FR-7291

Optical Waveguides and Integrated Optics Technology

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August 20, 1971

Naval Research Laboratory

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Naval Research Laboratory Washington, D. C. 20390	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

OPTICAL WAVEGUIDES AND INTEGRATED OPTICS TECHNOLOGY

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

This is an interim report; work on the problem is continuing.

5. AUTHOR(S) *(First name, middle initial, last name)*

R. A. Andrews

6. REPORT DATE August 20, 1971	7a. TOTAL NO. OF PAGES 34	7b. NO. OF REFS 61

8a. CONTRACT OR GRANT NO. NRL Problem N01-12 b. PROJECT NO. RR 002-07-41-5064 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 7291 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Dept. of the Navy (Office of Naval Research) Arlington, Virginia 22217

13. ABSTRACT

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DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Optical waveguides						
Microoptics						
Integrated optics						
Nonlinear optics						
Thin films						

DD FORM 1 NOV 65 1473 (BACK)
(PAGE 2)

Security Classification

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PROBLEM STATUS

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AUTHORIZATION

NRL Problem N01-12
Project RR 002-07-41-5064

Manuscript submitted April 14, 1971.

OPTICAL WAVEGUIDES AND INTEGRATED OPTICS TECHNOLOGY

I. INTRODUCTION

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

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

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

The purpose of this report is multifold. It is to provide an introduction to the field, indicate what has been accomplished and what the state of the art is at the present time, describe the fundamental functional units that make up integrated optical circuits, discuss applications and systems which are of potential use to the Navy, provide a discussion of advantages and disadvantages, along with a delineation of important areas of research, and finally draw conclusions about future prospects, with a time table for development. If it were not for the fact that this technology has just begun to emerge in the last three years, an analysis covering all these topics might not be practical. In the following sections an attempt has been made to cover all the relevant areas. Some aspects are covered in more or less detail than others, but in all cases references are given. The most general references are usually cited so that a given topic can be pursued in detail. An attempt has been made to include references to most of the published work in the field. However, since there is evidence of a sudden burst of interest, in this area, there is a lot of recent work which is not yet published.

The motivation for this particular report is the initiation at NRL of a research program in integrated optics and the need to point this research along relevant paths. The reader who is interested only in the potential application of this technology to the Navy needs can proceed directly to Sections IV and V, and then to the Conclusions. The material in Section III describes simple devices and techniques that have been demonstrated. An indication of what might reasonably be done in the near future is also given.

II. FUNDAMENTAL PRINCIPLES

The optical waveguide can be thought of as a slab of dielectric which confines light by multiple total internal reflections. This is illustrated in Fig. 1. The plane wave front is totally reflected alternately between the interfaces S_1 and S_2. The only requirement for this to happen is that the index of refraction n_1 of the guiding dielectric be greater than the index n_0 of the surrounding media, and that the angle of incidence θ be greater than the critical angle θ_c where

$$\theta_c = \sin^{-1}(n_0/n_1) \quad . \tag{1}$$

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

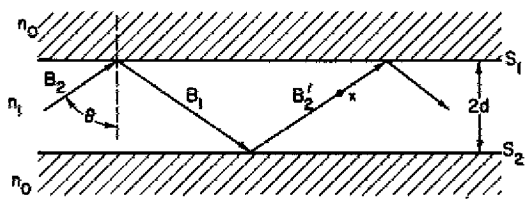


Fig. 1 - Optical waveguiding formed by a high-index dielectric layer between two lower index cladding layers. The waveguide boundaries are S_1 and S_2 and the refractive indices are n_1 and n_0, with $n_1 > n_0$. A possible light path is indicated by the rays B_2, B_1, and B_2', all of which are incident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

To obtain a more explicit description consider the geometry in Fig. 2. The direction of propagation is in the z direction, perpendicular to the plane of the figure. The waveguide dielectric layer has a width of $2d$ and an index of refraction n_1. The cladding material on each side is considered to be semi-infinite and defined by the index n_0 or n_2, where $n_1 > n_0$ and $n_1 > n_2$. Maxwell's curl equations for the electric and magnetic fields are

$$\nabla \times \mathbf{E} = -\mu_0 \dot{\mathbf{H}} \tag{2}$$

and

$$\nabla \times \mathbf{H} = \varepsilon_0 n^2 \dot{\mathbf{E}} \quad . \tag{3}$$

These give the wave equation for the electric field as

$$\nabla(\nabla \cdot \mathbf{E}) - (\nabla \cdot \nabla)\,\mathbf{E} = -\mu_0 \varepsilon_0 n^2 \ddot{\mathbf{E}} \tag{4}$$

and lead, in this case, to a solution of the form

$$\mathbf{E} = \mathbf{e}(x)\, e^{i(\omega t - \beta z)} \tag{5}$$

$$\mathbf{H} = \mathbf{h}(x)\, e^{i(\omega t - \beta z)} \tag{6}$$

where ω is the angular frequency and β is the wavevector component along the z axis or direction of propagation. Due to the geometry there is no y dependence in the problem. Hence $\partial/\partial y = 0$.

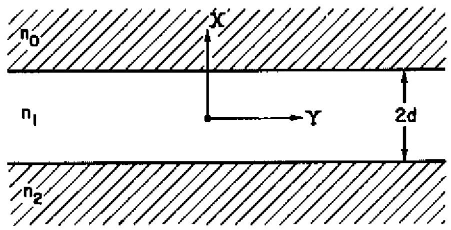


Fig. 2 - Optical waveguide geometry. The direction of propagation is along the z axis, which is perpendicular to the plane of the figure. The cladding layers have indices n_0 and n_2 such that $n_1 > n_0$ and $n_1 > n_2$.

Using Eqs. (4) and (5) to solve for **E** and assuming a transverse electric (TE) mode of propagation, then

$$e_x = e_z = 0 \tag{7}$$

and

$$\frac{d^2 e_y(x)}{dx^2} = (\beta^2 - k^2 n^2)\, e_y(x) \tag{8}$$

where $k^2 = \omega^2 \varepsilon_0 \mu_0 = (2\pi/\lambda_0)^2$ and λ_0 is the free-space wavelength of the propagating radiation. For the geometry in Fig. 2, Eq. (8) has a solution of the form

$$e_y = \left\{ \begin{array}{ll} Ae^{-\gamma_0 x}, & x > d \\ Be^{i\gamma_1 x}, & |x| \le d \\ Ce^{-\gamma_2 x}, & x < -d \end{array} \right\}. \tag{9}$$

This solution satisfies the condition that the field is trapped in the dielectric waveguide and that it goes to zero when $x \longrightarrow \pm\infty$. Substitution of Eq. (9) into Eq. (8) gives the conditions

$$\left.\begin{aligned} \beta^2 &= k^2 n_0^2 + \gamma_0^2 \\ \beta^2 &= k^2 n_1^2 - \gamma_1^2 \\ \beta^2 &= k^2 n_2^2 + \gamma_2^2 \end{aligned}\right\} . \tag{10}$$

The magnetic field **H** can be found from this solution for **E** and the curl equation (2):

$$\begin{aligned} H_x &= -\frac{\beta}{\mu_0\omega} e_y(x)\, e^{i(\omega t-\beta z)} \\ H_y &= 0 \\ H_z &= \frac{i}{\mu_0\omega}\frac{de_y(x)}{dx}\, e^{i(\omega t-\beta z)} \end{aligned} \tag{11}$$

At the boundaries $x = \pm d$, Maxwell's equations require that **H**, **E** tangential, and **D** normal be continuous. In order to satisfy the boundary conditions there must be two waves in the waveguide, one traveling up ($+x$ direction) and one traveling down (the B_1 and B_2 of Fig. 1). In this particular problem the boundary conditions imply that $e_y(x)$ and $de_y(x)/dx$ are continuous, or equivalently,

$$Ae^{-\gamma_0 d} = B_1 e^{-i\gamma_1 d} + B_2 e^{-i\gamma_1 d} \tag{12}$$

$$-\gamma_0 A e^{-\gamma_0 d} = i\gamma_1 B_1 e^{i\gamma_1 d} - i\gamma_1 B_2 e^{-i\gamma_1 d} \tag{13}$$

$$Ce^{-\gamma_2 d} = B_1 e^{-i\gamma_1 d} + B_2 e^{i\gamma_1 d} \tag{14}$$

$$\gamma_2 C e^{-\gamma_2 d} = i\gamma_1 B_1 e^{-i\gamma_1 d} - i\gamma_1 B_2 e^{-i\gamma_1 d} \tag{15}$$

Manipulating these equations gives

$$\tan 2\gamma_1 d = \frac{(\gamma_2/\gamma_1) + (\gamma_0/\gamma_1)}{1 - (\gamma_2/\gamma_1)(\gamma_0/\gamma_1)} \tag{16}$$

which can also be written as

$$2\gamma_1 d - \varphi_{12} - \varphi_{01} = m\pi \tag{17}$$

where m is any positive integer and

$$\varphi_{01} = \tan^{-1}(\gamma_0/\gamma_1) \tag{18}$$

$$\varphi_{12} = \tan^{-1}(\gamma_2/\gamma_1) \tag{19}$$

The B_2 term represents the plane wave traveling up and the B_1 term represents the plane wave traveling down, as shown in Fig. 1. As the wavefront is reflected off the boundary there is a phase shift. This can be determined from the boundary conditions, Eqs. (12)-(15). Assume for convenience that $x = 0$ at the boundary. Then for this situation only

$$A = B_1 + B_2 \tag{20}$$

and

$$-\gamma_0 A = i\gamma_1 B_1 - i\gamma_1 B_2 \tag{21}$$

Using the fact that

$$\frac{i - x}{i + x} = e^{2i \tan^{-1} x} \tag{22}$$

then Eqs. (20) and (21) give

$$B_1/B_2 = e^{2i\varphi_{01}} \tag{23}$$

where B_2 is the incident amplitude and B_1 the reflected amplitude. Similarly, at the other boundary,

$$B_2'/B_1 = e^{2i\varphi_{12}} \tag{24}$$

where B_1 is the incident amplitude and B_2' the reflected amplitude as shown in Fig. 1. Hence it is clear that $2\varphi_{01}$ and $2\varphi_{12}$ are the phase shifts upon reflection at the (0,1) and (1,2) boundaries, respectively. Equation (17) therefore represents the condition that, after two successive reflections, the wavefront is in phase with the original wavefront. In the general case Eqs. (12) and (13) give

$$B_1/B_2 = e^{i(\varphi_{01} - \varphi_{12} + m\pi)} \tag{25}$$

for any point x where $|x| \leq d$. Using this result, the solution for e_y in the region $|x| \leq d$ can be written as

$$e_y = B \cos(\gamma_1 x + \varphi) \tag{26}$$

where

$$B = 2B_2 e^{i\varphi} \tag{27}$$

and

$$\varphi = (\varphi_{01} - \varphi_{12} + m\pi)/2 \ . \tag{28}$$

This result, and Eqs. (12) and (14), give a final solution

$$e_y = \left\{ \begin{array}{lll} B \cos(\gamma_1 d + \varphi)\, e^{\gamma_0 (d-x)} , & x > d \\ B \cos(\gamma_1 x + \varphi) , & |x| \leq d \\ B \cos(-\gamma_1 d + \varphi)\, e^{\gamma_2 (d+x)} , & x < -d \end{array} \right\} \tag{29}$$

where now B is an arbitrary amplitude and γ_0, γ_1, γ_2, and β are given by Eqs. (10) and (16). In the waveguide the B_1 wave has a propagation factor

$$e^{i(\omega t+\gamma_1 x-\beta z)} = e^{i(\omega t-k'\hat{n}\cdot r)} \tag{30}$$

where $\hat{n}$ is the normal to the wavefront. Hence

$$\gamma_1 = kn_1 \cos \theta \tag{31}$$

and

$$\beta = kn_1 \sin \theta \tag{32}$$

where θ is the angle of incidence defined in Fig. 1 and n_1 is the index of refraction of the waveguide dielectric. The B_1 and B_2 waves traveling in the $-x$ and $+x$ directions, respectively, set up a standing wave pattern in the x direction.

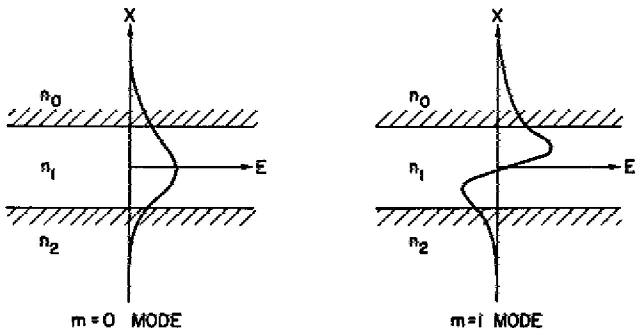


Fig. 3 - Electric field distribution in a waveguide for the lowest order TE mode ($m = 0$) and the next higher order mode ($m = 1$)

The lowest order ($m = 0$ in Eq. (17)) mode and the next to lowest order ($m = 1$) mode are shown in Fig. 3. In general, $m + 1$ determines the number of electric field extrema in the waveguide. If the waveguide were bound in the y direction then there would also be standing waves in the y direction and two integers would be used to specify the modes. Depending on the size of the waveguide and the indices, there may be a significant portion of the wave outside the waveguide in the boundary layers. This field, which decays exponentially in the x direction, is called the evanescent field and is the part of the solution (Eq. (29)) for $x > d$ and $x < -d$. γ_0 and γ_2 tend to be small — and hence an extended evanescent field — when d is very small and/or the index of refraction discontinuity at the boundary is small. The propagation factors for these waves in the x direction are found by solving Eqs. (10) and (16).

The propagation factor β along the waveguide is shown as a function of d in Fig. 4. A similarly shaped curve is obtained for β vs λ_0^{-1} with d held constant. As d becomes larger the number of modes increases and their spacing in terms of β or θ becomes closer. For the case where $n_0 \neq n_2$ there is a cutoff point or minimum value of d for which a guided wave can exist. The transverse magnetic (TM) solutions shown in Fig. 4 can be obtained in an exactly analogous manner to the TE solutions, starting with the

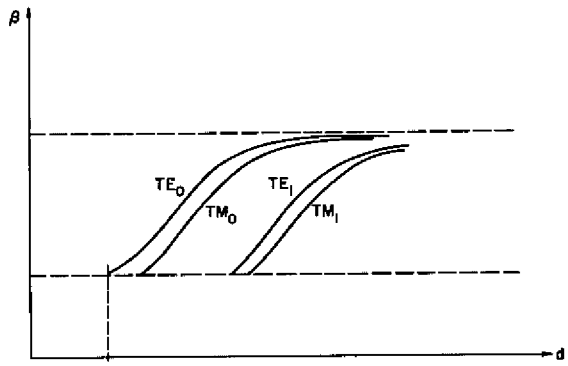


Fig. 4 – Plot of the z-axis propagation constant β versus the waveguide half-thickness d for several lowest order modes. In the case where $n_0 \neq n_2$ there is a cutoff point below which the waveguide cannot support a guided wave.

wave equation for **H** obtained from Eqs. (2) and (3), solving for $k_y(x)$, and obtaining **E** from the curl equation (3).

The above analysis is for the relatively simple case of three different isotropic dielectrics. Similar, but more complicated, analyses have been carried out for anisotropic waveguides and/or anisotropic boundary layers. There have been several analyses of this type published in the literature on optical waveguides (1-6). The theory of optical waveguides has also been used in the analysis of p-n semiconductor junctions (7-9). Much of this analysis is also very relevant to the optical waveguide problem.

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

III. FUNDAMENTAL OPTICAL WAVEGUIDE DEVICES

A. Optical Waveguides

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

From a practical consideration there are many ways to fabricate an optical waveguide. Among these are vacuum deposition (12), sputtering (12), epitaxy (13), polymerization (14), and ion bombardment (15). The technique used depends on the material involved and on whether an amorphous or crystalline film is desired. In all cases the goal is to produce a thin film of material on a substrate. This film should have low scattering and absorption losses and should have a uniform thickness. Also, surface irregularities should be very small compared to the wavelength of the propagating radiation. Vacuum deposition is suitable for solids which do not decompose on or before melting. However, in some cases it is possible to use two or more evaporation sources (which are the constituents of the desired compound) at various temperatures to obtain a stoichiometric deposition of a compound on a substrate. Solids which have components of various vapor pressures, such as glasses, cannot be evaporated but can often be sputtered to form a good optical waveguide. Epitaxy, either vapor phase, liquid phase, or chemical transport, can be used to produce single-crystal optical waveguides. As will be seen in a later discussion, the single-crystal properties are important for many devices which use such things as the electro-optic effect and nonlinear polarizability. The technology associated with the various forms of epitaxy has developed with efforts in the field of microelectronics. Many of the same techniques may prove useful in the production of micro-optics. Another technique for the production of amorphous waveguide films is the polymerization of various organic liquids. Films produced in this way tend to be very uniform and have low losses. The final method, ion bombardment, makes use of index changes due to damage caused by bombarding a surface with photons or other heavy particles. Depending on the energy of the ions, a layer of damage at some small distance beneath the surface of a solid produces a slab waveguide.

Very little work has been done to date on evaluating new materials, either amorphous or crystalline, and new methods for producing optical waveguides. As a general rule, amorphous waveguides have less losses than crystalline waveguides and are easier to produce; however, the crystalline waveguides offer more potential use. An evaluation of a waveguide usually means measuring the losses in units of decibels per centimeter (dB/cm). One method (16) is to use optical fibers in contact with the waveguide to measure the scattered light as a function of transmission distance. Table 1 gives some typical values for various materials. It is quite clear that the amorphous glass or organic films are superior to the semiconductor films. In practical applications, however, semiconductors are more useful since they are transparent in the infrared (IR) and have large nonlinear susceptibilities. Furthermore, because of the dimensions involved, the IR offers the possibility of approaching the $\lambda/10$ dimensional uniformity required more easily. Also, the IR scattering losses should be lower.

The waveguides that have been produced to date are mainly amorphous, with the exception of GaAs junctions (13, 18) using liquid epitaxy, and single-crystal GaAs (19) fabricated to optical waveguide dimensions. The reason is simple: amorphous films are easy to produce, and GaAs injection laser technology is fairly well developed. There seems to be promise in vapor phase epitaxy of various semiconductors as a means of producing optical waveguides. The problems are very formidable, however. Good epitaxial films of sufficient optical quality have not been produced to date, and films grown from liquid epitaxy (such as GaAs) are good, but control over thickness is very poor. Recent work (20) using ultrahigh vacuum and with careful substrate preparation seems to offer hope for good, well-controlled, vapor-phase-epitaxial semiconductor films.

As mentioned previously, the dimensional requirements ($\lambda/10$) are formidable. The surface of the waveguide must be smooth over dimensions on the order of several

Table 1
Energy Losses at 6328 Å in Dielectric Waveguides*

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

*Data from Ref. 14.
†Data from Ref. 17.

wavelengths. The waveguide can have a wavy surface and have uniform thickness and still have low losses, as shown in Fig. 5. A discontinuity in the surface causes the light to be scattered (21). If the light is initially propagating in a single mode, after scattering the light will propagate in many modes and some may be lost to radiation away from the waveguide. Besides surface irregularities, strains (22) may perturb the waveguide modes. This is especially true in anisotropic crystalline waveguides. Another problem encountered with epitaxial films are crystalline defects and inclusions of different crystalline structure. These are scattering sites and must therefore be eliminated by technological developments.

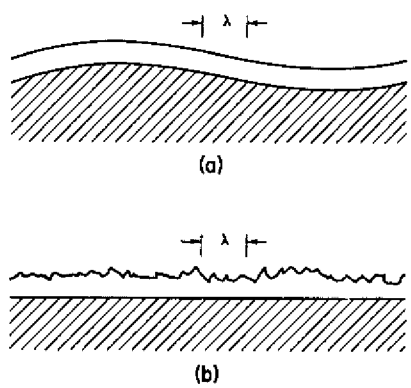


Fig. 5 – Examples of high- and low-loss irregular waveguides. Sketch (a) shows a uniformly thick but "wavy" waveguide with variations over distances large compared to λ. This waveguide has low loss. Sketch (b) shows a waveguide with thickness variations over distances small compared to λ. This waveguide has a high scattering loss.

The discussion thus far has considered slab waveguides. Everything discussed also applies to three-dimensional waveguides, with the added problem that the third dimension must also be accurate and uniform to within $\lambda/10$. One method of fabrication is the use of microphotolighographic techniques (23). With this method a dimension of 10 micron (μ) can be held easily, and 1μ seems to be a tolerance limit. This implies that λ should be in the range of 10μ in the IR for low losses. A further consideration is that these rectangular cross section waveguides have to be fabricated with bends to make practical integrated optical circuits. There are radiation losses involved with a waveguide bend (24). The tighter the radius, the larger the loss. Table 2 gives some values of R/λ where R is the radius of curvature of the guide for a loss of 0.087 dB per radian. The waveguide has index n_1 and the surrounding dielectric index is given by $n_2 = n_1(1-\Delta)$. The waveguide has a width which is the maximum value compatible with single-mode propagation in a waveguide with infinite height. The values of R are higher if the waveguide has finite height. If Δ is not greater than 0.01, then R becomes too large for practical use.

Table 2
Waveguide Radius of Curvature R for
a Loss of 0.087 dB/radian*

$\Delta = 1 - (n_2/n_1)$†	a/λ	R/λ
0.1	0.745	30
0.01	2.36	1,060
0.001	7.45	37,000

*Values from Ref. 24.
†The waveguide has an index of refraction n_1, and the surrounding dielectric has an index n_2.

A final area that must be considered is damage. Intensities on the order of $10^2 - 10^9$ W/cm^2 are easily attained due to the radiation confinement in the waveguide. Hence, it is obvious that absorption losses must be kept to an absolute minimum if these optical waveguides are to be practical.

B. Optical Elements

Two-dimensional analogs of simple passive optical elements such as lenses and prisms can be incorporated in optical waveguides. From the analysis of Section II it was found that radiation propagating in the waveguide has a propagation factor β given by Eqs. (10) and (16). β is proportional to the effective index of refraction for a particular mode of propagation and inversely proportional to the phase velocity. It is also a function of the parameters n_0, n_1, n_2, and d. Thus, for example, an increase in waveguide thickness increases β for a given mode. Hence, a section of waveguide with a change in thickness as shown in Fig. 6 represents a change in effective index. Radiation in a given mode incident on this boundary will be refracted, as shown. The thickness change is made over a distance large compared to λ in order to avoid large scattering losses. Figure 7 shows a prism and a lens constructed by the variation in waveguide width technique. The same effect can be obtained by variations in n_0, n_1, and n_2. Prisms (1) and lenses (25) have been experimentally fabricated using sputtered glass. By using sharp discontinuities, beam splitters and reflectors can also be fabricated.

With the use of absorbing material deposited on top of the waveguide, gratings, Frensel-zone lenses, and spatial filters can in principle be fabricated. Some success in this area has been reported (25).

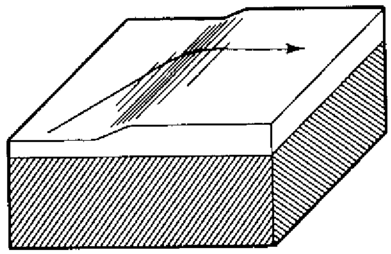
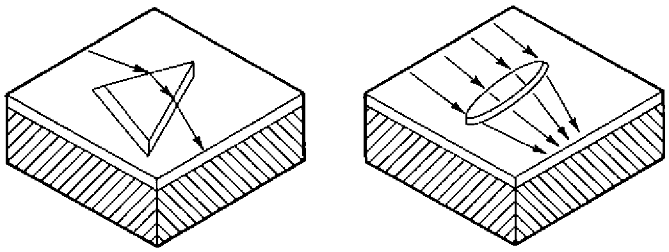


Fig. 6 - A guided wave which is refracted due to a gradual change in waveguide thickness



(a) (b)

Fig. 7 - Examples of simple waveguide optics: (a) a thin-film waveguide prism, and (b) a thin-film waveguide lens. In each case the bending of the light ray is due to a change in waveguide thickness.

C. Couplers

Propagation in an optical waveguide is associated with an evanescent field in the low-index cladding dielectric adjacent to the high-index guiding dielectric. If a second waveguide is placed in close proximity to the first the evanescent wave will interact with the modes of the second waveguide. The two waveguides now form a coupled system which must be analyzed (26, 4) as a single unit. If Φ_1 and Φ_2 are transverse modes of the isolated waveguides 1 and 2, where $\Phi_i = \psi_i e^{-i(\omega t - \beta z)}$, then when they are coupled the modes of the coupled system are symmetric and antisymmetric combinations of ψ_1 and ψ_2. That is,

$$\Phi_s = A_s(\psi_1 + \psi_2)\, e^{-i[\omega t - (\beta + \delta) z]} \tag{33}$$

and

$$\Phi_A = A_A(\psi_1 - \psi_2)\, e^{-i[\omega t - (\beta - \delta) z]} \tag{34}$$

where A_s and A_A are complex constants and δ is the shift in the propagation constant. The phase velocities for these two waves are different and are given by

$$v_s = \omega/(\beta + \delta) \sim (\omega/\beta) - (\omega\delta/\beta^2) \tag{35}$$

and

$$v_A = \omega/(\beta - \delta) \sim (\omega/\beta) + (\omega\delta/\beta^2) \; . \tag{36}$$

Thus, if initially all the optical energy is in one waveguide, i.e., $\psi = 1/2\,(\Phi_s + \Phi_A)$, then both modes are excited with equal amplitude, and as they propagate the optical energy transfers from one waveguide to the other and back due to interference effects. The energy is totally transferred in the distance it takes Φ_s and Φ_A to become out of phase by π radians. This distance is simply $\pi/(2\delta)$ where δ is a function of all the waveguide parameters (n_0, n_1, n_2, λ, d, ε, and W) as shown in Fig. 8. Hence, in principle, a waveguide coupler can be designed to couple any desired fraction of the optical energy from waveguide 1 to waveguide 2. Further, the amount of coupling can actively be varied using, for example, the electro-optic effect to vary n_0, n_1, or n_2. This idea is the basis for several patents in the fiber waveguide field (27-29). These devices have logical analogs using dielectric film waveguides. Reference 27 describes a series of devices in which light is coupled from one waveguide to another, depending on the magnitude of an electric field applied to the electro-optic medium in which the waveguides are immersed.

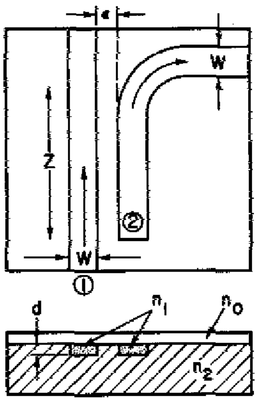


Fig. 8 - An optical waveguide directional coupler. Waveguides of thickness d and width W are coupled through their evanescent fields by adjusting their separation ε to a distance comparable to λ.

Figure 9 is an example of a shift register used in an optical logic system. Light enters through waveguide A and exists via waveguide B', C', D', or E', or a combination depending on whether an appropriate voltage is applied to electrode pairs (bb'), (cc'), etc. The medium between the waveguides is electro-optic. This device obviously works in a pulsed regime when the light source is a pulsed source of radiation. The devices in Ref. 29 are very similar, except there is the added possibility of having an optically pumped active waveguide to amplify the light.

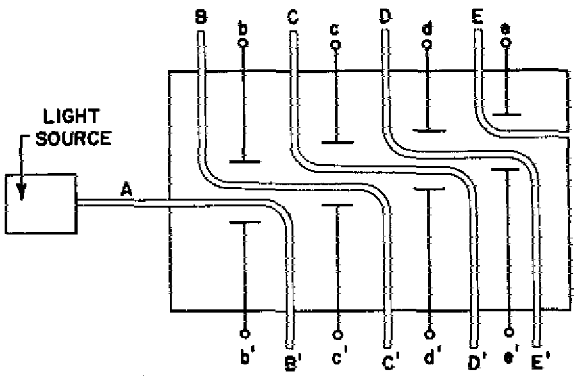


Fig. 9 - Shift register for an optical logic system. Light incident at A appears at B', C', D', or E', depending on the potential on electrode pairs (bb'), (cc'), etc.

Reference 28 describes a p-n-p semiconductor junction. Each junction acts as a dielectric waveguide and the coupling between them can be varied by adjusting the reverse bias on the junctions. Hence the basic unit is a pair of coupled waveguides. This unit can act as a switch, power divider, or amplitude modulator.

D. Thin-Film Lasers and Amplifiers

The concept of thin-film lasers or amplifiers is very simple: make an active dielectric waveguide and provide a pumping source, and possibly a resonator. The most common example is the injection laser (30, 31). The p-n junction forms a dielectric waveguide which confines the radiation in the active region of the junction. These junctions can be used as lasers or amplifiers (30). Figure 10 illustrates a junction device. Because of the high index of the semiconductor the cleaved faces have sufficient reflectance to form a laser cavity. When used as an amplifier these faces are antireflection (AR) coated. Alternately, the junction current can be kept below the threshold value for lasing and still have gain in the junction (32).

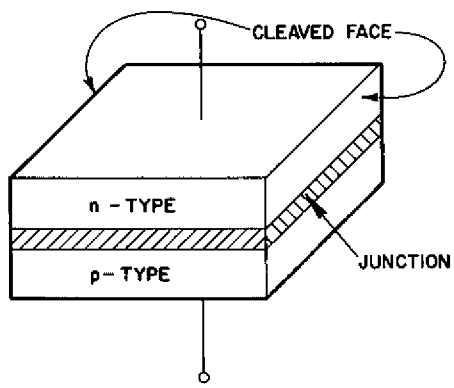


Fig. 10 - A semiconductor junction laser as an example of an optical waveguide source of radiation

Another approach to a waveguide laser source is to deposit a film of laser material and add reflectors and a pump source (33, 34). The material might be any of the usual solid-state laser materials, or even dye molecules suspended in organic waveguides. One possibility is sputtering neodymium-doped glass. The real problem is forming a resonator. A series of "scratch"-like discontinuities spaced at intervals of $\lambda/4$ is one approach, as shown in Fig. 11. Each discontinuity produces a partial reflection as discussed earlier. The reflections from successive discontinuities can be made to reinforce each other by proper design analogous to a multilayer dielectric mirror. Another alternative is to use a ring cavity configuration which eliminates the need for mirrors. This is shown in Fig. 11(b). A three-dimensional waveguide is deposited in the form of a ring and another waveguide is positioned close by to couple out a fraction of the resonator radiation.

The pumping source for a waveguide laser should be part of the thin-film device. There is no problem with an injection laser type device since the pumping is done electrically and only electrodes are required on the waveguide. Other semiconductor devices may require optical pumping. In this case such things as an electroluminescent film (33) or another injection laser may be required.

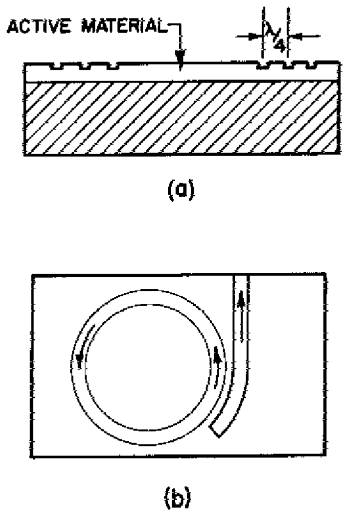


Fig. 11 - Optical waveguide laser resonators: (a) a linear resonator with reflections produced by λ/4-spaced thickness variations, and (b) a ring resonator with a closely spaced waveguide for an output coupler

Lasers have been fabricated of thin (~1 μ) platelets of CdSe (35, 36). These platelet lasers are optically pumped and can be coupled to a dielectric waveguide using the evanescent field, as with two coupled waveguides discussed previously (35). More importantly, an injection laser can be mounted in contact with the platelet to pump it transverse to laser action. A possible situation is shown in Fig. 12.

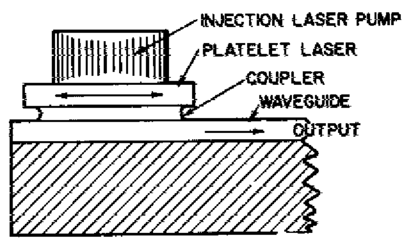


Fig. 12 - A semiconductor platelet laser source coupled to an optical waveguide. The platelet laser is pumped by an injection laser and radiation is coupled into the waveguide by evanescent field coupling through a low-index gap region (or coupler).

Laser radiation from 0.33 μ to 5.2 μ has been observed (37) from optically pumped semiconductors. In principle any of these could be made into a platelet laser and coupled to a dielectric waveguide. The serious problem is that most of these semiconductor lasers operate below room temperature.

E. Modulators

Modulation of light in a waveguide can be accomplished by modulating the source or by operating on the light external to the source. Considerable work has been done on the direct modulation of semiconductor lasers (38). The methods include amplitude modulation by variation of the injected current, pulse modulation by pulsing the injected current, pulse modulation by Q switching, pulse width modulation by amplitude modulation of mode-coupled lasers, frequency modulation by varying the injection current, and mode locking. Information rates as high as 1 billion bits per second (Gbit/sec) have been demonstrated using these techniques (38). Analogous techniques could presumably be used with the other thin-film laser devices described in the previous section.

External modulators may be classed as electro-optic, acoustooptic, and magneto-optic. The electro-optic modulators make use of phase changes in the waveguide modes due to the electric field. For example, in a waveguide of electro-optic material, or in a waveguide on an electro-optic substrate, the propagation factors for TE and TM modes vary differently with an applied electric field. If initially the optical radiation is linearly polarized with equal TE and TM components, then after passing through the modulator an appropriate relative phase shift can cause the light to be linearly polarized orthogonal to the original polarization. This is shown in Fig. 13. The analyzer blocks the light if its plane of polarization is rotated 90°. The output is an amplitude-modulated signal in response to the electrical signal driving the electro-optic waveguide. This principle is the basis for the modulators described in Ref. 39 and 40. This type of modulator has been demonstrated in GaP p-n junction (9, 41) and in GaAs epitaxial layer waveguide (18). In the latter case a half-wave voltage of 84 volts at 1.15μ using a sample 2.4 mm long was demonstrated. This is a reduction of voltage by almost a factor of 100 as compared to a comparable bulk material device. This reduction is possible because the light is confined to a waveguide with an aperture on the order of the wavelength of the light used, and diffraction spreading is eliminated (42).

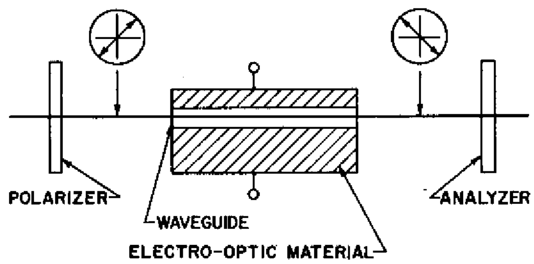


Fig. 13 - An optical waveguide light modulator. The electro-optic effect is used to vary the phase velocities of TE and TM waves, and thereby rotate the plane of polarization of the incident radiation. Addition of a polarizer-analyzer pair produces a modulator.

Another electro-optic effect characteristic of a p-n junction is the variation of the width of the depletion layer or high-index region of the junction with changes in the junction bias (9). This effect is most prominent in a reverse-biased junction. If light is reflected off the depletion layer, the light from the top interface interferes with the light from the bottom interface and an amplitude modulation is observed which is proportional to the variation in depletion layer width. Also if light is transmitted through a junction waveguide of varying width, the output will be amplitude modulated. These devices are described in Ref. 43.

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

Magnetooptic modulators (42) make use of induced optical activity instead of induced birefringence, and they require current-modulated signals instead of voltage-modulated signals as with electro-optic devices. A device of this type has not been demonstrated in optical radiation in terms of smaller magnetic fields. Also, the problem of producing a magnetic field confined to an area comparable to the device dimensions may be difficult.

F. Deflectors

Deflectors can operate either via the electro-optic (44) or acoustooptic effect (45). In the case of electro-optic deflectors, these devices are usually digital deflectors as opposed to providing a continuous scan. The digital devices work on the principle that the electro-optic effect rotates the plane of polarization of linearly polarized light in a suitable medium, and a polarizing prism such as a Rochan, Wollastan, or Thompson deflects the beam into one of two channels. The same effect is accomplished in optical waveguides using coupled waveguides, as discussed in Sect. III C. No exact analog of the digital deflector has been demonstrated in optical waveguides.

The acoustooptic deflector has the advantage of continuous deflection by electronic tuning of the acoustic frequency. The acoustic wave produces periodic index variations, which in turn deflect a portion of the optical radiation by Bragg diffraction. This process is particularly adaptable to dielectric film waveguides on a substrate. In this case, the acoustic wave is a surface wave, and the optical radiation is also on the surface of the substrate. The interaction can therefore be achieved with much less acoustic power than in the bulk case, and efficiency is improved. Waveguide devices of this sort have been analyzed (46, 47) and a particular configuration (46) is shown in Fig. 14. This device had a maximum observed deflection efficiency of 66% with an electrical input of 2.5 W, or an acoustic power of 0.18 W. There is no reason to believe that improvements cannot be made on this device.

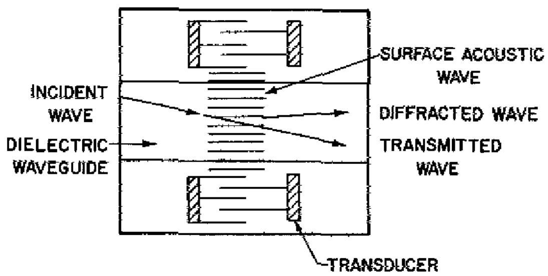


Fig. 14 - Acoustooptic deflector. The optical guided wave is Bragg scattered by the surface acoustic wave.

G. Detectors

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

H. Nonlinear Devices

The confinement of optical radiation in a waveguide and the accompanying intensity enhancement over long path lengths is attractive for potential application of nonlinear optical phenomenon. Such things as harmonic generation, unconversion, parametric oscillation, and optical mixing are possible, and conceivably at a higher efficiency than in the bulk material. The usual requirement of momentum or phase matching can be met in the waveguide by using various waveguide modes in place of the usual birefringence in bulk material. By propagating in different modes the various optical fields have a different effective index of refraction. The fact that a large birefringence is not a material requirement allows the use of many more materials, such as cubic semiconductor compounds, in the IR.

The requirement for nonlinear optical processes is for a waveguide of single crystal nonlinear material. One approach is to start with a large single crystal and cut (or cleave) a waveguide. This has been done with GaAs (19, 49). Waveguides with cross sections of $4\mu \times 10\mu$ have been fabricated. Another approach is to epitaxially grow semiconductor film waveguides. This is very difficult since the film must be near perfect optically. This in turn usually means no inclusions, large lattice irregularities, etc. Also, to observe a nonlinear effect, microtwinning must be absent.

Despite the problems, some nonlinear effects have been observed. Upconversion of $3.50\ \mu$ to $1.64\ \mu$ with a 240-mW pump at $1.117\ \mu$ was observed (49) with a quantum efficiency of 2% in a GaAs waveguide. Other mixing processes were observed in the same waveguide: $9.6\ \mu + 1.117\ \mu \rightarrow 1.26\ \mu$, and $9.6\ \mu + 1.152\ \mu \rightarrow 1.03\ \mu$. In these experiments the waveguide was held between two microscope objectives to couple the light into and out of the ends of the waveguide. This experimental situation is not appropriate for integrated optics but it is conclusive evidence that nonlinear processes can be observed in waveguides of nonbirefringent material and that these processes are efficient at low power levels.

An alternative approach to this type of effect is to use an amorphous waveguide on a single nonlinear crystal substrate. The evanescent wave will then induce a nonlinear polarization wave in the substrate. If conditions are correct, the nonlinear polarization will couple to a waveguide mode, and the result of the nonlinear parametric interaction will propagate down the waveguide. To obtain the correct conditions, the indices n_0, n_1, and n_2 and the waveguide thickness d must be adjusted so that there is a waveguide mode for each frequency involved in the interaction and the wavevectors add to zero to obtain phase matching. This type of an effect has not been observed; however, a similar effect has. The experiment in Ref. 50 describes the observation of the second harmonic of $1.06\ \mu$ radiation generation in a single-crystal ZnO substrate with the $1.06\ \mu$ radiation propagating in a ZnS film waveguide. The second harmonic was radiated by the nonlinear polarization in the form of Cerenkov radiation, and it propagates at a small angle to the waveguide in the substrate. This effect is due to the fact that the velocity of the fundamental wave in the waveguide determines the velocity of the induced polarization wave in the substrate. In this case the polarization wave at the second harmonic traveled faster than the speed of second harmonic light in the substrate.

Another potentially useful class of parametric interactions are those between surface acoustic waves and waveguide radiation. Interactions which change the polarization of the waveguide radiation with little or no frequency shift are conceivable. This type of interaction could be used for a variable frequency filter or a modulator. This is an area that needs investigation and may result in very unique devices.

I. Input and Output Couplers

If one has an optical waveguide device and a laser source that is not built into the waveguide, then the laser radiation must be coupled into the waveguide device. After a function is performed the radiation must be coupled out of the waveguide. This coupling must be done efficiently if the waveguide device is to have any advantage over a similar bulk device. Several schemes have been proposed and tried. These are listed in Table 3 along with the theoretical and the observed coupling efficiencies for a single lowest-order-mode laser beam. It is obvious that high efficiencies are possible. The merits and relative advantages and disadvantages of each of these schemes must be discussed separately.

The most obvious way to couple light into a waveguide is to focus it down on to the end of the waveguide. This is illustrated in Fig. 15(a) and it has been used by many

Table 3
Input and Output Optical Waveguide Couplers

Type of Coupling	Efficiency	
	Theoretical	Observed
1. Direct focus on end of waveguide	>90%	*
2. Direct focus on end of terminated waveguide	90 - 97% (Ref. 51)	NM†
3. Prism-film coupler	~81% (Refs. 6, 53)	80% (Ref. 57)
4. Grating coupler	—	40% (Ref. 58)
5. Acoustic wave coupler	—	NM
6. Holographic coupler	—	71% (Ref. 59)

*Depends on waveguide preparation (see text).
†NM - not measured.

people (3, 13, 15, 18, 19). Ideally one can couple greater than 90% of the optical radiation into the waveguide in this manner if the end surface A of the waveguie is flat (to $\sim\lambda/100$). Obviously this cannot be done with evaporated or sputtered waveguides which run to the edge of the substrate. Further, it is not possible to polish the end of the substrate and waveguide since differences in hardness will erode away one material much more than the other. If the waveguide is not sandwiched between two substrates, then the edge of the substrates and the waveguide will become rounded. This approach is possible where the waveguide or substrate-waveguide combination can be cleaved as in the case of GaAs (13, 18, 19). This approach can also be used if the waveguide is formed between two substrates (3) or formed inside a substrate (15), and the sandwich is carefully polished. It is doubtful, however, whether the 90% efficiency can be obtained with a polished surface.

The clear advantage of focusing as a coupling scheme is the resultant high maximum efficiency. The disadvantage is the difficulty of alignment which requires micromanipulation of the waveguide under a microscope objective. Also, the bulkiness of the coupler tends to defeat the advantages of the microoptics.

A variation of this approach, which may help in some cases, is to terminate the waveguide before the edge of the substrate, as shown in Fig. 15(b). This method is also capable of greater than 90% efficiency (51). In this technique the light is incident from below the substrate. The waveguide must be prepared so that it penetrates the substrate. This can be done, for example, by sputter etching the substrate before deposition of the waveguide material. Also, a mask could be formed on the substrate, followed by a diffusion or ion bombardment process (33, 15). Waveguides of this type have not been fabricated and evaluated, and hence no data is available on an application of this coupling scheme. It obviously has the same general advantages and disadvantages of the direct end-of-guide coupler. It has the further advantage that it can be used with a larger class of waveguides. However, since no data is available on the quality of the surface A, it is hard to say what the actual efficiency might be.

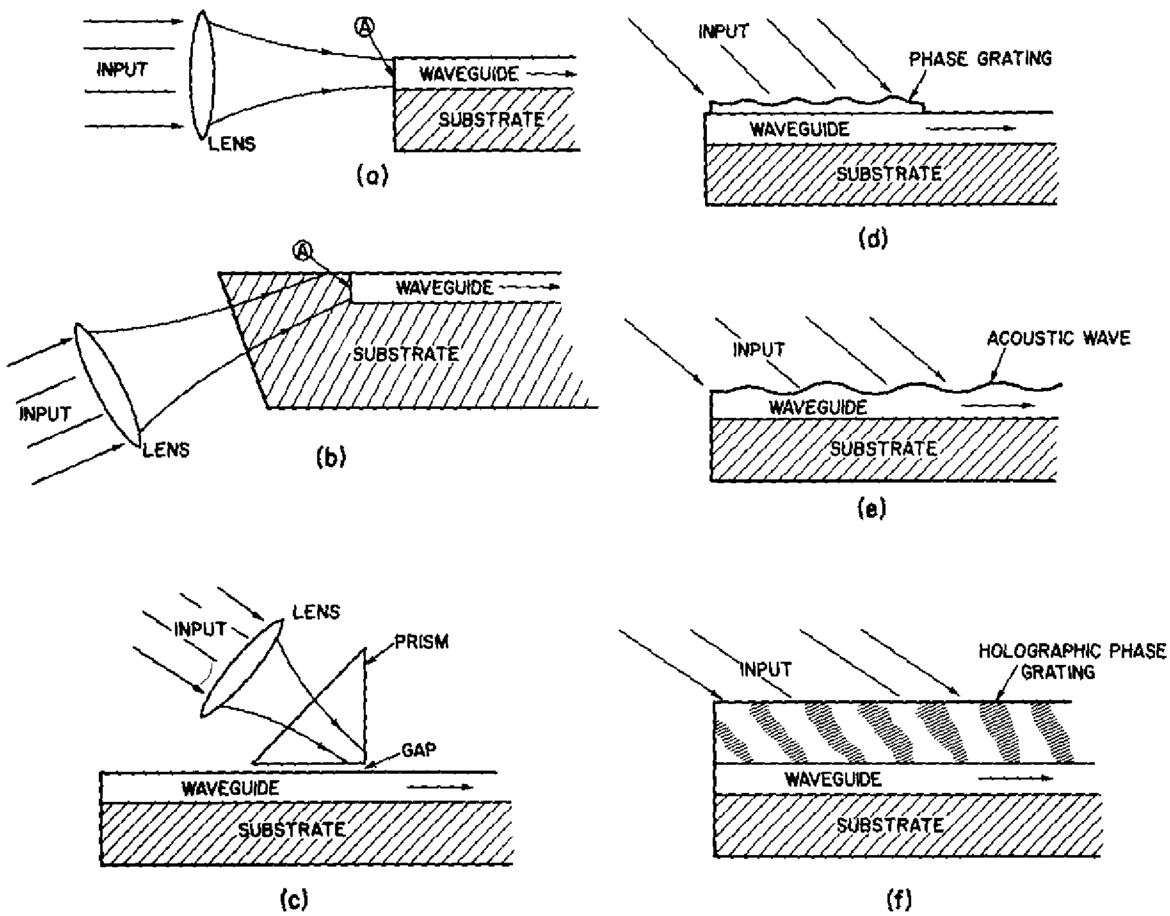


Fig. 15 - Input and output couplers: (a) direct coupling into the end of the waveguide, (b) coupling into a terminated waveguide, (c) prism coupler which uses evanescent wave coupling, (d) grating coupler, (e) grating coupler using an acoustic surface wave to produce the grating, and (f) grating coupler which uses a holographically produced phase grating.

A third coupling scheme is to use the evanescent wave from a totally reflecting interface, as shown in Fig. 15(c). Here the total internal reflection takes place in a prism and the evanescent field penetrates into the waveguide through the gap. Depending on the angle of incidence of the incoming light, the propagation factor of the evanescent wave along the waveguide direction will vary. If it happens to coincide with the propagation factor for a waveguide mode at that frequency, then light will be coupled into the waveguide. The reverse can also happen; if light is propagating in the waveguide it can couple out via a prism in close proximity. Hence for efficient coupling from the prism to the waveguide, the prism is truncated (equivalently, the focal spot is moved to the edge of the prism as shown) after the maximum possible optical radiation is coupled into the waveguide. Hence, the right-angle prism is used. The geometry is simply reversed for an output coupler.

This type of coupler has been theoretically investigated (52-55) and experimentally checked by many authoris (12, 53, 56, 57). This technique has relatively high efficiency but has the disadvantage of being bulky. Further, if narrow three-dimensional (3D) waveguides are used in the microoptics, its efficiency may decrease since tighter focusing will be required (51) to match the width of the 3D waveguide.

A fourth type of coupling makes use of a phase grating (58) and is shown in Fig. 15(d). In this technique a phase grating is produced directly on the waveguide surface by developing a photoresist which has been exposed to an appropriate interference pattern. The light transmitted through the grating establishes a polarization wave on the waveguide surface. This was has a propagation factor along the waveguide which is dependent on the angle of incidence of the incoming radiation, the periodicity of the grating, and the depth of modulation of the grating. For a fixed grating, variation of the angle of incidence allows the propagation factor of the above polarization wave to match that of a waveguide mode, and light is coupled into the waveguide. Similarly, light propagating in the waveguide is coupled out by the grating.

No theoretical study has been made of this coupler to indicate what the maximum coupling efficiency can be. Based on the experimental values available, it has relatively low efficiency. It does have the advantage, however, of being very adaptable in size to microoptics.

The acoustic wave coupler (47) and the holographic coupler (59) are based on the same idea as the grating coupler, but offer different techniques of producing the grating. In the former case the acoustic wave produces a surface (or waveguide wall) modulation. In the later case the grating is thick (4-μ thick with $d = 0.3$ μ) and it is produced by holographic techniques. This case is better than the thin grating since it suppresses losses due to unwanted grating orders. The relative advantages of these two schemes are the same as those of the grating coupler.

IV. SYSTEMS AND APPLICATIONS

A. General Considerations

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

a. Size. Optical waveguides have cross-sectional dimensions on the order of the wavelength of the light being guided. An integrated optical circuit can be fabricated as a thin dielectric film or films on a dielectric substrate in a manner very analogous to microelectronic circuits.

b. Weight. With the reduction in size, weight is reduced proportionately.

c. Cost. Once the technology is developed, the cost of a microoptical circuit would be a small fraction of the cost of conventional optics with the required polishing, coating, and mounting.

d. Alignment. A microoptical integrated circuit has fixed alignment and is easily isolated from the effects of vibration, acceleration, and temperature.

e. Service. Repair of microoptics is reduced to a simple replacement process.

f. Efficiency. In many cases confinement of the optical energy to a very thin layer with resultant high intensities permits a more efficient optical interaction. This is the case with acoustooptic and nonlinear parametric interactions. Also, the size of micro-optics is appropriate for ultrahigh-frequency modulators and optical data processors.

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

B. Communications

At the present time there is no practical optical communications systems of any type in existence (60). The answers to the question "Why optics?" are essentially (a) extremely large bandwidth, and therefore high data rates, (b) an ultralarge spectral range, (c) narrow optical beams with essentially no side lobes, (d) energy confinement for secret communication links and the elimination of clutter, (e) small terminals, antennas, and equipment in general, and (f) transmitters, receivers, and transmission line are free from the problems of electromagnetic interference.

There are counter arguments against optics which are based on the major problem areas. They are (a) atmospheric transmission losses, (b) economics, (c) pointing problems, (d) detector bandwidth at 10 μ, and (e) absence of existing ultrahigh-data-rate modulators. Integrated optics offers potential solutions to many of these arguments. Atmospheric transmission losses can be reduced by using a short transmission path, or by using optical waveguide data links. The economics of integrated optics has already been pointed out. The pointing problem requires sophisticated optics to scan the field of view, lock on to the signal, and point the transmitter. The size and weight limitation of the extra complex system can be overcome with an integrated optical system. The detector technology is constantly improving (48) and high-frequency modulation is easier to obtain in a waveguide device, as has already been discussed. Hence, some possible practical applications of integrated optical systems might be as follows:

a. Ship-to-ship, ship-to-shore, and man-to-man secure short-range atmospheric path communication. A possible system is shown in Fig. 16. In this system the input is incident on an array of photodiode detectors, the position depending on the direction of the incident signal. Depending on where the signal is sensed on the array, the output beam is directed by an XY scanner to match the direction of the incident signal. The scanner, modulator, and laser source form an integrated optical circuit. This system could be made small, lightweight, efficient, rugged, and relatively inexpensive.

b. Satellite-to-satellite communication. This type of communication can use a similar system. It would be lightweight, efficient, and extremely broadband.

c. Onboard ship and aircraft communications. Optical waveguides offer high data rates, lightweight, large bandwidth, and freedom from electromagnetic interference (EMI). The waveguides could well be used for communication links between aircraft systems or shipboard systems. Integrated optical systems can provide an interface between the fiber waveguides and electronic systems.

d. Repeater. Any optical communications system which uses fiber waveguides may require repeaters. These devices detect and retransmit a signal along extended fiber waveguides. They are placed at intervals along the transmission waveguide lines to prevent loss of the signal due to attenuation. Obviously, if they are to be incorporated

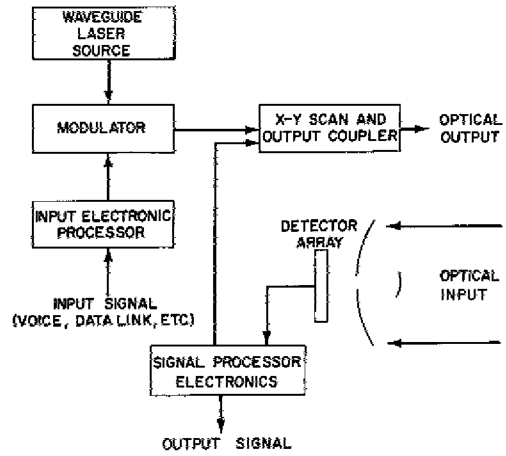


Fig. 16 - Possible short-range optical communications system. Much of this systems, which includes a pointing and lock-in capability, can be made as an optical integrated circuit.

in the fiber waveguide lines, they must be small, light weight, and efficient. A typical repeater might be an integrated optical circuit consisting of a fiber-to-rectangular-waveguide coupler, detector, amplifier, laser modulator, and rectangular waveguide/fiber waveguide coupler. This is a basic device which any medium or long-distance optical communications system will require.

C. Display

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

D. Computers

Optical computers with complete optical logic systems do not seem to offer any real advantage over conventional integrated circuit systems at the present time (61). The real future of optics in relation to computers lies in optical memories, computer interconnections, and input and output areas. Optical memories need an interface between them and the conventional integrated circuits. This can be provided by integrated optics in order to maintain compactness, light weight, and small size. Communications between computers, or between parts of a computer, require high data capability. Again this can be effectively provided by optical waveguides and the integrated optic interface to the electronics. Computer input eventually will require optical scanning of printed pages and/or pictures. The basic principal of operation is character or scene recognition via Fourier optics and optical data processing. The Fourier transform of the image of a character or a scene is sequentially compared with a collection of Fourier-transformed images of known characters and/or scenes. Practically, this can mean very complex systems. Fourier optics can be implemented in optical waveguides (3), and conceivably the entire system can be made into an integrated optical system.

V. DISCUSSION

In a manner analogous to electronics and integrated circuits, integrated optics can be conceived for almost any optical system. Whether the application is practical or not depends on the system requirements of size, weight, etc. The concept of mircooptics is well established, and many optical components and devices have been demonstrated in optical waveguide form. However, it is also very evident that there are many very difficult technological problems to be solved before all the advantages of microoptics can be realized. The extent of these problems cannot be overemphasized. The main areas that need work are as follows:

a. Low-loss film waveguides, both amorphous and crystalline. Techniques for producing amorphous films must be improved to reduce scattering losses and absorption and to provide controllable uniform thickness films. The relative merits of such processes as sputtering, polymerization, and ion implantation must be evaluated. Waveguides must be produced which can tolerate the high peak intensities (approaching 1 GW/cm^2) which make waveguide devices very attractive. In the case of crystalline waveguides, epitaxy of optical quality with semiconductors offers great potential for waveguide devices. However, the problem is extremely difficult. Epitaxial films must be single crystal over path lengths of 1 cm and be free of microtwinning and light scattering defects in the lattice. The advantages of the IR and longer wavelengths, as far as dimensional tolerances and semiconductor materials, are offset by the relative difficulty of producing high-quality, thick epitaxial films.

b. Dimensional control on waveguide and waveguide optics. Photolithography has a dimensional tolerance of about 1 μ. Techniques must be devised which can define a waveguide to a very minimum of $\lambda/10$ and also control waveguide thickness contours to the same tolerances.

c. Thin-film laser sources. The technology for producing laser sources adaptable to microoptics must be developed. Injection lasers are one possibility, and optically pumped semiconductor platelet lasers are another. Sources are needed which operate efficiently throughout the IR spectrum at room temperature.

d. Waveguide reflectors. It is very desirable to produce an engineered reflector in an optical waveguide by reinforced reflections analogous to a multilayer dielectric film. One approach is to produce precisely spaced grooves in one side of the waveguide (28). The exact techniques are still unknown. This capability is necessary in order to produce resonant cavities with the waveguide.

e. Thin-film waveguide laser sources. It is essential that laser sources be developed that are compatible with optical waveguides in size, weight, efficiency, etc. Semiconductor lasers offer the greatest promise as far as size, efficiency, and wavelength are concerned. Most semiconductors have not been made into room-temperature injection lasers, however. This means that optical pumping is the most probable approach. Other injection lasers or electroluminescent materials are possibilities for pumping.

f. Thin-film waveguide/fiber waveguide couplers. Optical fiber waveguides have been developed to the point where they have low enough losses to be used as transmission lines. Microoptics or integrated optical circuits are best suited to thin-film waveguide circuits for considerations of size and ease of fabrication. It is very important that a simple, easily fabricated, and efficient coupler be devised to join them.

g. Active waveguide devices. Techniques for efficient use of nonlinear parametric effects in waveguides must be devised. Effects such as frequency doubling, mixing, upconversion, and parametric oscillation could be very useful in integrated optics. The first problem is single-crystal nonlinear waveguides. A possible alternative to this that should be investigated is amorphous films on nonlinear single-crystal substrates. Other problems involve integration of the pump source, nonlinear material, reflectors, etc., into a single microoptical device. Besides the parametric effects, electrooptical and acoustooptical devices must be pursued for greater efficiency and versatility.

The above seven areas are just what appears obvious today. Any one of these problems could represent a research program, and others could appear as the technology advances.

It is evident from the discussion in Section III that, as far as the state of the art is concerned, modulation, deflection, simple optics, thin-film lasers, etc., have been demonstrated to be possible. In each case only a feasibility has been demonstrated by a particular technique. From what has been done, as much as possible has been inferred. The fact is that no really practical devices have been demonstrated. No integrated optical circuit has been constructed. It is equally evident from the discussion, however, that the possibilities and the potential of this technology are great indeed. The potential is great enough to offset the very formidable problems.

A reasonable timetable for the development of this technology could well be as follows:

2-5 years — single function devices, particularly fast and efficient modulation.

5-10 years — practical integrated optical circuits.

5-10 years — sophisticated single-function devices based on nonlinear parametric effects.

This projection is based, of course, on the assumption that a sizable effort will continue in the area and that the effort will grow as significant progress is made. This seems reasonable considering the number of organizations* that are expressing interest in this technology and initiating research now.

VI. CONCLUSIONS

Optical waveguides and integrated optics technology is in its infancy (no more than about 2 years old). Some theoretical work has been done, and preliminary experimental work has successfully demonstrated the feasibility of several simple optical waveguide devices. More and more interest is developing in the field, and many laboratories are beginning programs. There is no doubt that the problems that must be solved are quite formidable; however, they do not seem impossible. The real impetus behind the growing interest in microoptics is the great potential involved with successful applications — small size light weight, increased efficiency, elimination of EMI, etc. In the area of nonlinear optics many new semiconductor materials can be used with this technology. A real problem is the fabrication of waveguides of dimensions on the order of λ and smooth to the order of at least $\lambda/10$. This limitation in all probability means that the first really successful devices will be in the IR. Semiconductors are readily available, and there is a large semiconductor technology from which to build.

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*Bell Labs, IBM, Allied Chemical, North American Rockwell, Perkin-Elmer, Wheeler Labs, Stanford Univ., Univ. of Washington, California Inst. of Technology, Washington Univ., Univ. of California (Berkeley), Univ. of Illinois, Wright-Patterson AFB, Naval Electronics Laboratory Center, and NRL.

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

This report must conclude that microoptic technology should be pursued by the Navy and that there is sufficient potential for Navy application to warrant its support. This technology will grow from support outside the military, notably from optical communications research at Bell Labs.

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