Integrated optics

Improved stability and efficiency, obtained by miniaturizing optical components and mounting them on a common substrate, will benefit the communications field and other areas of technology.

Esther M. Conwell

The appearance of "Integrated Optics: An Introduction" by Stewart E. Miller in the September 1969 *Bell System Technical Journal* signalled the birth of an activity that now occupies thousands of researchers. Bell Labs, among others, had been concerned with optical communications for some time, encouraged in this activity by the advent of the laser. Miller pointed out that the then typical optical telephone repeater, involving a laser, modulator, detector, lenses, and so on, spread out on an optical bench, was a form of extremely short-range radio communication and as such suffered from a number of difficulties. The apparatus was sensitive to ambient temperature gradients, to temperature changes, to mechanical vibrations of the separately mounted parts. The elegant solution to these problems proposed by Miller was to combine the separate components on the same substrate or chip, connecting them by miniature transmission lines or waveguides. Because the size of the components need only be of the order of the wavelength of light in one, and possibly two, dimensions, the substrate could be quite small—centimeters or less. He proposed calling such an assembly of components an "integrated optical circuit," in view of its analogy to the assembly of electrical components on an integrated circuit chip.

Although Miller's emphasis and that of most of the ensuing work has been on communications, it does not take much vision to realize that this type of treatment might benefit many optical systems other than those used in communications. In addition, as will be detailed subsequently, the fallout of this work should include important applications to spectroscopy and other studies of thin films.

As the term is currently used, "integrated optics" encompasses many areas. It includes guided-wave optics, or, if you like, the use of microwave techniques at optical frequencies to perform such functions as transmission, modulation, switching, mixing and upconversion. All sorts of optical and electro-optical techniques are brought together to achieve these functions. Integrated optics involves miniaturization of components such as lasers, modulators, detectors, and so on. This is a necessary step before integration can take place, although, of course, in some cases achieving the miniaturized component may be a useful end in itself. Finally, it does involve integration of different optical functions, and ultimately perhaps also different electrical functions, on the same substrate.

In long-distance transmission it is clearly desirable to use low-loss glass-fiber guides of the type discussed in the article in this issue of PHYSICS TODAY by Alan Chynoweth. For short distances, however, such as are required to connect one component of an integrated optical circuit to another, it is preferable to use guides with planar or rectangular geometry. These are easier to fabricate and have simpler field patterns. As will be seen, such guides also form the basis for most components in integrated optics. We therefore begin our discussion with a description of these waveguides. The source of the guided waves, at this evolutionary stage, is usually an external laser. In the case of a multimode glass fiber it is quite satisfactory to simply butt the laser or LED (light-emitting diode) up against the fiber, or to focus its light on the end of the fiber. It is much more difficult to get the laser beam efficiently into a planar or rectangular guide by these techniques, because the beam width is generally much larger than the confining dimension (or dimensions) of the guide. We devote a section to the methods designed for efficient coupling of a laser beam into a waveguide. Sections on modulators and switches, devices based on periodic waveguides, detectors and miscellaneous components follow. Lasers and LED sources are for the most part covered in the article by Henry Kressel and his colleagues, although we shall mention some developments with peculiarly "integrated optics" flavor. We conclude with a discussion of the present status of integration and a view of the future.

The theory of the basic components—waveguides, couplers, switches, and so on—has numerous analogs in many fields of physics. We shall point out many of these as we go along. To supplement our necessarily brief discussion we include a bibliography of recent review articles. Where possible, we have left it to the bibliography also to provide references to (and credit for) the original work because it is not possible to do this thoroughly in these few pages.

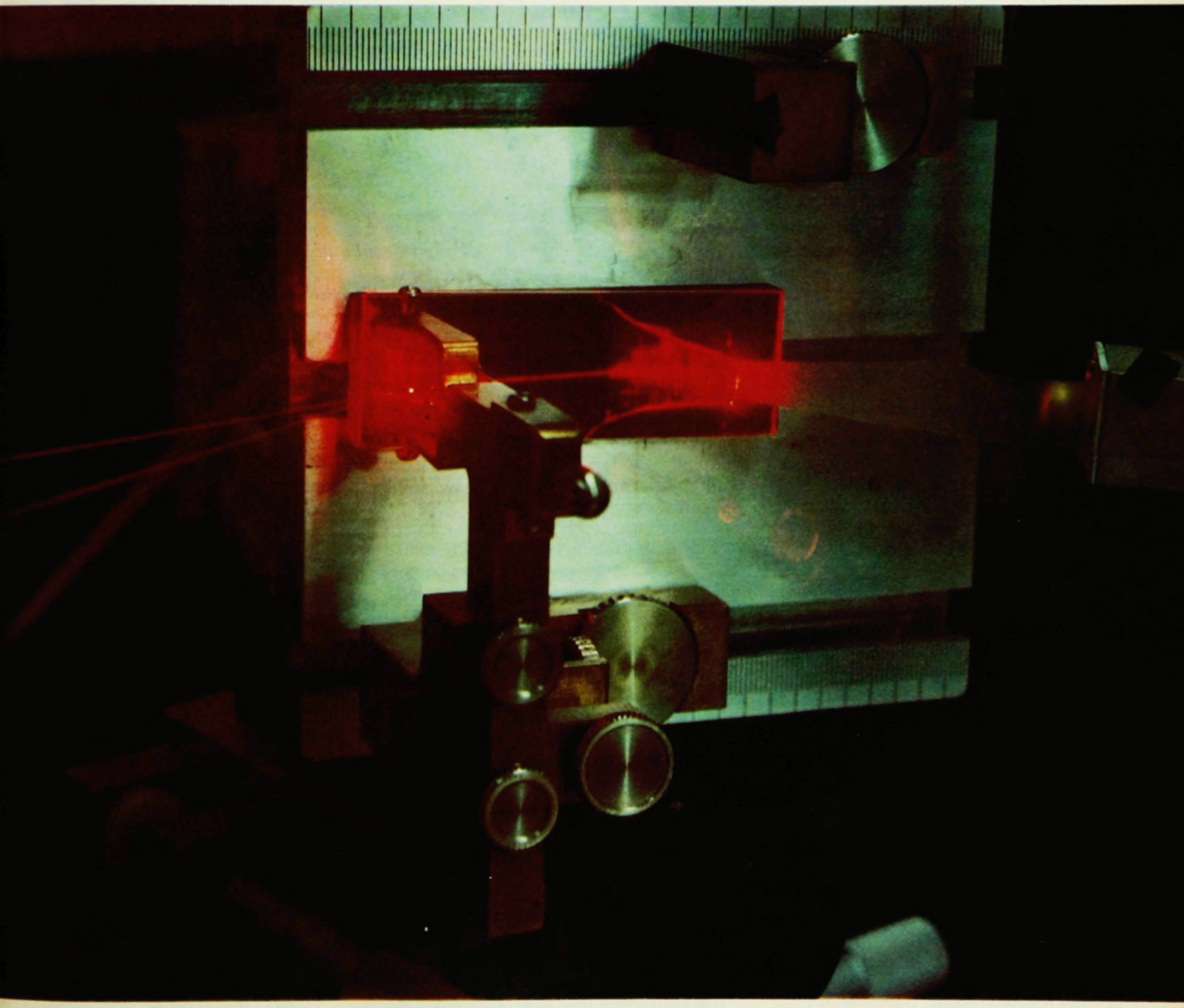
Waveguides

Waveguides may be constructed so as to confine the light in one dimension or in two. The former case will be considered first, since it is much easier to analyze.

The simplest guide of the one-dimensional confinement type has a sandwich structure, with the center of the sandwich a thin film with height of the order of the light wavelength. The outer layers of the sandwich are conveniently referred to individually as "substrate" and "cover"

A guided wave in an eight-micron-thick film of Lexan (polycarbonate). At the left, where the wave is coupled in, through a prism, from a helium–neon laser, the film is attached to a glass substrate. The bend in the guided light occurs where the film has been pulled away from the substrate, thus showing the guided light following the film. The end of the light track coincides with the end of the Lexan film. (After J. Maher, Xerox Webster Research Center, Webster, N.Y. Figure is printed by permission of Xerox.) Figure 1

Lightwave communications



(or "superstrate") and collectively as the "cladding." All three layers should have low absorption for the propagating light and, for reasons that will become clear subsequently, the dielectric constant of the film must be positive and larger than those of the cladding materials. Air is the most usual cover. The thin films have been made of a large variety of materials and by a variety of fabrication techniques. They include sputtered glasses, sputtered Ta_2O_5, sputtered and epitaxial ZnO, epitaxial GaAs, epitaxial garnets, sputtered and epitaxial $LiNbO_3$, nitrobenzene liquid, nematic liquid crystals and a number of other organics and polymers.[1,2,3] An example is shown in figure 1. Planar guides have also been formed by ion bombardment, which creates a thin layer of higher index at the top of a bulk sample, the remainder then acting as substrate. This technique has been particularly useful for forming guides in GaAs where ion bombardment raises the dielectric constant to a depth of the ion range by providing traps that remove free carriers.[3]

To obtain a detailed description of the guided waves we turn to the wave equations for the electric and magnetic fields. Taking the magnetic permeability equal to unity, we write for the former[4]

$$\nabla^2 \mathbf{E} = \frac{\epsilon}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} \qquad (1)$$

For specificity we choose the x direction of our coordinate system as the direction in which the waves travel and the z direction as the one in which they are confined. We may then consider the sandwich infinite in the y direction, neglect the y dependence of the fields and take our solutions as plane waves, which may be written

$$\mathbf{E} = \mathbf{e}F(z)\exp[i(k_x x - \omega t)] \qquad (2)$$

where $F(z)$ represents the amplitude of the field and $\mathbf{e}$ its direction, k_x the propagation vector and ω the angular frequency. A similar equation may be written for $\mathbf{H}$. For an isotropic medium or one with cubic symmetry, it turns out that electric and magnetic field components separate into two independent groups[4]

$$\begin{matrix} E_y, H_x, H_z & \text{TE} \\ H_y, E_x, E_z & \text{TM} \end{matrix} \qquad (3)$$

As indicated, solutions involving the first set of three are called TE modes, those involving the second set of three, TM modes. Separation into TE and TM modes may also be made for waves traveling in appropriate directions in lower symmetry media, such as uniaxial crystals ($LiNbO_3$, for example). The properties of TE and TM modes are overall quite similar and in what follows we shall generally speak of TE modes for specificity.

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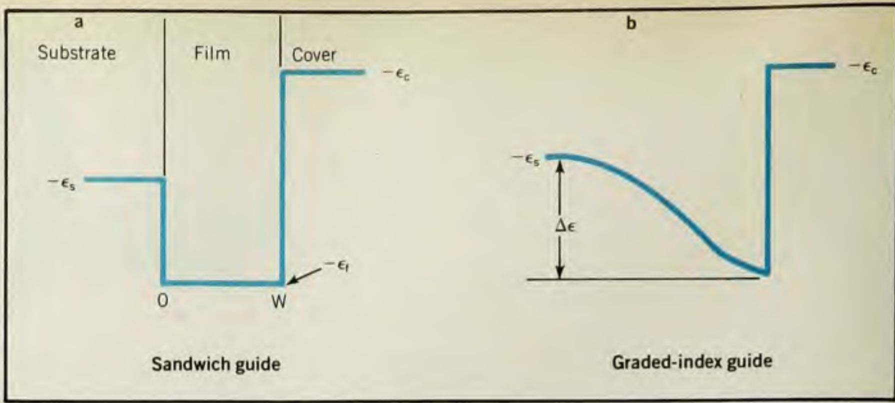

Variation of dielectric constant, ϵ, across the width of a sandwich guide (a) and a graded-index guide (b). The sandwich guide is made up of layers, the center of the sandwich being a thin film with thickness of the order of the light wavelength. The graded-index guide can be constructed by creating a thin layer of higher refractive index at the surface of a suitable single crystal or amorphous material by diffusion or by ion exchange. Figure 2

For TE modes, using equation 2, we may write the wave equation

$$\frac{d^2F}{dz^2} + k_0^2\left(-\frac{k_x^2}{k_0^2} + \epsilon(z)\right)F = 0, \qquad k_0 \equiv \omega/c \qquad (4)$$

Compare this with the one-dimensional Schrödinger equation[5]

$$\frac{d^2\psi}{dz^2} + \frac{2m}{\hbar^2}\left(E - V(z)\right)\psi = 0 \qquad (5)$$

It is clear that equation 5 is identical in form with equation 4 if $-\epsilon(z)$ is taken as "the potential" and $-k_x^2/k_0^2$ the eigenvalue. A plot of $-\epsilon(z)$ versus z for a typical sandwich guide is shown in figure 2. Because the requirement of continuity of tangential $\mathbf{E}$ and $\mathbf{H}$ at the boundaries $z = 0$ and W is, for TE modes, equivalent to the requirement of continuity of F and dF/dz at these boundaries, the problem of determining the TE modes in a sandwich guide is precisely that of determining the eigenfunctions for a particle in a square well. (For TM modes there is a slight difference because the boundary conditions are continuity of F and of $(1/\epsilon)dF/dz$.) The only difference from the usual quantum-mechanical problem is that the two sides of the well are generally of different heights. The guided modes correspond to the eigenfunctions of the particle bound in the well, decaying exponentially for $z > W$ and $z < 0$. We know then that the sandwich guide may have a number of modes, each characterized by its own value of k_x, the number being larger the larger W and the larger the difference between ϵ_f and ϵ_s ("well depth"). The modes may be numbered $m = 0, 1, 2, \ldots$, according to the number of zeroes they possess, the $m = 0$ mode having the largest k_x, $k_x^{(0)}$, $m = 1$ the next largest, $k_x^{(1)}$, and so on. Some typical modes are shown in figure 3a. A guide that will support only the $m = 0$ mode, called a "single-mode" guide, is particularly useful for some applications.

It is easily seen that there are limits to the possible values of k_x for guided modes. If equation 4 is to have an oscillatory solution inside the film, where $\epsilon(z) = \epsilon_f$, then $\epsilon_f > k_x^2/k_0^2$. If the solution is to decay exponentially in the cladding, $(k_x^2/k_0^2) > \epsilon_s, \epsilon_c$. Combining these two inequalities and using the fact that the index of refraction, n, is the square root of ϵ, we may write

$$n_f\omega/c > k_x > n_s\omega/c \qquad (6)$$

where we have assumed, as is generally the case, $n_s > n_c$. Solutions to equation 4 exist also for $k_x < n_s\omega/c$. They are oscillatory in the substrate, or both in the substrate and cover, and are called "radiation" modes.[1,6]

For many purposes it is useful to look at the guided modes from a different point of view, involving ray optics. In figure 3 the modes are shown as standing waves in the z direction. Inside the film their variation may be represented by $A_f\cos(k_z z - \phi_0)$, where, to satisfy the wave equation,

$$k_z = (k_0^2\epsilon_f - k_x^2)^{1/2} \qquad (7)$$

and A_f and ϕ_0 are determined from the boundary conditions. The standing wave could just as well be decomposed into two progressing waves, with wave vectors $k_x \pm k_z$, respectively, as indicated in figure 4. F in the film would then be given by

$$F_f = A_f\{e^{-i\phi_0}e^{ik_z z} + e^{i\phi_0}e^{-ik_z z}\} \qquad W \geq z \geq 0 \qquad (8)$$

To represent the guided modes in the cladding we take exponentially decaying F's

$$F_c = A_c e^{-p_c(z-W)} \qquad z > W \qquad (9)$$

and

$$F_s = A_s e^{p_s z} \qquad z < 0 \qquad (10)$$

where to satisfy equation 4

$$p_c = (k_x^2 - k_0^2\epsilon_c)^{1/2}, \quad p_s = (k_x^2 - k_0^2\epsilon_s)^{1/2} \qquad (11)$$

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and the A's are to be determined from the boundary conditions. From a ray-optic point of view, the progressing waves hit the walls of the guide repeatedly, undergoing total internal reflection each time. Upon each reflection the amplitude does not change but there is a change in phase, which we may take as $-2\phi_0$ for reflection at $z = 0$, $-2\phi_W$ for reflection at $z = W$. The magnitude of ϕ_0 may be determined from the continuity requirements on F and dF/dz (that is, on, E_y and H_x) at $z = 0$. This leads to

$$\tan\phi_0 = p_s/k_z \qquad (12)$$

Similarly, from the continuity requirements at $z = W$ it must be true that

$$\tan\phi_W = p_c/k_z \qquad (13)$$

However, if we treat the situation at $z = W$ formally, using equations 8 and 9 and writing down the conditions for equality of F and dF/dz at $z = W$, we get

$$\tan(k_z W - \phi_0) = p_c/k_z \qquad (14)$$

Clearly, compatibility of equations 13 and 14 requires that

$$k_z W - \phi_0 - \phi_W = m\pi, \quad m = 0, 1, 2, \ldots \qquad (15)$$

Equation 15, the dispersion relation for the guided modes, is called the "waveguiding condition." It is readily found that m must be identified as the mode number.

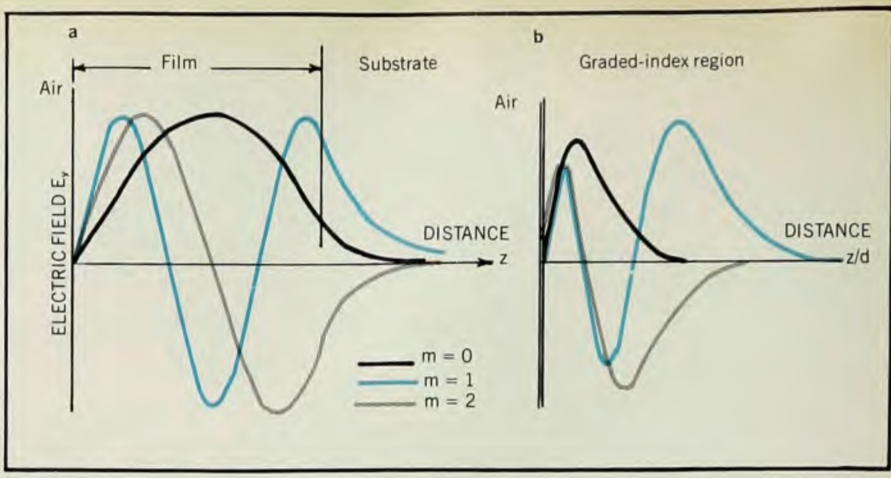
If we multiply equation 15 through by the factor 2, we can see that it has a simple physical interpretation. Following the exposition of P. K. Tien,[6] we consider an observer who moves synchronously with the wave in the x direction. What he sees is the pair of plane waves $e^{\pm ik_z z}$ folding back and forth. For them to represent a guide mode, they must interfere constructively; in other words the total phase change in one round trip must be an integer, m, times 2π. Because $-2\phi_0$ and $-2\phi_W$ represent the phase changes on reflection, and $-2k_z W$ the phase change due to the path length in one round trip, equation 15 expresses precisely the condition for constructive interference.

To complete the description of the modes from the ray point of view, each mode is characterized by a bounce angle θ_m, indicated in figure 4. This angle is largest for the fundamental and gets successively smaller with increasing mode number.

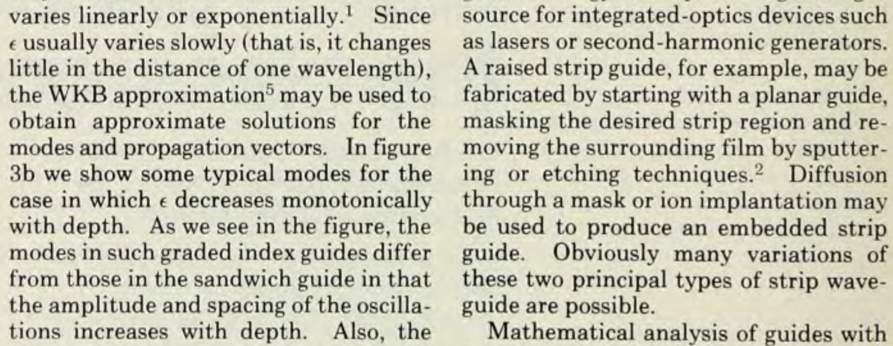
Most of the materials with desirable electro-optic or nonlinear properties for active waveguides or waveguide devices are single crystals, and it is difficult to obtain high-quality thin films of such materials. Notable examples are lithium niobate and lithium tantalate. A clever way to obtain waveguiding in such a case is to create a thin layer of higher refractive index at the top surface of a suitable single crystal by diffusion or ion exchange. With lithium niobate, for example, satisfactory guides may be made by heating in vacuum to diffuse out Li_2O, or by diffusing in various metallic impurities, such as titanium. A plot of $-\epsilon$ versus z for the resulting guide looks like figure 2b. Exact solutions of equation 4 for the modes can only be obtained for the cases where ϵ varies linearly or exponentially.[1] Since ϵ usually varies slowly (that is, it changes little in the distance of one wavelength), the WKB approximation[5] may be used to obtain approximate solutions for the modes and propagation vectors. In figure 3b we show some typical modes for the case in which ϵ decreases monotonically with depth. As we see in the figure, the modes in such graded index guides differ from those in the sandwich guide in that the amplitude and spacing of the oscillations increases with depth. Also, the penetration of the modes into the substrate increases with increasing mode number.

The guides we have been discussing so far confine light in one dimension only, the z dimension. Two-dimensional confinement can be obtained with various types of channel or strip waveguides. The additional confinement is desired for a number of purposes, such as steering the guided wave around curves or obtaining greater energy density from a given light source for integrated-optics devices such as lasers or second-harmonic generators. A raised strip guide, for example, may be fabricated by starting with a planar guide, masking the desired strip region and removing the surrounding film by sputtering or etching techniques.[2] Diffusion through a mask or ion implantation may be used to produce an embedded strip guide. Obviously many variations of these two principal types of strip waveguide are possible.

Mathematical analysis of guides with two-dimensional confinement is much more complex than that for planar guides, and no exact solutions for the modes are



Guided modes, shown here as standing waves in the z direction, for a sandwich guide (a) and a graded-index guide (b). Electric-field component E_y is plotted as a function of distance z for the three lowest TE guided modes. In the sandwich guide $(\epsilon_f - \epsilon_c)$ is much greater than $(\epsilon_f - \epsilon_s)$, the typical condition for an epitaxial semiconductor film in air on a semiconductor substrate. (From H. F. Taylor, J. Vac. Sci. Technol. **11**, 150, 1974.) In the graded-index guide (b), we have $\epsilon(z) = \epsilon_s + \Delta\epsilon e^{-z/d}$; $\Delta\epsilon$ is much less than ϵ_s and $(\epsilon_s - \epsilon_c)$ is much greater than $\Delta\epsilon$, as is typical for a diffused lithium-niobate guide in air. Figure 3



Ray picture of guided modes, shown in this figure as two progressing waves with wave vectors $k_x + k_z$ and $k_x - k_z$. The angle θ_m is given by $\tan\theta_m = k_x^{(m)}/k_z^{(m)}$. Figure 4 available. It is clear that when one dimension of the guide is much greater than the other the modes will differ little from the TE and TM modes of the planar guide. In any case, most phenomena are affected only quantitatively in going from a planar to a strip or channel waveguide. We refer the interested reader to the review by Herwig Kogelnik[1] for further discussion and references to the original calculations for these guides.

Couplers

The devices that convert the energy of an external light beam into a mode (or modes) propagating in a waveguide are called "beam couplers." The beam couplers in common use are prisms, gratings and tapered thin films, and we shall discuss them in that order.

As indicated earlier, it is possible to couple a laser beam into a guided mode by focussing it on the end face of the guide, but to do this with reasonable efficiency requires a well-polished, clean face and delicate adjustments. It is readily seen that it is not possible to launch a guided mode by having the laser beam incident on the top surface of the guide. Assume that the wave is traveling in air, in a direction that makes an angle θ_c with the normal to the film surface. The x component of the propagation vector in air is then $(\omega/c)n_c \sin\theta_c$. For this wave to feed the mth guide mode, with propagation vector $k_x^{(m)}$, continuity of tangential **E** and **H** at the film-air interface requires that

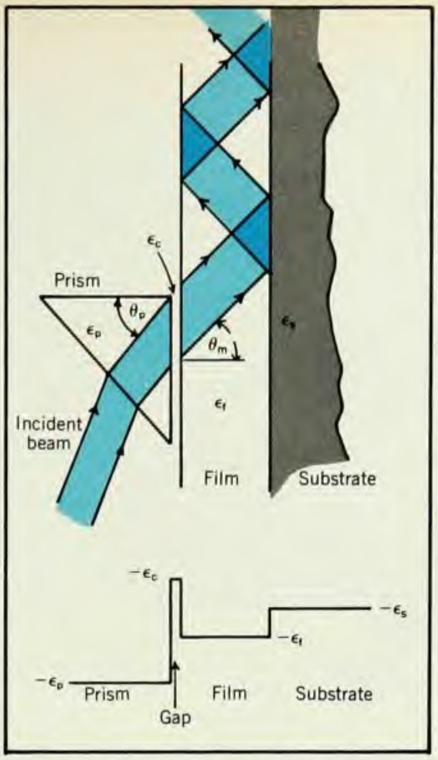
$$k_x^{(m)} = (\omega/c)n_f \sin\theta_m = (\omega/c)n_c \sin\theta_c \quad (16)$$

where θ_m is the angle shown in figure 4. (Equation 16 may also be thought of as the requirement of conservation of momentum.) We have already shown, however, that θ_m is larger than the critical angle. Thus $n_f \sin\theta_m > n_c$, and equation 16 cannot be satisfied, proving our statement that it is not possible to couple into a mode by simply having the laser beam incident on the top of the film.

Consider now what happens when the laser beam is incident on a prism with index of refraction $n_p > n_f$, as shown in figure 5. If the prism is not very close to the film surface the beam will be totally internally reflected at the interface between the prism and air. If, however, the prism is brought very close to the surface (say, within a wavelength of light) and the condition

$$(\omega/c)n_p \sin\theta_p = k_x^{(m)} \quad (17)$$

is satisfied, there will be a leakage across the air gap into the mth mode, as indicated in the figure. (This can be seen in figure 1.) In optical language this is frustrated total internal reflection. In quantum-mechanical language it is tunneling. As seen in the "potential diagram" of figure 5, tunneling takes place from the medium with $-\epsilon_p$ through the square barrier of "height" $-\epsilon_c$. The transmissivity, the ratio of the transmitted power per unit area of the boundary to the incident power per unit area, has been calculated in a number of different ways, one of the earliest involving ray optics.[6] Using the point of view stated above, we find that for TE modes it is precisely the quantum-mechanical transmissivity of a square barrier, provided allowance is made for oblique incidence of the light and the different heights of the two sides of the barrier. Thus the transmissivity depends strongly on the width of the gap, on the decay rate of the evanescent field within it (given by p_c, equation 11) and on the component of **k** in the prism normal to the "barrier" (given by equation 7 with ϵ_f replaced by ϵ_p).



Prism coupler (above) and the corresponding "potential barrier" (below). Leakage of light across the gap can be expressed in quantum-mechanical terms as tunneling through the potential barrier. Figure 5

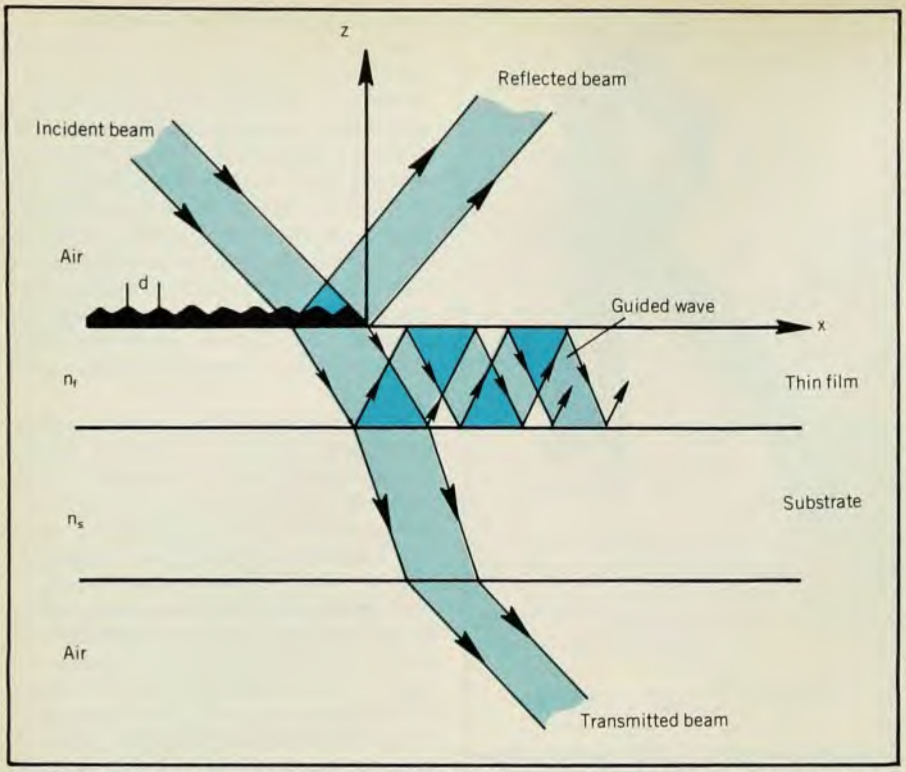
Provided $n_p > n_f$, any mode of the guide can be coupled in by a prism simply by adjusting the angle θ_p so that equation 17 is satisfied for that mode. It must be noted, however, that an *input* coupler also serves to couple light *out*. Thus, in order to maximize the energy that stays in the guide, it is customary to use a rectangular prism and arrange it so that, as shown in the figure, the right edge of the laser beam is as close as possible to the rectangular corner of the prism. Nevertheless, the maximum coupling efficiency of the prism coupler is only about 80%, provided the gap is uniform and the intensity in the incoming laser beam is uniformly distributed[6] or Gaussian.[7] Better efficiency can be achieved, for example, by decreasing the gap at the edge where the light starts coming in and increasing it where the light energy is substantial to make the "coupling-out" process relatively less important. Finally, it is clear that the prism coupler can be made 100% efficient when it is used as an output coupler, simply by making it long enough. By the reciprocity of linear optics, therefore, it should be possible to make a 100% efficient input coupler by tailoring the intensity distribution across the input beam to match the perfect output-coupler case.[6]

The prism coupler is useful as a laboratory tool, but clearly many of the potential advantages of integrated optics would be lost if it were used in integrated optical circuits. Fortunately the other two couplers mentioned are compatible with the realization of these advantages. The grating coupler is a phase grating usually made of photoresist that has been exposed to the interference pattern obtained by splitting and recombining a suitable laser beam, and then developed.[2] It is shown schematically in figure 6. Actually, the profile need not be rounded and symmetrical as shown, but may be angular and asymmetric, depending on the photoresist and the developing procedure. It is usually preferable to make the grating as thin as possible to perturb the guide modes the least. As with the prism coupler, the operation may be analyzed in many different ways.[7] One way of describing the action of a diffraction grating is to say it exchanges momentum with the light incident on it, the momentum being in units of $2\pi/d$ where d is the grating spacing. Thus the grating makes it possible to feed light into a guide mode with propagation vector $k_x^{(m)}$ provided

$$\frac{\omega}{c}\sin\theta_c + \frac{2\pi l}{d} = k_x^{(m)}, \qquad l = \pm1, \pm2, \ldots \quad (18)$$

By varying θ_c one should be able to couple into all of the guide modes. The grating also acts as an output coupler. Thus, just as in the case of the prism, an incident beam of uniform intensity couples in most efficiently if its boundary just intersects the end of the grating, as shown in figure 6. Also, as for the prism, the maximum coupling efficiency for an incident uniform beam is approximately 80%. The main disadvantage of the grating coupler is that a substantial portion of the incident energy may be transmitted through the film, as shown in figure 6, and lost in the substrate. Thus, grating couplers are not easily made with efficiencies as high as prism couplers. However, theory predicts that an efficiency close to 100% can be attained if the grating thickness and profile are suitably chosen.[7]

The tapered film coupler consists of a thin film that tapers down onto the substrate. A mode, guided in the film, that reaches the taper undergoes bounces with



Grating coupler. The grating is usually made of photoresist that has been exposed to an optical interference pattern and then developed; it need not be as rounded and symmetrical as shown here. It is not easy to obtain an efficiency as high as with prism couplers, although theory predicts efficiencies approaching 100% with appropriate grating design. Figure 6

progressively smaller angle θ_m, until θ_m becomes smaller than the critical angle. Beyond that point energy is refracted into the substrate so that ultimately most of the energy is transformed into an outgoing beam. By reversing the process, one can also couple a light beam into the film by focussing it on the tapered edge through the substrate.

Periodic waveguides

Waveguides with periodic variations in the properties of the thin film, usually in width or in index of refraction, form the basis for a number of integrated optical devices. As will be seen, these devices require very small spatial periods, not greater than one micron. Width variations, or corrugations, with such periods have been made by coating a uniform waveguide with a thin layer of photoresist, exposing this to the interference pattern of an ultraviolet (He–Cd) laser, developing and then ion milling.[2,3] This process can yield a periodicity of about 0.3 micron. To obtain a smaller period, about 0.1 micron, the photoresist is exposed through a high-index prism and a layer of index-matching immersion oil.[3] Periodic width variations may also be provided by an acoustic wave propagating along the guide. Periodic index variation may be achieved, for example, by exposing to an ultraviolet interference pattern a material, such as PMMA (polymethyl methacrylate) or gelatin, whose index is permanently changed by ultraviolet irradiation.

Mathematically the problem of finding the modes of the periodic waveguide is similar to that of finding the electron energy levels in a one-dimensional lattice. The guide modes may be taken as sums of Bloch–Floquet waves. The dispersion, ω versus k_x, shows bands of frequencies that are allowed to propagate in the structure separated by bands of frequencies that may not propagate, corresponding to the allowed and forbidden energy bands for electrons in a periodic potential.[8] As in the one-dimensional lattice, the gaps occur at the value of k_x given by the Bragg relation

$$k_x = \pm\pi/d \qquad (19)$$

where d is the spatial period. Waves with this value of k_x cannot propagate because they are strongly reflected, the reflections in each period or "cell" adding in phase. The size of the gap, or the discontinuity in allowed frequencies, that occurs at this k_x depends on how strongly the uniform guide is perturbed by the periodicity. For the typical situation in integrated optics, the perturbation is small. In any case, the existence of the gaps in transmission suggests the use of a periodic waveguide as a filter, and such filters have been made by corrugating a sputtered glass waveguide with the technique described earlier. They have shown reflectivities better than 75% and bandwidths less than 2Å for visible light.[1]

The fact that there is strong reflection of a wave with k_x given by equation 19 leads to a much more important application than filters, the distributed feedback laser. It was realized early that it would be difficult to fabricate a laser suitable for an integrated optical circuit with conventional end mirrors. Kogelnik and Charles Shank were able to demonstrate a successful dye laser with feedback provided by a periodic structure.[9] Since then, distributed feedback has been successfully demonstrated in GaAs injection lasers. To satisfy the Bragg condition in this case requires $d \approx 0.1$ micron, because the laser wavelength in air is approximately 0.8 micron and the index of refraction of GaAs at this wavelength is 3.6 (we take $\sin\theta_m \simeq 1$). This periodicity can be obtained with the high-index-prism and immersion-oil technique described earlier. Distributed-feedback lasers have been found to be very stable and frequency selective, frequently oscillating in a single longitudinal mode. (For further discussion of the properties of GaAs lasers the reader is referred to the article in this issue by Kressel.) More recently, the high reflectivity of periodic structures has been found useful for making end mirrors for integrated-optics lasers.

As noted earlier, in typical cases the periodic variation may be considered a small perturbation on a uniform guide. This makes possible another type of analytical approach to such devices, the "coupled mode" formalism.[10] Because the modes of the uniform guide constitute a complete orthonormal set, the modes of the periodic or perturbed guide may be expanded in terms of them. It will be found, however, that two modes interact particularly strongly. They are the modes i and j related by

$$k_x^{(i)} - k_x^{(j)} = \frac{2\pi l}{d} \qquad l = \pm 1, \pm 2, \ldots \qquad (20)$$

(In solid-state physics terminology equation 20 is the statement that the perturbation of the periodic lattice strongly mixes states differing by a reciprocal lattice vector.[8]) The interaction is strongest for $l = \pm 1$. Note that equation 19 is a special case of equation 20 with $l = 1$ and $k_x^{(j)} = -k_x^{(i)}$, as is appropriate for reflection. The effect of the perturbation is to transfer energy from one mode to the other (corresponding to scattering from one state to the other in the solid-state case). In the coupled-mode formalism this exchange is described by a pair of coupled first-order differential equations derived from Maxwell's equations with the aid of the assumption that the energy transfer takes place slowly. As has been pointed out by Amnon Yariv,[10] the coupled-mode approach may be used to describe many other types of phenomena—electro-optic, acousto-optic and magneto-optic modulation, second-harmonic generation, wave coupling in gratings, directional couplers, and so on.

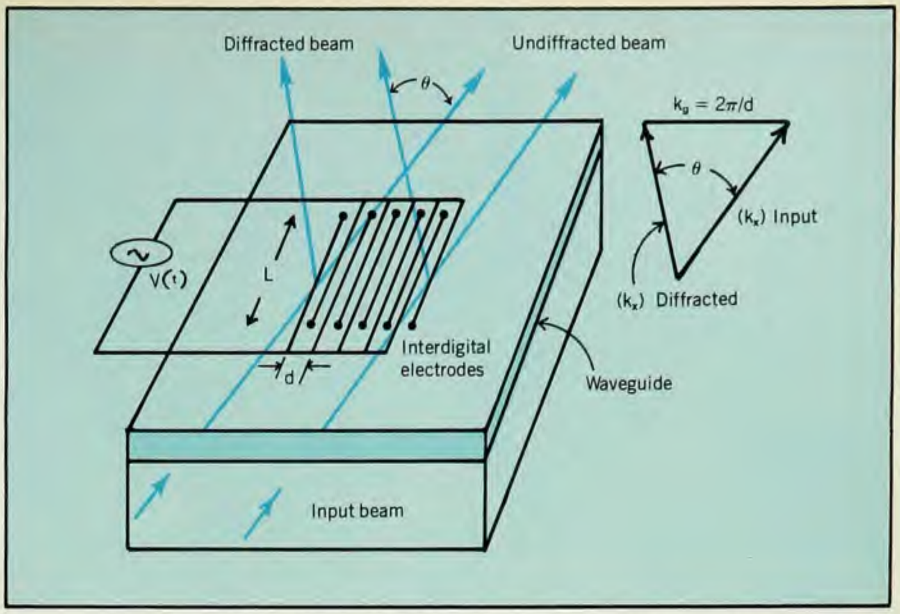
Equation 20 suggests that a periodic deformation may also be used to convert from one mode to another within a waveguide, and such a device has been demonstrated.[7] In another type of mode converter, the periodic deformation provided by an acoustic wave was used to couple a mode out of the guide into a substrate radiation mode, that is, a mode oscillatory in the substrate.[10]

Modulation

Optical modulation is the process by which information is put on a light wave. Usually this is done by a modulator external to the light source, although in the case of semiconductor lasers (as well as LED's) direct modulation of the amplitude may be obtained simply by varying the diode current. By prebiasing the laser just below threshold, direct modulation at rates as high as one gigabit per second has been obtained. However, even for applications where this frequency is adequate, separate modulation may be preferable because the laser has a tendency to oscillate, making the modulation hard to control.[3] An external modulator operates by altering some detectable property—amplitude, phase, polarization or frequency—of the light through a change in the index of refraction. The index change may be caused by an applied electric or magnetic field or an acoustic wave, the time-variation of which represents the information to be conveyed. Switching is the process by which the spatial location of a coherent light wave is changed in response to an applied field or acoustic wave. A device may act as both a modulator and a switch. In what follows we shall take up modulators first, describing a few of the more important types. For further discussion the reader is referred to some recent review articles.[10,11,12]

A number of the modulators to be described are similar in principle to bulk modulators, the main difference being that the light is confined within a waveguide. Since for maximum efficiency the modulating fields must be applied over the volume of the light beam, the power needed for a given depth of modulation decreases as the cross-sectional area of the light beam decreases. Thus a power savings of more than one order of magnitude should be possible for one-dimensional confinement, more than two orders of magnitude for two-dimensional confinement, and such power savings have actually been realized. By a similar argument, in the case of a modulation process that depends on electric field, voltage savings of more than an order of magnitude are achievable by applying the voltage across the small dimension of the guide.

A number of the outstanding modulators for integrated optics are based on the



Electro-optic diffraction modulation in a thin-film waveguide. Voltage applied to the interdigital electrodes causes a periodic variation in refractive index, which deflects part of the guided beam through an angle θ. (Adapted from reference 10.) Figure 7

Pockels or "linear electro-optic" effect, so called because the change in index is linear in electric field. This effect occurs in crystals without a center of symmetry. Lithium niobate and GaAs are compounds with relatively strong electro-optic effects. In a typical electro-optic waveguide modulator, a linearly polarized light beam is coupled into a channel waveguide and the linearly polarized beam is decomposed into two orthogonal polarization modes, one TE and one TM. An electric field is applied across the guide through electrodes alongside it. This changes the index of refraction, and thus the phase velocity, differently for the two modes, resulting in a phase difference $\Delta\phi$ between them when they leave the guide. A second polarizer, oriented the same as the first, turns this into an amplitude-modulated output with intensity given by $I_m \cos^2(\Delta\phi/2)$, I_m being the maximum intensity. (Note that if the TE and TM modes have different phase velocity in the absence of the field, this effect also makes a contribution to $\Delta\phi$, but one that can be cancelled out by a compensator.) In a recent modulator of this type, with the channel guide made by Ti-diffusion in lithium niobate, for a phase shift of 1 radian at 0.63 micron the modulating voltage required was 0.3 volts and the power 1.7 microwatts per megahertz of bandwidth.[13]

In another promising type of modulator, voltage applied between two sets of interleaved electrodes on an electrooptic material (usually lithium niobate or tantalate) generates a periodic index-of-refraction variation or phase grating. As shown in figure 7, the top of the crystal is a planar guide, made by a suitable diffusion. Modulation occurs due to diffraction of the guided wave by the grating; details of the diffraction process differ depending on the ratio of L to the grating spacing d.[10,11,12] For a large ratio, or a thick grating, which is the situation shown in figure 7, the situation is similar to that of x-ray (Bragg) diffraction by a crystal lattice. Conservation of momentum, expressed by the vector diagram at the right of figure 7, leads to the Bragg condition for the angle θ through which the beam is deflected

$$\sin\left(\frac{\theta}{2}\right) = \frac{\lambda_w}{2d}, \quad \lambda_w = \frac{2\pi}{|(k_x)_{inc}|} \qquad (21)$$

This type of modulator, which is also a switch, has the advantage of giving amplitude modulation without the need for an additional polarizer. The intensities in the undiffracted and diffracted beams, respectively, are $I_m(\cos^2\phi/2)$ and $I_m(\sin^2\phi/2)$, ϕ being the electro-optically induced phase shift.

The Bragg grating that produces the modulation we have just discussed may also be produced by an acoustic wave, through the photoelastic effect. The modulator that results is called an acousto-optic modulator. In the version of acousto-optic modulator used in integrated optics the acoustic waves are usually surface waves rather than bulk waves, conveniently produced by interdigital transducers set on top of the waveguide. This requires that the waveguide (or possibly the substrate) be piezoelectric. To produce the grating shown in figure 7 the transducers would be out at the left- and right-hand sides. Such modulators have been realized on lithium niobate with the waveguiding layer produced by diffusion.[11]

The two mode converters mentioned in the last paragraph of the section on periodic guides also function as modulators if

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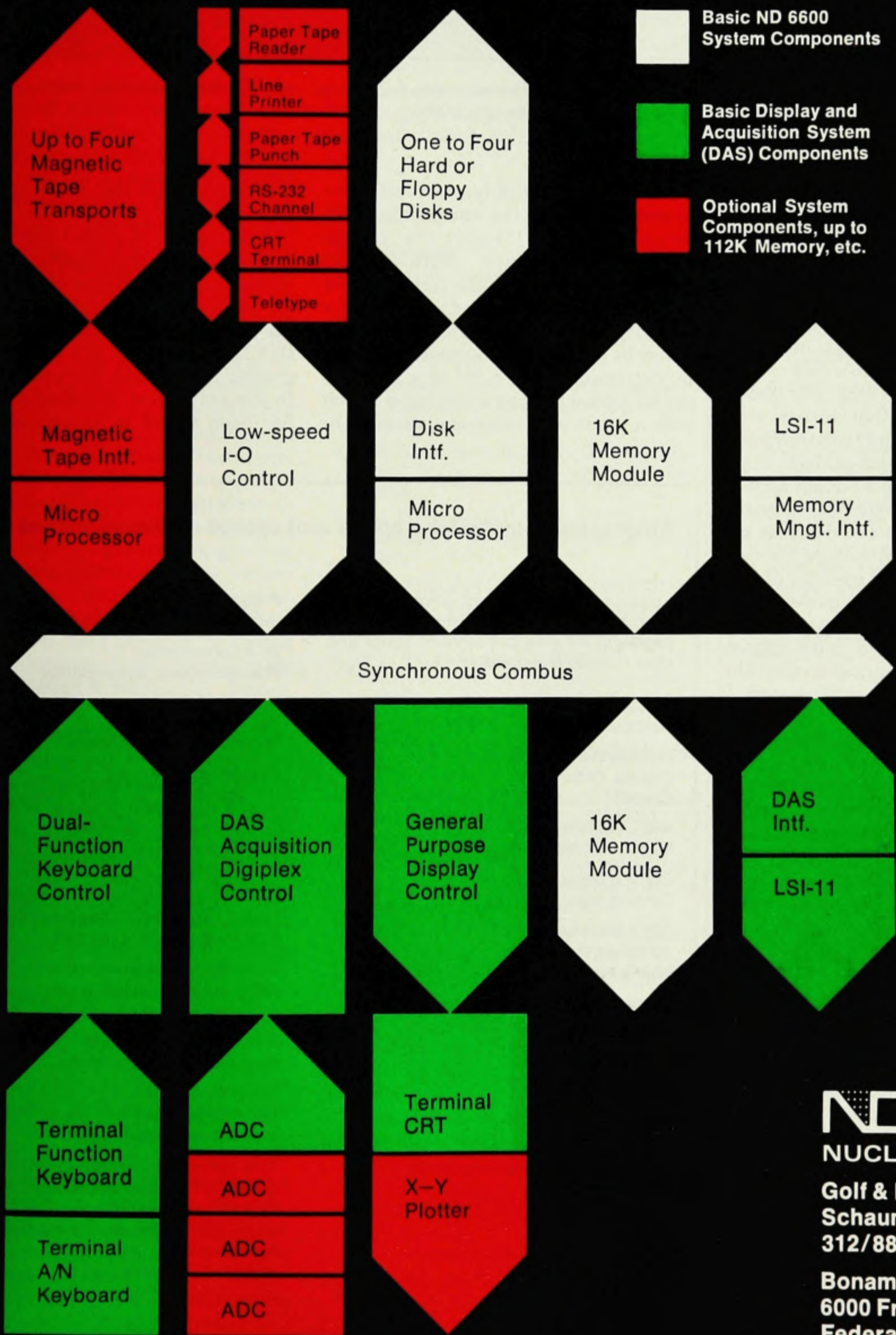

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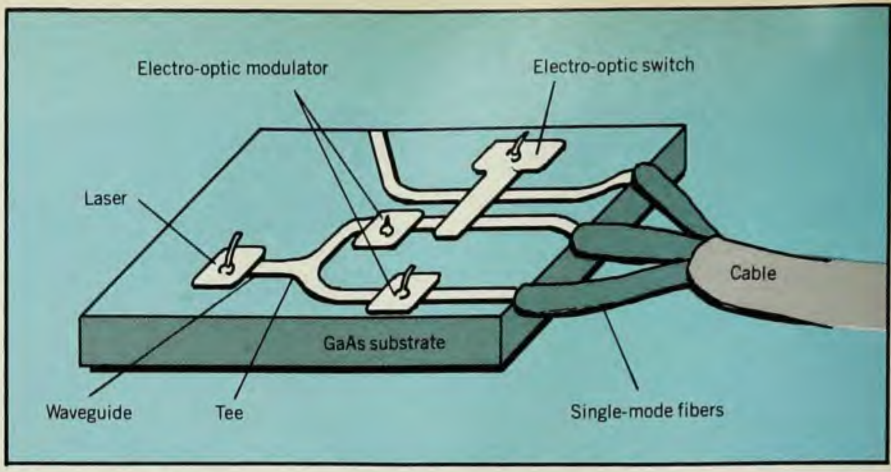
the amplitude of the periodic deformation, or of the acoustic wave, is controlled with an electrical signal by the techniques we have just been discussing.[10]

An important group of integrated-optics switch modulators, that (unlike most of those discussed so far) have no bulk analog, are based on the principle of directional coupling. This provides another example of coupled modes, in this case modes with the same k_x propagating in two parallel channels coupled by their evanescent fields, thus having a separation not greater than the light wavelength. As in the case of coupled pendulums, if energy is launched in one guide it will transfer gradually to the other, the transfer being complete in a distance L_0 called the "coupling length." This distance depends strongly on the separation between the guides, increasing rapidly as the separation increases. The energy will return to the first guide in the next L_0 and thereafter continue to oscillate between the guides with this characteristic period. If the k_x's of the guides differ somewhat, some energy will still be exchanged between them periodically, but the fraction exchanged decreases rapidly to zero as the difference between the k_x's increases. Assume now that we have a pair of coupled guides, covered with electrodes, which are matched so that, with no voltage applied, all the energy put into guide 1 initially will emerge from guide 2. If the material is electro-optic, a voltage applied between the two electrodes will cause the two k_x's to move apart and decrease the transfer. With enough voltage the coupling will be spoiled and energy put into guide 1 will all emerge from guide 1. For a configuration of this type, with guides formed by Ti diffusion into lithium niobate, 6 volts was required to spoil the coupling.[14] The guide widths were 2 microns, the separation between them 3 microns and the length of the interaction region 3 mm ($= 3L_0$). It is seen that the technology required to make such a switch is quite demanding. A similar switch has also been made with channel guides in GaAs defined by metal strips along them.[15] It is interesting to note that optical switching has been accomplished with 1 pico-joule, which is comparable to the energy required for semiconductor switching.[13]

Some applications to physics

Many of the techniques and phenomena described above are useful for physics applications. We take this opportunity to point out a few, and the reader will no doubt see others. One useful application is to the accurate determination of index of refraction and thickness of thin films, in particular films that can support two or more guided modes. By measuring the angles θ_p for which energy couples into (or, more conveniently, out of) a prism, with a knowledge of the prism index one can determine the $k_x^{(m)}$ with equation 17. With that information one can determine n_f and W by using the waveguiding condition (equation 15) and the various auxiliary relationships. With care, an accuracy of 0.0001 in the index can be obtained.[16] If the film or a surface of a solid has an index that varies with depth, it may be possible to determine the profile by determining the $k_x^{(m)}$ of a group of modes guided by the varying index region with a prism and using analytical techniques based on the WKB approximation.[17]

Attenuation of guided waves may be determined by monitoring the energy coupled out as a function of distance from the input coupler; therefore one may also use waveguiding to do spectroscopy in thin films. Clearly this affords a much greater path length than the thickness. In some studies of this kind attenuation has been found to be sensitive to the



Monolithic GaAs integrated-optics transmitter. In this artist's impression, the output is shown coupled to single-mode optical fibers. (From ref. 15.) Figure 8

Employers in integrated optics and optical communications

Some of the industrial and government research labs who are publishing and giving papers in the area of integrated optics and fiber communications are:

Bell Laboratories
Holmdel, New Jersey 07733

Bell-Northern Research
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Corning Glass Works
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presence of a monolayer of organic molecules.[18] Spectroscopy of guided waves should also provide an ideal method for studying some of the excitations or modes characteristic of thin films or surfaces.

Prisms and gratings have, of course, been used by many investigators to couple surface polaritons into solids. These studies have been limited to relatively small values of k_x in the grating case because of the coarseness of the gratings. With gratings made by holographic techniques developed for integrated optics it should be possible to study these phenomena at much larger k_x values.

Integration—the future

It should be clear, even from the relatively brief presentation above, that a wide variety of miniaturized components suitable for integration, some quite sophisticated, has been developed. There have also been some cases of integration of a few components. For example, a taper-coupled semiconductor laser has been integrated with a linear electro-optic modulator.[19] The functions of deflection (produced by an acousto-optic Bragg modulator), waveguiding and detection of the guided light (by p–n junction photodetectors) have been integrated on a silicon chip.[20] The latter is an example of "hybrid" thin-film technology, so called because the different components are made of different materials, chosen presumably to optimize each function. Considerable thought has been given to monolithic integrated optics, in which all optical functions—generation, guiding, coupling, modulation/switching, detection—are obtained in a single material. The only material in which all these functions have been obtained to date is GaAs, usually alloyed with other elements of columns III and V, notably Al. Indeed, because it was clear early that GaAs is the most likely material for monolithic integrated optics, more effort has been put on it than any other material.

Since most of the work in this general area has been done with optical communications in mind, a likely early candidate for an integrated system would be an optical transmitter or receiver. A program for the development of a GaAs integrated-optical circuit transmitter, such as shown in figure 8, is being carried out at the research labs of Texas Instruments. In figure 8 the laser output is shown coupled into channel waveguides. Electro-optical modulation and switching by means of a directional coupler are performed in the different channels and controlled separately. The outputs are shown coupled to single-mode optical fibers that join to form a transmission cable. As we have seen above, the individual devices have all been made; the task now is to integrate them and couple the circuit outputs to fiber-optic cables, for which coupling, incidentally, satisfactory technology is not yet available.

Despite the availability of components, integration and the introduction of fiber cables may not proceed very rapidly. A possible exception to this is in installations for ships and planes, where the smaller weight and freedom from electromagnetic interference and radiation are important considerations. It may also be that application of integrated-optics techniques to "solid-stating" of some existing optical systems, such as laser scanners, will move ahead quickly. However, the most significant advantage this technology offers—the greater available bandwidth—is for the most part not really needed yet. When industry does get around to exploiting this bandwidth, many new services, such as TV access to stores, educational resource centers, libraries, medical centers, and so on, can be made available to office and home.

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