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Evidence for self-mode-locking in *p*-Ge laser emission

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Investigations of the dynamics of the far-infrared *p*-Ge laser emission reveal strong periodic soliton-like intensity spikes with less than 100 ps duration. We interpret these spikes as self-mode-locking of *p*-Ge laser modes. The effect becomes more pronounced when a GaAs/AlGaAs/InGaAs quantum well structure on a semi-insulating GaAs substrate is inserted into the laser cavity. © 1998 American Institute of Physics. [S0003-6951(98)01647-7]

Far-infrared *p*-Ge lasers operate in the spectral range 50–140 cm^{-1} . Their mechanism of stimulated emission is based on direct optical transitions between light and heavy hole valence subbands in bulk *p*-Ge [Fig. 1(a)] in strong crossed electric and magnetic fields [Fig. 1(b)] when the crystal is cooled to liquid helium temperatures. The population inversion builds up for certain ratios of electric and magnetic fields, where light holes are accumulated on closed trajectories below the optical phonon energy, while heavy holes experience strong optical phonon scattering. The gain spectrum is very broad because lasing transitions lie in a wide range of hole momenta [Fig. 1(a)]. Far-infrared laser emission with a few μs pulse durations and peak powers of 1–10 Watt are widely reported.¹ Figure 2 shows the laser operating zone of applied *E* and *B* fields, which splits into low and high field regions. These correspond to low and high frequency laser emission, respectively.

Due to their wide spectrum *p*-Ge lasers are promising for generation of short (picosecond) pulses of THz radiation by means of active^{2–4} or passive mode-locking for time-resolved (linear and nonlinear) THz spectroscopy and other related applications. In Refs. 2–4 200 ps pulses of *p*-Ge laser radiation with a considerable power have been obtained by active mode locking, when the gain is externally modulated at the laser cavity roundtrip frequency. Without active mode locking, the laser still might have a strongly varying intensity, periodic with the roundtrip time of the laser cavity,^{3,5} which results from modes being accidentally in phase to some extent. For the low frequency part of the laser spectrum, which is split into several discrete lines containing only 10 to 20 longitudinal modes (Fig. 3), such coincidences are likely, especially in the rising edge of the laser pulse, and this has been interpreted in Ref. 3 as self-mode-locking. In the high frequency part of the spectrum, hundreds of modes oscillate simultaneously with random phases, and a sharply

peaked temporal structure due to some coincidental phase relation is much more unlikely.

In this letter the first evidence for self-mode locking in the high frequency region of the *p*-Ge laser is reported, appearing as a clear nonlinear effect at the peaks of a slowly oscillating laser intensity. As a result, a train of radiation spikes shorter than 100 ps is generated without active gain modulation or added passive elements.

The active Ga-doped Ge crystal $N_A \approx 7 \times 10^{13} \text{ cm}^{-3}$ has dimensions $4.5 \times 7.3 \times 28.0 \text{ mm}^3$. The crystal ends were polished flat and parallel to each other within 1 min accuracy, and two external copper mirrors were attached to them insulated from the Ge and the aluminum contacts with 20 μm teflon film [Fig. 1(b)]. The crystal is cooled by immersion in liquid helium at 4 K. Electric field pulses (2 μs) are applied along [110] via ohmic contacts covering the $4.5 \times 28.0 \text{ mm}^2$ surfaces of the sample. The magnetic field is applied along [1 $\bar{1}$ 0] in Faraday geometry. The laser radiation propagates along the long crystal axis [1 $\bar{1}$ 0], is conducted out of the cryostat, is detected after a teflon lens with a fast whisker-contacted Schottky diode [1T17(82), University of Virginia], amplified with a 10 GHz bandwidth amplifier (Picosecond Pulse Labs 5840) and recorded on a transient digitizer (Tektronix SCD5000) with 80 ps resolution. Spectroscopy was

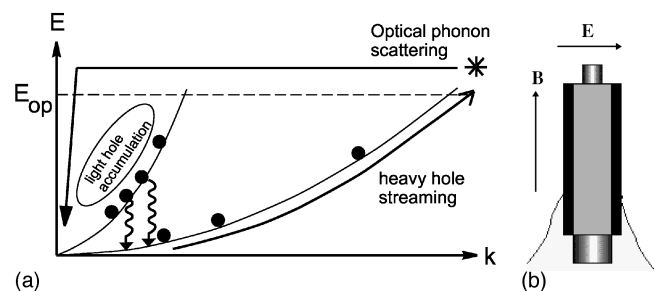


FIG. 1. (a) Pumping mechanism of the *p*-Ge laser. (b) Laser cavity construction. The black strips indicate Al coated lateral sides, with wires indium-soldered to them. The cylindrical end pieces are Cu mirrors, insulated from the crystal with 20 μm teflon film.

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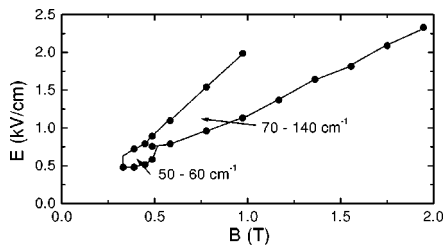


FIG. 2. Typical (E, B) field regions for low- and high-frequency operation of the p -Ge laser.

performed with a research grade Fourier transform infrared (FTIR) spectrometer (Bomem DA8) using “event-locked” gated-acquisition electronics⁶ (Zaubertek).

The p -Ge laser spectrum without intracavity frequency selection is $15\text{--}30\text{ cm}^{-1}$ broad and tunable between 50 and 140 cm^{-1} by changing the applied fields.¹ In the high-frequency region (Fig. 2), this spectrum can contain a few hundred longitudinal laser modes, but in the low-frequency region below 70 cm^{-1} , the spectrum is split into discrete lines related to shallow impurity transitions.⁷ The broadest of the low frequency laser emission lines is shown in Fig. 3. This is the first broadband spectral measurement of p -Ge laser output with resolution high enough to resolve the longitudinal mode structure. The observed equidistant mode spacing $\Delta\nu$ in Fig. 3 (in Hz) is related to the longitudinal round-trip time τ by $\Delta\nu = 1/\tau = c/2n_{\text{Ge}}L = 1363\text{ MHz}$, or $\tau = 734\text{ ps}$, where L is the active crystal length, and $n_{\text{Ge}} = 3.925$ is the refractive index. The corresponding mode beating pattern could easily display strong oscillations of the laser intensity at the round-trip frequency $\Delta\nu$, simply by having the phases of each mode accidentally similar. In the high field region, however, such coincidences and strong oscillations are much less likely.

Figure 4 shows digitally captured traces of the output intensity of this particular crystal in the high field region at three different time scales. The output intensity is strongly modulated at about 44 MHz [Fig. 4(a)]. These oscillations are much slower than the cavity round-trip frequency of 1363 MHz . At a higher temporal resolution, trains of very sharp spikes are found on the maxima of the slow intensity oscillations [Fig. 4(b)]. Such spikes are absent from the 44 MHz valleys and they start to grow rapidly as the intensity increases. The round trip time for the sharp spikes is 722 ps , which is close to the calculated cavity round-trip time of 734 ps . We take the occurrence of the sharp spikes to be evidence for self-mode-locking. Figures 4(c) and 4(d) show close-ups of portions of the trace in Fig. 4(b). Sampled data points are

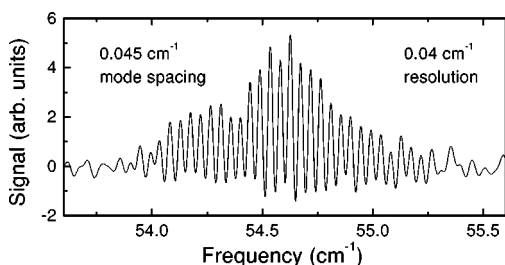


FIG. 3. Close-up of one of the spectral lines in the low-field regime showing longitudinal mode structure.

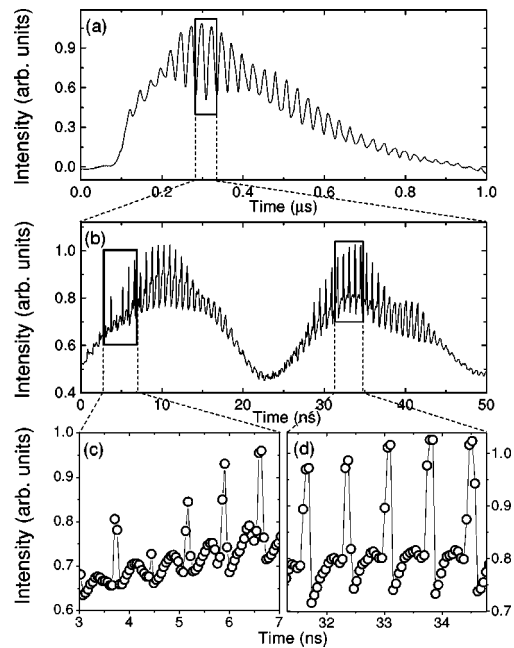


FIG. 4. (a) Laser output pulse showing 44 MHz oscillations. (b) A different shot at higher time resolution showing sharp spikes at the crests of the 44 MHz oscillations. (c) and (d) Further close-ups of (b) show that the unevenness in the peak heights is evidently a sampling effect, where points are sampled at a 50 ps interval.

indicated by circles. The unevenness in the rise of self-mode locking in Fig. 4(c) is clearly a sampling effect. The points are separated by 50 ps , showing that the self-mode-locked pulses have a width less than the 80 ps rise time allowed by the bandwidth of the electronics. These are the shortest pulses yet observed from p -Ge lasers.²⁻⁴

Additionally, we have investigated the temporal behavior of emitted radiation from this p -Ge laser when a GaAs/AlGaAs/InGaAs quantum well structure on a semi-insulating GaAs substrate with a thickness of 0.5 mm and parallel polished surfaces is inserted into the cavity between the active crystal and the back mirror. The short radiation spikes become much more pronounced and repeatable. This is shown in Fig. 5. The inset shows another shot at a finer timescale. The quantum well structure consists of $40\text{ nm } n^+$ -GaAs ($n > 10^{18}\text{ cm}^{-3}$), $40\text{ nm } n^+$ - $\text{Al}_{0.24}\text{Ga}_{0.76}\text{As}$ ($n > 10^{18}\text{ cm}^{-3}$), $15\text{ nm } i\text{-In}_{0.18}\text{Ga}_{0.82}\text{As}$, and $100\text{ nm } i\text{-GaAs}$ layers on top of a GaAs substrate.

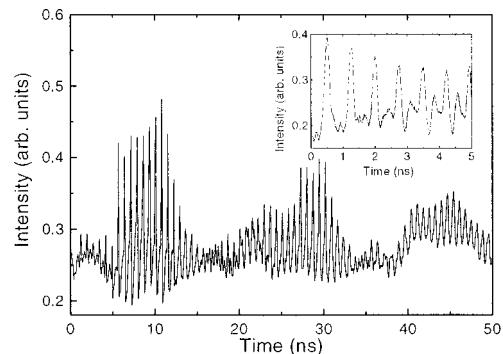


FIG. 5. Output of the self-mode-locked p -Ge laser with quantum well intracavity insert. Upon blocking the radiation, the signal drops to a baseline of about 0.05 , so the peaks occur on a constant background of about equal intensity. The inset shows a different shot with higher time resolution.

Thus these experiments demonstrate self-generation of intense spikes as short as 80 ps in the far-infrared *p*-Ge laser, which is shorter than obtained so far by active mode locking.²⁻⁴ We take this result as tentative evidence for self-mode-locking. Strong slow intensity oscillations seem to provide the conditions for buildup of these spikes. The experimental data are not yet conclusive with respect to the origin of either the slow oscillations or the short pulse formation. Various possibilities are discussed here briefly.

The most straightforward explanation for the 44 MHz oscillation is beating of transverse modes⁸ and this was in fact suggested in Ref. 9 to explain weak 50 MHz oscillations in the output of a *p*-Ge laser. The observed synchronization of spike generation to the rise in intensity might, however, suggest that actual modulation of the gain occurs at this low frequency, and peaks grow during a period of net gain and disappear when losses are dominant. The observed train of spikes corresponds to the formation of a soliton-like electromagnetic pulse traveling in the laser cavity. Since the active *p*-Ge laser crystal is a hot carrier system interacting with a high-intensity radiative field and operating in a strongly nonlinear regime in many aspects, several possible mechanisms can be suggested for self-mode locking. First of all, the population inversion in part of the crystal might be destroyed due to the inhomogeneity of doping and/or inhomogeneity of the electric field. This part could then act as a saturable absorber causing passive mode locking. The observed enhancement upon including a nonlinearly absorbing spacer into the cavity seems to support such an interpretation. However, the observed rapid rise in spike intensity remains somewhat surprising, considering the supposed low gain of the medium,¹ and this might suggest other mechanisms such as soliton mode locking due to nonlinear changes of the refractive index. Unfortunately, the magnitude of these index changes in *p*-Ge laser systems has been studied little so far, although the suggested strongly nonlinear birefringence caused by Faraday rotation¹⁰ and slightly different index for higher-order transverse modes,⁹ might turn out to be important factors for the generation of temporal¹¹ or spatial optical solitons, respectively.¹² Clearly, further experimental and theoretical studies are necessary to clarify this issue.

The passive way of obtaining picosecond far-infrared pulses from a *p*-Ge laser is much simpler than the active mode-locking scheme, which involves high-power radio frequency (rf) techniques.²⁻⁴ A disadvantage of self-mode-locking is the rather large background output intensity (about 40%–50%) observed in Figs. 4 and 5, which is suppressed

when the laser is actively mode locked with a sufficiently strong rf field. However, to the extent that this background is due to unlocked, or spatially separated (internal reflection) modes, it can possibly be removed by bringing these modes below threshold with an optimized resonator design. Also, hybrid mode-locking schemes, where active and passive mode locking are combined, could yield the advantages of both schemes: short pulses with low jitter and background. The rapid rise in pulse intensity suggests that pulse amplitude modulation telemetry with a mode-locked pulse train of THz laser radiation may be possible, although it remains unclear how to control such modulation. Potential applications might include secure, local area communication by THz beams or longer range communication in space.¹³

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