DEGENERATE FOUR-WAVE MIXING IN InSb AT 5K

D.A.B. MILLER, R.G. HARRISON, A.M. JOHNSTON, C.T. SEATON and S.D. SMITH
Department of Physics, Heriot-Watt University, Riccarton, Edinburgh, UK

Received 7 January 1980

We report the observation of degenerate four-wave mixing in InSb at 5 K using a cw CO laser operating in the spectral region just below the bandgap energy, where strong self-defocusing and optical bistability have previously been seen. Conversion efficiencies of ~1% are obtained with <13 mW beam powers, and higher efficiencies are predicted for improved phase-matching.

Recently there has been much interest in degenerate four-wave mixing (DFWM), stimulated particularly for its potential as a nonlinear mechanism for phase-conjugated wave generation [1]. DFWM has been observed in several materials (see, for example, the review of phase conjugation by Yariv [2]), and Na vapour [3], ruby [4] and CS_2 [5] have shown DFWM under continuous-wave (cw) laser excitation. DFWM is particularly attractive for phase-conjugation because it can be phase-matched for any angle of signal beam [1], and the ability to operate cw is an obvious advantage in, for example, continuous signal processing applications. We report in this paper the observation, at low powers, of cw DFWM in the cooled semiconductor, InSb.

The process of DFWM can be associated with any first order nonlinearity (i.e. proportional to intensity) in absorption or refractive index, or with the more complex nonlinearities found in, for example, saturation of the two-level system [6]. Nonlinear absorption and refraction have both been reported for InSb at 4 K and 77 K in the spectral region just below the bandgap energy [7]. Nonlinear absorption at ~4 K has been ascribed to saturation of acceptor-to-conduction band transitions [8,9]. However, for the experiments reported here, we work primarily in the intensity region where this absorption is effectively saturated [9,10] and consequently we expect it to make no further contribution to nonlinear effects. The negative (i.e. self-defocusing) nonlinear refraction remains [9,10], and it is this nonlinearity which we expect to give rise to DFWM. A novel mechanism for this bandgap resonant refraction, involving saturation of valence band to conduction band transitions, has been suggested for InSb by analogy with saturation in atomic vapours [11,12].

The apparatus used in our experiments is shown in fig. 1. The beam from an Edinburgh Instruments PL3 cw CO laser, capable of operating on any of ~50 lines in the spectral region 5–6 μm, is passed through a variable attenuator which retained the gaussian beam form [13]. The various beam splitters and mirrors divide this into two counterpropagating pump beams and a probe beam (at an angle of ~2° to the front pump beam) all focused onto an InSb sample held in a cryo-

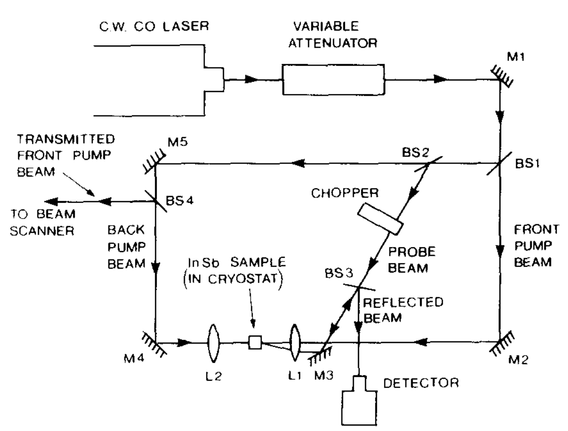

Fig. 1. Experimental apparatus. M1 – 5 are totally reflecting mirrors; BS1 – 4 are zinc selenide beam splitters; L1 and L2 are 15 cm focal length zinc selenide lenses.

stat at ~5 K. The sample was 7.5 mm long by 5 × 5 mm cross section, had carrier concentration 1 × 10^{15} cm^{-3} (n-type), and was anti-reflection coated on both end faces to eliminate Fabry-Perot fringing. The focused diameters of the beams on the crystal (at the 1/e^2 intensity points) were: front pump, 140 μm; back pump, 225 μm; probe 190 μm. The detector used was a Laser Precision Corp. Rk5100 Pyroelectric Power Meter. To make the measurement of reflected power insensitive to scatter from either front or back pump beams, only the probe beam was chopped and the Power Meter was only sensitive to signals synchronous with this 32 Hz chopping rate. The shape of the transmitted front pump beam was monitored on a real-time scanning system employing oscillating mirrors to scan the beam across a PbSnTe detector. The final alignment of the beams with crystal in position was adjusted, using mirrors M3 and M5, for the largest induced distortion of the beam profile of the transmitted front pump beam; this was found to correspond to the largest DFWM reflected signal.

Using the laser line at 1886 cm^{-1} near to the bandgap of InSb at ~5 K (~1899 cm^{-1}), DFWM was observed, with a reflected beam approximately following the path of the probe beam in the opposite sense. That it did not follow exactly the same path we attribute to the two pump beams not being collinear inside the sample. A typical set of results, showing the dependence of reflected power on incident powers, is given in fig. 2. All three input beams were derived from the same laser source whose power could be varied; since the DFWM reflected power should be proportional to the product of the three input beam powers in the small signal regime [1] a cubic dependence is to be expected in fig. 2. A cubic law plotted for comparison in fig. 2 shows good agreement up to ~12 mW, after which the measured reflection falls below the cubic theory. Such a fall-off is expected in principle, due for example to pump depletion or self-defocusing, although detailed reasons for which will require further work. As an additional check that the effect was a four-wave interaction, it was observed that there was no reflected signal within measurement error when any of the three input beams were blocked.

As can be seen from fig. 2, we have attained effective DFWM reflectivities of ~1% for cw laser beam powers <13 mW, and under these conditions, the overall transmission of the sample was ~60%. The high linear refractive index of InSb (~4) means that any nonparallelism of the crystal faces results in the originally counterpropagating pump beams no longer being exactly collinear inside the sample with a consequent loss of phase-matching for the DFWM process. Estimates show that the parallelism of our crystal (≲40 mrad) results in a pump beam collinearity lying outside the criteria for guaranteed phase-matching [14] of DFWM and so a considerable increase in efficiency should be possible with further attention to phase-matching in this system.

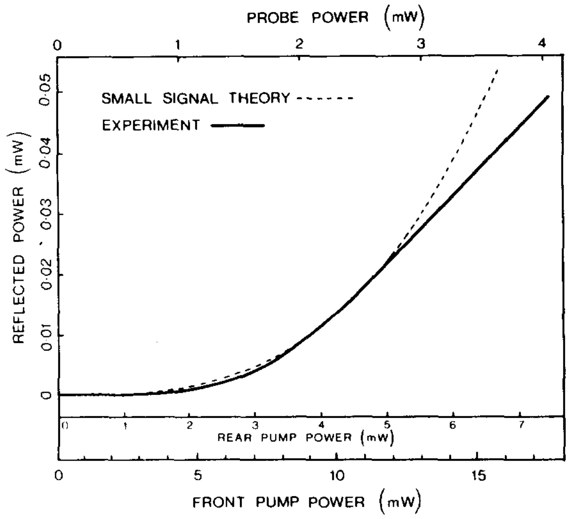

Fig. 2. Experimental results. All powers are corrected for beam splitter reflection losses and refer to those at the sample faces. The broken line is a cubic curve fitted to the low power data.

This observation also has consequences for the physics of optical switching and amplifying devices, using InSb [11,15], based on nonlinear Fabry-Perot action; for the "transphasor" configuration [11] in particular DFWM must play an important role since the multiple reflections inside the Fabry-Perot cavity set up the equivalent of counterpropagating pump beams inside the nonlinear medium, onto which a further signal beam is superimposed, thereby creating the conditions for phase-matched DFWM. Because the nonlinearities required for DFWM are similar to those needed for intrinsic Fabry-Perot optical bistability (i.e. saturable absorption and/or nonlinear refraction) we expect DFWM in other materials used for bistability. Of these materials, no DFWM has yet been reported for GaAs [16], using the saturable excitonic nonlinearity; because of the relatively low powers required for optical bistability with cooled GaAs, we expect that it too should display cw DFWM near the bandgap energy.

In conclusion, we have observed cw DFWM in cooled InSb at low power levels, and we expect that higher efficiencies can be attained by phase-matching. This observation is important for the possible use of InSb for cw phase-conjugation, and also for the detailed physics of devices based on nonlinear Fabry-Perot action. We also expect DFWM to be observable in GaAs. DFWM may prove a useful technique for the measurement of the nonlinearities themselves.

We acknowledge the valuable contributions made by W.J. Firth in many stimulating conversations.

References

[1] B.I. Stepanov, E.V. Ivakin and S.D. Rubanov, Sov. Phys. Dokl. 16 (1971) 46;
R.W. Hellwarth, J. Opt. Soc. Amer. 67 (1977) 1.
[2] A. Yariv, IEEE J. Quant. Electron. QE-14 (1978) 650;
A. Yariv, IEEE J. Quant. Electron. QE-15 (1979) 524.
[3] P.F. Liao, D.M. Bloom and N.O. Economou, Appl. Phys. Lett. 32 (1978) 813.
[4] P.F. Liao and D.M. Bloom, Optics Lett. 3 (1978) 4.
[5] J.Au. Yeung, D. Fekete, D.M. Pepper, A. Yariv and R.K. Jain, Optics Lett. 4 (1979) 42.
[6] R.L. Abrams and R.C. Lind, Optics Lett. 2 (1978) 94;
R.L. Abrams and R.C. Lind, Optics Lett. 3 (1978) 205.
[7] D.A.B. Miller, M.H. Mozolowski, A. Miller and S.D. Smith, Optics Comm. 27 (1978) 133.
[8] D.G. Seiler and L.K. Hanes, Optics Comm. 28 (1979) 326.
[9] D.A.B. Miller, Ph.D. Thesis, Heriot-Watt University, Edinburgh 1979 (unpublished).
[10] D. Weaire, B.S. Wherrett, D.A.B. Miller and S.D. Smith, Optics Lett. 4 (1979) 331.
[11] D.A.B. Miller and S.D. Smith, Optics Comm. 31 (1979) 101.
[12] D.A.B. Miller, S.D. Smith and B.S. Wherrett, to be published;
G.D. Holah, J. Dempsey, D.A.B. Miller, B.S. Wherrett and A. Miller, in: Proc. 14th Intern. Conf. on The physics of semiconductors, Edinburgh, 1978, Institute of Physics Conference Series No. 43 (Institute of Physics, London, 1979) p. 505.
[13] D.A.B. Miller and S.D. Smith, Appl. Optics 17 (1978) 3804.
[14] D.M. Bloom and G.C. Bjorklund, Appl. Phys. Lett. 31 (1977) 592.
[15] D.A.B. Miller, S.D. Smith and A. Johnston, Appl. Phys. Lett. 35 (1979) 658.
[16] H.M. Gibbs, S.L. McCall, T.N.C. Venkatesan, A.C. Gossard, A. Passner and W. Wiegmann, Appl. Phys. Lett. 35 (1979) 451.