SESSION VIII: New Devices and Techniques

THAM 8.2: Theory and Fabrication of Integrated Optics Directional Couplers in GaAs

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MOST RESEARCH in integrated optics to date[1] has involved developing methods of making optical waveguides and devices for ultimate use in integrated optical circuits. However, the number of examples of optical circuit elements actually demonstrated is still small. In this report the fabrication and performance of an optical directional coupler is described.

The coupler, analogous to the microwave element of the same name, consists of parallel-channel optical waveguides sufficiently closely spaced so that energy is transferred from one to another. For this coupling to take place cumulatively over a substantial length, the light must propagate with the same phase velocity in each channel. The amount of power coupled is determined by the overlap of the modes in the separate channels. Thus, it depends on the guides' separation, the mode penetration into the substrate, and the interaction length.

In this experiment parallel channel guides were imbedded at the surface of GaAs. They were formed by proton bombardment[2] through a gold mask. Bombardment compensates the free carriers, increasing the refractive index by $\Delta n \simeq .0058$ for the samples used here ($N_{substrate} = 2.6 \times 10^{18}$). The gold mask was fabricated by depositing on the GaAs surface a 1.8 μ thick layer of gold followed by a layer of photoresist. The resist was exposed through a photographic mask and developed down to the gold, to form stripes of clear area. The removal of the gold from these areas was accomplished by ion machining. The channel width as determined from the mask is 2.5 μ and the separation between channels is 3.9 μ. The guide depth is determined by the energy of the bombarding protons and is 3 μ for the 300 keV protons used.

HeNe 1.15 μ laser light was focused directly into a single channel through a GaAs face cleaved perpendicular to the plane of the guide. The presence of guiding was first confirmed with an image converter, and then an image scanner was used to display the relative guided light intensity in various channels. The experimental apparatus is the same as that described previously[2] except that here the image is scanned in the plane of the channel guides rather than perpendicular to it. Figure 1 shows a diagram of a large number of coupled channel waveguides and typical intensity profiles of the guided light. The incident light is focused into a single channel at z = 0, but is coupled into the adjacent guides as it propagates.

The normalized complex field amplitude in the n^{th} channel can be shown to obey the equation

$$\frac{dE_n(z)}{dz} = -iKE_{n-1}(z) - iKE_{n+1}(z) - \frac{\alpha}{2}E_n(z) \qquad (1)$$

where n is the guide number ($n = 0, \pm 1, \pm 2 \ldots$), α is a single guide attenuation, and K is the coupling coefficient between two adjacent guides. (The coupling coefficient between non-adjacent guides is negligibly small). With the boundary conditions

$$E_o(0) = 1 \qquad \text{and} \qquad E_{n \neq o} = 0 \qquad (2)$$

the solutions of equation (1) are

$$E_n(z) = (-i)^n J_n(2Kz)\, e^{-\frac{\alpha}{2}z} \qquad (3)$$

where J_n represents the Bessel function of n^{th} order. For a case where there are only two guides (n=0 and n=1) the solution is:

$$E_o = \cos(Kz)\, e^{-\frac{\alpha}{2}z} \qquad E_1 = -i\sin(Kz)\, e^{-\frac{\alpha}{2}z} \qquad (4)$$

From a comparison of equation (3) and the intensity profiles in Figure 1 (*b*), it was determined for that case, that K = 0.52 ± 0.02 mm^{-1}. It has also been found that different polarizations (E^x or E^y) of the input beam had no noticeable effect on K.

A theoretical value for the coupling coefficient can be obtained from a simple theory, in which the tail of a mode propagating in one guide generates polarization in an adjacent guide. This polarization in turn, excites the mode in the

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[1] *OSA Topical Meeting on Integrated Optics*, Las Vegas, Nevada, Feb., 1972.

[2] Garmire, E., Stoll, H., Yariv, A., Hunsperger, R. G., "Optical Wave-Guiding in Proton-Implanted GaAs", *Appl. Phys. Letters*, Vol. 21, p. 87; 1972.

[3] Marcatili, E. A. J., "Dielectric Rectangular Waveguide and Directional Coupler for Integrated Optics", *BSTJ*, Vol. 48, p. 2071; 1969.

[4] Yariv, A., "Proceedings of 1971 Esfahan Conference on Pure and Applied Quantum Electronics", *M.I.T. Press*; in press.

adjacent waveguide. The expressions for K are similar to those in an earlier analysis[3].

The demonstration of directional coupling between channel waveguides raises the attractive possibility of controlling the coupling by an applied electric field[3,4] taking advantage of the large electrooptic coefficient of GaAs. This would lead to new types of optical modulation and to electrically controlled light multiplexing.

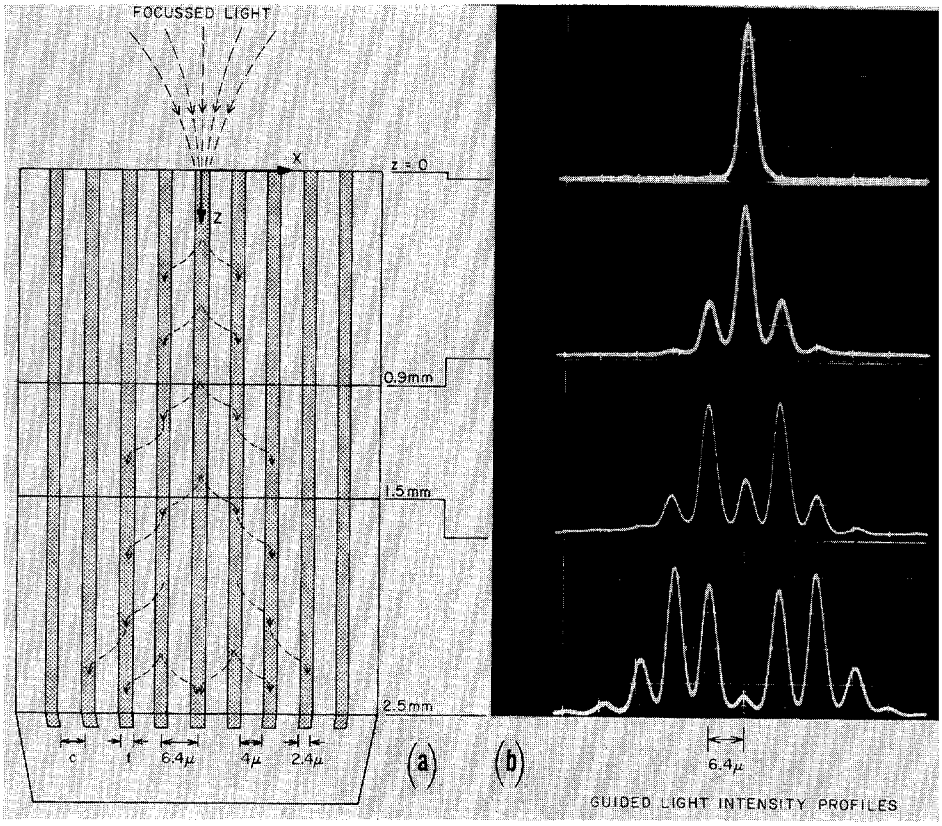

FIGURE 1—(*a*)—Channel optical waveguide directional coupler showing flow of light energy into adjacent channels. (*b*)—Photographs of guided-light intensity profiles for various lengths. The profiles have been displayed relative to (*a*) at the proper value of z; intensity scale is arbitrary.