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OPTICAL BISTABILITY AND TRANSPHASOR ACTION USING SEMICONDUCTOR MATERIALS

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We demonstrate optical bistability and signal gain in a nonlinear InSb Fabry Perot resonator. Bandgap resonant saturation is shown to explain the giant nonlinearity response. Conclusions are drawn about future device possibilities.

1. Introduction

The possibility of replacing electrical currents by optical beams in information processing devices has been greatly enhanced during the last year by the application of very large nonlinearities in semiconductors to optically bistable and derived devices. The most important of these is the transphasor or optical transistor in which one optical beam can control the amplification of another. The effects described in this paper are based upon the nonlinear Fabry Perot resonator in which the refractive index of the spacer material, and hence the optical thickness, is intensity dependent. This gives rise (Fig.(1)) to dispersive optical bistability - an effect that may be understood by considering the input-output characteristic of the resonator. The normally linear relationship between output and input (dotted lines) is drastically changed in the nonlinear case as the resonator tunes or detunes on to the laser frequency. As the resonator frequency approaches the laser frequency a greater proportion of the incident intensity circulates inside the resonator thus creating a larger nonlinear effect. Thus the characteristic bends from the minimum transmission line towards the maximum, i.e. becoming nonlinear. The process is catastrophic so that a differential gain region (output changing more than input) is reached followed by a region of negative slope. At this point the device switches to an upper state of transmission near the maximum allowed through the resonator. On now reducing the intensity, the internal field remains high until a lower level of incident intensity when switch-down occurs. The device thus displays hysterisis and the characteristics of a bistable element in which its state is automatically indicated by its transmission. In addition a differential gain mode can always be achieved by appropriate detuning. When the phase thickness of the resonator is changed by the addition of a second beam we achieve "the transphasor", the analogue of the transistor for electrical currents. These devices in which light is controlled by light in principle constitute "all-optical circuit elements". The possibilities for fast processing will be discussed.

The first observations of optical bistability were made by Gibbs and McCall [1] in 1975 using sodium vapour. Other nonlinear materials such as Kerr liquids [2] and ruby [3] as well as hybrid devices [4] have since been used. The first use of semiconductors followed from the discovery of self-defocusing at modest laser powers in InSb [5] and saturable effects due to excitons in GaAs [6]. Bistable resonators in InSb and GaAs were reported [7,8] in 1979. Semiconducting materials such as those mentioned have been known to exhibit a comparatively large passive non-resonant $\chi^{(3)}$ [9] (around 10^{-8} - 10^{-11} e.s.u.) but the discovery of strong nonlinear refraction in the region just below the optical bandgap in both materials gives susceptibilities many orders of magnitude higher with $\chi^{(3)}$ in the range 10^{-2} - 1 e.s.u. In both cases the giant effect can be explained by saturation mechanisms although the details vary, the nonlinearity in GaAs relying on the existence of excitons whilst that in InSb is ascribed to interband transitions. The advantages of using semiconductors in optically bistable devices are that

(i) the nonlinear refraction is sufficiently high for small power densities (as low as 10 W/cm^2 or 8 mW incident) to be used;

(ii) small resonator thicknesses (4 - 100 μm) - important because one limit on switching time is related to the cavity field build up time and so to the cavity length.

These factors when combined suggest that small low power, low energy, fast switching devices may ultimately be possible with semiconductors and be consistent with an integrated optic approach to the system architecture.

2. Experimental

Optical bistability was observed using the coincidence of the 60 or 70 CO laser lines from 1930 cm^{-1} to 1660 cm^{-1} with the bandgap of InSb at 5K (around 1900 cm^{-1}) and 77K (around 1840 cm^{-1}). The laser radiation was obtained from an Edinburgh Instruments PL3 CO laser and controlled with an attenuator and spatial filter [10] to give a near perfect Gaussian profile over several orders of magnitude. Optically polished parallel crystals of thickness 560 μm and 130 μm were used as the resonators with the natural reflectivity R = 0.36. The entire beam was observed at the detector and the output-input characteristic is shown in Fig.(2a). It shows steps corresponding to successive changes of optical thickness of $\lambda/2$ with 5 such steps being observed at 5K. Optical bistability is clearly seen in fourth and fifth orders in both transmission and reflection. At 77K with a thinner sample and with a crystal coated to a reflectivity of 0.7, bistability is observed with an input power as low as 8 mW. (Fig.2b). This latter curve was also studied dynamically by slowly sweeping the input power with an electro-optic modulator and then observing the fast switching. The combined time constants of detector and electronics was not shown to be faster than 500 ns; but switching was observed at least as quickly as this limit.

The early work on the nonlinear refraction indicated an electronic origin [11,12]. It was therefore possible to predict that the use of an additional beam would also change the refractive index. Using the configuration shown in Fig.(3) we have been able to optically control the nonlinear Fabry Perot resonator and demonstrate differential signal gain. Since this occurs by the transference of phase thickness from one beam to the other we term the device the 'transphasor' in analogy with the transistor. In any practical processing device it is likely that switching and control will be achieved in such a manner. Signal gains of up to 10 are demonstrated.

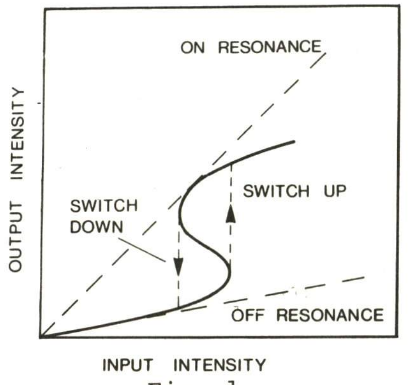

Fig. 1

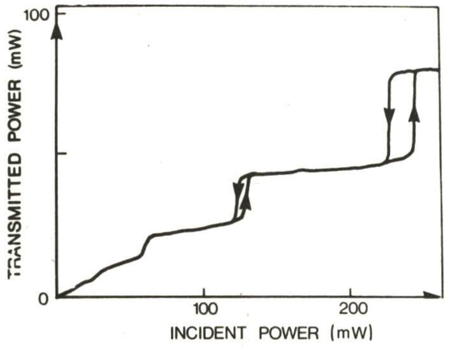

Fig. 2a

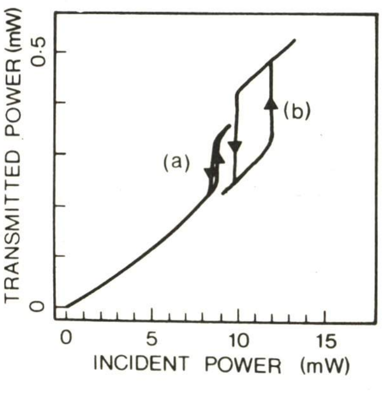

Fig. 2b

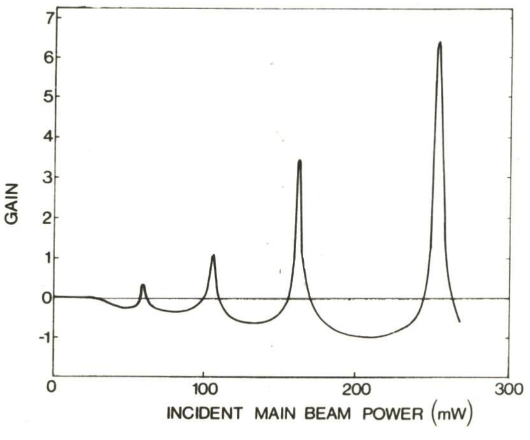

Fig. 3

3. Mechanism of Nonlinear Refraction in Semiconductors

Nonlinear effects in both refraction and absorption have been reported in InSb just below the bandgap energy [11]. Absorption in the band tail is shown to be saturable at extremely low intensities (less than 1 W/cm^2). It is possible to dissociate this from the nonlinear refraction occurring at around 10 W/cm^2 but a substantially linear band tail absorption remains at this power density. The band tail seems not to be well explained in the literature.

Figure (2a) gives us further information in that the intensity increment between each "step" increases with intensity. This implies that the nonlinearity is decreasing with increasing intensity, i.e. is itself saturating. Following the prediction of Javan and Kelley [13] we therefore examine the effect of saturation on refractive index. In atomic systems which are pumped below an absorbing transition nonlinear refraction arises due to the saturation of 'anomalous' dispersion. This gives a negative n_2 and self-defocusing as observed. If we therefore postulate that the band tail absorption can excite a system of oscillators at higher frequencies a change of refractive index

$$\Delta n = -\frac{2\pi}{\hbar n} \frac{|\mu|^2}{(\omega_o-\omega)} \qquad (1)$$

is obtained for each transition which is blocked (i.e. saturated). A detailed theory for a semiconductor requires knowledge of the density of interband energy differences ω_o and the distribution of the excited population. First approximations to such a theory are advanced in this paper with some simple assumptions about scattering mechanisms and lifetimes for each step. This approach explains both the qualitative features and the overall size of the effect. One of the difficulties of the theory is to explain how for $\hbar\omega < E_G$ and excitation mechanism exists which can block higher frequency (interband) transitions. We return to this point later. Given that excitation does take place for the power densities involved a carrier density between 1×10^{14} cm^{-3} and 6×10^{15} cm^{-3} may be generated for the range of intensities used and assuming a carrier recombination time of the order of 100's of ns. In general such optical generation of carriers can have the following effects giving rise to nonlinear refraction:

(i) Exciton screening

In a material such as GaAs where there is a prominent exciton feature near the bandgap the electron hole interaction can be screened out at certain carrier densities. For InSb this is around 1×10^{14} cm^{-3} close to the unexcited carrier density and therefore excitonic effects are not significant. In GaAs a density of 2×10^{16} cm^{-3} is required and this origin for nonlinearity has been demonstrated by Gibbs et al [8] . An n_2 of around 10^{-4} cm^2/W has been observed in the presence of an absorption coefficient $\alpha \sim 10^3$ cm^{-1}.

(ii) Free carrier plasma

The optically generated carriers constitute a free carrier plasma which gives a refractive index change given by

$$n_2(P) = \frac{-2\pi\, e^2\, \alpha\, \tau_R}{n\, m^*\, \hbar\omega^3} \qquad (2)$$

This process has been invoked for the case of silicon [14] and favours long wavelengths. For the case of InSb we have conducted two-beam pump and probe experiments [15] at different frequencies which are not consistent with this mechanism. The experiments indicate that our effect is bandgap resonant.

(iii) Dynamic Burstein-Moss shift

If we assume that a given number of carriers reach the bottom of the conduction band and that thermalisation has occurred the lower states of the conduction band will be blocked. This is analogous to the Burstein-Moss shift induced by impurities but in which the carriers are excited by the laser through the band tail absorption. By integrating eq.(1) over appropriate densities of states we can estimate the effect of blocking of these states on the refractive index and hence evaluate n_2. This yields [16]

$$n_2(\text{B-M}) = \frac{2\pi}{3n} \left[\frac{eP}{\hbar\omega}\right]^2 \frac{\alpha_{eff}(\omega)\tau_R}{\hbar(\omega_G-\omega)\hbar\omega} \qquad (3)$$

where P is the interband momentum matrix element and $\alpha_{eff}(\omega)$ represents the frequency dependent carrier generation function here taken empirically. τ_R is the normal recombination time. The model overestimates the completeness of the filling by assuming that scattering processes are complete.

(iv) Direct saturation

This process is closely related to (iii) but approaches the problem from a different limit. We assume that we can model the interband absorption with a set of two-level oscillators each of which is saturable and can be treated by standard nonlinear optical theory. The rate of pumping is controlled by the effective dipole moment (or empirically by $\alpha_{eff}(\omega)$) and the process by two time constants - the energy relaxation time T_1 within which population decays and the dephasing time T_2 which measures the uncertainty width of individual energy states. The calculation yields the result

$$n_2(\text{D-S}) = \frac{2\pi}{5n}\left[\frac{eP}{\hbar\omega}\right]^2 \frac{\alpha_{eff}(\omega)T_1}{\hbar(\omega_G-\omega)\hbar\omega} . \qquad (4)$$

Mechanisms (iii) and (iv) are related by comparing eqs. (3) and (4) by

$$n_2(\text{B-M}) = \frac{5}{3} n_2\ (\text{D-S}) \cdot \frac{\tau_R}{T_1} . \qquad (5)$$

There are two possible limits for T_1:

(i) If T_1 corresponds to the interband recombination time τ_R and we assume no intraband scattering. This maximises the contribution of (iii).

(ii) If we consider intraband scattering, one oscillator will be depopulated and reavailable for excitation as soon as an electron or hole moves out of a state k to a neighbouring state. The lowest limit of this would be if $T_1 = T_2$. Even taking this limit mechanism (iv) gives a substantially large value for n_2 possibly within 100 of the measured value. This limit gives in fact the lowest estimate for n_2 and the high speed limit.

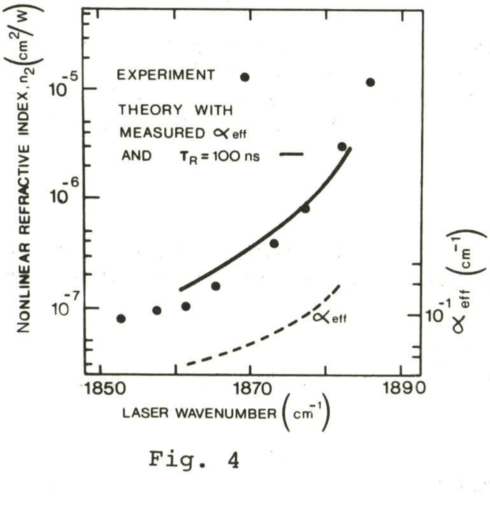

Fig. 4

In Fig. (4) we illustrate the bandgap resonant behaviour of the effect and show that with reasonable values, e.g. from the data of Miller [11] we extract $\alpha_{eff}(\omega)$ and with τ_R = 100 ns, mechanisms (iii) and (iv) give good order of magnitude estimates for the size of this giant nonlinearity. It seems therefore that bandgap resonant saturation is basically responsible for the large nonlinear refraction in InSb.

A Mechanism for Excitation with $\hbar\omega_G < E_G$: T_2-Tailing

We return to the problem of the excitation of carriers for laser photon energies less than the energy gap. Mechanism (iv) gives us a first method of suggesting a mechanism. Standard nonlinear optical theory for a two-level oscillator including power broadening or saturation is given by

$$\alpha(\omega,I) \sim \frac{\mu^2 T_2}{1 + (\omega_o-\omega)^2 T_2^{\,2} + I/I_S} , \tag{6}$$

where I_S is the saturation intensity. The dephasing time T_2 is related to intraband scattering mechanisms which for InSb give times of the order of 1 ps or less. The consequent line broadening

$$\Delta\omega = 1/c\pi T_2 \text{ cm}^{-1} \tag{7}$$

is therefore of the order of 30 cm^{-1}. Summing the number of oscillators representing the interband transitions and including this broadening mechanism we have the analogy of the simple models for free carrier absorption (a broadened zero frequency transition) and this gives a band tail capable of causing the excitation of the interband oscillators. The laser "pumping" is "off resonance" and with many oscillators corresponds to the case well-known in atomic vapours of inhomogeneous broadening and one would expect a modified form of "hole burning". Including these population effects by means of a density matrix treatment with a constant T_2 we obtain

$$\alpha(\omega) = \frac{1}{3nc}\left[\frac{eP}{\hbar\omega}\right]^2\left[\frac{2m_r}{\hbar}\right]^{3/2}\frac{\omega}{\hbar T_2}(\omega_G-\omega)^{-\frac{1}{2}} . \tag{8}$$

whence by combination with eq. (4) we find

$$n_2 \sim \frac{P^4}{\omega^4}\cdot\frac{T_1}{T_2}(\omega_G-\omega)^{-3/2} \tag{9}$$

The results of this evaluation are indicated in Fig. (4) and they show that reasonable order of magnitude agreement is obtained for plausible values of T_1 and T_2 although the frequency fit is not perfect.

Other possible excitation mechanisms may include impurity states and indeed we do observe impurity dependence of the effect. This is however rather weak and is directly related to the amount of absorption which itself would be sensitive to a change in the intraband scattering time T_2.

4. Speed of Response

If an all-optical processing device is to be competitive with very large scale integration or Josephson junctions we would require the following features:-

(i) near picosecond switching time
(ii) micron dimension - this ensures cavity field build-up time $\sim$ ps
(iii) small holding power (mW)
(iv) small switching energy (pJ)
(v) fast response of nonlinearity.

For the case of GaAs Gibbs et al [6] have already shown that exciton features can be screened out in times of the order of ps but show a much longer recovery time and have demonstrated bistable switching for near visible wavelengths of the order of 10's of ns. For InSb measurements so far have been restricted to 500 ns but we can use mechanism (iv) to demonstrate the limiting physical processes. Power broadening theory gives significant effects when

$$\frac{\mu^2 E^2}{\hbar^2} \quad T_1 T_2 > 1 + (\omega-\omega_o)^2 \; T_2^{\,2} \tag{10}$$

where μ is the dipole moment corresponding to P/ω in eqs. (3) and (4). The significant quantity here is $\mu E/2h$ sometimes known as the Rabi frequency which in our context has the significance that the minimum time to completely change the population from the lower to upper level of the oscillator is its reciprocal $2h/\mu E$. The square of the Rabi frequency must therefore be comparable with the product T_1, T_2. However, by utilising a high intensity (E) the system can be "driven" as fast as required. Thus an <u>increasing</u> laser field can readily induce a rapid nonlinear response. On <u>reducing</u> the field however relaxation must take place and its speed will be controlled by T_1. Approximate values $T_1 \sim 100$ ps, $T_2 \sim 1$ ps have been given from saturation of cyclotron resonance by Gornik et al. [17].

Device speculations [18]

Using the principles developed in the preceding paragraph we can deduce from experiment some possible device quantities: $n_2 \sim 10^{-4}$ cm^2/W for InSb with absorption coefficient $\alpha \sim 1\ cm^{-1}$. For GaAs a similar n_2 can be obtained but $\alpha \sim 10^2/cm^{-1}$.

Assuming it is possible to utilise an element 10 μm x 10 μm in dimension we can estimate the following:

(i) Holding power, i.e. the steady power required to hold the resonator near to the switching intensity $\sim$ 250 nW for InSb.

(ii) Switching energy. One photon per cm^3 gives $\Delta n = 10^{-17}$ in InSb; this yields a switching energy of 0.01 pJ.

(iii) Switching time. Switch up with an energy of 0.1 pJ implies that 100 mW will switch the device in 1 ps. Switch down will depend upon relaxation times.

5. Conclusions

We have demonstrated a series of optically bistable and derived effects in InSb and related them to observations in GaAs. It is shown that the very large nonlinearities are associated with band-gap resonant saturation and exciton screening respectively. The size of the effect is largest in InSb where the nonlinearity corresponds to a $\chi^{(3)} \sim 1$ e.s.u. The implications for all-optical switching and amplifying devices suggest that, with the very probable extension to other semiconductor materials, fast all-optical processing may become a practical possibility in the near future. [19]

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References

1) H.M. Gibbs, S.L. McCall and T.N.C. Venkatesan: Phys. Rev. Lett. 36 (1976) 1135.
2) T. Bischofberger and Y.R. Shen: Optics Lett. 4 (1979) 40.
3) T.N.C. Venkatesan and S.L. McCall: Appl. Phys. Lett. 30 (1977) 282.
4) P.W. Smith and E.H. Turner: Appl. Phys. Lett. 30 (1977) 282; P.W. Smith, E.H. Turner and P.J. Maloney: IEEE J. Quant. Electron. QE-14 (1978) 207; P.W. Smith, I.P. Kaminow, P.J. Maloney and L.W. Stulz: Appl. Phys. Lett. 33 (1978) 24, Appl. Phys. Lett. 34 (1979) 62.
5) D.A.B. Miller, M.H. Mozolowski, A. Miller and S.D. Smith: Optics Comm. 27 (1978) 133.
6) H.M. Gibbs, A.C. Gossard, S.L. McCall, A. Passner, W. Wiegmann and T.N.C. Venkatesan: Solid State Commun. 30 (1979) 271.
7) D.A.B. Miller, S.D. Smith and A. Johnston: Appl. Phys. Lett. 35 (1979) 658.
8) H.M. Gibbs, S.L. McCall, T.N.C. Venkatesan, A.C. Gossard, A. Passner and W. Wiegmann: Appl. Phys. Lett. 35 (1979) 451.
9) C. Flytzanis: Quantum Electronics, Vol.1A, eds. H. Rabin and C.L. Tang (Academic Press, New York, 1975) p.9.
10) D.A.B. Miller and S.D. Smith: Appl. Optics 17 (1978) 3804.
11) D.A.B. Miller: Ph.D. Thesis (Heriot-Watt University, Edinburgh, 1979).
12) D. Weaire, B.S. Wherrett, D.A.B. Miller and S.D. Smith: Optics Lett. 4 (1979) 331.
13) A. Javan and P.L. Kelley: IEEE J. Quantum Electron. QE2 (1966) 470.
14) R.K. Jain and M.B. Klein: Appl. Phys. Lett. 35 (1979) 454.
15) D.A.B. Miller, S.D. Smith and C.T. Seaton: First International Conference and Workshop on Optical Bistability, Asheville, North Carolina, U.S.A., 3-5 June 1980, to be published.
16) D.A.B. Miller, S.D. Smith and B.S. Wherrett: Opt. Comm. (1980), to be published.
17) E. Gornik, T.Y. Chang, T.J. Bridges, V.T. Nguyen and J.B. McGee: Phys. Rev. Lett. 40 (1978) 1151.
18) D.A.B. Miller, S.D. Smith and C.T. Seaton: IEEE J. Quantum Electron. Special Issue on Optical Bistability, to be published.
19) S.D. Smith and D.A.B. Miller: Proc. Fourth National Quantum Electronics Conference, Edinburgh, (1979), "Laser Advances and Applications" ed. B.S. Wherrett (pub. J. Wiley & Sons) 231-244.