III-8. Macroscopic Single-Mode Waveguide for the Construction of Optical Components

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The contemplated applications of laser radiation include optical systems which are similar to present microwave radar and communication systems. However, to provide the degree of sophistication presently obtainable at microwave frequencies, it is necessary to have high-performance optical components. One approach to the design of laser systems is to employ waveguide-type components, analogous to those presently available at microwave frequencies. This paper discusses single-mode, macroscopic, optical wave guide which is proposed as a construction medium for the fabrication of optical components. The term "macroscopic" implies that the waveguide dimensions are at least an order of magnitude greater than the wavelength of light, which is considered sufficiently large to permit fabrication with reasonable tolerances.

Operation of Dielectric Waveguide. Of the many waveguide configurations possible, including rectangular and circular pipes, the dielectric type, as shown in Fig. 1, appears most promising for large-size optical waveguide. This waveguide consists of a dielectric core imbedded in a medium with a lower dielectric constant.

The theory of propagation in a parallel-plate dielectric waveguide has been previously established;[1] a simplified ray analysis of TM propagation in the dielectric-slab configuration is outlined in Fig. 2 and illustrates that propagation is based on the phenomenon of total internal reflection. The internal fields are resolved into two plane TEM waves, which reflect from the interfaces at some angle, θ. If θ is greater than the critical angle for total internal reflection, θ_c, all the power remains within the central or "core"

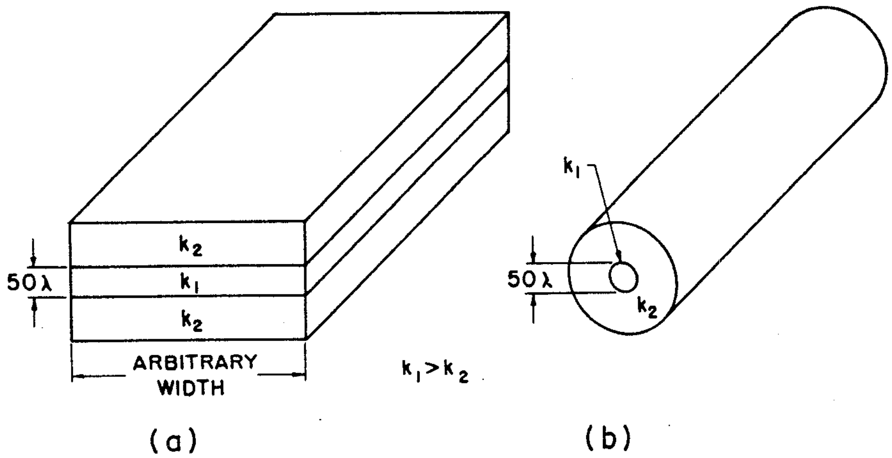

Fig. 1 Macroscopic Dielectric Waveguide. (a) Dielectric-slab waveguide. (b) Dielectric-rod waveguide.

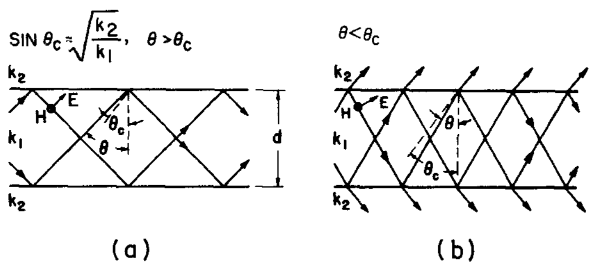

Fig. 2 Propagation in a dielectric-slab waveguide. (a) propagating TM mode. (b) Leaky TM mode (not propagating).

dielectric; for smaller angles, power is lost at each reflection. Waveguide modes associated with angles above θ_c are "propagating;" those below θ_c are "leaky." Only certain discrete values of θ will simultaneously satisfy the boundary conditions at both interfaces.

The condition for propagation depends on the dimensions of the core and on the difference of dielectric constant, Δk, across the interface. The core thickness required for a propagating mode of order m is

$$d > D_m = \frac{m}{\sqrt{\Delta k}} \frac{\lambda}{2}, \quad m = 0, 1, 2, \ldots, \tag{1}$$

where d is the core thickness, D_m is the critical thickness for the propagating mode of order m, Δk is the difference between dielectric constants of the inner and outer media, and λ is the free space wavelength.

Waveguide parameters may be chosen with respect to Eq. (1) to obtain a single-mode optical waveguide with macroscopic dimensions. If Δk is made small enough, D_1 will be many wavelengths. With d chosen slightly less than D_1, only the dominant mode ($m = 0$) will propagate; all higher modes will be leaky and therefore attenuated in the direction of propagation. In addition to the fields indicated by the ray analysis, there are also fields in the external medium. These decay exponentially in the transverse direction; for macroscopic optical waveguide a 400 db/mm decay is typical.

The losses associated with the propagating modes are caused by dissipation in the dielectric and are of the order of 0.10 db/cm. Therefore, the major application of this waveguide is expected to be lengths of a few centimeters containing several microwave-type components.

Experimental Verification. A macroscopic dielectric-slab waveguide with chlorobenzene as the core material and optical glass ($k = 2.440$) as the external medium has been designed and operated at Wheeler Laboratories. A liquid was chosen for the core to facilitate fabrication. The waveguide is 7.7 cm long with a core thickness of 32 microns ($\approx$ 50 wavelengths). The Δk necessary for single-mode propagation in this guide is 0.0001. This difference is achieved and maintained by temperature control of the liquid which has a temperature coefficient of dielectric constant of 0.001/°C. The experimental model is shown in Fig. 3. The glass plates are suspended in the liquid for convenience. In an operational configuration, the liquid would be sealed between the plates.

The operation of the waveguide was verified by comparing the observed field configurations with those predicted theoretically. Initially, Δk was

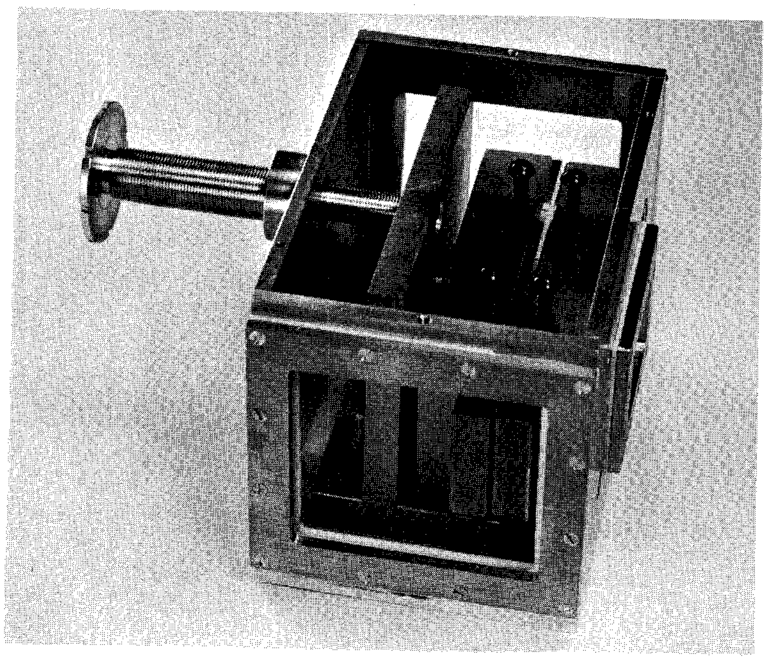

Fig. 3 Optical dielectric-slab waveguide.

adjusted to permit propagation in the first four modes. The waveguide was excited at one end with a collimated beam from a gas laser (.6328μ). The laser beam was polarized perpendicular to the plane of the interface, so that only TM modes were excited. A microscope focused on the other end of the waveguide permitted observation of the mode patterns. For excitation normal to the end of the waveguide the TM-0 mode (Fig. 4 (a)) was observed. As the angle of the laser beam was varied in either direction, the patterns shown in Fig. 4 (b) through (d) were observed. The waveguide was then adjusted, by decreasing Δk, to support only the dominant mode. In this case the mode pattern of Fig. 4 (a) was observed at angles from 0 to 10 milliradians. For all other angles, the waveguide was dark, indicating that all higher-order modes were leaky.

Since the observed patterns correspond to those expected for the various modes, the experiment demonstrates: 1) that macroscopic optical waveguide may be designed for single-mode operation; 2) that individual modes may be selectively excited in multimode optical waveguide by controlling the angle of incidence of the exciting beam.

Proposed Waveguide Configurations. A number of alternate techniques have been considered for obtaining the required Δk. The difference in the dielectric constants of various solids, liquids, or gases may be utilized (Fig. 5 (a)). A slightly different approach is the utilization of a temperature-induced, dielectric gradient to obtain optical waveguide propagation (Fig. 5 (b)) similar to rf propagation in an atmospheric duct. The variation of index of refraction with direction in a birefringent substance is another possibility (Fig. 5 (c)).

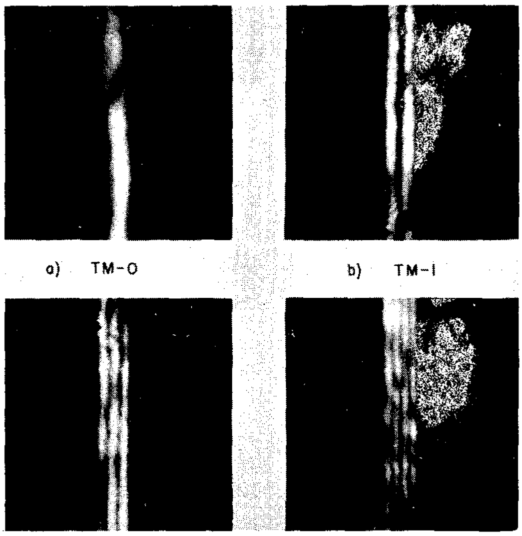

Fig. 4 Mode patterns in macroscopic optical waveguide (dielectric-slab configuration).

Proposed Waveguide-Type Components. As discussed earlier, the main objective of this paper has been to describe a waveguide which will permit the development of sophisticated optical components for application in laser radar and communication systems. There are two varieties of components which lend themselves to fabrication in macroscopic optical waveguide: 1) active components such as coherent amplifiers and single-mode oscillators; 2) passive components such as directional couplers, hybrid-T junctions,

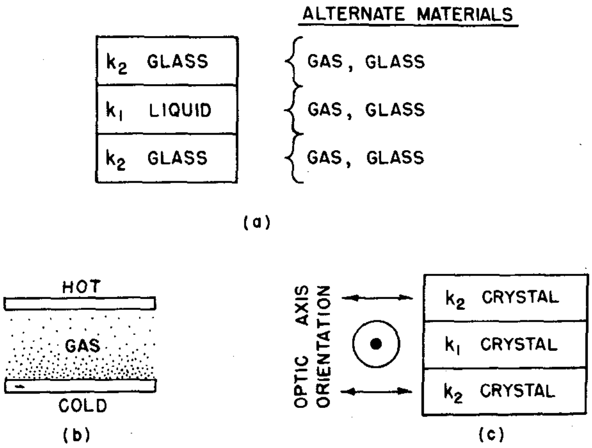

Fig. 5 Proposed techniques for controlling the relative dielectric constant of macroscopic optical waveguide.

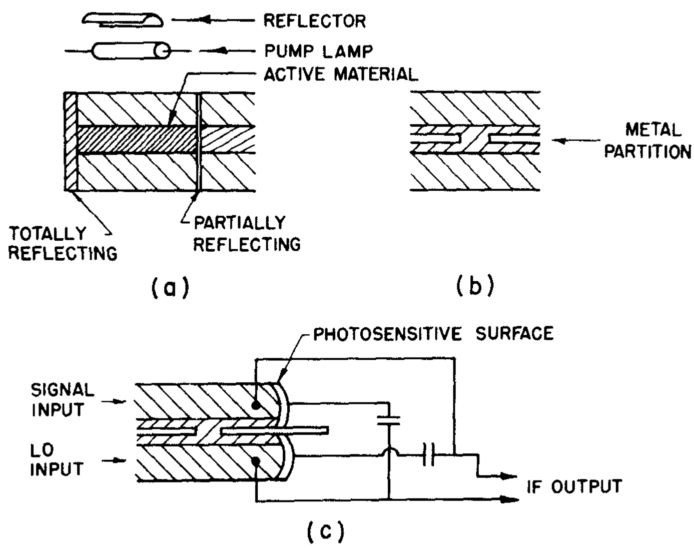

Fig. 6 Proposed optical waveguide-type components.
(a) Single-mode laser. (b) Directional coupler.
(c) Balanced mixer.

narrow band-pass filters, and balanced mixers for optical heterodyne detection. Typical components are shown in Fig. 6. In general, the manufacturing specifications on these components will be stringent, but feasible, while the electrical design procedures are expected to be adapted from techniques currently used for microwave components.

REFERENCES

1. R. E. Collin, *Field Theory of Guided Waves* (New York: McGraw-Hill, 1960).
2. R. A. Kaplan, "Optical Waveguide of Macroscopic Dimensions in Single-Mode Operation," *Proc. IEEE*, Vol. 51, p. 1144–1145 (August 1963).