by a factor of about 10 over a laminar flow and by about 50 over no flow (in this case). It is apparent therefore that a considerable improvement in heat transfer in a structure such as a superconducting solenoid can be obtained by the provision of cooling channels and by the establishment of appropriate flow conditions. The improvement can be so large as to reduce the need for stabilizing materials on the superconductor.

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OBSERVATION OF PROPAGATION CUTOFF AND ITS CONTROL IN THIN OPTICAL WAVEGUIDES*

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The first observation of optical cutoff in thin-film waveguides is reported. The waveguides consist of thin ($\sim 10\mu$) epitaxial layers of high-resistivity GaAs deposited on lower-resistivity GaAs substrates. The optical cutoff is controlled through the electro-optic effect by applying an electric field across the epitaxial layer.

Guiding and electro-optic modulation of light in thin epitaxial semiconductor films has recently been demonstrated.[1] In this paper we report the first observation and control of optical cutoff in such waveguides.

The optical waveguide consists of a GaAs high-resistivity epitaxial layer ($\sim 12\ \mu$) sandwiched between a metal film and lower-resistivity GaAs substrate as shown in Fig. 1. The existence of confined modes is due to a discontinuity Δn of the index of refraction at the epitaxial layer–substrate interface.[1]

The theory describing the propagation of modes in this structure can be adapted from that of the symmetric dielectric waveguide.[2] The symmetric guide can support, in general, two types of modes: TE waves where $\vec{E}$ is parallel to y, and TM waves in which $\vec{E}$ is parallel to x. The existence of a conducting plane (metal film) at $x=0$, however, limits the TE and TM modes in our case, to those possessing odd symmetry about $x=0$. These can be written as

$$E_y(TE) \propto \sin(hx)\exp(-i\beta z),$$
$$H_y(TM) \propto \sin(hx)\exp(-i\beta z), \quad |x| < t \tag{1}$$

$$E_y(TE) \propto \exp[-p(x-t) - i\beta z],$$
$$H_y(TM) \propto \exp[-p(x-t) - i\beta z], \quad |x| > t. \tag{2}$$

The lowest-order TE_1 and TM_1 (the numerical subscript gives the number of zero crossings in the interval $|x| < t$) modes can exist only if the condition

$$(2n_0\Delta n)(2\pi t/\lambda_0)^2 > (\pi/2)^2 \tag{3}$$

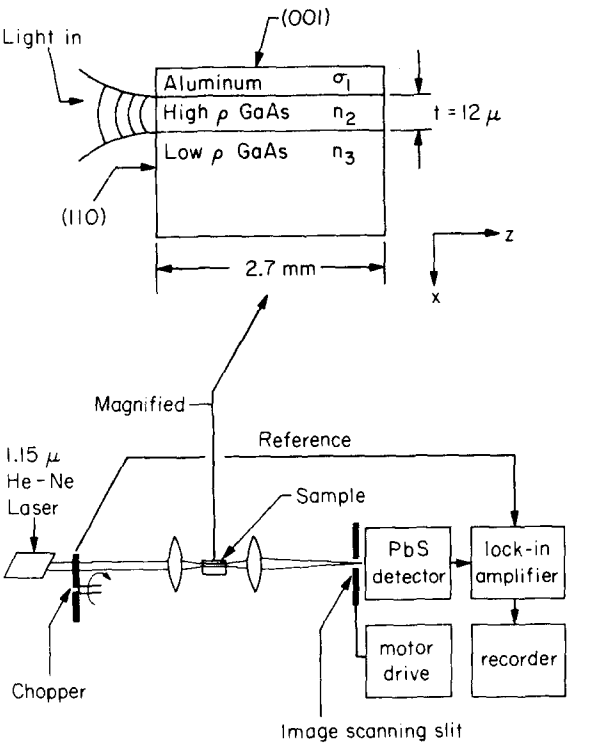

FIG. 1. The experimental setup.

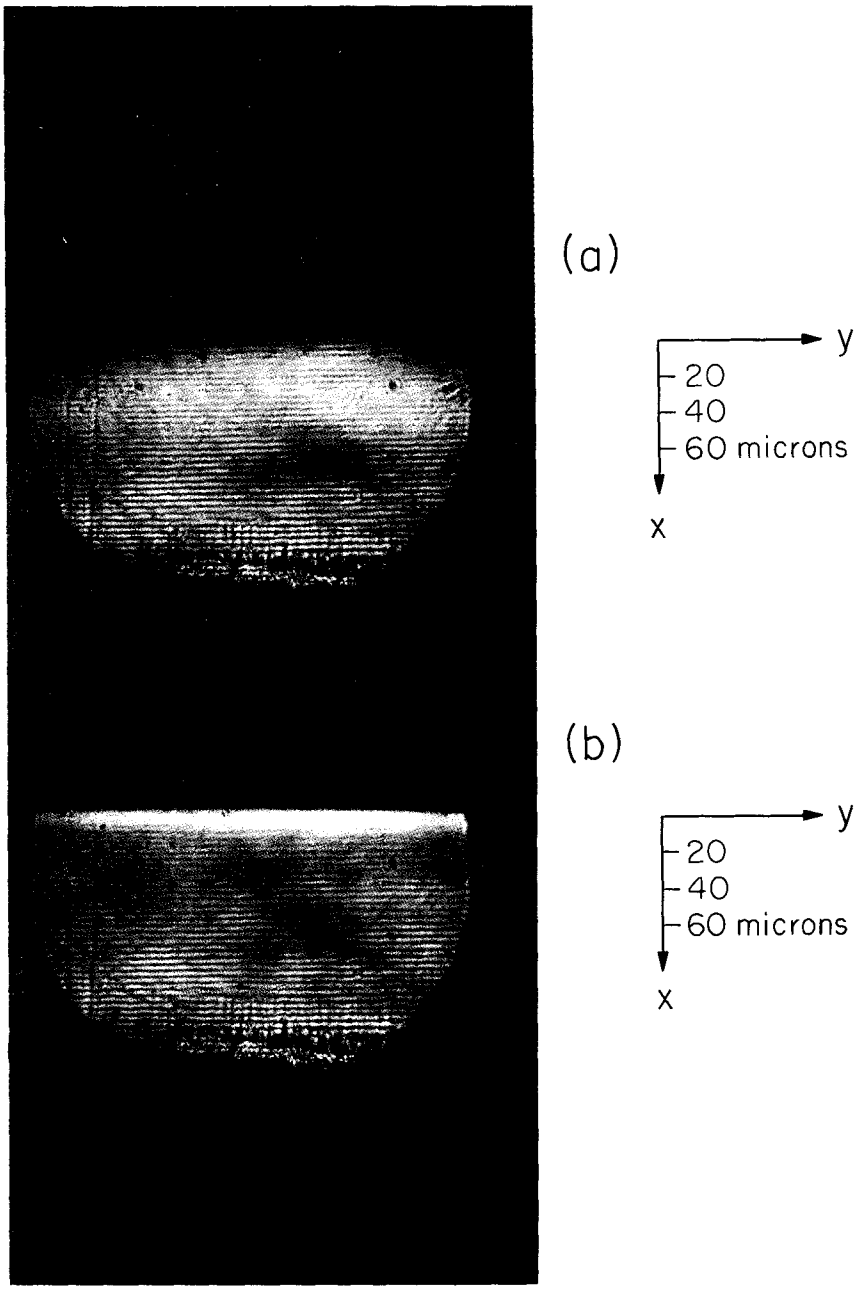

FIG. 2. (a) The intensity distribution in the output face of the waveguide in the cutoff condition with no applied field. The fringes are due to interference between the incident light and that reflected from the metal film. (b) The intensity distribution with the field applied. The upper bright stripe corresponds to the confined TE_1 mode. The direction of the displacement of the fringes relative to their position in (a) is used to determine the sign of Δn.

is satisfied. When the sign of the inequality in (3) is reversed, the field intensity increases with x so that confined propagation does not exist. This condition is referred to as cutoff.

The index discontinuity Δn at the interface $x=t$ is due, in our experiment, to two mechanisms. The first is the dependence of the index on the doping level. This discontinuity, which we denote as $\Delta n_{\text{chemical}}$, is known to lead to mode confinement in p-n junctions.[3,4] In our guide $\Delta N \approx 2\times 10^{16}$ cm^{-3} and we estimate $\Delta n_{\text{chemical}} \sim 10^{-4}$. The second contribution is due to the linear electro-optic effect in GaAs and is proportional to the reverse bias V applied to the metal-semiconductor junction. For the crystal orientation shown in Fig. 1 the electro-optic contribution to the index of a wave polarized along y is

$$\Delta n = n_0^3 r_{41} E_x/2,$$

and is zero for waves polarized along x.[5] We can consequently, write condition (3) for confined propagation as

$$\Delta n_{\text{chemical}} + \frac{n_0^3 r_{41} V}{2t} > \frac{1}{32 n_0}\left(\frac{\lambda_0}{t}\right)^2, \qquad (4)$$

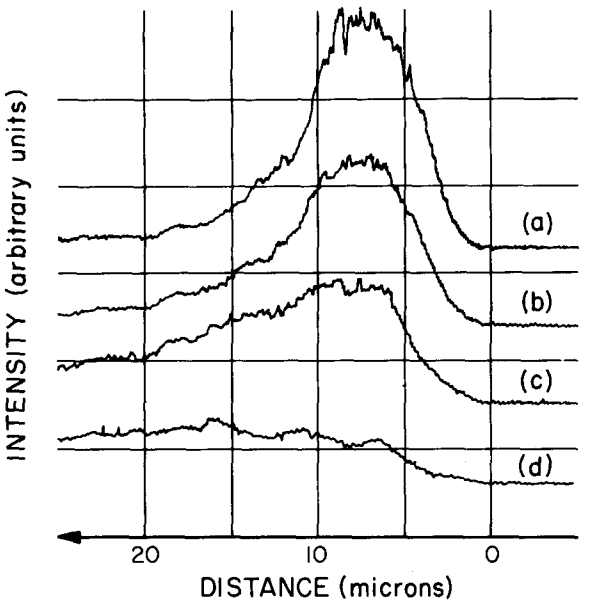

FIG. 3. The intensity distribution of the TE_1 mode measured with applied voltages of (a) 130, (b) 100, (c) 70, and (d) 0 V.

for the TE mode and as

$$\Delta n_{\text{chemical}} > (1/32n_0)(\lambda_0/t)^2, \tag{5}$$

in the case of the TM wave. r_{41} is the electro-optic coefficient of GaAs and the applied voltage is $V = E_x t$.

The doping level of the substrate ($N \sim 2\times 10^{16}$ cm^{-3}) and the thickness $t = 12\ \mu$ were chosen in our experiment so that at $\lambda_0 = 1.15\ \mu$ condition (5) was not fulfilled and no confined modes can exist. The application of a voltage V increases Δn by adding, as indicated in (4), an electro-optic contribution making it possible for a confined TE wave to exist. A magnified image of the output face of the crystal with and without an applied bias ($V = 130$ V) is shown in Fig. 2. The existence of a confined mode with the voltage on is clearly evident. In addition, we made the following observations: (1) When the optical polarization is rotated by 90° ($\vec{E} \parallel x$) so as to excite a TM wave, no confined mode exists with or without an applied field. This is consistent with the fact that there is no electro-optic contribution to Δn in the case of the TM wave. (2) By changing the crystal orientation we can reverse the sign (see caption under Fig. 2) of the electro-optic contribution to Δn as "seen" by the TE mode from (+) to (−). When this is done the application of a voltage does not lead to a confined mode in agreement with (4).

The gradual onset of confinement with increasing voltage is shown by the intensity profile plots in Fig. 3. The dependence of the guided intensity on the applied voltage can be used for modulation purposes.

In summary: The phenomena of propagation cutoff in thin optical waveguides is demonstrated. A continuous electro-optic control of the cutoff condition is used to demonstrate its effect on the intensity distribution of the dominant TE mode.

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