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Far-Infrared p-Ge Laser: Pulse Dynamics and Repetition-Rate Enhancement

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Abstract

A significant repetition-rate increase is found using copper heat sinks in a Voigt-configured permanent-magnet p-Ge laser with wavelengths near 200 μm. Studies of time resolved emission reveal unusual pulse dynamics which depend on the magnitude and duration of the applied electric field. Spectral content, free-space beam profiles, and polarization are essentially independent of these temporal effects. Lasing persists above 10 K, raising the possibility of a practical p-Ge laser without need for liquid helium as a coolant.

Key Words

Infrared and Far-infrared lasers, Far-infrared, Semiconductor lasers, Semiconductors

Introduction

The p-Ge laser is the only solid-state laser source in the 70-250 μm wavelength region[1]. Based on population inversion between light and heavy hole bands in crossed electric and magnetic fields, it provides narrow band tunable[2] radiation at spectral densities that are orders of magnitude higher than traditional thermal sources. Its chief disadvantage has been the requirement of liquid helium to cool both the Ge crystal and a superconducting solenoid.

We recently demonstrated[3] that lasing in p-Ge could be achieved using an ordinary permanent magnet, which coincidentally provides an easy set up for the favorable Voigt configuration. The relatively open permanent magnet architecture allows also the use of large Cu heat sinks. These effectively remove the Joule heat created during current pulses allowing a significant increase in repetition rate. Temperature dependence reveals that lasing persists above 10 K. Since the heat sinks could be cold fingers of a closed cycle refrigerator, the possibility of a p-Ge laser entirely free of liquid helium is convincingly established.

By varying the electric pulse magnitude and duration, some unusual pulse dynamics are revealed. Double emission pulses appear at sufficiently high electric field and for sufficiently long electric-field pulse durations. Spectroscopy, beam profiles, and polarization studies reveal that the extra emission pulse contains no new spectral content or mode structure.

Experiment

A 51 x 4.1 x 4.3 mm^3 Ga-doped p-Ge rod with N_A-N_D $\sim 9 \times 10^{13}$ cm^{-3} was placed between the poles of a 0.35 T permanent magnet with **B** ‖ [001] and light propagation ‖ [110]. Electric pulses were applied through indium Ohmic contacts on the [1-10] faces (4.3 x 51 mm^2). End surfaces of the rod were polished parallel to better than 1 arc-min. A Cu back reflector and a #750 mesh Cu output coupler were used. Radiation was detected with a Si-composite bolometer or a Ge:Ga photoconductor. Spectra were measured using event-locked Fourier spectroscopy[4,5].

Results

Figure 1 presents current, applied electric field and emission pulses vs time for a range of peak field strengths but for the same electric-field pulse duration. The numbers within each figure are the peak electric fields in V/cm associated with each trace. The ringing on the leading edge of the electric field pulses may be due to Gunn oscillations, whereas that on the trailing edge is due to the turn-off surge from the high-power pulse generator. The noise generated by this turn-off is picked-up by the detector as seen for times longer than 1.7 μs. This noise is observed even when the detector window is blocked, in which case the far-infrared signal is not seen. For low fields a single emission pulse occurs near the trailing edge of the voltage pulse. As the electric field is increased both the peak of the signal and its duration increase. Near the middle of the electric field range the pulse splits into two. These two pulses continue to diverge in time and eventually decrease in strength as the electric field is further increased. The leading pulse persists to the highest electric field values.

Similar emission pulse effects are observed if the pulse-generator's capacitor charging voltage is kept constant but the pulse duration is increased. Fig. 1 reveals that the electric field needs time to reach its maximum value, so that the observed pulse-width dependence has arguably the same origin as the electric-field dependence.

Since the two emission pulses have differing electric field dependences, they may also have differing spectral content, free-space beam profiles, or polarization dependence. Fig. 2 presents beam profiles for single and double pulse conditions. The profiles are Gaussian, as revealed by the fits, and they have identical half-widths within experimental error. There is evidence of a side lobe, but its strength also appears independent of the details of the emission dynamics.

Fig. 3 presents polarization data for the double pulse condition. Both pulses have their photon electric field polarized parallel to the applied electric field. Such polarization may have its origin in the oblique internal reflection modes which are known to occur[6]. Internal reflections from surfaces with Ohmic contacts are expected to be lossy. Likewise, the reflection coefficient below the critical angle for the clean faces is higher for polarizations perpendicular to the plane of incidence, i.e. parallel to the applied electric field. Alternatively, if the curvature of hole orbits in the magnetic field is ignored, then vertical transitions in momentum space between bands of differing effective mass give rise to oscillating dipoles parallel to the applied electric field.

Fig. 4 presents spectra of the emission for single and double pulse conditions. These were collected using the slow bolometer so they represent the time integrated spectral content of the emission pulses. Four major peaks appear in each spectrum. Since both spectra evidently have the same spectral content, the

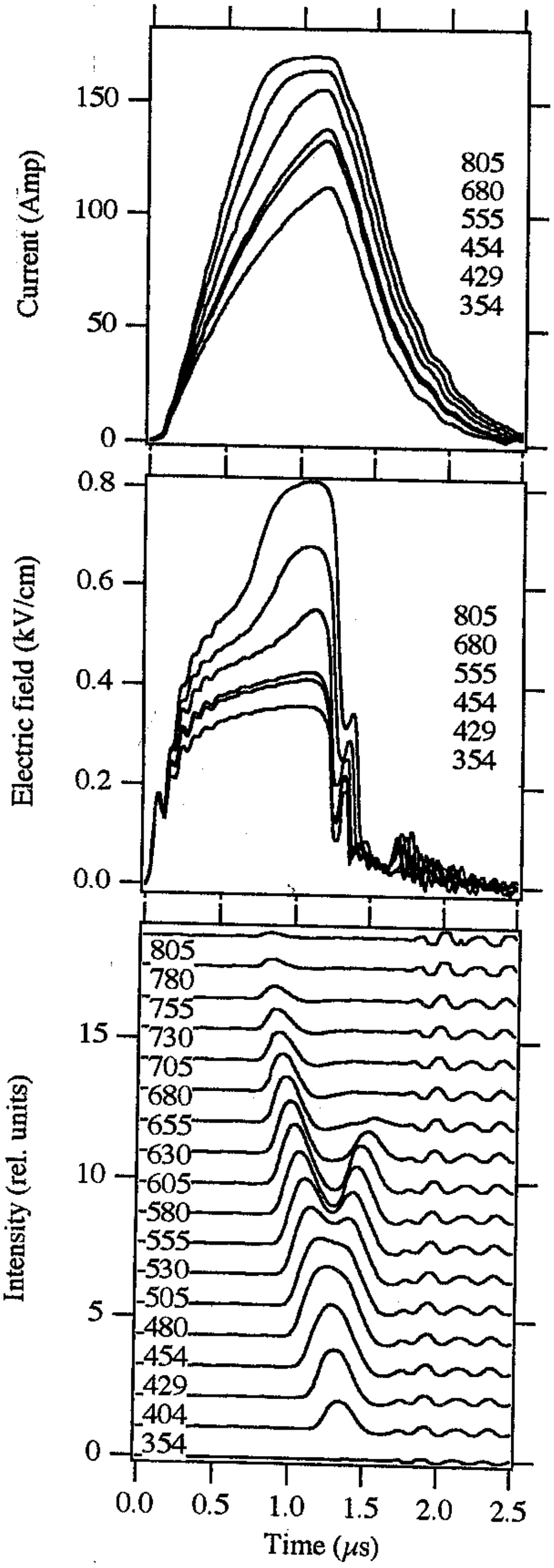

Figure 1. Pulse dynamics. Peak E-fields given in V/cm.

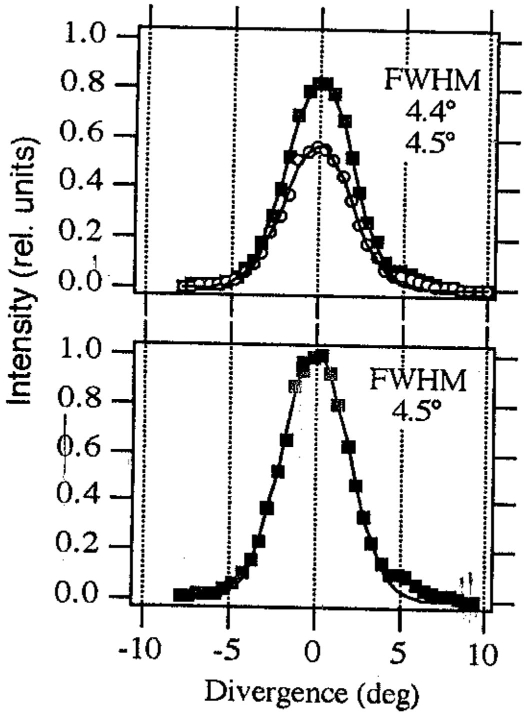

Figure 2. Beam profiles for double (top) and single emission pulses.

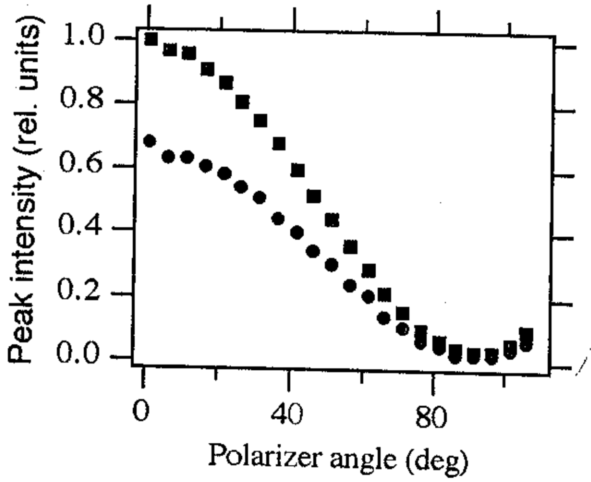

Figure 3. Polarization dependence for each pulse in double emission pulse conditions. Polarizer angle is measured with respect to the applied electric field.

second emission pulse apparently does not introduce new frequencies. Rather, the primary difference is that the two weak outer groups are attenuated in the double pulse spectrum relative to the central two peaks. This can be explained by mode competition since the total duration of oscillation for the double pulse is longer.

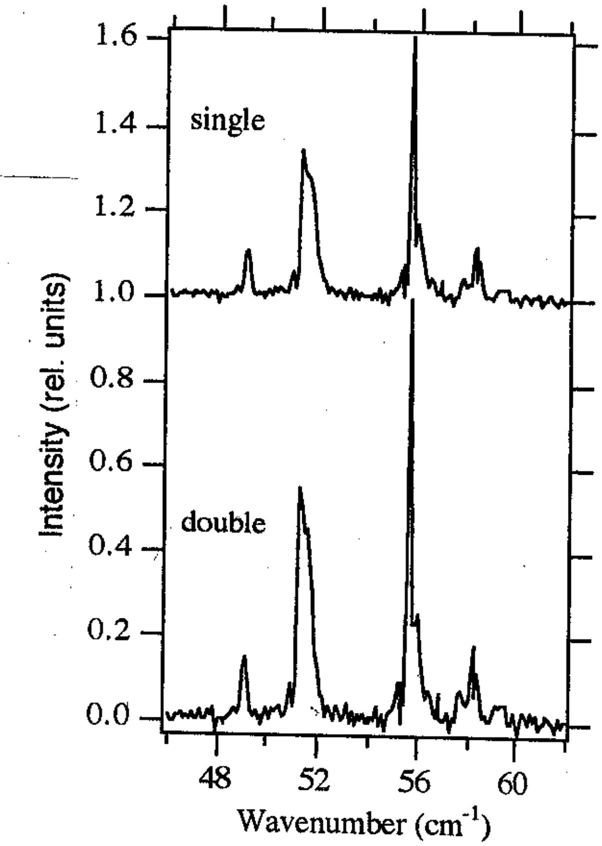

Figure 4. Emission spectra for single and double pulse output. The resolution is 0.2 cm^{-1}.

Repetition rate data are presented in Fig. 5. The upper plot gives peak signal using Cu heat sinks while the lower plot presents the same without. The heat sinks evidently increase the maximum repetition rate by a factor of about 2. Repetition rates are also higher for the single rather than the double pulse (where both pulses have the same repetition-rate dependence). An independent study[7] shows that even higher rep rates can be achieved by lowering the hole concentration and by using miniature crystals, at the expense of output power. These repetition rate increases are obtained by reducing joule heat during the pulse and by increasing the cooling rate between pulses. When, the temperature dependent losses are reduced quickly, the crystal is ready sooner for another laser shot.

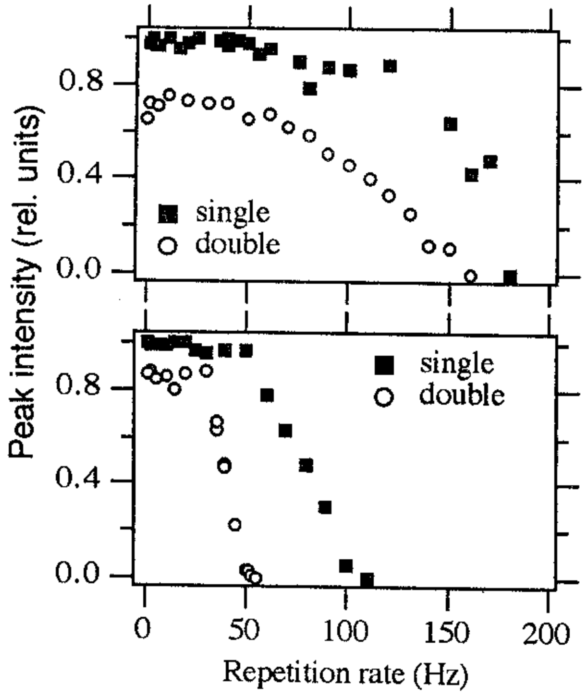

Figure 5. Peak signal vs repetition rate with (top) and without copper heat sinks.

Finally, we present the temperature dependence of the integrated pulse intensity in Fig. 6. The time-integrated signal drops steadily as temperature dependent losses are introduced, but lasing persists beyond 10 K. This means that a closed cycle refrigerator could substitute for liquid helium as a coolant to make a more practical device.

Summary

Unusual pulse dynamics are observed as a function of applied electric field for a Voigt-configured permanent magnet sub-millimeter p-Ge laser. These temporal effects appear to affect only the intensity and not the beam profile, polarization, or spectral content of the emission. Use of large Cu heat sinks are made possible by the open permanent-magnet architecture, providing a significant increase in repetition rate. Since lasing persists above 10 K, the heat sinks could also serve as cold fingers of a closed cycle refrigerator. By thus eliminating liquid helium, p-Ge lasers would become significantly more attractive as a practical source in a wavelength range where there is still no solid-state alternative.

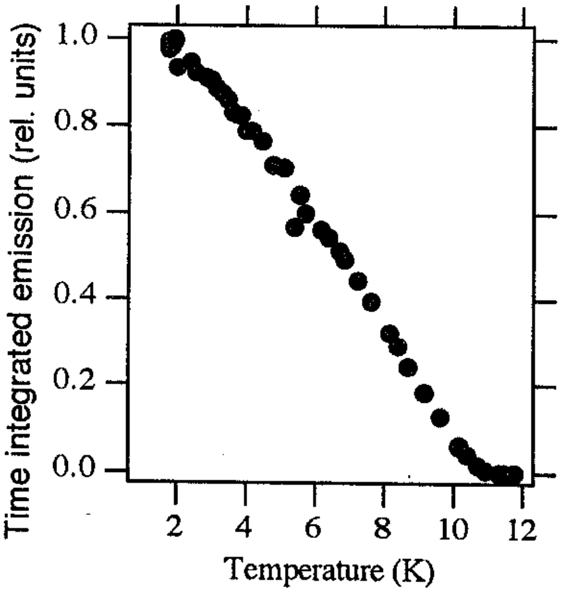

Figure 6. Integrated emission-pulse intensity vs temperature.

References and note

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