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Toward High-Power Semiconductor Terahertz Laser

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Toward High-Power Semiconductor Terahertz Laser

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Abstract: Injection seeding can increase electric-to-optical conversion efficiency and output power of p-Ge lasers. Preliminary experimental results support the approach to the maximum theoretical limit of 10-100 W in the frequency range 1.5 – 4.2 THz.

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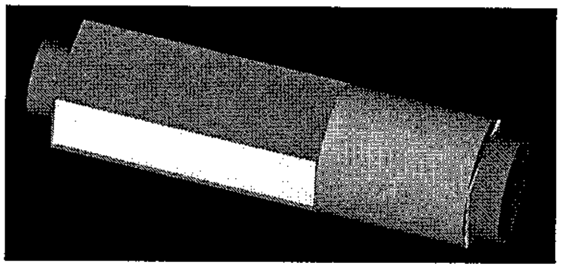
Terahertz electromagnetic radiation (0.3 - 10 THz) offers promise for detection of explosives, chem/bio agents, concealed weapons, medical imaging, drug discovery, secure local communication, satellite communication, and non-destructive testing. A primary problem is the lack of practical, transportable, efficient, tunable laser source. Low power sources can demonstrate principles and prove application concepts, but available technologies for high power sources, such as free electron lasers and synchrotrons, so far defy scaling to transportable dimensions. Existing optically pumped gas THz lasers are rather bulky as well and usually are very sensitive for any kind of cavity instabilities.

The p-type Ge laser remains the only portable THz laser with power exceeding 1 Watt [1]. The commercial version of the laser is available at [2]. The laser requires liquid helium temperatures, and typical active crystal dimensions are several mm transverse and several cm lengthwise. The system electronics draw less than 50 W average power to generating 1-5 μs THz pulses at 10-50 Hz repetition rate. Although the system usually uses a superconducting magnet, use of a closed cycle refrigerator with permanent magnet assemblies for cooling a p-Ge laser has been demonstrated by several workers as a practical alternative [3-5]. The theoretical limit for electrical-to-optical conversion efficiency for the p-Ge laser operation is 0.1-0.3 % [6-8]. While the highest experimental efficiency claimed so far is 0.01% [9], earlier experiments have been flawed by the several limitations of conventional p-Ge laser operation. The saturation intensity limit of the p-Ge active medium can reach 10 kW/cm^2 [6, 8], so that with just 1% output coupling, useable powers of 10-100 W are possible within the technology. The primary objective of this research is to more optimally use the already available gain and high saturation intensity limit of the p-Ge laser medium.

In this paper we propose to increase the p-Ge laser efficiency using the concept of injection seeding, which will help to approach to theoretically expected output power levels 10-100 Watts [6]. The gain in the p-Ge laser active crystal has typical values of 0.01-0.04 cm^{-1}, which leads to 100's of nanoseconds build-up time for reaching the saturation intensity. At the same time the gain is sensitive to the crystal temperature, which limits the maximum pulse duration to several μs due to overheating. During the build-up time the excitation current already overheats the active crystal to the temperature 15-20 K, causing untimely reduction of the gain and as a result reduction of the maximum output intensity. The seeding of the initial THz radiation inside the slave active crystal at the very beginning of the electrical excitation pulse, when the crystal is still cold (4K), and the gain is relatively high, will help to increase the efficiency of the laser. We have already reported the elimination of the build-up time in a single pass p-Ge amplifier using a multi-mode seed laser, together with an intensity boost [10]. Injection seeding with a single-mode laser can remarkably improve spectral purity and amplitude stability of the generated radiation.

In this work, we are using a small p-Ge laser with intracavity frequency selector based on Fabry-Perot resonance in a 104 μm thick Si etalon (Fig. 1, left). The active crystal has dimensions 18 mm x 7 mm x 5 mm. Fig. 1 (right) presents a plot of the zones of laser operation in the space of applied fields. Measurements for both polarities of magnetic field and with or without a wavelength selector are presented. The seed laser crystal itself is capable of 1 W peak output power, but with the intracavity wavelength selector, the peak power is reduced to ~100 mW. This highly monochromatic radiation is used to initiate lasing in a large amplifier crystal.



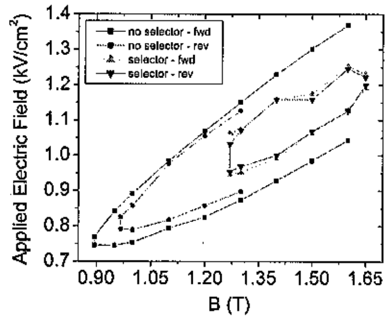


Fig. 1. (left) Laser operation zones for p-Ge seed laser. (right) Schematic of seed-laser consisting of (from left) output mirror, contacted active crystal, silicon spacer with evaporated metal grating, etalon, and back mirror.

For typical 0.25-0.5 cm^2 cross-section of the active crystal, a 1 kW/cm^2 intracavity intensity suggests several percent out-coupling to achieve 10 Watts output power. Factors such as radiation leakage due to scattering on the active sample edges, diffraction divergence of the beam, and leakage through the back mirror raise the estimated required out-coupling to 10-30%. For an average typical gain in p-Ge lasers of 0.02 cm^{-1}, the required active cavity length must be at least 10 cm, but natural doping non-uniformity of an active crystal and consequent gain reduction increase the estimated active cavity-length requirement to several tens of centimeters. To provide long roundtrip pass in the active p-Ge laser crystal, at the same time keeping reasonable crystal dimensions, total internal reflection from lateral sides of the active crystal are used (Fig. 2). Maximum wave slowing in the total reflection mode waveguide can reach a value determined by the Ge refractive index 3.925. Thus, a 10 cm long crystal operating in total reflection mode can provide a path length of ~ 75-80 cm per photon round trip (Fig. 2).

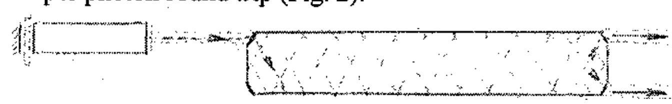


Fig. 2. Design of high power THz laser. The slave p-Ge laser operates on total reflection modes for long round trip path.

Directional collimated out-coupling of stimulated emission from the laser operating in total reflection mode are arranged by specially oriented bevels on the output end of the active crystal. The orientation angle of the bevel depends on the specific individual total reflection mode, i.e. the number of reflections of the lateral walls per round trip. Coupling of the radiation from a seed laser to the specific total reflection mode is arranged using similar bevel system on the back end of the active crystal. The angle of mode propagation inside the crystal is critical but not obvious, and it can be determined only from spectral data. It turns out that for crystallographic orientation 110, an angle of 40-45 degrees is acceptable. The design of the amplifier includes spherical mirrors to form a semiconfocal cavity.

Fig. 3 presents a photograph of several large amplifier laser crystals in various stages of preparation. One of the smaller crystals (67 mm) was the single pass amplifier used with non-selective injection in [10]. One of the largest crystals, with length 121 mm and with one curved end to form a semiconfocal cavity, has been tested so far for this work. Dual drive electronics for excitation and control of both oscillator and amplifier lasers have been assembled. Fig. 4 presents the current-voltage curve for the 121 mm crystal using a thyratron pulser. The onset of current saturation due to optical phonon scattering is revealed in Fig. 4 left. This so-called "streaming motion" of free holes in the crystal, which occurs under conditions of current saturation, is required for lasing. This figure also demonstrates that the thyratron pulser is a sufficiently stiff voltage source to excite the exceptionally low-impedance 121 mm amplifier crystal (~1 ohm) with 500 A of current for voltage drops exceeding 1 kV at the crystal. Lasing is observed within the circled region in Fig. 4 left, and Fig. 4 right presents its lasing zone. Experimental data will be presented to show the achieved reduction of the laser build-up time, the spectrum of the amplifier crystal with and without seeding, and a measurement of the achieved output power increase.

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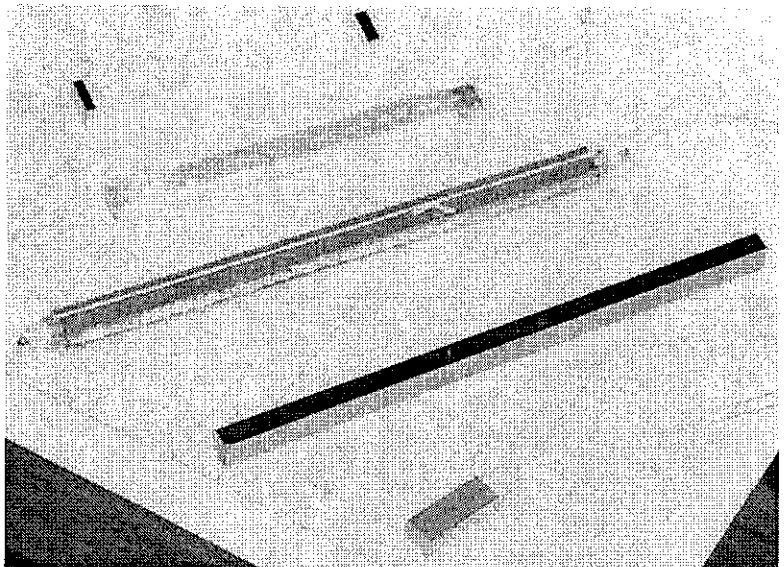

Fig. 3. Photograph of p-Ge laser crystals. From bottom, the 18 mm seed crystal, a large polished but uncontacted amplifier crystal, the 121 mm amplifier crystal with contacts and mirrors, and two shorter finished amplifier crystals.

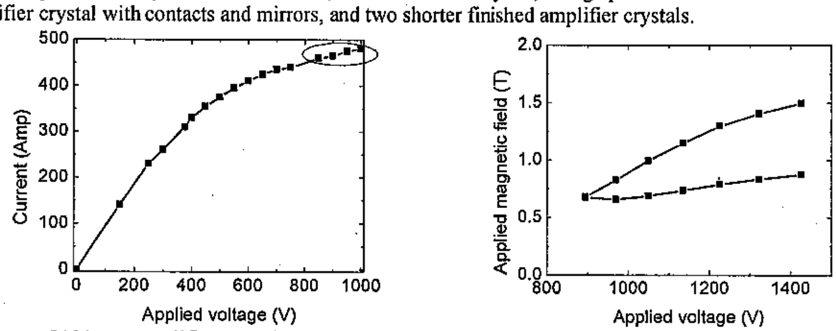

Fig. 4. (left) IV curve of 121 mm amplifier crystal showing desired current saturation. Laser operation is observed in the circled region and beyond. (right) Observed laser operation zone in space of applied fields.

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