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CdTe OPTICAL WAVEGUIDE MODULATORS (*)

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Résumé. — Des modulateurs de guides d'ondes opto-acoustiques et opto-électriques ont été réalisés dans des guides d'ondes n^-/n^+ CdTe, dans lesquels la couche n^- est produite par implantation de protons de haute énergie. Les modulateurs opto-acoustiques emploient des ondes acoustiques de surface de 27 MHz, générées par un transducteur à électrode interdigitale de 2,5 mm de long. Un faisceau diffracté contenant environ 10 % de la puissance optique à 10,6 μm a été produit avec une puissance acoustique de 0,5 W. Des modulateurs de phase opto-électriques de faible tension ont été réalisés en appliquant des électrodes en or sur des plaquettes n^+ de CdTe préalablement au bombardement protonique. Un dispositif comprenant un guide d'épaisseur 22 μm recouvert d'une électrode de 14 mm de long a permis d'atteindre une modulation de phase de 110° avec une tension de polarisation de 100 V. Ce facteur de modulation de plus de 1°/V dépasse de plus d'un facteur deux la valeur la plus élevée reportée pour un modulateur de laser CO_2 . Les performances de ces deux types de modulateurs devraient encore être meilleures à des longueurs d'ondes plus courtes, puisque les efficacités varient comme $1/\lambda^2$.

Abstract. — Acoustooptic and electrooptic waveguide modulators have been fabricated in n^-/n^+ -CdTe waveguides, where the n^- guide layers were produced by high-energy proton bombardment. The acoustooptic modulators utilize 27 MHz Rayleigh surface acoustic waves generated by 2.5 mm long interdigital electrode transducers. A diffracted beam containing about 10 % of the optical power at 10.6 μm was produced with 0.5 W of acoustic power. Low-voltage electrooptic phase modulators were constructed by plating gold modulator electrodes onto the n^+ CdTe wafers prior to proton bombardment. A device comprised of a 22 μm thick guide layer covered with a 14 mm long electrode produced 110° phase modulation with a 100 V bias. The modulation factor of over 1°/V is more than twice that reported for any CO_2 laser modulator. Performance of both the electrooptic and acoustooptic modulators should be greatly improved at shorter wavelengths, since the efficiencies are proportional to $1/\lambda^2$.

1. Introduction. — Optical waveguide modulators that operate at a small fraction of the drive power needed for bulk modulators are an essential element of proposed optical communications systems. A wide variety of waveguide devices (e. g., couplers, switches, mode selectors, and phase shifters) are being developed for signal processing, mostly based upon either the acoustooptic or the electrooptic effect. The reduced drive power requirement also makes waveguide modulators attractive for some CO_2 laser systems. The low optical absorption and high electrooptic coefficient of CdTe make it an excellent material for some optical waveguide devices. Since CdTe is a semiconductor that can be made either n-type, p-type, or semiinsulating, a great deal of flexibility is possible in fabricating CdTe-based devices.

Optical waveguides are readily formed in high-conductivity n^+ -CdTe by using high-energy proton bombardment to produce low-carrier-concentration, high-refractive-index surface layers [1]. The thickness (t) of these layers is slightly greater than the well-

defined proton range (R) in CdTe, which for proton energies (E_p) from 0.7 to 5 MeV is given by

$$R (\mu\text{m}) = 13.5 (E_p)^{1.5}. \quad (1)$$

The refractive index of n^- -CdTe layers is increased because free carriers make a negative contribution to the dielectric constant

$$\epsilon_{fc} = - \frac{N_e^2 \lambda^2}{4 \pi^2 c^2 m^*} \quad (2)$$

where N is the carrier concentration, λ is the wavelength in free space, and m^* is the carrier effective mass. For example, removing the carriers from n^+ -CdTe with $N = 1.8 \times 10^{18} \text{ cm}^{-3}$ increases the refractive index at 10.6 μm by 0.3, from 2.37 to 2.67. This large index difference gives strong optical confinement in the n^- waveguide layer.

We have used n^-/n^+ CdTe waveguides produced by proton bombardment as the base for the fabrication of acoustooptic and electrooptic modulators for CO_2 laser radiation. These waveguides have very low optical propagation losses at 10.6 μm (Ref. [2]). Since the losses result primarily from free-carrier absorption of the evanescent tail of the optical wave

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that penetrates into the n^+ substrate region, the waveguide attenuation decreases strongly with increasing guide layer thickness, varying for example from about 10 dB/cm for $t = 15 \mu\text{m}$ to about 1 dB/cm for $t = 40 \mu\text{m}$ for TE_0 and TM_0 propagation modes at 10.6 μm .

2. Acoustooptic modulators. — When an optical beam in a condensed medium is intercepted by an acoustic beam, part of the optical beam can be deflected by diffraction, with an accompanying frequency change that is equal to the acoustic frequency [3]. For efficient acoustooptic diffraction the angle θ between the propagation direction of the incident optical beam and the acoustic wavefronts must satisfy the Bragg condition

$$\sin \theta = \frac{\lambda}{n} \left(\frac{1}{2\lambda_a} \right) = \frac{\lambda f}{2nv_a} \quad (3)$$

where λ_a is the acoustic wavelength, f is the acoustic frequency, n is the refractive index, and v_a is the acoustic velocity. For the case of plane optical and acoustic wavefronts the diffraction efficiency is approximated by

$$\eta = \frac{1}{2} \left[\frac{\pi L}{\lambda \cos \theta} \right]^2 M_2 P_a \quad (4)$$

where L is the width of the acoustic beam, P_a is the acoustic power density and M_2 is a figure of merit for the diffraction medium given by

$$M_2 = \frac{n^6 p_{\text{eff}}^2}{\rho v_a^3} \quad (5)$$

with p_{eff} the effective elasto-optic coefficient and ρ the density of the medium.

Surface acoustic waves can provide near-optimal power overlap with an optical beam propagating in a waveguide, because the energy of a Rayleigh surface wave is contained in a penetration depth equal to about half its wavelength. The particle motion of such a wave is retrograde elliptical in nature, so that complex variations in strain as a function of depth are associated with both strain components. An exact calculation of the efficiency of Bragg diffraction of a guided optical wave by a Rayleigh wave would require an overlap integration taking into account all the components of the elasto-optic tensor. However, eq. (4) can be used to obtain a reasonable estimate of the efficiency from the average acoustic power density in the waveguide region.

Acoustooptic waveguide modulators were prepared on thin n^+ -CdTe samples with dimensions of about $0.7 \times 10 \times 20 \text{ mm}$. The broad faces were (111) planes, and the length of the samples was in the $[1\bar{1}0]$ direction, so that the two end faces could be cleaved. A surface wave transducer consisting of 40 pairs of interdigital gold electrodes 2.5 mm long with a periodicity of 50.8 μm was fabricated on one of the polished (111) faces, which had been coated with a 1 μm thick

layer of sputtered ZnO. The ZnO overlay structure is necessary to obtain a reasonable efficiency for the conversion of electric to acoustic power. The transducer, which launched Rayleigh waves along the $[11\bar{2}]$ direction, had a peak radiation resistance of 3.5 Ω at 26.9 MHz, with a bandwidth of 0.7 MHz. For an acoustic wavelength of 50.8 μm this resonant frequency implies a surface wave velocity of $1.37 \times 10^5 \text{ cm/s}$, in agreement with the value calculated from the bulk elastic constants of CdTe. Series resistance of 5 to 10 Ω in the gold fingers limited the transducer conversion efficiency to about 3 % and the input electrical power for cw operation to less than 1 W.

After transducer fabrication, an optical waveguide 22 μm thick was formed just below the ZnO layer by bombardment of the CdTe at room temperature with 1.31 MeV protons. This thickness closely matches the penetration depth of the 27 MHz Rayleigh waves. Modulator evaluation was performed by focusing a CO_2 laser beam on one of the cleaved (110) end faces and using a high-speed HgCdTe photodiode to measure the change in the optical transmission through the waveguide when RF signals were applied to the transducer. Figure 1 shows the modulation of the

FIG. 1. — Oscilloscope display showing modulation of a 10.6 μm optical beam in a CdTe waveguide produced by 27 MHz surface acoustic waves.

incident laser beam produced by a 7 μs , 18 W RF pulse. Note that over 8 % of the radiation is diffracted out of optical beam by the acoustic waves. As much as 70 % of this diffracted radiation has been detected by moving the photodiode to the Bragg angle.

The modulation efficiency measured for 18 W RF excitation is plotted in figure 2 as a function of the angle of incidence of the laser beam on the cleaved face. The modulation exhibits the strong angular dependence characteristic of Bragg scattering. The angle of 11.7° between the Stokes and anti-Stokes peaks in figure 2 is in excellent agreement with the value of 11.6° for 2θ calculated from the acoustic wavelength by using eq. (3). A slight transducer misalignment and the strong acoustic beam-steering factor for the particular crystallographic orientation used are most likely responsible for the fact that the

FIG. 2. — Modulation efficiency of a 10.6 μm CdTe waveguide acousto-optic modulator as a function of incident angle of the optical beam.

pattern is not centered about normal incidence. The observed width of the two peaks is due to the large fractional bandwidth of Bragg diffraction at the acoustic frequency employed, which is near the lower frequency limit for this type of diffraction [3]. No significant increase in modulation efficiency was observed when the incident laser beam was stopped down from $f/20$ to $f/40$.

From the measured diffraction efficiency and estimated acoustic power density, the effective elasto-optic coefficient calculated from eq. (4) is about 0.05, which is close to the reported value of the shear wave coefficient, $p_{44} = 0.057 \pm 0.007$ (Ref. [4]). The agreement is not surprising, since shear displacement is the dominant Rayleigh wave motion. No indication of acoustic power saturation was seen even at the highest power levels, estimated to be about 0.5 W of acoustic beam power. Since this power level is only about one-third of the threshold for strong nonlinear acoustic effects, a cw acousto-optic modulation efficiency of about 50 % appears possible with improved transducer design and fabrication, which could reduce transducer conversion losses to less than 3 dB.

3. Electrooptic modulators. — One method of electro-optic modulation utilizes the linear change in the refractive index of a crystal caused by an applied electric field to produce a phase shift in the optical beam [5]. The magnitude and sign of the index change depend on the directions of the applied field, optical polarization, and optical propagation relative to the crystal axes. The phase shift produced in a parallel-plate CdTe modulator by a field applied in the [100] direction for a [011] polarized wave propagating along the [011] axis is

$$\Delta\phi = 2\pi \frac{l}{\lambda} (\Delta n) = \pi \frac{n^3 r_{41}}{\lambda} \frac{l}{t} V_b \quad (6)$$

where l is the modulator length, r_{41} is the electrooptic coefficient ($5.3 \pm 0.6 \times 10^{-12}$ m/V for CdTe at 10.6 μm , Ref. [6]), t is the modulator thickness (plate separation), and V_b is the applied voltage. In non-

waveguide modulators, diffraction effects limit the practical value of l/t to about 30 at 10.6 μm .

Electrooptic waveguide modulators were prepared on heavily doped ($\sim 10^{18} \text{ cm}^{-3}$) n^+ -CdTe samples with about the same dimensions used for the acousto-optic devices. The broad faces were (100) planes, and the length was in the [011] direction. The modulators were fabricated by plating a gold Schottky-barrier modulator electrode on one of the (100) faces, then bombarding the sample at room temperature through the gold with 1.31 MeV protons. The gold electrode was 1.7 mm wide and 14 mm long, aligned in the [011] direction. The n^+ -CdTe substrate served as the second modulator electrode. The electrical characteristics of the gold-CdTe structure are significantly changed by bombardment, but the barriers still exhibit diode-type behavior, with limiting forward resistance indicating a bombarded-layer resistivity of $5 \times 10^6 \Omega \cdot \text{cm}$ and reverse breakdown voltages as high as 100 V. Zero-bias capacitance measurements revealed a 22 μm thick surface layer fully depleted of charge carriers. For a gold-CdTe barrier height of 0.7 eV (Ref. [7]), this depletion depth yields an average flat-band carrier concentration of less than $3 \times 10^{12} \text{ cm}^{-3}$ in the bombarded layer. There is a wide variation in resistivity within the layer, since we have found that the carrier removal efficiency varies inversely as proton energy, giving rise to a large peak in resistivity at the end of the proton path.

To make phase modulation measurements on the waveguide modulators, a CO_2 laser beam was coupled into the guide by focusing onto one of the cleaved end faces of the sample and exciting the TE_0 waveguide mode. This mode had 9 dB propagation loss in the 2 cm path through the waveguide, including less than 1 dB loss due to the gold electrode. The output beam from the modulator was heterodyne detected with a HgCdTe photodiode by using a second CO_2 beam offset in frequency by 40 MHz to generate a beat signal that was measured with an oscilloscope. The oscilloscope traces in figure 3 show the phase shift produced by applying 10- μs , 5 % duty cycle, negative

FIG. 3. — Oscilloscope display of a CO_2 laser heterodyne beat signal intermittently phase-shifted by a CdTe waveguide electro-optic modulator.

voltage pulses to the gold electrode. In this experiment, 105 V bias pulses gave a phase lag of 110 deg.

Figure 4 shows the phase shift measured for two different waveguide modulators as a function of bias

FIG. 4. — TE_0 mode phase shift of two n^-/n^+ -CdTe waveguide electrooptic modulators as a function of bias voltage.

voltage. As expected, the phase shift increases linearly with voltage. The measured values are only slightly lower than those calculated from eq. (6) for the length to thickness ratio $l/t = 636$. This close agreement indicates that the proton-bombarded layers are of high crystal quality, as is also shown by their excellent cleavage properties. Although the field distribution in the waveguides is not expected to be highly uniform, the performance of the modulators does seem to correlate well with the average field given by V_b/t .

The usefulness of n^-/n^+ CdTe waveguide modulators with guide layers less than about 20 μm thick would be limited because of their high propagation loss, which exceeds 5 dB/cm. For a given modulation factor, which requires a fixed length to thickness ratio, the total propagation loss is decreased by increasing the thickness, since the necessary increase in optical pathlength is more than offset by the decrease in absorption coefficient. For example, a modulator 4 cm long and 45 μm thick should have a total propagation loss of less than 3 dB and a modulation factor of over 1.5 deg/V. Moreover, if a narrow rib waveguide structure were used to confine the radiation in the waveguide plane, the device capacitance could be reduced to less than 5 pF, giving the modulator a subnanosecond response time capability.

4. Conclusion. — Both the acoustooptic and the electrooptic CdTe waveguide modulators require substantially less drive power than their bulk counterparts. The acoustooptic modulator is similar in efficiency to bulk germanium devices ten times its length. The electrooptic phase modulation of over 1 deg/V measured in the CdTe waveguide modulators is some twenty times that obtained in the best bulk electrooptic devices, and more than twice that reported for GaAs waveguide modulators [8]. The performance of both the acoustooptic and electrooptic modulators should be greatly improved at shorter wavelengths, since their power efficiencies are proportional to $1/\lambda^2$.

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