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REPORT 1339

DEVELOPMENT OF OPTICAL WAVEGUIDES AND COMPONENTS

PROGRESS, FEBRUARY 1965 TO MARCH 1966

by

E. RONALD SCHINELLER and DONALD W. WILMOT

WHEELER LABORATORIES, Inc.

For

National Aeronautics and Space Administration

CONTRACT NAS 12-2

1966 APR 14

JOB 466.1

N66 32757
(ACCESSION NUMBER)

113
(PAGES)

CR-76843
(NASA CR OR TMX OR AD NUMBER)

(THRU)

1
(CODE)

16
(CATEGORY)

FACILITY FORM 602

WHEELER LABORATORIES

122 Cutter Mill Road - Great Neck, N. Y.

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Report 1339

DEVELOPMENT OF OPTICAL WAVEGUIDES AND COMPONENTS - PROGRESS, FEBRUARY 1965 TO MARCH 1966

By E. Ronald Schineller
and Donald W. Wilmot
Wheeler Laboratories, Inc.

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Summary

A study of optical waveguides and waveguide components, initiated on a previous contract, has been continued. Emphasis has been on the development of large-size waveguide and components which operate in a single-mode manner. The anticipated applications of these devices include laser communication and tracking systems.

The waveguide portion of this study has been directed toward obtaining a practical, all-solid, dielectric-slab waveguide. A significant result of this program has been the operation of two pseudo-solid waveguides. One of these consisted of a fused-silica core with a cladding of a different grade of fused silica having a slightly lower refractive index. This guide limits propagation to three waveguide modes over a large temperature range. The other pseudo-solid guide was fabricated from precision optical glasses and was also limited to the three lowest-order waveguide modes. The waveguide work has also included theoretical and experimental investigations of various fabrication techniques including precision glass machining, optical cementing, precision annealing of glass, proton and neutron irradiation, and vacuum deposition. In addition, various novel types of optical waveguides have been studied. Included are dielectric guides with a low-index core, metal plasma waveguides, and a bisected version of the previously studied dielectric-slab waveguide.

The effort on components during this reporting period has been devoted to the experimental study of waveguide directional couplers and a waveguide laser. Slot-type couplers have been implemented, and coupling ranging from 7 to 17 db has been demonstrated. The variation of the amount of coupling with waveguide conditions is shown to agree with theory although the actual magnitude of the observed coupling is lower than that predicted by a simple theoretical model. An evanescent-field coupler has also been tested. However, coupling has not yet been observed in this configuration - probably because of a difference in phase velocity existing between the component waveguides, which upsets one of the necessary conditions for coupling.

An experimental model of a waveguide laser has been implemented. This laser comprises a core of Nd-doped glass and a liquid cladding. Partially transmitting aluminum mirrors at either end of the waveguide form the laser cavity. Near- and far-field radiation characteristics of this laser, pumped below threshold, indicate an intense, directed beam at a wavelength of 1.06 microns caused by directed fluorescence. It is expected that lasing will occur when the effective Q of the resonant cavity is increased.

These studies and experiments are considered confirmation of the general feasibility of all-solid waveguide components, and the experimental work on the slot coupler indicates the practicality of designing such components.

Contents

List of Figures

Contents (continued)

List of Figures Page

Contents (continued)

List of Figures Page

I. Introduction.

This report covers a thirteen month program for development of optical waveguides and waveguide components. The work was performed during the period FEB 1965 to MAR 1966, and is a continuation of a previous program on the same topic (Ref. 7). The objective of the entire program is to develop a single-mode waveguide medium for construction of high performance optical components, and to investigate and develop component designs similar to those available at microwave frequencies.

The waveguide which has been utilized is a dielectric waveguide composed of a core dielectric surrounded by a cladding dielectric of lower refractive index. In order to provide a waveguide with practical dimensions in which propagation is restricted to a single mode, the difference in refractive indexes between core and cladding is made very small. This approach results in a guide which has all the advantages of single-mode operation and yet is sufficiently large for component development. The propagation characteristics of this guide were investigated extensively on the previous contract and component designs were studied. Effort on the present contract has been directed to development of the waveguide in more rugged, practical configurations utilizing solid materials only, and to fabrication and testing of several component designs.

The principal results of the investigation on the present contract are described in Sections II and III of this report. Section II describes the various approaches toward development of a completely solid waveguide medium; section III describes the development of a directional coupler and a single-mode laser fabricated within the waveguide medium. A paper entitled, "Optical Waveguide Modes in a Bisected Dielectric Slab", to be published as a correspondence in the Journal of the Optical Society of America is included as Appendix I of this report. This paper describes the nonconventional behavior of a dielectric waveguide constructed with a real metal bisecting wall. Appendix II presents a survey of past and present work in the field of optical waveguides. Detailed results of an investigation of irradiation techniques for forming optical waveguides are presented in Appendix III.

II. Waveguide Development.

A theoretical and experimental investigation of techniques for fabrication of optical waveguide is presented in this section. The objective has been the development of a waveguide medium which is rugged, capable of operation over a wide temperature range, and which is suitable for construction of compact components. Several types of waveguide have been investigated; the greatest effort has been directed to the dielectric waveguide with very small difference in refractive index between core and cladding. The essential requirement is two materials with very good optical quality having refractive indexes differing by a required small amount.
The requirement that the waveguide be insensitive to temperature variations has restricted the consideration to solid materials only. An investigation of potential solid materials, as well as techniques for obtaining a small difference in refractive index between them as required by this waveguide are discussed in Part B of this section. However, first, a number of alternate waveguide configurations which have been considered are discussed in Part A. Finally, various techniques for assembling the composite materials in the required waveguide configuration are presented in Part C.

A. Configurations.

The first waveguide configuration considered is the dielectric-slab waveguide with a core dielectric surrounded by a cladding dielectric of slightly lower refractive index. As mentioned, this type has received the greatest effort and its theory of operation has been presented in detail in previous reports. Although the theory of operation is rather straightforward, its practical implementation is difficult because of the severe requirements on the refractive index of the waveguide materials. However, this waveguide has been successfully operated in liquid-solid and pseudo-solid configurations and the observed performance is in excellent agreement with the theory. Specific problems related to its practical implementation are treated in Parts B and C below.

A variation of the dielectric waveguide described above, utilizes a core dielectric surrounded by cladding dielectric of higher refractive index. This waveguide has also been investigated both theoretically and experimentally, in a slab configuration. Analysis indicates that there are discrete modes of propagation, each having a well-defined field pattern and a particular propagation constant. However, the number of modes is determined solely by the waveguide size and refractive index of the core, and is independent of the difference in refractive index between core and cladding regions. Also, all of the modes propagate with some attenuation, i.e., the waveguide supports only leaky modes. The attenuation depends on the difference in refractive index, and is different for different modes. Therefore, some mode discrimination can be obtained by index selection of the core and cladding materials.

A graph of attenuation vs. difference in dielectric constants for the waveguide with low index core for the first three modes of propagation in waveguide sizes of 50 and 100 wavelengths is shown in Fig. 1. (It should be noted that the dielectric constant is equal to the square of the refractive index for lossless media. The difference in dielectric constants (Δk) is equal to twice the product of refractive index and difference in refractive index ($\Delta k = 2n\ \Delta n$) when the difference is small. Therefore, Δk and Δn are linearly related, differing only by a factor of about three, and either term can be used depending on which is more convenient.) The curves in Fig. 1 indicate that the attenuation is greater for higher order modes, but decreases as both the difference in dielectric constants and the waveguide size are increased. It is possible to select the waveguide parameters to obtain an operating point where the attenuation for the lowest order ($m = 1$) mode is tolerable for some applications, and yet the attenuation of higher modes is sufficient for mode discrimination. For example, for a 100 wavelength guide with a difference in dielectric constants of 2×10^{-3}, the loss is 2.5 db/cm for the $m = 1$ mode and 9.5 db/cm for the $m = 2$ mode.

The above results suggest that while the waveguide with low index core is not as attractive as the conventional type because of the inherent attenuation, it may be useful for certain specific applications. One such application which was investigated briefly is a scanning device. The direction of the leakage radiation from the

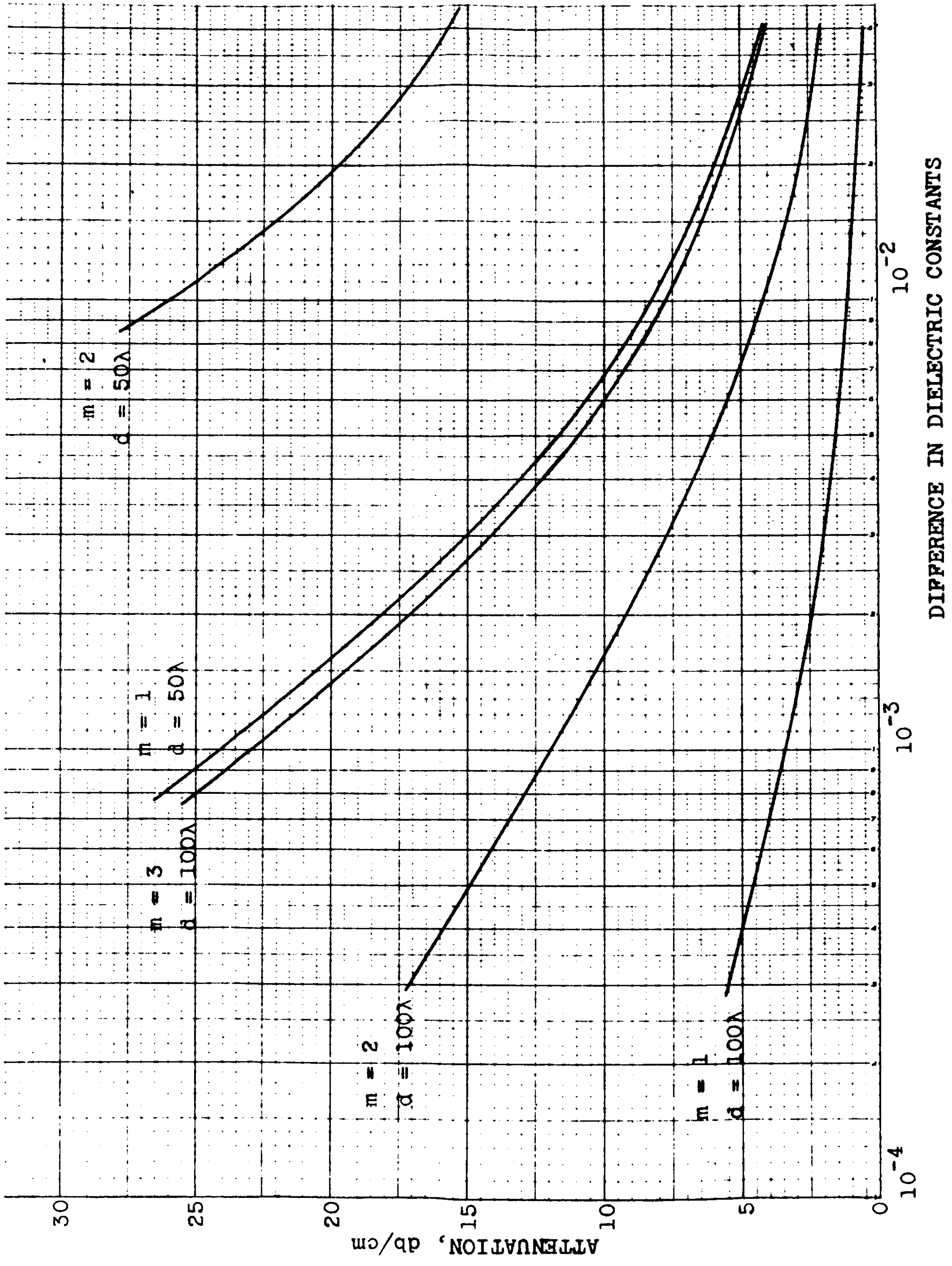


Fig. 1 - Attenuation of dielectric-slab waveguide with low index core.

sides of the waveguide depends on the difference in dielectric constants between the core and cladding regions. Therefore, if one of the waveguide media were made of an electro-optic material, the direction of the radiated beams could be scanned electronically.

Another type of waveguide which has been studied briefly as an alternative approach for a solid waveguide is a metal plasma waveguide. Most metals act as a plasma at optical frequencies. Waveguides utilizing a plasma as the core region and a conventional dielectric for the cladding have been proposed and analyzed by others (Ref. 5). A configuration which could be implemented at optical frequencies would be a layer of metal, such as silver or aluminum, deposited on a glass substrate; the metal serves as the plasma core and the glass or air surrounding it as the cladding.

However, since metals are relatively lossy plasmas at optical frequencies, (Ref. 3) such a waveguide can have high attenuation. In order to reduce the attenuation, it is necessary to design the guide so that most of the energy propagates in the glass or air region, rather than the metal. This can be achieved by making the metal very thin, i.e., a small fraction of a wavelength. In this case, the effective waveguide size (defined as the region within which most of the energy propagates) is many wavelengths in size. However, even for the case of a very thin metal, the attenuation is at least a few db/cm. Also the theory of operation becomes complicated when the metal is very thin and fabrication is more difficult. In view of these limitations, this type of waveguide is not considered as attractive as the dielectric type, and further investigation is not planned.

B. Materials.

An investigation of solid waveguide materials has been conducted specifically for the dielectric-type waveguide. The fundamental requirements of the bulk materials for the component parts of the guide are: (1) the dielectric must be transparent (low loss) at the operating wavelength, (2) the material must be very homogeneous, i.e., the variation in refractive index must be very small. In addition to these requirements on the bulk material, it is necessary to obtain two such materials having a difference in refractive index in the range of 10^{-4} to 10^{-5}.

Three materials which have been considered are glass, fused silica and plastics. In general, the highest quality optical glasses have sufficient homogeneity specifications for the waveguide application. The glass which has been used extensively in this work is astronomical objective quality, borosilicate crown (BK-7) glass from the Schott-Jena company. Initial evaluation of this material was performed by testing thin slabs, 75 mm x 25 mm x .054 mm, which were fabricated by optical grinding and polishing. The glass slab, 85 wavelengths wide, formed the waveguide core and was immersed in a liquid (chlorobenzene) cladding. In general, operation of this waveguide was excellent. Single-mode operation was easily achieved and under multi-mode conditions, all higher order modes were clearly visible. This glass is considered a suitable material for waveguides in sizes up to 100 wavelengths.

Various grades of fused silica are commercially available which have stated homogeneity specifications sufficient for the waveguide application. The Ultrasil grade of fused silica manufactured by Engelhard Industries has been tested in the same arrangement as that described above. A .06 mm (95 wavelengths) slab of Ultrasil was immersed in a turpentine cladding. Although it was possible to achieve single-mode operation, the modes observed were not as clear as those for the BK-7 glass. Consequently, although fused silica is still considered a satisfactory waveguide material, it will preferably be used in waveguide sizes of about 50 wavelengths where the material requirements are less stringent.

Another class of materials investigated for the waveguide medium are the various types of plastic. In general, the optical quality of plastics is not sufficient for the waveguide application because of insufficient homogeneity. The only one with nearly sufficient homogeneity is methyl methacrylate (common names lucite and plexiglas) which has an index variation of the order of 10^{-4}. However, lucite is not commercially available in sheets thin enough for a waveguide core. An order was placed with National Photocolor

Corp. (maker of thin plastic sheets called "pellicles"), but they were unable to cast lucite in thin sheets with good surface quality. A brief experimental attempt conducted at Wheeler Laboratories to cast lucite on a pool of mercury was also unsuccessful. For the above reasons, the use of presently available plastics as waveguide materials is not considered feasible.

As mentioned previously, a major problem to be overcome after selection of the bulk material is that of obtaining two such materials with a very small, but precise difference in refractive index. For the waveguides of 50 to 100 wavelength size being developed, the required difference in refractive index is from 10^{-4} to 10^{-5}. A number of techniques which have been investigated for achieving this difference are: (1) heat re-treatment of glass, (2) selection of slightly different grades of a given material, and (3) atomic irradiation.

Heat re-treatment of glass is a technique whereby two identical samples of glass, which were made from the same melt, are re-annealed through slightly different temperature cycles. After treatment, both samples will have identical properties except that the refractive indexes differ by the desired amount.

The effect of heat treatment on the refractive index of glass is treated briefly in Ref. 2. Two methods of annealing, (1) constant temperature and (2) constant cooling rate, are discussed. For typical glasses, the constant cooling rate method requires less stringent temperature control. However, both methods appear feasible for our requirements.

A conference was held with representatives of Bausch and Lomb, Inc., Rochester, N. Y. to discuss the feasibility of heat re-treatment techniques. Subsequent to this meeting, an order for two samples of glass with a refractive index difference of 10^{-5} and index variation within the individual pieces limited to 10^{-6} was placed with B&L. Upon receipt of this glass, waveguide parts were fabricated by grinding and polishing thin slabs from the higher index material to serve as the core, and thicker slabs from the low index material for the cladding. These slabs were then assembled for testing in what we have called a pseudo-solid waveguide configuration. In this arrangement, illustrated in Fig. 2, a thin core is sandwiched

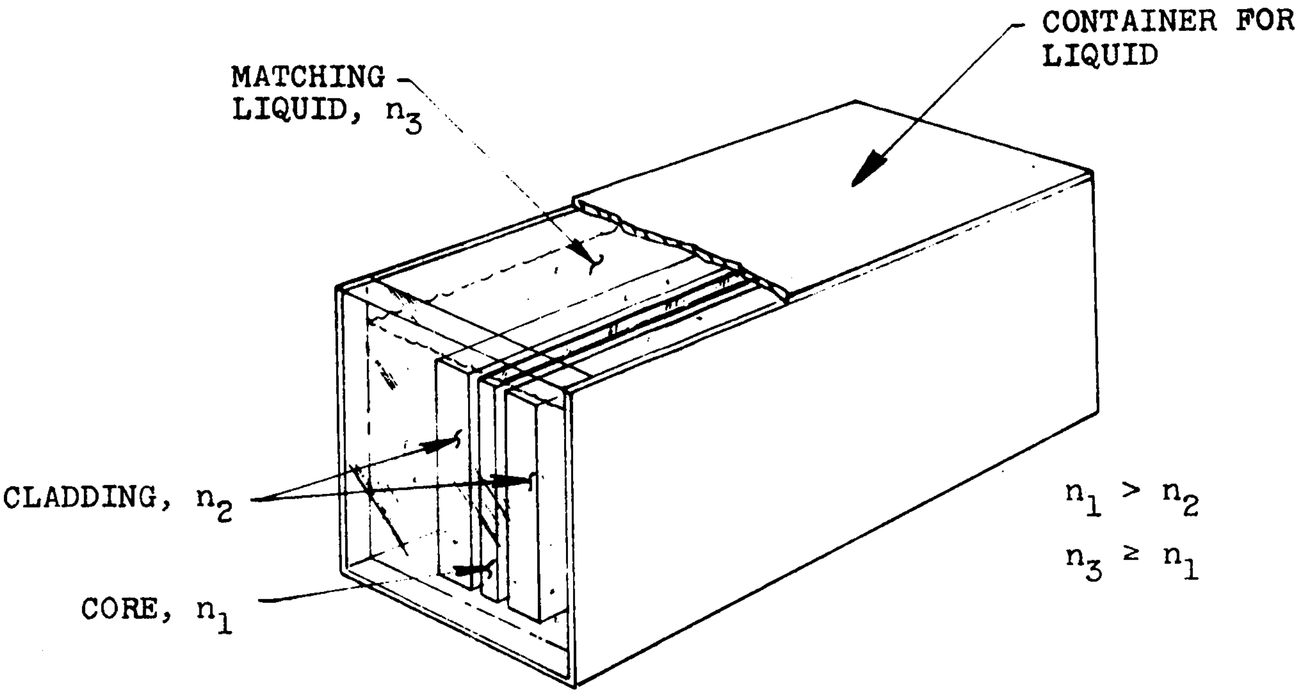


Fig. 2 - Pseudo-solid waveguide.

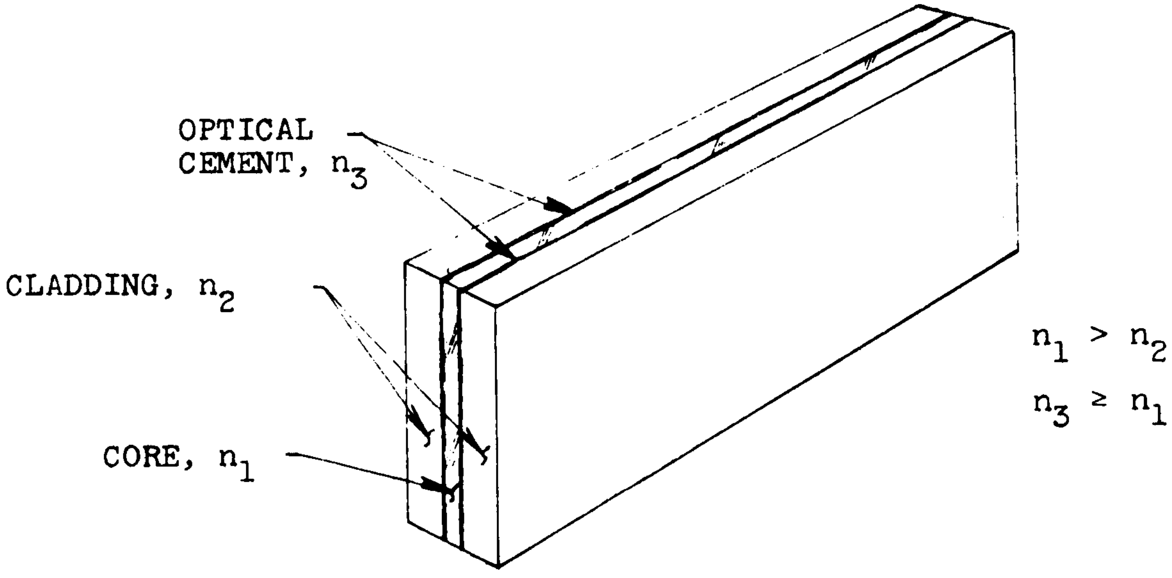


Fig. 3 - Completely solid waveguide.

between two claddings, and the entire assembly is immersed in liquid. The liquid region is very thin and serves only to fill the gap between the core and cladding. Ultimately, the core and cladding will be joined by one of the techniques discussed later, thus eliminating the liquid entirely.

The pseudo-solid waveguide was tested by observing propagation as the refractive index of the liquid was varied. With the index equal to, or greater than, the core index, the guide was restricted to three modes of propagation, independent of the liquid index. This suggests that the difference in refractive index between the two glasses was about 4×10^{-5}, which is larger than that required for single-mode operation with this thickness. Subsequent to these tests, measurement of the refractive indexes of these glasses at B&L indicated a refractive index difference of $3 \times 10^{-5} \pm 1.5 \times 10^{-5}$. Therefore, the value of 4×10^{-5} suggested by the waveguide evaluation falls within the tolerance of the B&L measurement and tends to verify the conclusions regarding the waveguide behavior.

It was possible to operate this guide over at least a twenty degree Centigrade temperature range with no observable change in propagation characteristics. This experiment confirms that a waveguide fabricated entirely from solid materials can operate in a stable manner over a wide temperature range. When the index of the liquid was lower than the core index, the presence of the liquid was apparent and the number of modes varied with the index of the liquid. This behavior indicates that even a thin layer of dielectric cannot be tolerated between the core and cladding if its refractive index is lower than that of the core. However, the successful operation when the index of the liquid in the gap was high is significant in that it suggests assembly of the waveguide parts by cementing techniques as discussed later. Although single-mode operation was not achieved, Bausch and Lomb reports that it should be possible to obtain the required index difference of 1×10^{-5} on another try, using the same heat re-treatment technique.

The second technique mentioned for obtaining materials with the required small difference in refractive index is specific selection of materials. In particular, two grades of fused silica, Ultrasil and Suprasil have been investigated. Both grades of silica have sufficient homogeneity specifications, and also are reported to have a nominal index difference of 10^{-4}. These materials could be used to fabricate a waveguide with Ultrasil (which has the higher index) as the core, and Suprasil as the cladding. However, a serious limitation of this technique is that the index of the individual grades can vary by as much as 10^{-4} from batch to batch. Therefore there is a relatively small probability of obtaining the required index difference by a random selection of samples from the two grades. Nevertheless, in order to evaluate the materials, samples of Ultrasil and Suprasil silica were fabricated into waveguide cores and claddings respectively, and were tested in the pseudo-solid configuration. The results were similar to those obtained with the glass materials except that the modes were not as clear.As with the glass guide, when the index of the liquid (turpentine) was higher than the core index, three modes propagated; when the liquid index was lower than the core index, the number of modes varied with the index of the liquid. These results indicate an index difference of about 4×10^{-5} which is quite reasonable based on the reported variation from batch to batch. In view of the somewhat poorer performance compared to that observed for the pseudo-solid glass waveguide, and because of the random selection process, the selection of grades of fused silica is not considered as attractive a technique for solid waveguide fabrication as the heat re-treatment technique discussed earlier.

The third technique for acquiring materials with a small difference in refractive index is atomic irradiation. The basic approach here is to start with a sample of high quality optical material and change the refractive index of part of the material by irradiation. A waveguide can then be fabricated either by, (1) fabricating cores and claddings from the irradiated and un-irradiated regions and then assembling as a waveguide, or (2) irradiating a thin localized region corresponding to the size of a waveguide core with the un-irradiated region serving as the cladding. This second technique eliminates the need for separate fabrication of cores and claddings.

A survey and study of various types of radiation and their effects on optical materials has been conducted,and is presented in detail in Appendix II of this report. Only the more significant results of this study are presented below.

There are two fundamental processes for inducing an index change in optical materials such as glass. The first technique is to introduce absorption bands (color centers) into the material which have an index change associated with them. This requires some form of ionizing radiation such as gamma rays. The amount of index change which can be achieved by this technique is generally very small, being marginal even for the waveguide application. Also the amount of absorption which is introduced can be prohibitive. A method of avoiding the absorption is to induce color centers in the ultraviolet region of the spectrum while operating the waveguide in the visible. The absorption in the visible band is negligible but sufficient index change is present to form a waveguide. Although the color center approach did not appear promising enough for experimental testing on this contract, it will be considered as a possible technique for future work.

The second method of changing the index of a dielectric is to irradiate the material with particles such as neutrons and protons, which cause displacements of the atoms and a resultant density change. Density changes may be obtained which correspond to a change in the index of the material as large as 10^{-2}.

In view of the rather large index change which can be obtained, this technique was considered in greater detail both on a theoretical and experimental basis. Study of the penetration depth of neutrons and protons indicates that neutron penetration is always large compared to the width of a typical waveguide, while the penetration depth of protons can be made comparable to the waveguide width. Therefore, neutron irradiation is applicable for changing the bulk properties of a material, which can then be fabricated into a core or cladding. On the other hand,proton irradiation might be used to irradiate the surface of a material to form a waveguide core, with the remaining substrate acting as the cladding. Irradiation with protons is discussed in greater detail in Part C where assembly techniques are considered.

The variation of refractive index with neutron irradiation for both fused silica and glass is discussed in Appendix III. The neutron dosage to produce a change in refractive index of 1×10^{-5}, as required for a single-mode waveguide of 100λ dimensions, is

10^{16} neutrons/cm^2. In order to experimentally confirm these calculations, three samples of Ultrasil fused silica were sent to Brookhaven National Laboratories (BNL) for neutron irradiation in their reactor. These samples will receive dosages of 2.5×10^{16}, 5×10^{16} and 10×10^{16} neutrons/cm^2 which correspond to irradiation times of 1, 2 and 4 weeks respectively. The samples have not yet been returned from BNL. Actually, the dosage times mentioned above should result in an index change which is greater than 1×10^{-5}; however, these experiments are intended as diagnostic tests to determine the exact index change for this particular grade of silica. Also, the index change can be reduced after irradiation by re-annealing; this will provide a method to "trim" the material for the exact index difference required.

The technique of index modification by irradiation with atomic particles is considered a feasible technique and will be investigated further. However, the use of neutrons to modify the bulk index of a material, although feasible, does not appear as attractive as the heat re-treatment technique discussed previously. On the other hand, the use of protons to modify limited regions of a material is considered attractive because it eliminates the need for separate fabrication of the waveguide parts as discussed below.

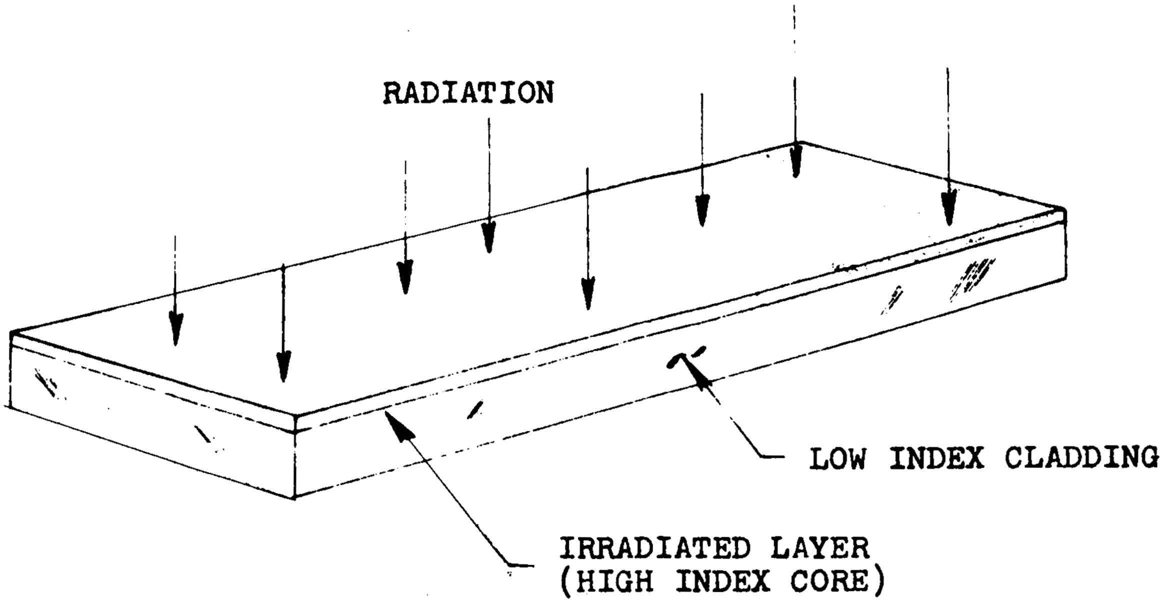
C. Fabrication.

A number of techniques have been considered for fabrication of all-solid waveguides. First, techniques for assembling samples of waveguide materials which have previously been processed to have the required index difference and have been fabricated into cores and claddings are discussed. Second, the technique of radiating limited regions of a material to form waveguides without separate fabrication of cores and claddings is presented. Finally, an investigation of vacuum-deposition techniques for waveguide fabrication is reviewed.

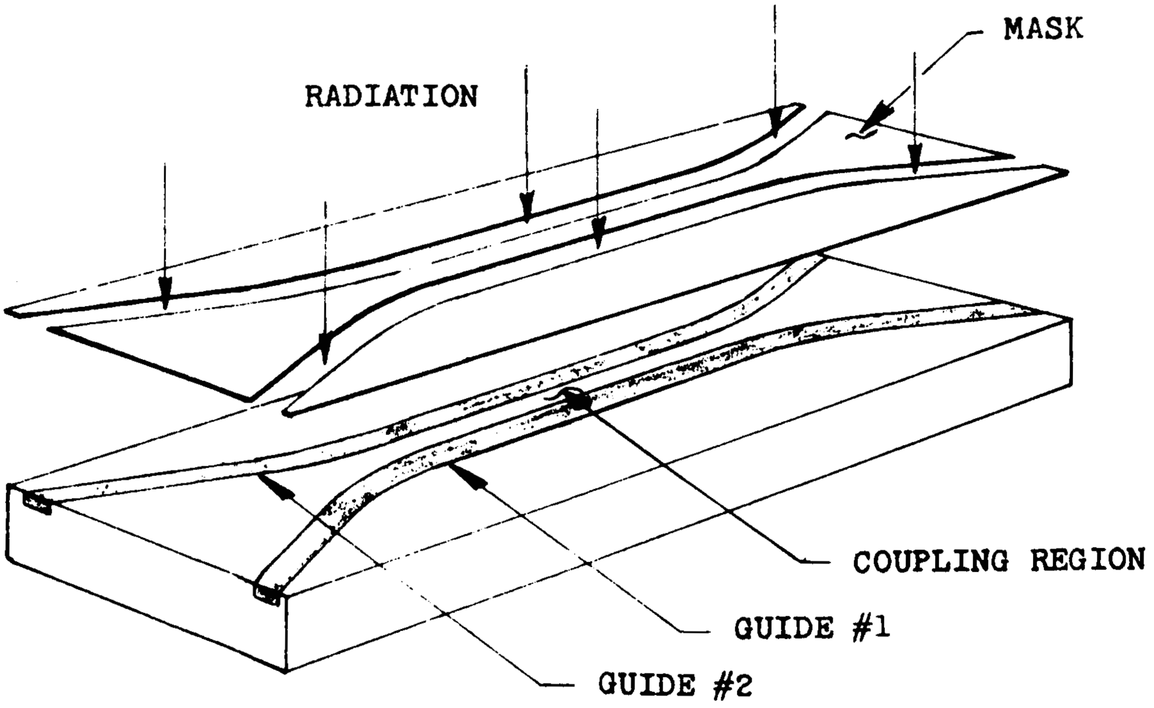
In the first approach, waveguide cores and claddings such as those utilized in the pseudo-solid waveguide experiment would be permanently bonded together. The most obvious technique is to bond the pieces together with an optical cement having a refractive index equal to either the core or the cladding. Unfortunately, optical cements whose index can be selected to this precision are not presently available. However, the results of the pseudo-solid waveguide experiment indicated that a dielectric material (such as an optical cement) can be used between the core and cladding provided the index is higher than both the core and cladding. Such a waveguide is illustrated in Fig. 3. Subsequent analysis of this waveguide has confirmed that a high index dielectric can be used between the core and cladding, provided the index is not too high and the layer is not too thick. Analysis indicates the thickness should be limited to about one wavelength (although a thickness of a few wavelengths was present in the experimental pseudo-solid waveguide). Within these limitations, a waveguide which is single-mode without the cement will operate single-mode with the high index cement. The attenuation of the higher (leaky) modes is somewhat lower than for the simple guide, but is still expected to be sufficient for mode discrimination.

An alternative technique for bonding the core and cladding materials is to heat the glasses to the melting point and fuse them together. The problem with this technique, of course, is that such heat treatment will change the optical properties of the glass. For this technique to result in a high quality glass after fusion, the glass would have to be cooled as in a normal annealing cycle. The resulting index difference between the two glasses might be quite different from that prior to assembly. However, Bausch and Lomb has indicated that it may be feasible to select two types of glass which could be fused together in this way, and which would have the desired index difference after annealing. However, it is not a conventional process, and estimates are it would require about a one man-year development program. Because of the developmental nature of this technique, it was not investigated further on the present contract.

The technique of irradiating a surface region of a glass slab to form a waveguide has been mentioned previously and is illustrated in Fig. 4(a). Some form of radiation which is absorbed in a thin surface layer is used to change the index of the glass or silica. In addition to the requirements for producing the desired index change, it is also necessary that the radiation have a penetration depth equal to the desired waveguide size. Fortunately, protons in



(a) Slab waveguide



(b) Directional coupler.

Fig. 4 - Formation of printed waveguides and components by irradiation of glass.

the energy range of 1 Mev have a penetration depth of about 30 microns. The penetration is a function of the energy of the incident protons and can therefore be controlled to give the desired waveguide size. The exact distribution of the refractive index in the altered region is not straightforward, but depends on a number of factors which are discussed in Appendix III. However, it appears that by choosing the right particle energy, and possibly by varying the energy during the irradiation, it should be possible to obtain a fairly homogeneous layer of high index material.

This surface irradiation technique is also attractive because of the possibility of forming "printed" components. Radiation would be directed at particular regions of a surface either by scanning a narrow beam of particles or by using masking techniques. An example of how a directional coupler might be printed on a glass slab, using the masking technique, is illustrated in Fig. 4(b).

In order to experimentally measure the index change and penetration depth of protons, three samples of Ultrasil fused silica were sent to NASA Goddard Space Flight Center for irradiation with protons. The samples were irradiated with dosages of 10^{17} to 5×10^{17} protons/cm^2 at an energy of 1.5 Mev. The dosage of 10^{17} protons/cm^2 was initially calculated to yield an index change of about 1×10^{-4}. However, after sending these samples to Goddard for irradiation, revised calculations indicated a much larger change of about 10^{-2} would be obtained. Upon receipt of the irradiated samples from Goddard, a preliminary measurement using an Abbe Refractometer, indicated an index change of about 10^{-3}. The accuracy of this measurement is uncertain because the Abbe is not intended for measurement of these samples. Even so, the measured value of 10^{-3} is reasonable because some of the index change introduced by the irradiation may have been removed by annealing, since the samples became hot during irradiation. A more accurate determination of the index of these samples is planned during the next contract period.

One additional technique which has been considered for fabrication of waveguides is vacuum deposition of dielectrics. The simplest technique here is to deposit a high index dielectric (which serves as the core) on a lower index substrate (the cladding).

In order to determine the feasibility of deposition techniques, a conference was arranged with members of Dr. Georg Hass' group at the Physics Research Facility of ERDL, Fort Belvoir, Va. Conclusions are that vacuum deposition is not considered feasible for fabrication of macroscopic waveguides for the following reasons. First, it is not possible to deposit good quality films in thicknesses greater than a few microns, and second, the homogeneity of vacuum-deposited dielectrics is insufficient for macroscopic waveguides. In addition to these problems, there is the problem of obtaining the necessary small difference in refractive index between the deposited dielectric and the substrate. For these reasons, vacuum deposition is not considered a feasible technique for fabrication of macroscopic waveguides.

Most of the objections to the deposition technique do not apply if microscopic rather than macroscopic waveguides are considered. In this case, the thickness of a few microns is quite reasonable and the homogeneity requirements are greatly relaxed since the required index difference can be much larger. One possible problem which might still rule out this technique is scattering. Although vacuum deposited dielectrics have very low scattering when light is transmitted through a thin layer (of the order of wavelengths) the scattering may result in excessive loss when propagating through several centimeters of the material. This requires further investigation, probably of an experimental nature. Although most of the emphasis on this project is for development of macroscopic waveguides, evaluation of any techniques for optical waveguide and component development are to be considered. Therefore some limited investigation of vacuum deposition as a technique for fabricating microscopic waveguides is planned.

III. Component Development.

The construction of a variety of optical components within a single-mode waveguide has been studied in detail during the current program. Preliminary design as well as estimates of the performance of such components had been studied under the previous contract and results are presented in Ref. 7 . Effort on the present contract has concentrated on the design and experimental testing of two such components, a directional coupler and a single-mode waveguide laser. The directional coupler is important because it is a fundamental device in almost any waveguide system and appears in a different form in free-space optical systems. The waveguide laser is important because it has some attractive features in itself, namely single-mode operation with all the associated advantages, and also because it is the natural approach for incorporating a laser source into an optical waveguide system.

A. Directional Coupler.

A directional coupler within a waveguide medium is a device for dividing (or coupling) power between two different guides in a very precise and controlled manner. Two basic configurations which are described in Ref. 7 and which have been tested on this contract are the evanescent-field coupler and the slot coupler. The evanescent-field coupler is treated first; then the slot coupler which was operated successfully is discussed with examples of its performance.

A sketch of an experimental model of the evanescent-field coupler is shown in Fig. 5. Two solid waveguide cores are located parallel and close together in a liquid cladding. The waveguide cores in this experiment were formed of BK-7 glass, and chlorobenzene served as the liquid cladding. Energy is expected to couple from one guide to the other by means of the evanescent fields extending into the cladding. The fields from the excited guide extend into the coupled guide and excite a propagating mode. The amount of coupling depends on the waveguide parameters and on the separation between the two waveguides. For the BK-7 slabs, which have a width of 85 wavelengths, and with a separation of 30 wavelengths, the calculated coupling in a 5 cm length is -12 db. However, in the experimental test, coupling was not observed. The limit of detection for this experiment is about -25 db as determined by background illumination and detector noise; therefore the inability to observe coupling implies that the coupled signal was lower than that in the input guide by at least 25 db.

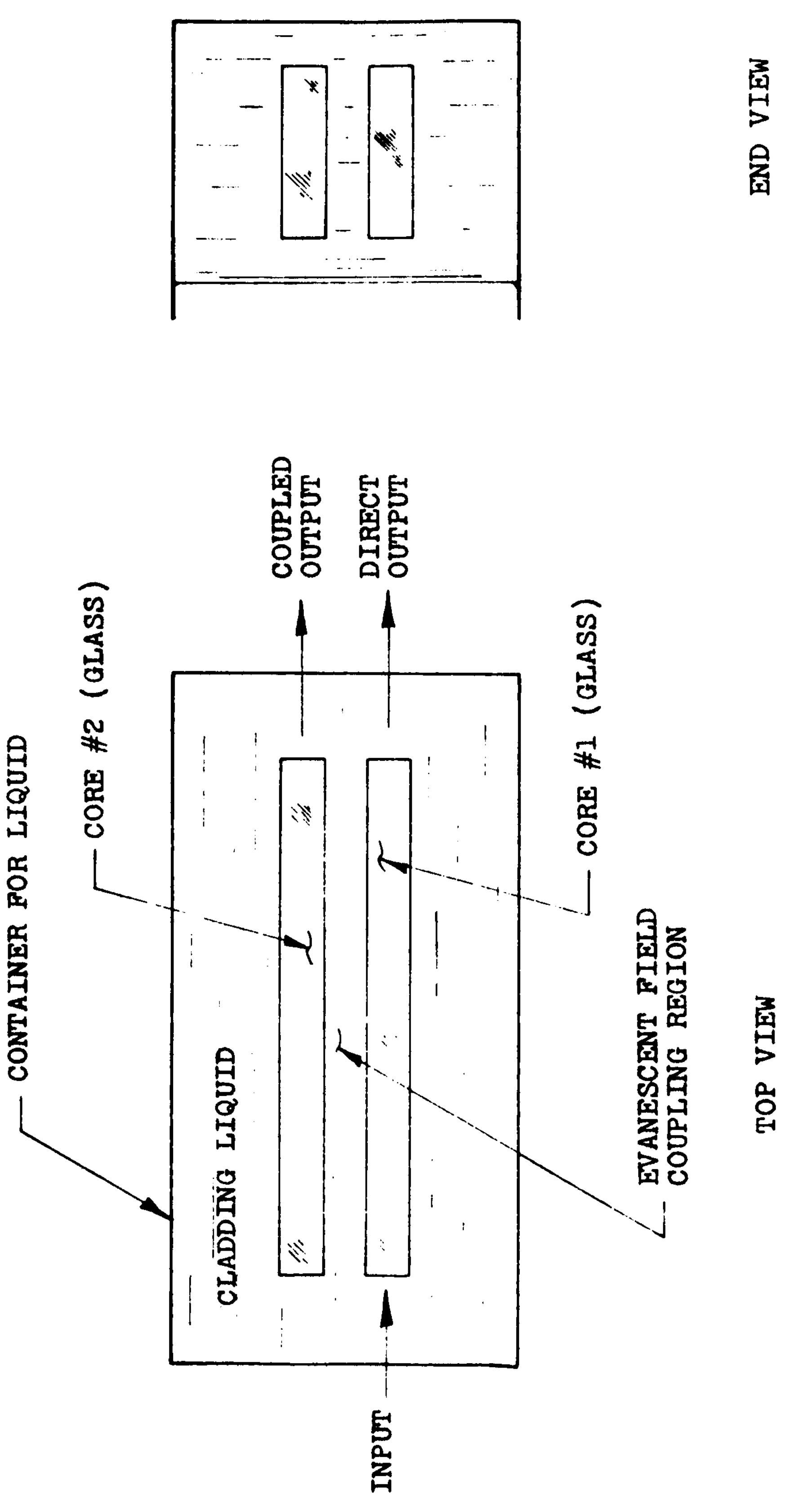


Fig. 5 - Sketch of experimental model of evanescent-field coupler.

The disagreement between the calculated and observed coupling in this particular experiment is believed caused by a difference in the phase velocity of the two waveguides. Such a difference would result from a difference in refractive index between the two waveguide cores, which is possible to a limited degree because of the homogeneity tolerance on the glass. The amount of degradation in coupling caused by a difference in the phase velocities in the guides has been treated in Refs.1,10. An approximate criterion is that to obtain appreciable coupling, the difference in the phase length of the coupling region in the two guides must be less than a half-wavelength. For the 5 cm coupling length employed in the evanescent-field coupler, the phase length is about 10^5 wavelengths and a difference in phase length of a half wave is not unreasonable. In order to overcome the problems involved in the evanescent-field coupler, a number of techniques are applicable. First, the difference in phase velocity could be reduced by improved homogeneity; however, this is difficult because the glasses utilized are already of the highest quality presently available. An alternative approach is to reduce the waveguide size. For waveguides operating in only a single mode, the coupling increases as the waveguide size is reduced. Therefore, a given amount of coupling could be achieved in a shorter coupling region, if the waveguide size were reduced. Although it is believed that an evanescent-field coupler can be operated in a smaller size (of the order of 50 wavelengths), testing of this coupler was deferred in favor of the slot-type coupler, which provides greater coupling than the evanescent-field type and can therefore be made to operate with the existing large-size waveguides.

An example of the slot-type directional coupler is illustrated in Fig. 6. This coupler consists of two bisected waveguides (see Appendix I) with a common bisecting wall between them. A "slot" is provided in the bisecting wall to allow coupling of energy from one guide to the other. The coupling calculated as a function of the difference in dielectric constants between core and cladding for the two lowest propagating modes is illustrated in Fig. 7. The coupling increases as the difference in dielectric constants increases. Therefore, to obtain maximum coupling under single-mode conditions,

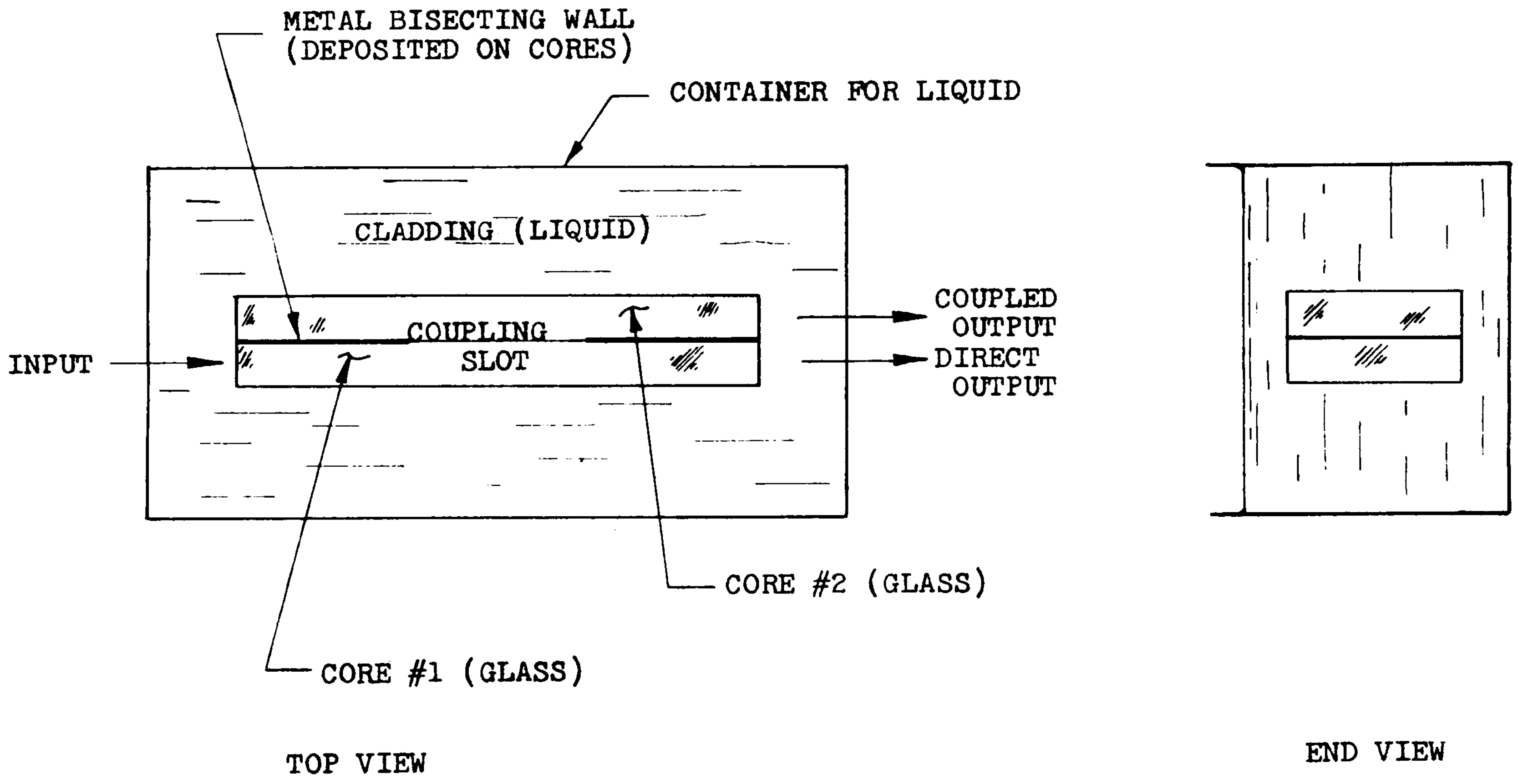


Fig. 6 - Sketch of experimental model of slot coupler.

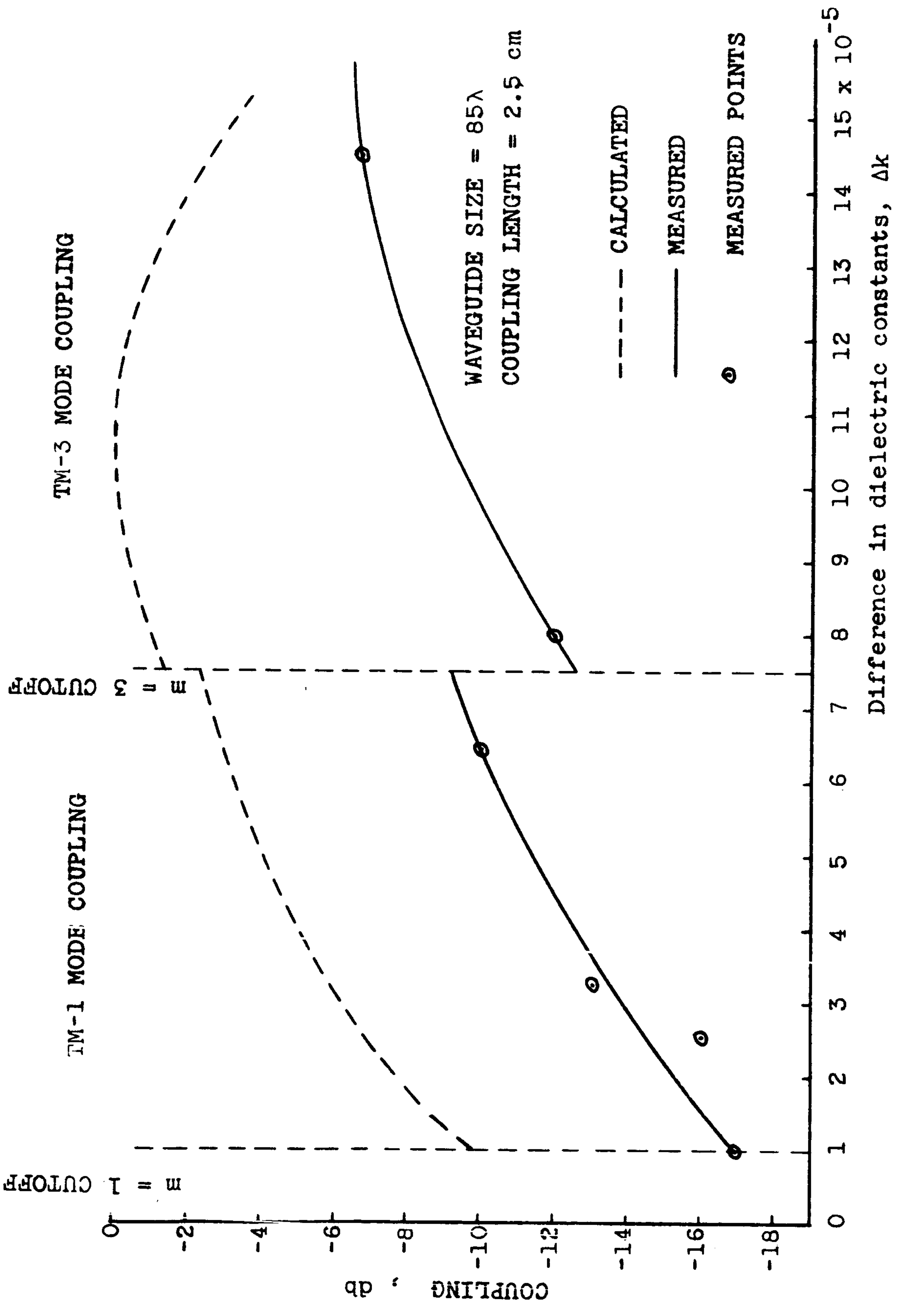


Fig. 7 - Slot directional coupler -- measured and calculated coupling.

the guide is operated with the largest difference in dielectric constants that is compatible with single-mode operation. The amount of coupling also increases as the waveguide size is decreased; however appreciable coupling can be obtained with the slot coupler for guides 85 wavelengths wide.

An experimental model of the slot coupler was constructed by vacuum depositing aluminum on two BK-7 glass slabs and assembling these as shown in Fig. 6. A photograph of the aluminized slabs is shown in Fig. 8. The non-aluminized region is the coupling slot; coupling lengths of 0, 2.5 and 5 centimeters can be obtained by using different vertical locations on the slabs. The BK-7 slabs forming the waveguide cores are located with the aluminized surfaces in mutual contact; the assembly is then immersed in a chlorobenzene cladding. The experimental model differs somewhat from the ideal model in that there is a thin layer of liquid cladding in the coupling region between the two guides; in the ideal case the waveguide cores are in intimate contact. The effect is to reduce coupling below that calculated for the ideal case as discussed later.

Experimental measurements of this coupler were performed under a variety of different conditions by photographing and measuring the field patterns at the output plane of the two waveguides when only one was excited. In all cases, the guide was excited with a plane wave from a He-Ne gas laser operated at 0.6328 microns. The measured patterns were taken by projecting an enlarged image of the waveguide outputs and scanning this image with a small aperture photocell.

Patterns of the field distribution in both input and coupled waveguides operating in the TM-1 mode are shown in Figs. 9 through 12 for increasing values of difference in dielectric constant (the coupling length was 2.5 cm in all cases). A plot of the coupling vs. difference in dielectric constants, obtained from these measurements, is presented in Fig. 7 for comparison with the calculated curves. It can be seen that the measured coupling is lower by about 7 db. In spite of the difference between the measured and calculated curves, these results are considered in good agreement because, (1) the variation or change in coupling with dielectric constant difference is nearly identical to that calculated, and (2) the

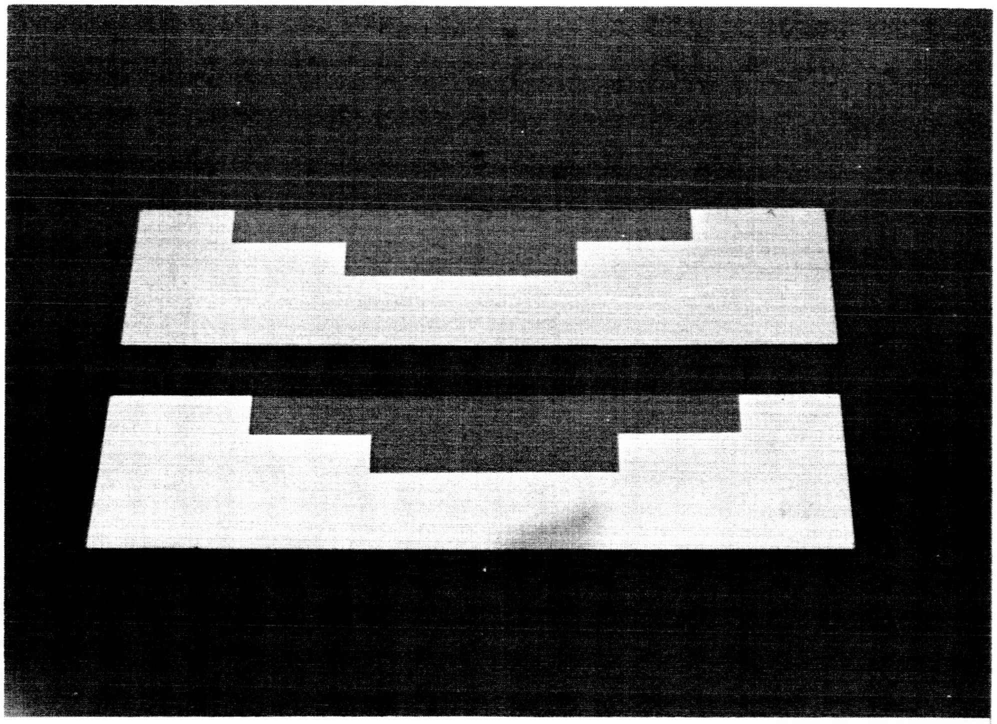


Fig. 8 - Photograph of aluminized BK-7 glass slabs for slot coupler.

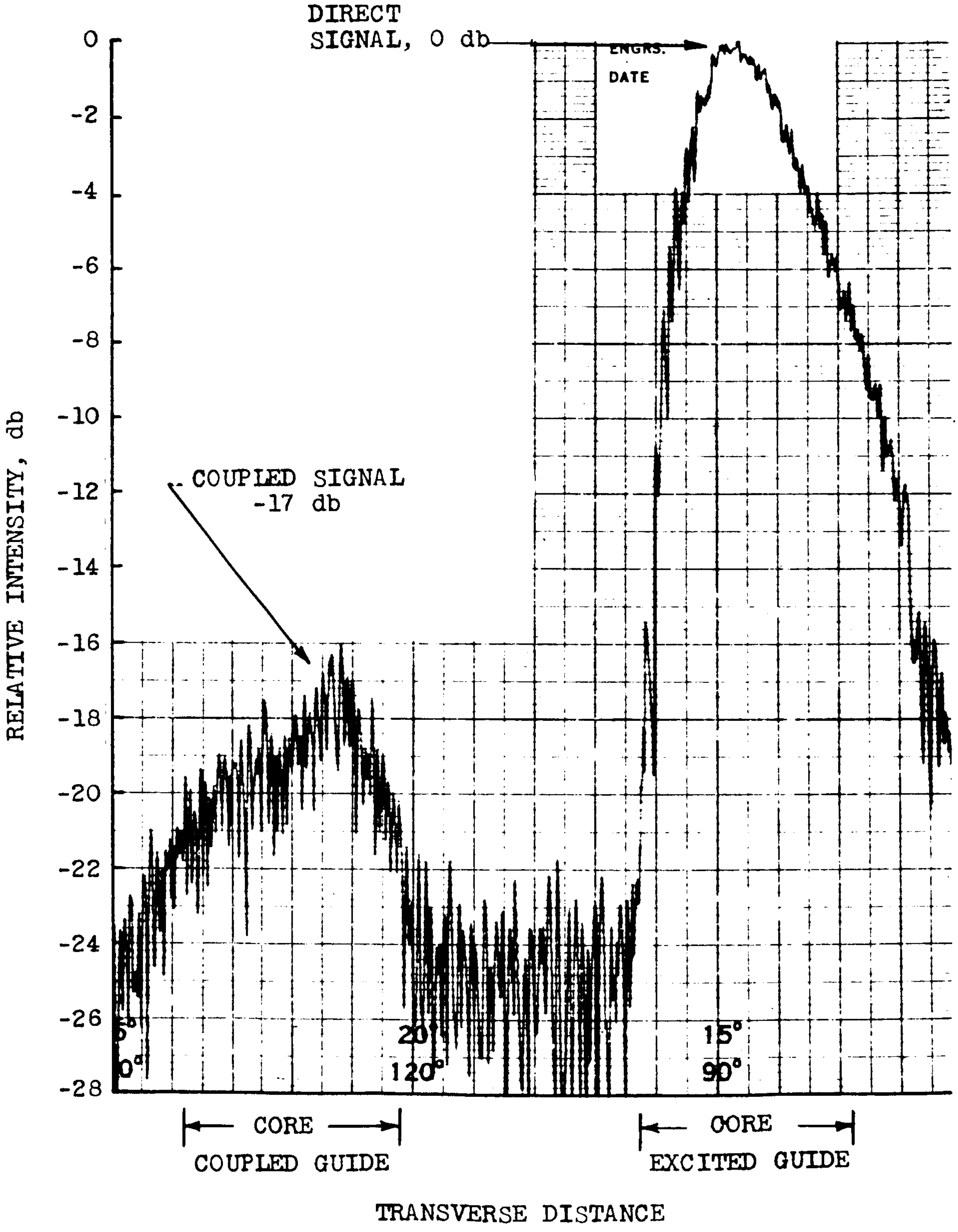


Fig. 9 - Measured mode pattern of coupled waveguides; TM-1 mode, $\Delta k = 1.0 \times 10^{-5}$

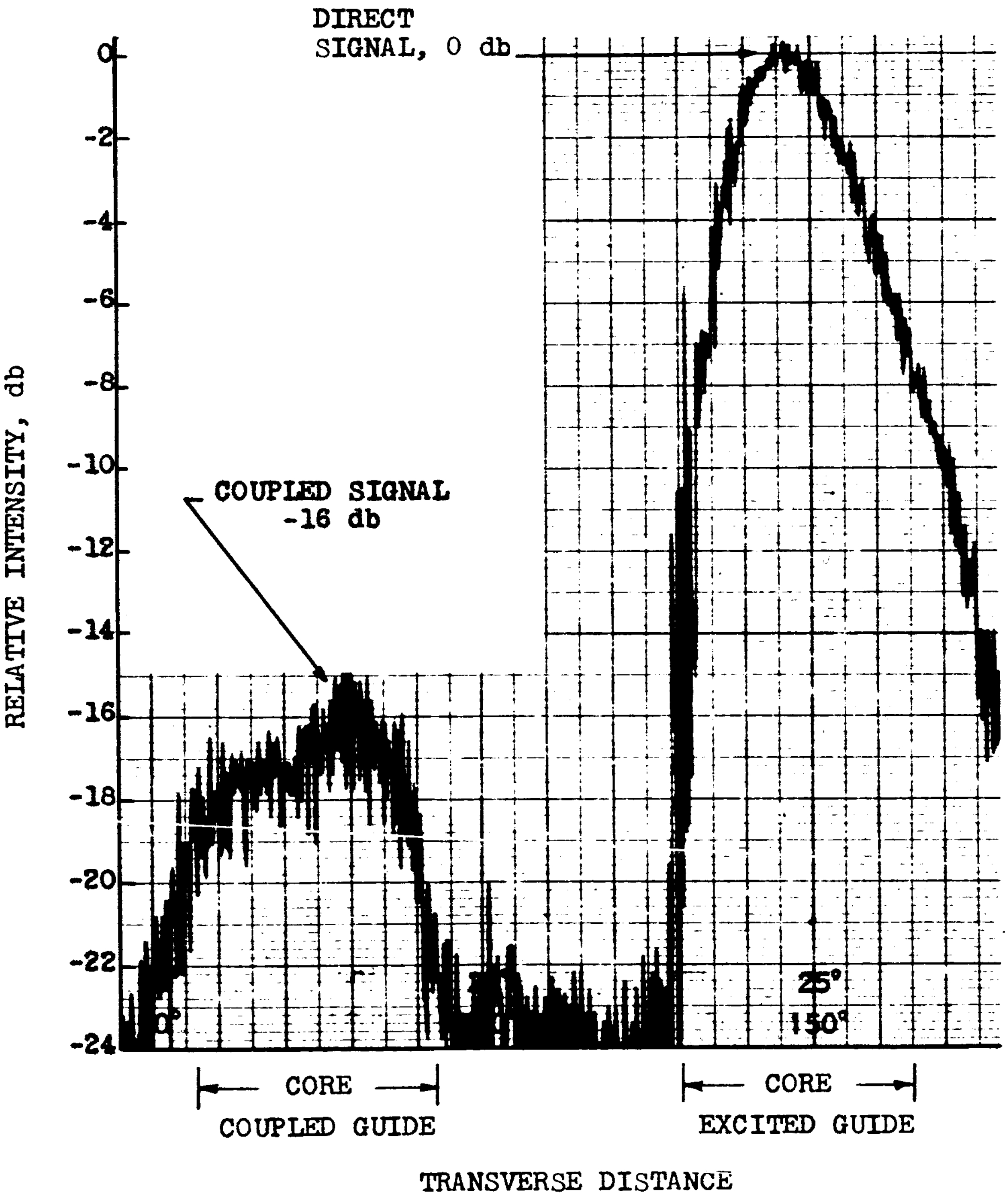


Fig.10 - Measured mode pattern of coupled waveguides; TM-1 mode, $\Delta k = 2.6 \times 10^{-5}$.

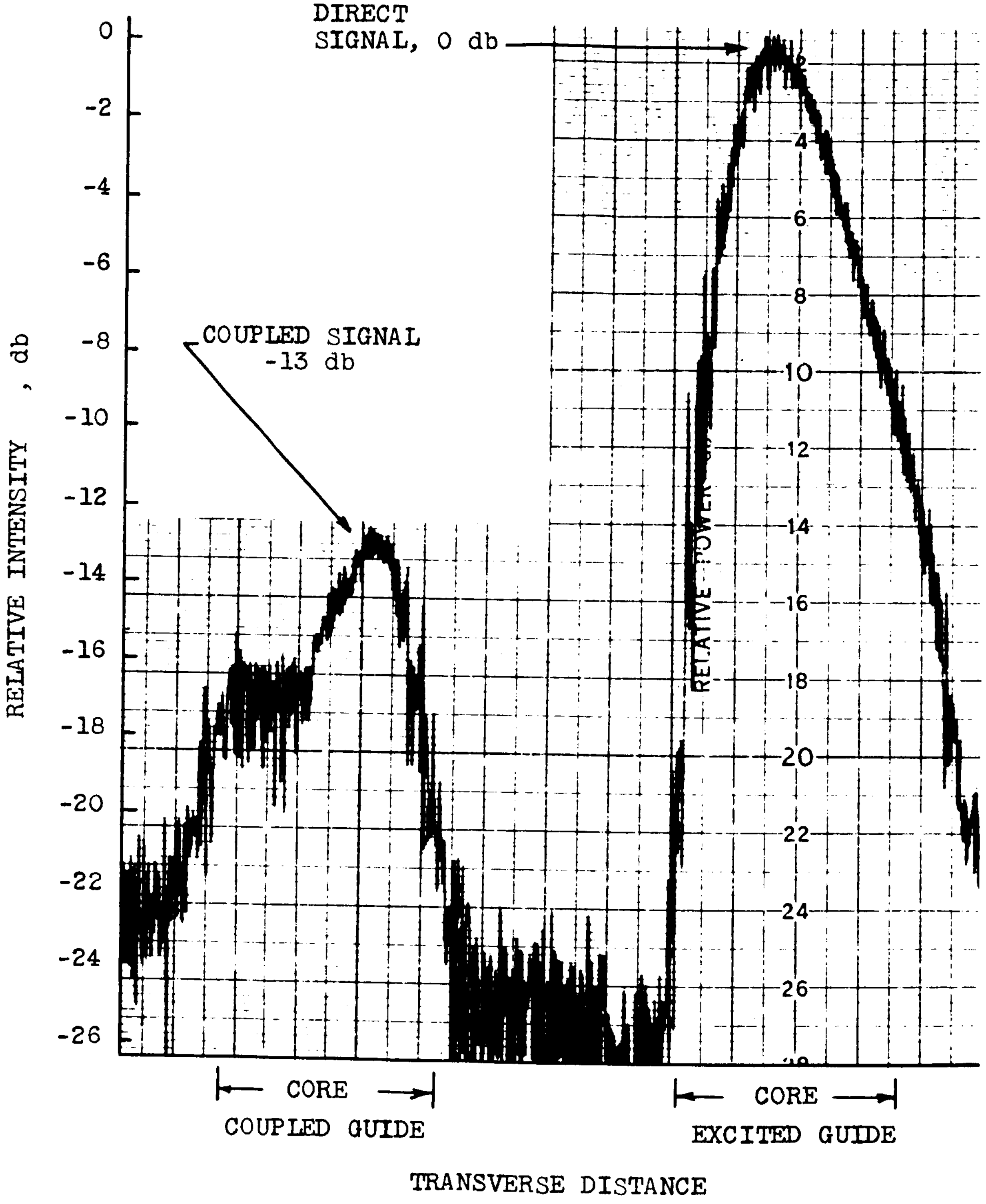


Fig. 11 - Measured mode pattern of coupled waveguides; TM-1 mode, $\Delta k = 3.2 \times 10^{-5}$.

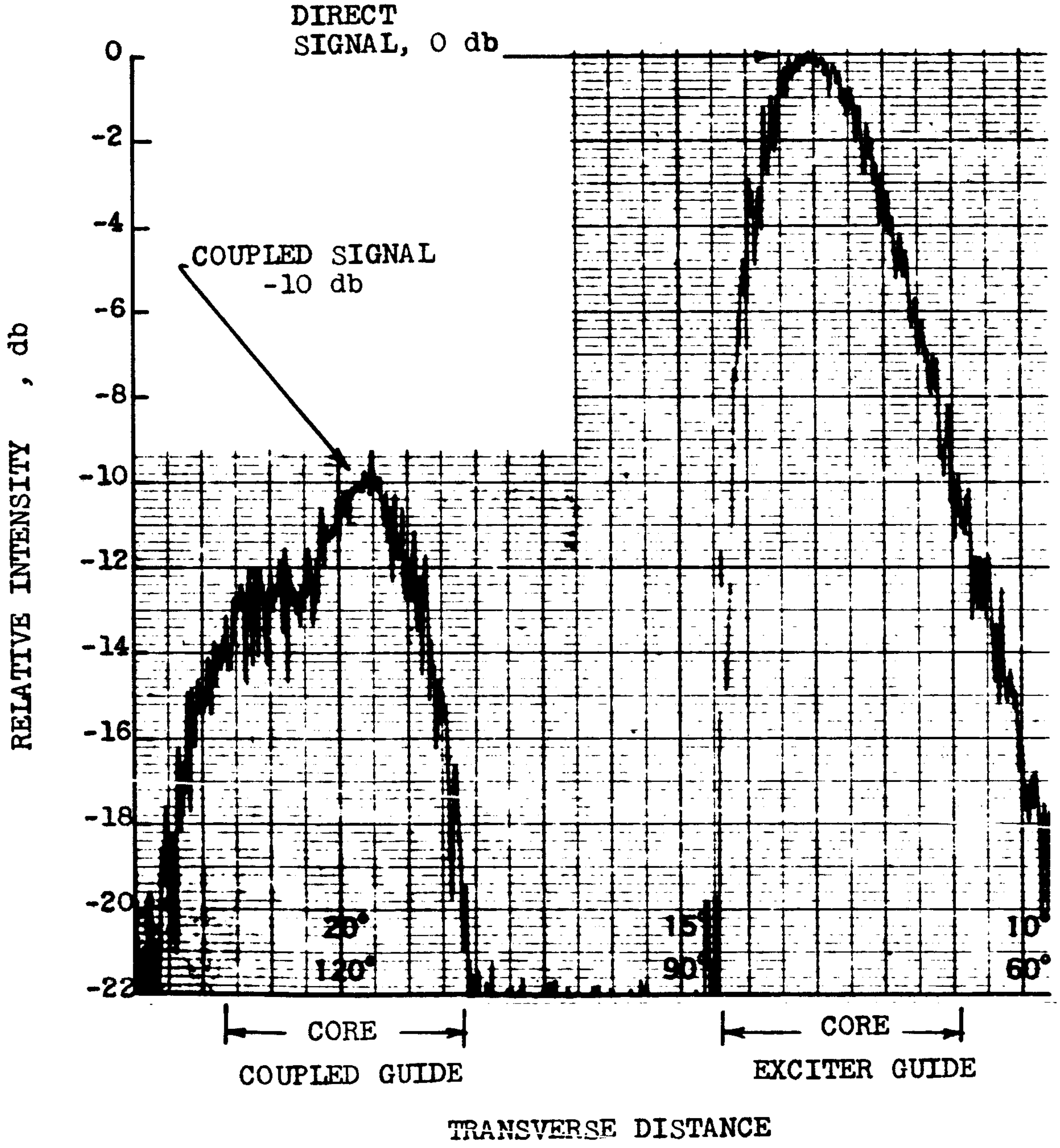


Fig. 12 - Measured mode pattern of coupled waveguides; TM-1 mode, $\Delta k = 6.4 \times 10^{-5}$, excitation on axis.

difference in magnitude is believed caused by the thin layer of cladding material in the coupling region as mentioned earlier. This thin layer of cladding causes the guide to operate similar to an evanescent field coupler with very small spacing, the major effect being a reduction in coupling. It is believed that this effect can be eliminated in improved, all-solid configurations of the slot coupler by using cementing techniques,for example. The lower coupling observed may also be partially attributed to a difference in phase velocity between the two waveguides as discussed previously for the evanescent-field coupler. However, this effect should be smaller than before because of the shorter (2.5 cm) coupling length.

In a single-mode waveguide coupler, the coupling is independent of the angle of incident radiation; a variation in the excitation angle should result only in a change in the absolute signal level in both the input and coupled waveguides. In order to check this property experimentally, a number of patterns were recorded as the angle of incident radiation was varied. Comparison of Figs. 12 and 13 indicates that the coupling is very nearly the same for on-axis excitation as for off-axis excitation in the negative direction; however, the pattern in Fig. 14 indicates the coupling is lower for excitation in the positive off-axis direction. This difference is believed caused by the presence of some higher modes which have not been sufficiently attenuated; improved excitation as well as damping of leaky waves in the cladding should eliminate the problem.

In order to provide additional data on the performance of the coupler, the difference in dielectric constants was increased so that the TM-3 mode could propagate. A pattern showing TM-3 mode coupling is given in Fig. 15; as for the TM-1 mode, the coupling is lower than that calculated. A measured curve of the TM-3 coupling vs. difference in dielectric constants based on measurements at two values of dielectric constant is plotted in Fig. 7. The coupling varies somewhat differently from that calculated; however, it is difficult to make a comparison because of the lack of data points for the measured curve. Also, the calculations assume that only the TM-3 mode is excited, whereas it is difficult experimentally to avoid excitation of the TM-1 mode. The presence of the TM-1 mode

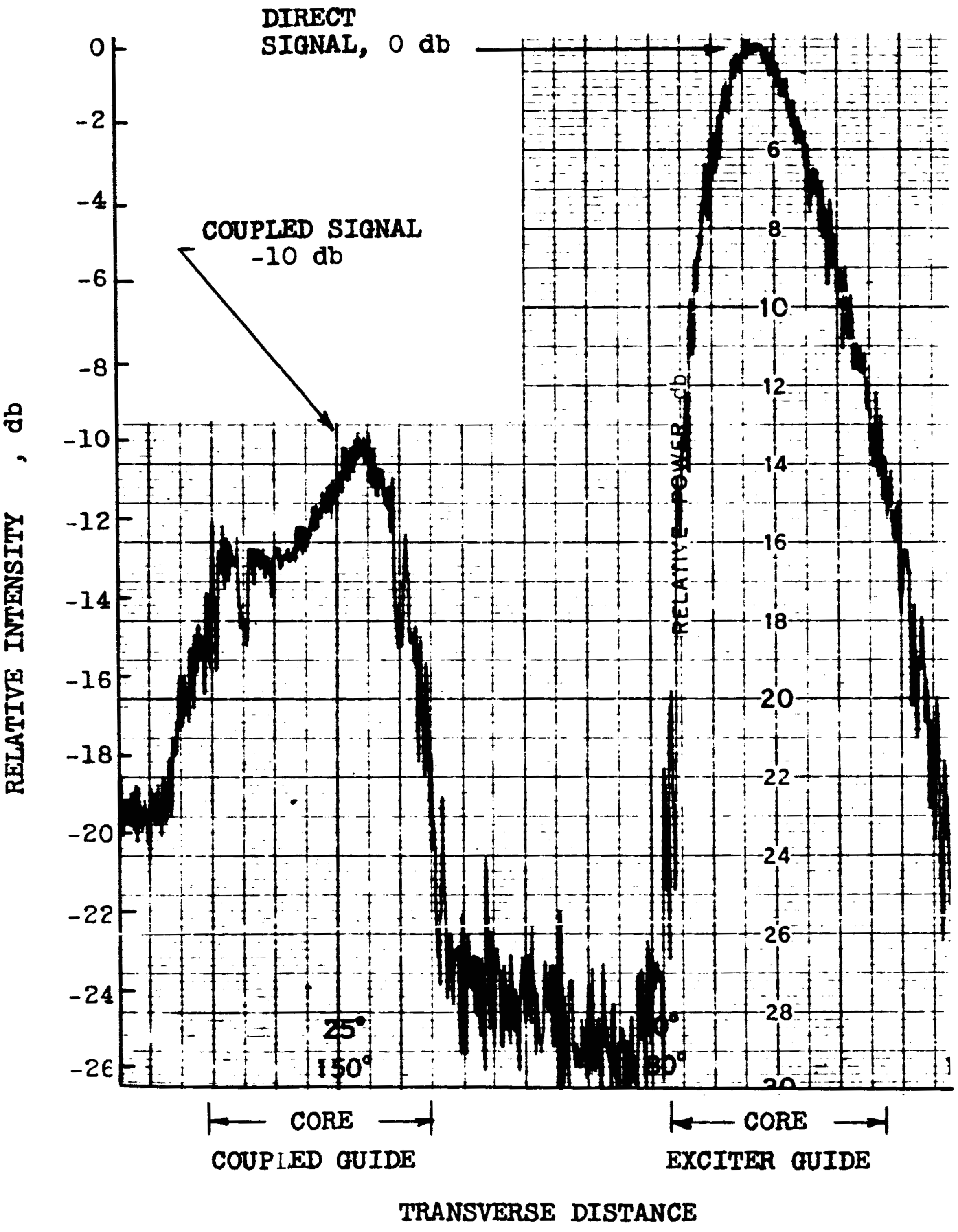


Fig. 13 - Measured mode pattern of coupled waveguide; TM-1 mode, $\Delta k = 6.4 \times 10^{-5}$, excitation -0.4° off axis.

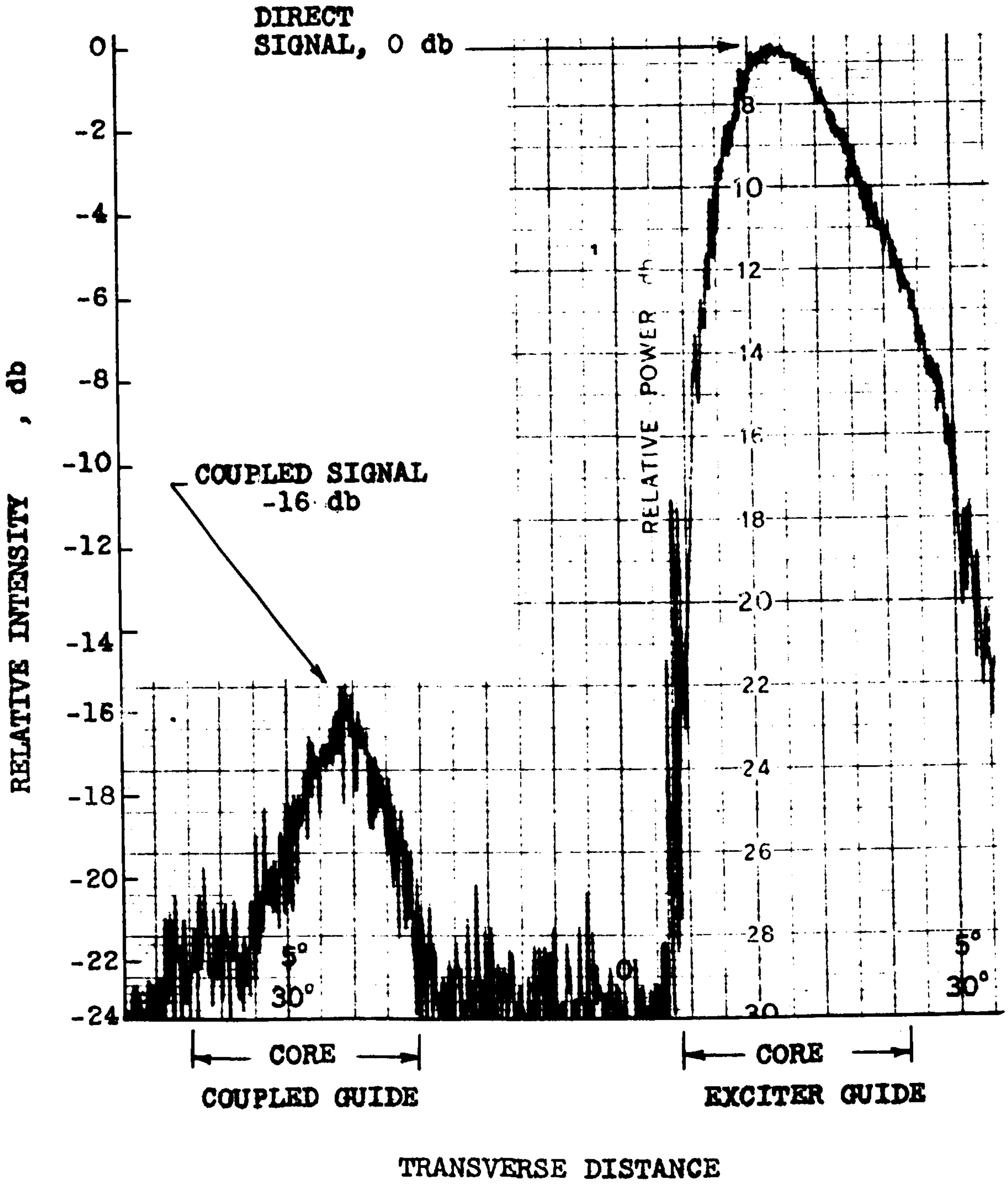


Fig. 14 - Measured mode pattern of coupled waveguides; TM-1 mode, $\Delta k = 6.4 \times 10^{-5}$, excitation +0.4° off axis.

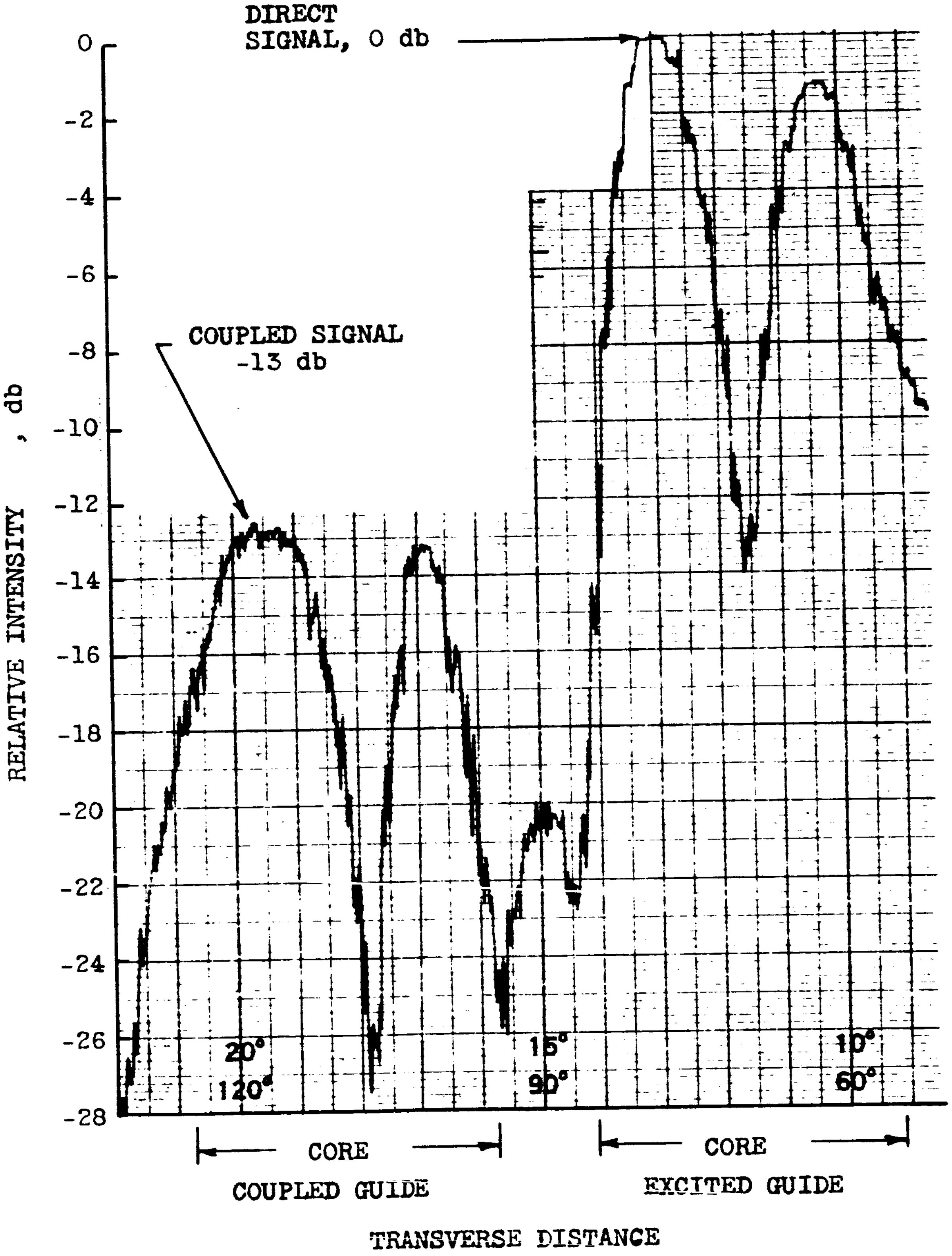


Fig. 15 - Measured mode pattern of coupled waveguides; TM-3 mode, $\Delta k = 8 \times 10^{-5}$.

will, of course, affect the TM-3 mode coupling. Therefore, within the restrictions mentioned, the results are considered in reasonable agreement with the theory.

One additional pattern showing TM-9 mode coupling is given in Fig. 16. This pattern is presented only as a verification that energy can be coupled from any given mode in one guide to the same mode in the other guide. In the ideal case, the coupling increases for the higher modes as the difference in dielectric constants is increased, provided the modes can be individually excited. In most applications, the waveguides forming a directional coupler would be restricted to a single mode of propagation. However, experiments with multi-mode coupling are often useful for analyzing coupler operation, and some limited applications of multi-mode couplers may exist.

Future effort on the development of the slot coupler will be directed to elimination of the liquid cladding layer between the two guides by cementing techniques as discussed previously, and to implementation of the coupler in completely solid form. An example of how an all-solid model might look is shown in Fig. 17, which is a photograph of the bisected BK-7 glass waveguides sandwiched between two thicker slabs of cladding glass. In a working model, the bisected cores will be fabricated from the high index Bausch and Lomb glass (discussed in Section II), the claddings will be fabricated from the low index glass, and the parts then permanently cemented together.

B. Waveguide Laser.

A variety of techniques for controlling the number of transverse laser modes have been developed. Fabrication of lasers in a waveguide medium has been suggested as an additional technique. If a single-mode waveguide, fabricated from a material capable of population inversion, is terminated by plane mirrors to form a resonant cavity, the resulting laser will oscillate in only a single, transverse mode. All other modes "leak" from the waveguide and, therefore, have insufficient gain for oscillation. Such a laser, utilizing the large-size, single-mode waveguide emphasized on this

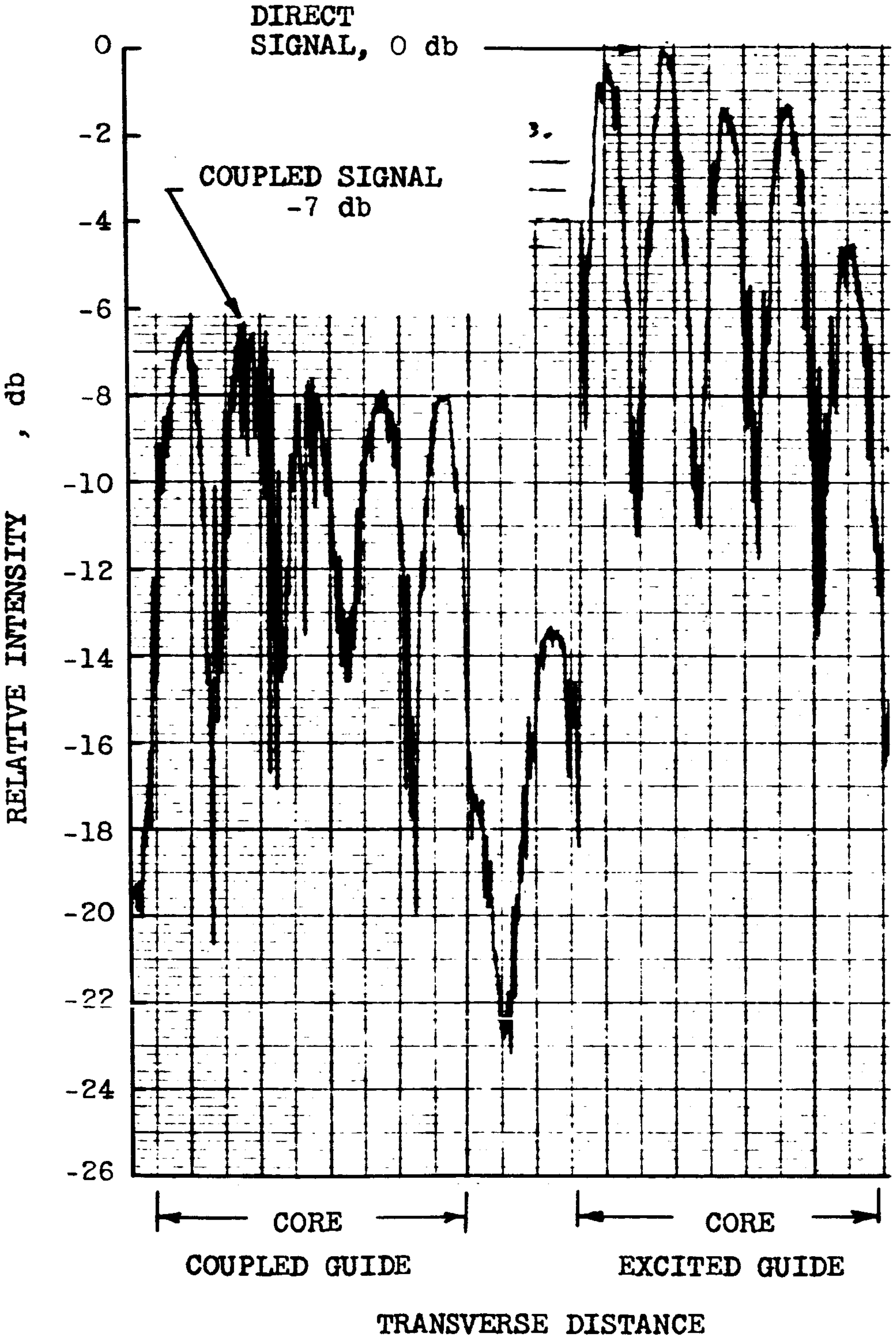


Fig. 16 - Measured mode pattern of coupled waveguides; TM-9 mode, $\Delta k = 85 \times 10^{-5}$.

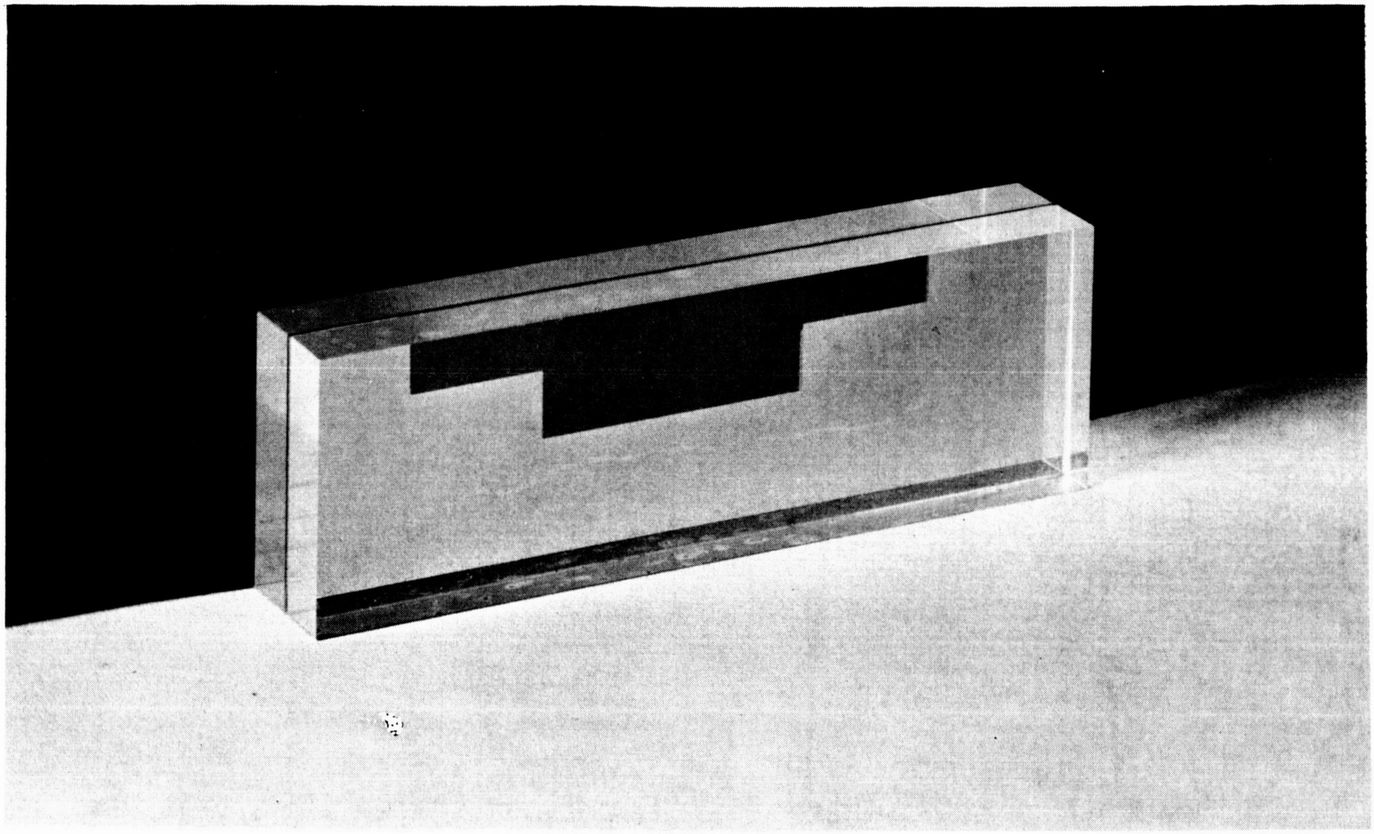


Fig. 17 - Proposed model of all-solid, slot directional coupler.

contract has some unique advantages. On one hand, its threshold pump power will be lower than conventional 1 cm rod lasers because of the reduction in active volume. Therefore, CW operation can be obtained with lower pump powers. (Of course the output power will also be lower than for the larger laser). On the other hand a 50λ single-mode laser has an active volume about 2000 times larger than a single-mode fiber laser with a more conventional index difference; the greater volume in this case permits a higher output power. However, the main motivation for considering waveguide lasers on this contract has been the desire to develop a laser source compatible with the other components to be designed in the waveguide system. For example, such a laser could serve as the local oscillator of a waveguide heterodyne detector. While it is expected that the ultimate applications for such a laser will require CW operation, initial testing has been restricted to pulsed operation.

Early in this study many possible laser materials and configurations were considered. It was decided to restrict initial work to liquid-solid systems to avoid the fabrication problems inherent in an all-solid configuration. This left two general arrangements to be considered, a liquid-core waveguide with solid cladding, and a solid-core waveguide with liquid cladding. In both of these configurations, either the core or the cladding or both could be a laser-active material.

After a brief survey of reported and proposed liquid laser materials, it was determined that only the chelate laser comprising europium benzoylacetonate (EuB_3) in alcohol solution (Ref. 4) appeared of value for our application. The main advantage of EuB_3 is its high absorption at the pump frequency, a very desirable property in a small size laser. However, even this material suffers from the experimental disadvantages that it is chemically unstable and often requires cooling to -100° C. For these reasons, as well as our ultimate interest in all-solid systems, it was decided to concentrate entirely on solid laser materials.

In addition to the laser requirements, it is necessary that any material chosen be capable of operating as a waveguide. This places the additional constraint on the laser material, that it have a refractive index homogeneity of the order of 10^{-6}. This requirement rules out most of the common, crystalline, laser materials. In fact the only solid laser materials obviously suitable for large-size waveguide applications are the various Nd-doped glasses fabricated by continuous melting techniques.

An Nd-doped soda-lime silicate glass developed by Corning (Corning Code 0580) is of a remarkably high optical quality (Ref. 9) and was chosen for this program. Two disadvantages of the Code 0580 glass are: (1) the laser output is in the infrared (1.06μ) so detection is inconvenient, and (2) it has low pump light absorption relative to EuB_3. A slab of this glass, the size of a waveguide core, absorbs only about 5% of the incident pump light on a single pass. In spite of these objections, its use is justified because the pump threshold is reasonable and the optical quality is excellent.

An experimental waveguide laser has been constructed and preliminary tests performed. The waveguide core consists of a thin slab of Code 0580 glass, 77 mm x 25 mm x 0.048 mm, with both ends aluminized for 4% transmission; the slab is immersed in dichlorobenzene which serves as the cladding. The waveguide and an FX-38A flashlamp were located at conjugate foci of an elliptical reflector. A sketch of the experimental laser is shown in Fig. 18 and a photograph is shown in Fig. 19. As can be seen in the sketch, the ellipse is partitioned by a glass window, located midway between the conjugate foci. Water is circulated through the sealed upper half which contains the flashtube, while the open bottom half, which contains the Nd-doped core, is immersed in a temperature-controlled container of dichlorobenzene.

An alternative configuration which utilizes an external mirror, covering both the core and cladding, is currently being implemented to achieve a higher reflectivity, as discussed later. For a laser of this size the external mirrors must be very close to the ends of the core to avoid diffraction losses. While this is difficult for the liquid-solid configuration, it will not be a problem in future work with all-solid waveguides, since the mirrors can then be vacuum deposited directly on both the core and cladding.

In order to first evaluate the laser as a waveguide, the mirrored core was replaced by a similar Nd-doped core that was unmirrored. This waveguide was then excited with a plane wave from a He-Ne (0.6328 micron) gas laser. Mode patterns were observed and

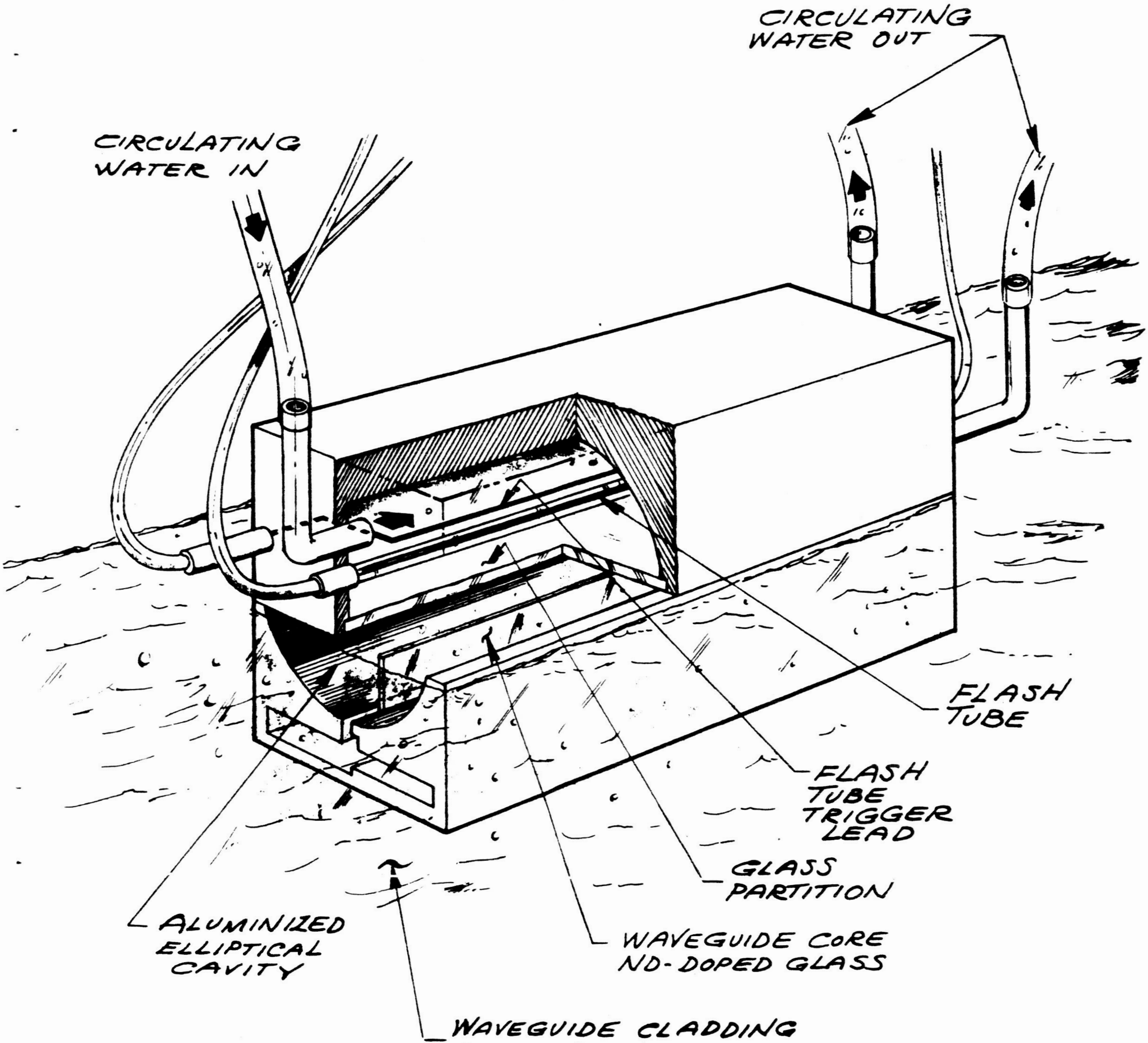
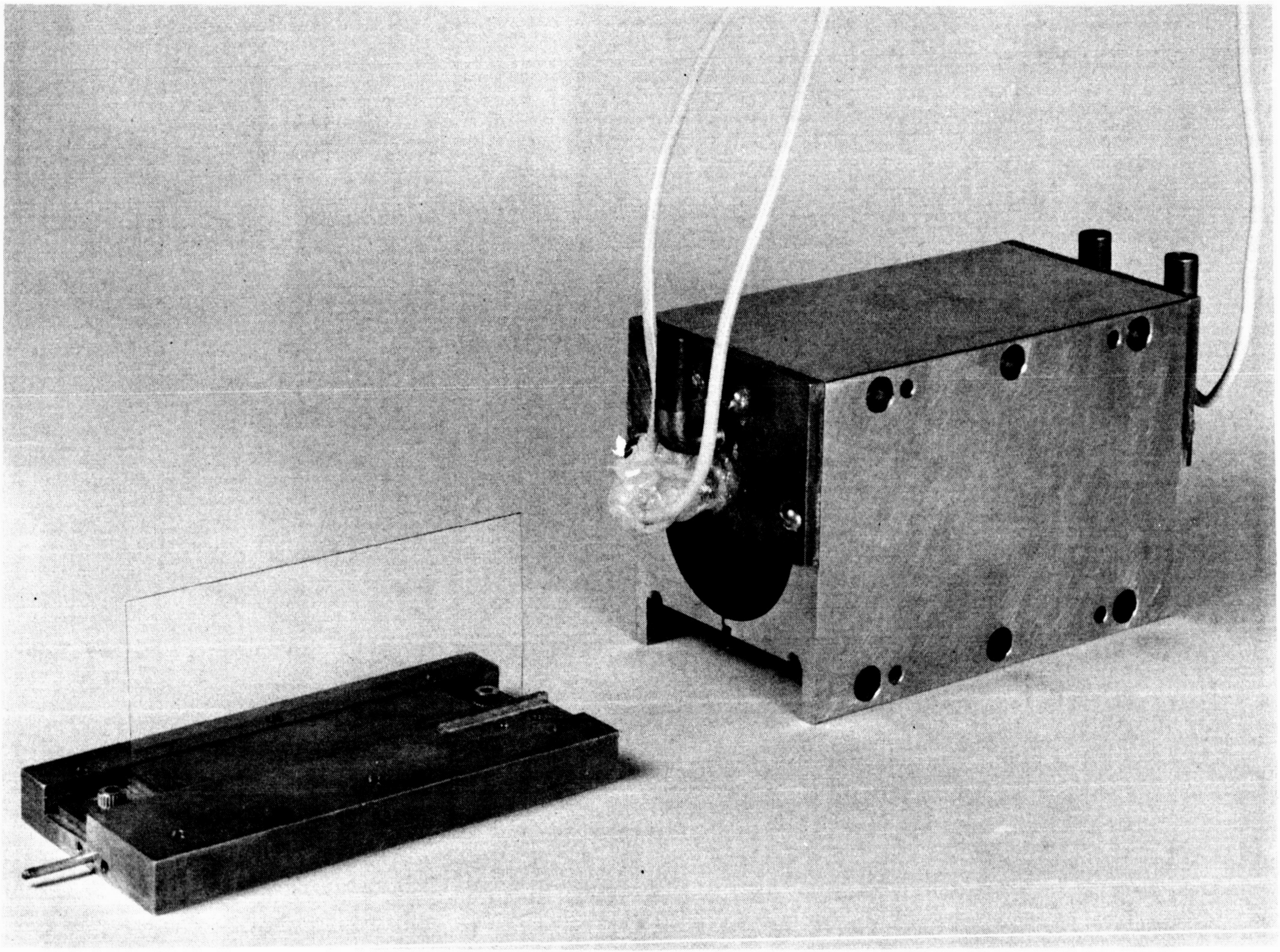


Fig. 18 - Sketch of experimental laser configuration.



mode cut-off conditions were monitored; in all cases the guide operated according to theory. These experiments confirmed the basic suitability of Code 0580 glass as a waveguide material; the laser properties of this glass have been well established by previous work at Corning Glass Works (Refs. 6,8,9).

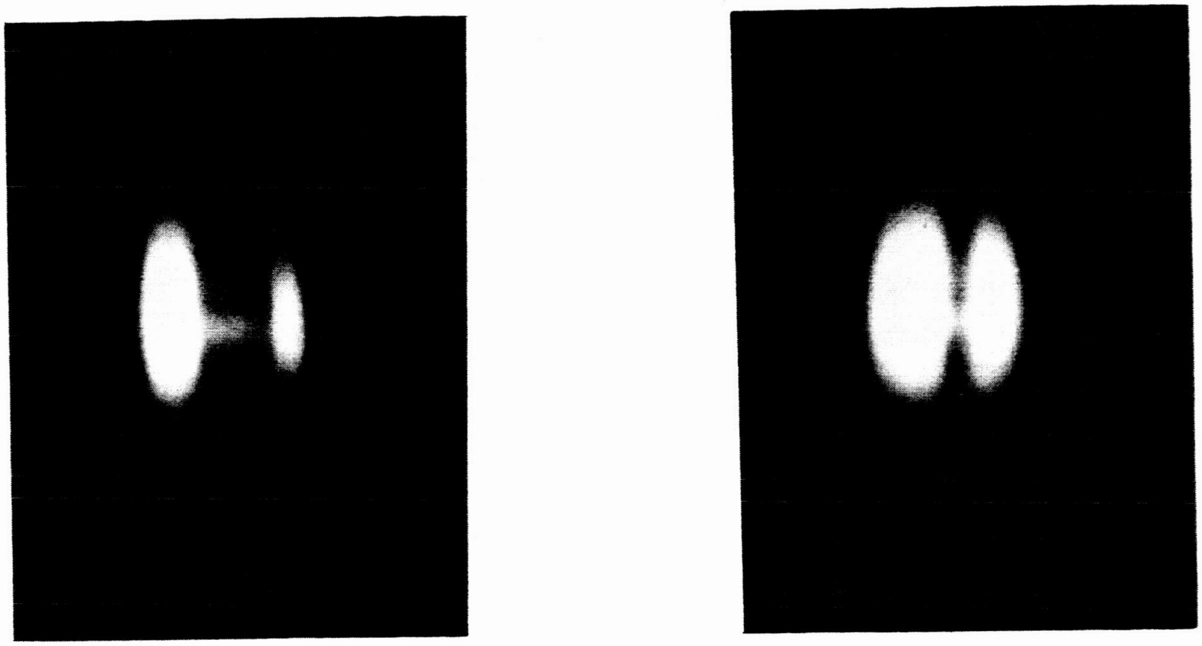
The threshold energy for our configuration was calculated by scaling the results observed with 0.6 cm rods of this glass. Measurements performed on a large number of such rods at Corning (Ref. 9) indicated a threshold energy of 11 joules. In scaling this value to our configuration, three factors were considered; (1) a reduction in threshold due to the small active volume of our configuration, (2) an increase in threshold because of the small pump light absorption of the thin slab, and (3) an additional increase in threshold to account for a lower effective reflectivity. The reflectivity of the present configuration is low because of aluminum losses (about 10%) and the absence of mirrors on the cladding. This results in a reflectivity of the order of 70%. With all these factors considered, the predicted threshold energy is of the order of 60 joules for single-mode operation and somewhat lower for multi-mode operation. By the use of external silver mirrors, which cover both core and cladding, the effective reflectivity can be increased to around 96% and the threshold will be reduced to about 9 joules. The threshold can be reduced still further by the use of low loss dielectric mirrors.

Initial experimental work has been performed at pump energies in the range from 1 to 16 joules. Early work used pump energies in this range for two reasons: (1) it was feared that high energies could damage the thin slab and (2) an initial calculation indicated that the threshold energy was in this range. The program so far has not resulted in observation of laser action. Nevertheless, observations of this laser below threshold have produced some interesting and informative results.

Some of the more significant results pertain to material stability. It was confirmed that the thin core slabs do not deteriorate upon repeated pumping at energies up to 16 joules. (It had been feared that thin cracks observed at much higher pump energies in thick rods might occur at low energies for the thin slabs pumped over a limited area.) Furthermore, the dichlorobenzene also appears suitable, although some deterioration seems to occur after repeated use. This is evidenced by a slight cloudiness at room temperature; however, the cloudiness is not observed at the IR operating temperature of 45° and no alteration of the index of refraction of the liquid has been detected.

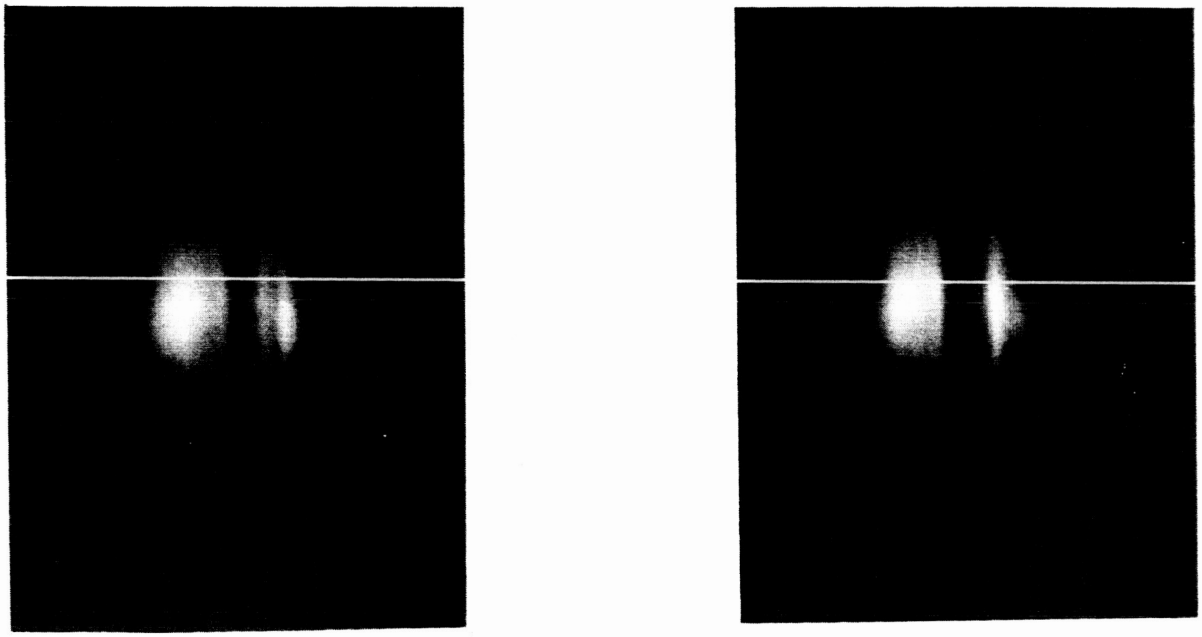
Near- and far-field photographs, recorded with Polaroid IR film, are reproduced in Figs. 20 and 21. The far-field photographs (Fig. 20) were taken at a constant energy of 16 joules as the waveguide temperature was varied. The radiated beam shown in these photographs has also been detected with a phototube and its time dependence observed. The beam showed no evidence of the characteristic "spiking" common to such lasers. The patterns observed at lower temperatures correspond to operation with the refractive index of the waveguide core lower than that of the cladding [Fig. 20(a)]. As the temperature is raised, the radiated beams tend towards the on-axis direction [Fig. 20(b)] in a manner characteristic of that observed for side leakage from a low-index-core waveguide (Section II). The pattern changes significantly in the vicinity of 45°C which corresponds to zero difference in refractive index between core and cladding; above 45°C the beam has multiple near-axis lobes [Fig. 20(c) and (d)]. This change in shape is indicative of the onset of guided propagation. No attempt has been made to quantitatively explain the fine structure of these beams; their complexity arises from the unusual field distribution in the aperture resulting from the partial mirrors, as well as the presence of high order leaky modes.

The near-field photograph of Fig. 21(a) shows the bright edge that occurs when the slab is operated above the temperature for zero index difference. There is no magnification in these photographs so that mode structure in the aperture is not visible. Fig. 21(b) shows a similar photograph taken through a 100 Angstrom pass-band filter centered at 1.06 microns. It is evident that most of the extraneous radiation around the slab is outside the pass-band of the filter and is probably from the flash lamp. However, a significant amount of radiation from the edge is within the filter pass band; therefore, the observed bright edge is attributed to fluorescence trapped within the waveguide.



(a) T = 42.5° C.

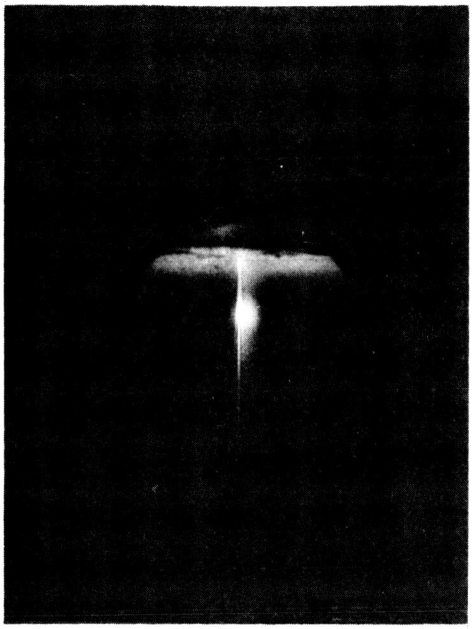
(b) T = 43.7° C.



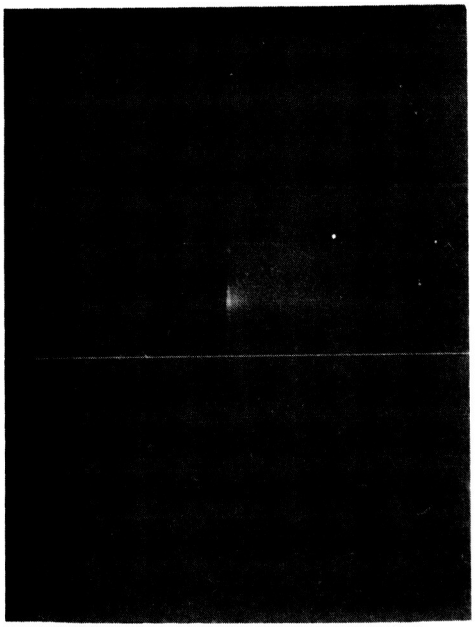
(c) T = 45.5° C.

(d) T = 46.9° C.

Fig. 20 - Far-field pattern of waveguide laser with mirror on core only.



(a) Near field seen through a low-pass filter ($\lambda > 1\mu$).



(b) Near field seen through a narrow-bandpass filter (100 Angstroms) centered at 1.06 microns.

Fig. 21 - Near-field pattern of waveguide laser with mirror on core only (operating temperature 48° C).

In summary, the waveguide laser has been implemented and tested, but laser action has not yet been observed. Preliminary observations, below threshold energy, confirm the stability of the thin glass core and the liquid dichlorobenzene cladding in an optically-pumped environment; below-threshold fluoresence-trapping has been observed and studied. Future work will be directed toward raising the Q of the waveguide cavity by providing "full" silvered mirrors so that lasing can be obtained at a lower pump energy.

IV. Conclusions and Recommendations.

The progress on a program for development of single-mode optical waveguide and waveguide components is presented in this report. Various techniques for construction of completely solid waveguides have been investigated and preliminary experimental evaluations have been conducted. The study has also included the design and experimental testing of a directional coupler and a laser fabricated in waveguide.

The objective of the waveguide program is the development of a waveguide which is rugged, compact and relatively insensitive to ambient temperature variations. To meet these objectives the construction of waveguides and components from solid materials is required. The type of waveguide which has received the greatest attention is the dielectric guide in macroscopic (multi-wavelength) size with a small difference in refractive index between core and cladding. This guide has very attractive operational properties but requires tight tolerances on fabrication and materials. In addition to the development of this guide, several alternative configurations were evaluated, but were found to be less attractive. A different version of the dielectric guide, with core index lower than the cladding has been shown to be useful in some limited applications, but suffers from an inherent attenuation. In addition, a metal plasma waveguide was investigated but was also found to have excessive attenuation.

To obtain the small refractive index difference required by the dielectric waveguide, several techniques have been considered. One technique which has been successfully tested is heat re-treatment of glass. In this approach, two separate samples of a high quality glass are heated and re-annealed through slightly different temperature cycles to obtain a slightly different index. The first trial of this technique resulted in glasses with an index difference of 3×10^{-5} as compared to the desired difference of 1×10^{-5}. It is expected that the required difference can be obtained on the next trial.

Another technique for modifying the refractive index of glass is atomic irradiation. Two different mechanisms for achieving an index change have been considered. First, irradiation with atomic particles such as neutrons and protons produces an index change by modifying the density of the material. Preliminary experiments have been initiated to confirm predicted values of index change. Results obtained for the proton irradiation are in general agreement with predictions.

Neutrons penetrate deeply into optical materials and are useful only for changing the bulk index. Protons, on the other hand, can be adjusted to penetrate to a depth equal to a typical waveguide width, e.g., 30 microns. This suggests a promising technique for forming a waveguide along the surface of a slab of glass without any additional fabrication.

The alternative mechanism for inducing an index change with atomic irradiation is by color center production. In this process, an ionizing radiation such as gamma rays or electrons, is used to induce absorption bands or color centers in the material, and, associated with the absorption is an index change. The index change is generally very small but may be sufficient for the waveguide application.

Various techniques have been considered for waveguide assembly. The most attractive technique is to bond the component parts with an optical cement whose refractive index is higher than both the core and cladding. A preliminary evaluation of this configuration where the cement was simulated by a high index liquid has been conducted. Results have confirmed that the cement has a negligible effect on propagation characteristics. Further investigation of the cementing technique is planned.

A particularly promising approach is to cement together relatively thick pieces of core and cladding glass as a unit, and then grind the core to the required size. This technique facilitates optical fabrication in that it eliminates the need for fabrication of thin slabs of glass.

A different approach to waveguide assembly which has been considered is vacuum deposition of dielectrics on a glass substrate. Vacuum-deposited dielectrics are not generally suited for multi-wavelength sized guides, because films cannot be deposited thick enough and the homogeneity of the deposited dielectric is insufficient. However, it is planned to investigate the use of vacuum-deposition techniques for fabrication of small waveguides of single-wavelength size.

In connection with waveguide components, a waveguide directional coupler and a waveguide laser have been designed and experimentally tested. Two configurations of the directional coupler, an evanescent-field type and a slot-type were evaluated. Coupling was not observed experimentally with the evanescent field type; the lack of coupling is attributed to a difference in phase velocity between the two guides comprising the coupler. It should be possible to overcome this problem by using somewhat smaller sized waveguides.

An experimental slot-type directional coupler comprising bisected dielectric slab waveguides has been evaluated. The measured coupling varied in a manner similar to that calculated, but was lower by a constant amount of about 7 db. The discrepancy is attributed chiefly to a difference between the experimental arrangement and the theoretical model of the coupler. An improved model of the slot coupler utilizing cementing techniques to join the waveguides is planned.

A waveguide laser comprising a slab of neodymium doped laser glass with liquid cladding has been experimentally tested. The objective is the development of a single-mode laser which is compatible with the waveguide system. In initial tests of this laser, a narrow beam output at 1.06 microns was observed; however, this has been attributed to fluorescence trapping rather than laser oscillation. The inability to achieve laser action is attributed to insufficient cavity Q. In the initial tests mirrors were deposited onto the waveguide core and the effective reflectivity was only about 70%. It is planned to use external mirrors covering both the core and cladding regions in order to increase the reflectivity to about 95%. Subsequent to successful laser operation of this configuration, implementation of an all-solid version is planned.

In summary, significant progress has been achieved in the development of completely solid waveguides; it is recommended that this work be continued with emphasis on heat re-treatment, cementing, and surface irradiation techniques. Successful operation of certain components has also been achieved, and it is recommended that this work be continued with increasing emphasis on development of practical, completely solid versions.

V. Acknowledgements.

The work described in this report was performed during the period 1965 FEB to 1966 MAR for the National Aeronautics and Space Administration under contract NAS 12-2. Technical direction at NASA has been provided by Janis Bebris of the Electronics Research Center, Cambridge, Mass.

The work at Wheeler Laboratories was performed by E. Ronald Schineller (Project Supervisor) and Donald W. Wilmot, with technical assistance by Thomas J. Ernst and Robert W. Heuman. Consultation was provided by Henry W. Redlien and Ned A. Spencer, of WL, and Paul W. Levy of Brookhaven National Laboratories. Advice and general direction was provided by Frank H. Williams and Harold A. Wheeler.

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1758, 1770, 1814

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Appendix I.

OPTICAL WAVEGUIDE MODES IN A BISECTED DIELECTRIC SLAB

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1966 FEB 7

This Appendix was previously designated Wheeler Laboratories Report 1335P. It will be published as a Letter to the Editor in the Journal of the Optical Society of America, June 1966.

The design of optical systems, capable of fully exploiting the temporal and spatial coherence of the laser, has resulted in an interest in waveguide techniques at optical frequencies.[1,2] During an experimental study of various optical waveguide configurations, the propagation of a dielectric slab bisected by a metal sheet was investigated. It was observed that the Transverse Electric (TE) modes resembled those found on similar structures at microwave frequencies; however, for the Transverse Magnetic (TM) modes, significant differences, arising from the complex impedance of metals at optical frequencies, were observed.

The bisected dielectric waveguide is shown schematically in Fig. A1.1. In the experimental guide the core width was many wavelengths, and therefore, the propagating rays for low-order modes were very nearly parallel to the bisecting wall[3]. The experimental model of the waveguide, shown in Fig. A1.2, consisted of a liquid core (chlorobenzene) and a cladding of Schlieren-quality, borosilicate crown glass (BK-7), 77 mm long; an optically flat front-surface mirror of vacuum-deposited aluminum formed the bisecting plane. The core width was set at 50λ (.032 mm) and the waveguide was excited by a CW gas laser (.6328 microns). Individual modes were excited by matching the angle of incidence on the waveguide aperture to the angle at which the rays for that mode propagate in the guide. The propagating modes were observed by projecting a magnified image of the waveguide aperture onto a screen. In order to obtain direct measurements and continuous plots of the aperture distribution, a photomultiplier with a small sampling aperture was scanned through the image.

Measurements for a variety of different waveguide conditions were performed with this arrangement. Temperature control enabled us to slowly vary the difference in refractive index between the core and the cladding as the various modes were monitored. In this way, as the difference in index was increased, it was observed that new modes were introduced in pairs; i.e. for every TE mode that began to propagate, a TM mode of the same mode number began to propagate at the same operating point. Furthermore, only odd-numbered modes, for both polarizations, were observed. Experimental results are presented below for a particular operating point where the difference in refractive index between core and cladding was about 0.0002. For this difference, it was expected that modes with mode numbers as high as four would propagate. With the input radiation polarized to excite TM modes, the only modes observed were the TM-1 and TM-3; the measured aperture distributions of these modes are shown in Fig. 3. Similarly, when the polarization of the input laser beam was rotated 90° to excite TE modes, only the TE-1 and TE-3 were observed; the patterns were identical, except for polarization, to the TM-1 and TM-3 modes. It should be noted that the even-numbered TM modes, including the usually-dominant TM-0 mode, were not observed on this structure.

This behavior is quite different from that occuring with a perfectly-conducting bisector where only one mode, either TM or TE, exists for each mode number. With a perfect conductor, only the TM modes with even mode numbers (TM-0, TM-2, TM-4, etc.), and the TE modes with odd mode numbers (TE-1, TE-3, TE-5, etc.), can propagate. From the TM modes experimentally observed, it can be inferred that the aluminum bisecting wall behaves quite differently from a perfect conductor. The elimination of the expected TM modes, particularly the dominant TM-0 mode, and the appearance of completely different TM modes indicate that the modes in an optical waveguide with a real metal bisector are not simply lossy versions of the perfect-conductor modes, as is generally the case at microwave frequencies.

To obtain an exact analysis for the real metal, it is necessary to rederive the characteristic, or "eigenvalue", equations for this structure, taking into account the complex impedance of real metals at optical frequencies. However, for the specific case considered above, the behavior observed can be explained by considering the free-space reflection of the metal and the symmetry (or antisymmetry) properties of the modes on a dielectric slab that is not bisected.

For a dielectric slab bisected by a perfect conductor, the bisector acts as an anti-symmetry plane for TE modes, and the guide propagates only the odd-numbered modes of the unbisected structure; however, for TM modes, the bisector acts as a symmetry plane, and the guide propagates only the even-numbered modes. For a real metal bisector, the reflection phase for perpendicular polarization (TE modes) is nearly the same as for a perfect conductor. Therefore, for TE modes, the metal bisector still acts as an anti-symmetry plane and the guide propagates the odd-numbered modes (TE-1, TE-3, etc.) as for a perfect conductor. However, for the case of parallel polarization (TM modes) with a real conductor, the reflection phase at grazing angles differs by about 180° from that of a perfect conductor at the same angle of incidence. Therefore, for TM modes, the metal bisector acts as an anti-symmetry plane rather than a symmetry plane, and the guide propagates the odd-numbered modes (TM-1, TM-3, etc.) of the unbisected structure, rather than the even-numbered modes as for a perfect conductor.

It has been shown that this particular bisected optical waveguide supports only the odd-numbered TM and TE modes of propagation. An important consequence of this result is that the TM-0 mode, which is typically the dominant mode on such a structure, cannot be supported by a large size, bisected-slab waveguide at optical frequencies. This behavior is due to the complex impedance exhibited by metals at optical frequencies and illustrates the fact that it is not valid in waveguide computations to assume that a metal is a perfect conductor at these frequencies.

The work described above has been part of a program for the development of waveguide and waveguide components performed under NASA contracts NASw 888 and NAS 12-2. The work was carried out by the authors and H. M. Heinemann under the supervision of H. W. Redlien.

Footnotes

(1) R. A. Kaplan, Proc. IEEE, 51, 1144 (1963).

(2) D. B. Anderson, "Application of Semiconductor Technology to Coherent Optical Transducers and Spatial Filters", in Optical and Electro-Optical Information Processing Technology, edited by Tippett, Berkowitz, Clapp, Koester and Vanderburgh (MIT Press, Cambridge, Mass., 1965).

(3) E. R. Schineller, D. W. Wilmot, J. Opt. Soc. Am.; 55, 1571A (1965).

(4) J. Kane, H. Osterberg, J. Opt. Soc. Am., 54, 347 (1965).

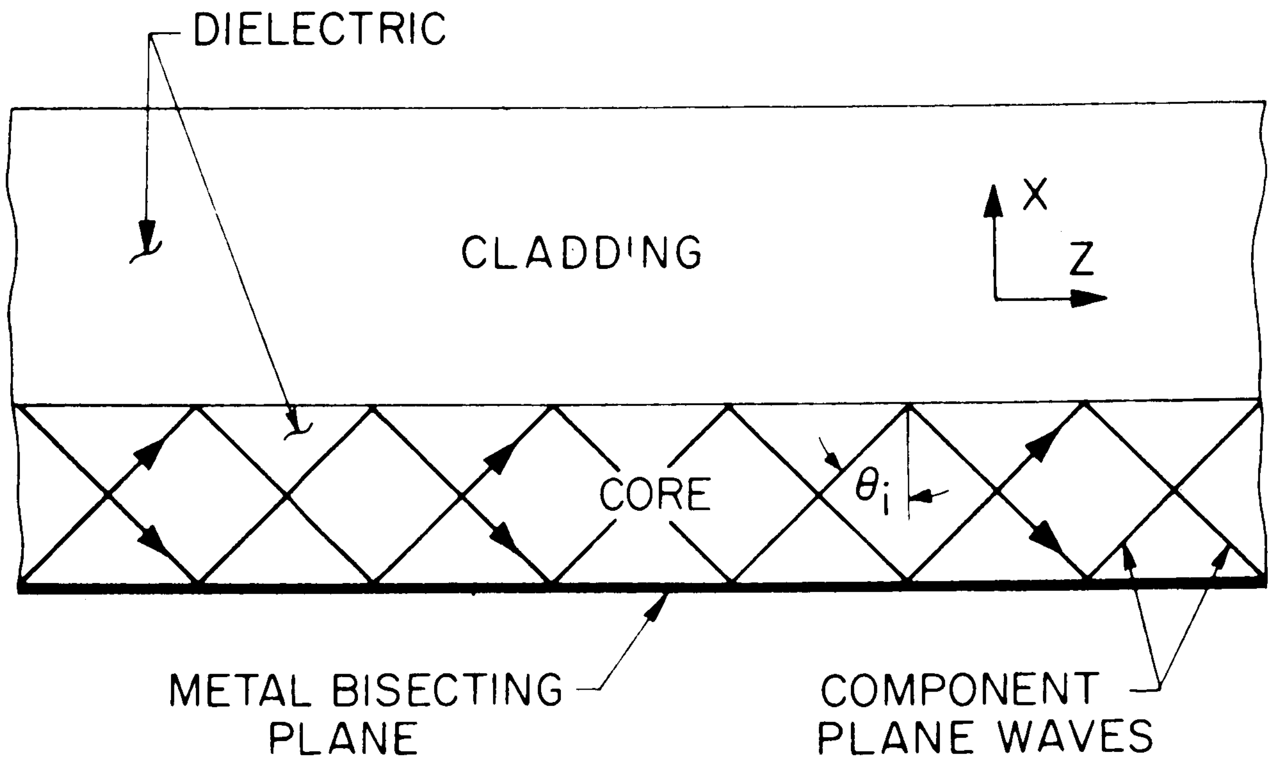


Fig. A1.1 - Bisected dielectric-slab waveguide.

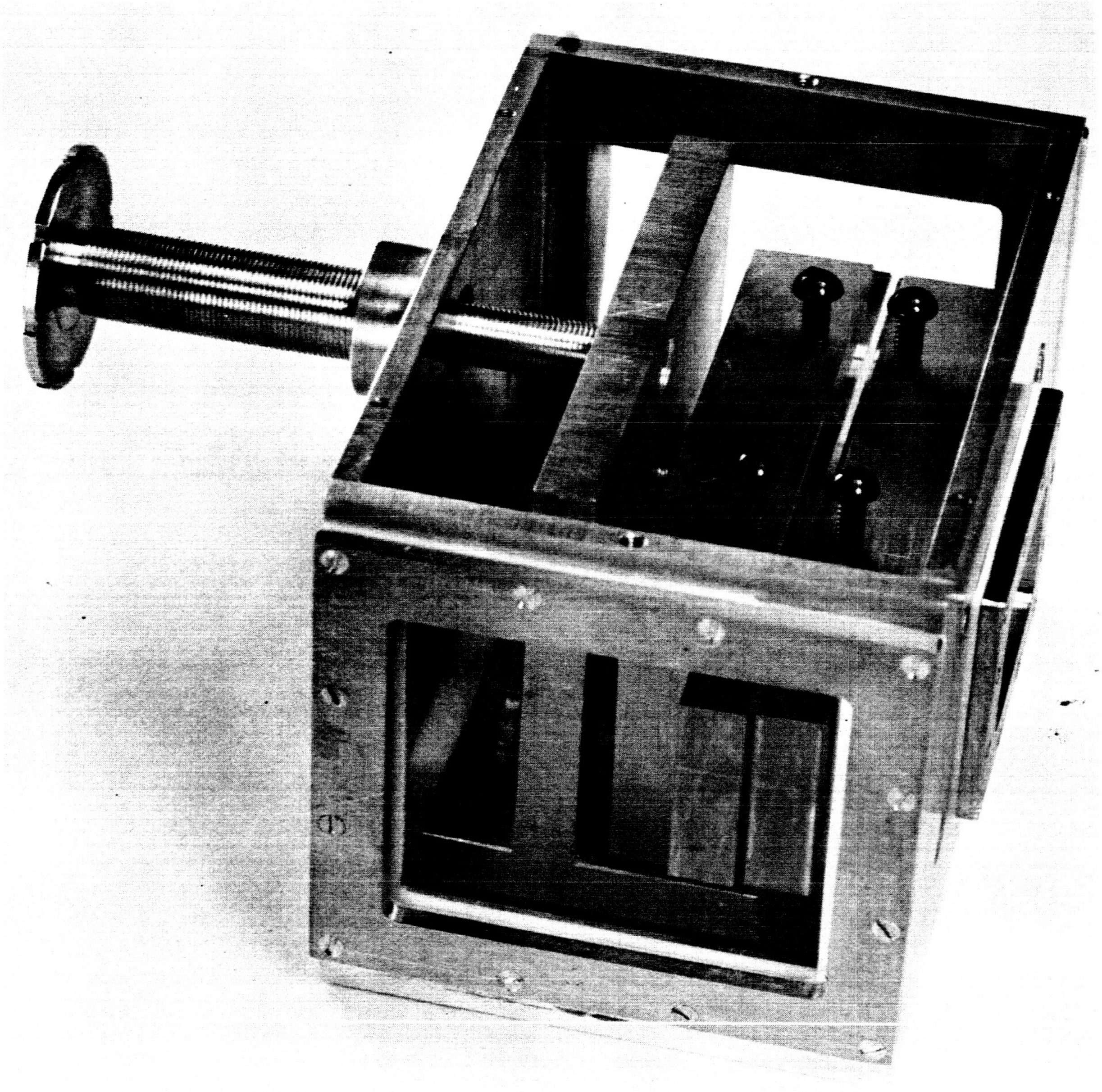


Fig. A1.2 - Experimental waveguide.

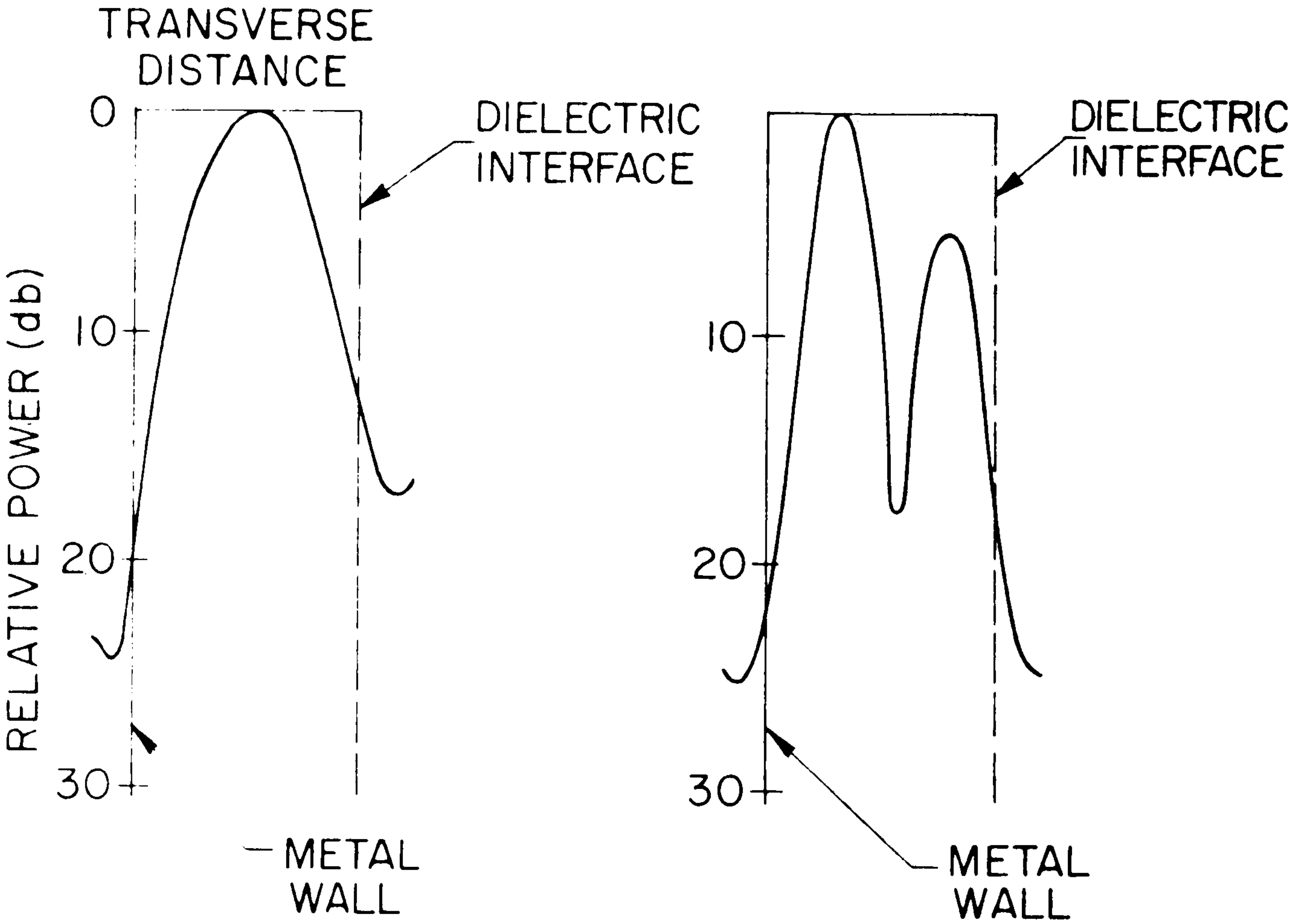


Fig. A1.3 - Measured aperture distribution of the TM modes in a bisected dielectric-slab waveguide at optical frequencies.

Appendix II. A Survey of Optical Dielectric Waveguides.

The optical waveguide and components discussed in the body of this report represent a novel approach to the problem of developing precision components for laser systems. However, the general field of optical waveguide has been in existence for some time. A survey of the literature in this field has been conducted in order to place the current Wheeler Laboratories work in proper perspective. This Appendix includes a brief outline of past and present literature as well as a discussion of the program at Wheeler Laboratories. The Appendix concludes with an annotated bibliography.

A. Historical Development and Related Topics.

Optical dielectric waveguides have evolved from two separate fields - fiber optics and microwave engineering. In the field of fiber optics the trend toward improved spatial resolution of arrays of conventional, non-modal fibers resulted in the development of smaller and smaller fibers, until finally the fiber size was of the order of wavelengths and modal behavior was noted (Refs. 19 and 21).

In the field of microwave engineering the use of dielectric waveguides for microwave frequencies was proposed and studied at an early stage (Refs. 5, 6 and 7). It soon became obvious that the metallic waveguide was the most suitable waveguide at these frequencies. However, for various special applications the dielectric waveguide was considered. Over the years the trend in the microwave industry has been toward the higher frequencies. As the frequency has gone up, various forms of the dielectric waveguide have been reconsidered and applied (see for instance Refs. 8 and 10). It should be noted that the microwave analogies have been recognized by the optical workers (Refs. 12 and 18).

The early work on fiber optics is thoroughly discussed in a continuing series of articles by N. S. Kapany in the Journal of the Optical Society of America. This series includes a variety of papers starting with a paper on the guiding properties (non-modal) of cylinders (Ref. 11), and includes such topics as optical leakage between non-modal fibers (Ref. 14) and the analysis of modes on small dielectric fibers (Ref. 21). There are a number of general articles on conventional non-modal fibers. In particular, the Appendix, "Fiber Optics" by N. S. Kapany in the "Principles of Optics" (Ref. 13) as well as the "Fiber Optics Handbook" published by Mosaic Fabrications, Inc., (Ref. 22) should be mentioned.

The past and current microwave literature on dielectric waveguides, pertinent to present optical applications, includes classical references (Refs. 6 and 7) as well as more recent work on dielectric-rod antennas (Ref. 24) and waveguides (Ref. 10). In particular the report on dielectric rods and tubes by Beam, et al. (Ref. 8), the papers by D. D. King on dielectric image lines (Ref. 10) and the articles by J. W. E. Griemsman on H-guides (Ref. 31) should be of interest.

Another body of literature that is applicable to this study is the work on beam waveguides at millimeter and optical frequencies (Refs. 20 and 34). In general, this form of optical waveguide, usually a series of lenses, is not a dielectric waveguide of the same type as the others discussed herein. The objective for such waveguides is usually low-loss long-distance transmission. In one particular case, when the discrete glass lenses are replaced by a continuous gas lens as proposed in work at the Bell Telephone Laboratories (Ref. 37), the beam waveguide does become recognizable as a dielectric waveguide.

B. Current Literature.

The current literature on optical dielectric waveguides falls into several catagories: studies of waveguide modes, analysis of coupling between fibers, design of waveguide-type devices (fiber lasers, optical switches, etc.), physiological optics, and the analysis of self-trapping of light in non-linear materials. The first category listed above, studies of waveguide modes, is the common basis of all the others. The theoretical and experimental analysis of modes on cylindrical fibers reported in various papers by N. S. Kapany (Refs. 25 and 29) and E. Snitzer (Ref. 23) cover this topic quite thoroughly. The analytical work by Marcatili on various tubular dielectric waveguides, including metallic optical waveguides, is also of interest (Refs. 36 and 45). In addition, there are articles on the modes supported by planar optical dielectric waveguides. (Refs. 28 and 35).

The subject of coupling between optical fibers is important for two reasons. In the case of various assemblies of many small fibers, the coupling causes degradation of performance and must be avoided. On the other hand, there is a current interest in utilizing controlled coupling in various waveguide devices (see next paragraph). The subject of coupling is one area in particular where it would appear useful to utilize the voluminous microwave literature on the subject (Ref. 9). Current optical work on coupling includes a theoretical paper by A. L. Jones (Ref. 39) as well as experimental and analytical work by N. S. Kapany, et al. (Ref. 33) and E. Snitzer (Ref. 23).

The recent interest in waveguide-type devices is motivated in part by the current work on optical computers (Refs. 32 and 41). In order to develop digital-type computers working at optical frequencies it is necessary to develop appropriate optical sources and logic elements. The optical source can take the form of a diode laser, in which the radiation is confined in the vicinity of a p-n junction by a dielectric-waveguide mechanism (Ref. 27). Alternately, the optical source might be a fiber laser, a device proposed in the early stages of laser development by E. Snitzer (Ref. 16). The fiber laser in one form consists of an Nd-doped glass fiber, often non-modal, with mirrors on both ends. When a small fiber is used, a degree of laser mode selectivity is obtained by virtue of the waveguide mode characteristics of the fiber. A similar configuration utilizing a rectangular geometry rather than the conventional circular fibers has also been reported (Ref. 30). The proposed logic elements take a variety of forms, including optical switches comprising coupled fibers in which electro-optical manipulation of coupling characteristics can direct the light to either of two output ports (Refs. 33 and 44). An alternate type of logic element consists of a fiber containing a saturable absorber in its glass cladding. By controlling the absorption coefficient of the cladding with an external light source, such a laser can be turned on and off (Ref. 43).

A recent paper by D. B. Anderson (Ref. 42) proposes the fabrication of a variety of optical waveguide-type components including waveguides, bends, Tee's, hybrids, parametric amplifiers and modulators. The proposed waveguide medium for most of these components consists of a 1 micron layer of vacuum-deposited silicon dioxide. To date no experimental work on this waveguide is reported in the literature.

There are at least two cases where the unique advantages of waveguide techniques are proposed to overcome the inherent limitations of conventional optical devices. The first of these is the suggestion by Newstein and Solimene of TRG (Ref. 26) that a single-mode waveguide medium offers some advantages for optical modulator construction. The other example is the wide-angle interference filter being developed by Wheeler Laboratories (Ref. 4). In one form this filter employs an array of small (3μ) single-mode dielectric fibers in place of the customary spacer layer found in a conventional Fabry-Perot configuration. This results in a filter with a field of view considerably larger than that of conventional interference filters.

Most of the papers discussed above are directed towards developing, improving, or understanding optical components. There is also some literature in which optical waveguide theory is called upon in an attempt to explain various observed phenomena. In this category are the papers on physiological optics which try to relate the characteristics of color vision to the waveguide characteristics of retinal rods and cones (Refs. 17 and 40). A similar example is the work on the self-trapping of light in non-linear materials (Ref. 38). This work originated from attempts to explain the unusual, thin cracks formed in glass that was exposed to high energy bursts from Q-spoiled lasers. It has been postulated that the cracks occur because the electric field of the high intensity light modifies the refractive index of the glass (by means of some electro-optic mechanism). The situation is such that a small dielectric waveguide is formed in the material, the light is concentrated within this waveguide, and then the field intensity becomes sufficiently large to cause electrical breakdown of the glass. Now that the self-trapping mechanism has been discovered it is likely that applications for it will be found.

C. Discussion and Conclusions.

The current literature indicates three distinct areas of optical waveguide interest: long distance optical transmission, individual components for specific applications, and general scientific interest. The Wheeler Laboratories optical waveguide program sponsoted by NASA (Refs. 1, 2 and 3) differs in two respects from the work in the general literature. In the first place,it is the only program involving both analytical and experimental work which is aimed at developing an entire series of compatible, microwave-analogous, optical components specifically adapted to laser communication and tracking applications. Secondly, the program is unusual in that the work has concentrated upon a rather unique type of waveguide - large-size, single-mode dielectric waveguide. This latter point is emphasized because the use of a single-mode medium is believed to be the only practical way to design a series of compatible, precision components, i.e., components which can be mated end-to-end in a simple manner. An example of such a system is a waveguide laser coupled to a waveguide modulator, followed by various directional couplers, filters, circulators, detectors, etc. The large size is desired to facilitate construction of such components and systems.

While the present Wheeler Laboratories work represents a unique approach to optical waveguide and component design, it has benefited from the literature. The microwave literature has been invaluable for component design information, as can be seen from the directional coupler analysis (see Section III of this report), while the work by Kapany and by Snitzer on waveguide modes and coupling between waveguides has been particularly helpful.

D. Annotated Bibliography.

The following references, listed in chronological order, are intended as a survey of the literature in this field. They do not constitute an all-inclusive list, nor are the particular references cited necessarily the earliest or most comprehensive articles on the particular topic. Rather they are a collection of the pertinent references which are most often referred to by the authors of this report.

The notations following the references are intended to indicate the contents which are of interest for our present purpose - optical waveguide and component design; in several instances the papers contain additional material in related fields which is not cited herein.

Wheeler Laboratories Publications.

(1) R. A. Kaplan, "Optical Waveguide of Macroscopic Dimension in Single-mode Operation", Proceedings of IEEE, vol. 51, p. 1144-1145; 1963 AUG. (First published report of experimental work on WL waveguide configuration.)

(2) D. W. Wilmot, "Macroscopic Single-Mode Waveguide for the Construction of Optical Components", presented at the International Symposium of the Professional Technical Group on Microwave Theory and Techniques of the IEEE, New York, N.Y.; 1964 MAY. (Discussion of waveguide components in dielectric slab configuration includes experimental data on the waveguide.)

(3) E. R. Schineller, D. W. Wilmot, "Single-Mode Macroscopic Optical Waveguide", presented as paper WG15 at the Fall Meeting of the Opt. Soc. of Amer.; 1965 OCT. (Experimental study of waveguide operation.)

(4) D. W. Wilmot, E. R. Schineller, "A Wide-Angle Narrow-Band Optical Filter", presented as paper ThD15 at the Fiftieth Anniversary Meeting of the Optical Society of Amer.; 1966 MAR. (Discusses fabrication of narrow-band optical filters within a fiber waveguide medium. The resultant filter has a larger usable field-of-view than conventional configurations.)

General Literature.

(5) Hondros, Debye, "Elektromagnetische Wellen an Dielektrischen Drähten", Ann. der Phys., vol. 32, p. 465-476; 1910. (The first published paper on transmission along dielectric wires.)

(6) J. R. Carson, S. P. Mead, S. A. Schelkunoff, "Hyper-Frequency Waveguides - Mathematical Theory", B.S.T.J., vol. 15, p. 310-333; 1936 APR. (An early classical paper on waveguide theory. It includes mathematical expressions for the fields as well as the cut-off frequency of dielectric rod waveguides.)

(7) C. H. Chandler, "An Investigation of Dielectric Rod as Waveguide", Jour. Appl. Phys. vol. 20, p. 1188-1192; 1949 DEC. (A classic, early paper on dielectric waveguides at microwave frequencies, including resonators and waveguide bends.)

(8) R. E. Beam, et al., "Investigations of Multi-Mode Propagation in Waveguides and Microwave Optics", Microwave Laboratory, Northwestern University, Final Report to the Army Signal Corps.; 1950 NOV 30, DDC No. ATI-94929. (Contains a detailed theoretical analysis of dielectric tube and rod waveguides, including detailed plots of field intensity, phase velocity, etc.)

(9) S. E. Miller, "Coupled Wave Theory and Waveguide Applications", B.S.T.J., vol. 33, p. 661; 1954 MAY. (A general analysis of directional couplers.)

(10) D. D. King, "Properties of Dielectric Image Lines", IRE Trans. on Microwave Theory and Techniques, vol. MTT-3, p. 75; 1955 MAR. (Discussion and experimental data on a bisected, dielectric-rod configuration at microwave frequencies. Data on bends and twists is included.)

(11) N. S. Kapany, "Fiber Optics. Part 1. Optical Properties of Certain Dielectric Cylinders", Jour. Opt. Soc. Am., vol. 47, p. 413-422; 1957 MAY. (Reports the results of investigations of various factors affecting the light transmission of non-modal fibers. Includes (1) measurements of refractive index and index homogeneity of glass, quartz, and plastic fibers, (2) measured radiation patterns of bent non-modal fibers, and (3) a geometrical analysis of propagation in non-modal fibers.)

(12) N. S. Kapany, W. A. Oberheim, "Microwave Analogs of Fiber Optics", Jour. Opt. Soc. Am., vol. 41, p. 870; NOV 1958. (A talk abstract suggesting microwave simulation of optical waveguide propagation.)

(13) N. S. Kapany, "Fiber Optics", Appendix N in "Concepts of Classical Optics", by J. Strong, Freeman & Co., San Francisco; 1958. (A detailed summary and analysis of conventional, non-modal fiber optics with emphasis on applications.)

(14) N. S. Kapany, "Fiber-Optics. V. Light Leakage due to Frustrated Total Reflection", Jour. Opt. Soc. Am., vol. 49, p. 770-778; 1959 AUG. (An approximate analysis of coupling between non-modal fibers.)

(15) A. F. Harvey, "Periodic and Guiding Structures at Microwave Frequencies", IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, p. 30-61; 1960 JAN. (Contains a brief analysis of propagation on dielectric slabs and rods as well as a very extensive bibliography covering the microwave literature on this subject.)

(16) E. Snitzer, "Proposed Fiber Cavities for Optical Masers", Jour. Appl. Phys., vol. 32, p. 36-39; 1961 JAN. (Discusses possibility of laser action in the first few modes of a multimode optical dielectric waveguide.)

(17) E. Snitzer, M. Polanyi, "Possible Waveguide Mode Effects in Retinal Receptors", Jour. Opt. Soc. Am., vol. 51, p. 476; 1961 APR. (A talk abstract which discusses relation between waveguide modes and color vision.)

(18) E. Snitzer, F. Hoffman, "Glass Fibers Acting as Receiving Dielectric Antennas in the Visible Spectrum", Jour. Opt. Soc. Am., vol. 51, p. 1463; 1961 APR. (Talk abstract concerned with measured reception pattern of modal fibers, discusses angle and wavelength sensitivity of excitation for various modes.)

(19) E. Snitzer, H. Osterberg, "Observed Dielectric Waveguide Modes in the Visible Spectrum", Jour. Opt. Soc. Am., vol. 51, p. 499-505; 1961 MAY. (An experimental study of optical waveguide modes, including theory and analysis of the results as well as many photographs.)

(20) G. Goubau, F. Schwering, "On the Guided Propagation of Electromagnetic Wave Beams", IRE Trans. on Antennas and Propagation, vol. AP-9, p. 248-256; 1961 MAY. (The initial proposal and analysis of beam waveguides. Specific calculations apply to microwave frequencies but theory is general. Beam modes and diffraction losses are discussed.)

(21) N. S. Kapany, J. J. Burke, "Fiber Optics. IX. Waveguide Effects", Jour. Opt. Soc. Am., vol. 51, p. 1067-1078; 1961 OCT. (A theoretical analysis of cylindrical dielectric waveguide modes, including some theoretical and experimental work on coupling between modal fibers.)

(22) J. W. Hicks, P. Kiritsy, "Fiber Optics Handbook 1961", 2 ed. Mosaic Fabrications, Inc., 205 Chapin Street, Southbridge, Mass.; 1961. (A brief general summary of terminology, techniques and applications of conventional, non-modal fiber optics.)

(23) E. Snitzer, "Optical Dielectric Waveguides", in Advances in Quantum Electronics, J. Singer, ed.,Columbia University Press, p. 348-369; 1961. (Theoretical analysis of cylindrical waveguide modes including field plots, experimental results, a discussion of fiber coupling and a proposal for the use of fiber coupling as a mode-selective mechanism in fiber lasers.)

(24) F. J. Zucker, "Surface and Leaky-Wave Antennas", in Antenna Engineering Handbook, Jasik, ed., McGraw-Hill; 1961. (Analysis and design data for dielectric-rod antennas at microwave frequencies. Includes a bibliography and data on other types of surface-wave antennas.)

(25) N. S. Kapany, J. J. Burke, "Dielectric Waveguides at Optical Frequencies", Solid State Design, p. 35-42; 1962 JAN. (A general discussion of optical waveguide modes including mode chart and photos.)

(26) M. Newstein, N. Solimene, "Analysis of Laser Modulation Techniques", Technical Research Group (TRG) Report No. ASD-TDR-62-9, DDC No. AD-283 462; 1962 JUN. (Contains discussion of modulator technique utilizing optical waveguide.)

(27) A. Yariv, R. C. C. Leite, "Dielectric-Waveguide Mode of Light Propagation in p-n Junctions", Applied Phys. Letters, vol. 2, p. 55-57; 1963 FEB 1. (Analysis of the modal characteristics of a p-n junction.)

(28) J. G. Hirschberg, "Cladded Laminar Optics for the Ultraviolet", Jour. Opt. Soc. Am., vol. 53, p. 507; 1963 APR. (Talk abstract discussing guiding by non-modal dielectric-slab configuration comprising a magnesium fluoride cladding on a slab of fused silica.)

(29) N. S. Kapany, J. J. Burke, C. C. Shaw, "Fiber Optics. X. Evanescent Boundary Wave Propagation", Jour. Opt. Soc. Am., vol. 53, pp. 929-935; 1963 AUG. (A theoretical and experimental study of modal propagation in cylindrical fibers with an absorbing core; contains plots of per cent power in core and effective attenuation coefficient versus waveguide parameters.)

(30) V. R. Bird, D. T. Carpenter, P. S. McDermott, R. L. Powell, "Rectangular Optical Dielectric Waveguides as Lasers", in "Lasers and Applications", W.S.C. Chang, ed., Ohio State University Press, p. 147-147; 1963. (Discussion of fabrication of rectangular dielectric waveguides from solid laser materials such as ruby and $CaWO_4$. Lasing in high-order modes is reported.)

(31) J. W. E. Griemsmann, "Design of Millimeter Waveguide Components", DDC No. AD-413 774; 1963. (Investigates millimeter wave application of H-guides. Contains theory, experiment and design data on directional couplers, bends, wave launchers, etc.)

(32) D. K. Pollack, et al.,ed., "Optical Processing of Information", Spartan Books, Inc., Baltimore; 1963. (Proceedings of first conference on optical information processing. Contains some discussions concerning applicability of waveguide techniques to this field.)

(33) E. Snitzer, "Some Properties of Fiber Optics and Lasers (Part A)", in "Optical Processing of Information, Pollock, et al.,ed., Spartan Books, Inc., Baltimore, p. 61-62; 1963. (Survey of dielectric-waveguide properties with emphasis on their application as optical computer components. Switching of light from one waveguide to an adjacent one by dynamically controlled fiber coupling is proposed. Fiber lasers are also discussed.)

(34) G. Goubau, J. R. Christian, "Some Aspects of Beam Waveguides for Long Distance Transmission at Optical Frequencies", IEEE Trans. on Microwave Theory and Techniques, vol. MTT-12, p. 212-220; 1964 MAR. (Discussion and experimental extension of beam waveguide concepts to optical frequencies. Attenuation of less than 1 db/km is predicted.)

(35) J. Kane, H. Osterberg, "Optical Characteristics of Planar Guided Modes", Jour. Opt. Soc. Am., vol. 54, p. 347-352; 1964 MAR. (Derivation, starting with Maxwell's equations, of the propagation characteristics of optical dielectric-slab waveguides. Includes the effect of core losses and also discusses the case where the cladding index of refraction differs on each side of the core.)

(36) E. A. J. Marcatili, R. A. Schmeltzer, "Hollow Metallic and Dielectric Waveguides for Long Distance Optical Transmission and Lasers", B.S.T.J., vol. 43, p. 1787-1809; 1964 JUL. (The field configurations and propagation constants are determined for hollow circular waveguides made of dielectric material or metal. Attenuation and loss due to bending is considered, but no experimental results are reported. It is concluded that hollow dielectric guide is suitable as a laser medium and that the TE_{01} mode in hollow metallic guide is suitable for long distance transmission since its computed attenuation is only 1.8 db/km.)

(37) D. W. Berreman, "A Lens or Light Guide Using Convectively Distorted Thermal Gradiants in Gases", B.S.T.J., vol. 43, p. 1469; 1964 JUL. (Discussion and experimental work on a dielectric guide utilizing refractive index gradients caused by temperature gradients in a gas.)

(38) R. Y. Chiao, E. Garmire, C. H. Townes, "Self-Trapping of Optical Beams", Physical Review Letters, vol. 13, p. 479-482; 1964 OCT. (Discusses the creation, by the light itself, of dielectric waveguides in materials with non-linear refractive index. It is shown that a critical power for trapping exists, and above this power the light will be trapped regardless of its power density.)

(39) A. L. Jones, "Coupling of Optical Fibers and Scattering in Fibers", Jour. Opt. Soc. of Am., vol. 55, p. 261-271; 1965 MAR. (A theoretical analysis of optical coupling between dielectric fibers.)

(40) G. Biernson, A. W. Snyder, "Electromagnetic Effects in the Cones of the Human Retina", Electronics Letters, vol. 1, p. 89-90; 1965 JUN. (Attempt to relate excitation efficiency of various modes in the retinal cones to the characteristics of color vision.)

(41) J. T. Tippett, et al.,ed., "Optical and Electro-Optical Information Processing", M.I.T. Press, Cambridge, Mass.; 1965. (Proceedings of second conference on optical information processing. Contains papers on waveguide effects.)

(42) D. B. Anderson, "Application of Semiconductor Technology to Coherent Optical Transducers and Spatial Filters", in "Optical and Electro-Optical Information Processing", Tippett, et al.,ed., MIT Press, p. 221-234; 1965. (Proposes the construction of microscopic optical waveguide and waveguide components such as transformers, bends, and hybrids using a 1 μ silicon dioxide film on a highly-doped silicon substrate. Optical parametric amplifiers are also discussed. No experimental results on the waveguide components are reported.)

(43) C. J. Koester, C. H. Swope, "Some Laser Effects Potentially Useful in Optical Logic Functions", in "Optical and Electro-Optical Information Processing", Tippett, et al.,ed., MIT Press, p. 253-267; 1965. (Discusses application of fiber waveguide laser to optical computing. Includes experiments on coupling between two fiber lasers and proposes the use of a saturable absorber in the fiber cladding, in conjunction with an auxiliary light source, as a means of switching the laser on and off for binary logic.)

(44) N. S. Kapany, G. M. Burgwald, J. J. Burke, "Light Amplification and Switching Using Fiber Optics and Laser", in "Optical and Electro-Optical Information Processing", Tippett, et al.,ed., MIT Press, p. 305-320; 1965. (Includes a theoretical and experimental study of coupling between cylindrical dielectric waveguides, it also contains a plot of coupling versus separation for the slab configuration. Fiber lasers, oscillators, and amplifiers are also discussed, as well as a method for switching between fibers by dynamically controlling coupling.)

(45) E. A. J. Marcatili, "Light Transmission in a Multiple Dielectric (Gaseous and Solid) Guide", B.S.T.J., vol. 45, p. 97-103; 1966 JAN. (Contains the approximate analysis for guiding by a thin-wall glass tube containing a high-density gas. The computed attenuation of .052 db/km suggests that such a guide is suitable for long distance transmission.)

Appendix III. Irradiation of Dielectrics for Waveguide Fabrication.

The present waveguide development program has involved the investigation of a variety of techniques for the fabrication of an all-solid, macroscopic, dielectric waveguide. One of the more novel approaches to this problem has been an investigation of various types of irradiation, such as neutron, proton, gamma ray, etc., as means for selectively modifying the index of refraction of a suitable dielectric material. It is well known (Refs. 16 and 19) that irradiation changes the physical properties of most materials. However, at present most of the literature concerning radiation effects on optical materials concentrates on avoiding "radiation damage". The objective of this Appendix is to consider utilizing such radiation damage as a means of precisely adjusting the index of refraction of optical glass and fused silica.

Two general methods of waveguide fabrication involving radiation are available. In some cases the characteristics of the radiation are such that the effects occur homogeneously throughout a bulk material. Irradiation of this nature constitutes a method, similar to the precision annealing and special selection techniques discussed in Section II of this report, for adjusting the bulk refractive index of glass or quartz. Waveguide assembly of separately irradiated samples would then take the form of conventional grinding, polishing, and cementing operations. Other types of radiation have very limited penetrating power and affect only a surface layer of the dielectric. In this case the possibility exists of obtaining a surface layer, with the proper dimensions and index of refraction, to function as a waveguide without further processing.

A survey of irradiation effects has been undertaken to confirm the general feasibility of the technique and to determine the most promising methods of irradiation. The various types of radiation, listed in Table A3.1, have been considered, along with the main mechanisms of index change (Table A3.2). An important consideration throughout this survey has been the high optical quality required of the irradiated dielectric. The index of refraction must be homogeneous to 10^{-5} and the absolute value of the index, or at least the difference between two samples, must be

TYPE	DESCRIPTION	MATERIAL EFFECTS
Alpha	Helium nucleus Charge = +2e Atomic mass no. = 4	Ionization, atomic displacement.
Beta	Electrons, positrons Charge = ± e	Ionization, some atomic displacement
Gamma	Electromagnetic (emitted from nucleus)	Ionization.
Neutrons	Charge = 0 Atomic mass no. = 1	Atomic displacement.
Electrons	Charge = -e Mass = 1/1837 of proton	Ionization, some atomic displacement.
Protons	Charge = +e Atomic mass no. $\approx$ 1	Ionization, atomic displacement
Heavy Ions	Ionized atoms Atomic mass no. > 1	Ionization, atomic displacement.
Infrared	Electromagnetic $1\mu < \lambda < 100\mu$	Thermal effects only.
Ultraviolet	Electromagnetic $.01\mu < \lambda < .4\mu$	Ionization and induced chemical changes.
X-rays	Electromagnetic $10^{-6}\mu < \lambda < 10^{-2}\mu$	Ionization.

Table A3.1 - Types of irradiation.

EFFECTS	MECHANISM OF INDEX CHANGE	COMMENTS
Atomic Displacement.	Change in density or polarization of component atoms.	Possibly useful. Sometimes results in strains and associated birefringence. Often accompanied by color centers, which can be annealed out.
Ionization.	Formation of color centers.	Index change associated with absorption.
Chemical Changes.	Modification of chemical bonds, producing new compound with different index of refraction.	Not yet much literature on transparent optical materials other than plastics.
Thermal.	Change in structure (different crystalline phase) and/or introduction of internal strains.	Useful when uniform and highly controlled as in precision annealing. Localized heating such as with IR beam results in a strained, birefringent material.

Table A3.2 - Irradiation effects.

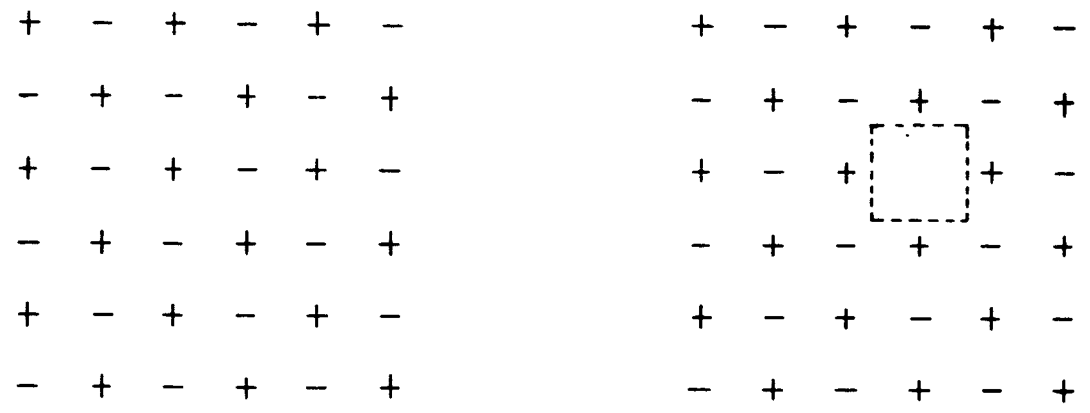
controllable to 10^{-4}. It should be noted that the radiation study reported herein is concerned only with a preliminary engineering evaluation of irradiation techniques as they apply to waveguide fabrication. In all cases the simplest possible theoretical model has been applied and the results are only intended to indicate general suitability or, at best, order of magnitude estimates of parameters.

The following sections of this Appendix present the results of this survey. Parts A and B discuss two basic mechanisms of index change - color centers and atomic displacements. Parts C through G discuss the effect of various types of irradiation including neutron, proton, heavy ion, electron and electromagnetic.

A. Color Centers.

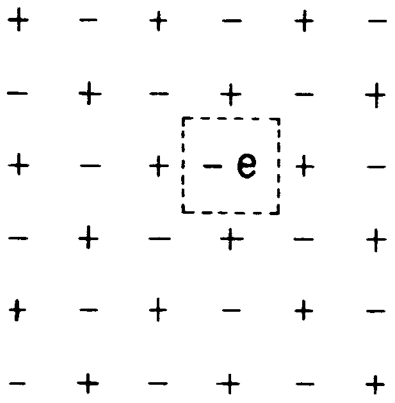
One possible mechanism for changing the index of refraction of a dielectric is the creation of color centers. The term "color center" refers to a free electron which is trapped at a lattice defect as shown in Fig. A3.1. Such an electron exhibits an absorption spectrum similar to that of the single electron in hydrogen. There is, of course, a variation of the index of refraction associated with such a resonance. It should be noted that the simple description above applies specifically to a particular color center - the F-center in alkali-halide crystals (Ref. 5). Color centers in other materials may involve several electrons or holes bound to impurity atoms as well as lattice defects. The situation is also complicated by the non-crystalline nature of glass and fused silica. Nevertheless, the extensive literature on alkali-halide color centers has been useful in this work (see for instance, Refs. 1 and 5).

Color-center production requires creation of free electrons within the material. A color center is formed whenever a passing free electron is captured by a region of localized positive charge, as occurs for instance at a negative-ion vacancy in the alkali halides. There are always a limited number of defects existing in every material (Ref. 5), so it is possible to form color centers with a purely ionizing radiation, e.g., gamma rays, X-rays, etc. This approach is attractive since these natural



a) perfect lattice

b) lattice defect
(negative vacancy)



c) Color center
(F-center)

NOTE: + represents positive ions
- represents negative ions

Fig.A3.1 - Schematic representation of defects and color centers.

defects are usually randomly distributed and the resultant index change will be homogeneous. If the natural defects do not provide sufficient color centers, additional ones may be added by creating new defects with other types of irradiation such as neutrons, and then "coloring" these defects with ionizing irradiation.

Two specific techniques for applying color-center resonances to the control of index of refraction will be considered. The first technique, which is the simplest in concept, involves the use of color-center resonances occuring in the visible spectrum near the desired operating wavelength. This case is idealized in that it assumes that a single, simple resonance can be introduced in the chosen material at the desired wavelength. This is not possible in general, but consideration of this technique is justified by its simplicity and the basic insight it yields. The second technique considered is the utilization of color-center resonances located in the ultraviolet (UV) with the waveguide operated off-resonance in the visible. This is the more promising approach because off-resonance the ratio of index change to attenuation is larger, and the possibility of low-loss operation exists.

In the first approach, involving color centers in the visible, the well known color centers in glass and fused silica have been considered. In general, for simple color centers such as these, the maximum change in refractive index occurs at the three-db points of the associated absorption curve (Ref. 1). The maximum value of this index change, Δn_{max}, is approximately;

$$\Delta n_{max} \approx \frac{\lambda_o}{8\pi} \alpha_{max}, \tag{3.1}$$

where α_{max} is the absorption coefficient in napiers/cm.

For the specific example of borosilicate crown glass there is a color center, activated by gamma irradiation, at 0.615 microns (Ref. 8). The saturation (maximum possible) value of the absorption coefficient at the center frequency is 0.575 napiers/cm, corresponding to an attenuation of 2.5 db/cm and a maximum index variation of 1.4×10^{-6}. Since this index change is only of the order of the homogeneity of the best glasses, it is too low to be applicable for the waveguide application. In fused silica the induced index change is even smaller than in glass. Therefore, for any hope of success with color centers in the visible, a stronger resonance must be found. However, since this will also increase the absorption, it appears that there will always be a substantial loss.

As an example, for the case of a 50λ, single-mode, dielectric-slab waveguide, the inherent attenuation due to color center absorption would be of the order of 40 db/cm, if only the core is irradiated, and about 15 db/cm, if only the cladding is irradiated. In either case, the inherent losses are excessive. Therefore, the use of visible color centers is not practical because operation near the resonance results in excessive loss and off resonance there is insufficient index change.

Fortunately, the alternate method, involving the off-resonance use of color centers located in the UV, is more promising. The UV color centers are considerably stronger (more attenuation and index change) than those in the visible. For example, there is a color center in glass at 0.256 microns that is 25 times stronger than the one at 0.615 microns (Ref. 8). Presently, very little empirical data is available and some simple computations of index variation at wavelengths off-resonance do not correlate well with the data that is available. However, measurements performed at the National Bureau of Standards (Ref. 20) and partially reproduced in Fig.A3.2 indicate that an index change of 2 x 10^{-5} was observed near 0.6328 microns for gamma-irradiated glass, and there is negligible attenuation. It can be assumed that this change is at least partially due to color centers in the UV. Because of this data, the introduction of UV color centers is considered a possible mechanism for controlling the index of refraction of glasses for waveguide applications.

To summarize, the use of color centers to adjust the refractive index of glass is attractive because of the homogeneity of the resultant material and because purely ionizing radiation such as gamma rays does not introduce many additional defects and internal strains. Although color centers in the visible can be ruled out because of the losses associated with operation near the center of the resonance, the off-resonance operation with strong UV color centers offers promising possibilities.

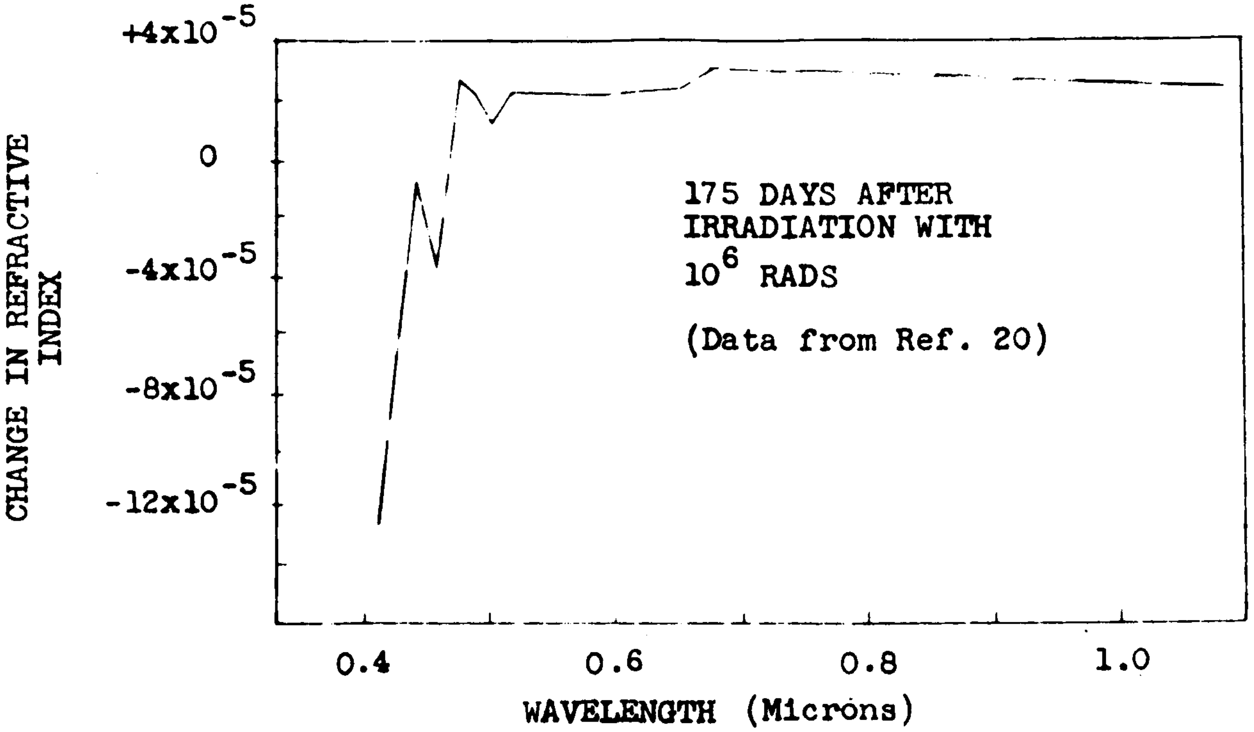


Fig. A3.2 - Change in index of refraction, as a function of wavelength, for borosilicate crown glass irradiated with gamma rays.

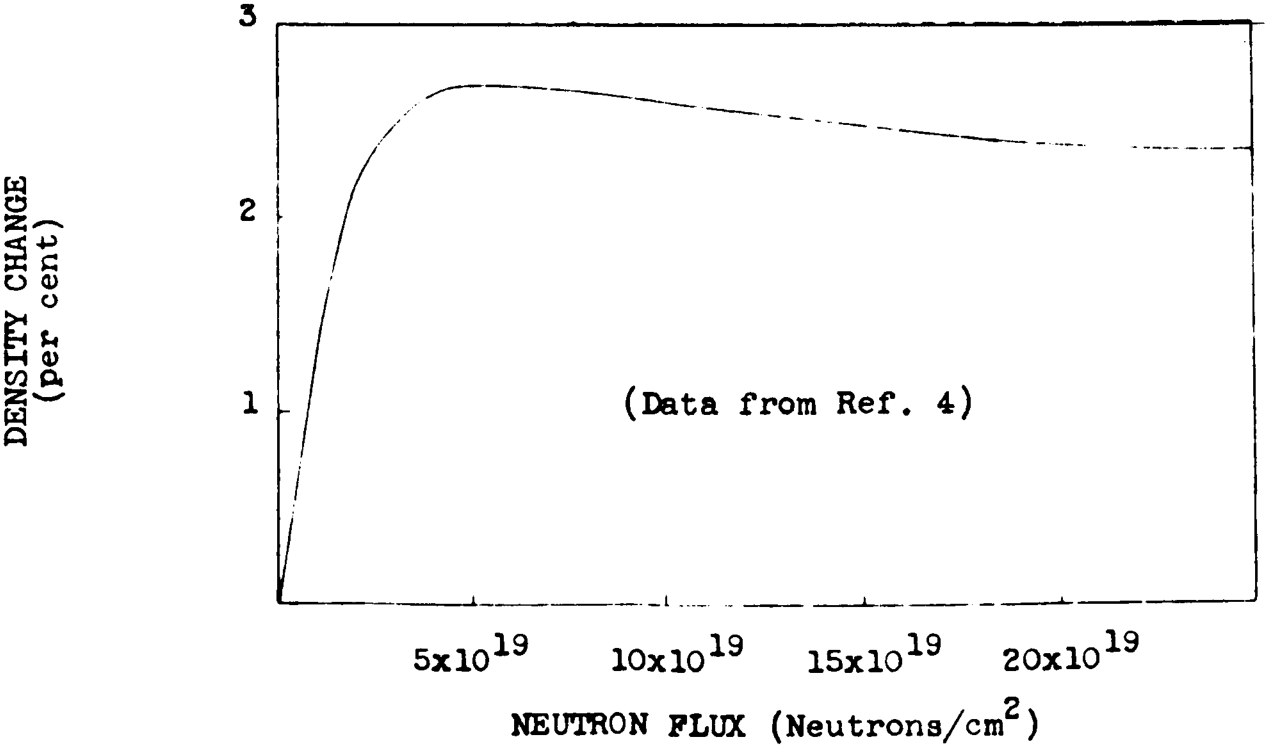


Fig. A3.3 - Change in density of fused silica resulting from irradiation in nuclear reactors.

B. Atomic Displacements.

Atomic displacements result mainly from irradiation with neutrons, protons, heavy ions and electrons. An atomic displacement occurs whenever a target atom is permanently displaced from its normal position by impact with an irradiating particle. Such movement of atoms results in a new average interatomic distance throughout the irradiated portion of the sample. This, of course, corresponds to a density change (see Fig.A3.3) and subsequent alteration of the index of refraction, which is proportional to density. It has been experimentally observed that the density may either increase or decrease depending upon the target material. In fused silica, for example, the density increase is the main reason for the observed increase in refractive index during neutron irradiation. The situation for irradiation of glass is more complex than for fused silica (Ref. 7) and the description of index change by means of atomic displacements will be restricted to fused silica in this report.

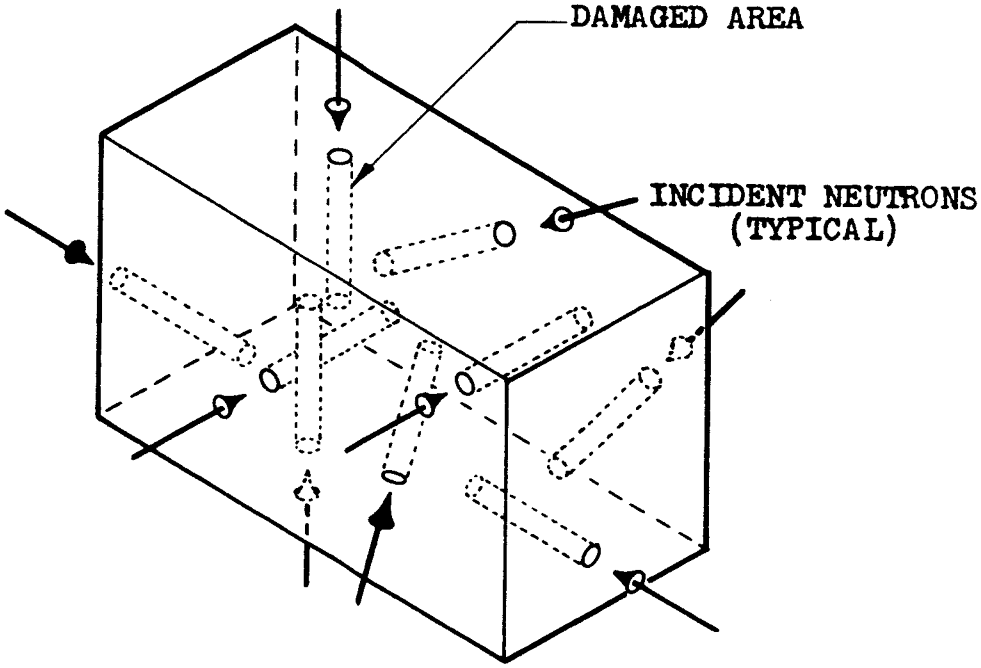
In addition to the index modification related to density change, there is also a small contribution to the index variation caused by a change in the polarizability of the target atoms. This occurs because the displaced atom experiences different electrostatic forces in its new environment which alter its polarizability, as well as that of adjacent atoms. Although this effect is observable, it is small in fused silica (Ref. 4) and will not be considered further herein.

It should be noted that there is no inherent absorption loss associated with the density-related index change discussed above. Therefore, this approach does not generally suffer from the same loss limitations as the color-center approach described previously. However, there may be the inadvertent introduction of loss-producing color centers, since the displaced atoms constitute "lattice" defects which may be converted into color centers during irradiation. Fortunately, these undesired color centers can be completely and permanently removed in most materials by controlled annealing (Ref. 15). An additional problem is the internal strain caused by the displacements, and the birefringence associated with such strain which may be detrimental to waveguide operation. This is an important topic which requires further investigation.

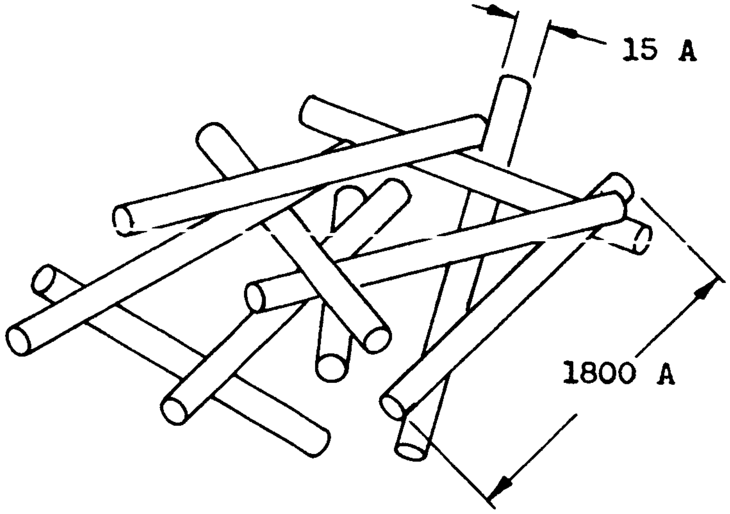
In order to utilize atomic displacements for modifying the refractive index of dielectrics, the change in index must be related to the radiation dosage. Although many types of irradiation produce displacements, very little data concerning the associated index change is available. In order to relate the index change to the dosage for different types of radiation, it is useful to first relate index change to atomic displacements (regardless of how they are produced), and then to compute the dosage, for the radiation of interest, needed to produce the required displacements.

The index of refraction is related to both the total number of displacements and their microscopic distribution. Fig.A3.4 is a schematic illustration of a sample of fused silica isotropically irradiated with neutrons. By various means (Refs. 9 and 21), it has been determined that neutron-induced displacements are distributed in rod-shaped regions with an average volume of the order of (70 Angstroms)^3; the shape has been determined from optical scattering data (Ref. 9). It is estimated that the refractive index external to the rod-shaped region is that of the unirradiated material (n = 1.46 for fused silica), while the index of the rod is equal to the saturated value of the irradiated material (n = 1.47 for fused silica). The sample illustrated in Fig.A3.4(a) is referred to as "unsaturated". As the bombardment continues, an overlapping of the rod-shaped regions occurs as shown in Fig.A3.4(b). Finally, the case is reached where the rods are no longer distinguishable and the material again appears homogeneous, but with higher index of refraction. This final state is referred to as "saturation".

It can be seen that the unsaturated material is similar in form to one type of artificial dielectric and its bulk refractive index can be computed using artificial dielectric techniques (Ref. 22). It turns out that, if the difference in index between the rod region and the undamaged region is small, as is the case in fused silica ($\Delta n \approx .01$), and if the orientation of the rods is random, the bulk index of refraction is directly proportional to the total volume of the rods. It follows that the bulk index is directly proportional to the number of displacements and, for this case, it is only



a) Early stage of irradiation.



b) Detailed view of a portion of the irradiated sample (unsaturated).

Fig. A3.4 - Microscopic distribution of neutron damage.

necessary to determine the proportionality constant to obtain the desired relation. Fig. A3.5 indicates the empirical relationship between neutron dosage and the bulk refractive index of fused silica. An auxiliary scale has been added to this curve to indicate the corresponding number of displacements. This curve indicates a linear relationship between index and displacements at low dosages. Since only small index changes are required for waveguide fabrication, the nonlinearities at high doses will be ignored. The relation between index change and displacements, obtained directly from this curve is:

$$\Delta n = 10^{-23} (N_d), \tag{3.2}$$

where N_d is the number of displacements. This relation will be applied to any type of radiation where the index change is caused by displacements. However, for radiation other than neutrons, this involves the assumption that the microscopic damage distribution (rod shape and orientation) is similar to that for neutrons. Particularly if the rods are not random, but oriented along the same axis, a more detailed computation is necessary. Nevertheless, it will be assumed herein that Eq. 3.2 holds for all types of radiation.

The treatment above applies to the unsaturated case; a dielectric material exhibiting saturation of its index of refraction should be rather homogeneous. Furthermore, the resultant index of refraction at saturation should be the same for all types of irradiation. For instance, the index of refraction of fused silica at saturation is raised 0.012 above the unirradiated value by neutron irradiation; and 0.013 by heavy ion (neon) irradiation. Unfortunately, most waveguide applications require an index change much smaller than this saturation value so that reannealing to remove some of the displacements, as discussed in Ref. 15, would be necessary. It is unlikely that such a process would be as desirable as simply heat re-treating unirradiated glass.

In summary, it appears that adjustment of refractive index by means of irradiation-induced atomic displacements is a reasonable technique for waveguide fabrication. The index change resulting from unsaturated irradiation is controllable and sufficient for the

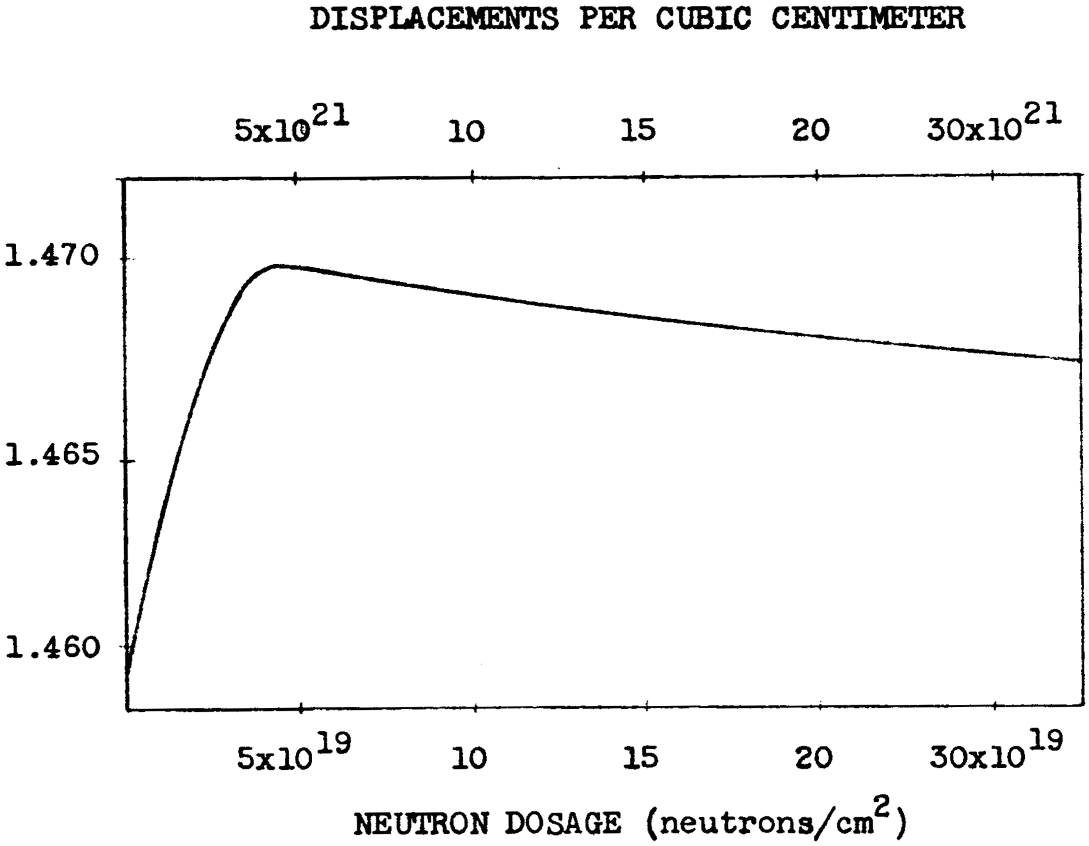


Fig.A3.5 - The variation in the refractive index of fused silica resulting from irradiation in a nuclear reactor.

waveguide application. It is recommended that additional work, mainly experimental in nature, be conducted to resolve the more serious questions which concern such things as birefringence, strain, homogeneity, etc., that are not readily calculated. The following sections discuss the application of specific types of irradiation, and further conclusions will be presented therein.

C. Neutron Irradiation.

Neutron irradiation is of interest because of its ability to cause atomic displacements and, thereby, modify the refractive index of dielectrics as discussed in the preceding section. Neutrons differ from other atomic particles because they lack an electrical charge. Since they lose no energy by direct ionization, they are very penetrating; the range of neutrons in fused silica, for instance, is much greater than the waveguide width and for our purposes can be considered infinite. Therefore, neutron irradiation is applicable only to causing bulk index changes; it would not be useful for surface modification.

Neutron irradiation of both crystalline quartz and fused silica is one of the more completely documented aspects of irradiation effects, due mainly to the efforts of W. Primak at Argonne National Laboratories (Ref. 10). Therefore, the formula relating displacements to index need not be used; the experimental data can be applied directly. The variation of the refractive index of fused silica, plotted in the previous section, indicates that at low dosage levels, the index can be related to neutron dosage, Φ, by the empirical relation,

$$\Phi = 10^{21} (\Delta n). \tag{3.3}$$

This equation can be used to calculate the neutron dosage necessary to create a given index change. The dosage required for a 50λ, single-mode waveguide at 0.6328 microns is about 4×10^{16} neutrons/cm^3 ($\Delta n = 4 \times 10^{-5}$). This corresponds to an exposure of about one week in a reactor with a flux of 10^{11} neutrons/cm^3-sec, (Ref. 11).

It would be possible to terminate the description of neutron effects at this point. The required dose for waveguide fabrication has been estimated above and the spatial distribution corresponds to that discussed in Part B of this Appendix. However, it was apparent from the previous section that a knowledge of neutron displacement production is necessary to extend these results to other particles (as was done in Eq. (3.2)). For this reason, the mechanism of neutron displacement production is outlined below; it should be noted that many of the factors discussed apply equally well to other particles.

The number of displacement-producing collisions between neutrons and target atoms is given by,

$$N_k = \Phi N_o \sigma_d , \tag{3.4}$$

where N_k is the number of displaced atoms, Φ is the neutron flux, N_o is the atomic density of the target dielectric, and σ_d is the cross-section for displacements. The displaced atoms, referred to as "knock-ons", acquire considerable energy in these collisions and create additional displacements. Therefore, the calculation of total displacements requires an estimate of the number of displacements per "knock-on" as well as the number of primary displacements.

The number of displacements created by the knock-on depends on how its energy is dissipated. In general, the knock-on loses energy by ionization as well as by creating displacements. For simplicity, it is generally assumed that energy is lost by ionization only, until the threshold for ionization, E_i, is reached, where

$$E_i \text{ (Kev)} \approx A_k . \tag{3.5}$$

A_k is the atom weight of the target atoms. For fused silica E_i is of the order of 20 Kev. The remaining energy is absorbed mainly by displacements giving the number of displacements (N_d) per knock-on as,

$$N_d \approx \frac{E_i}{2E_d} \; . \qquad (3.6)$$

E_d is the minimum energy required to displace an atom and is nominally 25 ev. Therefore, in fused silica there are about 400 displacements per knock-on. Actually the number is somewhat higher than this due to displacements occuring above the threshold for ionization; these are not included in this number. The total number of displacements can now be computed with the formula

$$\begin{aligned} N_t &\approx 400 \, \Phi \; N_o \, \sigma_d \, , \qquad (3.7) \\ &\approx 100 \, \Phi \; . \end{aligned}$$

Two uses for neutron irradiation are evident from the previous discussions. In the first case, neutrons can be used to change the bulk refractive index of waveguide materials. However for reasons of economics, as well as homogeneity, neutron irradiation is probably not as attractive as precision reannealing for this application. A second, but possibly more important application of neutrons is in the basic study of radiation effects. They have already served this purpose in establishing a general relationship between displacements and refractive index (Eq. 3.2). Future experimental work with dielectric waveguides fabricated from neutron-irradiated fused silica should elucidate the fundamental characteristics of radiation-processed optical waveguides, without the additional complications imposed by the complex spatial distributions of other, less-penetrating particles (see Part D of this Appendix).

D. Proton Irradiation.

Protons, like neutrons, are considered herein mainly as a means for producing an index change by atomic displacements. Since the penetration depth of protons at reasonable energies is of the order of waveguide sizes, proton irradiation is particularly applicable for waveguide fabrication. In this regard, W. Primak (Ref. 13 and 23), in the course of optical strain measurements, has reported observation of possible waveguide phenomena in proton-irradiated fused silica. It should also be noted that useful proton fluxes are readily available; beam currents up to 250 microamps, corresponding to 1.56×10^{15} protons per second, can be obtained from commercial accelerators (Ref. 14).

Protons differ from neutrons by virtue of their positive charge, which means they are basically an ionizing radiation. As a consequence, proton "damage" is distributed between two basically different regions within the target dielectric. In one region, ionization is dominant; in the other, displacements predominate. Both regions contain some atomic displacements and exhibit a refractive index different from the preirradiation value.

The first region is called the "ionization region" and extends from the surface of the target inward to the point where proton energy has dropped below the threshold of ionization as given by Eq. (3.5). Its length, determined almost entirely by ionization interactions, is about equal to the conventional range, which is a well documented quantity. The range as a function of energy for protons in fused silica is plotted in Fig.A3.6 in units of g/cm^2. This is the conventional unit for range and it can be converted to centimeters by dividing by the density of the target material ($2.2\ g/cm^3$ for fused silica). (It can be shown that range is proportional to the ratio of atomic mass to atomic number of the target material. Since this is often near unity, the range, expressed in g/cm^2, is nearly independent of target material, which explains the use of such unusual units for representing a distance.) The data in Fig.A3.6 actually applies to aluminum, but the discussion above, as well as consideration of ionization potentials, indicates that it is a good approximation for fused silica. This equation can be used to compute the proton energy required to produce a given size waveguide. As an example, a 1.5 Mev proton has a range of 27 microns (43λ at 0.633 microns) which is of the order of waveguide core dimensions.

There is a complex variation of refractive index within a proton-irradiated dielectric, as seen in Fig.A3.7. In order to compute the index change as a function of position it is necessary

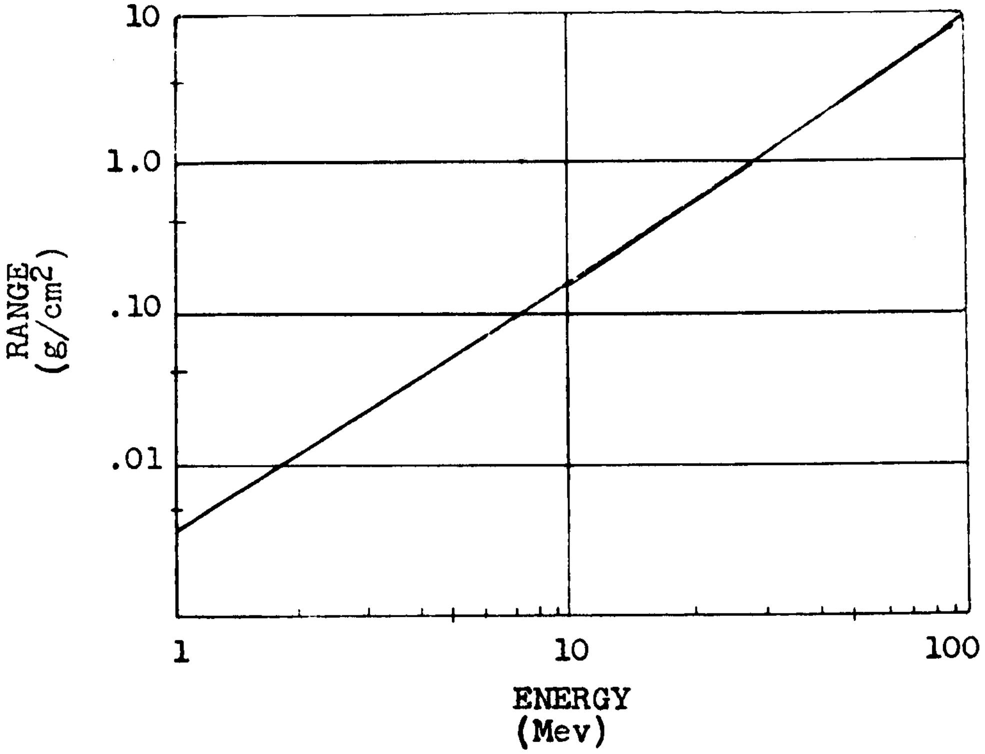


Fig. A3.6 - Range of protons in fused silica.

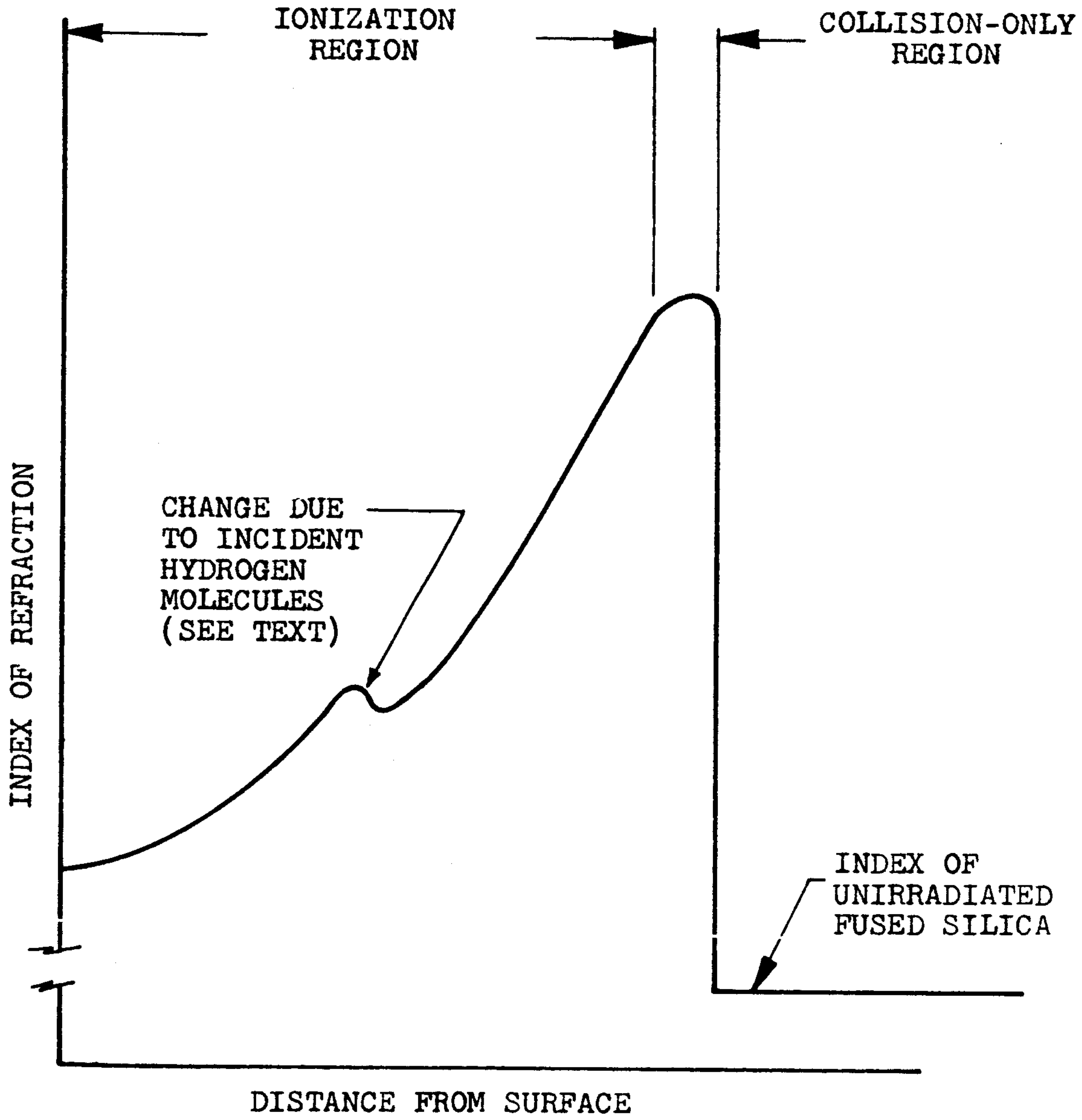


Fig.A3.7 - Schematic illustration of refractive index profile of fused silica after proton irradiation.

to consider the various displacement effects occurring. The mechanism of displacement production in the ionization region follows a process of knock-on production similar to that indicated previously for neutrons. The maximum amount of energy that can be transferred to the "knock-on" atoms, E_m, is given by the conventional expression (Refs. 2 and 6),

$$E_m = \frac{4M_1M_2}{(M_1 + M_2)^2} E, \tag{3.8}$$

where M_1 and M_2 are the masses of the incident and target atoms respectively. This yields a maximum energy transfer of 0.17E for protons in fused silica. Since the energy transferred to the knock-on by 1.5 Mev protons is of the same order as that transferred by 1/2 Mev neutrons (typical for atomic reactors), it is expected that the same general type of microscopic rod structure will be observed in this region (see Fig. A3.4).

The cross section for displacements is inversely proportional to proton energy (Refs. 2 and 6). Consequently, for non-saturating irradiations, it is expected that the number of displacements, and, therefore, the refractive index, will increase with distance from the surface. Fig.A3.7 is a schematic illustration of the expected index of refraction profile as a function of distance from the surface. Additional index variations evident in this figure are discussed below.

At the end of the ionization region, when the proton energy becomes too low for ionization, there will be a very short section, termed the "collision-only" region where the energy is dissipated almost entirely in displacement-producing collisions. The number of displacements in this region is of the order of 400 displacements per incident proton, regardless of the initial proton energy. Therefore, since about 4×10^{21} displacements/cc corresponds to saturation and this region is of the order of 10^{-5} cm thick, saturation occurs in this region for dosages in excess of 10^{14} protons/cm^2.

As seen in Fig.A3.7 a third factor, complicating the profile, is the presence of molecular Hydrogen ions (H_2^+) in the incident beam. These molecules are accelerated to the same energy as the protons. However, as they strike the target surface they split into two protons, each carrying half the incident energy. Therefore, these molecules give rise to an additional, superimposed variation in the index profile, similar to the primary variation but occurring at half the range.

Although the index profile described above is complicated, the cross sections for displacement in the various regions can be computed and the variation of refractive index as a function of position estimated quantitatively via Eq. (3.2). Two important factors not included in such a computation are the effect on refractive index of the microscopic structure (rod-shaped regions, Fig.A3.4) and the effect of the internal strain produced by the localized variations in density. For these reasons some experimental work is recommended, specifically with 1.5 Mev protons since their penetration approximates waveguide sizes. A reasonable dosage for a first trial would be about 10^{14} protons/cm^2, which is sufficient to barely saturate the collision region. This should result in an index profile in which all the characteristic variations are well defined, and will permit some quantitative observations of index profile.

While the procedure suggested above is intended for diagnostic purposes, it will probably not produce a single-mode waveguide. In fact, it may be impossible to form a good single-mode waveguide by irradiation with protons of only one energy. A low proton dosage, which would yield the small index change required, results in the complex index profile of Fig.A3.7, while large doses, which can saturate the entire waveguide region and therefore produce a very homogeneous layer, result in too large an index difference. These difficulties can be avoided by the use of more sophisticated radiation procedures, such as the one discussed below.

The proposed procedure involves an initial irradiation with 1.5 Mev protons at a flux just sufficient to obtain the desired difference in index of refraction between the "collision-only" region and the unaffected region beyond. This results in the profile illustrated in Fig. 3.7. It should then be possible to "sweep" the collision-only region toward the surface by reducing the proton energy. As the proton energy is reduced, the beam current must be modulated in such a way that the resultant density of displacements at every point corresponds to the desired refractive index. In other words, after the initial 1.5 Mev dose, smaller doses at lower energies will be used to add additional displacements as required to level out the index profile.

Although this technique appears attractive, the associated problems of internal strain and inadvertently introduced color-center absorption must be considered. While the color-centers may be removable by annealing, as discussed in Part C for neutron irradiation, the internal strain may pose a more fundamental problem. It should be noted that precision annealing may play an important part in any irradiation program. It not only can remove color-center absorption, but can be used for final adjustment of the magnitude of refractive index (see Section III in the body of this report), and it may play a role in resolving the problem of internal strain.

In summary, protons are useful for waveguide fabrication by surface processing and provide the possibility of implementing printed circuit techniques at optical frequencies. Although protons appear to be a suitable form of irradiation for such applications, additional work, much of it experimental, remains before proton-fabricated, printed-circuit waveguides become a reality.

E. Heavy Ion Irradiation.

The effect of heavy-ion bombardment is similar to that of protons. However, the heavy ions are significantly less penetrating, and,consequently,considerably higher energies are required to produce a given depth of penetration. For example, the fabrication of a 27-micron waveguide requires only 1.5 Mev protons as opposed to 75 Mev neon ions, which are more difficult to obtain. While the situation improves with the lighter ions such as helium, there appears at present to be little point in working with the heavy ions, since protons have a similar effect and are more readily available.

F. Electron Irradiation.

Electron irradiation modifies the index of refraction of optical materials by either color-center or atomic-displacement effects. The characteristics of electron-irradiated targets differ from those produced by proton or heavy-ion irradiation because of the small mass of the electron. For a given energy the electron must be traveling at a higher velocity than other particles. The small mass of the electron makes it less efficient in transferring energy to the target atoms, and it must travel at relativistic velocities to transfer sufficient energy for displacements. Therefore, the stopping mechanism for electrons is different from that of protons. Ionization is always the predominant stopping process and occurs efficiently at all energies above 25 ev (Ref. 17). In contrast, direct displacement production by electrons is inefficient and can not occur at all for energies below a threshold of about 300 Kev.

As a result, there will be two distinct damage regions which do not correspond to the two regions produced by proton irradiation. Near the surface of the target material there will be an ionization region, similar to that in protons, which contains a small number of displacements. This is followed by an "ionization-only" region of the order of 350 microns containing virtually no displacements.

The use of electrons for modifying <u>bulk</u> refractive index by means of either color-center or atomic-displacement effects is possible but does not appear attractive. Atomic displacement effects can be ruled out on the basis of the inefficiency of the displacement process, as well as the relatively high energies required. Color-center effects are more promising because the ionization efficiency is very high for electron bombardment. However, the energies required to penetrate a sample of significant size are high and other types of ionizing radiation, such as gamma rays, are probably more useful for this purpose.

The application of electrons for <u>surface</u> processing of waveguides has also been investigated. It appears that modification of a surface layer by introduction of atomic displacements is possible;

however, the energies involved are of the same order as for protons, and the low efficiency of displacement production is a disadvantage.

A more promising use for electron irradiation is the introduction of a thin layer of color centers along a fused silica substrate. An incident energy of only 60 Kev will produce an "ionization-only" region 27 microns deep in which an index variation occurs as a result of color center introduction. This technique will only be useful if UV color centers can be employed as discussed in Part A. Formation of a surface waveguide by means of color centers is particularly attractive because such a waveguide should be relatively free of the internal strain which is expected to be the main problem with the other surface processing techniques covered by this study.

While electron irradiation is capable of producing any of the radiation effects discussed herein, the waveguide application for which it is recommended is the creation of surface layers containing induced color centers.

G. Electromagnetic Irradiation.

A variety of material changes can be produced by electromagnetic irradiation. These include ionization, atomic displacement, chemical changes and thermal effects. The most common is ionization, arising from the photoelectric effect, compton scattering or pair production (Ref. 12). Atomic displacements may be created by the resultant energetic electron, which is referred to as a "delta ray" or by any one of several complex ionization effects (Ref. 15). In any case, the use of purely ionizing radiation to produce displacements is an inefficient process. Therefore, for the purposes of the present study ionizing electromagnetic radiation, such as ultraviolet light (UV), X-rays, and gamma rays, is considered mainly as a means of providing free electrons to activate color centers. The change in index produced by gamma irradiation of glass is illustrated in Fig. A3.2. The general subject of color centers was covered in Part B and will not be considered further.

Recently, some interesting observations of the effect of UV on vacuum-deposited silicon monoxide coatings have been reported. Apparently some chemical effects occur which modify the index of refraction of the layer (Ref. 18). However, although there is not much data presently available, this phenomenon may be of interest in the future.

Electromagnetic radiation in the infrared and visible portions of the spectrum is not sufficiently energetic to cause ionization, since the photon energy is less than the ionization potential for most materials (13.6 ev for oxygen). Therefore, radiation at these wavelengths produces only thermal effects, similar in character to index of refraction changes that occur during annealing. However, localized index changes produced in this way are of interest, since the creation of a high-index skin on the surface of a glass sample would form a dielectric waveguide. Such localized heat treating would necessarily introduce considerable internal strain, but this may not be any more severe a problem than it will be with proton irradiation. For these reasons localized heat treating is considered a worthwhile subject for future study.

H. Conclusions and Recommendations.

It has been shown that radiation effects can be grouped into two categories, bulk and surface effects. For waveguide applications bulk irradiation effects do not compare favorably with the more conventional approaches such as heat re-treatment. However, two bulk index modification effects, worthy of further consideration, are gamma-ray activation of UV color centers and neutron creation of atomic displacements. Experimental evaluation of these techniques is recommended because of the insight they may yield into similar, but more complicated, surface irradiation effects.

The possibility of using irradiation techniques to fabricate printed-circuit optical waveguides and components will be the main motivation for future work on radiation effects. Two techniques which presently appear promising are proton and electron irradiation. Proton irradiation forms a waveguide by increasing the refractive index in a 50λ surface layer along a fused silica substrate by means of atomic-displacement effects. The main disadvantage to this technique is the internal strain associated with such a layer. The alternate approach is to use low-energy electron irradiation to produce a high-index layer of similar size by color-center activation. It appears that such electronic irradiation may not produce severe internal strain. However, loss considerations require the use of UV-located color centers on which relatively little literature is available.

In conclusion, it is recommended that future effort be directed toward surface processing techniques employing electrons and protons as discussed above. In the course of such a study diagnostic work, including irradiation of bulk samples with neutrons or gamma rays, may be required. Furthermore, additional irradiation techniques such as UV-induced chemical changes and localized heat treating, by means of focused IR beams, should continue to be considered.

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