TWO BEAM OPTICAL SIGNAL AMPLIFICATION AND BISTABILITY IN InSb

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Received 20 June 1979

We report the application of bandgap resonant nonlinear refraction to optical amplifier and switch devices – based on a nonlinear Fabry-Perot interferometer constructed from an InSb crystal. One such device, called a "transphasor", amplifies small power changes in one laser beam to give larger changes in a second. The effects are interpreted by a microscopic mechanism which includes the effects of power broadening as a contribution to $\chi^{(3)}$ to explain its large value of $\sim 10^{-2}$ esu.

1. Introduction

The very large intensity variation of transmitted laser beam width discovered by Miller et al. [1] for frequencies just below the fundamental absorption edge of InSb has been interpreted as the defocusing effect of an intensity-dependent refractive index. Quantitative macroscopic analysis of the propagating wave-front by Weaire et al. [2] correctly predicts near- and far-field beam patterns which distinguish between focusing and defocusing and yields a value for n_2 (defined from $n = n_1 + n_2 I$) of 6×10^{-5} cm^2/W at 5 K for 1886 cm^{-1}. Arguments have been presented [1,3] to show that the nonlinear refraction is an electronic rather than a thermal effect; it should therefore respond directly to the distribution of intensity inside the crystal. One corollary is that the propagation of one laser beam can be influenced by a second if both beams traverse the same volume of crystal, and a second is that if the material is in the form of a plane parallel slab constituting a Fabry-Perot interferometer its optical thickness, and therefore transmission, will be intensity dependent. It is known that a Fabry-Perot etalon filled with a saturable absorber, such as Na vapour, can give rise to optically bistable action as first demonstrated by Gibbs [4] primarily due to refractive effects. Other nonlinear Fabry-Perot devices have been reported in ruby crystals [5], rubidium vapour [6] and in liquids [7].

In this letter we report the first realisation of an optically bistable device in a semiconductor crystal as well as observation of differential gain both in one beam and, via the modulation of the transmission of one laser beam by a second, in a two beam system. This latter device is analogous to the three terminal transistor and, operating by transferred phase thickness, we term it a "transphasor".

2. Experimental

The basic optical element is a crystal of pure InSb ($N_D - N_A \sim 10^{14}$ cm^{-3}) 580 μm thick with polished plane parallel faces held at 5 K in a helium cryostat. We examined the transmission of 1895 cm^{-1} radiation, as a function of intensity, the gaussian beam being derived from an Edinburgh Instruments PL3 cw CO laser. The intensity and beam form was precisely controlled by the combination of multilayer attenuator and spatial filter, described by Miller and Smith [8]. The results, in the form of output power versus input power, are shown in fig. 1. In the absence of intensity dependent effects this would of course be a straight line whereas, in terms of the intensity inside the interferometer, I_{int}, the transmission, T, is given by

$$T = 1/(1 + F\sin^2(\delta_0/2 + \gamma I_{int})), \qquad (1)$$

where $\gamma = 2\pi n_2 L/\lambda$ for crystal length L, and free space wavelength λ, F is the finesse and δ_0 an initial mistuning. The relation to the actual experimental parameter, the incident intensity I_0 is made by solving (1) simultaneously with

$$T = \frac{I_{int}}{I_0} \frac{1-R}{1+R}, \qquad (2)$$

where R is the reflectivity of the crystal surfaces (0.36 in our case). Eqs. (1) and (2) predict bistability above second order effects (i.e. when the intensity induced optical thickness changes by 2 $\lambda/2$ or more); we observe bistability in 5th order. The steep regions from 3rd order upwards show differential gain, i.e. the output changes more than the input, whereas the flat regions in between are insensitive to intensity change and show "limiter" action. Further details of this device are discussed elsewhere [9].

We have extended the application of the nonlinear interferometer by utilising two laser beams, either by splitting off a part of the incident beam or by use of a second CO laser. In this case use is made of the high linear refractive index (n = 4) so that refraction constrains two beams incident at slightly different angles to traverse the same crystal volume. We then find that we cannot only modulate one beam with the other but obtain real signal gain (up to ~ 10) corresponding exactly in intensity values to the "steps" of fig. 1. This differential gain is illustrated in fig. 2.

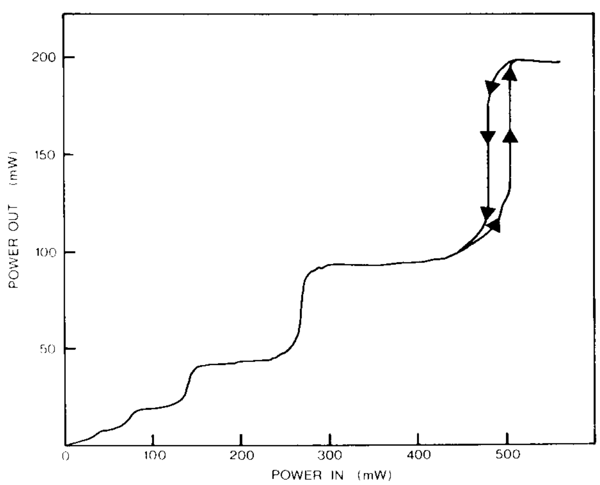

Fig. 1. Nonlinear transmission of InSb interferometer at 1895 cm^{-1} near the absorption edge at 5 K. Beam diameter (1/e) is 180 μm. Bistability is seen in 5th order.

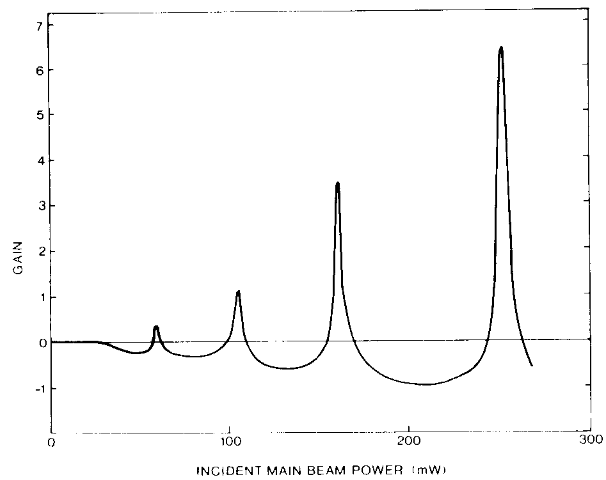

Fig. 2. Differential amplification between two CO laser beams at 1895 cm^{-1} in an InSb interferometer. Allowing for different mistuning, the strongly amplified regions correspond to near-vertical steps in fig. 1.

In these very sensitive regions one beam "transfers" a small optical thickness change causing a larger change in the second beam – an exact optical analogy to the transistor.

Since the size of the device is quite small – 200 μm diameter × 580 μm thick – these "optical circuit elements" may have some potential as fast switches, amplifiers and memory elements. It is therefore of interest to speculate on the basic microscopic mechanism with a view to determining ultimate speeds which depend, amongst other things, upon the material response.

Firstly, we note that the magnitude of the intensity-dependent index (easily estimated from the intensity intervals for a $\lambda/2$ optical thickness change from figs. 1 or 2) is $n_2 \sim (1-10) \times 10^{-5}$ cm^2/W; this corresponds to a third order susceptibility $\chi^{(3)} \sim 10^{-2}$ esu – about five orders of magnitude greater than the largest quoted values for this and similar materials due to either valence or free electron effects [e.g. 10]. Specific inclusion of the observed strong resonance at the energy gap, fig. 3, could raise this value by two or three orders, as evidenced by the $\chi^{(3)}$ Raman effect well known in spin-flip Raman scattering [11], but this still leaves the susceptibility low. We need therefore to postulate an additional mechanism to explain our results. This we provide by in-

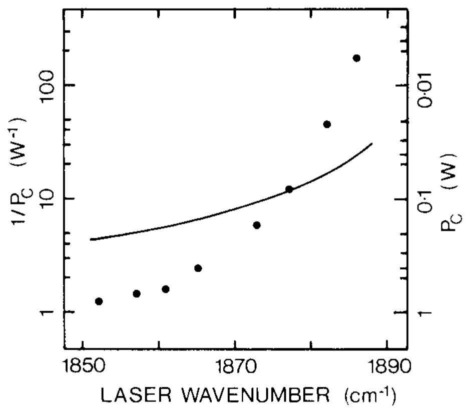

Fig. 3. Reciprocal of power, P_c, required to double the far-field beam width (at half peak intensity) as a function of laser wave number. The line is a theoretical curve with τ/T_2 = 10; points experimental data. (InSb crystal 7.5 mm long at ~ 5 K; incident spot diameter 130 μm (1/e.)

cluding the effects of saturation and power broadening, two associated effects. Such a mechanism has been postulated by Javan and Kelly [12] and confirmed [13] for atomic vapours as a mechanism for near-resonant intensity dependent refraction. The simplest model we can advance is to treat each vertical interband transition as a two level oscillator and to sum over the density of valence-conduction band transitions.

Standard theory, Yariv [14], gives for the real part of the susceptibility χ' the result

$$\chi'(\omega) = \frac{\mu^2 T_2 N}{\epsilon_0 h} \frac{(\omega_0 - \omega) T_2}{1 + (\omega_0 - \omega)^2 T_2^2 + 4\Omega^2 \tau T_2}, \qquad (3)$$

where we assume N 2-level systems, with only the lower states initially occupied, μ is the transition dipole moment and τ and T_2 are energy and phase relaxation times respectively. The "Rabi-frequency", $\Omega = \mu E_0/2\hbar$ where E_0 is the electric field of the laser beam.

The condition for significant saturation effects is therefore

$$4\Omega^2 \tau T_2 > 1 + (\omega_0 - \omega)^2 T_2^2. \qquad (4)$$

The value of μ is related to the strength of linear interband absorption [15] and the Rabi frequency can therefore be reliably estimated as ~ 10^{11} Hz at 1 kW/cm^2. The relaxation times can be estimated, to orders of magnitude from mobility data [16]: the dephasing time T_2 is probably ~ 10^{-12} s, while the energy relaxation time τ could be as long as 10^{-10} s. In any event it is clear that the LHS can be of the order of unity for typical cw intensities. Saturation or power broadening will therefore be significant if the observational frequency is within ~ $1/T_2$ of resonance at ω_0. This implies $(\omega - \omega_0) \equiv 30$ cm^{-1} in agreement with the resonant results of fig. 3. The magnitudes of the important physical quantities therefore support the proposition that power broadening can be a significant contribution to the large value of $\chi^{(3)}$.

Using the above arguments and summing over the appropriate band states we obtain the result

$$n_2 = \frac{-\mu^4}{16\epsilon_0^2 n_1^2 h^3 c} \left[\frac{2m_r}{E_G}\right]^{3/2} \frac{\tau}{T_2} \left[\frac{E_G}{E_G - h\omega}\right]^{3/2}, \qquad (5)$$

where m_r is the reduced effective mass (conduction and heavy hole bands) and E_G is the energy gap, and substituting quantities from comparison with linear absorption [15]

$$n = -7.2 \times 10^{-11} \frac{\tau}{T_2} \left[\frac{E_G}{E_G - h\omega}\right]^{3/2} \text{cm}^2\text{W}^{-1}. \qquad (6)$$

The theoretical curve in fig. 3 shows sensible agreement for $\tau/T_2 = 10$ although the experimental resonance is sharper (N.B. τ and T_2 have been assumed constant).

A characteristic of such a saturation process is however that the rate of change of refractive index with intensity will itself decrease with increasing intensity. Evidence for this can be seen in figs. 1 and 2 in which each "event", i.e. the introduction of $\lambda/2$ of optical thickness change, requires an increasing intensity interval ranging from ~ 100 W/cm^2 at first order to 1 kW/cm^2 at 5th order. Defocusing during propagation will also lead to increased intensity spacing, but geometrical consideration suggests that this effect should be small within only 580 μm of path.

The microscopic model we propose explains the defocusing, the band-gap resonance, the large size and the intensity dependence of the effects derived from nonlinear refraction. It suggests that devices will have very short limiting time constants possibly of the order of picoseconds.

We acknowledge experimental assistance from A. Johnston, and discussion with B.S. Wherrett, D.L. Weaire and W.J. Firth.

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