Channel optical waveguide directional couplers

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We report the first demonstration of channel optical waveguide directional couplers. The closely spaced channel waveguides were fabricated in GaAs by proton implantation. Optical coupling was observed at 1.15 μ with complete light transfer out of the initial channel into adjacent channels in lengths of typically 2 mm.

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 the following we report on the fabrication and performance of the optical directional coupler.

The optical directional coupler, analogous to the microwave element[2] of the same name, consists of parallel channel optical waveguides sufficiently closely spaced 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's 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[3] through a gold mask. Bombardment compensates the free carriers, increasing the refractive index by $\Delta n \simeq 0.0058$ for the samples used here ($N_{\text{substrate}} = 2.6 \times 10^{18}$). The gold mask, shown in Fig. 1, 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.[4] 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.

He-Ne 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 guide-light intensity in various channels. The experimental apparatus is the same as that described previously,[3] except that here the image is scanned in the plane of the channel guides rather than perpendicular to it. Figure 2 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 nth channel can be shown to obey the equation

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

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 nonadjacent guides is negligibly small.) With the boundary conditions

$$E_0(0) = 1 \quad \text{and} \quad E_{n\neq 0} = 0, \tag{2}$$

the solution of (1) is

$$E_n(z) = (-i)^n J_n(2Kz) \exp(-\tfrac{1}{2}\alpha z), \tag{3}$$

where J_n represents the Bessel function of nth order. For a case where there are only two guides ($n = 0$ and $n = 1$), the solutions are

$$\begin{aligned} E_0 &= \cos(Kz) \exp(-\tfrac{1}{2}\alpha z), \\ E_1 &= -i \sin(Kz) \exp(-\tfrac{1}{2}\alpha z). \end{aligned} \tag{4}$$

From a comparison of (3) and the intensity profiles in Fig. 2, we determine that $K = 0.52 \pm 0.02\ \text{mm}^{-1}$. It has also been found that different polarizations (E^x or E^y) of the input beam had no noticeable effect on K.

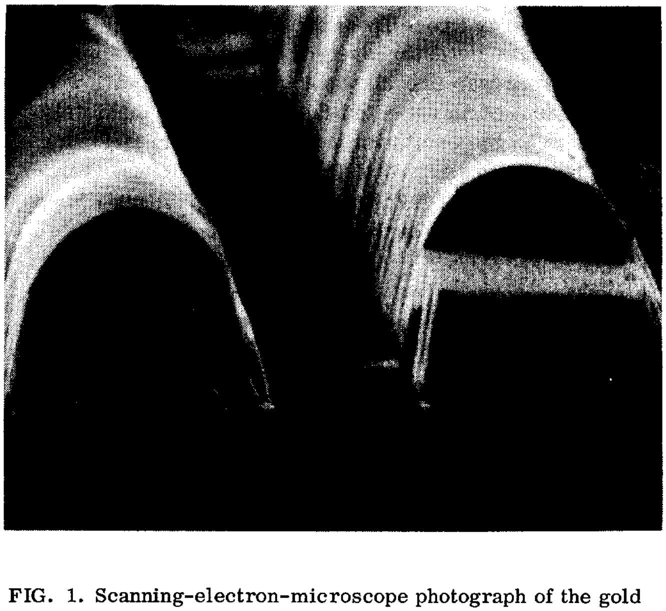

FIG. 1. Scanning-electron-microscope photograph of the gold mask on the GaAs substrate used in the fabrication of the directional couplers. The remains of the photoresist can be seen on top of the gold stripes. Magnification, 10 000×.

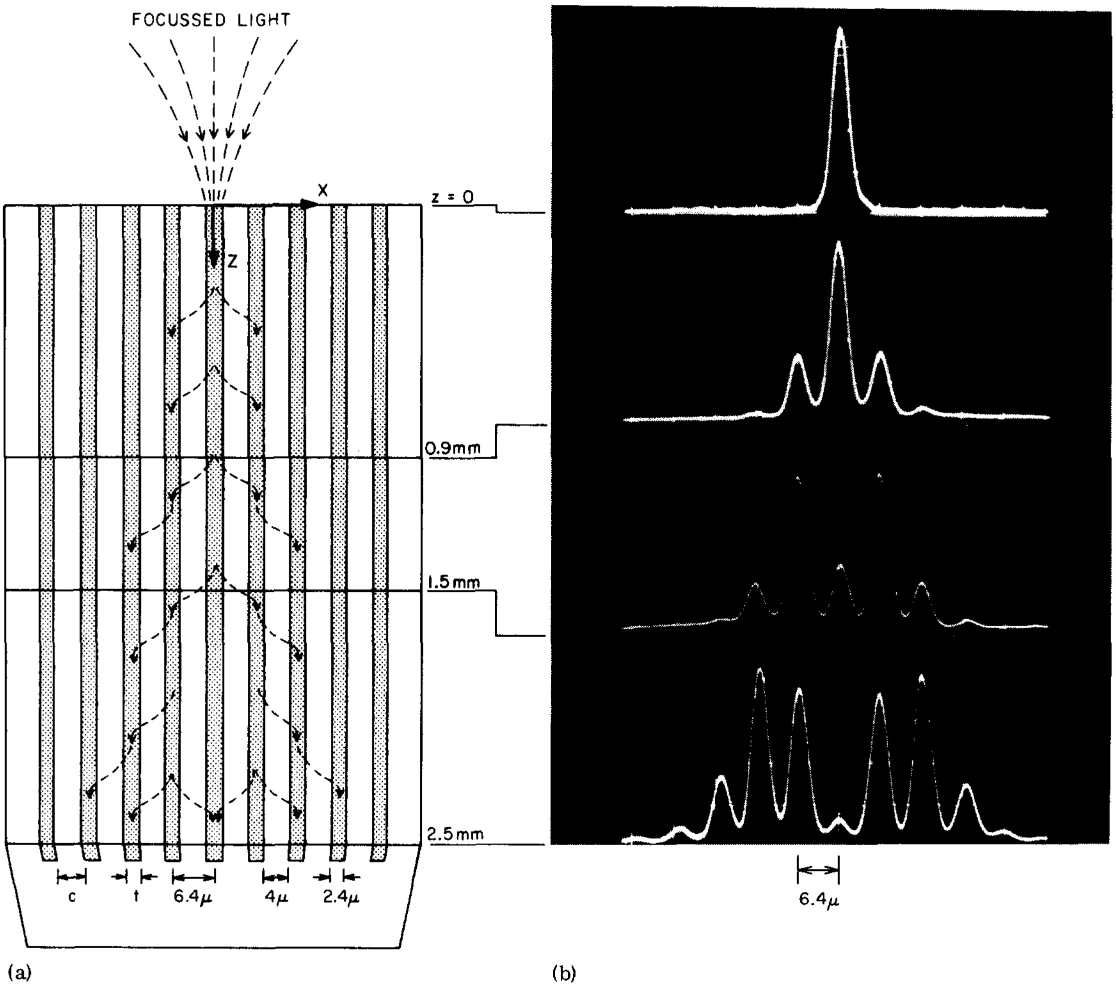

FIG. 2. (a) Sketch of channel optical waveguide directional coupler showing flow of light energy into adjacent channels. (b) Photographs of guided-light intensity profiles for various lengths. The profiles have been displayed relative to the sketch at the proper value of z. Intensity scale is arbitrary.

A theoretical value for the coupling coefficient K can be determined from an analysis by Marcatili.[5] His analysis, which pertains to well-confined modes, gives for either polarization

$$K=\frac{2k_x^2 q_x \exp(-q_x c)}{k_z a(q_x^2+k_x^2)}, \qquad (5)$$

where a is the channel width, c is the separation between channels, k_x and k_z are the propagation constants along the x and z axes, respectively, and q_x is the exponential falloff in the x direction outside the guide. Although the waveguide modes in this experiment are not well confined, we can use (5) to make qualitative comparison between theory and experiment. For the dielectric discontinuity and guide dimensions *assumed* above, the theory yields $K = 0.6\ \text{mm}^{-1}$. This value is a strong function of Δn. For example, a 10% reduction in Δn will increase K to $0.74\ \text{mm}^{-1}$.

The precise properties of proton-implanted waveguides are not yet fully known. Annealing is required to reduce optical damage, yet it also causes some decrease in dielectric discontinuity (increase in free carriers) plus possibly some widening of the guide. The data shown above pertain to samples implanted with a dose of 6×10^{14} protons/cm^2 and annealed in H_2 for 10 min at 500 °C, which exhibit a loss of 2 cm^{-1}. Samples with a longer anneal time (total of 20 min) have a higher value of K (about $0.7\ \text{mm}^{-1}$), and samples with a higher dose (2×10^{15} protons/cm^2) had a lower coupling coefficient (about $0.4\ \text{mm}^{-1}$). Thus, the measurement of K in channel directional couplers is a sensitive indicator of guide parameters.

The demonstration of directional coupling between channel waveguides raises the attractive possibility of controlling the coupling by an applied electric field[5,6] while taking advantage of the large electro-optic coefficient of GaAs. This would lead to new types of optical modulation and to electrically controlled light multiplexing.

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