SUMMARY OF THE DEVELOPMENT
OF OPTICAL WAVEGUIDES
AND COMPONENTS

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Summary

An investigation of the application of waveguide techniques at optical frequencies has been performed at Wheeler Laboratories for the National Aeronautics and Space Administration. The overall objective has been the development of single-mode waveguide and waveguide components for laser systems analogous to waveguide systems presently existing at microwave frequencies.

A variety of different types of waveguide configurations have been investigated for feasibility as a guiding medium. The dielectric waveguide in its various forms has been found to be the most attractive on the basis of low loss and adaptability to component design. Most effort has been directed to a single-mode waveguide with "macroscopic" dimensions. The cross-sectional dimensions of this guide can be many wavelengths, but propagation is restricted to only a single mode by providing a very small difference in refractive index at the interface between the core and cladding. The propagation characteristics of this guide have been theoretically analyzed employing transmission line concepts originally derived for microwave waveguides.

Experimental models of the dielectric guide have been implemented in the slab and circular geometry using a combination of liquid and solid materials for the waveguide core and cladding; experimental results have shown waveguide characteristics which are in excellent agreement with the theory. Single-mode operation has been achieved in dielectric slab guides fabricated with both liquid cores and glass cores up to 100 wavelengths wide. Several variations of the conventional dielectric guide including metal-wall-bisected and air-interface-bisected configurations have also been investigated.

An investigation of various techniques for fabricating practical, all-solid versions of the macroscopic single-mode waveguide has shown two to be feasible. In one approach, two high quality glasses with the required small index difference of 10^{-4} to 10^{-5} were obtained by special annealing of the glass. The waveguide core and claddings formed in this way are then joined with a thin layer of optical cement whose index is controlled to about 0.001.

Completely solid waveguides fabricated with this technique have been operated in a single-mode in sizes of 60 wavelengths cross section.

An alternative and rather novel approach to forming solid waveguides involves irradiation of optical materials. Various types of irradiation alter the refractive index of optical materials to the values needed for the core and cladding of a waveguide. With certain types of irradiation such as protons and electrons, the penetration can be controlled so that only a localized region is affected. The resulting high index channel forms a complete waveguide with no further fabrication required. A waveguide was formed by irradiating a slab of fused silica with $1\frac{1}{2}$ MEV protons; light guiding was observed in the irradiated region in good agreement with the calculations.

The design and performance of many common waveguide components has been studied, and experimental models of several have been fabricated and tested. An experimental model of a waveguide laser comprising a neodymium-doped glass slab as the core and a liquid cladding was fabricated, and single-mode operation was obtained. Modulators in optical waveguide have been theoretically evaluated and partially demonstrated by modulation of mode cut-off characteristics. A slot-type coupler was implemented and coupling ranging from 7 to 17 db was obtained. The characteristics of waveguide filters have been investigated. A very significant advantage of fabricating optical filters in waveguide is the removal of the mutual dependence of angle and frequency characteristics inherent in conventional filters. This makes possible the construction of narrow-band filters which can operate over a wide field-of-view. The construction of optical detectors in a waveguide has been studied and a preliminary experimental evaluation was conducted. It has been found that construction in single-mode waveguide makes the detector sensitive to the amplitude and phase of an incident signal, a property usually observed only in coherent detectors.

A review was undertaken to place the unique attributes of optical waveguide in the proper perspective with respect to alternative free-space techniques. In terms of overall systems, it is expected that the primary advantages will be small size, light weight and stability, as well as improved performance. In the case of

particular components such as filters and detectors, unique and improved performance can be achieved as a direct result of the waveguide construction.

I. Introduction.

This report summarizes the results of a program for the development of optical waveguide and waveguide components conducted during the period 1964 FEB through 1967 MAR for the National Aeronautics and Space Administration. The overall objective of the program has been an investigation of the application of waveguide techniques at optical frequencies, specifically involving the development of a single-mode waveguide medium for construction of optical components analogous to those presently existing at microwave frequencies.

The waveguide which has been investigated most extensively is the dielectric type with very small difference in refractive index at the interface between a central core and surrounding cladding. This guide limits propagation to a single-mode even for waveguide sizes of many wavelengths. Low-order modes are propagated by total internal reflection, since their ray angles are below the critical angle of the dielectric interface. Ray angles of high-order modes are above this angle and leak into the cladding, as illustrated in Fig. 1, where they are intentionally dissipated.

The specific objectives of the program have been the development of single-mode waveguide and components, including (1) a theoretical analysis and performance evaluation of a variety of waveguide configurations and component arrangements, (2) experimental implementation and demonstration of propagation characteristics, and (3) the development of fabrication techniques for practical models. As an example of the experimental demonstration of waveguide characteristics, a photograph and measured field pattern of the TM-0 mode in an early experimental waveguide is shown in Fig. 2; the field pattern is in good agreement with that derived from the theoretical analysis.

Three comprehensive reports cover the detailed theoretical and experimental studies performed during the course of the program (Refs. 1,2,3). In addition seven publications and papers (Refs. 4 to 10) report certain discoveries and novel waveguide features determined in the program. For example, Ref. 4 is the first announcement of single-mode propagation in a waveguide of the order

CLADDING, n_2 CORE, n_1
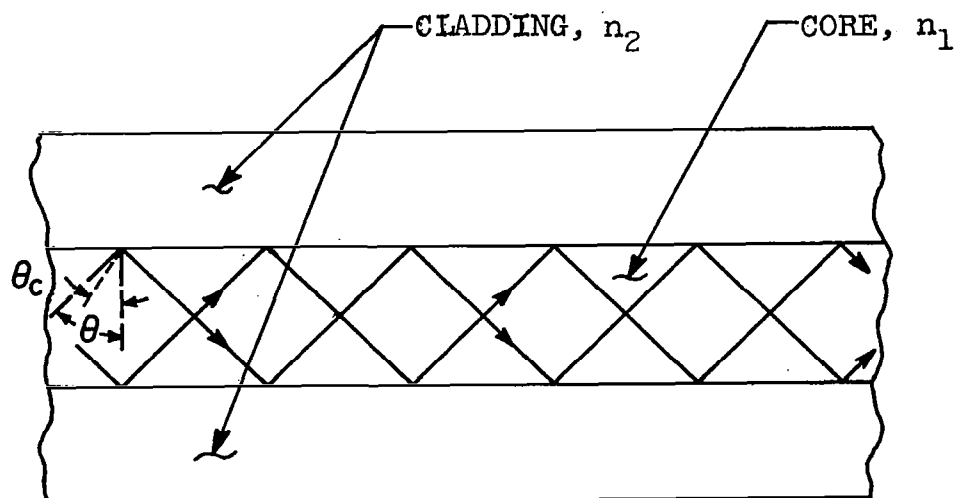
(a) propagating mode ($\theta > \theta_c$).
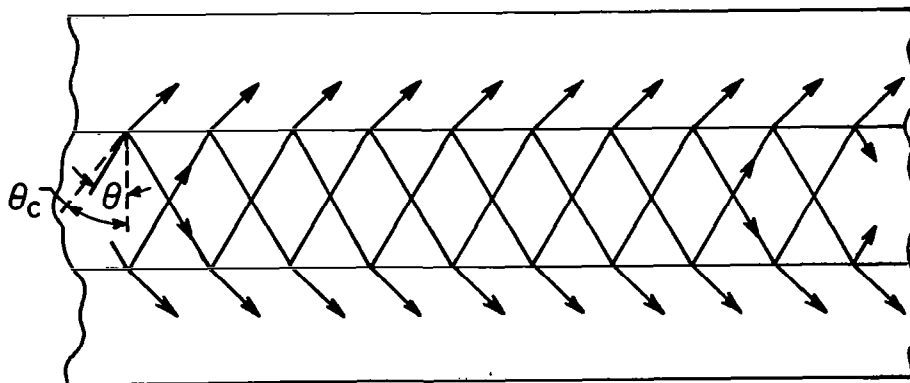
(b) leaky mode ($\theta < \theta_c$).

Fig. 1 - Propagation in a dielectric-slab waveguide.

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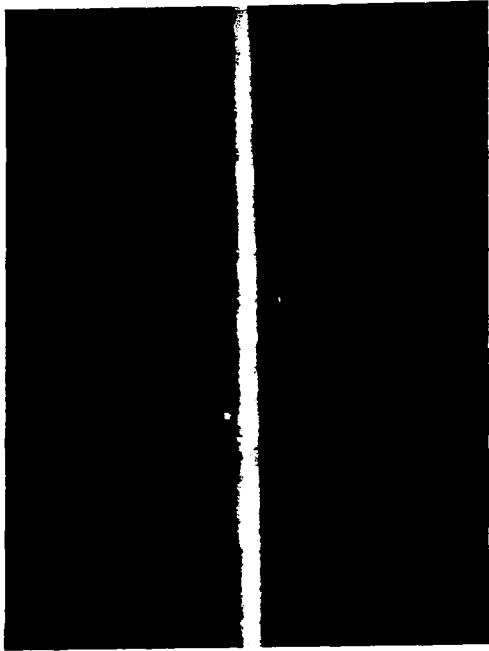
(a) photograph.
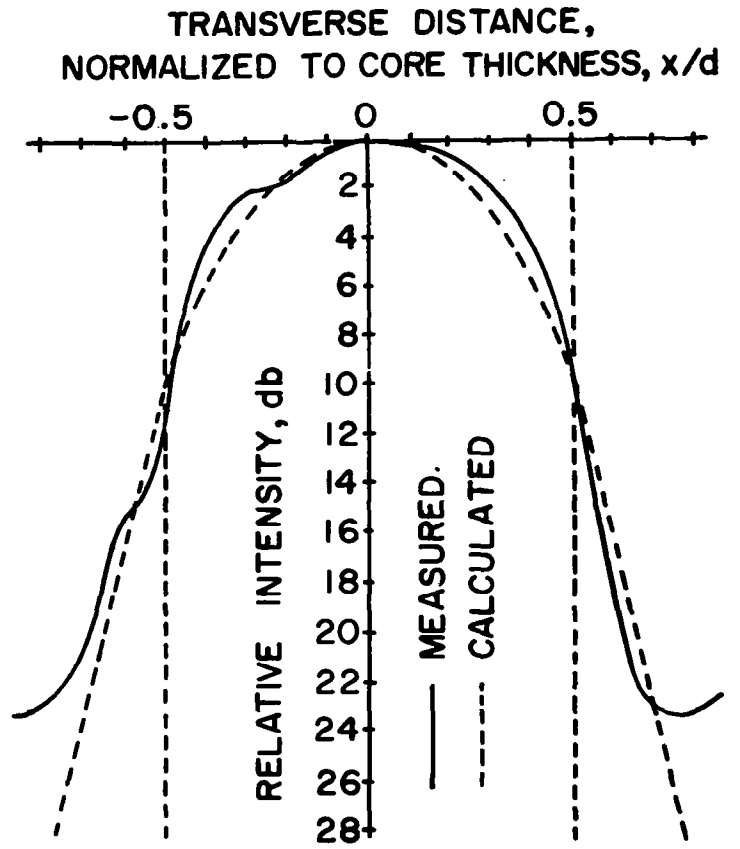
(b) measured pattern.

Fig. 2 - TE-0 mode in a liquid-core, dielectric-slab waveguide
(d = 75λ).

of 50 wavelengths cross section. Ref. 8 describes a metal-bisected waveguide, which indicates certain special properties of this guide resulting from the reflection of metals at grazing incidence at optical frequencies. Ref. 9 describes an interference filter built with waveguide principles, which exhibits the normally unattainable property of wide field-of-view and narrow bandwidth. Ref. 10 is a description of a waveguide fabrication technique employing proton irradiation.

This present summary report is divided into three major parts. Section II reviews the unique properties of waveguide in order to place them in perspective with the more common "free-space" or "beam" approach to optical systems. Section III reviews the development of the waveguide medium in considerable detail; Section IV reviews the component studies.

II. Waveguide Attributes and System Applications.

A study has been undertaken to place the unique attributes of optical waveguide in the proper perspective with respect to alternative free-space or beam techniques for the construction of optical systems. The study is divided into three parts consisting of (1) a discussion of the properties of waveguides, (2) a description of several types of waveguide systems and (3) an illustration of two applications where the properties of waveguide provide unique advantages in performance.

A. Fundamental Properties of Optical Waveguide Propagation.

Four properties of optical waveguide which differentiate it from free-space systems are outlined below.

1. Bounded Medium.

Optical waveguide is a bounded medium where signals can be transmitted and processed with almost complete isolation from spurious signals. Such spurious signals may arise from external noise sources, mismatched fields at the input of the system, scattering, or from adjacent signal channels. Most free-space systems are susceptible to interference from such sources, and some degradation of performance may result.

2. Small Size.

Optical waveguide permits transmission of signals from point to point with a cross-sectional size much smaller than a beam-type system. This reduction in size is possible because the waveguide eliminates diffraction spread encountered in any free-space system. Although this spread is a much less severe problem at optical frequencies than at microwave frequencies, it may be significant, expecially in systems where a large number of parallel transmission channels are utilized. In such cases, the potential reduction in size and weight can be a significant factor.

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3. Mode Selection.

Single-mode optical waveguides propagate energy in a fixed, precisely defined field pattern, with intentional attenuation of all higher-order modes. The waveguide acts as a form of spatial filter, selecting only a fundamental field pattern incident on the guide and rejecting multi-mode fields. This mode-selection property facilitates design of high-performance components.

4. Angle-Invariant Performance.

The propagation characteristics of a single-mode waveguide (field pattern, phase velocity) are determined by the waveguide parameters and are independent of the angle of excitation. The waveguide acts as an angle converter, converting a beam incident from any direction (within its reception pattern) to a "beam" propagating along the axis of the guide. This means that the performance of any components fabricated in the waveguide is also completely independent of the direction of the incident signal. This property provides significant advantages for certain components, such as optical filters.

B. Types of Waveguide Systems.

There are several ways in which waveguides may be utilized in an optical system. Three different approaches are outlined below.

1. Single-Channel.

The original concept of this program envisioned the construction of laser systems employing a single waveguide (or a few waveguides) for processing of signals in a manner directly analogous to microwave systems. It is expected that, for these systems, the advantages over free-space systems will be small size, light weight and stability, as well as improved performance because of the properties listed above. However, a significant limitation of single waveguide systems is the small collecting area of the waveguide. This can be overcome by placing a lens in front of the guide

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focused to illuminate the input end. The collecting area of the
system then becomes that of the lens; however, the field-of-view is
narrowed since the resultant field is equal to the diffraction-
limited beamwidth of the lens. An example of a single-channel
optical waveguide system comprising a super-heterodyne monopulse
tracking receiver is illustrated in Fig. 3.

2. Multiple-Channel.

In order to overcome the problem of either limited collect-
ing area or small beamwidth encountered in a single-waveguide system,
a large number of waveguides can be arrayed together. If the array
itself is used as the collecting area, the beamwidth may be as large
as that of the individual waveguides, and the collecting area is in-
creased by the number of waveguides. If the array is located at
the focal plane of a lens as before, the collecting area is that of
the lens, but the (solid-angle) beamwidth is increased over that of
the single-channel beamwidth by the number of waveguides arrayed.
Consequently, it is possible to achieve both large area and wide
beamwidth, and still retain the properties of waveguide systems.

3. Hybrid.

In addition to exclusively waveguide systems, the unique
properties of waveguides can be utilized to construct optical com-
ponents for use in conventional, free-space systems. For example,
an array of single-mode waveguides transmits a beam essentially
undistorted, and may therefore be located in a conventional optical
system (Ref. 9). If optical filters are formed within the waveguide
array, the resulting "waveguide-array-filter" can have wide field-
of-view and small bandwidth, a property which is not possible with
conventional filters, as discussed below. An example of such a
"hybrid" system using both waveguide and free-space techniques is
illustrated in Fig. 4.
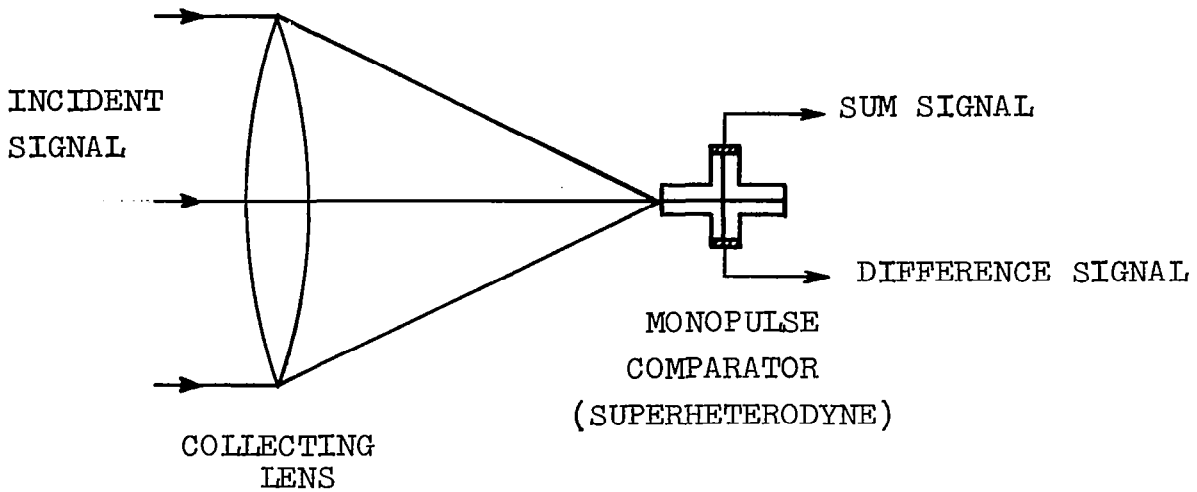
(a)   receiver system.
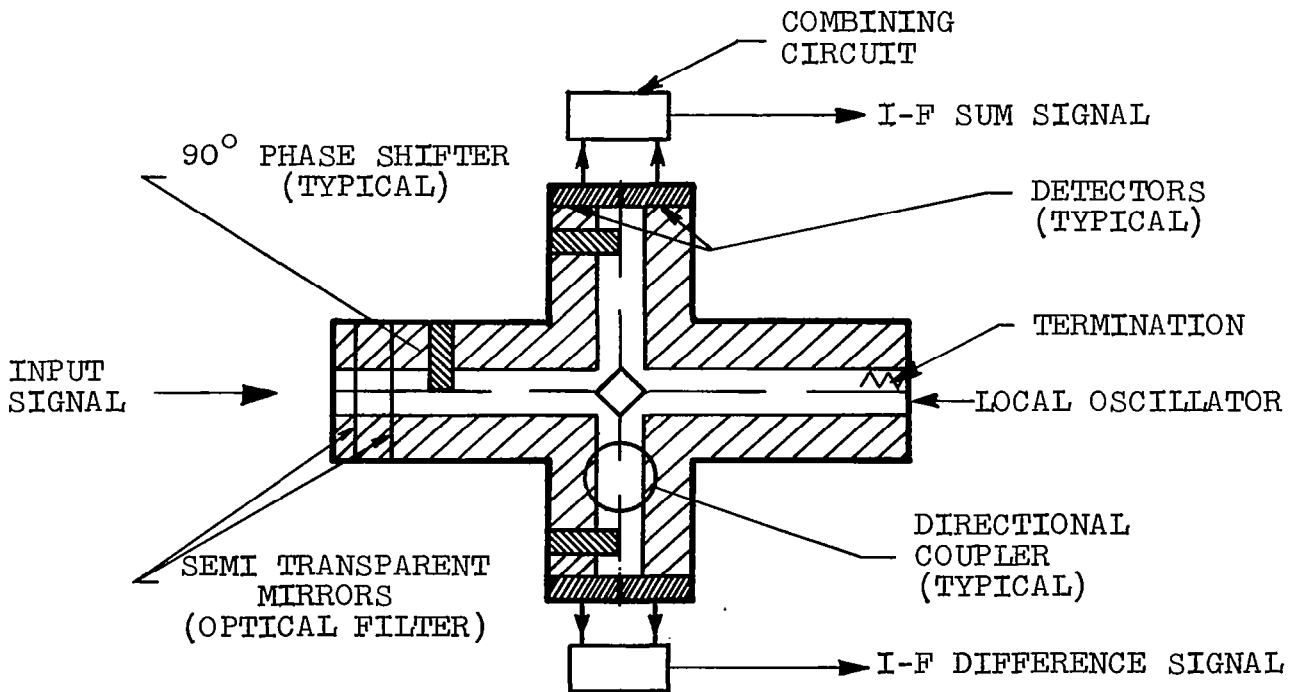
(b)   expanded view of monopulse comparator.

Fig. 3 - Optical monopulse receiver utilizing single-mode waveguides.

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INCIDENT
SIGNAL

θ

θ = field of view

IMAGE
TUBE

OUTPUT

WAVEGUIDE ARRAY CONTAINING
WIDE-ANGLE, NARROW-BAND
OPTICAL FILTER

Fig. 4 - Optical receiver utilizing an array of single-mode
waveguides.

C.   Applications.

A realistic comparison of complete optical systems using waveguide and free-space techniques is difficult at this stage, because practical configurations of the waveguide are still under development. However, in view of th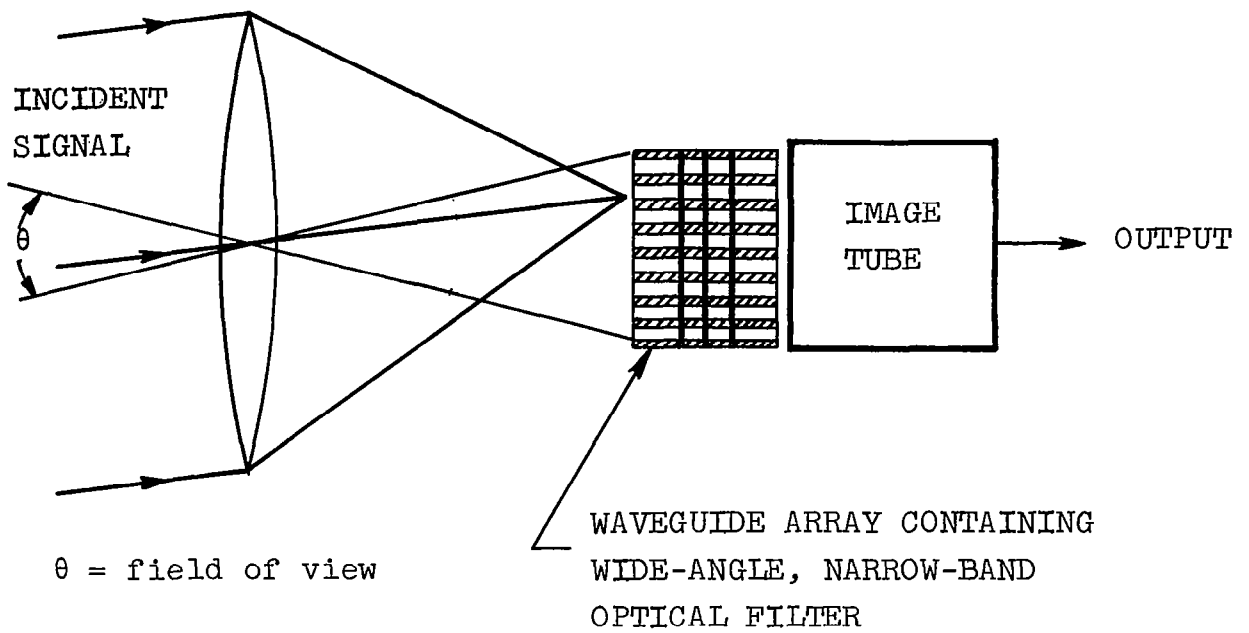e progress achieved to date with various fabrication techniques, and the unique properties of waveguide systems, it appears that such systems will be advantageous in many cases where high performance, small size and light weight are major objectives. There are, however, described below two particular components which promise more immediate application and demonstrate the unique advantages of waveguide techniques.

1.   Filters.

Conventional optical interference filters fabricated in free space are limited in performance by the mutual dependence of their angle and frequency characteristics. As a result of this behavior, narrow-band filters are restricted to operation over a narrow field-of-view. Conversely, if a wide field is required, the bandwidth cannot be made as small as may be desired. Because of the angle-independent properties of waveguide devices described previously, fabrication of an optical filter within a waveguide provides independent control of both field-of-view and bandwidth. Therefore, it is possible to fabricate a filter with a wide field and a small bandwidth. A more detailed discussion of the properties of waveguide filters and their application in actual systems is presented in Section IV.

2.   Detectors.

Optical detectors are fundamentally power sensitive devices, i.e., the output signal is proportional to the square of the amplitude of the incident signal and is independent of its phase. Construction of a detector in a waveguide medium results in a fundamentally different behavior. The detected signal in this case is determined by the excitation efficiency of the waveguide.

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The excitation efficiency is dependent on the spatial phase of the incident signal (Refs. 1, 3). This makes the waveguide detector behave as a coherent or phase-sensitive detector rather than an incoherent detector. Further discussion of the properties of optical waveguide detectors is also presented in Section IV.

To summarize, this discussion of optical waveguide techniques has indicated several unique properties of waveguide which may eventually be exploited to advantage over free-space systems. Two specific components, filters and detectors, have been described where the direct application of waveguide techniques provides improved performance over conventional optical components.

In addition, the use of arrays of waveguides has been shown to be an effective method for overcoming the limitation of small collecting area inherent in single-channel waveguide systems, while still maintaining the basic advantages of waveguides.

III. Waveguide Development.

After an initial survey and study of different types of waveguide for application at optical frequencies, the greatest effort has been directed to the conventional dielectric waveguide comprising a core dielectric surrounded by a cladding of lower refractive index. Considerable emphasis has been placed on the concept of "macroscopic" or large size waveguide whereby the guide cross-section is many wavelengths, but propagation is restricted to a single mode because of a very small difference in refractive index between the core and cladding.

This section is divided into three parts. First, a discussion of the waveguides theoretically investigated is presented. Second, the experimental implementation of these guides and the performance achieved are reviewed. Finally, an investigation of techniques for fabricating practical all-solid versions of the guides is described.

A. Theoretical Investigation.

The conventional dielectric waveguide in the slab geometry is illustrated in Fig. 5(a). Since the primary waveguide requirement for this investigation is single-mode propagation, the conditions for controlling the number of modes have been studied in detail. The mode cutoff equation for the slab configuration is given in Fig. 6; this equation is plotted on coordinates of waveguide size and difference in refractive index to provide a convenient chart for determining the number of propagating modes. If the guide is to propagate only the lowest order mode (m = 0 mode propagating, m = 1 mode leaky), then the product of d/λ and the square root of $2n\Delta n$ must be less than 1/2. Therefore, if the difference in refractive indexes is very small, the waveguide size can be many wavelengths and propagation is still restricted to a single mode. This concept of large size and small index difference has been exploited to produce what is called "macroscopic" optical waveguide.

In addition to the mode cutoff conditions, the theoretical analysis of this waveguide has included (1) calculation of the field patterns of the modes and (2) preparation of dispersion

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CLADDING, n_2

CORE, n_1

d

(a) Conventional (un-bisected).

CLADDING, n_2

CORE, n_1

d/2
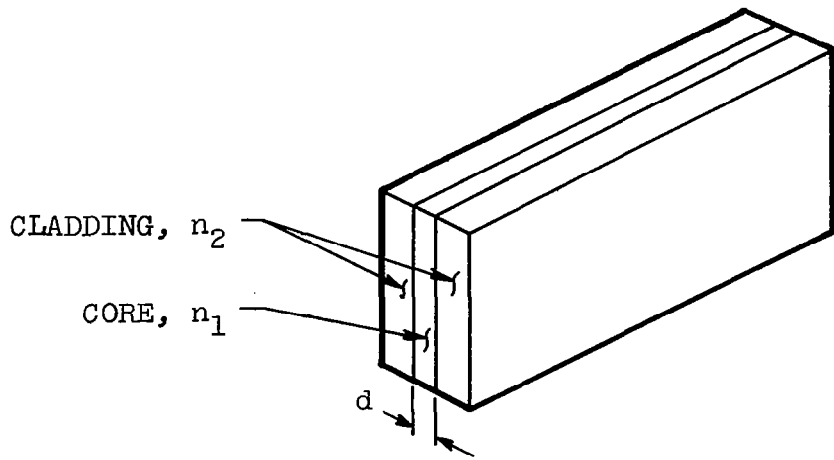
METAL WALL
(VACUUM DEPOSITED)
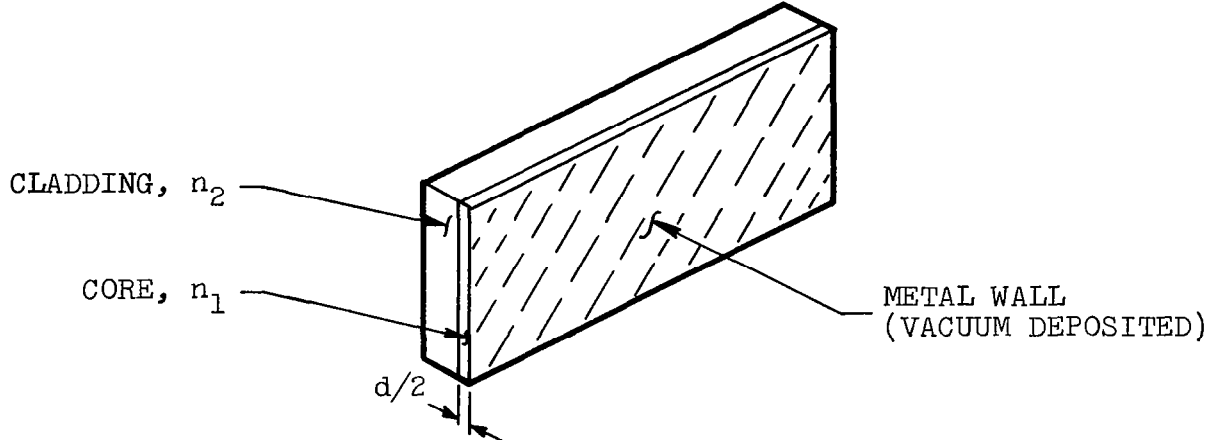
(b) Metal-wall bisected.

CLADDING, n_2

CORE, n_1

d/2
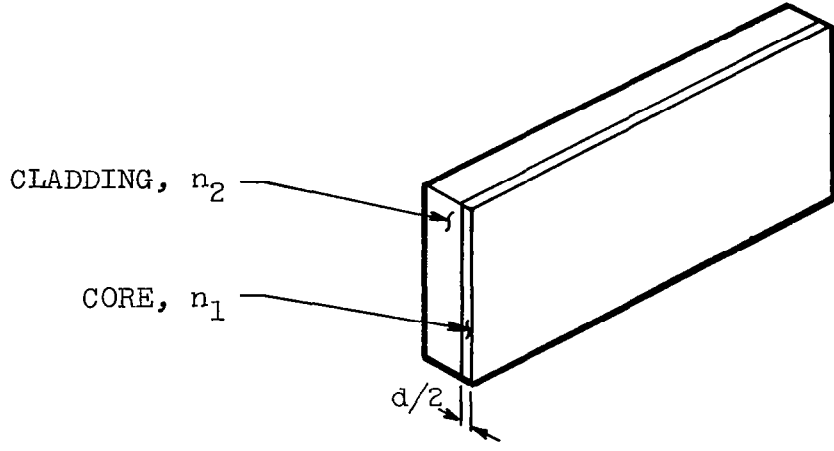
(c) Air-interface bisected.

Fig. 5 - Configurations of dielectric-slab waveguide.

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MODE CUTOFF EQUATION: $\dfrac{d}{\lambda}\sqrt{2n\Delta n} = \dfrac{m}{2}$

Operating region
for fundamental
modes, TE-0, TM-0

DIFFERENCE IN REFRACTIVE INDEX, $2n\Delta n$

CORE WIDTH, d/λ

Fig. 6 - Mode chart for dielectric-slab waveguide.

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curves showing the variation of the phase velocity with frequency, waveguide size and index difference.

In general, the investigation of this waveguide has shown it to be attractive for application to laser systems. The guide can be operated single-mode in convenient sizes, and the attenuation is negligible in the lengths required for component construction.

In addition to the dielectric waveguide described above, two bisected versions of this guide have been investigated. The first type, illustrated in Fig. 5(b), is the metal-bisected guide, comprising one-half of the conventional dielectric guide with a metal wall at the bisecting plane. The propagation characteristics of this guide have been calculated for the case of a perfectly conducting wall and also for a real metal wall, which introduces some dissipative losses. The results are reported in a Wheeler Laboratories' correspondence to the Journal of the Optical Society of America (Ref. 8) and show that for multi-wavelength guides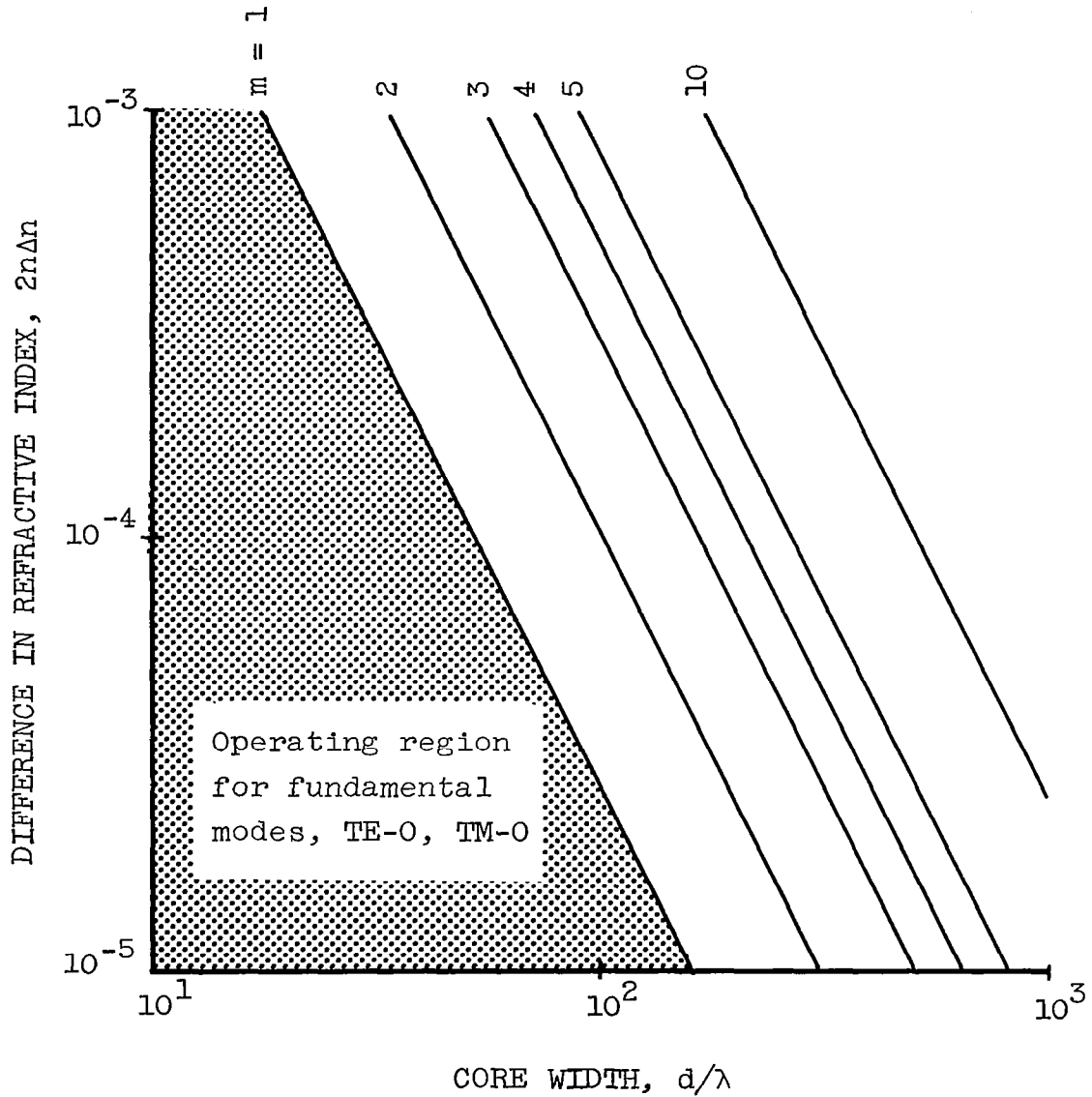 where the waves propagate near grazing, a real metal wall behaves as an open circuit for TM-modes and as a short circuit for TE-modes. This behavior, which is fundamentally different from that obtained with a perfect conductor, yields all the odd-numbered modes of the conventional (unbisected) configuration. Nevertheless, this guide can be made to propagate in only a single mode with relatively low loss, and is a useful configuration for certain specific applications such as the slot-type directional coupler discussed later.

An alternative configuration of the bisected guide is the air-interface bisected guide illustrated in Fig. 5(c). In this case, the metal wall of the previous guide is simply replaced by an air interface. For low-order modes in a multi-wavelength guide, the plane waves in the guide are incident on the core-cladding interface at angles much greater than the critical angle. Under these conditions, the interface behaves very nearly like an open circuit for TM-modes and a short circuit for TE-modes. (This behavior is identical to that obtained with the metal wall.) Therefore, the air-interface-bisected guide can also be operated single mode with low loss and it may be advantageous in specific applications.

In contrast to the conventional dielectric guide with high
index core, a waveguide with a core index lower than the cladding
has also been investigated. Since the core index is lower than the
cladding, light propagating in the core never experiences total
internal reflection, and consequently there are no theoretically
lossless modes. However, there are still discrete modes of propaga-
tion, each having a well-defined field pattern and a particular
propagation constant. For the case of large waveguide size, the
attenuation of the low-order modes can be quite low. An evaluation
of the slab configuration has indicated that by proper choice of
guide size and index difference, the attenuation of the lowest mode
can be tolerable, while that of all higher-order modes is
sufficiently high to provide needed more discrimination (Ref. 2).
The above results suggest that, while the waveguide with low index
core is not as attractive as the conventional type because of its
inherent attenuation, it may be useful for specific guided wave
applications.

B. Experimental Investigation.

In order to confirm the propagation characteristics of
the waveguides described above and to demonstrate the feasibility
of fabricating and operating them, several guides have been
experimentally evaluated. One of the primary objectives was to
determine whether the tight tolerance on the index of the materials
required for operation of macroscopic size guides could be maintained.
A description of the experimental waveguides and a summary of the
results obtained is given below.
In order to obtain the small index difference required
for single-mode, multi-wavelength guides, early experimental
models utilized a combination of liquid and solid materials for the
core and cladding. The refractive index of liquids generally varies
much more rapidly with temperature than solids. Consequently,
by utilizing liquid and solid materials with nominally the same
index for the core and cladding, the difference in index can be
controlled to the small values required, by stringent, but
straight-forward temperature regulation. Four versions of liquid-

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solid guides which have been evaluated are illustrated in Fig. 7. The liquid-core guide in Fig. 7(a) utilizes two high quality glass plates for the cladding and a liquid as the core. This configuration has the advantage that the core size can be varied to study the propagation characteristics. A photograph of two of the glass slabs used as the cladding for this guide is shown in Fig. 8(a). Excellent single-mode operation was achieved in waveguide sizes up to 100λ (Ref. 1). The solid-core guide illustrated in Fig. 7(b) comprises a thin slab of high quality glass immersed in a liquid cladding. A photograph of one of the glass cores is shown in Fig. 8(b). This guide configuration served as a test of the homogeneity of solid materials such as glass for use as the waveguide core; it is also useful for evaluating certain components such as the directional coupler. Photographs of the four lowest order TE-modes in a guide of this type are shown in Fig. 9. These photos were obtained by illuminating one end of the waveguide with a He-Ne gas laser operating at 0.633 microns, and photographing the pattern at the opposite end through a microscope. The waveguide core was a slab of Schott astronomical objective quality BK-7 glass, ground and polished to a thickness of 54 microns. In general, the propagation characteristics of this guide were in excellent agreement with theory, and confirm the feasibility of implementing macroscopic optical waveguides.

The corresponding versions of the two waveguides discussed above, in the circular geometry are, illustrated in Fig. 7(c) and 7(d). These guides were formed by using fused silica tubes and rods for the liquid-core and solid-core configurations respectively. The results, which are described in detail in Ref. 1, were in general not as good as those obtained with the slab guides. This has been attributed to gradients in refractive index of the materials presumably formed by the drawing process of fabrication. However, single-mode operation was observed, and it is believed that macroscopic waveguides in circular geometry are feasible.

An experimental evaluation of the low-index-core waveguide in slab geometry was also conducted. The results were in general agreement with the predicted behavior; it was possible to operate the guide with sufficient mode discrimination so that the guide is
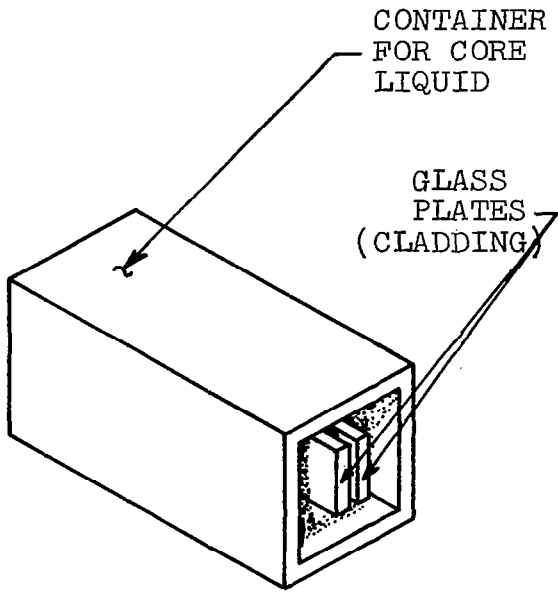
(a) Dielectric-slab liquid core waveguide.
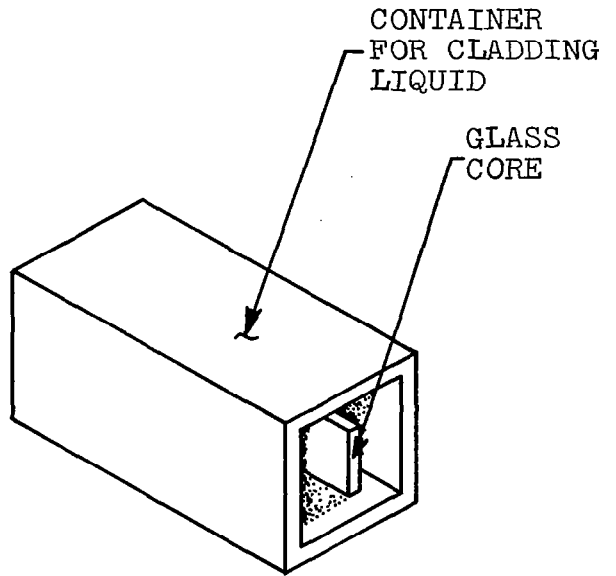
(b) Dielectric-slab solid core waveguide.
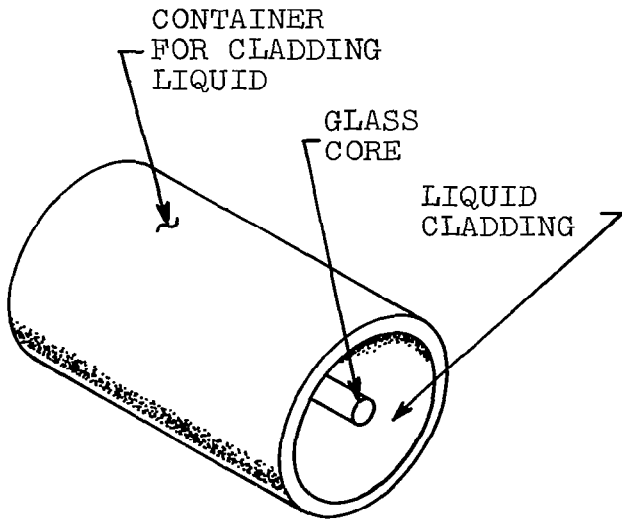
(c) Cylindrical fiber waveguide.
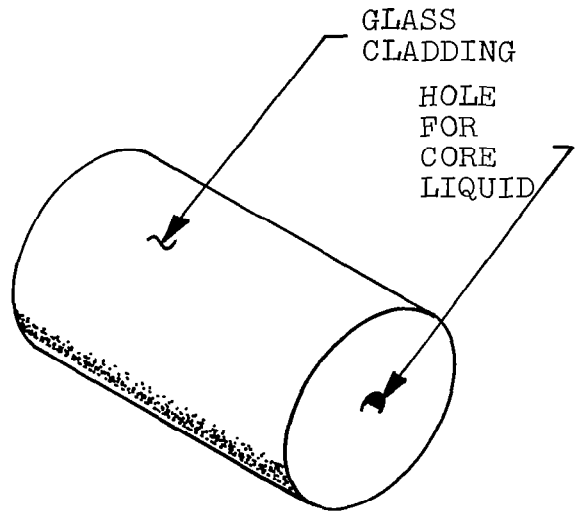
(d) Cylindrical tube waveguide.

Fig. 7 - Sketches of experimental liquid-solid waveguide models.
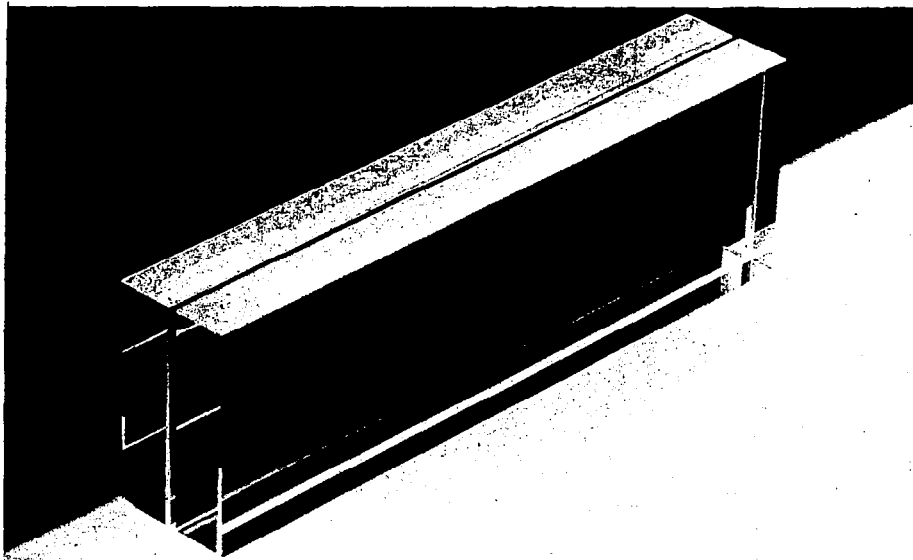
(a) Cladding glass (75mm x 25mm x 8mm) of liquid-core
     waveguide.
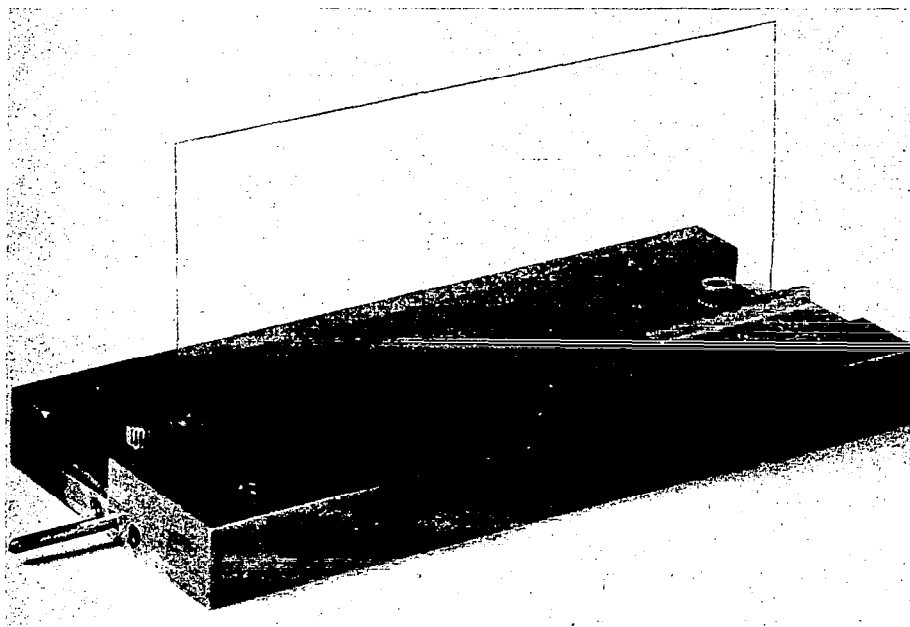
(b) Core glass (75mm x 32mm x 0.050mm) of solid core
     waveguide (liquid forms the waveguide cladding).

Fig. 8 - Photographs of component parts of liquid-solid waveguides.
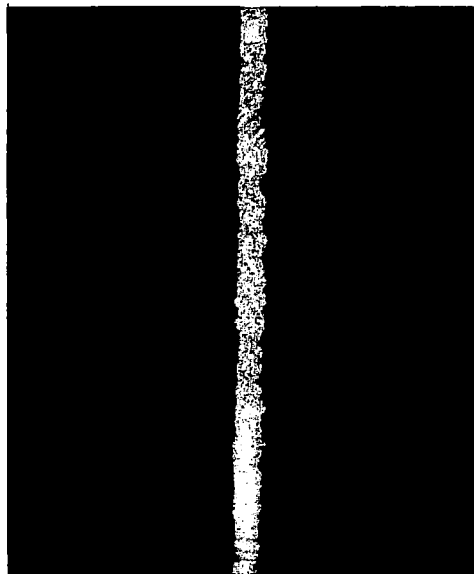
(a) TE-0.
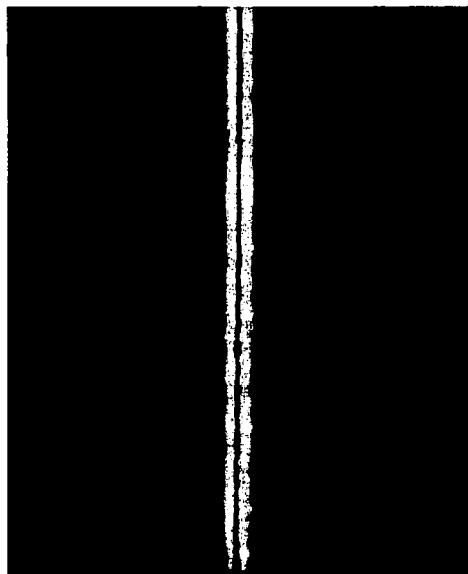
(b) TE-1.
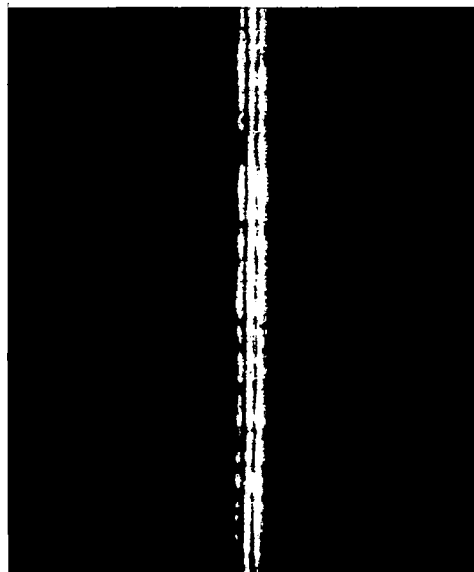
(c) TE-2.
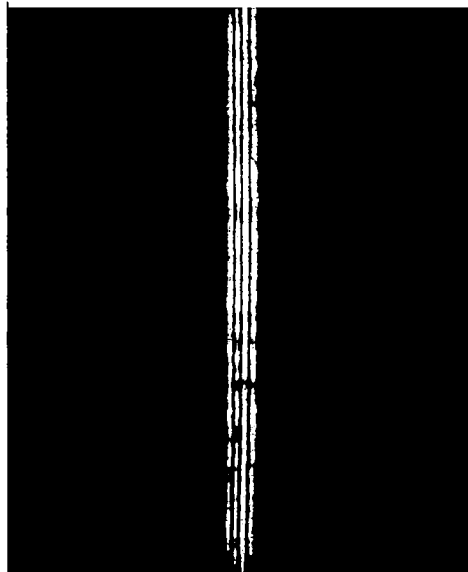
(d) TE-3.

Fig. 9 - Mode patterns in BK-7 glass-core, liquid-cladding dielectric-
slab waveguide (d = 85λ).

effectively single mode. A practical advantage of this guide is that the index control required to maintain single-mode propagation is much less stringent than for the conventional waveguide with high index core.

The series of experiments described above are considered a successful demonstration of the feasibility of operating experimental models of single-mode macroscopic waveguide. In particular, the successful operation of the solid-core waveguide demonstrated that high quality glasses are available with sufficient homogeneity for waveguides in sizes up to 100 wavelengths and that the required surface tolerances could be achieved with conventional optical grinding and polishing procedures. Therefore, the next step in the program was to investigate and develop techniques for fabricating more practical versions of the waveguide.

C. Solid Fabrication Techniques.

The ultimate objective of this program has been the development of optical waveguides and components which are compact, rugged and insensitive to environmental conditions. The liquid-solid waveguides discussed previously are not considered suitable for meeting these objectives primarily because of the high temperature sensitivity, and the general problem of containing liquids. Therefore, the approach to forming practical waveguides has been directed towards the implementation of all-solid configurations.

The optical requirements for fabricating a macroscopic single-mode waveguide from two solid materials are, first, sufficient homogeneity within the materials, and second, the required small index difference between the two. After selection of the materials, they must be fabricated and assembled in the waveguide configuration. In one technique which will be described, the two operations are essentially combined.

After a survey of various materials, high quality glass and fused silica were determined to be best suited for this application; this choice is based on both the manufacturers' quoted specifications and on the results obtained with the experimental liquid-solid waveguides. An investigation of other materials such

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as plastics indicated that scattering and index inhomogeneities were excessive for this application (Ref. 1).

Having selected the waveguide materials on the basis of their optical quality, the next step was to obtain two such materials with the required small index difference. It has been possible to obtain glasses with index differences of 10^{-4} to 10^{-5} by special annealing or re-annealing. In the case of special annealing, the final annealing cycles of two samples of glass are adjusted to provide the required difference; in the case of re-annealing a single sample of glass is divided into two parts and each re-annealed with a slightly different cycle to provide the required difference.

An alternative technique for achieving the required index difference is to use atomic irradiation to modify the index of glass or fused silica. Studies of such radiation effects are reported in the literature. Refractive index changes can be caused by either of two mechanisms. First, various types of particle irradiation such as protons, neutrons and heavy ions create atomic displacements in a target material. These displacements change the density of the material, and associated with the density change in an index change. In the case of fused silica, index increases of up to 0.01 have been observed, while in certain glasses index reductions of even greater magnitude have been reported (Ref. 12).

The other mechanism for index change by irradiation is color center production. Various forms of ionizing radiation such as gamma rays and electrons create absorption bands (color centers) in a material with an associated index change. Index changes of 10^{-4} in the visible band have been observed in various glasses through introduction of color centers in the ultraviolet (Ref. 11). The absorption in the visible band in such cases can be very low. The index change of 10^{-4} is less than that resulting from displacement production, but is sufficient for formation of macroscopic waveguides.

The technique of modifying the refractive index of a bulk material by irradiation does not appear as attractive as the annealing techniques, because the latter are relatively straightforward and inexpensive. However, it is possible to select certain types of irradiation whose penetration can be controlled to affect only a localized region of a material. In this way, it is possible to

irradiate a material so as to increase the index of a localized region corresponding to the desired core size of a waveguide, and thereby form a complete waveguide in a block of glass with no further fabrication required. This approach appears very promising and is discussed in greater detail below.

After having obtained two optical materials with the required index difference, these must be fabricated into the desired core and cladding shapes and then assembled to form the waveguide. The technique which has been most successful for construction of slab waveguides is to fabricate the waveguide parts by grinding and polishing and then to assemble them with optical cement as illustrated in Fig. 10(a). If the optical cement layer between the core and cladding meets certain requirements outlined below, the propagation characteristics of the guide are substantially the same as a guide with no cement. The requirements of the cement layer have been analyzed in detail and results are presented in Ref. 3. Typically, the cement layer must have a thickness less than a quarter wavelength and an index higher than the core index by no greater than 0.005. It has been possible to obtain cements with an index controlled to 0.001 by using a mixture of epoxies, and cement thickness of 0.15 micron ($\lambda/4$) by cementing under pressure, thus meeting the required specifications.

Macroscopic optical waveguides have been fabricated by the grinding and cementing technique in both the air-interface-bisected and conventional dielectric slab configurations. Fig. 10(b) is a photograph of a conventional slab guide fabricated in accordance with Fig. 10(a). (The core and cladding glasses and the cement are not distinguishable in the photo because of the similar optical properties.) This guide has a core thickness of 48 microns ($d = 76\lambda$ at 0.633 microns) and an index difference between core and cladding of 6×10^{-5}, which results in three propagating modes. These solid waveguides have been experimentally evaluated and the results are in good agreement with theory. Photographs of the three propagating modes obtained with the guide of Fig. 10(b) are shown in Fig. 11.

In summary, the grinding and cementing technique appears to be a practical technique for forming solid optical waveguides in

OPTICAL
CEMENT, n_3

CLADDING, n_2

CORE, n_1

$n_1 > n_2$
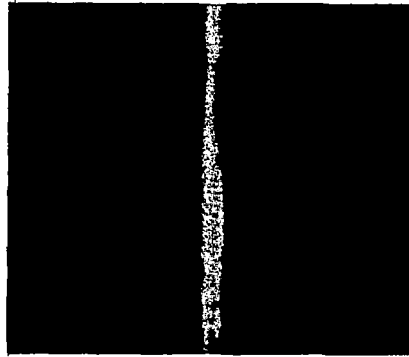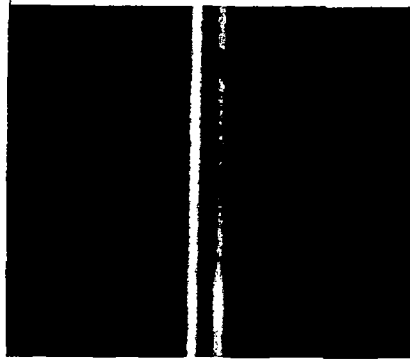
$n_3 \geq n_1$
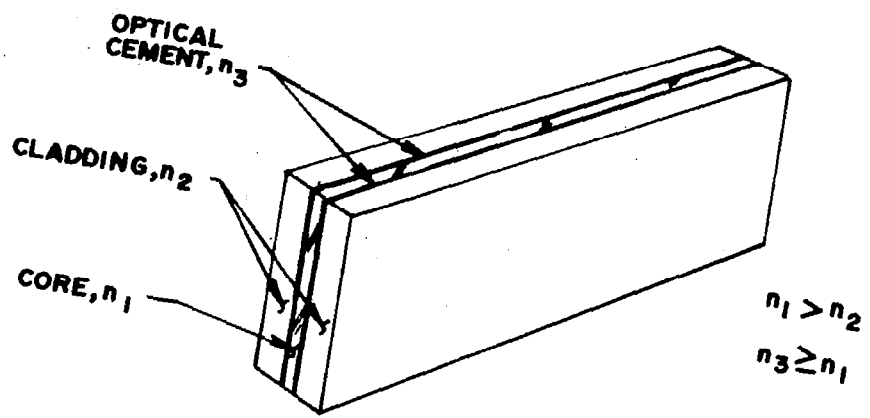
(a) Sketch.
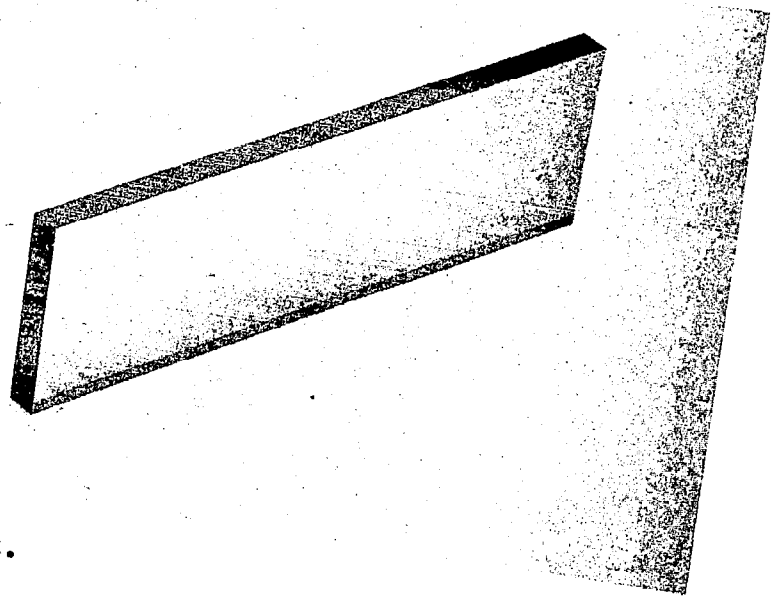
(b) Photograph.

Fig. 10 – Solid dielectric slab waveguide fabricated by assembly
of multiple layers.

(a) TE-0, TM-0.

(b) TE-1, TM-1.

(c) TE-2, TM-2.

Fig. 11 - Mode patterns in three-mode dielectric-slab waveguide
formed by assembly of multiple layers (d = 76λ).

the slab geometry; it is probably restricted to forming single wave-
guides or small numbers of waveguides.

As mentioned previously, a method of forming waveguides
which does not require assembly of the component parts is irradiation
of localized regions of a material. Considerable effort has been
directed to development of this technique, with most of the effort
involving proton irradiation of fused silica. A detailed description
of the effects of proton irradiation and the procedures which can be
used to form optical waveguides are presented in Refs. 2, 3. In
summary, protons can be used to irradiate a surface and induce a
high index region beneath the surface of the material as illustrated
in Fig. 12. The high index "channel" is limited to a region beneath
the surface because the major index change occurs in the so-called
displacement region. This high index region serves as the waveguide
core; the unaffected regions on both sides serve as the claddings.

An experimental evaluation of this technique has been
conducted by irradiating 2 cm x 1 cm x 0.1 cm slabs of fused silica
on one face with protons of several energies and dosages. The
resulting waveguide was tested by immersing the slab in a matching
liquid to eliminate reflections from the surfaces, and illuminating
one end of the slab with a laser. A photograph of the opposite end
illustrating light guiding in a waveguide formed by irradiation with
$1\frac{1}{2}$ Mev protons is given in Fig. 13. The location and size of the
waveguide (high index channel) are in good agreement with calcula-
tions. One problem which has been encountered when using large
dosages is mechanical strain induced in the material. This reduces
the homogeneity of the material and deteriorates the mode patterns
observed; therefore, further investigation of this effect is re-
commended.

The proton irradiation technique can be applied to
fabrication of arrays of waveguides or waveguide components comprising
several complex shaped guides. Such techniques are again described
in detail in Refs. 3; two are illustrated in Fig. 14. In Fig. 14(a),
two waveguides are formed by varying the proton energy over two
discrete ranges; the extension to larger numbers of guides is
obvious. Another approach shown in Fig. 14(b) is to irradiate a
material through a mask so as to form the desired waveguide pattern.
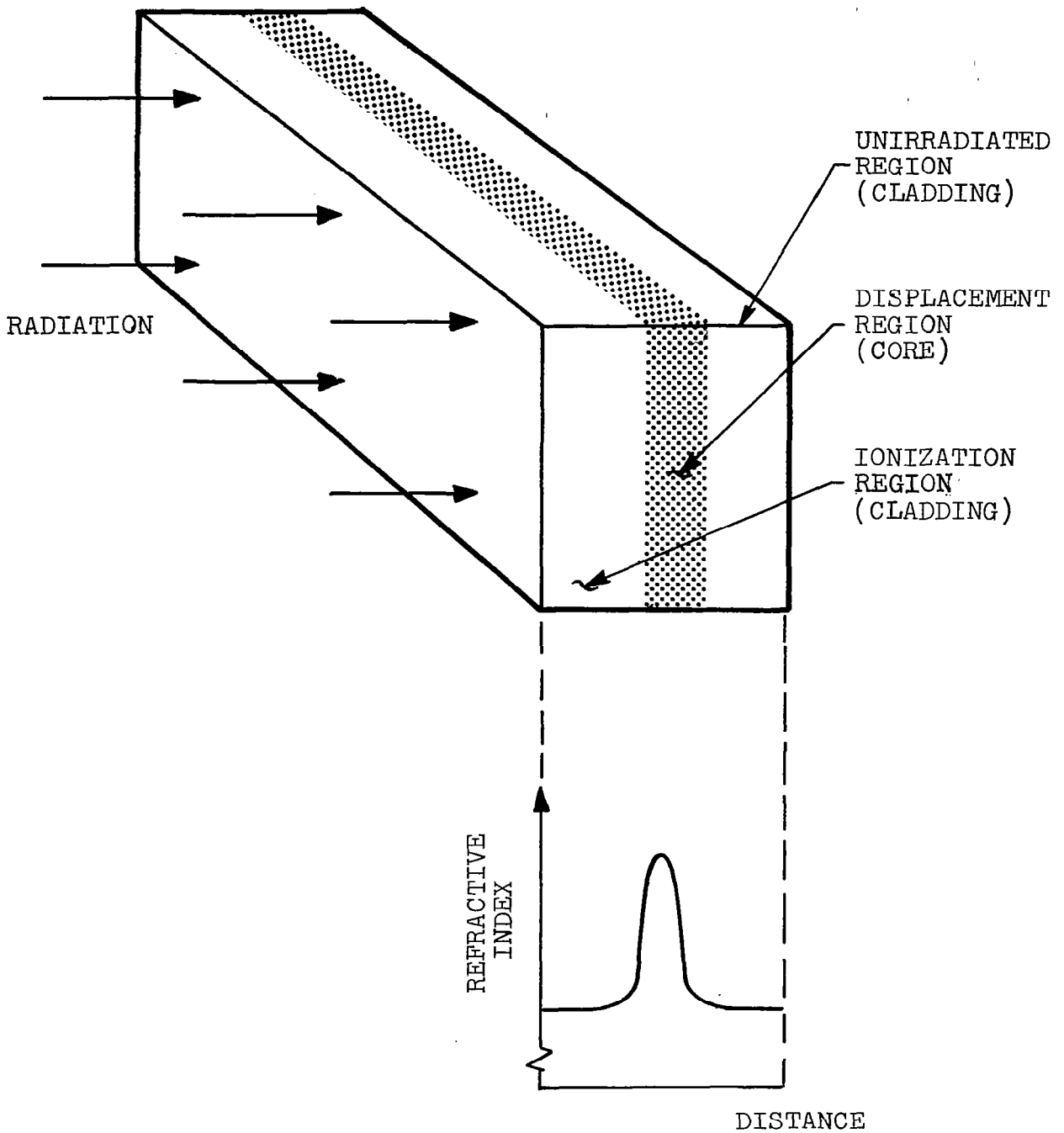
Fig. 12 - Formation of optical dielectric-slab waveguide by
proton irradiation of fused silica.
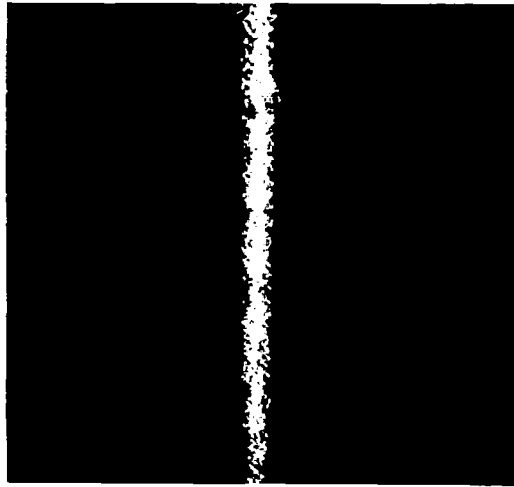
(a)   TM-0 mode (single mode guide).

(b)   TM-1 mode (multi-mode guide).

Fig. 13 - Mode patterns in solid dielectric-slab waveguides
formed by proton irradiation of fused silica.

RADIATION
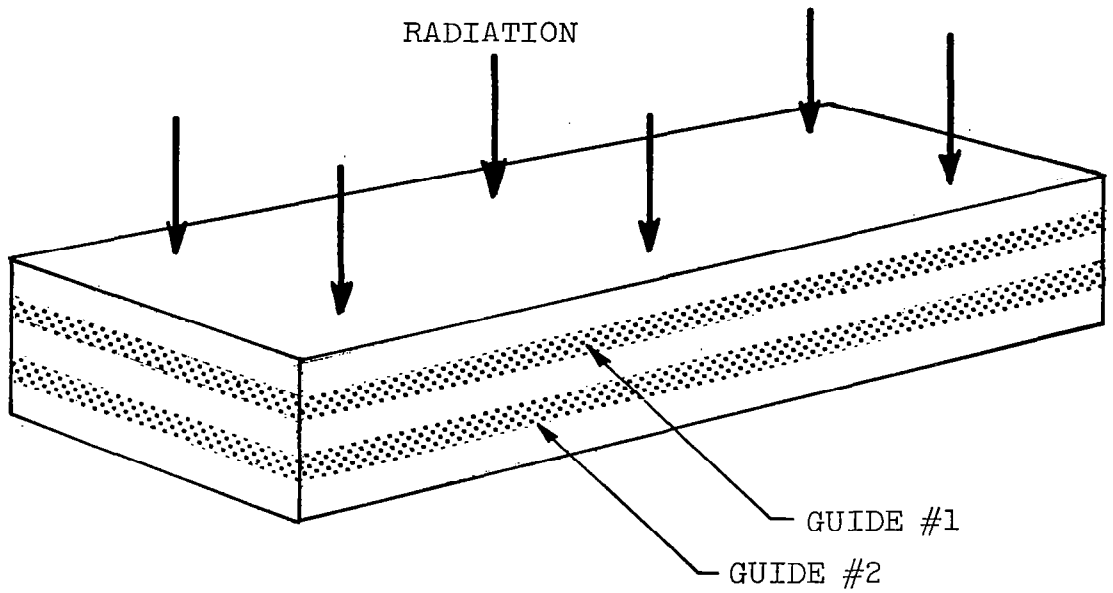
GUIDE #1

GUIDE #2

(a)   Irradiation over two energy ranges.

MASK

RADIATION

COUPLING REGION
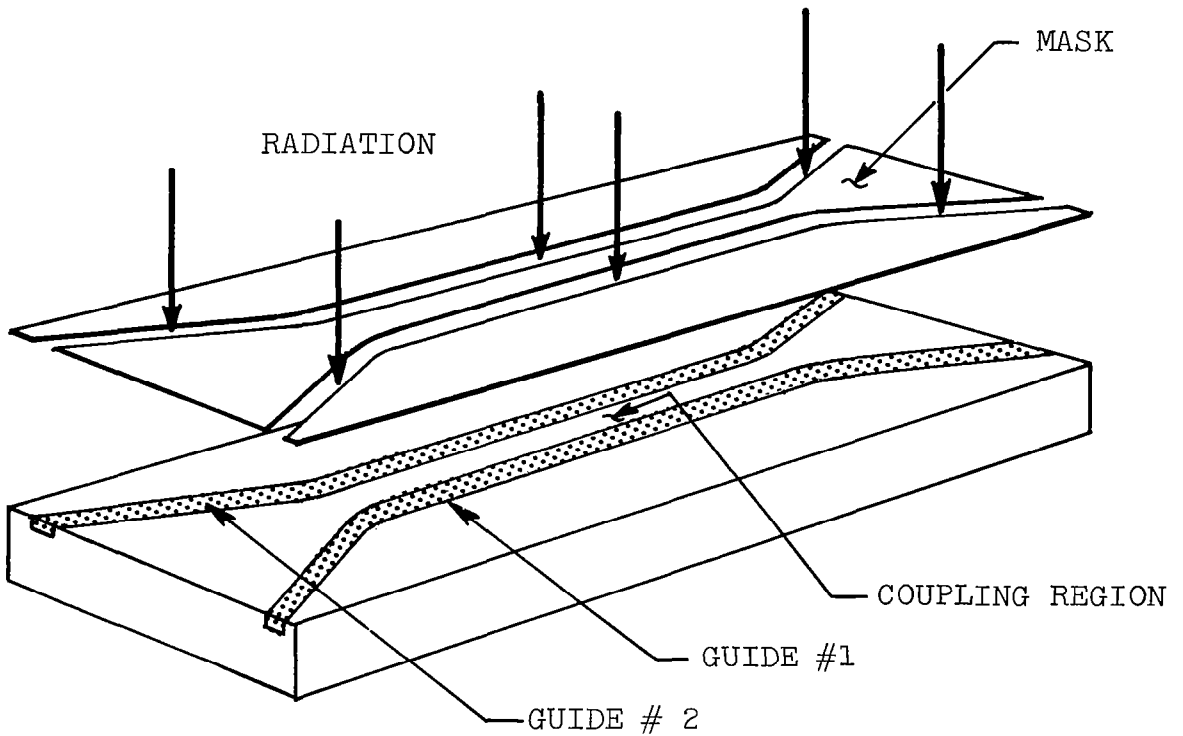
GUIDE #1

GUIDE # 2

(b)   Irradiation through a mask.

Fig. 14 - Formation of dual waveguides in a directional coupler
         configuration by proton irradiation of fused silica.

The two waveguides in each of these cases could be made to form a directional coupler. By using a combination of the above techniques, a two dimensional array of waveguides similar to a fiber-optic faceplate can be formed. Thus proton irradiation is considered quite versatile and appears very promising as an ultimate technique for waveguide formation.

The other mechanism for waveguide formation by irradiation which was mentioned previously involved production of color centers. Refractive index changes of 10^{-4} in glass have been reported with gamma and electron irradiation. While the penetration of gamma rays is too great to irradiate a small region corresponding to the waveguide size, electron irradiation in the energy range around 100 Kev penetrates about 50 microns. Therefore, it is expected that electron irradiation can be used in the same manner as proton irradiation.

No experimental evaluation of the electron irradiation technique was conducted during this program. However, results of the investigation suggest that it may also be a valuable technique for fabrication of macroscopic waveguides with a small index difference. Since there is no density change involved in this case, electron irradiation should not create the problem of strain encountered with proton irradiation.

IV. Component Development.

The primary objective of this program, as stated previously, has been the development of high performance optical waveguide components for application to laser systems. Therefore an investigation of the design of many of the common optical components in a single-mode waveguide has been conducted. The components selected for study were patterned after already existing microwave devices and chosen primarily on the basis of their applicability to waveguide systems for optical communication and radar. Early work was directed to theoretical design and performance calculations, with emphasis on identifying the fundamental differences between waveguide and free-space components. Results of this study are presented in detail in Ref. 1. An experimental evaluation of these components has also been conducted in varying degrees in order to confirm the design principles and demonstrate the feasibility of actually constructing and operating the components. This work is discussed in Refs. 2, 3.

This section summarizes the design and experimental evaluation of lasers, modulators, directional couplers, filters and detectors, fabricated in single-mode waveguide.

A. Laser.

A natural approach for incorporating a laser transmitter or local oscillator in an optical waveguide system is to design the active portion of the laser as a wave-guiding medium. In addition to being a compact way of building a laser into the system, the waveguide approach provides a method of controlling the number of transverse modes. In particular, if a waveguide is restricted to a single mode of propagation, a laser built in this guide will oscillate in only a single transverse mode. The single-mode property is desirable of course to obtain a spatially-coherent output. Macroscopic single-mode waveguide has an advantage over the more conventional approach of reducing the waveguide size to the order of a wavelength to obtain single-mode operation. The cross-sectional area of the guide and hence the active volume of the laser are greater for the macroscopic guide and therefore greater power output can be obtained.

Many of the common laser materials were investigated for the waveguide laser. In addition to the normal requirements for laser materials, it must also be suitable for use as a waveguide. This introduces the additional requirement of very good index homogenity. After a survey of various materials, a neodymium-doped glass fabricated by Corning (Code 0580) was selected. For initial testing this glass was fabricated into a thin slab and placed in a liquid (dichlorobenzene) to form the cladding. The liquid-solid configuration permits the number of waveguide modes to be controlled by temperature regulation; the laser output was then studied as the number of waveguide modes was varied. A photograph of the experimental laser is shown in Fig. 15. The laser slab and a xenon flash lamp are located at the conjugate foci of an elliptical reflector as shown. Water circulates through the region surrounding the flash lamp for cooling, and the entire assembly in Fig. 15 is immersed in the cladding liquid in a temperature controlled tank. External dielectric mirrors are used to form the laser cavity.

Laser action was achieved at a pump energy of about 25 joules. Both the spatial and temporal output were observed as the number of waveguide modes was varied. Photographs of the output are given in Ref. 3. The photographs of the aperture pattern and the diffraction-limited beamwidth of the output indicated that the laser was oscillating in only a single transverse mode (spatially coherent) even when the waveguide was capable of propagating many modes. The reason for this increased mode discrimination is uncertain, but is believed to be caused by greater diffraction losses to higher modes at the external mirrors. This results from a small but finite spacing between the end of the waveguide and the mirrors, which introduces some diffraction loss. The power output and efficiency of this laser were very low, but no attempt had been made to optimize these parameters, since the primary objective was to study the spatial output.

Construction of a completely solid version of this laser was initiated, but work was not completed in time to permit experimental testing. The solid model was formed by reannealing the Corning laser glass to provide two samples with an index difference of 6×10^{-5}, and assembling the core and cladding by the cementing
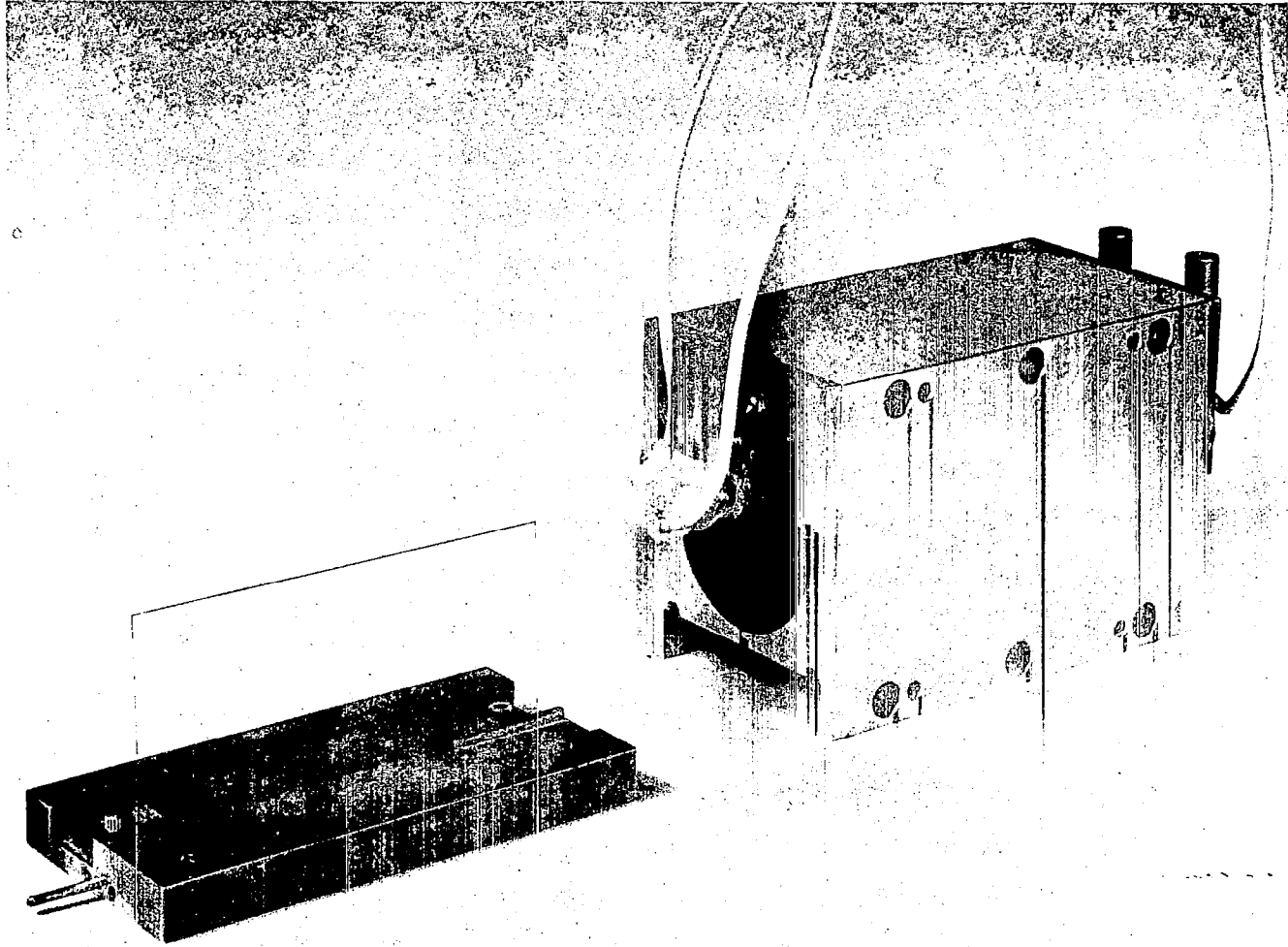
Fig. 15 - Photograph of experimental model of waveguide laser.

technique described earlier. A photograph of the basic waveguide
which was to form the solid waveguide laser was given in
Section III (Fig. 10b).

The results obtained have demonstrated the feasibility
of operating a laser in a single-mode waveguide. This provides
another technique for controlling the number of transverse modes in
a laser. The waveguide laser also has the property of permitting a
long cavity length with small cross-section by eliminating diffraction
losses.

B. Modulators.

The design of several types of laser modulators in a
single-mode waveguide has been considered and details are given in
Ref. 1. In general, it is possible to construct any of the conven-
tional types of modulators (amplitude, polarization, frequency) in
a waveguide by utilizing any of the known electro-optic materials
for the waveguide core or cladding, as illustrated in Fig. 16. The
operation is basically the same as for a similar modulator operated
in an unbound medium. However, a significant advantage of the wave-
guide medium is a potential reduction in the cross section of the
beam to be modulated. Since the waveguide eliminates diffraction
spread, the cross-sectional size can be reduced to about one wave-
length, independent of the length of the modulation region. The
small size results in a small volume for the modulation region which
can reduce the required modulator power.

One novel type of amplitude modulator has been considered
whereby the modulation is obtained by switching a waveguide from a
propagating to non-propagating condition. If the refractive index
of the waveguide core is higher than the cladding, the guide
propagates and maximum signal is transmitted; if the core index is
equal to or lower than the cladding, the transmitted signal is
highly attenuated. This modulator can in theory provide close to
100% modulation with a very small change in the index of the electro-
optic material.

A preliminary experimental evaluation of waveguide modula-
tors was conducted by constructing a waveguide with a nitrobenzene

WAVEGUIDE
CLADDING

WAVEGUIDE
CORE

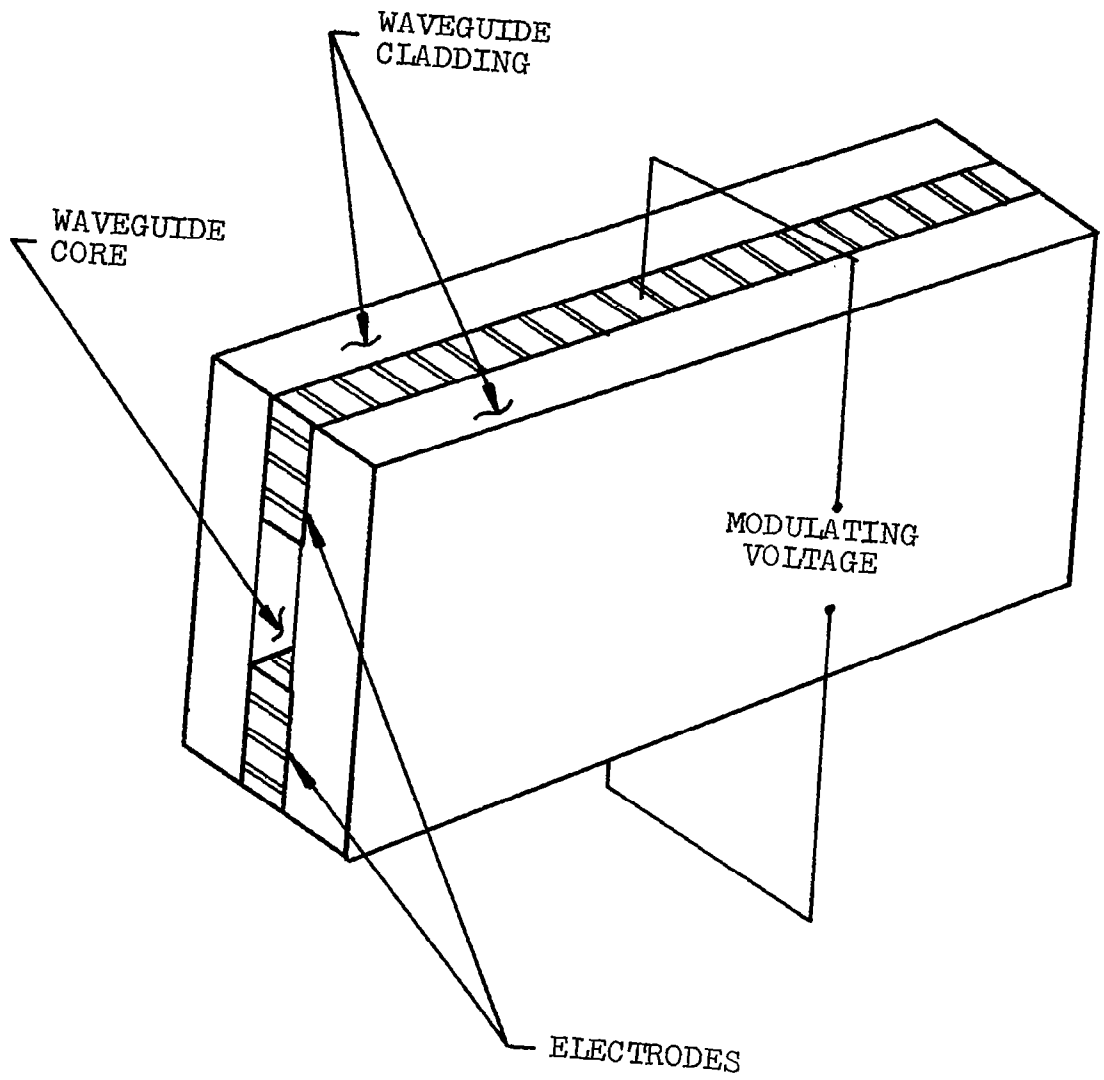MODULATING
VOLTAGE

ELECTRODES

Fig. 16 - Optical waveguide modulator.

core. By application of an electric field to the waveguide core
(as in Fig. 16), it was possible to vary the number of propagating
modes. This was considered a successful demonstration of the
waveguide modulator concept.

In conclusion, most of the conventional types of electro-
optic modulators can be operated in a waveguide medium. The possi-
bility of obtaining a very small modulation region requiring low
modulator power appears to be the most significant advantage.

C. Directional Coupler.

A directional coupler is a device for dividing or combining
electromagnetic waves in a coherent manner. The most common optical
version of the directional coupler is a half-silvered mirror. At
microwave frequencies, there are a great variety of different types
of directional couplers constructed in waveguide. Two types of
waveguide couplers which have been considered on this project are
the evanescent-field coupler and the slot coupler.

The evanescent-field coupler consists of two waveguides
located close together whereby energy couples from one guide to the
other in the same way as the so-called "cross-talk" observed in
fiber optics. An analysis of the coupling for an evanescent-field
coupler in the slab geometry is presented in Ref. 1. In summary, for
two waveguides propagating only a single-mode, the coupling increases
as the separation between the guides and the waveguide size decreases.
Reasonable values of coupling can be obtained in convenient waveguide
lengths of the order of a few centimeters. An experimental model of
the evanescent-field coupler was implemented in the liquid-solid
configuration. The coupler consisted of two glass-slab waveguides,
85 wavelengths wide in a liquid cladding. However, it was not
possible to hold the coupling parameters (waveguide size, index, and
separation) to the tolerances required to sufficiently simulate the
theoretical model. Consequently, coupling of low-order modes was not
observed, although some higher-mode coupling was observed where the
index difference is greater and tolerances are less severe. It
is believed that this coupler could be implemented either by
using stricter fabrication tolerances to more closely approximate

the theoretical model, or by using smaller waveguides where the coupling is stronger and tolerances are looser. However, further attempts at implementing this coupler were discontinued in favor of the slot coupler described below, because it provides greater coupling per unit length than the evanescent-field coupler.

An illustration of the experimental model of the slot-type directional coupler is given in Fig. 17. The coupler consists of two metal-bisected waveguides with a common metal wall between them. A "slot" is provided in the bisecting wall to allow coupling of energy from one guide to the other. An analysis of the coupling is given in Ref. 1 and curves of the coupling as a function of the waveguide width, refractive index difference and slot length are given in Ref. 3. As a typical example, 3 db coupling can be obtained with single-mode waveguides 50 wavelengths wide in a length of 1 cm. In general, the coupling increases as the waveguide width is reduced and as the index difference and slot length are increased.

An experimental model of the slot coupler was constructed by vacuum deposition of aluminum on two glass slabs (85 wavelengths wide) to form the bisected waveguides, and assembling these as shown in Fig. 17. The aluminized surfaces are located in mutual contact to provide minimum spacing between the guides. Actually, there is a finite spacing which results in a thin layer of cladding liquid between the guides; this has the effect of reducing the coupling below that calculated for the ideal case.

Experimental measurements of the coupler were performed under a variety of conditions by exciting one waveguide and observing the output in each guide at the opposite end. The coupling was determined by measuring the mode pattern in each with a phototube (Ref. 2) and comparing the signal level. An example of the mode patterns for the case of 10 db coupling is shown in Fig. 18. Comparison of the measured and calculated coupling indicates that the measured is lower than the calculated by a constant difference of 7 db. For example, with a slot length of 2.5 cm and an index difference of 2.5×10^{-5} (maximum value for single-mode operation) the observed coupling was -10 db as compared to -3 db calculated. These results are considered a good experimental confirmation however, because the variation of coupling with index difference is the same
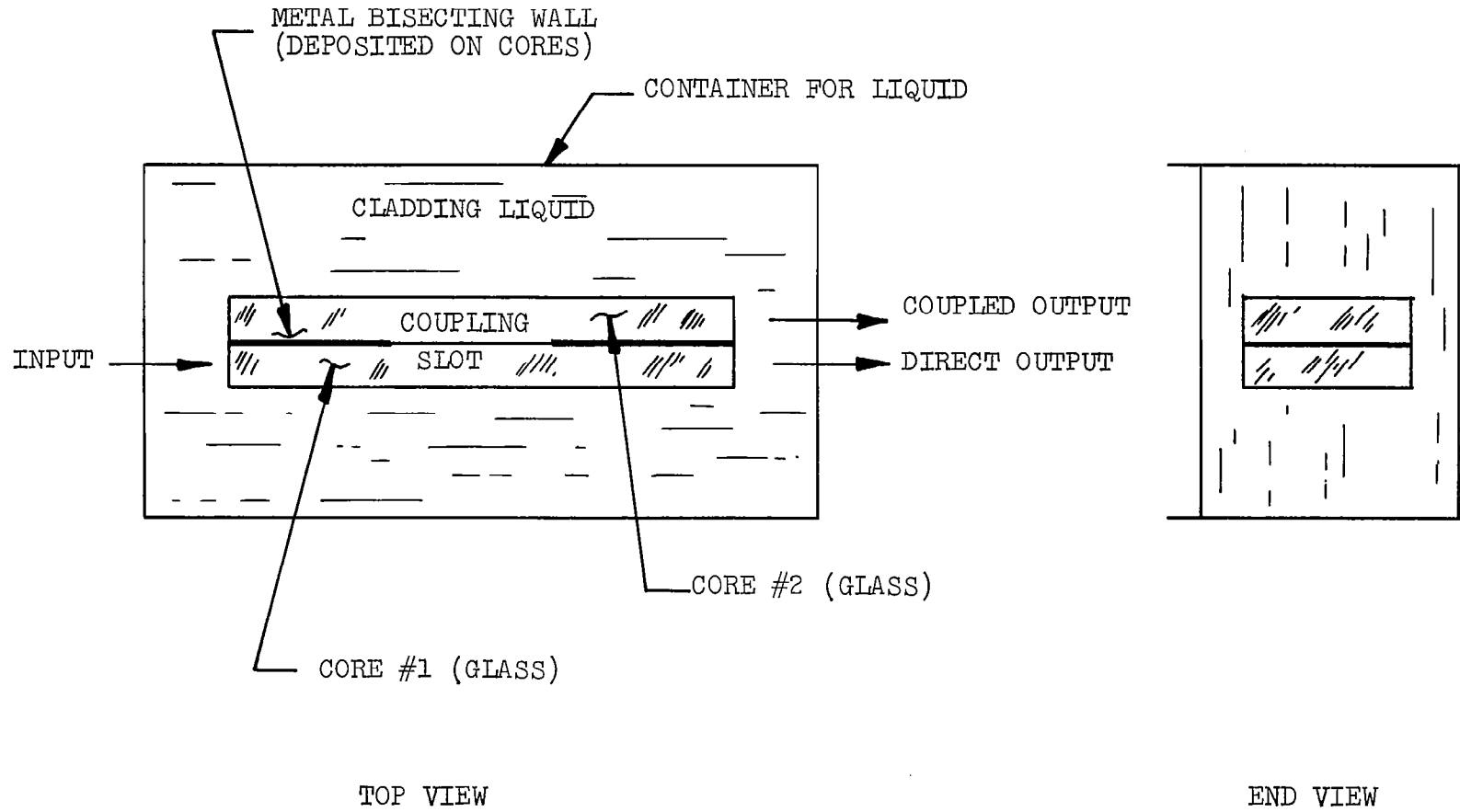
Fig. 17 - Sketch of experimental model of slot directional coupler.
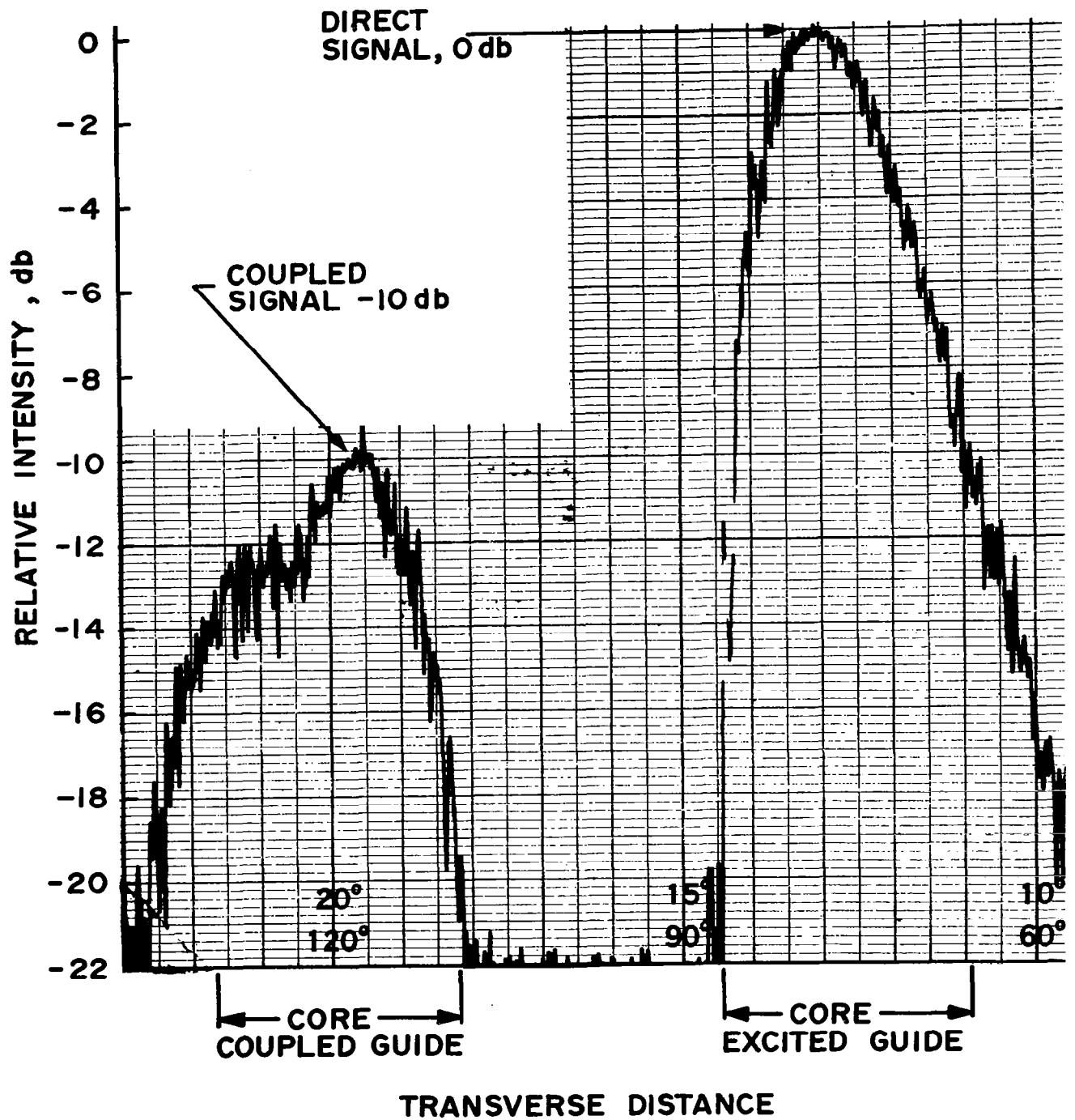
Fig. 18 - Measured mode pattern of coupled waveguides of slot directional coupler (TM-1 modes).

as that calculated, and the discrepancy is attributed to the thin
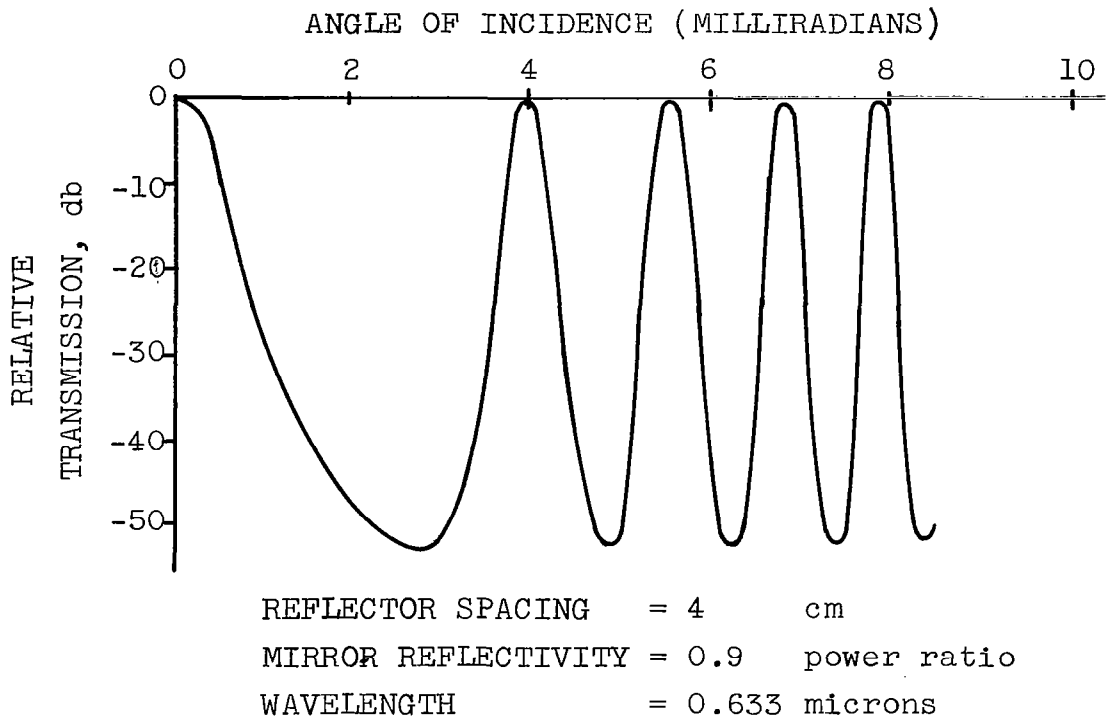layer of liquid between the guides.

Preliminary work concerning implementation of a solid
model of the slot coupler has been initiated. The procedure is to
form two solid, metal-bisected guides in the manner described in
Section III and join these with optical cement. Since development
of the cementing techniques was not completed until late in the
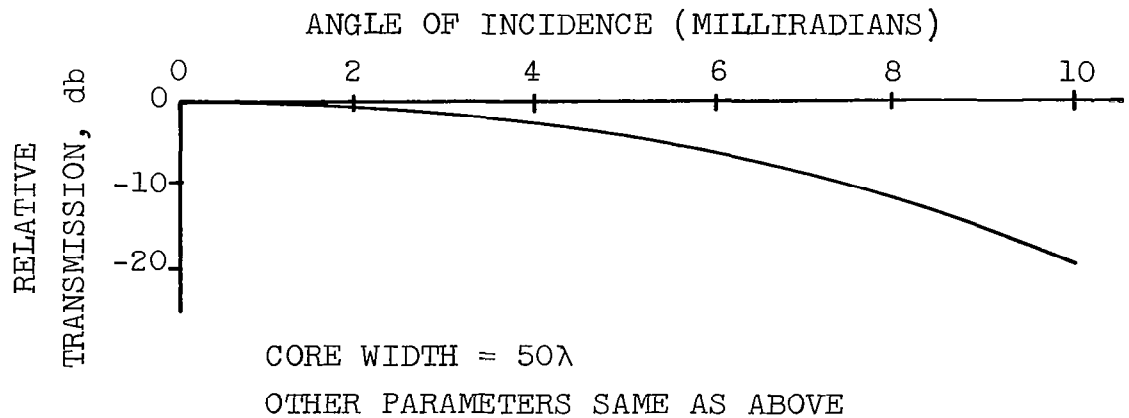contract, a solid model of the coupler was not completed.

D. Filters.

The design of optical filters in a waveguide medium has
been considered and the performance of such filters has been analyzed.
The results of this investigation have shown that optical filters
fabricated in a waveguide have a unique property in that the angle
and frequency response are independent. This means a waveguide filter
can overcome the serious limitation of conventional optical filters,
namely that it is not possible to obtain narrow-band filters with
a wide field-of-view.

For conventional optical interference filters, the center
frequency shifts as the angle of incident radiation is varied off
normal. Therefore, for a given signal frequency, the transmission
will vary with angle, as illustrated in Fig. 19a for the case of
a Fabry-Perot filter. Since the tolerable frequency shift of a
filter is less than the bandwidth, there is a maximum angular range
over which the filter can be operated. This means that narrow-band
filters are limited to a narrow field-of-view as well.

This limitation is removed however, if an optical filter
is constructed in a single-mode waveguide. An illustration of a
Fabry-Perot waveguide filter is given in Fig. 20. Two (or more)
semi-transparent mirrors are located in the guide in a transverse
plane; filtering is accomplished by interference in the same manner
as conventional filters. However, for the waveguide filter, the
phase velocity is determined entirely by the waveguide parameters
and is independent of the excitation angle. Therefore the center
frequency of such a waveguide will not vary as the angle of
incidence is varied, and the bandwidth can be made as narrow as

43

ANGLE OF INCIDENCE (MILLIRADIANS)

REFLECTOR SPACING   = 4   cm
MIRROR REFLECTIVITY = 0.9   power ratio
WAVELENGTH   = 0.633 microns

(a) Fabry-Perot filter in free space.

ANGLE OF INCIDENCE (MILLIRADIANS)

CORE WIDTH = 50λ
OTHER PARAMETERS SAME AS ABOVE

(b) Fabry-Perot filter in waveguide.

Fig. 19 - Transmission vs. angle of incidence of conventional
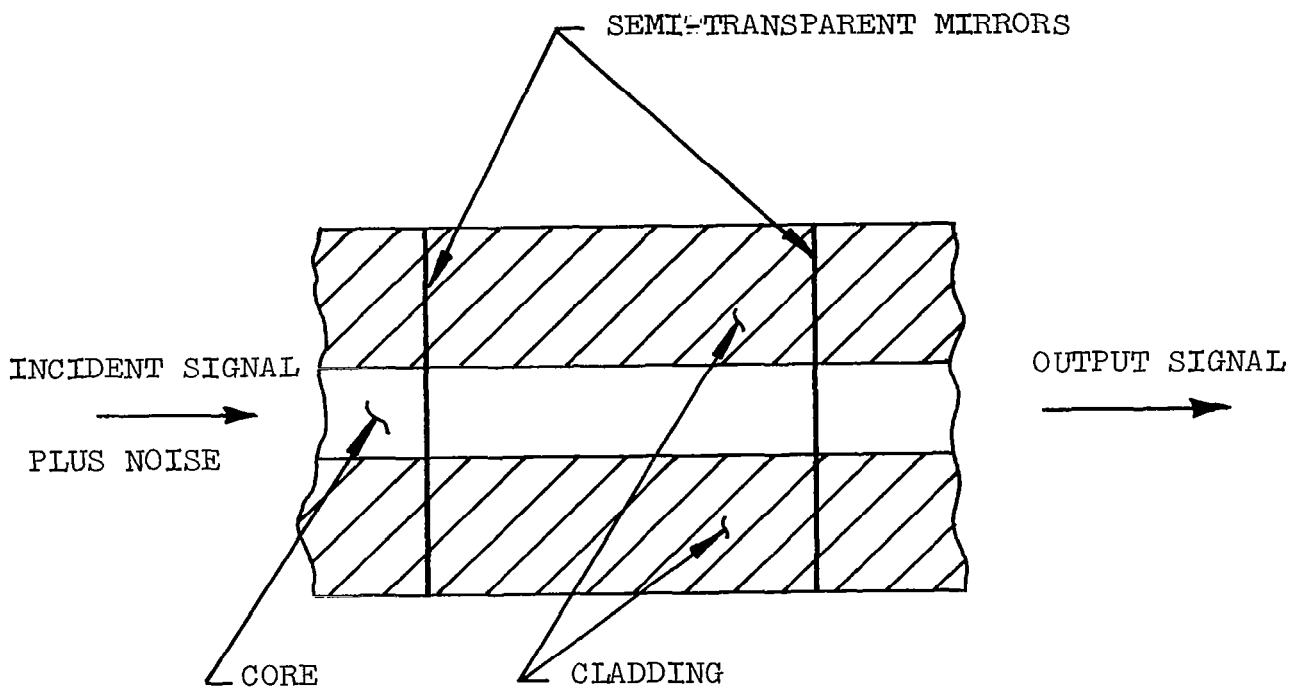and waveguide-type optical filters.

Fig. 20 - Optical waveguide filter.

required. The field-of-view is equal to the beamwidth of the waveguide ($\theta = \lambda/d$) and this can be controlled independently by selecting the appropriate waveguide size. The transmission vs. angle of a waveguide filter with the same length and reflectivity as the conventional filter of Fig. 19a is given in Fig. 19b. This angle response is determined by the waveguide size of 50 λ; it should be noted that any response could be obtained by selecting the appropriate waveguide size.

It may be noted that the field-of-view and cross-sectional size of the filter are now related. For the case of a single wave-guide, this means that a filter with wide field is limited in aperture size as discussed in Section II. Fortunately, this limita-tion can be overcome by arraying a large number of optical waveguides side by side. As shown in Section II this increases the area while maintaining the same field-of-view. Thus it is possible to con-struct an optical filter in an array of single-mode waveguides which has wide field-of-view, small bandwidth and large collector area. A more detailed description of filters using an array of waveguides is given in Ref. 9.

Optical waveguide filters of the type described above have a potential advantage over conventional optical filters in any system where background noise is high and a relatively wide field-of-view is required. Examples of optical communication and radar systems where this situation exists are quite common (Refs. 13, 14). As a particular example, a laser communication system between the earth and moon was considered. For the system parameters chosen, and utilizing the smallest bandwidth conventional filter consistent with the field-of-view, the background noise was found to exceed receiver noise by almost 40 db. If a waveguide filter were used in this system, the bandwidth could, in principle, be made as small as desired while still maintaining the required field of view. Therefore an improvement in signal-to-noise ratio of almost 40 db would be obtained.

E. Detectors.

An optical waveguide detector is formed by locating any of the conventional types of photo-detectors in a single-mode

waveguide. An example of such a detector which utilizes a photo-conductive material bonded to the output as shown in Fig. 21.

The investigation has shown that waveguide detectors possess a unique property relative to conventional optical detectors. Conventional optical detectors are fundamentally power sensitive devices, i.e., the output is proportional to the square of the amplitude of the incident signal and is independent of its phase. On the other hand, the output of a waveguide detector depends on the excitation efficiency of the waveguide which in turn depends on the field pattern of the waveguide mode and on both the amplitude and phase of the incident field (Refs. 1, 3). This detector is therefore sensitive to the spatial phase of the incident signal and has a reception angle equal to the diffraction limited beamwidth. In this respect, it achieves the spatial properties of a coherent detector such as a superheterodyne receiver. It also suffers from the same limitation as coherent detectors in that the aperture size must be small if the beamwidth is to be large.

The properties of a spatially coherent detector may be advantageous in particular applications. One application which has been considered in order to illustrate the difference in performance between waveguide detectors and conventional detectors is the precise measurement of spatially-coherent optical fields containing nulls and associated phase reversals. If a conventional detector is used to scan such an optical field, the measured pattern contains considerable fill-in in the vicinity of the null, because the detector integrates the total power over the aperture. If a waveguide detector is used, the fields on opposite sides of the null are of opposite phase and effectively cancel in the waveguide. Therefore this detector measures a minimum depth limited only the detector noise. In typical examples given in Ref. 3, the measured depth of the null for the waveguide detector is 5 to 30 db deeper than for a conventional detector. It is also shown that the location of the minimum is more accurate for the waveguide detector. For a given detector size, the position error of the spatially coherent detector is about one-tenth that of the conventional detector.

An early experimental evaluation of the waveguide detector was conducted by locating a photomultiplier tube at the output of
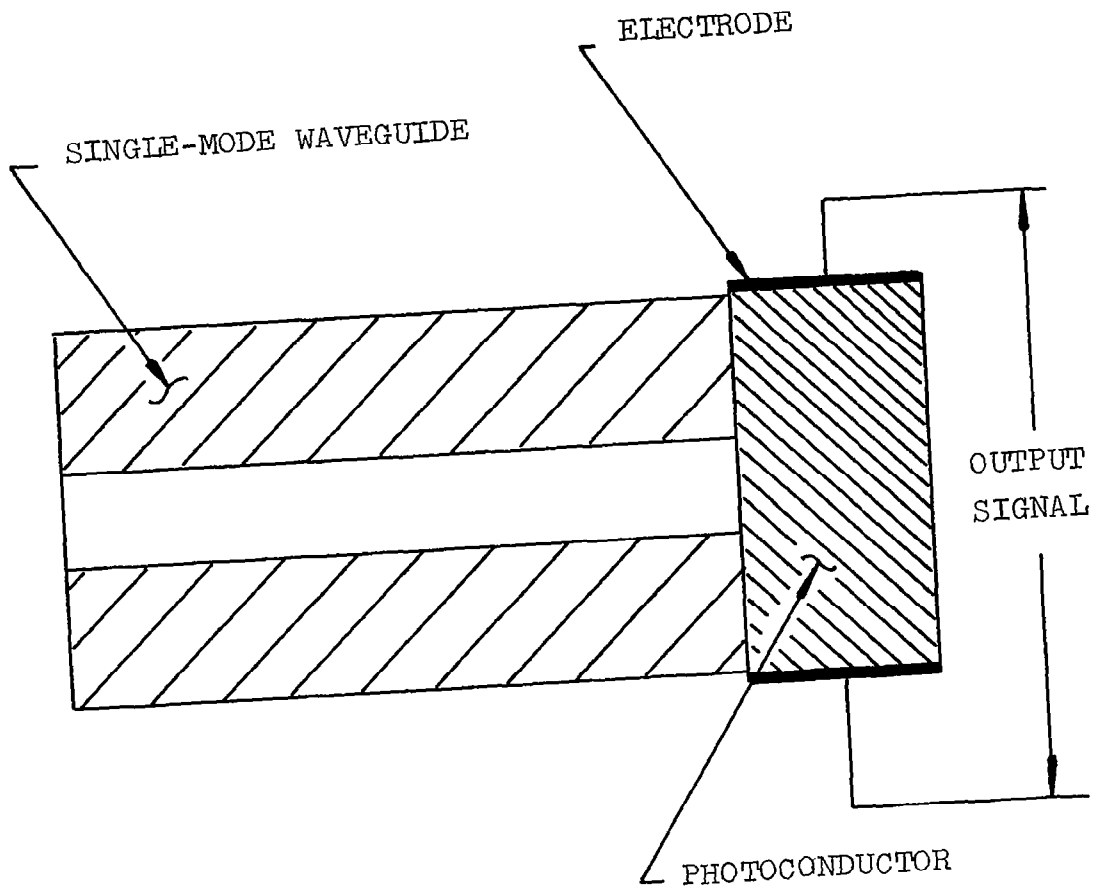
Fig. 21 - Optical waveguide detector.

a waveguide. A diffraction pattern was then scanned with the wave-guide detector and with a conventional detector of the same size. (Ref. 1) The measured null depth was 7 db deeper for the waveguide detector, in good agreement with calculations. It was planned to implement a more refined model of a waveguide detector utilizing a completely solid waveguide. However, the development of solid wave-guides was completed too late in the contract to permit fabrication.

The performance evaluation of the detector illustrates the superior performance of a waveguide detector in a particular appli-cation. However, it is believed that the unique properties of this detector will find application in other areas as well. For example, the improved accuracy in location of a null might be applied to improving the tracking accuracy of an optical radar system.

V. Conclusions and Recommendations.

A three-year program for development of single-mode optical waveguide and waveguide components is summarized in this report. It has included the design, fabrication and testing of laboratory models of waveguides and components and development of techniques for fabrication of practical versions of the waveguide. A general study of the application of waveguide techniques to laser systems has been conducted.

The waveguide development began with a study of various types of waveguide to determine those types best suited for application at optical frequencies. The dielectric waveguide has been found to be most useful on the basis of low loss and adaptability to component design. This guide has the property that the number of modes is controlled by the waveguide size and the difference in refractive index between the core and cladding materials. This property has been exploited to produce what we have called "macroscopic" single-mode waveguides, i.e. the waveguide cross section is many wavelengths but propagation is restricted to a single mode by providing a very small difference in refractive index between the core and cladding. This property makes the guide very versatile in that the optimum waveguide size can be selected for a particular application.

The feasibility of operating single-mode waveguides based on this concept has been demonstrated by successfully implementing waveguides with liquid and solid materials for the core and cladding. The performance of such guides has been found to be in excellent agreement with theory in waveguide sizes up to 100λ.

The ultimate objective of this program has been the development of compact, rugged optical components, which are insensitive to environmental conditions. Toward this goal, several techniques have been developed for fabricating completely solid versions of the guide. High quality optical glasses for the waveguide core and cladding with refractive index differences as small as 10^{-5} have been obtained by special annealing and re-annealing. Waveguides in the slab geometry have been formed from this glass by grinding and polishing the glasses and joining them with a thin

layer of optical cement. Cement layers less than a quarter wave-length thick and index slightly higher than the core have been obtained; the cement has been shown to be essentially invisible under these conditions. This fabrication technique is considered useful for fabricating small numbers of waveguides in the slab or square geometry.

Another technique which has been found useful for fabricating solid waveguides is atomic irradiation of optical materials. The refractive index of a material can be changed by using particle irradiation to change the density, or by using ionizing radiation to introduce color centers. In either case, a type of radiation can be selected which affects only a localized region of the optical material. In this way a complete waveguide can be formed by one irradiation with no further fabrication. Proton irradiation has been used to form a high-index channel in fused silica which acts as a waveguide. The size and propagation characteristics of the waveguide were in good agreement with theory. A theoretical investigation has indicated that electron irradiation of certain types of glasses can also be used to form waveguides. The irradiation technique is believed to be a very useful technique for formation of waveguides with complex shapes, for combinations of waveguides to form components and for formation of large arrays of waveguides. Further development of this technique is recommended as an ultimate method for waveguide fabrication.

Concerning the development of optical waveguide components, a theoretical design and performance evaluation of many common optical components has been conducted, and experimental models of several of these have been fabricated and tested.

A laser fabricated in single-mode waveguide has been designed and tested. Fabrication of the laser in the waveguide provides a natural and compact method for incorporating a laser in a waveguide system. It also provides an additional technique for transverse mode control. The successful operation of the waveguide laser demonstrated the general feasibility of implementing and operating such a device.

A number of different types of waveguide modulators which utilize an electro-optic material for the core or cladding have

been considered. Most of the common types of free-space modulators can be operated in the waveguide medium. A significant advantage of the waveguide medium is that the volume of the modulating region can be smaller than for a free-space type and hence the required modulator power can be reduced. One novel type of modulator was studied where the core index of a waveguide is changed so as to switch the waveguide from a propagating to a non-propagating condition. This modulator can provide almost 100% modulation with a very small index change and correspondingly small voltage change.

A theoretical analysis of waveguide directional couplers of the evanescent-field and slot type has been made. The slot-type provides somewhat greater coupling per unit length, but both types yield reasonable values of coupling in convenient sizes. An experimental model of the slot coupler was implemented and tested; results were in good agreement with theory. Cementing techniques for fabricating solid models of the slot coupler have been developed, but a model was not completed.

An investigation of optical waveguide filters has indicated a unique property, in that, unlike conventional filters, the angle and frequency response is independent. This property permits the fabrication of narrow-band filters with wide field-of-view. This can provide a very significant reduction in receiver background noise in many systems.

A theoretical study of the properties of detectors constructed in waveguide has been conducted and a simple experimental evaluation has been made. Unlike conventional detectors which are power sensitive, fabrication of a detector in waveguide makes the detector sensitive to both the amplitude and phase of a signal. This gives a waveguide detector the spatial properties of a coherent detector. The phase sensitive property provides increased accuracy in null measurements which gives a potential advantage in precision tracking systems.

As part of the overall program for application of waveguide techniques at optical frequencies, an evaluation of the performance of optical waveguide systems as compared to free-space systems was made. It is shown that the properties of waveguides such as small size and angle-invariant performance provide potential

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advantages. In the case of particular components such as filters and detectors, these properties result directly in unique and improved performance, which can be exploited to advantage with little additional development.

For complete waveguide systems, a realistic evaluation is difficult at this stage because final models of the waveguide are still under development. However, it is expected that for these systems, the primary advantages over free-space systems will be the small size, light weight and stability, as well as improved performance. The use of arrays of waveguide has been shown to be an effective method for overcoming the limitation of small collecting area inherent in single-channel systems, while still maintaining the advantages of guided propagation.

VI. Acknowledgements.

VII. References.

The following list of references is divided into three parts: first, three interim reports describing work over the appropriate periods; second, a list of papers and publications associated with this program; finally, several references to outside work.

Many additional references to the outside literature are contained in the interim reports. A general survey and annotated bibliography of work in the field of optical dielectric waveguides is contained in Ref. 2.

A. Interim Reports.

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B. Wheeler Laboratories Publications.

(4) 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.)

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(6) E. Ronald Schineller, "Variable Optical Double Prism Attenuator With Multiwavelength Spacing", Proceedings of the Symposium on Quasi-Optics, vol. XIV, p. 517-535 Polytechnic Press; June 1964.

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C. General Literature.

(11) I. H. Malitson, M. J. Dodge, M. E. Gonshery, "Radiation-Induced Instability in Refractive Properties of Some Optical Glasses", presented at the Fall meeting of the Optical Society of America, Philadelphia, Pa.; Oct. 1965. Also: NBS Report No. 8943.

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