Stimulated emission at the second cyclotron harmonic of *p*-Ge light holes in fields E⊥H

A. V. Murav'ev, Yu. N. Nozdrin, and V. N. Shastin
Institute of Applied Physics, Academy of Sciences of the USSR

(Submitted 15 July 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **48**, No. 5, 241–244 (10 September 1988)

An emission at the second harmonic of the cyclotron resonances of light holes in *p*-Ge in crossed electric and magnetic fields (**E⊥H**) is reported. The spectral characteristics of this emission have been measured. The mechanism and observation conditions are discussed.

Studies of sources of long-wavelength stimulated IR light using hot holes in *p*-Ge in fields **E⊥H** have recently attracted much interest (e.g., Refs. 1–8). Experiments[3] have confirmed the idea of a laser operating on transitions between states of light (l) and heavy (h) holes.[1] Stimulated emission at the cyclotron resonance of light holes has also been observed.[4,5] In these two mechanisms the stimulated-emission effects arise in approximately equal electric fields, but with different relations between the electric and magnetic fields; they also differ substantially in terms of spectral characteristics. The light from a laser operating on *l-h* transitions is broad-band light $(\Delta\nu \lesssim 20\ \mathrm{cm}^{-1})$, and the emission frequencies, $\nu = 45$–50 and 75–$125\ \mathrm{cm}^{-1}$, are determined largely by the distribution of light holes. The stimulated emission on the cyclotron resonance of light holes is, in contrast, narrow-band light $(\Delta\nu \lesssim 0.1\ \mathrm{cm}^{-1})$, and the emission frequencies $\nu = 30$–$50\ \mathrm{cm}^{-1}$ (Ref. 4) and $\nu = 70$–$85\ \mathrm{cm}^{-1}$ (Ref. 5) are determined by the relation $\nu = \nu_l^c = eH/2\pi c^2 m_l^*$ $[\mathrm{cm}^{-1}]$, where c is the velocity of light, and $m_l^* = 0.046 m_0$, where m_0 is the mass of a free electron.

In this letter we wish to report the observation of a stimulated emission on the second harmonic of the cyclotron resonance of light holes. We report results which verify that higher cyclotron-resonance harmonics influence the output of a *l-h* laser.[7] These results add to the picture of the role played by Landau quantization in stimulated-emisson effects involving *p*-Ge hot holes in $\mathbf{E} \perp \mathbf{H}$ (Refs. 5–7).

The experimental apparatus is similar to that described in Ref. 3. The active element was one of several *p*-Ge samples with hole densities $p \approx (5$–$7) \times 10^{13}\ \mathrm{cm}^{-3}$, in the form of rectangular parallelepipeds with dimensions of $5 \times 7 \times 50$ mm and

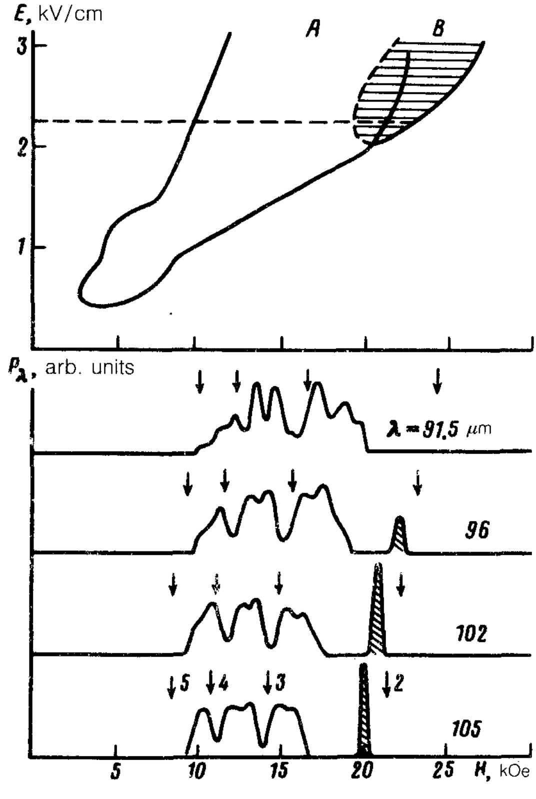

FIG. 1. Emission regions and plot of the spectral power density P_λ versus the field H at $E \approx 2.3$ kV/cm. The arrows show the positions of the resonances $\lambda^{-1} \equiv \nu = \Delta n \cdot \nu_l^c$ with $m_l^* = 0.042 m_0$.

$4.5\times 7.5\times 60.0$ mm. The samples were placed in a solenoid and cooled with liquid helium; electric-field pulses were applied to the lateral faces (5×50; 4.5×60.0) through ohmic contacts. The fields were directed along the crystallographic axes: $\mathbf{H}\|\langle 111\rangle$, $\mathbf{E}\|\langle 110\rangle$. The emission developed on total-internal-reflection modes[3] and was detected along the direction of the magnetic field. Spectral measurements were carried out with a grating monochromator with a resolution as high as 1 cm^{-1}.

In field region A (Fig. 1) we observed the known[3,6-8] stimulated emission on *l-h* transitions. Figure 1 shows the spectral power density of the stimulated emission as a function of the magnetic field, $P_\lambda(H)$, for certain wavelengths λ. Note that this dependence is oscillatory in region A and that an independent region of stimulated emission (the hatching; this region is resonant in terms of H) appears in fields $E\gtrsim 2$ kV/cm (region B). The positions of the observed features in regions A and B are proportional to λ^{-1} and do not depend on E or the dimensions of the samples, so these features can be linked with harmonics of the cyclotron resonance of heavy holes. As has now become clear, corresponding features have been observed previously in stimulated-

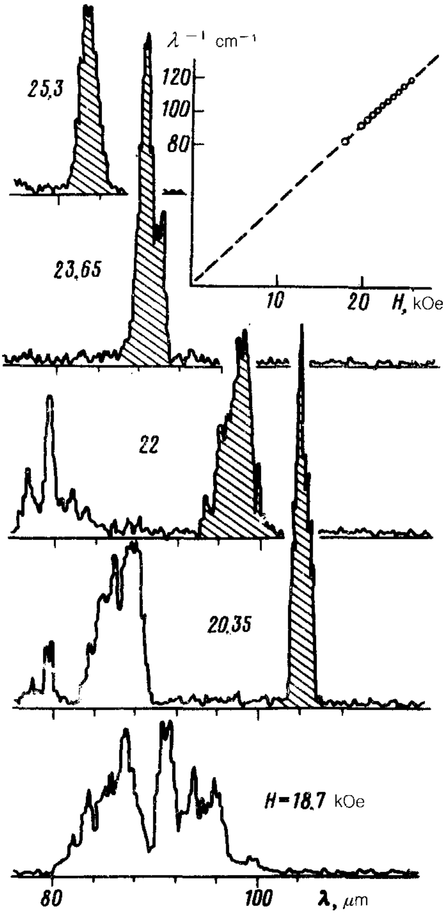

FIG. 2. Spectra of the stimulated emission, $P(\lambda)$, for $E\approx 2.6$ kV/cm. The inset shows the H dependence of the frequency of the hatched line.

emission spectra (Ref. 8, for example), but their relationship with harmonics was not noticed because of the cutting of the spectrum by the resonator lines.

Figure 2 shows the tuning of the stimulated-emission spectrum as the magnetic field H is varied. In region B, the spectrum acquires an emission line which is comparatively narrow, $\Delta\nu \approx 1$–$3\ \mathrm{cm}^{-1}$, and whose frequency tunes in proportion to H and corresponds to twice the cyclotron-resonance frequency of the light holes, $\nu \approx 2\nu_l^c$ with $m_l^* = (0.040 \pm 0.002)m_0$. We might note that m_l^* is slightly smaller than the effective mass which is ordinarily used, $m_l = 0.042m_0$. The higher harmonics (third through fifth) differ from the second in that they appear in the spectra against the background of a wide-band *l-h* emission (see Ref. 7, where an emission at higher harmonics was linked with a denudation of the low-lying Landau levels of light holes in a nonlinear region of *l-h* emission). The emission at the second harmonic, on the other hand, is completely independent, implying the existence of an independent associated amplification mechanism.

An interpretation of the effects of the cyclotron-resonance harmonics requires appealing to quantum-mechanical ideas regarding the valence-band states of Ge in fields $\mathbf{E}\perp\mathbf{H}$. Figure 3 shows results calculated on the total-energy spectrum of these states as a function of the dimensionless drift energy $\mu \sim E^2/H^3$ (cf. Ref. 5). The repulsion of energy levels is a consequence of the interaction and hybridization of l and h states or, in other words, a consequence of tunneling.[10] The distinction between light and heavy holes is totally arbitrary in hybridization regions; it simply reflects the different degrees of localization of the wave functions. A population inversion arises in a system of this sort because of a strong differentiation of states in terms of the degree

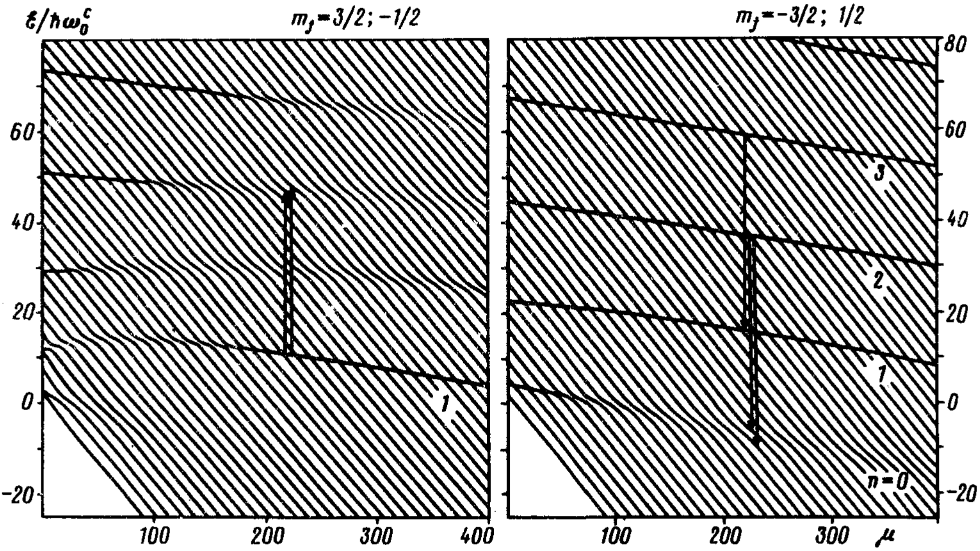

FIG. 3. Spectrum of the total energy $\mathscr{E}$ of hole states in fields $\mathbf{E}\perp\mathbf{H}$, expressed in units of the cyclotron energy $\hbar\omega_0^c = \hbar eH/m_0c$. The Luttinger Hamiltonian was calculated in the isotropic approximation ($\gamma_L = 13.2$; $\tilde{\gamma} = 4.92$; $k = 3.3$] (Ref. 9); $\mu = m_0^2c^3E^2/2e\hbar H^3$ is the dimensionless energy of the drift motion. The motion of holes along $\mathbf{H}$ and the scattering by optical phonons have been ignored.

of interaction with optical phonons. Under conditions of dynamic heating in strong fields $\mathbf{E}\perp\mathbf{H}$ (regions A and B), this interaction with optical phonons is the primary mechanism for the scattering of light holes over a time $\tau \leqslant 10^{-12}$ s. The low-lying Landau levels of the "light" holes with indices $n \leqslant 3$ in region B ($\mu = 150$–400) and up to $n \leqslant 7$ in region A ($\mu \gtrsim 300$) are magnetized, and they interact weakly with optical phonons. Their lifetimes are considerably greater and are determined by the relative weight of the "heavy" wave function (and also by a scattering by acoustic phonons and charged impurities over $\tau \approx 10^{-11}$ s). Optical transitions from these states to lower-lying *h* states provide a gain on *l-h* transitions, which agrees qualitatively with semiclassical representations.[6] Furthermore, transitions between light states with $\Delta n > 1$ are allowed because of the *l-h* hybridization; an inversion associated with these transitions may also arise because of various admixtures in the heavy wave function. As a result, there will be an additional gain at frequencies near cyclotron-resonance harmonics of the light holes, as is confirmed by numerical calculations of the matrix elements for the optical transitions. We believe that the emission at the second harmonic is determined by $2 \rightarrow 0$ and $3 \rightarrow 1$ transitions with the quantum numbers $m_j = -3/2, 1/2$; see Fig. 3. The arrows pointing upward show competing transitions, which are of longer wavelength. Correspondingly, to the extent that the 3,4,... states become magnetized with decreasing field H (with increasing μ), transitions of the type $3 \rightarrow 0$, $4 \rightarrow 0$,... add to the gain on the *l-h* transitions and lead to an oscillatory behavior of $P_\lambda(H)$ in region A (Fig. 1). The doubling of the number of resonances can be explained on the basis that the anisotropy of the valence band and the motion of holes along **H** should lift the prohibition against optical transitions between ladders with quantum numbers $m_j = 3/2, -1/2$ and $m_j = -3/2, 1/2$ (Fig. 3).

We would like to stress the importance of stimulated emission at the second harmonic of the cyclotron resonance of light holes for developing a tunable, narrow-band source of long-wavelength IR light.

We wish to thank A. A. Andronov for a useful discussion of the results and also S. A. Pavlov and V. A. Kozlov for their collaboration.

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Translated by Dave Parsons