* Dr. Morris is Project Officer of Solid State Physics in the General Physics Program, Office of Naval Research and Acting Director of Electronics Section.

† Electrooptics is defined as the study of systems or components which process radiant energy combined with those which process electrical energy.

In September the Committee petitioned the Chief of Naval Research to give it formal status as a project management body with its own budget. Its membership included representatives from the physics, electronics, mathematics, metallurgy and aeronautics programs at ONR as well as from the Naval Research Laboratory and the Naval Electronics Laboratory Center.

Under the new formal arrangement the Committee will make recommendations on funding specific proposals, identify problem research areas, define application possibilities, and guide research from the basic to the applied area.

The group will continue to serve as the clearinghouse and data exchange for electrooptics research in the Navy, and welcomes to its meetings all Navy research managers who have something to give or to gain.

In order to make its activities better known to the Naval and research communities, the Committee suggested a special issue of Naval Research Reviews. We here express our gratitude to the editors for their assent and encouragement.

Navy Researchers Team With University Scientists to Test Neutron Radiation for Cancer Treatment

The Naval Research Laboratory (NRL) has joined forces with a group of university scientists in a new program for the treatment of cancer with fast neutron beams generated by the NRL cyclotron.

Sponsored by the National Cancer Institute (NCI), the program marks the first significant involvement of a Navy facility in a major cancer research effort, and represents another DOD example of technology transfer to the civilian community.

The NRL research group headed by Dr. R. O. Bondelid, will be collaborating with a panel of therapeutic radiologists and radiobiologists from the middle Atlantic states, headed by Dr. Charles C. Rogers, Associate Professor of Radiology at the Virginia Commonwealth University's Medical College of Virginia. This team of scientists believes that neutron therapy research may lead to significant improvement in the treatment of localized malignancies.

For some time a similar neutron therapy program has been progressing at the Medical Research Council cyclotron at the Hammersmith Hospital in London. There have been exchanges of staff and information between that unit and members of the present team.

(Continued on Page 20)

Integrated Optics Technology*

R. A. Andrews†
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Background

In recent years, optics has come to play an ever-increasing role in military and industrial systems due to the availability of high-brightness coherent laser sources. Such items as radar, range finders, and target designators are but a few of the optical systems that are commonplace today. The number of applications continues to grow at an ever-increasing rate.

In the past few years an optical waveguide and integrated optics technology has begun to emerge. Optical waveguides are analogous to microwave waveguides, but operate at shorter wavelengths. In the optical region, electromagnetic radiation can be confined to waveguides of dimensions on the order of 0.1 to 10.0μ. These waveguides can be bent to guide the light and they can be made into passive and active optical devices. Such elements as lenses, prisms, reflectors, gratings, filters, lasers, amplifiers, modulators, deflectors, frequency mixers, and detectors can be fabricated with and around these optical waveguides. This type of capability offers a tremendous potential for optical systems and devices. Several optical elements can be combined to form an integrated microoptical circuit. The advantages and potentials are analogous to the integrated electronics technology. By employing integrated optics a savings of size and weight by a factor of 10^4 can be achieved. Once the technology is developed, the cost would become a small fraction of the bulk devices. A small rigid microoptical circuit is free of alignment problems and environmental effects. In many cases integrated optical devices can be more efficient than the comparable bulk device. This is especially true in the case of modulators.

The development of this technology has begun to accelerate. Many principles, devices, and techniques have successfully been demonstrated. The areas which need more effort are becoming well defined, along with the important problems. The future of the optical waveguide and integrated optics technology appears to be promising and rapidly expanding.

The optical waveguide can be thought of as a slab of dielectric which confines light by multiple total internal reflections. This is illustrated in Figure 1. The plane wave front is totally reflected alternately between

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*Condensed from NRL Report 7291, "Optical Waveguides and Integrated Optics Technology," R. A. Andrews (Aug. 1971).

†Dr. Andrews is the Branch Head of Interaction Physics at the Naval Research Laboratory. His field of interest is non linear and intergrated optics.

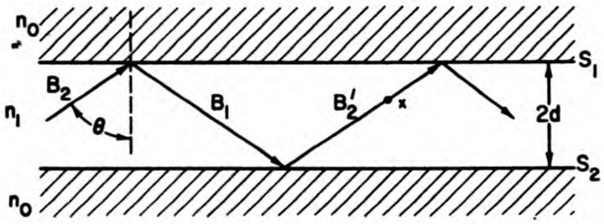


Figure 1 — Optical waveguiding formed by a high-index dielectric layer between two lower index cladding layers. The waveguide boundaries are S_1 and S_2 and the refractive indices are n_1 and n_0, with $n_1 > n_0$. A possible light path is indicated by the rays B_2, B_1, and B_2, all of which are incident at the same angle θ (total internal reflection) with the boundaries.

the interfaces S_1 and S_2. The only requirement for this to happen is that the index of refraction n_1 of the guiding dielectric be greater than the index n_0 of the surrounding media, and the angle of incidence θ be greater than the critical angle. For a given waveguide thickness $2d$ and indices n_1 and n_0 light will propagate with an angle of incident θ only if, after two successive reflections, the wavefront is again in phase with the original wavefront. If this were not the case, then down the waveguide, after many reflections, wavefronts with a range of phases between 0 and 2π would add to zero amplitude, or equivalently the wave would not propagate. This requirement implies that at an arbitrary point x the phase of one wavefront obtained from another by two successive reflections must equal the phase of the second wavefront at x, or differ by a multiple of 2π. This requirement permits propagation for only discrete values of θ. Each value of θ is associated with a mode of propagation and each mode has a characteristic velocity of propagation. As θ increases, the velocity of propagation to the right also increases. One can associate a different effective index of refraction, which is a function of d, n_1, and n_0, for each waveguide mode.

A detailed analysis of light propagation in a waveguide can be made using Maxwell's equation. There have been several analyses of this type published in the literature on optical waveguides (1-9). The most important results of such an analysis are that (a) light of wavelength λ can be confined to a dielectric slab of thickness $\sim\lambda$ if the slab has a higher index of refraction than the cladding material on either side of it, (b) in general, several modes of propagation exist which have different phase velocities, (c) the propagation factors for the different modes are function of the material indices and the waveguide dimensions, (d) a field exists in the cladding dielectric called the evanescent wave which propagates in the waveguide direction with the same velocity as the field in the waveguide, and (e) the magnitude of the evanescent wave and the depth of penetration depend on the indices and the waveguide dimensions. These rather unique characteristics can be employed to make optical waveguides and optical devices employing waveguides. These topics are discussed in the following section.

Fundamental Optical Waveguide Devices

Optical Waveguides

The principal requirement for an optical waveguide is a thin slab of dielectric clad with another dielectric (or dielectrics) of a lower index of refraction. There is considerable discussion in the literature (10,11) about various forms of optical waveguides and their characteristics. Waveguides may be flat slabs, rectangular, cylindrical, or any other shape. The cylindrical waveguides are commonly referred to as optical fibers and they are drawn into long lengths. Slabs and rectangular waveguides are particularly amenable to integrated optics. The possibility of using a metal clad dielectric is not considered due to the high energy losses. When light is reflected off a metal surface the energy losses depend on the metal, the wavelength of the light, surface condition, polarization, and angle of incidence, and the losses are typically on the order of 1-2% per reflection. Hence, metal clad waveguides are extremely lossy in the optical region. In the dielectric clad waveguide, losses are due to absorption in the dielectrics and scattering losses. If the cladding has no absorption at the optical wavelength being propagated, then no energy is absorbed from the evanescent wave and the waveguide reflections are lossless.

From a practical consideration there are many ways to fabricate an optical waveguide. Among these are vacuum deposition (12), sputtering (12), epitaxy (13), polymerization (14), ion bombardment (15), and ion exchange (10). The technique used depends on the material involved and on whether an amorphous or crystalline film is desired. In all cases the goal is to produce a thin film of material on a substrate. This film should have low scattering and absorption losses and should have a uniform thickness. Also, surface irregularities should be very small compared to the wavelength of the propagating radiation. Epitaxy, either vapor phase, liquid phase, or chemical transport, can be used to produce single-crystal optical waveguides. As will be seen in a later discussion, the single-crystal properties are important for many devices which use such things as the electrooptic effect and nonlinear polarizability. The technology associated with the various forms of epitaxy has developed with efforts in the field of microelectronics. Many of the same techniques may prove useful in the production of microoptics. As a general rule, amorphous waveguides have less losses than crystalline waveguides and are easier to produce; however, the crystalline waveguides offer more potential use. An evaluation of a waveguide usually means measuring the losses in units of decibels per centimeter (dB/cm). One method (17) is to use optical fibers in contact with the waveguide to measure the scattered light as a function of transmission distance. Table 1 gives some typical values for various materials. It is quite clear that the amorphous glass or organic films are superior to the semiconductor films. In practical applications, however, semiconductors are more useful since they are transparent in the infrared (IR) and have large nonlinear susceptibilities. Furthermore, because of the dimensions involved, the IR offers the possibility of approaching the $\lambda/10$ dimensional uniformity required more easily. Also, the IR scattering losses should be lower.

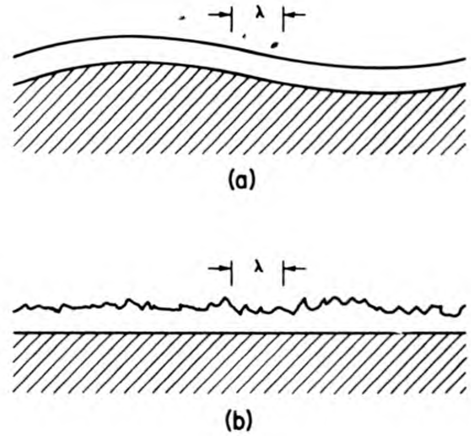
TABLE 1
Energy Losses at 6328 Å in Dielectric Waveguides*

Material	Loss (dB/cm)
ZnO	60
ZnS	5
Ta_2O_5	1
Sputtered glass (Corning 7057)	~0.9
Polyester epoxy	~0.9
Polymers (Vinyltrimethylsilane Dimethylsiloxane)	~0.9
Fiber waveguide†	2×10^{-4}

*Data from Ref. 14
†Data from Ref. 18.

As mentioned previously, the dimensional requirements ($\lambda/10$) are formidable. The surface of the waveguide must be smooth over dimensions on the order of several wavelengths. The waveguide can have a wavy surface and have uniform thickness and still have low losses, as shown in Figure 2. A discontinuity in the surface causes the light to be scattered (19). If the light is initially propagating in a single mode, after scattering the light will propagate in many modes and some may be lost to radiation away from the waveguide. Besides surface irregularities, strain (20) may perturb the waveguide modes. This is especially true in anisotropic crystalline waveguides. Another problem encountered

Figure 2 — Examples of high- and low-loss irregular waveguides. Sketch (a) shows a uniformly thick but "wavy" waveguide with variations over distances large compared to λ. This waveguide has low loss. Sketch (b) shows a waveguide with thickness variations over distances small compared to λ. This waveguide has a high scattering loss.



with epitaxial films are crystalline defects and inclusions of different crystalline structure. These are scattering sites and must therefore be eliminated by technological developments.

Optical Elements

Two-dimensional analogs of simple passive optical elements such as lenses and prisms can be incorporated in optical waveguides. Radiation propagating in a waveguide has a propagation factor β, which is proportional to the effective index of refraction for a particular mode of propagation and inversely proportional to the phase velocity. It is also a function of the parameters n_0, n_1, n_2, and d. Thus, for example, an increase in waveguide thickness increases β for a given mode. Hence, a section of waveguide with a change in thickness as shown in Figure 3 represents a change in effective index. Radiation in a given mode incident on this boundary will be refracted, as shown. The thickness change is made over a distance large compared to λ in order to avoid large scattering losses. Figure 4 shows a prism and a lens constructed by the variation in waveguide width technique. The same effect can be obtained by variations in n_0, n_1, and n_2. Prisms (1) and lenses (21) have been experimentally fabricated using sputtered glass. By using sharp discontinuities, beam splitters and reflectors can also be fabricated.

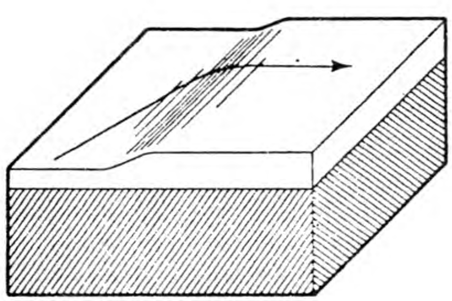


Figure 3 — A guided wave which is refracted due to a gradual change in waveguide thickness

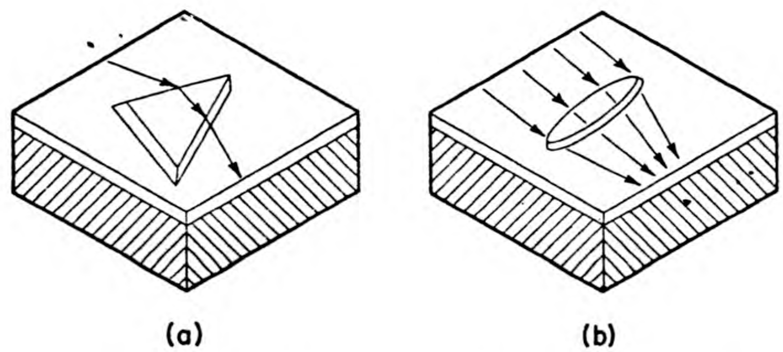


Figure 4 — Examples of simple waveguide optics: (a) a thin-film waveguide prism, and (b) a thin-film waveguide lens. In each case the bending of the light ray is due to a change in waveguide thickness.

With the use of absorbing material deposited on top of the waveguide, gratings, Fresnel-zone lenses, and spatial filters can in principle be fabricated. Some success in this area has been reported (21).

Couplers

Propagation in an optical waveguide is associated with an evanescent field in the low-index cladding dielectric adjacent to the high-index guiding dielectric. If a second waveguide is placed in close proximity to the first the evanescent wave will interact with the modes of the second waveguide. The two waveguides now form a coupled system which must be analyzed (22,4) as a single unit. The result is that if initially all the optical energy is in one waveguide, then the optical energy transfers from one waveguide to the other and back due to interference effects. The energy is totally transferred in the distance δ, where δ is a function of all the waveguide parameters (n_o, n_1, n_2, λ, d, ϵ, and W) as shown in Figure 5. Hence in principle, a waveguide coupler can

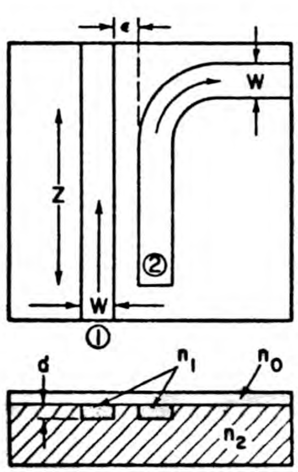


Figure 5 — An optical waveguide directional coupler. Waveguides of thickness d and width W are coupled through their evanescent fields by adjusting their separation t to a distance comparable to λ.

be designed to couple any desired fraction of the optical energy from waveguide 1 to waveguide 2. Further, the amount of coupling can actively be varied using, for example, the electrooptic effect to vary n_0, n_1, or n_2. This idea is the basis for several patents in the fiber waveguide field (23-25). These devices have logical analogs using dielectric film waveguides. Figure 6 is an example of a shift register used in an optical logic system. Light enters through waveguide A and exists *via* waveguide B′, C′, D′, or E′, or a combination depending on whether an appropriate voltage is applied to electrode pairs (bb′), (cc′), *etc*. The medium between the waveguides is electrooptic. This device obviously works in a pulsed regime when the light source is a pulsed source of radiation.

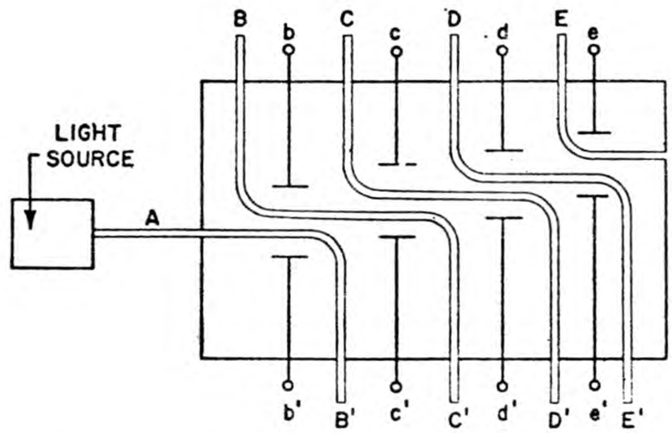


Figure 6 — Shift register for an optical logic system. Light incident at A appears at B′, C′, D′, or E′, depending on the potential on electrode pairs (bb′), (cc′), etc.

Thin-Film Lasers and Amplifiers

The concept of thin-film lasers or amplifiers is very simple: make an active dielectric waveguide and provide a pumping source, and possibly a resonator. The most common example is the injection laser (26,27). The p-n junction forms a dielectric waveguide which confines the radiation in the active region of the junction. The junctions can be used as lasers or amplifiers (26). Figure 7 illustrates a junction device. Because of the high index of the semiconductor the cleaved faces have sufficient reflections to form a laser cavity. When used as an amplifier these faces are antireflection (AR) coated. Alternatively, the junction current can be kept below the threshold value for lasing and still have gain in the junction (28).

Another approach to a waveguide laser source is to deposit a film of laser material and add reflectors and a pump source (29,30). The material

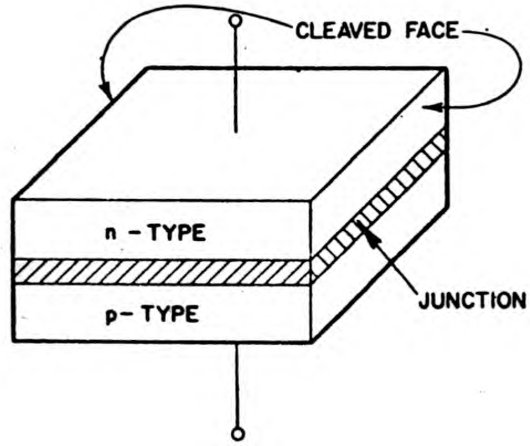


Figure 7 — A semiconductor junction laser an an example of an optical waveguide source of radiation

might be any of the usual solid-state laser materials, or even dye moleclues suspended in organic waveguides. One possibility is sputtering neodymium-doped glass. The real problem is forming a resonator. A series of "scratch"-like discontinuities spaced at intervals of $\lambda/4$ is one approach, as shown in Figure 8. Each discontinuity produces a partial reflection as discussed earlier. The reflections from successive discontinuities can be made to reinforce each other by proper design analogous to a multilayer dielectric mirror. Another alternative is to use a ring cavity configuration which eliminates the need for mirrors. This is shown in Figure 8(b). A three-dimensional waveguide is deposited in the form

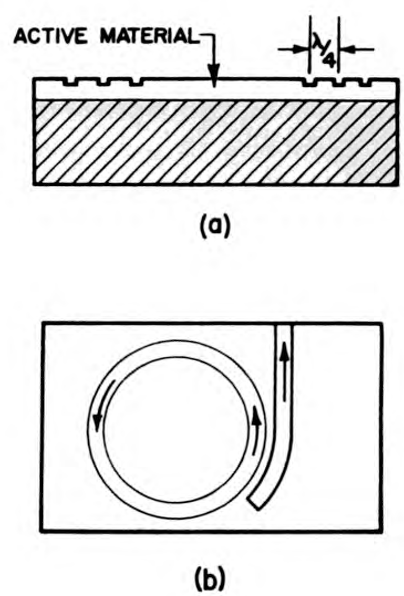


Figure 8 — Optical waveguide laser resonators: (a) a linear resonator with reflections produced by $\lambda/4$-spaced thickness variations, and (b) a ring resonator with a closely spaced waveguide for an output coupler

of a ring and another waveguide is positioned close by to couple out a fraction of the resonator radiation.

The pumping source for a waveguide laser should be part of the thin-film device. There is no problem with an injection laser type device since the pumping is done electrically and only electrodes are required on the waveguide. Other semiconductor devices may require optical pumping. In this case such things as an electroluminescent film (29) or another injection laser may be required.

Lasers have been fabricated of thin ($\sim 1\mu$) platelets of CdSe (31,32). These platelet lasers are optically pumped and can be coupled to a dielectric waveguide using the evanescent field, as with two coupled waveguides discussed previously (31). More importantly, an injection laser can be mounted in contact with the platelet to pump it transverse to laser action. A possible situation is shown in Figure 9.

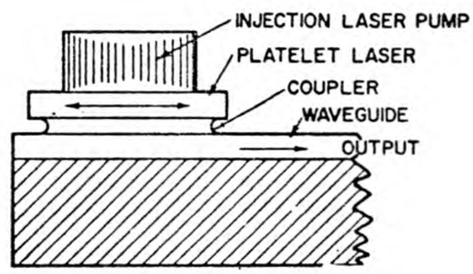


Figure 9 — A semiconductor platelet laser source coupled to an optical waveguide. The platelet laser is pumped by an injection laser and radiation is coupled into the waveguide by evanescent field coupling through a low-index gap region (or coupler).

Modulators

Modulation of light in a waveguide can be accomplished by modulating the source or by operating on the light external to the source. Considerable work has been done on the direct modulation of semiconductor lasers (33). Information rates as high as 1 billion bits per second (Gbit/sec) have been demonstrated using these techniques (33). Analogous techniques could presumably be used with the other thin-film laser devices described previously.

External modulators may be caused as electrooptic, acoustooptic, and magnetooptic. The electrooptic modulators make use of phase changes in the waveguide modes due to the electric field. For example, in a waveguide of electrooptic material, or in a waveguide on an electrooptic substrate, the propagation factors for TE and TM modes vary differently with an applied electric field. If initially the optical radiation is linearly polarized with equal TE and TM components, then after passing through the modulator an appropriate relative phase shift can cause the light to be linearly polarized orthogonal to the original polarization. This is shown in Figure 10. The analyzer blocks the light if its plane of polarization is rotated 90°. The output is an amplitude-modulated

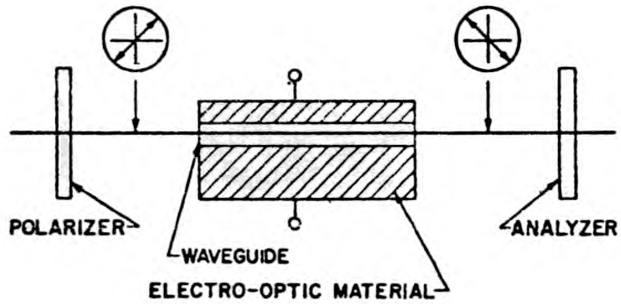


Figure 10 — An optical waveguide light modulator. The electrooptic effect is used to vary the phase velocities of TE and TM waves, and thereby rotate the plane of polarization of the incident radiation. Addition of a polarizer-analyzer pair produces a modulator.

signal in response to the electrical signal driving the electrooptic waveguide. This principle is the basis for the modulators described in References 34 and 35. This type of modulator has been demonstrated in GaP p-n junction (9,36) and in GaAs epitaxial layer waveguide (37). In the latter case a half-wave voltage of 84 volts at 1.15μ using a sample 2.4 mm long was demonstrated. This is a reduction of voltage by almost a factor of 100 as compared to a comparable bulk material device. This reduction is possible because the light is confined to a waveguide with an aperture on the order of the wavelength of the light used, and diffraction spreading is eliminated (38).

Acoustooptic modulators are basically light deflectors and they will be discussed in the next section.

Magnetooptic modulators (38) make use of induced optical activity instead of induced birefringence, and they require current-modulated signals instead of voltage-modulated signals as will electro-optic devices. A device of this type has not been demonstrated in optical radiation in terms of smaller magnetic fields. Also, the problem of producing a magnetic field confined to an area comparable to the device dimensions may be difficult.

Deflectors

Deflectors can operate either *via* the electrooptic (39) or acousto-optic effect (40). In the case of electrooptic deflectors, these devices are usually digital deflectors as opposed to providing a continuous scan. The digital devices work on the principle that the electro-optic effect rotates the plane of polarization of linearly polarized light in a suitable medium, and a polarizing prism such as a Rochan, Wollastan, or Thompson deflects the beam into one of two channels. The same effect is accomplished in optical waveguides using coupled waveguides. No exact analog of the digital deflector has been demonstrated in optical waveguides.

The acoustooptic deflector has the advantage of continuous deflection by electronic tuning of the acoustic frequency. The acoustic wave produces periodic index variations, which in turn deflect a portion of the optical radiation by Bragg diffraction. This process is particularly adaptable to dielectric film waveguides on a substrate. In this case, the acoustic wave is a surface wave, and the optical radiation is also on the surface of the substrate. The interaction can therefore be achieved with much less acoustic power than in the bulk case, and efficiency is improved. Waveguide devices of this sort have been analyzed (41,42) and a particular configuration (41) is shown in Figure 11. This device had a maximum observed deflection efficiency of 66% with an electrical input of 2.5 W, or an acoustic power of 0.18 W. There is no reason to believe that improvements cannot be made on this device.

Detectors

There is a vast technology built up in the area of semiconductor photodetectors (48). No attempt will be made here to review this area. It is sufficient to point out that most of these photodetectors are semiconductor junctions in some form. They have been fabricated with response times on the order of 10^{-9} sec in the IR out to beyond 10μ. Since they are basically junctions, they can conceivably be incorporated into an optical waveguide circuit. The major operational difference would be that the incident light would be in the plane of the junction and not normal to the junction. Actual incorporation of one of these devices into a waveguide circuit has not been achieved, but there does not seem to be any insurmountable problems.

Input and Output Couplers

If one has an optical waveguide device and a laser source that is not built into the waveguide, then the laser radiation must be coupled into

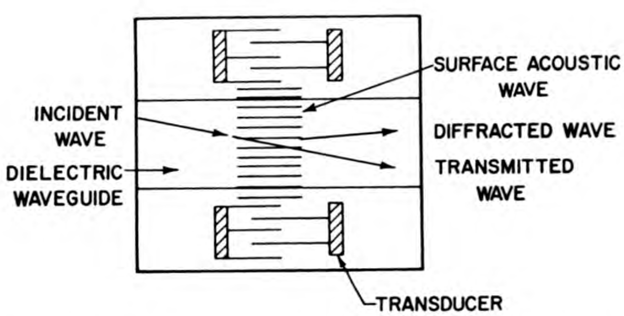


Figure 11 — Acoustooptic deflector. The optical guided wave is Bragg scattered by the surface acoustic wave.

the waveguide device. After a function is performed the radiation must be coupled out of the waveguide. This coupling must be done efficiently if the waveguide device is to have any advantage over a similar bulk device. Several schemes have been proposed and tried.

The most obvious way to couple light into a waveguide is to focus it down on to the end of the waveguide. This is illustrated in Figure 12(a) and it has been used by many people (3,13,15,51). Ideally one can couple greater than 90% of the optical radiation into the waveguide in this manner if the end surface A of the waveguide is flat (to $\sim\lambda/100$). The clear advantage of focusing as a coupling scheme is the resultant high maximum efficiency. The disadvantage is the difficulty of alignment which requires micromanipulation of the waveguide under a microscope objective. Also, the bulkiness of the coupler tends to defeat the advantages of the microoptics. A variation of this approach, which may help in some cases, is to terminate the waveguide before the edge of the substrate, as shown in Figure 12(b). This method is also capable of greater than 90% efficiency (43). In this technique the light is incident from below the substrate. The waveguide must be prepared so that it penetrates the substrate. Waveguides of this type have not been fabricated and evaluated, and hence no data is available on an application of this coupling scheme. A third coupling scheme is to use the evanescent wave from a totally reflecting interface, as shown in Figure 12(c). Here the total internal reflection takes place in a prism and the evanescent field penetrates into the waveguide through the gap. Depending on the angle of incidence of the incoming light, the propagation factor of the evanescent wave along the waveguide direction will vary. If it happens to coincide with the propagation factor for a waveguide mode at that frequency, then light will be coupled into the waveguide. The reverse can also happen; if light is propagating in the waveguide it can couple out *via* a prism in close proximity. Hence for efficient coupling from the prism to the waveguide, the prism is truncated (equivalently, the focal spot is moved to the edge of the prism as shown) after the maximum possibility optical radiation is coupled into the waveguide. Hence, the right-angle prism is used. The geometry is simply reversed for an output coupler.

A fourth type of coupling makes use of a phase grating (44) and is shown in Figure 12(d). In this technique a phase grating is produced directly on the waveguide surface by developing a photoresist which has been exposed to an appropriate interference pattern. The light transmitted through the grating establishes a polarization wave on the waveguide surface. This wave has a propagation factor along the waveguide which is dependent on the angle of incidence of the incoming radiation, the periodicity of the grating, and the depth of modulation of the grating. For a fixed grating, variation of the angle of incidence

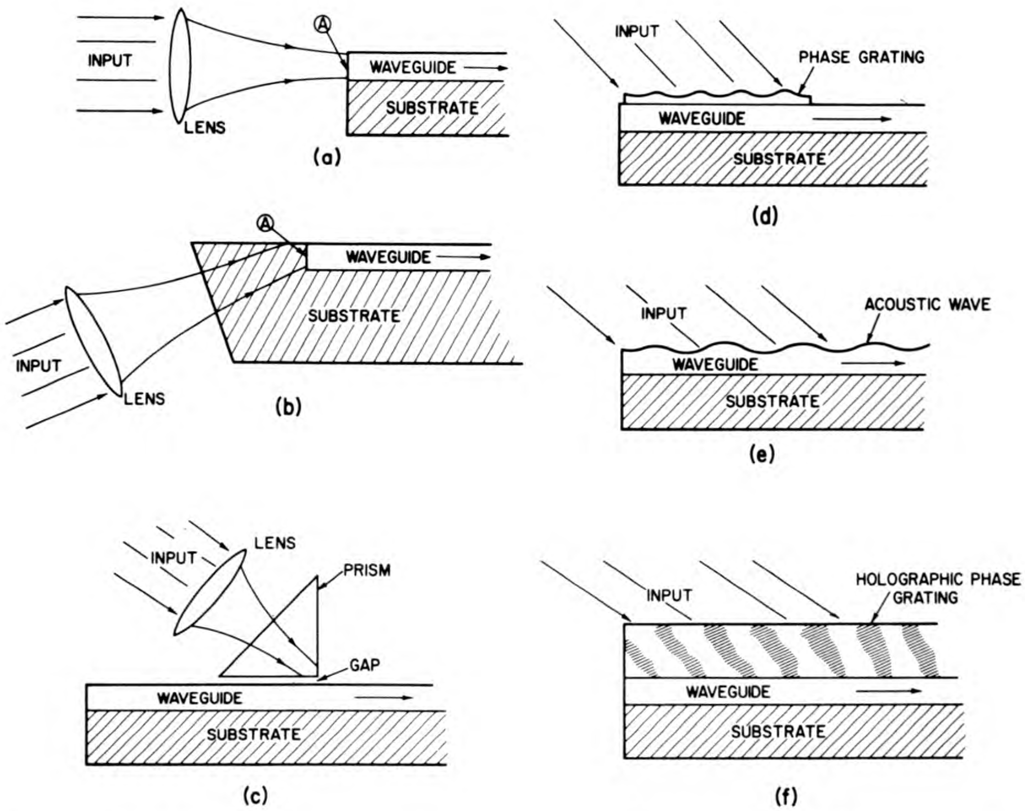


Figure 12 — Input and output couplers: (a) direct coupling into the end of the waveguide, (b) coupling into a terminated waveguide, (c) prism coupler which uses evanescent wave coupling, (d) grating coupler, (e) grating coupler using an acoustic surface wave to produce the grating, and (f) grating coupler which uses a holographically produced phase grating.

allows the propagation factor of the above polarization wave to match that of a waveguide mode, and light is coupled into the waveguide. Similarly, light propagating in the waveguide is coupled out by the grating. The acoustic wave coupler (42) and the holographic coupler (45) are based on the same idea as the grating coupler, but offer different techniques of producing the grating.

Applications

Any of the individual elements discussed in the previous section-modulator, deflector, *etc.* can be used in a large conventional optical system. The only requirement would be suitable couplers to couple light into the waveguide device and then to couple it out again. This sort of approach may be practical if the optical waveguide device with its associated waveguide couplers is more efficient than the equivalent bulk optical device, or if an appropriate bulk optical device does not exist. However, most practical applications of this technology will probably involve the integration of several of these devices or elements into a microoptical system. What these systems might consist of and what applications they might have are discussed below. First, however, it is appropriate to list several characteristics of integrated optics in general that might mean a distinct advantage over conventional bulk optics for specific applications:

- *Size*. Optical waveguides have cross-sectional dimensions on the order of the wavelength of the light being guided. An integrated optical circuit can be fabricated as a thin dielectric film or films on a dielectric substrate in a manner very analogous to microelectronic circuits.
- *Weight*. With the reduction in size, weight is reduced proportionately.
- *Cost*. Once the technology is developed, the cost of a microoptical circuit would be a small fraction of the cost of conventional optics with the required polishing, coating, and mounting.
- *Alignment*. A microoptical integrated circuit has fixed alignment and is easily isolated from the effects of vibration, acceleration, and temperature.
- *Service*. Repair of microoptics is reduced to a simple replacement process.
- *Efficiency*. In many cases confinement of the optical energy to a very thin layer with resultant high intensities permits a more efficient optical interaction. This is the case with acoustooptic and nonlinear parametric interactions. Also, the size of microoptics is appropriate for ultrahigh-frequency modulators and optical data processors.

For a discussion of particular applications it is convenient to consider three separate areas: communications, display, and computers. In each of these areas there are arguments for and against the use of optics in general. Optics offer something new or better in many cases, but a really practical application would depend on one or more of the characteristics of microoptics listed above.

Communications

At the present time there is no practical optical communications systems of any type in existence (46). The answers to the question "Why optics?" are essentially (a) extremely large bandwidth, and therefore high data rates, (b) an ultralarge spectral range, (c) narrow optical beams with essentially no side lobes, (d) energy confinement for secret communication links and the elimination of clutter, (e) small terminals, antennas, and equipment in general, and (f) transmitters, receivers, and transmission line are free from the problems of electromagnetic interference.

There are counter arguments against optics which are based on the major problem areas. They are (a) atmospheric transmission losses, (b) economics, (c) pointing problems, (d) detector bandwidth at 10μ, and (e) absence of existing ultrahigh-data-rate modulators. Integrated optics offers potential solutions to many of these arguments. Atmospheric transmission losses can be reduced by using a short transmission path, or by using optical waveguide data links. The economics of integrated optics has already been pointed out. The pointing problem requires sophisticated optics to scan the field of view, lock on to the signal, and point the transmitter. The size and weight limitation of the extra complex system can be overcome with an integrated optical system. The detector technology is constantly improving and high-frequency modulation is easier to obtain in a waveguide device, as has already been discussed. Hence, some possible practical applications of integrated optical systems might be as follows:

- Ship-to-ship, ship-to-shore, and man-to-man secure short-range atmospheric path communication.
- Satellite-to-satellite communication.
- Onboard ship and aircraft communications.
- Repeater.

Display

There is an obvious and ever-present need for displays, plotting boards, *etc*. These display panels can be effectively linked to a computer to provide real-time plots and information. Color displays are possible using laser sources at different wavelengths. Systems of this type that exist today are bulky, heavy, and environment sensitive. A display system including laser sources, modulators, and scanners could be packaged as an integrated optical system.

Computers

Optical computers with complete optical logic systems do not seem to offer any real advantage over conventional integrated circuit systems at the present time (47). The real future of optics in relation to computers lies in optical memories, computer interconnections, and input and output areas. Optical memories need an interface between them and the conventional integrated circuits. This can be provided by integrated optics in order to maintain compactness, light weight, and small size. Communications between computers, or between parts of a computer, require high data capability. Again this can be effectively provided by optical waveguides and the integrated optic interface to the electronics.

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Computer input eventually will require optical scanning of printed pages and/or pictures. The basic principal of operation is character or scene recognition *via* Fourier optics and optical data processing. The Fourier transform of the image of a character or a scene is sequentially compared with a collection of Fourier-transformed images of known characters and/or scenes. Practically, this can mean very complex systems. Fourier optics can be implemented in optical waveguides (3), and conceivably the entire system can be made into an integrated optical system.

Conclusions

Optical waveguides and integrated optics technology is in its infancy (no more than about 3 years old). Some theoretical work has been done, and preliminary experimental work has successfully demonstrated the feasibility of several simple optical waveguide devices. More and more interest is developing in the field, and many laboratories are beginning programs. There is no doubt that the problems that must be solved are quite formidable; however, they do not seem impossible. The real impetus behind the growing interest in microoptics is the great potential involved with successful applications—small size, light weight, increased efficiency, elimination of EMI, *etc*. In the area of nonlinear optics many new semiconductor materials can be used with this technology. A real problem is the fabrication of waveguides of dimensions on the order of λ and smooth to the order of at least $\lambda/10$. This limitation in all probability means that the first really successful devices will be in the IR. Semiconductors are readily available, and there is a large semiconductor technology from which to build.

The problems to be solved are such that a realistic timetable probably puts useful devices 5 years away, and integrated optical circuits and systems 10 years away. Incorporation into military systems is probably 7 years for simple devices, and 12 years for integrated optics. There is the possibility that some devices may arrive sooner, notably modulators since they promise to be more efficient and faster than bulk devices and there is a real need for them in many areas.

References

1. Snitzer, E., "Optical Dielectric Waveguides," pp. 348-369 in "Advances in Quantum Electronics," New York:Columbia University Press, 1961
2. Kane, J. and Osterberg, H., "Optical Characteristics of Planar Guided Modes," *J. Opt. Soc. Amer.* **54:**347-352 (Mar. 1964)
3. Shubert, R. and Harris, J. H., "Optical Surface Waves on Thin Films and Their Application to Integrated Data Processors," *IEEE Trans. Microwave Theory and Tech.*, **MIT-16:**1048-1054 (Dec. 1968).

4. Marcatili, E. A. J., "Dielectric Rectangular Waveguide and Directional Coupler for Integrated Optics," *Bell System. Tech. J.*, **48:**2071-2102 (Sept. 1969)
5. Rozzi, T. E., "Model Analysis for Nonlinear Processes in Optical and Quasi-Optical Waveguides, *IEEE J. Wuant. Electr.*, **QE-6:**539-546 (Sept. 1970)
6. Tien, P. K. and Ulrich, R., "Theory of Prism-Film Coupler and Thin-Film Light Guides," *J. Opt. Soc. Am.*, **60:**1325-1337 (Oct. 1970).
7. Anderson, W. W., "Mode Confinement and Gain in Junction Lasers," *IEEE J. Quant. Electr.*, **QE-1:**228-236 (Sept. 1965)
8. Nelson, D. F. and McKenna, J., "Electromagnetic Modes of Anisotropic Dielectric Waveguides at p-n Junctions," *J. Appl. Phys.*, **38:**4057-4074 (Sept. 1967)
9. Reinhart, F. K., Nelson, D. F., and McKenna, J., "Electro-Optic and Waveguide Properties of Reverse-Biased Gallium Phosphide p-n Junctions," *Rhys. Rev.*, **177:** 1208-1221 (Jan. 15, 1969)
10. Karbowiak, A. E., "Optical Waveguides," *Advances in Microwaves*, Vol. 1, ed. by Leo Young, New York:Academic Press, 1966.
11. Gloge, D., "Optical Waveguide Transmission," *Proc. IEEE*, **58:**1513-1522 (Oct. 1970)
12. Tien, P. K., Ulrich, R., and Martin, R. J., "Modes of Propagating Light Waves in Thin Deposited Semiconductor Films," *Appl. Phys. Letters*, **14:**291-294 (May 1, 1969)
13. Hall, D., Yariv, A., and Garmire, E., "Observation of Propagation Cutoff and Its Control in Thin Optical Waveguides," *Appl. Phys. Letters*, **17:**127-129 (Aug. 1, 1970)
14. Tien, P. K., "Light Wave Propagation in Thin Films and Thin Film Quantum Electronic Devices," 1970 Sixth Intern'l Quantum Electr. Conf., paper 12.6, Kyoto, Japan (Sept. 1970)
15. Schineller, E. R., Flam, R. P., and Wilmot, D. W., "Optical Waveguides Formed by Proton Irradiation of Fused Silica," *J. Opt. Soc. Am.*, **58:**1171-1176 (Sept. 1968)
16. Giallorenzi, T. G., West, E. G., Kirk, R., Ginther, R., and Andrews, R. A., "Optical Waveguide formed by Ion Exchange in Glasses" (to be published)
17. Goell, J. E. and Standley, R. D., "Sputtered Glass Waveguide for Integrated Optical Circuits," *Bell System. Tech. J.*, **48:**3445-3448 (Dec. 1969)
18. Kapron, F. P., Keck, D. B., and Maurer, R. D., "Radiation Losses in Glass Optical Waveguides," *Appl. Phys. Letters*, **17:**423-425 (Nov. 15, 1970)
19. Marcuse, D., "Mode Conversion Caused by Surface Imperfections of a Dielectric Slab Waveguide," *Bell Sys. Tech. J.*, **48:**3187-3215 (Dec. 1969)
20. McKenna J. and Morrison, J. A., "The Effects of Strain on Electromagnetic Modes of Anisotropic Dielectric Waveguides at p-n Junctions," *Bell Sys. Tech. J.*, **41:**1933-1956 (Nov. 1968)
21. Shubert, R. and Harris, J. H., "Optical Guided-Wave Focusing and Diffraction," *J. Opt. Soc. Am.*, **61:**154-161 (Feb. 1971)
22. Kapany, N. S., Burke, J. J., Frame, K. L., and Wilcox, R. E., "Coherent Interactions Between Optical Waveguides and Lasers," *J. Opt. Soc. Am.*, **58:**1176-1183 (Sept. 1968)
23. Nethercat, A. H., Jr., "Electro-Optic Light Coupling of Optical Fibers," U.S. Patent 3,208,342 (Sept. 1965)
24. Ashkin, A., "Coupled Junction Semiconductor Devices for Optical Wavelengths," U.S. Patent 3,451,410 (Nov. 1967)
25. Kapany, N. S., "Apparatus for Coupling and Amplifying Light Between Optical Fibers," U.S. Patent 3,408,131 (Oct. 1968)
26. Gooch, C. H., ed., "Gallium Arsenide Lasers," New York:Wiley-Interscience, 1969
27. Pilkuhn, M. H., "The Injection Laser," *Phys. Stat. Solid*, **25:**9-62 (1968)
28. Stern, F., "Light Amplifying Device," U.S. Patent 3,465,159 (Sept. 1969)
29. Miller, S. E., "Integrated Optics: An Introduction," *Bell Sys. Tech. J.*, **48:**2059-2069 (Sept. 1969)

30. Goell, J. E. and Standley, R. D., "Integrated Optical Circuits," *Proc. IEEE* **59:**1504-1512 (Oct. 1970)
31. Keune, D. L., Holonyak, N., Jr., Burnham, R. D., Dapkus, P. D., and Dupuis, R. D., "Thin Semiconductor Laser to Thin Platelet Optical Coupler," *Appl. Phys. Letters,* **16:**18-20 (Jan. 1, 1970)
32. Smiley, V. M., Lewis, A. L., and Taylor, H. F., "Mode Hopping and Tuning of Thin CdSe Platelet Lasers," *J. Opt. Soc. Am.,* **60:**1321-1324 (Oct. 1970)
33. Paoli, T. L. and Ripper, J. E., "Direct Modulation of Semiconductor Lasers," *Proc. IEEE* **58:**1457-1465 (Oct. 1970)
34. Nelson, D. F. and Reinhart, F. K., "Semiconductor Junction Electro-Optic Light Modulator," U.S. Patent 3,462,211 (Aug. 1969)
35. Kahig, D., "Optical Wave Modulator," U.S. Patent 3,464,762 (Sept. 1969)
36. Reinhart, F. K., "Reverse-biased Gallium Phosphide Diodes as High-Frequency Light Modulators," *J. Appl. Phys.,* **39:**3426-3434 (June 1968)
37. Hall, D., Yariv, A., and Garmire, E., "Optical Guiding and Electro-Optic Modulation in GaAs Epitaxial Layers," *Optics Comm.,* **1:**403-405 (Apr. 1970)
38. Chen, F. S., "Modulators for Optical Communications" *Proc. IEEE,* **58:**1440-1457 (Oct. 1970)
39. Kulcke, W., Kosanke, K., Max, E., Habegger, M. A., Harris, T. J., and Fleisher, H., "Digital Light Deflectors," *Proc. IEEE,* **54:**1419-1429 (Oct. 1966)
40. Gordon, E. I., "A Review of Acoustooptical Deflection and Modulation Devices," *Proc. IEEE,* **54:**1391-1401 (Oct. 1966)
41. Kuhn, L., Dakss, M. L., Heidrick, P. F., and Scott, B. A., "Deflection of an Optical Guided Wave by a Surface Acoustic Wave," *Appl. Phys. Letters,* **17:**265-267 (Sept. 15, 1970)
42. Chang, W. S. C., "Acoustooptical Deflections in Thin Film," *IEEE J. Quant. Electr.,* **QE-7:**167-170 (Apr. 1971)
43. Marcuse, D. and Marcatili, E. A. J., "Excitation of Waveguides for Integrated Optics with Laser Beams," *Bell Sys. Tech. J.,* **50:**43-57 (Jan. 1971)
44. Dakss, M. L., Kuhn, L., Heidrick, P. F., and Scott, B. A., "Grating Coupler for Efficient Excitation of Optical Guided Waves in Thin Films," *Appl. Phys. Letters,* **16:**523-525 (June 15, 1970)
45. Kogelnik, H. and Sosnowski, T. P., "Holographic Thin Film Couplers," *Bell Sys. Tech. J.* **49:**1602-1608 (Sept. 1970)
46. Lindgren, N., "Optical Communications—A Decade of Preparations," *Proc. IEEE* **58:**1410-1418 (Oct. 1970)
47. Smith, W. V., "Computer Applications of Lasers," *Proc. IEEE,* **54:**1295-1300 (Oct. 1966)

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The number of cancer deaths in the U.S. during 1971 has been estimated at 335,000. Although it is not expected that this treatment alone will solve this enormous problem, neutron radiotherapy and other improvements in cancer treatment may significantly reduce the death toll. According to Dr. Rogers, present treatment methods including surgery, x rays, gamma rays, and chemotherapy have been increasing successful in controlling certain malignant tumors. However, many cannot be removed surgically, even though they are localized, without excessive damage to the patients, and many such tumors are also resistant to treatment by medicine or conventional radiations like x or gamma rays.

Fiber Optics Communications

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Introduction

Fiber optics communications is a new, rapidly evolving area of technology which may soon find widespread civilian and military application. Improvements during the past ten years in optical transmission lines, sources, and detectors—the basic elements of fiber optics communications link—now make this technology worthy of consideration for a wide variety of information transfer uses.

Advantages of Fiber Optics

Perhaps the most impressive aspect of fiber optics for communications is the almost infinite bandwidth potential. A 15μm diameter, single mode fiber has a bandwidth of the order of 10 GHz per kilometer of length. A 1-cm cable composed of closely-packed fibers has a capacity of over 100,000,000 TV channels! However, sources, modulators, and detectors needed for full utilization of the transmission line bandwidth have yet to be developed.

Even in systems using presently available emitters and detectors, the fiber optics transmission line is much smaller in size and lighter in weight than an electrical line of equivalent bandwidth—attributes that can translate into cost and performance improvements in military systems. A properly jacketed optical cable will neither emit nor pick up electromagnetic radiation, insuring security of communication and immunity from interference and crosstalk to a degree not possible with electrical cables. Ground loop and ground shift problems are eliminated by the use of an insulating transmission medium. Suitable design of fiber optics terminations should reduce reflections and ringing, which can cause problems in electrical lines. Finally, the glasses used in some of the new, low-loss fibers should resist fire damage to temperatures approaching 1000°C, as compared with the 300°C rating for high-temperature electrical cable.

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Fiber Optics Transmission Lines

A light beam propagating in a glass cylinder will be confined to its interior by total internal reflection if

$$n_a \sin\theta \leq \sqrt{n_1^2 - n_a^2}$$

where n_a and n_1 are, respectively, the refractive indices of the surrounding air and the glass ($n_a = 1.00$) and θ is the angle between the propagation vector of the incident beam and the axis of the cylinder. However, in practice, minute irregularities at the glass-air interface cause much of the light to be lost by scattering at each encounter with the surface. The surface-scattering problem can be elininated if the cylinder consists of a core of high-index material surrounded by a cladding of lower index. The condition for confinement becomes

$$n_a \sin\theta \leq \sqrt{n_1^2 - n_2^2}$$

where n_1 and n_2 are the core and cladding refractive indices, respectively. If the cladding is several wavelengths thick, the light will propagate in the core and cladding and not contact the surface of the cylinder. Flexible glass optical fibers with radii from a few micrometers to several hundred micrometers have been produced.

Three methods are commonly used to make glass fibers. The double-crucible method employs an inner crucible containing higher-index glass and an outer crucible with glass of a lower index. The contents of both crucibles are heated to melting, and the fiber material is drawn simultaneously from the two crucibles. A second technique, the preform method, employs a rod of higher-index core material inserted in a hollow cylinder of lower-index material. One end of the rod and cylinder is heated to softening and is drawn into a fiber. The ratio of rod and cylinder diameters is maintained in the fiber as the ratio of core and cladding diameters. The third method is ion exchange. A glass cylinder is placed in a hot salt solution, and ions in the glass are exchanged with ions in solution by diffusion. The cylinder is then drawn into a fiber which has a parabolic refractive index profile.

Optical fibers are also fabricated of plastic, but the attenuation of present fibers is too great for these to be of much interest for optical communications. Low-loss fibers consisting of glass cladding surrounding a liquid core have recently been produced in the laboratory. However, the core refractive index of these fibers is sensitive to ambient temperature, the repairability of breaks is questionable, and they may be difficult to manufacture in large quantity. Glass fibers seem to offer the most promise for optical communications.

There are two distinct types of fiber for communications purposes— the single mode and the multimode. The single-mode fiber has a very large information transfer bandwith, of the order of 10 GHz per kilometer of length. However, coupling of light from incoherent sources, such as light-emitting diodes, into single-mode fibers is very inefficient. The multimode fiber has a bandwidth roughly two orders of magnitude lower than the single mode fiber, but will couple efficiently to incoherent sources. Coupling considerations dictate the use of bundles containing tens or hundreds of multimode fibers with presently available semiconductor sources. Single-mode fibers will be required for very wide band intercity links of the future.

The development of low-loss fibers has been the main factor responsible for the recent interest in fiber optics communications. The attenuation factor of commercially available fiber optics is about 1000 dB/km. Absorption by impurities and scattering due to refractive index nonuniformities are the two mechanisms responsible for the loss. Recently developed techniques for glass purification and process control have enabled researchers in several laboratories to produce fibers with losses substantially below 1000 dB/km. The loss factor of 4 dB/km recently reported by Corning Glass Works is close to the theoretical limit from Rayleigh scattering by frozen-in refractive index inhomogenieties. At the present time, low-loss fibers are still a developmental item and are not sold commercially.

Sources

A source capable of cw, room-temperature operation is required for fiber optics systems with communications bandwidths much above the audio range. Considerations of cost, reliability, power requirements, size, and necessity for external modulation rule out gas lasers, such as HeNe, and solid-state lasers, such as Nd:YAG, as sources for most fiber optics communications applications. The semiconductor laser is anticipated to be the coherent source for use with single-mode fibers in very wide-band systems of the future. However, cw, room-temperature devices will remain in the developmental stage until operating life is improved. The light-emitting diode (LED), incoherent counterpart of the semiconductor laser, is left as the choice for present-day systems.

The LED is simply a semiconductor chip, which contains a PN junction, mounted on a header and encapsulated beneath a transparent window. Light is emitted when the forward bias on the junction (in volts) is approximately equal to the energy gap (in electron volts). Optical output power is close to a linear function of the current passing through the device. It can be modulated at high rates by varying the driving current. The maximum frequency is limited by carrier lifetime; cutoff frequencies in the neighborhood of 50 MHz are observed in the fastest commercial devices. The most efficient LED's are made of GaAs, which emits in a 400 Å-wide band centered near 9000 Å. External power-conversion efficiencies are typically in the 2-10% range. The spectral emission peak can be shifted to shorter wavelengths by doping at a sacrifice of power and efficiency.

Detectors

The three types of detector which can be useful in fiber optics communications are the silicon PIN photodiode, the silicon avalanche photodiode, and the photomultiplier. Photodiodes are semiconductor junction devices in which the current or voltage depends on the intensity of light falling on the junction region. When a reverse bias of a few volts is applied, the current in the device is close to a linear function of light intensity. PIN photodiodes include an intrinsic layer between the P- and N-doped regions to increase the volume of the active region, and, as a consequence, the quantum efficiency of the device. The avalanche photodiode has internal gain. The device is biased so strongly (>100 volts dc) that the internal electric field is capable of accelerating photo-generated carriers to an energy such that they can create new electron-hole pairs by collision with valence-band electrons. For each electron-hole pair originally created, a large number of carriers are collected by the electrodes. Spectral response of silicon PIN and avalanche photodiodes peaks near 9000 Å, which is well-matched to the GaAs sources. Photomultipliers are vacuum tubes containing a light sensitive cathode and several internal stages of amplification. A bias in the 1000-2000 volt range is required for most tubes. Best response is in the visible spectral range (4000-7000 Å), but new cathode materials have fair efficiency into the near infrared.

Bandwidths are above 100 MHz for silicon PIN photodiodes and photomultipliers and approach 1 GHz for some silicone avalanche photodiodes.

A comparison of the three types of detector as fiber optics communications receivers shows that the photomultiplier has the best signal-to-noise ratio for visible light, and the photomultiplier and silicon avalanche detector are about equal at 9000 Å. Although the silicon PIN photodiode has the least favorable signal to noise ratio, factors such as low cost, high reliability, and low bias requirements combine to make it the choice in many applications.

Integrated Optical Circuits

The electronics industry has demonstrated that order-of-magnitude improvements in size, weight, power requirements, reliability, speed of operation, and cost can be achieved by fabricating many components on a single substrate. It is suggested that similar advantages can be achieved in fiber optics communications systems by replacing discrete components with integrated optical circuits (IOC's). An IOC is a transparent substrate upon which different types of optical components and waveguide interconnections are fabricated. Some components which might be contained in IOC's include optical sources, detectors, modulators, amplifiers, switches, filters, directional couplers, and fan in and fan out elements. An increasing number of laboratories are engaged in research directed towards developing IOC's, primarily for use in fiber optics communications.

Fiber Optics Systems

Based on considerations of size, cost, power requirements, and reliability, gallium arsenide LED sources and silicon PIN detectors are the choice for use in many fiber optics communications applications. After the choice of source and detector has been made, the main tradeoffs involve signal bandwidth, transmission line length, and fiber optics attenuation factor. Results of a calculation of the maximum fiber optics attenuation factor (in dB/km at 9000 Å) consistent with a particular length-bandwidth requirement are given below:

		Length (m)		
		50	300	1000
Bandwidth Requirement	4 kHz analog	1100 dB/km	180 dB/km	50 dB/km
	5 MHz analog	550	90	25
	2 Mb/sec PCM	800	130	40
	10 Mb/sec PCM	600	100	30
	50 Mb/sec PCM	500	80	20

A signal-to-noise ratio of 30 dB for the analog signals and an error rate of 10^{-7} for the digital signals was assumed. According to the table, attenuation factors in the 500-1100 dB/km range will be required for aircraft applications (maximum distance $\sim$50 m) and in the 80-180 dB/km range will be needed for naval vessels (maximum distance ~300 m). Recalling that commercial (high-loss) fiber optics have attenuation in the neighborhood of 1000 dB/km, we see that low-loss fibers will be needed for wide-bandwidth communications on aircraft and for even low-bandwidth signals on ships.

Applications

Long Land Lines

At the present time, optical links are not economically viable in comparison with the competing technologies—land-based or satellite microwave relay, millimeter waveguide, and coaxial cable—for long land-line applications. This will change, however, if efforts to develop very-wide-band optical modulators and detectors, reliable cw, room-temperature lasers, and, eventually, integrated optical circuits, are successful. In fact, fiber optics may ultimately provide the only solution to the distribution of Picturephone® and other wideband services to the home at a price most people can afford.

Submersible Tow Cables

Long submersible tow cables for sensor arrays must be strong, have low weight in water, and have telemetry capability. Such cables generally contain a copper transmission line for the telemetry, a layer of neutrally buoyant material, and a strength member. A fiber optics transmission line is much smaller and more neutrally buoyant than a copper line of equivalent bandwidth. Thus, use of fiber optics for the telemetry could lead to substantial savings in cable size and cost.

Secure Voice and Television Links

Many of the electrical lines on naval vessels and military land stations are used to transmit classified information. In an effort to prevent these lines from emitting radiation, a number of precautions are taken. These include using heavy cables with extra shielding, running cables through steel conduits, physically separating secure lines by large distances from other lines, and reducing signal voltages. These precautions, which generally increase costs without completely eliminating the problem, are not needed with fiber optics lines.

Data Links

The use of fiber optics for lines carrying digital signals to or from computers will eliminate system malfunction due to ground shifts and errors caused by electromagnetic pickup. Savings in size and weight and increased bandwidth potential will also be realized.

Data Bus

The multiterminal multiplex system, or data bus, is evident in the design of new civilian and military aircraft and is planned for future ships and submarines. The properties of a data bus transmission line, which handles much of the information flow for an entire platform, become increasingly crucial. The use of fiber optics could lead to improvements in bandwidth, reliability, error immunity, damage susceptibility, and security.

Conclusions

Fiber optics offers a number of advantages in comparison with competing technologies for communications applications. Sources and detectors for fiber optics communications are commercially available, but low-loss fibers, required for most applications, are still in the developmental stage. With continued improvements in components, fiber optics may eventually handle a substantial portion of the information transfer requirements for military and civilian sectors.

(Continued from Page 20)

It is now thought that fast neutron beams have several characteristics which may contribute to their effectiveness in the treatment of local tumors where the other radiations have failed. The most important such characteristic depends on the fact that many tumors are deficient to oxygen due to insufficient blood supply.

Tumor cells under these conditions are much more resistant to damage by x or gamma rays than are well-oxygenated healthy cells. Thus, it is difficult to kill the tumor cells without excessive damage to nearby healthy tissue. Cell damage from neutron beams, on the other hand, is less dependent upon oxygen content, allowing the tumor to be destroyed without increasing the damage to healthy tissue.

The NRL cyclotron is considered an excellent facility for this project, not only because of the favorable characteristics of its neutron beam, but also because of the broad relevant experience of its staff, and the central location of NRL which will allow close collaboration with numerous cancer treatment centers.

Present plans call for modification of the NRL facility to accommodate a limited number of cancer patients in the program. This would be completed in about a year, at which time the pilot study of patient treatment will begin. Until then, present investigations of the physical characteristics of this neutron beam and its effect on a variety of biological subjects, including human cells, will be continued.

Glass Fiber Optical Waveguides for Laser Communications Systems

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The development of a low-loss reliable inexpensive optical transmission line is crucial to the implementation of any laser communication or data transmission system. The most promising candidate for such a transmission line is the glass fiber optical waveguide. The major obstacle to the use of such fibers are the relatively high losses due to scattering and absorption in the glass material. Recently, by careful purification of the starting materials, fibers have been fabricated in which absorption losses amount to only 20 percent of an overall loss of 5 dB/km. The reduction of the scattering losses is now imperative. Our research indicates that a reduction by a factor of six and perhaps more in the scattering attenuation coefficient can be realized.

Introduction

Of the many applications that have been prophesied for the laser since it was first developed, perhaps the most promising (and at present one of the least exploited) lies in its use in the field of communication. The great potential in this area derives from the capability of a laser beam for carrying information in much the same way as radio waves can be modulated and used for signal transmission. The advantage of using a laser beam as the carrier is the enormous information carrying capacity accompanying the use of optical frequencies. Because the frequency of a light wave is a factor of 10^5 to 10^8 higher than radio frequencies, the information carrying capacity is increased by roughly the same factor. A. D. Pearson of Bell Telephone Laboratories has illustrated the enormous magnitude of this increase by the following example. Imagine that half the population of the United States simultaneously place telephone calls to the other half of the population; these hundred million (or so) conversations could be carried on one laser beam and use only 20 percent of its capacity.

In an optical communication system a laser beam on which the information is carried must be transmitted between two points perhaps

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many kilometers apart. To transmit such a beam through the atmosphere (as is done with radio and micro-waves) is impossible because clouds, rain, snow, dust and other airborne contaminants quickly dissipate the beam. Some form of transmission line is needed to transmit the optical signal faithfully with a minimum of loss. What is needed is the optical analog of a coaxial cable to guide the beam from source to receiver. One such transmission line could consist of a series of glass lenses mounted within an evacuated pipe. The lenses would be anti-reflection coated to minimize losses at the vacuum-glass interfaces and the whole assembly would be encased within some protective armoring and perhaps buried in the earth. The operation of such a light guide is straight-forward and is illustrated in Figure 1. There are a number of disadvantages to such a system, not the least of which would simply be the cost. Other severe limitations would involve the reliability of the system when subjected to vibration and temperature changes; the precise alignment of the lenses would probably have to be maintained through some complicated (and therefore undesirable) servomechanism.

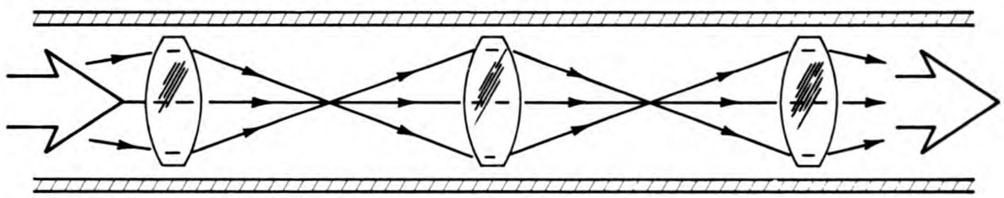

Figure 1 — A sketch illustrating the guiding of an optical beam by a series of lenses

Another possibility is the so-called gas lens in which a flow of gas is maintained in a small diameter metal tube which is heated from outside. As a result of the heating the gas near the surface of the tube has a lower density, and therefore a lower refractive index, than that near the axis of the tube. Thus, a radial gradient in the refractive index is established causing the light beam to be continuously focused or guided along the tube. The general idea of the gas lens is sketched in Figure 2. As with the arrangement of glass lenses this system presents alignment difficulties and is relatively expensive. The chief advantage of these transmission lines is their low loss.

The third type of guide is the glass fiber optical waveguide. Here the light beam is confined within and guided along a solid glass fiber of cylindrical cross-section. The major advantages of this type of line are its relatively low cost and lack of alignment problems. The fibers are very small in diameter (less than a millimeter) and can be arranged into bundles, protected with some sort of flexible sheathing and then handled,

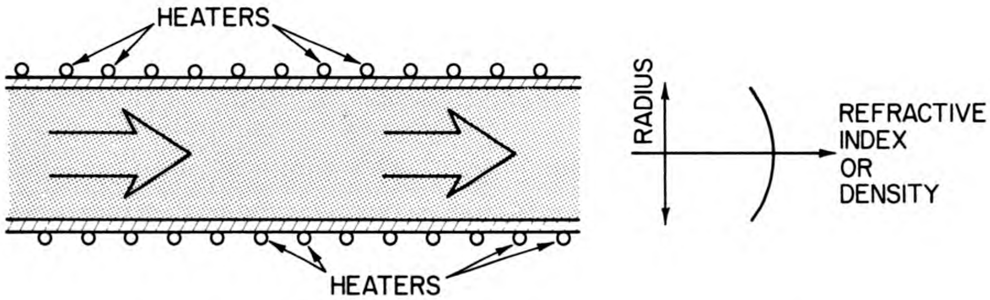

Figure 2 — A rough sketch of a gas lens showing the radial density and refractive index profiles

i.e. either buried or strung above ground, much like cables. The principal problem associated with the glass fiber guide is its comparatively high loss. The principal thrust of this paper is to enumerate the sources of this loss and to discuss some of the more promising avenues of research leading to the development of materials for which the loss is acceptably small.

Glass Fiber Optical Waveguides

Glass fiber optical waveguides generally are formed of a central glass core surrounded by a glass clad (see Figure 3). The cladding glass has a lower refractive index than the core material so that a light beam injected into one end of the compound fiber is confined to and guided along the line by total internal reflection. The fiber cores range in diameter from roughly 1 to 100 μm and typical clad-core diameter ratios are on the order of ten to one.

An alternate type of glass fiber guide has been developed (see Figure 4). In this type of self-focusing fiber a radially parabolic refractive index profile is created within a glass filament; light is guided along such a fiber in just the same fashion as in the gas lens system described above. The desired refractive index profile can be achieved by ion-exchange techniques in which, for example, thallium ions in the glass fiber near the surface are replaced by sodium or potassium ions.

To operate a glass fiber optical waveguide as a transmission line in a long distance communications system, it is essential that signal losses within the line be kept at an acceptably low level. For economical operation the distance between amplifiers or repeaters in the line cannot be smaller than a few kilometers or so. Since the allowable signal loss between repeaters is about 40 dB, attenuation coefficients less than 20 dB/km are an absolute necessity; realistically, it does not appear to be impossible to reduce the losses to 5 dB/km or perhaps even lower.

Developing such low loss optical fibers represents the major need in the deployment of an optical fiber communications system. Since a

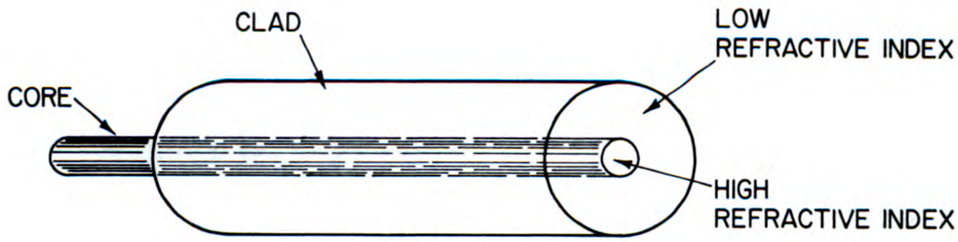

Figure 3 — A rough sketch showing the construction of a compound core-clad glass optical fiber waveguide

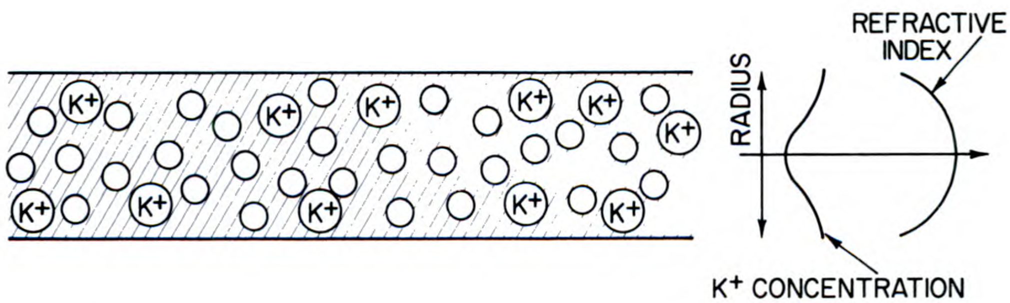

Figure 4 — An illustration of an ion-exchange optical fiber waveguide showing the radial ion (e.g.K^+) concentration and refractive index profiles

loss level of 10 dB/km corresponds to an optical attenuation coefficient of $\alpha = 2.5 \times 10^{-5}\text{cm}^{-1}$ the optical quality of the material to be used in the glass fibers must be very high indeed. Simply stated, the problem is to develop such a low loss bulk material capable of being drawn into fibers and then to maintain the low loss levels during the fiber drawing and cladding process. To analyze the problem it is convenient to consider separately the bulk material losses and the fiber waveguide losses. The bulk losses arise from optical absorption and scattering processes in the glass while the fiber waveguide losses are principally due to irregularities and imperfections at the core-clad interface in the compound fiber.

Bulk Scattering Losses: The largest of these losses arises from the presence of inhomogeneities such as small bubbles, metallic inclusions or crystals in the bulk glass. With careful preparation and homogenization procedures, it is possible to essentially eliminate these sources of scattering. The only remaining scattering losses then are those inherent in and characteristic of the bulk material. These inherent scattering mechanisms are the thermodynamic fluctuations in such quantities as density and composition that are in equilibrium in the molten glass and are "frozen" into it as the melt is cooled through the glass transformation region. One need only consider the Rayleigh scattering (when considering the origin of optical attenuation) since this is usually many times more intense than Ramon scattering. Since the intensity of the

Rayleigh scattering, and therefore, the magnitude of the optical attenuation coefficient, decreases as one increased the optical wavelength as $1/\lambda^4$, *i.e.* α varies as the fourth power of the optical frequency, ν it is, in principle, possible to render the bulk scattering losses as low as desired by operating at low optical frequencies (long wave-lengths)—for example, in the infrared region of the electromagnetic spectrum. However, because of the high infrared absorptions present in optical glasses, practically speaking, one is limited to the red and near infrared portion of the spectrum, say from about 6000 to 12,000 Angstroms. This is illustrated in Figure 5.

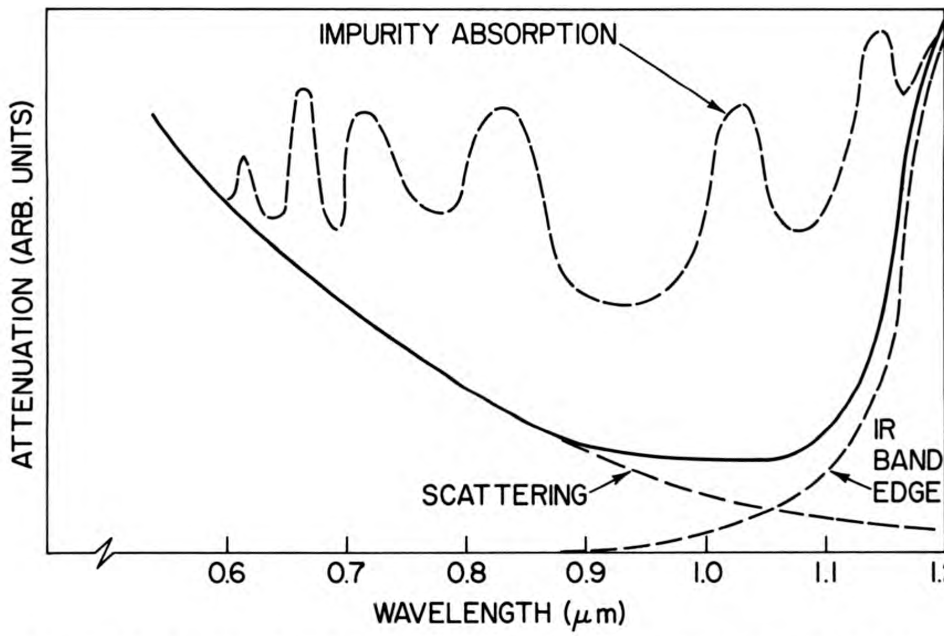

Figure 5 — A typical plot of the bulk attenuation mechanisms—scattering and absorption—versus wavelength. The graph is intended only to be illustrative.

Optical Absorption Losses: At wavelengths longer than about 12,000 A (1.2μm) fundamental vibrational processes in optical glasses lead to intolerably high infrared absorption coefficients. (Below about 6000A, the Rayleigh scattering losses are intolerably large.) Consequently, one must look to minimize the optical absorption in the 6000-12,000 A region. In state-of-the-art optical materials, the losses at these wavelengths may be governed principally by the presence of impurities rather than by fundamental absorption mechanisms or processes. Trace amounts—from 0.01 to 1 part per million—of water and of transition metal ions (chiefly chromium, manganese, iron, cobalt, nickel and copper) can lead to absorptions in the range 20 to 200 dB/km. It seems that the major problem is one of chemical purification: one must start the fabrication process with ultra-pure materials and maintain the product glass free from contamination throughout the glass melting, fiber pulling and cladding processes. This does not appear to be an unreasonably optimistic hope. Recent work at Bell Laboratories indicates that in very pure fused silica (SiO_2 glass—"Suprasil Wl" manufactured by Amersil, Inc.) the optical absorption at the 1.06μm wavelength of a YAℓG:Nd laser is approximately 2 dB/km. Moreover, researchers at Corning have recently announced the development of a material from which they were able to make relatively short fibers having a total loss of 5 dB/km. They attribute most of this loss to scattering, rather than absorption, mechanisms. It seems that within certain rather wide limits, the choice of a glass material from which the fibers are to be formed is not limited by any fundamental absorption processes, but rather by the purity that can be achieved in the starting materials out of which the glass is made.

Interfacial (Waveguide) Losses: These arise principally from the presence of imperfections at the interface of the core and clad and from variations in the size and shape of the fiber core. In both of the commonly used techniques for producing clad fibers—the so-called preform and double-crucible techniques—there are serious problems with obtaining a uniform, high quality interface. With the announcement by Corning of a 5 dB/km total loss clad fiber, it appears that these difficulties are not insurmountable. For the self-focusing fibers, there are no interfacial problems *per se;* however, it may be impossible to maintain the desired refractive index profile over sufficiently long lengths of fiber to make their use feasible in long distance applications.

Scattering Losses in Glass

When a beam of optical radiation passes through a transparent material medium, a small but not insignificant portion of the radiation is scattered away from the direction of the beam. Apart from gross inhomogeneities such as bubbles, metallic inclusions and small crystallites, the scattering in a glass medium arises because, on a molecular level, the material is not uniform because of vibrational motions of the atoms or molecules and thermodynamic fluctuations present in the material. (In a perfect crystal in which the atoms are completely stationary, there would be no scattering.) These vocal variations away from a uniform structure in the material result in the material having a local refractive index that varies from point to point in the material.

Now in a glass the effects of density and concentration variations must be modified; the system is not one in thermal equilibrium. A reasonable generalization can be obtained by recognizing that as a glass is formed by cooling the melt through its glass transformation region, the time required for the fluctuations to reach their equilibrium values becomes very long indeed. (The visocity becomes large and the diffusion coefficient becomes small so that within a few degrees of temperature change the characteristic relaxation times for equilibration of the fluctuations become of the order of magnitude of many centuries.) The fluctuations are thermally arrested—frozen into the glass. Consequently, the magnitude of the density and concentration variations (and hence the scattering loss) for a piece of glass or a glass fiber is not determined by the actual temperature of the material but rather by some higher *fictive* temperature T_f at which the fluctuations were arrested. These need not necessarily be equal for both the density and concentration variations but one expects that both are on the order of T_g—the glass transition temperature.

In order to minimize the scattering losses; it is essential that both the density and composition be made as homogeneous as possible. An obvious possibility is to utilize a single component glass such as fused silica (SiO_2) or boron trioxide (B_2O_3) thereby eliminating concentration fluctuations. In such cases one deals only with density fluctuations which are essentially governed by the product of the fictive temperature and the isothermal compressibility *of the melt at this temperature*. In fused silica the compressibility is small but the fictive temperature is quite high being approximately 1600°K; the scattering attenuation coefficient (for $\lambda = 6328A$) is 3.9 dB/km. In B_2O_3 the situation is reversed; *i.e.* the fictive temperature is lower ($T_f \approx 550°K$) but the compressibility is much larger. The net effect is a larger attenuation coefficient.

Since it is desirable to reduce the losses below those of SiO_2, a basic study of the fictive temperature and compressibility of glass melts was undertaken. In order to develop materials for which the glass transition region occurs at relatively low temperatures with small compressibilities, it is necessary to modify the covalent character of the bonding in the random glass network. This can be done by dissolving ions within the network, and consequently our investigation first concentrated on the alkali silicate glass systems Li_2O-SiO_2, Na_2O-SiO_2 and K_2O-SiO_2.

Ultrasonic measurements of the sound speed in these melts were performed to determine the compressibilities. One finds in the K_2O-SiO_2 system, for example, that the compressibility remains relatively constant up to about 30 mole percent K_2O; on the other hand the fictive temperature falls precipitously with the addition of alkali. This is shown in Figure 6. The result is that one expects (in the K_2O-SiO_2 system) a minimum in the scattering losses *due to density fluctuations* in the composition range of 20 to 30 percent K_2O content. The question remains, of course, as to whether the reduced value of these losses will be offset by an increase in the attenuation associated with scattering from concentration fluctuations.

The composition fluctuations are inversely proportional to the dependence of the chemical potential on the concentration at T_f, this means that desirable compositions are then those rather far removed from

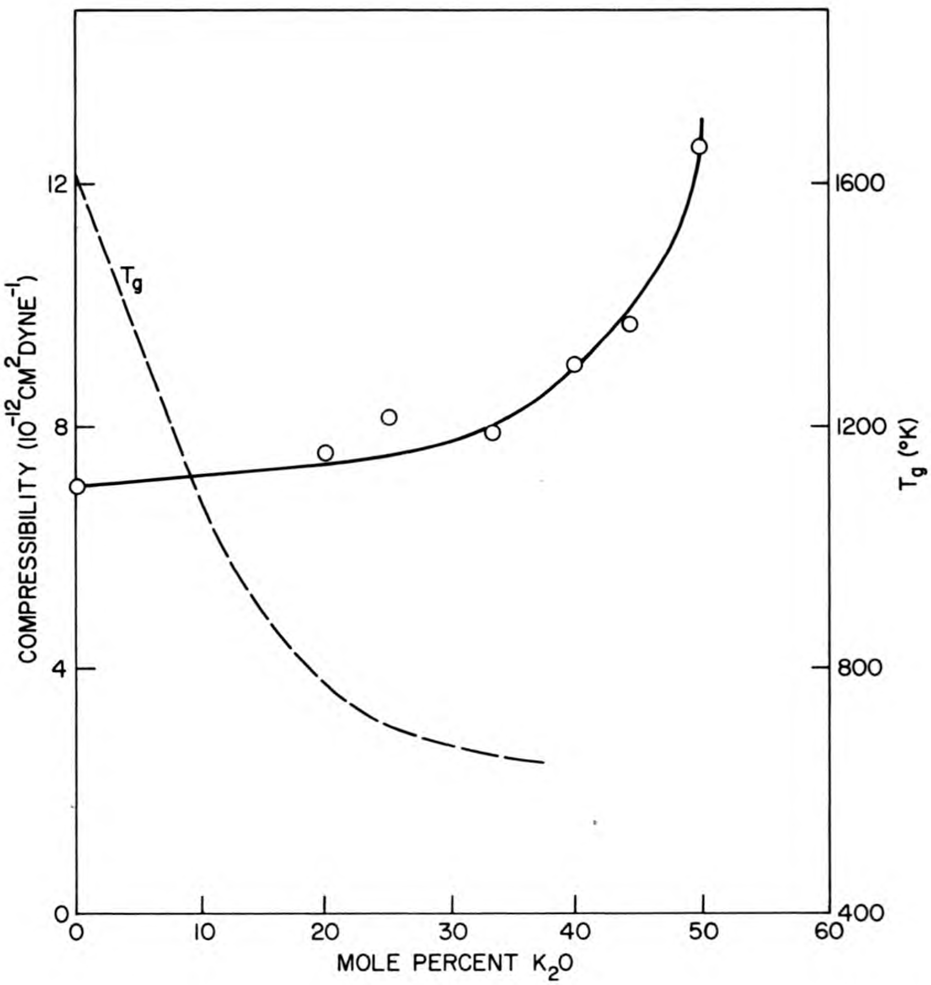

Figure 6 – The compressibility and glass transition temperature of K_2O-K_2O glasses as a function of mole percent K_2O

miscibility gaps in the phase diagram of the material and possibly at concentrations for which the *liquidus* exhibits a maximum corresponding to the existence of crystalline compounds. To avoid problems with immiscibilities it was decided to investigate the K_2O-SiO_2 system first, since here any regions of immiscibility are confined to temperatures below the glass transformation range.

The results of the light scattering study in the potassium silicate system are shown in Figure 7. These data indicate a sharp minimum at 25 mole percent K_2O content at which composition the total scattering loss is only slightly larger than that associated with density fluctuations alone. For this glass – sodium trisilicate (Na_2O-SiO_2) – the total scattering attenuation is

$$\alpha_s = 2.6 \text{ dB/km},$$

one-third less than that in fused silica.

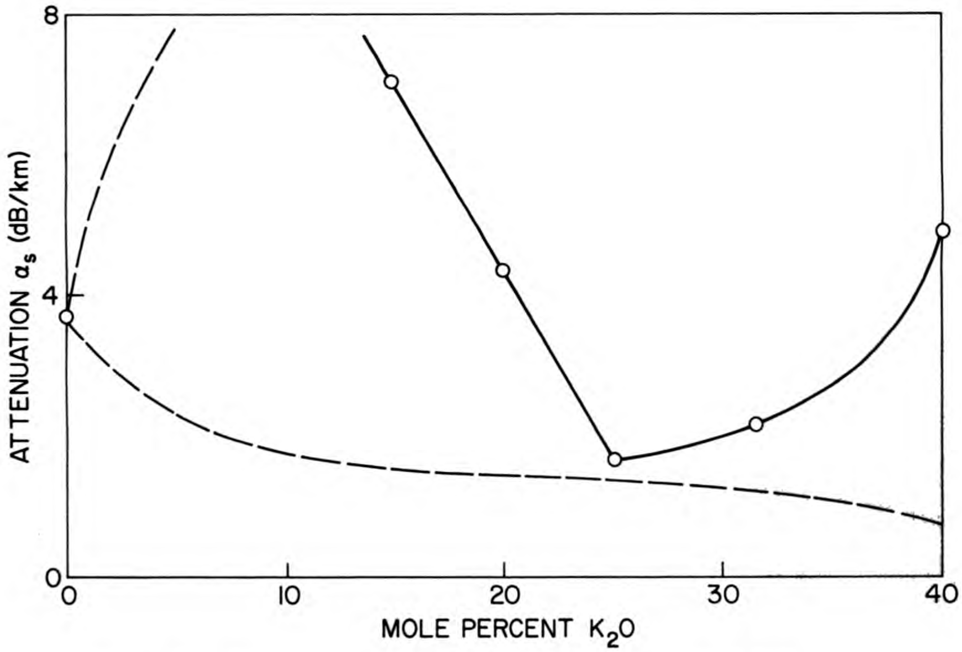

Figure 7 – The scattering attenuation coefficient for K_2O-SiO_2 glasses as a function of mole percent K_2O content

Comparable behavior was observed in other alkali silicate glasses. Both the compressibility and the glass transition temperature were found to decrease with decreasing ionic radius. This would imply that the lithium silicate system offers great potential as an optical fiber material since the losses from density fluctuation scattering are expected to be quite small. However, in the binary Li_2O-SiO_2 system, the formation of homogeneous glasses is confined to the concentration range 30 to 36 mole percent Li_2O. At Li_2O contents less than 30 percent the melts undergo liquid-liquid phase separation while above 36 percent the melts crystallize rather than supercooling to form a glass. For the 30-36 percent Li_2O glasses, the overall scattering losses are in the neighborhood of 10 dB/km, considerably larger than in SiO_2 or K_2O-$3SiO_2$ glasses.

In the sodium silicate system, the light scattering measurements (Figure 8) show that two domains of low scattering losses exist—one between about 25-33 percent Na_2O and the other above about 44 percent. In the 44 percent Na_2O glass the scattering attenuation is the smallest thus far reported. For this glass

$$\alpha_s = 1.6 \text{ dB/km}.$$

What other glass systems are available as potential candidates for an optical fiber material? A brief consideration of the periodic table (Figure 9) indicates that the list is rather limited. The transition elements are

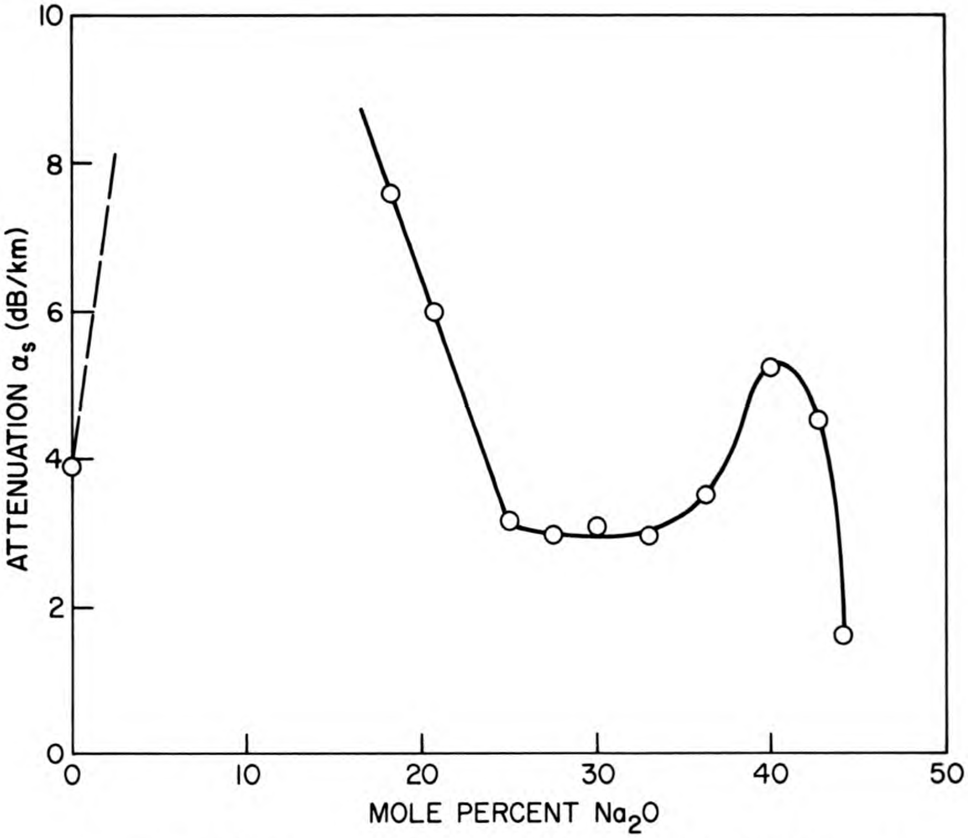

Figure 8 — The scattering attenuation coefficient for Na_2O-SiO_2 glasses as a function of mole percent Na_2O content

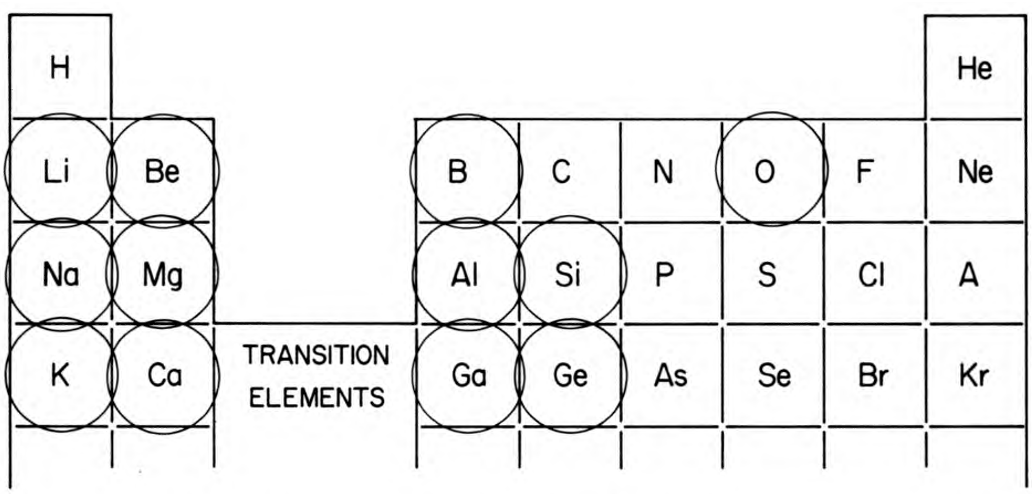

Figure 9 — The first few elements of the periodic table. The circuled elements are the only ones offering potential promise for use in glass fiber optical guides

ruled out because they absorb radiation in the 6000-12,000 Angstrom region. Hydrogen, nitrogen and the noble gases are obviously ruled out. The heavier elements (those in the fifth and higher periods) must be discarded because of their high compressibilities. One expects similar behavior from boron and the halogens although these remain a possibility because these elements greatly lower the glass transition temperature of silicate base glasses. The heavier chalcogen elements, s, Se and Te generally lead to immiscibilities as do phosphates and arsenates. Basically, there are six elements that remain to be studied: beryllium, magnesium, calcium, aluminum, gallium and germanium. The oxides of the first five are currently being investigated in mixtures with SiO_2 and as third components in alkali silicate glasses. Germania (GeO_2) based glasses remain as a whole family of glasses to be studied.

Summary and Conclusion

The implementation of a long range optical communication system requires the development of low loss materials for use in glass fiber optical transmission lines. Of the three major sources of loss—absorption, scattering, and waveguide losses—it is only within the past two years that the latter two have become significant. Until recently, the absorption losses have been three to ten times greater than those attributable to scattering and waveguide defects. The recent announcement by Corning of a fiber with overall attenuation of 5 dB/km at 8500 Angstroms of which 1 dB/km arises from absorption, 1 dB/km from waveguide imperfections and 3 dB/km from bulk scattering, greatly changes this picture. The "leverage" loss mechanism is now the scattering. Our development of a material with 1.6 dB/km scattering loss at 6328A ($\approx$0.5 dB/km at 8500A) means that we have a reduced scattering loss of from 3 dB/km to 0.5 dB/km at 8500A. Assuming that the 1 dB/km figure can be maintained for the absorption and waveguide losses, this would result in a 2.5 dB/km overall loss fiber—a factor of two improvement over the best existing fiber.

Selected References

R. D. Maurer, "Scattering of Light in Glass Media," *J. Chem. Phys.* **25,** 1206 (1956)

D. Marcuse and S. E. Miller, "Analysis of a Tubular Gas Lens," *Bell Syst. Tech. J.* **43,** 1759-1782 (1964)

A. D. Pearson and A. R. Tynes, "Light Guidance in Glass Media," *Am. Ceram. Soc. Bull.* **49,** 969-973 (1970)

A. R. Tynes, A. D. Pearson and D. L. Bisbee, "Loss Mechanisms and Measurements in Clad Glass Fibers and Bulk Glass," *J. Opt. Soc. Am.* **61,** 143-153 (1971)

H. Kita, I. Kitano, T. Uchida and M. Furnkawa, "Light Focusing Glass Fibers and Rods," *J. Am. Ceram. Soc.* **54,** 321-326 (1971)

T. C. Rich and D. A. Pinnow, "Total Optical Attenuation in Bulk Fused Silica," *Appl. Phys. Lett.* **20,** 264-266 (1972)

J. Schroeder, R. Mohr, C. J. Montrose and P. B. Macedo, "Light Scattering in Glass," *J. Am. Ceram. Soc.* (to be published)

Ability of Animals to Withstand Pressures in Ocean Depths*

A hypothesis that has been carried in the textbooks since it was first advanced some eightly years ago now needs revision as the result of research by a Florida State University oceanographer.

As phrased by the French scientist Paul Regnard in 1891, "pressure sensitivity increases with the organic complexity of animals"—in other words, the simpler the makeup of an animal, the deeper he will be able to dive and survive the intense hydrostatic pressure, sometimes several tons per square inch, under the ocean.

It is true, said Professor Robert J. Menzies of Florida State University's Oceanography Department, that some very complex animals, such as man, have the most pronounced sensitivity to pressure. Ears begin to feel the pressure in dives of less than twenty feet below the surface. How far man can go down and survive pressure alone is unknown, because other physiological problems limit diving, but some scientists think that pressure per se will eventually fix the limits of diving several hundred feet down.

It is obvious to students of deep sea biology, Menzies pointed out in a paper read to the 17th International Congress of Zoology at Monaco in September, 1972, that the 1891 hypothesis is in direct contrast with the known facts regarding the depth distribution of marine life, because all levels of aquatic organic complexity from bacteria to fishes are known to exist in depths as great as 8000 meters, or at a hydrostatic pressure equivalent to 800 atmospheres. From this simple observation it follows that factors other than organic complexity are more important determinants in deep sea colonization and hydrostatic pressure acclimitization.

Menzies and his associates in the Oceanography Department under Office of Naval Research sponsorship have conducted a series of laboratory tests of the ability of various organisms to withstand different degrees of pressure.

If the complexity of animals is measured simply by the number of organs, it is immediately apparent that the Flagellata show about the same pressure resistance as the sponge, Coelenterata, flatworms and Crustacea even though the number of organs is different. It is apparent that the tunicate shows a higher resistance than the protozoan, coelenterate and sponges.

The postulated trend from highest pressure resistance to the lowest is shown as a stippled band and it seems evident that the measured values of pressure resistance do not follow this trend until one reaches an organ number in excess of twenty-three.

From the annelids to the vertebrates there does seem to be a decline in pressure resistance as the number of organs increases. Similarly there seems to be a decline in the opposite direction from annelids to the sponge.

Some of the other factors associated with ability to withstand the many atmospheres of pressure deep in the oceans have been under study by Menzies, his colleagues, and his students. Phylum by phylum they have been testing

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(Continued on Page 48)

Generalized Optical Data Processors

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Since the advent of the laser, optical data processing is beginning to experience a renaissance in its application to large and complicated data reduction and processing problems. Its primary strength has come primarily through its parallel processing capability. The digital computer, being a serial device, is at present running into a data rate limit on the order of something less than one hundred megabits per second. At this data rate the optical computer is just coming into its own.

It is, however, not simply a matter of going from one type to another. Rather, the optical computer is at present limited in its ability to have data put in and taken out at rates that correspond to its processing rate. These input-output problems are presently being worked on and recent work by the Naval Research Laboratory and the University of Illinois and others in photodichroics appears to be resolving this problem. It now appears that we will be able to write-in and read-out at rates that correspond to microseconds, and if one considers that data arrays on the order of 10^6 to 10^8 elements can be read at this rate, then the data rate limit described earlier can certainly be surpassed.

Since the input-output problem seems resolvable, attention is again directed at what can be done between the input and output planes. Traditionally, most of the emphasis on formulating the data processing problem and identification of the appropriate filters to do a given task has been done through Fourier transform theory.

It is rather interesting to note that the Fourier transforms are a natural by-product of electromagnetic propagation between two apertures and quadratically varying phase correcting elements. In addition, the fact that spherical and parabolic shaped dielectric media can be obtained so easily has made it even easier to go the route of the Fourier transform processor.

There is, however, no *a priori* reason why one should restrict himself to building only Fourier transformers. The general integral equation that describes the process of propagation between two apertures can just as easily be modified by appropriate complex filters to other kinds of transforms. One could suppose that we would call the basic elements "lenses" just as we refer to the spherically shaped dielectric structures used now, but for the sake of less confusion these will be referred to as system elements.

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To describe what we mean more explicitly, consider the two apertures shown in Figure 1. Aperture s_1 is the radiating or transmitting aperture and aperture s_2 is the observation or receiving aperture. The distance R is the point-to-point separation of the points (x,y,z) and (x',y',z'). In general, it is assumed that $(z'-z) >> (x'-x), (y'-y)$.

In the free-space case, we can represent the process of propagation from s_1 to s_2 as a convolution of the exciting field and the spatial impulse response $h(x'-x, y'-y, z'-z)$ where $h()$ has the form $\exp(jkR)/R$. In the case of the Fourier transform processor, we modify this impulse response function by multiplicatively adding a quadratic phase element $\exp[-jk(x^2+y^2)/2f]$ appropriately between the apertures, adjust their separation to twice the focal length f, and we have the Fourier transform at s_2 of the field distribution in s_1.

The question then naturally follows as to what else can we do to the impulse response to generate either other mathematical operators or other transforms. There are several examples that illustrate this question. If we were to illuminate the input aperture with a field distribution $f(x)$ and then fill the aperture with an amplitude mask that varied like $\exp[-\alpha(y)x]$, then the output aperture s_2 would contain the Laplace transform if a lens were placed as described above.

A second example requires that we add another aperture s_3 in sequence, place a lens as above; then place a filter whose response varies like jx' in s_2; add a lens appropriately between s_2 and s_3; and the output aperture s_3 will then contain a field distribution proportional to the x derivative of the input field distribution.

These elementary examples are only suggestive of what can be done in general. In fact, if one examines the form of the convolution described above, it is an integral equation of a type that encompasses a broad class of transforms, namely Hankel, Laplace, Mellin, Abel, and others. These transforms are also similar to something called a fractional integral representation, which can be broadly represented by a set of operators called the Rodrigues operators.

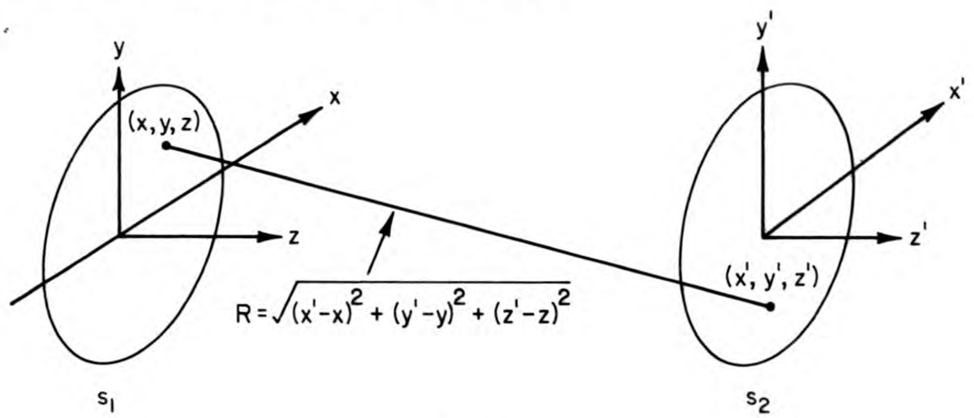

Figure 1

It is important to make this last association, since almost all the functions found in the Bateman Manuscript Project Tables can be represented by the Rodrigues operators. Thus it seems implicit that, with appropriate modification of the impulse response of an optical system, we can generate almost any desirable output function. If this is the case, and we are by no means suggesting that this is an elementary task, then we can generate, by appropriate cascading of systems, optical systems that yield functional forms of any specific type desired. Since almost all functions of the type described above have integral representations, then through these equivalent representations we can describe processors of almost any desired type.

One might at this point wonder why anyone would desire such generalized processors. The answer really rests in examining the needs of the information processing system designer. From the point of view of the Navy, the sonar people would gladly welcome a processor that generated the ambiguity function of an incoming signal. The ambiguity function of a signal is an integral relationship over the signal involving the time delay and the doppler shift of signal where both the delay and doppler shift are incorporated in an exponential type representation very similar to our elementary processor described above.

An additional motivation for more generalized processors is that the Fourier spectrum of many signals, such as square or triangular shaped objects, is far too broad. If one considers the simple example of transmitting a simple truncated distribution of light such as a spatially limited plane-wave, we find that the far-field distribution of energy (proportional to the Fourier transform) is like a $(\sin x')/x'$ function or a broad antenna pattern with high sidelobes. In many cases, this is very undesirable, such as in laser range-finders. Thus one would like to know the optical processor that would reshape the beam to give the minimum distribution on target. In this case it is simple, we should transmit a $(\sin x)/x$ pattern, which has a far-field distribution of a spatially truncated plane-wave.

More fundamental is the question of pattern recognition. If one is searching spectra for specific patterns that represent known objects, such as targets, then one would like to optimize this process. This optimization would not only include signal-to-noise ratio questions, but questions of boundedness on spatial signal spectrum. It would be desirable for certain spectra not to use a Fourier spectral representation since it is so broad for sharp, square, triangular or rectangular objects. It is more appropriate to examine other representations for optimal distributions.

Although much of the discussion above remains in the abstract and needs considerable analysis, there is still sufficient reason to examine what happens between the input-output planes of optical processors. In posing this question we are enabling, potentially, more efficient use of a processor that is basically operating at the speed of light.

The Future of Integrated Optical Technology

LCDR Ralph Hudson*
Office of Naval Research

In order to introduce the concept of optical integrated circuits, the relationship between this technology and the electronics and microwave technologies will be discussed. Following this the generic military functions of communication, sensors, and signal processing will be developed. Representative systems are cited to identify the potential scope of optical integrated circuits technology. In summary, then, to broaden the horizons and challenge the imagination, certain speculations will be offered about where this technology may have led us by the year 2000.

Signal Technologies

To address the question of what are optical integrated circuits, it is useful to first identify the power/signal dichotomy. The power (energy) transformation technology involves weapons, engines, motors, mechanical linkages, *etc*. The signal technology involves computers, displays, telephone lines, cameras, books, *etc*. Optical integrated circuits are in the signal domain. They are concerned with reception, transformation and transmission of data, signal and/or information. While it does take energy to manipulate signals, it is not the same order of magnitude as the manipulation of things (masses). This technology is categorized as classically "signal" *vice* "power" to foreclose any misunderstanding that we may be talking about faster aircraft or bigger bombs. The kind of impact we are talking about is exemplified in the "smart" bomb, an ECM-equipped aircraft or an NTDS ship.

In addition to optics, there are two other technologies which are fundamentally signal technologies: electronics and microwaves. To illustrate how optical integrated circuits relate to these other signal technologies, a historical perspective is shown in Figure 1. The vertical axis relates to the frequency or wavelength of the signals involved. Electronics may be characterized as having wavelengths much longer than the circuit elements. Microwave or radio frequency (RF) technology involves components whose size approximates a wavelength, say within an order of magnitude. Optics, at least classically, has involved components much larger than a wavelength. Very crudely one might say

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each technology spans three to five orders of magnitudes in frequency. The milestones (represented by numbered triangles) shown in Figure 1 are intended to show the state of development of the three technologies. Cross-technology comparisons between milestones reveal a time lag between the various technologies which seem to be closing quite rapidly. While the vertical scale spans orders of magnitude, the horizontal axis, representing historical time, barely spans a generation. In that short period of time we have seen what amounts to an information (signal) revolution probably comparable in scope and impact to the industrial (power) revolution. That revolution is a direct result of the technology development on display here.

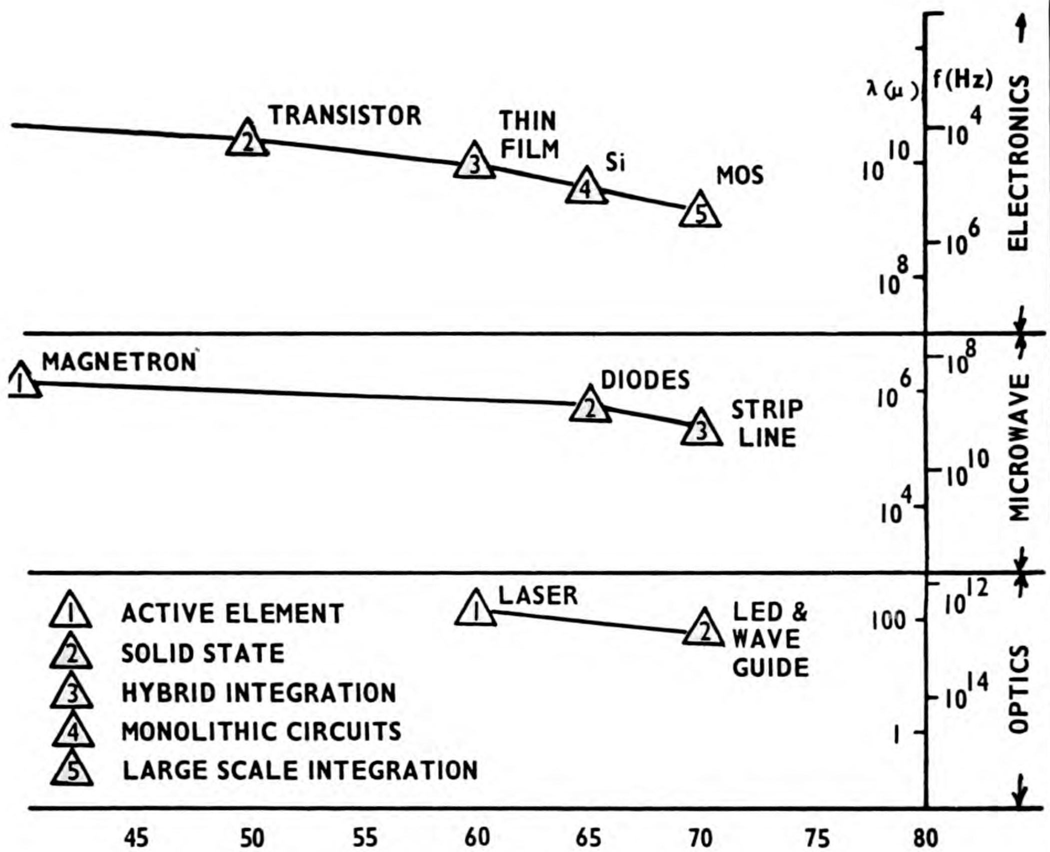

Figure 1 — Signal technology historical perspective

Advantages of Optical Circuits

Having established the relationship between optical integrated circuits and the other signal technologies, it is interesting to delineate the potential advantages and novel features of the new technology in relation to military weapon systems. These are described in terms of the properties of optical circuits and the properties of integrated circuits.

Optical technology enjoys a spectrum of advantages which derive from the very small wavelengths of the signals involved. In general, optical devices can be as small as our technology can make them; thus, there is also a weight saving. Also, the small wavelength means that a modest aperture spans many wavelengths. This allows processing of information carried by the spatial modulation of an optical signal as well as the more conventional temporal modulation. This feature accounts for the very high processing rates associated with optical computers. There are advantages with respect to generation or pick-up of electromagnetic interference in optical data transmission systems. A very high order of electromagnetic isolation derives from the fact that the magnitude of the induced fields decays exponentially with distance measured in terms of wavelengths. The fiber optic data transmission systems based, as they are, on dielectric waveguides are fire-resistant, short-circuit safe, suitable for use in a hazardous environment, and do not create ground loops between subassemblies. Finally there is a unique advantage in terms of signal bandwidths which can be transmitted and processed with optical systems. Bandwidths in excess of one gigahertz (10^9 Hz) appear feasible, and yet when such a signal is transmitted on an optical carrier of say ten thousand gigahertz, it would occupy a negligible part of the available spectrum.

Importance of Integration

On the other hand, the advantages of integration of optical circuits are mechanical stability, reproducibility, size, weight, cost and reliability, minimization of package feed throughs. These advantages are clearly not independent, however, they do represent what can reasonably be expected when a complex optical system is integrated. Possibly the last advantage is worth emphasizing. Many of the size, weight, and bandwidth advantages of optical circuits will be swamped out by the connections until we reach a moderate level of integration. Historically it appears that soon after a technology develops a complete array of solid state components, it becomes connection-limited. Electronics has been connection limited since the development of the transistor. If any military black box is disassembled and the transistors, resistors, capacitors and inductors are sorted in one pile and the leads, wires, connectors and circuit boards into another pile, almost certainly most of the volume, cost, and potential failures are in the interconnection pile. This will be the case whether we are talking about electronics or microwave and hybrid or monolithic integrated circuits.

In summary,

> we are interconnection limited and integrated connections don't count.

As each new level of integration is achieved, the black box functional capability and complexity will continue to increase until limited by the cost and reliability limitation of the interconnections.

Satellite-to-satellite communications provide a unique opportunity to enjoy all the advantages of optical technology without penalty from the normal atmospheric attenuation. In this application performance will be measured in a bandwidth/transmission power ratio. The effective "antenna gain" of even a small lens can be several orders of magnitude greater than a microwave antenna. This ability to concentrate any available transmitter on the intended recipient makes optical data transmission very attractive.

Tethered weapon systems such as towed sonars or "wire" guided weapons could profit from the size advantages of fiber optic data transmission systems. Towed sonars are currently employing a multitude of twisted pairs for the many separate sensor channels. These produce a very heavy cable with associated heavy handling gear. With a fiber data transmission system, the tether would only be as big as required to meet the mechanical strength requirements, a possible reduction over current technology by a factor of four in weight and space.

Optical Sensors

Radar systems are presently limited in resolution by wave length so that the primary function is object detection. Optical radar would easily yield one or two orders of magnitude improvement in resolution, sufficient for object classification or identification at tactical weapon ranges. Such an optical radar would be much more difficult to jam because of the very low "antenna side lobes" of the lens. One can envision rather unconventional applications for a very low-power optical radar. For example it may prove useful in an aircraft for a sensor inside the cockpit to track the head and eye movements of the pilot. Using this as a human control input to the computer may facilitate many pilot functions such as sensor or weapon designation and instrument scanning.

The generic military functions within the realm of integrated optical circuits are signal transmission, signal processing and sensors. Each of these functions will be illustrated with specific military functions and a description of the unique advantages that integrated optical circuits might have to offer.

Optical Data Transmission

Flight deck communications present a unique challenge. The ambient audio noise environment coupled with the persistent wind over the deck virtually rule out conventional acoustic transmission. This problem has been attacked using microwave broadcasters (commonly called Mickey

Mouse headsets). This approach has proven functional; however, they are subject to clandestine monitoring and they occupy a crowded portion of the spectrum and thus suffer from electromagnetic interference. Transmission over an optical channel would relieve the spectrum congestion. Further, a suitable frequency (or wavelength) could be selected for atmospheric absorption to limit the range of transmission.

As the Navy expands its fleet of air-capable ships the requirement for air to ship communications will expand very rapidly. These aircraft will serve to extend the range of the ship sensors. Maximizing airborne sensors within the weight constraint imposed by small-ship compatibility probably implies a minimum of sensor data processing on the aircraft. Transmission of unprocessed sensor data will require very high-data-link bandwidths. Optical data systems offer a maximum bandwidth with minimum interference, weight, and space. In addition, the beam can be most effectively constrained to the intended recipient.

Optical star trackers have application for back-up navigation. Functionally such a device is very similar to an infrared seeker on a missile. In either use, this function is currently accomplished with mechanical pointing directed through feed back from some form of centroid sensor. Integrated optical technology could eliminate all of the mechanical gadgetry using electronic aperture steering driven by a two axis, phase comparison, monopulse optical circuit.

Optical Processing

Optical signal processing can be conveniently considered of two types: distributed and discrete. The realm of distributed signal processors relies upon processing, in parallel, all of the data in a spatially modualted optical signal. Included in this category are optical memory, optical correlator, and optical transformation. This class of processors is discussed in detail in a companion article in this issue.

Discrete signal processing functions include modulation, switching, frequency selection and direction selection. These discrete functions are quite analogous to similar functions in the microwave technology. In effect these are the functional building blocks from which the military subsystems already discussed are assembled.

Future Requirements

An overview of the trend in military weapon systems is toward increasing data rates. Contributing to this trend will be the availability of light and reliable integrated optical sensors. As the data rates go up, integrated optical data transmission system will become more attractive. Since the human bandwidth will not be increasing, our data processing capability must expand in proportion to our increasing data rate. Integrated optical processors will be required to meet this challenge.

Consider the sort of projections that might have been suggested some 25 years ago with respect to the potential military applications of solid state electronics. Those projections would appear trivial in comparison with the modern phased-array radar, the airborne digital computer, and the satellite-assisted communications systems of today. These systems are feasible as a direct result of the integration of electronic and microwave circuits. Today optical technology stands on the threshold of dramatic growth as a result of integration of optical circuits. All of the functional elements are in hand, though many have come to hand just recently. These include low-loss fiber optic data transmission lines, solid state lasers, thin film wave guides, thin film modulators and deflectors, and solid state detectors.

If this technology develops only as rapidly as electronics have over the next 25 years, the new capabilities will stagger the imagination. However, there is considerable evidence that the development of integrated optical circuits will proceed even faster because of the strong technology base of integrated electronic circuits. This technology base includes theory and practice in solid state physics, microfabrication, availability of exotic materials, and theory of electromagnetic propagation. The Navy is embarked on an aggressive program of research and development to realize the potential of integrated optical circuits at the earliest possible time.

(Continued from Page 39)

animals in a pressure vessel designed and constructed by Donald Phillips of the department.

The colleague who has worked most closely with Menzies is Robert Y. George, research associate and adjunct professor of oceanography at Florida State University. George holds a Ph.D. degree in marine zoology from the University of Madras, India.

Menzies and George are the authors of a book, *Abyssal Environment and Ecology of the World Oceans,* that was published by John Wiley and Sons in December.

Menzies' and George's discoveries in the area of pressure-resistance have come so rapidly during the past two years that only one of them so far has been reported in a scientific journal, although others have been reported at several international conferences.

They reported on experiments related to hydrostatic pressure resistance and temperature in the March, 1972, issue of *Marine Biology*. Again they demolished a view that had been held for some time, that creatures of the Tropics and other hotter climes usually are better equipped to survive intense pressures of the ocean depths than are Arctic or other cold-to-warm water species.

Again using their pressure tank filled with "instant ocean," water of thirty per cent salinity, the scientists compared fiddler crabs and other animals from the intertidal waters off Panama with similar creatures taken from the shallows

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off FSU's Marine Laboratory at Turkey Point where there is a wide seasonal range of temperature in the Gulf waters.

They found that the species from colder waters survive more readily. Menzies explained that prevailing contrary views may have come from observation only of reversible behavioral responses of animals to pressure—not always a good guide to their real ability to survive.

He explained that hydrostatic pressure usually affects animals in a four-step process. When confronted with extreme pressure an animal typically reacts at first with a sudden outburst of violent activity. Crabs, for instance, crawl rapidly around a pressure chamber, shrimps swim more rapidly than usual and fish swim violently.

This response is followed by paralysis, or tetany, in which the animal exhibits uncoordinated muscular contractions.

The third phase is inactivity, and this phase is followed by death.

In the experiments at FSU, observations were made and photographs and movies taken of the initial stages (sometimes the first reaction does not occur) and the experiments were extended until a fifty percent kill of organisms occured when they were immersed for one hour at a specific pressure.

Within the temperature range of the experiments it was shown that the reversible responses increased with increasing temperatures but the results were quite different for ultimate survival.

It is ecologically significant that among the species thus far tested, the pressure required to achieve a fifty percent kill increases with decreasing temperature, even though the rate of increase is not constant or consistent. These data suggest that the survival of invertebrates with reference to lethal pressure should be better among cold-water species (or species living in water of varying temperatures who have been acclimated to cold water) than for tropical species living at high temperature.

The latest discovery, made only a few weeks ago, is that the larva of a tiny fly that is a pest along the Gulf Coast—an animal that never has occasion to live in the ocean depths during any of its life stages—has an ability to withstand pressure greater than in the deepest part of the ocean, the Mariana Trench.

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Argon Excited Optical Waveguide

An optical waveguide formed by Ag^{+} ion exchange in glass irradiated by 5145 Å argon light. The light is coupled in and out of the waveguide by a set of coupling prisms and is projected on a screen.

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