second harmonic. This postulate is substantiated by the facts that the conversion efficiency at maximum laser intensity was still rising slowly and that there was considerable spatial structure in the output beam. Fourth and higher order terms might also be contributing to the second harmonic and modifying its dependence upon laser intensity.

KDP was found to be a somewhat better doubling material than ADP, both by Savage and Miller,[4] and by us. However, KDP was much more readily damaged by the focused laser beam than was ADP, probably because it absorbs third and fourth harmonics while ADP does not.

In view of the uncertainties associated with the intensity distribution at the focus, only qualitative values for actual nonlinearity coefficients may be inferred. Assuming an ideal focus, the matrix element for second harmonic generation in ADP is 3×10^{-10}, in good agreement with the calculations by Klienman[5] for KDP. Due to the spatial divergence of the red extraordinary and ordinary rays,[2] estimates of the calcite matrix element for tripling are even more uncertain. Using the present data, our best estimate for this number is 10^{-16}.

It appears that harmonic generation is an excellent technique for obtaining laser beams at shorter wavelengths, particularly in the uv region. The power output of our laser was considerably below that reportedly available.[6] Presumably with these higher peak powers, third harmonic conversion efficiencies in the precent range could also be obtained.

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DIELECTRIC-WAVEGUIDE MODE OF LIGHT PROPAGATION IN *p-n* JUNCTIONS

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INDEXING CATEGORIES

A. lasers

A. *p-n* junctions

B. dielectric-waveguide

effect

T

The condition for coherent laser emission from forward-biased *p-n* junctions[1-3] can be written as[4]

$$\frac{I_c}{A} = \frac{8\pi e \nu^2 d\Delta\nu}{\xi\eta c^2}(l + l'), \tag{1}$$

where

I_c/A = injected current density at threshold
ν = emitted frequency,
$\Delta\nu$ = spontaneous emission linewidth,
l = loss constant of the medium bounding the junction,
l' = effective increase in l due to the finite transmission loss of the boundaries,
η = quantum efficiency of the radiation process (photon/injected carrier),
ξ = $1 - N_1/N_2$, where N_1 and N_2 are the populations of the lower and upper levels, respectively, responsible for the emission process,
d = penetration depth of the electromagnetic field away from the junction.

In order for the reported values[1-3] of I_c/A to agree with Eq. (1), one must use values of $d \sim 50\ \mu$.[4] The question arises as to the nature of the mechanism which could confine the light generated near the

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junction to such small distances. The presence of free-charge carriers in the p and n regions and their absence from the depletion layer leads to a discontinuity in the real part of the dielectric constant at the junction boundaries which can indeed give rise to energy confinement via the dielectric-waveguide effect.[5] If we let K stand for the ratio of the dielectric constant in the p and n regions to that in the depletion layer, take the thickness of the depletion layer as $2t$, and use the coordinate system shown in Fig. 1, it can be shown that the junction can support both TE and TM waves.[5]

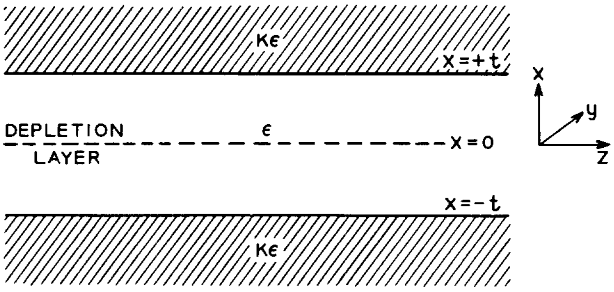

Fig. 1. Model of p-n junction.

The components of the even TE wave are:

$$E_y = A \exp\left[-p(|x| - t) - j\beta z\right] \qquad |x| > t;$$

$$E_y = B \cos(hx) \exp(-j\beta z) \qquad |x| < t \,. \tag{2}$$

The remaining field components are

$$H_x = -\frac{\beta}{\omega\mu} E_y;$$

$$H_z = \frac{j}{\omega\mu}\frac{\partial E_y}{\partial x} \,. \tag{3}$$

The condition

$$(pt)^2 + (ht)^2 = (K-1)(kt)^2 \,, \tag{4}$$

where $k = \omega/c$ follows directly from the wave equation. The continuity of E_y and H_z at $|x| = t$ yields

$$pt = ht \tan(ht) \,. \tag{5}$$

Restricting the problem to cases where $ht << 1$ and $4(K-1)(kt)^2 << 1$, we obtain

$$p = (K-1)k^2 t \,. \tag{6}$$

There are a number of contributions to the discontinuity in the dielectric constant. If we denote the conductivity of the p and n regions by σ_2 and that of the depletion layer as $-\sigma_1$ (the minus sign accounts for the fact that in the immediate vicinity of the junction, light is generated rather than being absorbed) and if, furthermore, we characterize the carrier density in the p and n regions by

$$\omega_p = (Ne^2/m^*\epsilon^{(0)})^{1/2}$$

where N is the carrier density, we can write[6]

$$K = 1 + \frac{\omega_p^2}{\omega^2}\left[1 + \frac{\sigma_1\sigma_2}{(\omega\epsilon^{(0)})^2}\right] + j\,\frac{\sigma_1}{\omega\epsilon^{(0)}} \tag{7}$$

for $\sigma_1 >> \sigma_2$ and $\omega_p^2/\omega^2 << 1$.

The penetration depth d is defined as

$$d = \frac{1}{Re(p)} \,, \tag{8}$$

which, using Eqs. (7) and (8) is given by

$$d_{\mathrm{TE}} = \frac{c^2}{\omega_p^2 t} \,, \tag{9}$$

where the condition $\sigma_1\sigma_2/(\omega\epsilon^{(0)})^2 << 1$ has been assumed and c is the velocity of light in the medium.

For a typical GaAs degenerate junction with $2t = 0.1\ \mu$ and $N_e = 10^{18}\ \mathrm{cm}^{-3}$, Eq. (9) yields $d = 45\ \mu$.

For the same diode we estimate:

$$\omega_p^2/\omega^2 \sim 6 \times 10^{-4} \,,$$

$$\sigma_1/\omega\epsilon^{(0)} \sim 10^{-2} - 10^{-3} \,,$$

$$\sigma_1 \sim 100\,\sigma_2 \,,$$

$$4(K-1)(kt)^2 \sim 5 \times 10^{-3} \,,$$

$$(ht)^2 \sim 2 \times 10^{-3} \,,$$

so that the inequalities used in deriving Eq. (9) are fulfilled.

A similar analysis for the TM waveguide ($\bar{E}$ normal to the plane of the junction) yields

$$d_{\mathrm{TM}} = \frac{c^2}{\omega_p^2 t}\left(1 + \frac{\omega_p^2}{\omega^2}\right) \tag{10}$$

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Since the laser threshold is, by Eq. (1), proportional to *d* and since $\omega_p^2/\omega^2 \sim 6 \times 10^{-4}$, we would expect essentially equal thresholds for laser oscillations in TE and TM polarizations.

In closing we note that although the dielectric confinement mechanism is, along with the high recombination efficiency, the main reason for the occurrence of laser action in *p-n* junctions, the mechanism postulated above should be operative in any *p-n* diode with or without biasing current. As a matter of fact, the experimental verification of the dielectric-waveguide effect in *p-n* junctions was obtained on nonlasing GaAs diodes.[7]

Useful comments and suggestions by J. K. Galt, R. Kompfner, and J. M. Whelan are gratefully acknowledged.

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OBSERVATION OF THE DIELECTRIC-WAVEGUIDE MODE OF LIGHT PROPAGATION IN *p-n* JUNCTIONS

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Theoretical considerations of the propagation of electromagnetic energy near a *p-n* junction[1] show that the "sandwich" formed by having a depletion layer bounded by the *p* and *n* regions can act as a dielectric waveguide.[1,2] The confinement of the energy is due to a dielectric discontinuity

$$\delta\epsilon = \epsilon^{(0)}\left(\frac{\omega_p^2}{\omega^2}\right)$$

between the depletion layer and the bounding media. ω_p, the plasma frequency due to free charge carriers, is assumed, for simplicity, to be the same on the *p* and *n* sides. This is not far from reality for the GaAs junctions described in this Letter.

INDEXING CATEGORIES	
A. lasers	E/T
A. *p-n* junctions	
A. GaAs(Tl)	
B. dielectric-waveguide effect	

The junction waveguide supports both TE and TM propagation. Since the dielectric discontinuity as given by Eq. (1) is very small, $\omega_p^2/\omega^2 \sim 10^{-3}$ is a typical value in degenerate junctions, the lateral dimension (in a direction normal to the junction plane) of these waves is far larger than the thickness of the depletion layer. The decay of the energy density in the normal direction is described by e^{-2px} where p is given by

$$p = \frac{\omega_p^2 t}{c^2}, \tag{1}$$

where $2t$ is the junction thickness and c is the velocity of propagation in the medium.

If we define a penetration depth d as the distance between the two points at which the energy density is down to $1/e$ of its value at the junction we get

$$d = \frac{c^2}{\omega_p^2 t}. \tag{2}$$

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