Fig. 4. Computed energy extraction versus incident pulse energy density for an amplification length \( L = 1 \text{ m} \), TIL = 0.15 ns, and a small signal gain \( Q = 0.046 \text{ cm}^{-1} \): curve 0, \( m = 0.023 \text{ cm}^{-1} \); curve 0.

ACKNOWLEDGMENT

The authors wish to thank P. Vincent for help with the computations and P. Cottin and M. Huguet for technical assistance.

REFERENCES


in a three-layer form (thin-film deposition [7]) and in a graded-index form (by diffusion [SI]-[10]).

In this correspondence we have developed a first-order perturbation approach for determining the propagation constants for a truncated square-law medium. The profile is shown in Fig. 1(a). This study enables one to find the effect of cladding on the propagation constants of an infinitely extended square-law medium. The perturbation approach has also been applied to a complimentary error-function distribution which has been assumed to be a perturbed form of an exponential distribution. These types of distributions are found in waveguides formed by diffusion techniques [9].

II. THEORET

A. Cladded Square-Law Medium

For a cladded square-law medium, the refractive-index distribution \( n(x) \) would be given by

\[
\begin{align*}
  n(x) & = n_1^2 + A \left( -x^2/a^2 \right)^{2/2}, & |x| \leq a \\
  & = n_2^2, & |x| > a.
\end{align*}
\]

We will carry out an analysis of the TE modes of such a waveguide. If for \( Ey \) we assume a solution of the form

\[
Ey = \#(x) \exp \left[ i(wt - Pz) \right]
\]

then \( I \) can be shown to satisfy the following equation

\[
\frac{d^2\psi}{dx^2} + (n''(x)k^2 - \beta^2)\psi = 0
\]

where all symbols have their usual meaning.
B. Perturbation Theory for Lowest Order Modes

In order to study the effect of cladding on the lowest order modes we write the wave equation in the form

$$\frac{d^2 \psi}{dx^2} + [n^{(0)}(x) + n'\chi(x)]k^2 - \beta^2 \psi = 0 \quad (3)$$

where $n^{(0)}(z) = n_0^2 - Ax/a_2$ and $n'(z)$, which is to be considered as the perturbation, is zero for $1.1, n^{(0)}(z) = n^{(2)}(z)$ when $n^2(x) = 0$ are the well-known Hermite-Gaussian functions.

In first-order perturbation theory the propagation constants would be given by

$$\beta_n^2 = ft^{(0)} + \beta_n^{(0)} = \left[ n_0^2 k^2 - k \frac{\sqrt{A}}{a} (2n + 1) \right] + \left[ k^2 \int_a^\infty n'(x) \mid \psi^{(0)} \mid^2 \ dx \right]. \quad (4)$$

The integral appearing in (4) can always be put in terms of error functions. For example, for $n = 0$, $p(0)$ would be given by

$$\beta_n^{(0)} = \frac{k_0}{2} \left[ \left( \frac{A}{2k_0} - g^2 \right) \text{erfc} (\xi_0) + \frac{g^2}{\sqrt{\pi} \xi_0} \exp (-\xi_0^2) \right] \quad (5)$$

where $\xi_0 = (2a/x)$ and erfc represents the complimentary error function. Similarly, one can calculate the perturbation for higher order modes. For the lowest, order mode, the group velocity would be given by

$$V_g = \frac{\partial \beta_n}{\partial k} \left[ n_0 \chi - \sqrt{\frac{A}{2k_0}} + \left( \frac{A}{2k_0} + n_1^2 - n_2 \chi \right) \text{erfc} (\xi_0) \right] + \frac{k_0}{2 \pi} \left( \frac{A}{2k_0} + g^2 - A \right) \exp (-\xi_0^2) \quad (6)$$

where $n_\chi = n(1 - (X/n_\chi)(dG/dX))$.

C. Perturbation Theory for Modes Near Cutoff

For the analysis of modes near cutoff we assume $n(0)'(x)$ and the perturbation $n'(x)$ to be given by

$$n'(x) = n_2^2 - n_1^2 \chi, \quad [\chi < \chi_c] = 0, \quad [\chi > \chi_c] = \chi_c$$

The modes #0 of the unperturbed wave equation are well known [1]. The unperturbed propagation constants $\beta(0)$ can be obtained from the solution of the following transcendental equation [1]

$$7 \tan \chi_c = 6 \quad \text{symmetric modes}$$

$$\cot \chi_c = -6 \quad \text{antisymmetric modes} \quad (8)$$

where $y^2 = n_1^2 k^2 - p^2$ and $y^2 = n_1^2 k^2$. The perturbation in the propagation constant would be given by

$$\beta^{(1)} = -L \frac{\pi A}{2k} \left[ \gamma^{(0)} \right]^2 \frac{d\chi}{dx}$$

$$= -\pi A \left[ \frac{\cos 2\gamma_\chi}{2\gamma_\chi} + \sin 2\gamma_\chi \right] \left[ 1 - \frac{1}{2\gamma_\chi^2} \right] \frac{d\chi}{dx} \quad (9)$$

where $A = (a + 1/8) - 1/2$. The upper and lower signs correspond to symmetric and antisymmetric modes, respectively. The total number of modes would be the same as in a slab waveguide with core and cladding refractive indices $n_c$ and $n_e$, respectively.

D. Some Numerical Results

We have applied the previous analysis to calculate the total number and the propagation constants of the modes propagating through GaAs p-n junctions. We have considered a distribution in between the extreme cases considered by Zachos and Ripper [111 and Rutz [12], namely parabolic in the depletion region and constant in the p and n regions. The following values have been used in the calculations: $n_c = 12.95; n_e = 12.85; A = 0.0448; a = 1 \text{pm}; h = 8383 \text{ii}$. These correspond to typical GaAs laser medium parameters. The calculated values of $\beta/\chi_c$ before and after applying the perturbation theory are shown as horizontal lines in Fig. 1(b). For the values of parameters chosen here we see that only two modes can propagate in this waveguide.

Using the perturbation theory previously dealt with one can also study the effect of cladding on the group velocity. For example, corresponding to the values of various parameters given previously, the group velocity of the lowest order mode [see (10)] would be 0.2004 where $c$ is the velocity of light, in free space. The corresponding value for an infinitely extended square-law medium is 0.196. Thus the perturbation theory predicts a 2.24% increase in the group velocity of the fundamental mode due to the presence of the cladding.

E. Perturbation Theory for Planar Waveguides Formed by the Out-Digression Technique

Some of the waveguides fabricated by Kaminow and Carruthers [a] have the following dielectric-constant profile

$$\epsilon(x) = n_2(x) = n_2(z); \quad x < 0$$

$$\epsilon(x) = n_0 + A \epsilon \text{erfc} (227\sqrt{a}), \quad x > 0. \quad (10)$$

Numerical calculations of such a profile have been reported by Smithgall and Dabby [3]. Since the above refractive-index distribution resembles the exponential distribution one can consider it to be a perturbed form of the following distribution

$$E(z) = \epsilon_{10} \quad x < 0$$

$$= \epsilon_0 + AE \exp (-z/d), \quad x > 0. \quad (11)$$

The modes for such a dielectric-constant distribution are given by $c51$

$$4 \beta = AJ_{1}(\epsilon \exp (-1/2d)), \quad x > 0$$

$$B = \epsilon \exp (P14), \quad x < 0 \quad (12)$$

where $\psi = 2k_\chi x; p_\psi = 2\pi/\chi_\psi; p = (\beta/\chi_\psi - \epsilon)k^{1/2}; \quad i = 0, 1$ and $B^{(0)}$ being the corresponding propagation constants which are determined from the solution of the following transcendental equation

$$J_{\nu+1}(\xi) - J_{\nu+1}(\xi) = -\frac{p_\psi A}{\pi \sqrt{\Delta \epsilon}}. \quad (13)$$

The constants $A$ and $B$ in (12) are to be determined from the normalization and continuity conditions. The perturbation can be assumed to be zero for $x < 0$ and $A \epsilon \text{erfc}(2\sqrt{a}) - \exp (-x/d)$ for $x > 0$. Using (12) for the unperturbed eigenfunctions we have calculated the propagation constants corresponding to the system analyzed by Smithgall and Dabby [3]. The values of various parameters are $\epsilon_0 = 2.268; \quad 4 \epsilon = 0.9185; \quad a = 0.56 \text{pm}; \quad d = 0.4767 \text{pm}; \quad k = 12. \text{pm}^{-1}$. This set of values gave $\psi = 7.500$ and $B/k = 1.6425$ for the lowest order mode. Applying the first-order perturbation theory
Nonlinear Optical Susceptibility of Thiogallate CdGaS,

B. F. LEVINE, C. G. BETHEA, ASD H. PI. KASPER

Abstract—The nonlinear optical coefficient $d_{n}$ of CdGaS,Sl was measured to be 5 times larger than $d_{n}$ (LiNbO$_{3}$). This large nonlinearity is in good agreement with theory.

INTRODUCTION

There is a large and continuing interest in tertiary chalcopyrites [1]-[3] (e.g., AgGaS$_{2}$) due to their large nonlinear optical susceptibilities $d_{n}$ and their favorable phase-matching properties. Although (as discussed in detail previously [4]) AgGaS$_{2}$ has a rather large nonlinear coefficient [3.5 times larger than $d_{n}$ (LiNbO$_{3}$)] the magnitude of $d_{n}$ is significantly reduced from the optimum possible value. The reason for this [4] is that the Ag-S bond has a negative nonlinearity which subtracts from the larger positive GaS nonlinearity, thereby reducing the net crystal nonlinear coefficient $d_{n}$ (AgGaS$_{2}$). Thus, in addition to being theoretically interesting, there could be significant device potential in investigating a similar chalcopyrite with the negative Ag-S bond replaced by a positive bond such as Cd-S. The tertiary thi’ogallate (defect chalcopyrite) CdGaS$_{2}$, should therefore have an even larger nonlinear coefficient than AgGaS$_{2}$, (as suggested previously [4]). Because of this and our success in growing good-quality single crystals of CdGaS$_{2}$, we have measured $d_{n}$ (CdGaS$_{2}$).

EXPERIMENTAL

CdGaS$_{2}$, was first reported by Hahn et al. [5] to crystallize with the tetragonal thiogallate structure (cell 7). Crystals have been grown by both vapor transport [5, 7] and by the Stockbarger method [5]. and, the optical [9, 10] and luminescence [11] properties of both pure and Cu-doped CdGaS$_{2}$, have been investigated.

Our crystals were prepared using stoichiometric amounts of 99.9999 percent pure Cd, and 0.1-mole percent of 99.9999 percent pure Ga, which were enclosed in evacuated and sealed silica ampoules. These ampoules were heated to 1060°C in a horizontal furnace and then slowly cooled at a rate of 1°C/h. Inspection afterwards showed that a melt had formed in the process. The furnace had a natural temperature gradient inside, being cooler at the ends, and therefore, nucleation began at the ends of the ampoule forming crystals by directional freezing. Crystals with dimensions up to 1 cm were grown in this manner.

Because our CdGa$_{x}$ crystals had excellent quality [1, 1. 21 growth faces, we found it convenient to use a large 1 cm plate (~1 cm$^{2}$) which was polished to a thickness of 0.3 mm for our measurements. The second-harmonic coefficient was measured with the Maker-fringe technique [1a], using a single TEM$_{00}$-mode YAG laser. The sample rotation was about a vertical axis which contained the projection of the c axis, and both the fundamental and second-harmonic fields were polarized vertically (V). The effective nonlinear coefficient (at normal incidence) for such a geometry is easily seen to be

$$d_{eff} = 3 \sin^{2} \theta \cos \phi$$

where $\theta$ is the angle between the c axis and the crystal plane. For a [1, 1, 21 plate of CdGaS, (for which $c/a = 1.808$) this angle B is 32.5°. From the Maker-fringe spacing, the coherence length at 1.064 pm was found to be

$$l_{c} = 2.10 \mu m.$$ (2)

Using Hobden’s [10] value for the index of refraction at 2a = 0.532 pm and our experimental result for $l_{c}$, we find

$$n_{s} = 3.237 \quad n_{2w} = 2.453.$$ (3)

The other linear property required is the absorption, which we found to be negligible at the fundamental and to have the value

$$a_{2w} = 0.85 \text{ cm}^{-1}.$$ (4)

at the harmonic frequency. The transparency range of 0.45-13 pm is shown in Fig. 1.

By comparing the second harmonic from the CdGaS, plate with that produced by a quartz reference [12], and making use of (1)-(4) we found

$$d_{eff} (\text{CdGaS}_2) / d_{eff} (\text{SiO}_2) = 80 \pm 15 \text{ percent.}$$ (5)

Therefore, using (13) $d_{eff} (\text{SiO}_2) = 0.80 \times 10^{-6} \text{ ESU}$ at 1.064 $\mu m$ we have

$$d_{eff} (\text{CdGaS}_2) = 64 \times 10^{-6} \text{ ESU}.$$ (6)