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High-power terahertz p-Ge laser with injection seeding

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Abstract

The peak-power of the p-Ge inter-valence-band laser operating in the frequency range 1.5-4.2 THz has been extended to the level of 100 W. The approach is based on injection seeding of a large p-type germanium active crystal operating as a slave laser on total internal reflection modes with long optical path.

Keywords: terahertz, far infrared, laser

1. Introduction

The well-established inter-valence-band hot-hole laser in p-type germanium, tunable from 1.5 to 4.2 THz, is known already to generate coherent pulsed THz radiation at the level of 1 W peak power.[1] We demonstrate here that a coupled system of two p-Ge lasers, consisting of a large slave laser operating on total internal reflection modes with injection seeding from a small seed laser can generate terahertz emission with peak output power of order 100 W. This value exceeds the sum of the saturated output powers of each individual laser. Internal-reflection-mode operation in the slave laser maximizes the optical path for efficient energy extraction to permit unusually large output coupling. In addition, injection seeding increases the efficiency by eliminating the usual laser build-up time and initiating oscillation in the slave laser when its gain is highest.

The theoretical limitation for the saturation intensity of stimulated emission within active p-Ge laser crystals is 1-10 kW/cm^2.[2] To reach high output power densities the active crystal must be optically long. For typical small signal gain of 0.02-0.05 cm^{-1}, the roundtrip pass must be at least several tens of centimeters. To provide long roundtrip path in the active p-Ge laser crystal, while maintaining reasonable crystal dimensions, we adopted a design based on total internal reflection from lateral sides of the active crystal.[3,4] Considering the high refractive index of Ge and the resulting rather steep angles of total reflection, a 10 cm long crystal operating in total reflection mode can provide an optical path length up to 80 cm per photon round trip. Though the total reflection mode in a rectangular rod-shaped active crystal has multiple self crossings, it is significantly more efficient in filling the active volume than the usual axial mode cavity configuration. Thus, the total reflection mode configuration for the p-Ge laser cavity is expected to produce higher output power. Though the advantages for high power and efficiency of injection seeding and large active crystals are well established, this combination has never been reported for hot-hole p-Ge lasers.

2. Experimental Details

Fig. 1 presents a schematic of the seed-slave coupled laser system. A large p-Ge crystal in the shape of a rectangular rod served as a slave laser. Electrical excitation pulses were applied via ohmic contacts perpendicular to the long axis of the crystal. A separately excited small p-Ge laser served as the seed laser. Collimated output is achieved via polished bevels[5] at the corners of the slave laser crystal. The seed laser injects radiation into the slave crystal via similar polished bevels such that a preferred internal reflection mode is excited. The optimum bevel angle was determined from the strongest modes in the active slave-crystal spectrum.

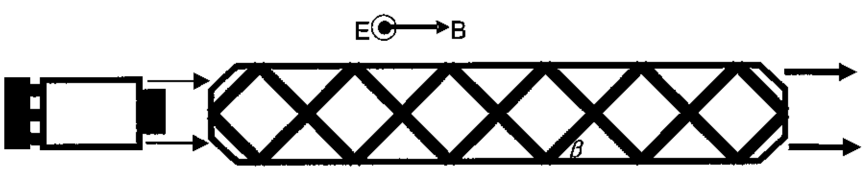

Fig. 1. Coupled laser scheme for high power terahertz laser.

Seed and slave lasers were inserted collinearly within the bore of a superconducting solenoid immersed in liquid helium at 4 K. The laser emission was detected by a Ge photoconductive detector, which allowed estimation of the absolute incident terahertz power according to the photo-induced conductivity when operated in the linear response regime.

3. Results

Fig. 2 presents time resolved measurements that show the effect of seeding in reducing the delay between excitation and development of the stimulated emission of the slave laser. Here, laser signal is detected for different delay times of the slave-laser excitation relative to that of the seed laser. When the seed laser emission is present and overlaps the slave laser excitation, the slave-laser-emission delay is reduced from about 500 ns to only 200 ns. Thus, seeding allows better use of the available gain and improves efficiency. Additionally, the slave-laser-emission rise time is reduced by a factor of ~2, indicating that the gain at the moment of slave laser emission is about twice higher. This effect is due to the colder active crystal conditions early in the excitation of the slave laser. A third benefit is that peak power is higher with injection. Because the detector is here working in a strongly sub-linear regime, the power increase is in fact larger than it appears. Seeding is also found to have a strong effect on the emission spectrum.

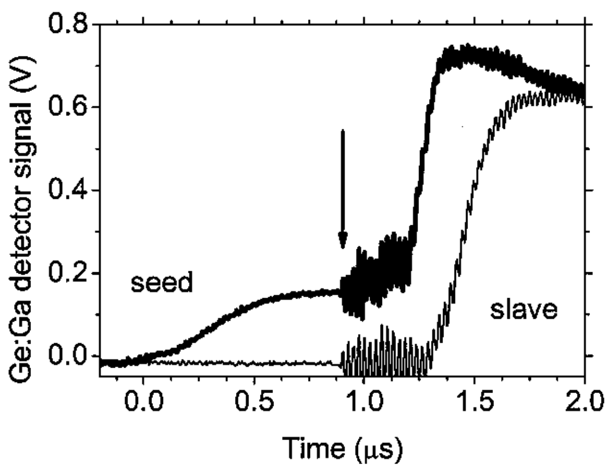

Fig. 2. Coupled laser emission with (heavy trace) and without (light trace) injection seeding. The arrow indicates the beginning of the slave laser excitation, and the noise burst from electromagnetic interference persists while the slave laser excitation current ramps to its optimum value.

Qualitatively, it was noticed that the emission intensity of the slave laser, even without injection seeding, was far stronger than that of the seed laser, which as a traditional p-Ge laser might be supposed to have an emission power of ~1 W.[1] To obtain a more quantitative estimate, the output intensity of the two laser system was measured using a Ge:Ga detector with variable input aperture to avoid saturation. This measured peak power was estimated to be 50-150 Watts. For a laser emission pulse length of ~2 μs, we obtain an emission pulse energy of 200-300 μJ.

4. Discussion and summary

The dissipated electrical power in the slave laser crystal is of order 500 kW. Claimed theoretical conversion efficiency (optical output/electrical input) is 10^{-3} to 10^{-4}.[1,3] The output power of order 100 Watts estimated in this work corresponds to an efficiency of 10^{-4}, in good agreement with the theoretical expectations. The minimum required power for the seed laser is not determined in this work, but from the characteristics of the seed laser used here it can be stated that the seed laser power need not exceed ~100 mW. Any other terahertz laser with output of this power in the range 1.5-4.2 THz might be used instead. In summary, p-Ge laser emission with peak power of order 100 W was achieved by means of injection seeding of a large active p-Ge slave laser operating on total internal reflection modes.

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