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Far-infrared p-Ge laser with variable length cavity

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Abstract

Operation of a far-infrared (1.5–4.2 THz) p-Ge laser in an open quasi-optical resonator is demonstrated. This contrasts with previous designs where mirrors were fixed to surfaces of the active crystal. Enhanced stability and tuning of the laser cavity length are demonstrated, which are steps toward continuous tunability without mode-hops.

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Keywords: Far infrared; Terahertz; Tunable laser; Laser resonator; Semiconductor laser

1. Introduction

This paper is devoted to electro-dynamic design improvements for the p-Ge far-infrared laser. The p-Ge laser mechanism is based on intersubband transitions of hot holes [1], where an inversion population is built up between light and heavy hole subbands in crossed electric and magnetic fields at cryogenic temperatures. The laser has a wide gain spectrum, which allows tuning over the spectral range 50–140 cm^{-1} (70–200 μm or 1.5–4.2 THz) [2–5]. The laser normally generates a 20–30 cm^{-1} wide spectrum with up to a thousand longitudinal modes. Single mode generation [4] can be achieved using an intracavity frequency selector, which has the form of a tunable Fabry–Perot etalon coupled with the main laser cavity [2–5]. Because the selective element is placed inside the laser cavity, remarkable spectral power density is concentrated in a single longitudinal mode [4] having a width of several MHz [6].

Previous electro-dynamic cavity designs for the p-Ge laser usually used polished surfaces of the active p-Ge crystal to define reflecting planes [1]. Either total internal reflection was used to achieve a ring cavity configuration internal to the active crystal, or external metal mirrors were applied in contact with the crystal end faces through Teflon film isolation. Such electrodynamic cavities are very sensitive to the degree of parallelness of the opposite crystal faces. Some effort was made to improve stability by implementing curved mirrors

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on the back surfaces of transparent spacers, which were similarly placed in contact with crystal end faces [7,8]. A fundamental problem with all of these closed cavity schemes is that tunability of the laser frequency is allowed only by hopping between laser modes, which are rigidly determined by the dimensions of the active crystal and other solid cavity components [5]. A typical spectral distance between longitudinal modes of the p-Ge laser is ~1 GHz with a mode width of several MHz [6]. Such mode-hop tuning limits applications such as molecular spectroscopy and chemical sensing, since molecular lines can have much less than GHz widths.

In this paper we report the first demonstration of an open semi-confocal cavity for the p-Ge laser, where one of the laser mirrors is spherical and has a variable separation from the laser rod. Such a free-standing, freely movable mirror in principle allows continuous adjustment of the laser cavity length and hence continuous tuning of the emission line.

2. Experiment and results

The laser crystal was cut from monocrystalline Ge doped by Ga with $N_A = 7 \times 10^{13}$ cm^{-3} in the form of a rectangular parallelepiped $5 \times 7 \times 28$ mm^3 with the long axis along the [1 1 0] crystallographic direction. The crystal end faces were polished parallel to each other within 30″. The surface roughness in the central portion of the active crystal ends was determined to be ~10 nm. The edges were rounded during polishing giving a final deviation from flatness of 100 nm.

The laser cavity (Fig. 1) had a plane mirror attached directly to one end of the active crystal and a concave spherical mirror separated from the free end of the crystal by ~3 cm. The plane mirror was polished $SrTiO_3$ commercial substrate wafer material. The spherical mirror (II-VI, Inc.) had a gold reflecting surface deposited on a silicon substrate with 12.7 mm diameter and 15 cm radius of curvature.

We note that $SrTiO_3$ mirrors, first used by Bespalov [9], work as well as traditional copper mirrors, which must be insulated from the crystal, usually by plastic film (Teflon, polyethylene, or Mylar). $SrTiO_3$, however, does not degrade by oxidation and requires no isolation. Moreover, it is harder than copper, hence less susceptible to damage. It is an ordinary item of commerce, in contrast to the custom copper mirrors.

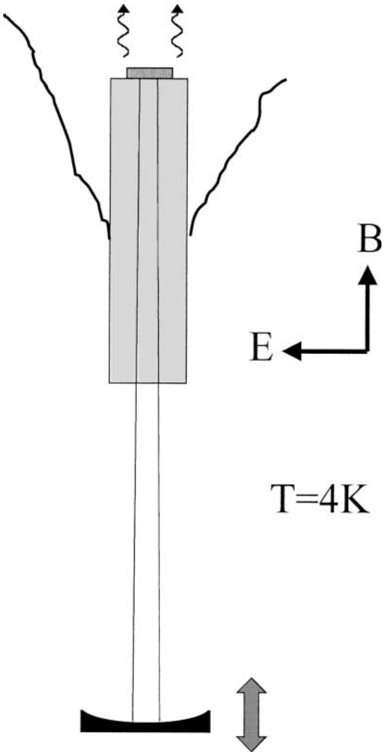

Fig. 1. Schematic of open quasi-optical resonator construction for the far-infrared p-Ge laser. The output coupler is a plane $SrTiO_3$ mirror attached directly to the active crystal. The spherical mirror is an evaporated gold reflector on a curved silicon substrate. The position of the active crystal and plane mirror relative to the curved mirror can be adjusted in situ. Wires are shown connected to the ohmic contacts, and the orientation of the applied electric field **E** is indicated. The cavity construction is inserted into a superconducting solenoid, giving an orientation for the applied magnetic field **B** as shown. The system is inserted into a bath of liquid helium at 4 K.

The $SrTiO_3$ mirror had a size 4 mm × 4 mm, which is smaller than the active sample cross section to allow the output of radiation around the mirror. The experiment was also performed with the cavity inverted, such that the spherical mirror was on the top. In this case, sufficient radiation escaped around the spherical-mirror edges to be detected. (Also, in the inverted case, a traditional plane copper mirror was used instead of $SrTiO_3$.)

The system was immersed in liquid helium. A superconducting solenoid applied a magnetic field in Faraday configuration along the long axis of the active crystal (**B**||1 1 0). Electric field pulses with 1–2 μs duration were applied through ohmic Ga–In alloy contacts soldered on the lateral sides of the active crystal along [−1 1 0] crystallographic orientation, so that **E** was perpendicular to **B**. Laser emission was detected using a 4 K Ge:Ga photoconductor immersed in the same Dewar as the laser.

Laser operation was observed up to a maximum pulse repetition rate of 15 Hz for Fig. 1 configuration. We note that the 3 cm gap between mirror and active crystal was filled with liquid helium. The laser crystal could be lifted with respect to the spherical mirror, thereby changing the cavity length, by up to 1 cm without quenching the laser emission. The laser quenched when the distance between the mirror and the active crystal face exceeded 4 cm. Returning the mirror to within 4 cm caused the laser to oscillate as before. No special mirror adjustments were performed during the cavity length tuning, and mirror alignment accuracy was defined only by the mechanical parts with an uncertainty of order 1 degree. This experiment demonstrates a high degree of laser cavity stability, which was not similarly tested in previous closed semi-confocal cavity experiments with p-Ge lasers [7,8].

When the laser cavity was inverted, such that the spherical mirror was on top, laser stability was degraded, and emission was quenched at repetition rates above 1 Hz. Fig. 2 compares laser generation zones for Fig. 1 and inverted constructions. Higher field thresholds for the inverted construction indicate a more lossy cavity. The extra loss and low repetition rate of the inverted construction are explained by scattering of the laser radiation on helium bubbles, which are generated at the active crystal and rise to be trapped by the inverted spherical mirror. It evidently takes on the order of 1 s for such trapped bubbles to dissipate.

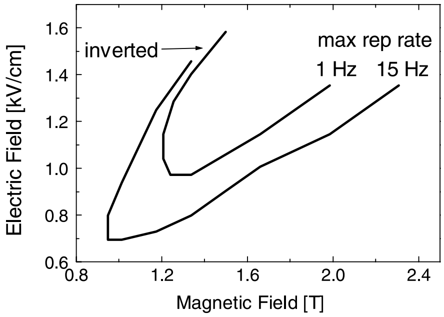

Fig. 2. Laser generation zones for Fig. 1 and inverted constructions. The maximum pulse repetition rate is indicated for each case.

3. Discussion

Although usual for solid state lasers, open quasi-optical cavities for the p-Ge laser have been avoided because of liquid-helium conditions, relatively low gain (<10% per roundtrip even for several-cm length active crystals), and the large refractive index (giving 36% reflections at crystal/vacuum interfaces). Nevertheless, we here demonstrated stable operation of the p-Ge laser with an open cavity, even inside a bubbling bath of liquid helium. This development potentially allows tuning of the laser cavity length and of the emission frequency without mode-hops.

For the laser cavity shown in Fig. 1, noting that the effective cavity length L is less than the focal distance F of the spherical mirror, the transverse width of the main mode is $2a = 2[L\lambda/(2\pi)]^{1/2}$. For $L \sim 3$–6 cm and $\lambda \sim 100$ μm, this gives a mode width of ~2 mm, which is less than the aperture of the output mirror (4 mm). This insures good resonator quality, so long as the displacement of the mode center on the output mirror is below ~1 mm, which corresponds to a critical spherical-mirror misalignment of ~0.5 degree. Such is almost 2 orders of magnitude less strict than the required mirror parallelness in the plane-mirror Fabry–Perot cavities traditional for p-Ge lasers. This has allowed the demonstration here of stable p-Ge laser operation without any special mirror adjustments.

Reflections caused by the substantial index mismatch between Ge and vacuum can create unwanted spectral resonances [10], which could interfere with continuous tunability of the laser. Such effects might be minimized by orienting the active crystal at Brewster's angle. This would require Voigt configuration of the applied fields [11], where the emission is perpendicular to the magnetic field, to avoid polarization rotation by the Faraday effect.

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