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## Single axial-mode selection in a far-infrared *p*-Ge laser

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Single axial-mode operation of the pulsed far-infrared *p*-Ge laser with an intracavity Fabry–Perot type frequency selector has been observed by means of Fourier-transform spectroscopy. A spectral resolution better than 1 GHz has been achieved on an ordinary continuous-scan spectrometer using the event-locked technique for pulsed emission sources. A laser active-cavity finesse of at least unity has been directly confirmed from the measured emission spectral width. Analysis of the envelope of the corresponding interferogram suggests that the finesse exceeds 10. © 2000 American Institute of Physics. [S0003-6951(00)00215-1]

A practical goal for the far-infrared (far-IR) *p*-Ge laser, which operates over the wide frequency range from 50 to 140  $\text{cm}^{-1}$  (1.5–4.2 THz), is tunable single line or single mode generation. Operation on magnetic-field tunable cyclotron-resonance lines<sup>1</sup> and use of intracavity frequency selection<sup>2–5</sup> have made considerable progress toward this goal. However, single axial-mode generation, although suggested,<sup>2</sup> has not been demonstrated until now.

Stimulated emission in *p*-Ge lasers occurs on direct optical transitions between light- and heavy-hole valence subbands in bulk *p*-Ge at liquid-helium temperatures in strong crossed electric *E* and magnetic *B* fields. Population inversion is built up via light hole accumulation at the optimal ratio *E/B*, when heavy holes repeatedly emit an optical phonon after being accelerated beyond the threshold energy 37 meV, but light holes move on closed cyclotron orbits below this threshold and have a much longer lifetime. The usual pulse duration is a few microseconds with usual peak powers of 1–10 W. A large gain bandwidth ( $\Delta\omega/\omega \sim 1$ ) makes this active medium promising for wide range tunability.

Without frequency selection, the usual spectrum of *p*-Ge laser emission has a width up to 30  $\text{cm}^{-1}$ . This broad, multimode band is tunable in the range 80–140  $\text{cm}^{-1}$  by changing the applied *E* and *B* fields. At low fields, the band separates into discrete emission lines, related to shallow-impurity transitions, down to 50  $\text{cm}^{-1}$ . The longitudinal mode separation for a typical *p*-Ge laser with an active crystal length of about 4 cm and mirrors attached to the ends of the crystal is  $\sim 0.03 \text{ cm}^{-1}$  ( $\sim 1 \text{ GHz}$ ). Thus, in the high-field broadband regime, the laser generates up to 1000 longitudinal modes simultaneously.

According to the results of narrow-band heterodyne spectroscopy,<sup>6</sup> the width of each mode is on the order of 1 MHz, which is defined only by the limitations of the laser pulse duration (1–4  $\mu\text{s}$ ). This result is supported by transient

recordings using a fast detector and oscilloscope, where it was observed that the intensity pattern, which is periodic at the cavity round-trip frequency, persists throughout the entire laser pulse duration.<sup>6–10</sup> Previous broadband spectroscopic studies<sup>2</sup> of wavelength selection using an external cavity lacked sufficient resolution to distinguish individual axial modes. The purpose of this letter is to demonstrate, using broadband spectroscopy with higher resolution than previously employed, that the *p*-Ge laser with such a cavity can generate a single axial mode. An active-cavity finesse (defined as the axial mode interval divided by the cavity resonance bandwidth)<sup>11</sup> greater than unity is conclusively demonstrated from the spectral width of the observed emission line. Analysis of the envelope of the corresponding interferogram strongly suggests that the finesse is at least 10. This means that no satellite spectral emission lines, such as transverse modes, occur farther than  $\sim 100 \text{ MHz}$  from the central line.

A recently developed method for spectroscopy of low-duty-cycle pulsed emission sources was used in this work. This technique, called event-locked Fourier spectroscopy (ELFS),<sup>12</sup> permits use of an ordinary commercial continuous-scan Fourier spectrometer with the full spectral range and resolution allowed by that instrument, even for sources with repetition rates of just 10 Hz and pulse durations of only microseconds, as holds for the *p*-Ge laser. To date, ELFS has been used to characterize energy transfer in the pulsed near-IR luminescence spectra of rare-earth doped laser crystals,<sup>13–15</sup> determine the power spectrum of new “quantum fountain” lasers emitting at 15  $\mu\text{m}$  and pumped at 10  $\mu\text{m}$  by a pulsed  $\text{CO}_2$  laser,<sup>16</sup> measure the time resolved photoluminescence spectrum of  $\text{Si}_{0.5}\text{Ge}_{0.5}/\text{Si}$  strained undulated multiquantum-well structures,<sup>17</sup> and characterize the spectrum of *p*-Ge lasers in nonselective cavities.<sup>18,19</sup> ELFS has permitted broadband spectroscopy of *p*-Ge laser emission with at least three times better spectral resolution than previously reported.<sup>2</sup>

The construction of the selective resonator for the *p*-Ge

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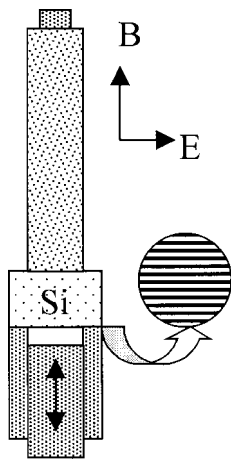


FIG. 1. Cavity construction for *p*-Ge laser with intracavity tuning element. The elements from top down are the copper output coupling mirror, the *p*-Ge active crystal, the Si spacer with evaporated Al stripes, and the brass Fabry-Perot resonator.

laser is shown in Fig. 1. The operation of such cavities has been discussed previously.<sup>2,3</sup> The cavity consisted of a  $7.2 \times 4.5 \times 28.0 \text{ mm}^3$  *p*-Ge crystal and a 7.85 mm Si spacer with evaporated Al stripes, which are 0.5 mm wide with a 1 mm period. The backmirror was a tunable Fabry-Perot cavity machined from brass, where the piston is adjusted by a precision screw. The diameter of the output mirror was smaller than the active crystal cross section to allow output of the generated emission. The size of the Si and Ge crystals defines the cavity length and gives a mode spacing of 1099 MHz or  $0.037 \text{ cm}^{-1}$  (using  $n_{\text{Ge}} = 3.926$ ,  $n_{\text{Si}} = 3.382$ ).

The laser crystal was cut from single-crystal, Ga-doped Ge with a concentration  $N_A = 7 \times 10^{13} \text{ cm}^{-3}$ . The ends of the crystal were polished and made parallel to each other with 30 arc sec accuracy and with better than  $0.1 \mu\text{m}$  flatness. The lateral sides of the crystal were left unpolished to suppress transverse modes. Crystallographic orientation was such that  $B \parallel [110]$  and applied  $E \parallel [-110]$ . Electric field pulses were applied to the laser from a thyatron pulser via ohmic Al contacts evaporated on the  $4.5 \times 28 \text{ mm}^2$  lateral sides of the crystals. The entire system was inserted in a superconducting solenoid and cooled by liquid helium. The radiation was guided to the spectrometer emission port by a brass light pipe.

The published technical description of ELFS can be summarized as follows.<sup>12</sup> As an electronics and software solution, ELFS introduces no (or trivial) additional optics and no mechanical hardware to the commercial Fourier-transform spectrometer that is used. Interferogram points are sampled on the fly while the mirror scans. Needed points are skipped in a given scan to accommodate slow excitation rates since smooth scanning is impossible at arbitrarily slow speeds. Missing points are then filled during subsequent scans to obtain the necessary spectral range. Artifacts and noise from speed variations<sup>20</sup> are avoided by acquiring interferogram values at times that are locked to excitation events rather than to the occurrence of reference fringes. Recorded scan-speed determines precise retardation at the acquisition times, independent of the inevitable speed variations caused by vibrations and mechanical imperfections. The result of the speed variations is to give uneven spacing to the precisely

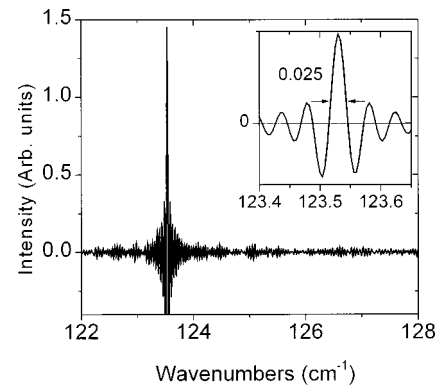


FIG. 2. Emission spectrum of *p*-Ge laser with selective cavity. Inset: Close-up of peak showing that the measured FWHM (in  $\text{cm}^{-1}$ ) is the same as the expected instrumental line width. The resolution and 40–140  $\text{cm}^{-1}$  range of the complete spectrum are sufficient to show that only a single longitudinal mode is present. The fields applied to the active crystal were 1.0 T and 1530 V/cm.

known interferogram point positions, so that a least-squares fit to harmonic functions is used instead of fast Fourier transform (FFT) to obtain the spectrum (ELFS transform). A study of the relative quality of the ELFS transform and FFT as applied to interferograms of varying point-spacing randomness reveals the conditions under which the ELFS transform must be used to obtain adequate results.<sup>21</sup> FFT is used here because the position uncertainties are much smaller than the minimum far-IR wavelength. Provision for a reference detector to correct each interferogram point for shot-to-shot intensity fluctuations is an ELFS feature, but it was not used in these measurements. ELFS has robust error correction protocols to automatically recover from unacceptable events (e.g., missed shots).

A maximum optical retardation  $L = 23.8 \text{ cm}$  was used on a Bomem DA8 Fourier spectrometer with the ELFS accessory (Zaubertek). For an unapodized interferogram of a monochromatic source, the instrumental lineshape is  $\sin(x)/x$  and the resulting linewidth [full width at half maximum (FWHM)] is  $0.603/L = 0.025 \text{ cm}^{-1}$ .<sup>22</sup> This value corresponds to 750 MHz, which is less than the 1099 MHz separation of axial modes. Resources used with the spectrometer were a  $12 \mu\text{m}$  mylar pellicle beamsplitter with a 40–140  $\text{cm}^{-1}$  useful range, and a 4 K Si composite bolometer (Infrared Labs) with a  $370 \text{ cm}^{-1}$  low pass filter. The interferogram sampling period was chosen sufficient to give a  $140 \text{ cm}^{-1}$  spectral range, which corresponds to data collection at only 1 out of every 56 fringes of the interferometer's HeNe reference laser. Hence, the useful spectral range of our measurements is 40–140  $\text{cm}^{-1}$ . It is generally accepted (see, however, Ref. 23) that the *p*-Ge laser does not emit outside this range. Collection time for the data presented here (with 10 Hz laser-repetition rate) was about 20 min. Transform time was insignificant.

Figure 2 presents a spectrum in the high field region when the selective resonator is used. The distance between adjustable mirror and the surface of the Si spacer with evaporated Al strips was  $121 \mu\text{m}$ , with an uncertainty of  $5 \mu\text{m}$ , as determined with an optical microscope. For the  $3\lambda/2$  Fabry-Perot resonance,  $81 \mu\text{m}$  is predicted for the emission wavelength  $\lambda$ , in agreement with Fig. 2. Only this single line of laser emission is observed over the useful spectral range,

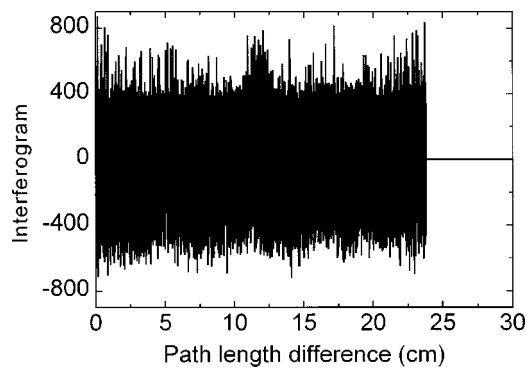


FIG. 3. Interferogram. The data consist of interference fringes with flat amplitude up to the maximum path-length difference, followed by zero padding.

and no other signals above the noise level are found. The inset shows that the observed line width is the same as the instrumental line width. (The small point spacing that gives the smooth profile was obtained by zero padding the interferogram to a resolution of  $0.005 \text{ cm}^{-1}$ , which preserves the instrumental line width.) A line shape essentially identical to the instrumental line shape function, complete with strong ringing, suggests that the *p*-Ge emission is much narrower than the  $0.025 \text{ cm}^{-1}$  spectrometer resolution. The spectrum is sufficiently sharp to show that there are not two modes separated by the  $0.037 \text{ cm}^{-1}$  axial mode spacing, which demonstrates conclusively that the active-cavity finesse exceeds unity.

The flat amplitude of the interferogram over the entire available range of optical retardation (Fig. 3) provides evidence that the finesse actually exceeds 10. (At the end of the actual collected data is the beginning of the zero padding used to smooth the calculated spectrum.) The small-scale amplitude noise is caused by 20%–30% pulse-to-pulse instability of the laser output intensity. Note that the traditional sharply peaked center burst at zero path-length difference does not appear in this interferogram, and the absence of visible variation of average amplitude suggests that the emission line is much more narrow than the instrumental line-width. Additional strong, closely spaced modes would cause a slow modulation of the interferogram amplitude. Estimating this modulation to be less than 10% suggests that separation of additional (transverse) modes, if present, cannot be greater than 100 MHz giving a finesse value better than 10. Prior information from heterodyne mixing studies<sup>6</sup> that the *p*-Ge laser spectrum consists of separate modes with 1–2 MHz width, and from transient recordings with evidence of 40 MHz transverse mode beating,<sup>10,19</sup> suggests that there still can be a number of strong transverse modes oscillating within our extrapolated resolution envelope.

In conclusion, a single axial mode can be generated by the *p*-Ge laser with a Fabry–Perot type intracavity frequency

selector with a demonstrated finesse better than unity and an estimated finesse better than 10, which gives  $\sim 100$  MHz maximum width of the *p*-Ge laser spectrum at  $\sim 3$ – $4$  THz frequency. Potential applications of a single frequency *p*-Ge laser tunable in the wide spectral range 1.5–4.2 THz include, for example, high-resolution traditional and intracavity spectroscopy of semiconductors and semiconductor structures.<sup>24</sup>

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