Optical bistability and signal amplification in a semiconductor crystal: applications of new low-power nonlinear effects in InSb

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We report the observation of optical bistability for a plane parallel semiconductor crystal which forms a Fabry-Perot interferometer using only the natural reflectivity of its surfaces. Nonlinear transmission is observed for cw laser intensities above $\sim 100\ \mathrm{W/cm^2}$ for radiation at $1895\ \mathrm{cm^{-1}}$ near the energy gap of InSb at 5 K. The effect is interpreted in terms of a very large intensity-dependent refractive index giving a $5\lambda/2$ optical thickness change for an intensity of $\sim 2\ \mathrm{kW/cm^2}$. Clear bistability is seen in fifth-order interference, the first such observation above first order in an intrinsic, one-element system, in addition to regions exhibiting signal amplification. The same crystal also shows strong modulation of the transmission of one laser beam induced by a second, with real signal gain, thus demonstrating an "optical transistor."

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Since the first observation of optical bistability of Gibbs *et al.*[1] with Na vapor in a Fabry-Perot interferometer, there has been considerable interest in such systems containing other optically nonlinear media, with several subsequent observations in intrinsic systems of bistability and differential gain in solids[2-4] and liquids.[5,6] All of these systems rely on nonlinear refraction to give an intensity-dependent optical length change inside the cavity. A theory has been developed for this dispersive case for plane waves[1,7,8] (and for Gaussian beams under a self-focusing nonlinearity for certain special cases,)[8] that can explain the general form of the results. Recently the transient behavior has also been investigated including, for example, experimental and theoretical studies in intrinsic dispersive plane-wave devices.[5,6] Much of the interest in these systems arises from their potential device application as fast totally optical switching and amplifying systems.

In this letter we report the use in such devices of the strong nonlinear refractive effect recently discovered in this laboratory in the cooled semiconductor InSb irradiated with a cw CO laser.[9] Recent macroscopic analysis[10] establishes that this is a self-defocusing nonlinearity which can produce optical length changes greater than half a wavelength with modest laser powers, and so nonlinear Fabry-Perot action should be easily observed. The effect shows a strong increase as the photon energy approaches band-gap energy, and for the present experiments we have chosen to work near to the band gap ($1899\ \mathrm{cm^{-1}}$ at ~ 5 K).[11] In this region also, at the intensities used here, the absorption is not strongly nonlinear, and refractive and absorptive effects can be clearly separated.[12] The microscopic mechanism of this effect will be discussed elsewhere,[13] but thermal effects are shown to be extremely unlikely[9,10] for two reasons: first, the required power levels seem too low and, second, the observed effect is self-defocusing rather than the self-focusing expected thermally. A probable explanation is that this is an electronic nonlinearity (seen here *below* the band gap) which is the causal consequence of the existence of saturable absorption (for photon energies *above* the band gap) in electronic transitions between valence and conduction bands. It is important to emphasize that this proposed mechanism is different from that discussed by Gibbs *et al.*[4,14,15] that relies on the distinct free exciton absorption levels in GaAs; in any case, InSb does not display any such strong free excitonic structure. The existence of nonlinear refraction which is a consequence of the existence of nonlinear absorption is already well established in atomic vapors,[16] leading to the general conclusion that for photon energies below the energy of an absorbing transition, self-defocusing should be observed, in agreement with Ref. 10. The influence of picosecond intraband carrier scattering on this refractive effect in semiconductors will also be discussed elsewhere.[13,17]

To observe nonlinear Fabry-Perot action we have examined the total transmission of an initially Gaussian[18] beam, from an Edinburgh Instruments PL3 cw CO laser, focused onto a thin crystal of InSb held in a cryostat at ~5 K. No external mirrors have been used; the plane-parallel natural reflectivity (~36%) faces of the crystal form the cavity. The cavity is not tuned in any way and there is no attempt to mode-match the cavity and the input beam (to do so would require curved crystal faces). The measured finesse F of this system on the laser line used in these experiments ($1895\ cm^{-1}$) was ~0.5; this low value is likely to be partly due to absorption inside the crystal, which we estimate to be ~50%–60% per pass leading to an *effective* reflectivity R of 18%–14% and calculated finesse $F\,[=4R/(1-R)^2]$ of ~1–0.75.

With this extremely simple system, we have been able to demonstrate optical differential gain and bistability. Because the nonlinearity utilized here is so strong it has been possible to observe nonlinear Fabry-Perot action not only in first order (when the effective nonlinear cavity length change is less than half a wavelength), where previous observations have been made in intrinsic systems,[1–6] but also in higher orders.

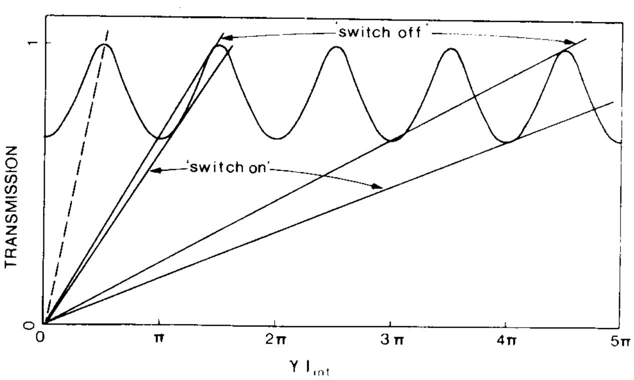

FIG. 1. Intersections between relations (1) and (2) (see text) for $\delta_0 = \Pi$ and $F = 0.5$ demonstrating no bistability (i.e., only one intersection between straight line and curve) in first order and progressively wider bistable regions at higher orders (second and fifth orders shown). (Straight lines of shallower gradient correspond to higher incident intensity I_0.)

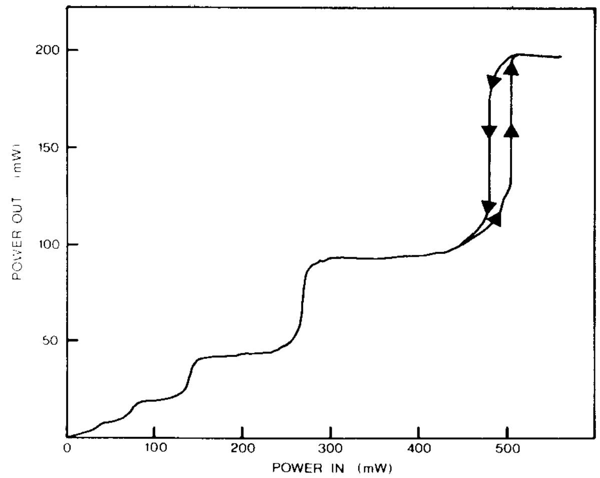

FIG. 2. Transmitted power plotted against incident power for a cw CO laser beam (wave number $1895\ cm^{-1}$ and incident spot size $180\ \mu m$) passing through a plane-parallel InSb crystal [$5\times5\ mm\times560\ \mu m$ thick, $N_D - N_A \sim 3\times10^{14}\ cm^{-3}$ (n type)] at ~5 K.

Using the plane-wave theory[7,8] for a lossless Fabry-Perot interferometer, it is easily demonstrated that for a low finesse cavity in which bistable action is impossible in first-order operation, optical bistability should become more likely as the nonlinear length change moves to higher order. This can be seen in Fig. 1. Here the relation[7,8]

$$T = 1/[1 + F\sin^2(\delta_{0/2} + \gamma I_{int})], \qquad (1)$$

for the transmission T of Fabry-Perot resonator as a function of the intensity inside the cavity I_{int}, is plotted for a finesse F of ~0.5 with an initial mistuning δ_0 of π. ($\gamma = 2\pi n_2 L/\lambda$ where L is the crystal length, λ is the free space wavelength, and n_2 is the first-order nonlinear refractive index defined by $n = n_1 + n_2 I$). The other relation required for the solution is the "straight line"

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

where R is the reflectivity of the cavity mirrors and I_0 is the incident intensity. Equations (1) and (2) give two relations between I_{int} and T so I_{int} is eliminated to give a single relation between T and I_0. This is done graphically, and bistability can only exist if the "straight line" [Eq. (2)] has more than one intersection with the "curve" [Eq. (1)]. As can be seen, there is no bistable solution in first order, and this simple plane-wave theory only predicts bistabiity in second and higher orders. Indeed, bistability in first order is totally impossible according to this theory for any tuning of the resonator, and bistability in second order is critically dependent on resonator tuning.

Our experimental results (Fig. 2) demonstrate operation up to fifth order where bistability is clearly seen with two stable states for a given input intensity and distinct switching between one state and the other. There is also effective differential gain at the third- and fourth-order transitions, with the change in output power being greater than the change in input power. Clearly, the simple plane-wave nonabsorptive theory[7,8] is not strictly applicable here because we utilize a Gaussian incident profile, and detailed explanation of the form of Fig. 2 must await a more complete theory, but the qualitative conclusion that bistability is easier to observe at higher order is borne out by this experiment. It is worth noting too that, both theoretically and from our experiments, at higher orders it is no longer necessary to tune the resonator to obtain bistability.

It is also apparent from these results (Fig. 2) that the transitions become further apart in power with increasing order. This is qualitatively consistent with a self-defocusing nonlinearity since we would expect the beam to be spread out inside the crystal to some extent and hence to be less effective in producing refractive index changes due to its reduced intensity. This behavior certainly contrasts strongly with the calculations of Marburger and Felber[8] on a self-focusing nonlinearity where the transitions are expected to get closer with increasing order, eventually becoming indistinguishable. It may be that very-high-order operation can only be achieved successfully with a defocusing nonlinearity.

Using a modification of this simple system we have also been able to observe "optical transistor" action, where a powerful beam is modulated by a weak beam, with an overall small signal power gain greater than six. Clear peaks in the gain can be seen which correspond to the adjacent orders of interference in the bistability observation. This experiment, which is therefore a demonstration not just of differential gain capable of amplifying changes in a single beam but of true optical transistor signal gain action where changes in one beam result in amplified changes in another, will be discussed elsewhere.[17]

We have therefore demonstrated optical "circuit elements" in a simple solid state device where the active volume is only $580 \times 200\ \mu m$ diam. Operation of similar devices at higher temperatures is a possibility since this refractive effect has also been observed at 77 K (Ref. 9). This simplicity should make it possible to manufacture similar devices for use in integrated optical systems for switching and signal amplification.

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