Spectral condensation near an impurity absorption line in a germanium-hot-hole laser

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The output spectrum of a long-wave IR laser operating on intersubband transitions of hot holes in p-type Ge has been measured. The impurity absorption spectrum in an active sample has also been measured. It is concluded from the results that there is a "condensation" of the output spectrum of a p-Ge laser near an absorption line corresponding to a transition from the ground state of a shallow acceptor to the first excited state. © *1995 American Institute of Physics.*

Lasers for the long-wave part of the IR region operating on interband transitions of hot holes in p-type Ge in crossed electric and magnetic fields have an unusually broad stimulated-emission spectrum,[1] with a line structure similar to that in the absorption spectrum of the acceptor dopant. This circumstance was pointed out in Refs. 2–5, where the acceptor dopant was gallium (the ionization energy of the ground state in this case is $E_{\mathrm{Ga}}= 11.07$ meV). This point was recently confirmed by measurements of the emission spectrum of thallium-doped germanium[6] ($E_{\mathrm{Tl}}= 13.10$ meV). It was shown in Ref. 5 that a recombination involving spontaneously emitted optical phonons in the course of photoionization of the ground state (g.s.) of the acceptor by emission developing on intersubband ($l \rightarrow h$) transitions may lead to a population inversion of excited states (ex.s.) and to a corresponding gain on ex.s.→g.s. optical transitions. This circumstance can explain the presence of so-called E and C lines in the stimulated-emission spectra.[4,5] However, in view of certain experimental data (cf. Refs. 2 and 3), this circumstance does not explain the generation near the G absorption line (g.s.→1 $^{\mathrm{st}}$ex.s.). According to the alternative interpretation proposed in Ref. 6, the discrete nature of the observed output spectra of p-Ge lasers is formed exclusively by transmission windows in the impurity absorption spectrum in the active sample.

In an effort to learn more about the mechanism for the formation of the G generation region, we have carried out some detailed measurements of the output spectrum of a Ge:Ga laser with improved resolution (as good as 0.3 cm^{-1}). We have compared the spectra of stimulated emission with the spectrum of impurity absorption in the original Ge:Ga single crystal.

Active samples for the Ge:Ga laser (N1 and N2) were fabricated as rectangular parallelepipeds with dimensions of $5 \times 7 \times 50$ mm from a Ge single crystal with a Ga-

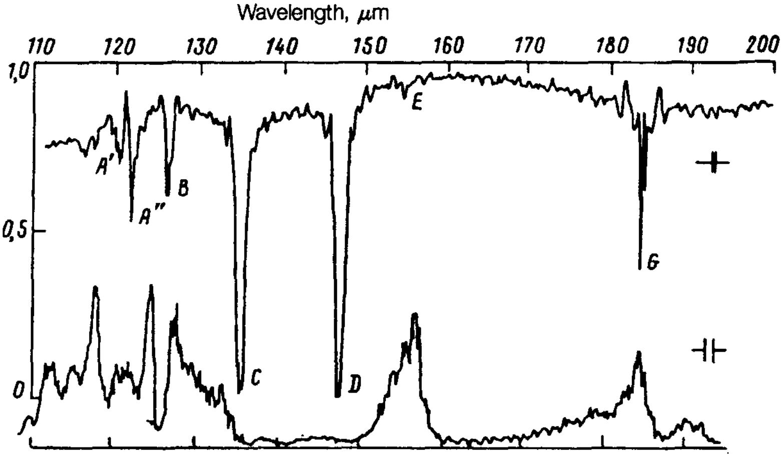

FIG. 1. Bottom: Output spectrum of a Ge:Ga laser in fields $E = 750$ V/cm and $H = 6.3$ kOe (sample N1). Top: Absorption spectrum of Ge:Ga.

center concentration $N_A = 7 \times 10^{13}$ cm^{-3}. A magnetic field of 3–20 kOe was oriented along the long axis of the sample, in the [110] crystallographic direction. Electric-field pulses 4 μs long were applied through ohmic contacts deposited on the 5×50-mm^2 lateral faces of the sample. The applied field was therefore in the orientation **E**∥[−110] direction ($\mathbf{E} \perp \mathbf{H}$). The ends of the sample were treated optically and were mutually plane-parallel within 30″. The stimulated emission developed on axial modes of the Fabry–Perot resonator formed by plane copper mirrors (7 and 4 mm in diameter) applied to the ends of the sample through 20 μm of a Teflon film. The light was extracted by means of diffraction by the smaller mirror. The laser output passed through a grating monochromator and was detected by a cooled broad-band n-GaAs photodetector.

Figure 1 shows the output spectrum (bottom) of a laser using a Ge:Ga active sample for values of the applied fields **E** and **H**, at which both low- and high-frequency ($\lambda < 140$ μm) generation develops. The resolution of the spectrometer was ~0.3 cm^{-1}.

Shown at the top in Fig. 1 is the absorption spectrum of a Ge:Ga platelet 2.5 mm thick cut from the same single crystal as the active sample of the laser. The absorption spectrum was measured by a Fourier spectrometer with a resolution of 0.02 μm at liquid-helium temperature in the absence of external fields. All the absorption lines (designated A'' through G, in accordance with Ref. 7) belong to the Ga acceptor. The slight splitting of the lines clearly is attributable to internal stress in the Ge platelet. We did not observe lines of other shallow acceptors in the spectrum. Direct measurements of the absorption spectrum of shallow impurity centers in the presence of fields $\mathbf{E} \perp \mathbf{H}$ are difficult, because of impact ionization of these centers. There has been no theoretical analysis of localized states in such strong fields $\mathbf{E} \perp \mathbf{H}$.

The correlation between the absorption spectrum and the spectrum of stimulated

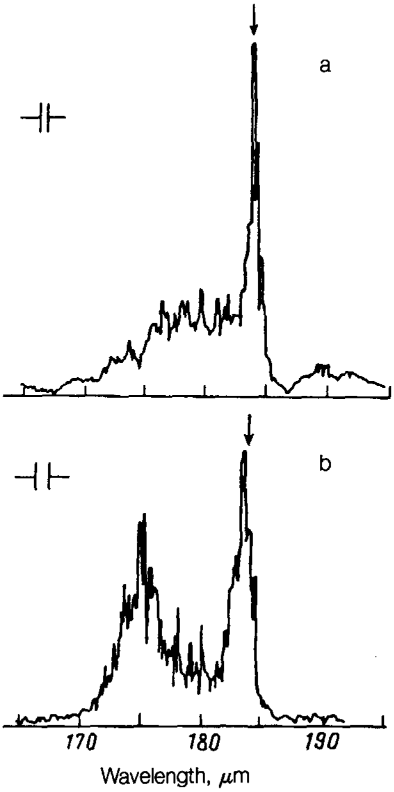

FIG. 2. a—Output spectrum of a Ge:Ga laser in fields $E=660$ V/cm and $H=5.9$ kOe (sample N1); b—$E=620$ V/cm and $H=5.7$ kOe (sample N2). The arrow marks the G absorption line.

emission is obvious. The peak in the emission spectrum at the wavelength 133 μm, on the "blue" side of absorption line C, corresponds to the "C" emission line observed in Ref. 4. The wide line at 155 μm corresponds to the E line (Ref. 2). Near the G absorption line we observe, in all the test samples, a narrow spectral peak in the emission at 183.5 μm and a valley at 186.5 μm. These features undergo essentially no shift as the applied fields are varied. Figure 2 shows laser output spectra near the G absorption line in fields for which there is no emission at higher frequencies. In this case the generation near the G line is not suppressed by competition from the high-frequency part of the spectrum,[2,3] and the spectral features just mentioned are more obvious. It was found possible to improve the resolution of the spectrometer to 0.2 cm^{-1} (Fig. 2a).

The total spectral width of the emission band near line G is, on the whole, a distinctive feature of a given sample (Fig. 2). It has values of 15–25 μm (5–10 cm^{-1}) and depends on the strengths of the applied fields. The dip in the emission at 186.5 μm apparently corresponds to the position of absorption line G in the presence of fields, as suggested in Ref. 6. However, impurity absorption alone cannot explain all the structure in the observed output spectra of the p-Ge laser.

In the opinion of the authors, the peak at 183.5 μm (for the Ge:Ga laser), whose measured spectral width ($\Delta\lambda \simeq 0.7-1$ μm) is essentially determined by the resolution of the spectrometer, and whose spectral intensity is greater than the general level by a factor of 2 to 4, arises because of a "condensation" of the spectrum near impurity absorption line G. This spectral condensation has been well documented in dye lasers and can be attributed to many factors[8,9] associated with particular features of the nonlinear dynamics of the stimulated emission.

It is important to note that the emission spectrum of a Ge:Tl laser which was studied in Ref. 6 is similar, in corresponding fields, to the emission spectrum of the Ge:Ga laser, with the one distinction that it is shifted in accordance with the position of the thallium absorption lines: The peak near line G is at a frequency of 72 cm^{-1}, and the dip is at 71 cm^{-1} (the value for the G transition[7] is 71.8 cm^{-1}). The emission region near the E lines corresponds to the interval 78.4–81.3 cm^{-1} (79.5 cm^{-1}). The entire low-frequency part of the output spectrum also shifts in the short-wave direction because of the shift of line G.

Since the spectrum of the gain due to intersubband transitions in a p-Ge laser is determined by a superposition of homogeneously broadened ($\Delta\nu\simeq 10\ \mathrm{cm}^{-1}$) lines corresponding to different values of the longitudinal momentum for the lower populated Landau level of light holes,[10] the presence of a relatively narrow ($\delta\nu\simeq 1\ \mathrm{cm}^{-1}$) absorption line should lead to an increase in the saturation parameter and in the corresponding gain in the nonlinear regime at adjacent frequencies in the homogeneous-broadening band. We believe that this interpretation explains the condensation of the low-frequency region of the laser output near the g.s.$\rightarrow 1^{\mathrm{st}}$ex.s. absorption transition. A similar mechanism has been discussed[11] with regard to the spectral condensation in dye lasers.

The narrow emission peak in the short-wave wing of absorption line G can also be attributed to a periodic spatial modulation of impurity absorption (due to the distribution of the radiation field in the resonator) and thus a selective gain. The effect is not seen on the long-wave side of the absorption line because of additional absorption corresponding to transitions to the valence band (1^{st}ex.s$\rightarrow$cont.s.), which occurs primarily at low frequencies. The latter depends on the width of the absorption line and the degree of mode locking of the laser. This topic requires further research.

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