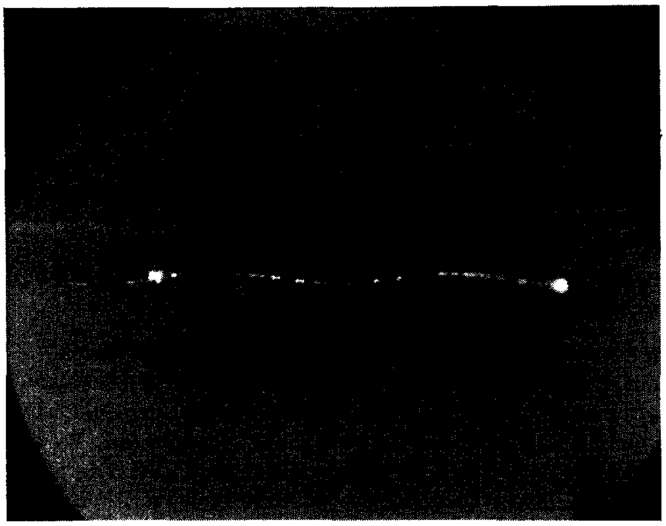

FIG. 4. Scattered light from 50-μm guide. Input spot on right-hand edge. Bright spot at left-hand side is a scattering center, probably a defect in the guide. "Amplitude" of sinusoidal path is approximately 50 μm.

stability at the diffusion temperature. 50-μm-diam glass fibers and 160-μm-diam copper wire were initially used to shadow mask the substrate from the SiO evaporation. Figure 2 shows the 50-μm-wide 10-μm-deep guide by scattered light. Figures 3(a) and 3(b) show the near-field output intensity from the 50- and 160-μm guides, respectively. Total length of these waveguiding regions was approximately 6 mm. Losses in these guides were found to be 10 dB/cm from scattered-light measurements. The chief scattering source was the thermally etched surface of the diffused region. Improvement in the surface quality of the guides was obtained by lowering the temperature, including an excess of equilibrium amount of ZnSe powder in the ampoule, and shortening the diffusion times. Silica fibers were used to produce 10-μm-wide by 3-μm-deep guides 5 mm long whose losses were less than the background threshold of the measuring apparatus which was approximately 3 dB/cm for guide lengths much less than 1 cm. The lack of substrates with large single-crystal regions was the only limiting factor on the total guide length.

The refractive index gradients (assumed to be approximately error function arising from an infinite source diffusion) in the edges of the waveguides give rise to an interesting new effect: The beam path in a large three-dimensional diffused guide closely resembles the light propagating in a self-focusing fiber optic guide.[12] Figure 4 shows the smoothly sinusoidal path of the light beam through a 50-μm-wide 10-μm-deep guide by its scattered light. Changing the input spot position changes the "phase" and "period" of the light path.

All of the guides described here are multimode due to large refractive indices in the guiding region as compared to the substrate for given guide dimensions. Refractive index and/or composition vs depth measurements are needed to accurately characterize mode propagation in these diffused structures and are being pursued. Waveguides with smaller geometries (4 μm wide by 2.5 μm deep with small surface compositions) have been fabricated in (Zn, Cd)Se, but their mode properties have not yet been adequately characterized. Better masking techniques and knowledge of diffusion parameters should produce marked improvement in the performance of diffused optical waveguides.

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High-power effects in nonlinear optical waveguides

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(Received 24 May 1972; in final form 5 July 1972)

ZnO optical waveguides have been found to withstand power fluxes up to 10^{11} W/cm^2 in picosecond pulses before damage occurred. Under the high power, a TE_0 mode at 1.06 μm generated a TM_1 mode at 0.53 μm. A ray theory of second-harmonic generation in waveguides has been developed and the experimental results are compared with it.

In the experiments to be described, high-power picosecond pulses at 1.06 μm were coupled into ZnO optical waveguides. No work on waveguides at such high powers has been previously reported. The samples were fabricated by sputtering ZnO onto fused quartz substrates.[1,2] On one sample that was studied extensively, electron micrographs of the surface showed, apart from a small-scale (~250 Å) graininess, many plateaus up to perhaps 10 μm across, about 300 Å higher than the background and smoother. The average thickness measured by a Talysurf was 0.47 μm. With a Debye-Scherrer camera the c axis of each crystallite was found to be oriented within 5° of the normal to the substrate.

The incident radiation consisted of a pulse train of 1.06-μm picosecond pulses from a mode-locked Nd-doped glass laser. The pulses are spaced 5 nsec apart in an envelope about 200 nsec wide.[3] A 2-mm beam was focused into the sample with a 12.5-cm lens. The incident power $I(\omega)$ was varied with calibrated attenuators and monitored with a photodiode.

Optical coupling was accomplished by means of photoresist gratings[4] with 6.35 mm between the input and output couplers. A low-power cw YAG laser was used in measurements of the input efficiency[4] with the relative power coupled out. Assuming that all the transmitted energy is coupled out at the output coupler,[2] we conclude that the loss at 1.06 μm is about 10 dB/cm. The guide had only one TE mode at 1.06 μm, presumably a TE_0 mode. The ratio of the speed of light in vacuum to that of mode propagation in the guide, n_{eff}, measured in the conventional way,[4] was compared to the theoretically calculated value based on bulk indices. Crude corrections were made here and in all the other theoretical calculations to take into account the loading of the film by the photoresist. The resulting n_{eff} was in fair agreement with the experimental value for the TE_0 mode.

With the picosecond pulses it was more difficult to find the optimum angle for feeding in the TE_0 mode, mainly because the laser repetition rate was only 1/min. In our technique the angle was first set crudely by maximizing the waveguiding trace intensity as visualized with an image converter, then finely by maximizing the output coupled beam, which was detected with a photomultiplier. The resultant n_{eff} was 1.802, agreeing within experimental error with that measured at low power. A calibration of the photomultiplier with a thermopile showed the maximum output power to be ~8 kW. Assuming that all the energy in the mode was coupled out and using a beam width of 300 μm at the output coupler, we find the power flux in the TE_0 mode at the output to be 6×10^9 W/cm^2. With 100 μm as the diameter of the input spot, this leads to a power flux at the input coupler of $\sim 8\times 10^{10}$ W/cm^2, based on the assumption that the loss at high power is the same as that measured at low power. (Output power increased linearly with input, within experimental error, at high power.) For powers ~3 dB greater than this value, visible damage, probably due to melting and evaporation, occurred in a region several hundred μm around the focused spot. Microscopic investigation showed damage in both the photoresist and the ZnO film, never just in the photoresist alone, implying that the ZnO film damages first. No visible damage occurred for conditions off waveguiding.

Second-harmonic generation (SHG) was observed in the two guides studied. It was reported previously for ultrathin GaAs slabs at ~10 μm,[5] but the modes could not be identified. We found that a green harmonic was coupled out into a sufficiently intense beam (0.16 W) to be observed visually. The beam polarization identified the mode as TM, and n_{eff} was measured as 1.758. Low-power cw measurements indicated the guide had two and possibly three modes at 0.53 μm with n_{eff}'s of ~1.97, ~1.77, <1.49, presumably TM_0, TM_1, and TM_2, respectively, in rough agreement with theory. Thus, the second harmonic is identified as a TM_1 mode. Spectrometer measurements showed the wavelength to be 0.53 μm. For conditions just off waveguiding, the harmonic disappeared. The harmonic beam emanated from the input coupler. A photograph showed the green TM trace was ~100 μm wide and 300 μm long, traveling only in the input coupler region and not in the bare ZnO beyond. This suggests that phase-matching conditions were better satisfied under the photoresist. We found the harmonic power $I(2\omega)\propto I^2(\omega)$ over four orders of magnitude in $I(2\omega)$.

In our theoretical discussion of SHG of guided waves, unless otherwise specified, we use the coordinate system and notation of Ref. 1. Anisotropy of the dielectric constant, small in the case of ZnO, is neglected. We assume that a TE mode propagates in the ZnO film at the fundamental frequency ω with the electric field given by

$$\mathbf{E}_1(\omega)=\hat{\mathbf{e}}_y\{\mathcal{E}_1^+(\omega)\exp[ik_{1z}(\omega)z]+\mathcal{E}_1^-(\omega)\exp[-ik_{1z}(\omega)z]\}\times\exp\{i[k_{1x}(\omega)x-\omega t]\}, \tag{1}$$

where $\hat{\mathbf{e}}_y$ is a unit vector in the y direction and amplitudes $\mathcal{E}_1^+$ and $\mathcal{E}_1^-$ replace B and A of Ref. 1, respectively. For the film orientation with c axis along z, this mode creates a nonlinear polarization $\mathbf{p}^{NLS}(2\omega)=\hat{\mathbf{e}}_z\chi_{32}E_1^2(\omega)$. The nonlinear polarization gives rise to a source term in Maxwell's equations for the film medium.[6] The solution of the resulting wave equation for 2ω consists of a solution of the homogeneous equation (free wave) varying as $\exp\{i[k_{1x}(2\omega)x-2\omega t]\}$ and a particular solution (forced wave) varying as $\exp\{i[2k_{1x}(\omega)x-2\omega t]\}$.[6] The electric field of the forced solution is found to have x and z components, from which it can be concluded that it will feed only free waves of TM symmetry,[7] as was observed.

From the conditions that the tangential components of $\mathbf{E}$ and $\mathbf{H}$ at 2ω must be continuous at the film boundaries, we conclude that $k_{1x}(2\omega)$ must equal $2k_{1x}(\omega)$. Phase matching requires that $2k_{1x}(\omega)$ coincide with a value for a guide mode at 2ω. Following the waves at 2ω through two successive reflections and applying the boundary conditions, we find a simple relation between the amplitude $\mathcal{E}_1^-$ and the amplitude $\mathcal{E}_1'^-$ of the wave traveling in the same direction after two reflections,

$$\begin{aligned}\mathcal{E}_1'^-=\mathcal{E}_1^-\exp(i\Delta)+i\exp(i\phi_{10})&\\ \times(\exp(2im'\pi)\{G[\phi_{10}(\omega)]\sin\phi_{10}-F[\phi_{10}(\omega)]\cos\phi_{10}\}&\\ +\exp(im'\pi)\{G[\phi_{12}(\omega)]\sin\phi_{12}-F[\phi_{12}(\omega)]\cos\phi_{12}\}),&\end{aligned} \tag{2}$$

where

$$\Delta=2k_{1z}W-2\phi_{10}-2\phi_{12}\equiv 2m'\pi, \qquad \text{(Ref. 1)} \tag{3}$$

$$F(\phi)=\frac{8\pi\chi_{32}|\mathcal{E}_1^-(\omega)|^2}{\epsilon_1(2\omega)-\epsilon_1(\omega)}\frac{\epsilon_1(\omega)}{\epsilon_1(2\omega)}\sin\theta_1\frac{\cos\theta_1}{\cos\theta_2}\sin2\phi, \tag{4a}$$

$$G(\phi)=\frac{8\pi\chi_{32}|\mathcal{E}_1^-(\omega)|^2}{\epsilon_1(2\omega)-\epsilon_1(\omega)}\left(\frac{\epsilon_1(\omega)}{\epsilon_1(2\omega)}\right)^{1/2}\times\sin\theta_1\left(\cos2\phi+\frac{\epsilon_1(2\omega)-\epsilon_1(\omega)}{\epsilon_1(2\omega)-\epsilon_1(\omega)\sin^2\theta_1}\right). \tag{4b}$$

W and ϵ_1 are the width and dielectric constant of the film, respectively, and θ_1 and θ_2 the angles with the z axis made by the fundamental and harmonic, respectively. Unless otherwise specified, all quantities in Eqs. (2) and (3) relate to 2ω. If 2ω is a guide mode, m', defined by Eq. (3), must be an integer. It is then apparent from Eq. (2) that in a symmetric guide, where $\phi_{10}=\phi_{12}$, there would be no SHG of odd modes. For the particular parameters of our system, which was, of course, nonsymmetric, if the two terms in braces in Eq. (2) had been additive, the power generated at 2ω would have been larger by a factor $\sim 5\times 10^2$.

Expression (2) gives the complex gain in amplitude in the distance $2W\tan\theta_2$, one "zigzag". For m', an integer, the increments in successive zigzags add in phase. If we neglect the depletion of the fundamental, since the amount of 2ω generated is relatively small, the amplitude of 2ω after travel through a distance L (starting from negligible amplitude at $x=0$) may be obtained by multiplying the second term in Eq. (2) by $L/2W\tan\theta_2$. The power at L in the guide mode at 2ω may then be calculated from the usual expression for a TM mode.[8] It can be seen from this that $I(2\omega)\propto I^2(\omega)$.

For the non-phase-matched case, let $2m'\pi=2m\pi+\delta$, where m is an integer and $|\delta|<\pi$. The increment in each zigzag then differs in phase by δ from that in the previous one. This results in successive regions of constructive and destructive interference, as in bulk SHG.

The measured n_{eff} values (1.802 for ir, 1.758 for green) represent some sort of average over the distance sampled by the observation, ~ 100 μm. Both output beams emerge in relatively small solid angles, too small for any overlap of n_{eff}'s. The results can nevertheless be reasonably explained by postulating that there was matching of n_{eff}'s, or phase matching, over some portion of the 300-μm green track, too small to be seen in the n_{eff} measurements. From the theory described above, the generation of 0.16 W in the green would require a distance of about 20 μm or less, in which ir and green are phase matched. Phase matching over such a distance could be brought about if a couple of suitably located plateaus of the type mentioned earlier were included in the 300-μm track. Upon emerging from such a phase-matched region into one with W differing only slightly, most of the generated green would be transmitted as a mode suitable to the new W.

It is possible, although less likely, that the observed green intensity could have been produced with the measured n_{eff}'s prevailing throughout, i.e., without phase matching. The experimental resolution was such that periodic bright and dark regions spaced by 25 μm or less would not have been detectable in the photograph of the green TM trace. 25-μm spacing would correspond to $|\delta|=0.2$. For this $|\delta|$, the calculated power in the bright regions would still be $\simeq 0.16$ W. With increasing $|\delta|$, the generated power goes down fairly rapidly. The value of $|\delta|$ calculated from the observed difference in n_{eff}'s, using bulk indices, is larger than unity. However, both $|\delta|$ and the generation rate are sensitive to the values of all the indices, and the possibility of accounting for the results without invoking phase matching cannot be ruled out. For the TM_0 and TM_2 green modes, the n_{eff}'s are further still from the 1.802 value of the ir. Thus, despite their being even modes, they are too far from phase matching to be seen.

The authors thank M. Dakss and L. Hope for numerous valuable conversations, W. Lee for providing the ZnO film, T. Emma and C. Tufts for material analysis, A. Riesinger for a mode computer program, and L. Vivenzio, S. Hussain, and T. Illing for technical assistance.

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Determination of deep energy levels in Si by MOS techniques

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(Received 15 May 1972)

Ions are implanted into a Si-SiO_2 interface. If the distribution is several hundred angstroms wide, the ions create interface states at energies corresponding to their bulk levels. With most elements investigated, agreement with previous data is good. Energy levels of the elements Se, Be, Cd, Sn, Ti, Pb, S, C, Ba, Ta, V, Mn, Cs, and Ge were determined by the MOS technique.

Characterization of deep levels in semiconductors is usually a very time-consuming and tedious task. First, the atomic species to be investigated has to be incorporated into the crystal, then the activation energy of conductivity is determined. Optical techniques, as an alternative, have not been very successful in silicon, while, for fast-diffusing impurities like Au, p-n junction techniques have recently been applied.[1,2]