Tunable THz-laser for applications in FIR astronomy

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Abstract

We summarize recent results of Ge:Be lasers reaching duty cycles up to 2.5%. We have studied the laser emission of a small Ge:Be laser cube with a volume of 27 mm^3 and a Be concentration of 1.5×10^{14} cm^{-3} by using permanent magnets. The laser was operated in a standard closed-cycle He refrigerator, and the laser intensity was measured as a function of temperature. The laser emission detected in the Voigt configuration revealed linear polarization.

I. Introduction

We plan to develop a compact, tunable, and continuous wave THz laser within the next 2-3 years. The laser will operate as a local oscillator in heterodyne receivers preferably on the platform SOFIA (Stratospheric Observatory for Infrared Astronomy) or on the space station.

In our previous reports [1, 2] we have demonstrated the capabilities of the p-type germanium laser as a possible tunable THz laser. The pulsed p-type Ge laser operates in crossed electric and magnetic fields at temperatures from 4 to 20 K. Typically, the crystal is immersed in liquid helium (LHe) and emits a reasonable output power of a few watts. A more detailed description of the lasing mechanism, crystal preparation and experimental set-up have been published [1, 2]. The laser fulfills several local oscillator requirements: tunability from 1 to 4 THz [3], single line operation and mode line widths below one MHz [4].

The limited observation time on airplanes and satellites requires a high duty cycle or continuous wave operation. Therefore, the main drawback of the p-Ge laser is its pulsed operation. With the development of a new type of Ge laser [3,5,6] and the miniaturization of Ge lasers [7], it seems to be possible to overcome this problem. Figure 1 displays our progress to the present duty cycle of 2.5%, i.e., emission of 32 μs long laser pulses at repetition rates close to 1 kHz.

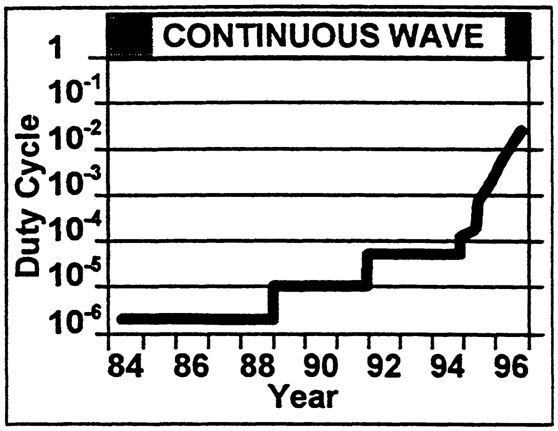

Figure 1: Improvements in the duty cycle since the invention of Ge lasers. New lasers with double acceptors (Ge:Be) have a drastically increased duty cycle.

II. Ge:Be laser operation with permanent magnets

The reduced size of our laser crystals leads to lower demands on power supplies and on the size of the magnets and makes small table-top cryostats viable for laser operation. We have built a table-top standard LHe-cryostat with a horizontal superconducting coil. We mounted the p-Ge laser in vacuum simplifying the construction of external resonators.

Recently, p-Ge laser operation using permanent magnets in LHe has been reported [8]. A tunable permanent magnet was proposed by using so called 'magic spheres' enabling a tunable magnetic field from 0 to 4 T [9].

Figure 2 displays the laser emission of a Ge:Be laser cube with a volume of 27 mm^3 mounted between one, two and three pairs of NdFeB permanent magnets reaching magnetic fields across the crystal of 0.43 T, 0.61 T and 0.69 T, respectively. Each individual magnet had a size of 10x10x6 mm^3.

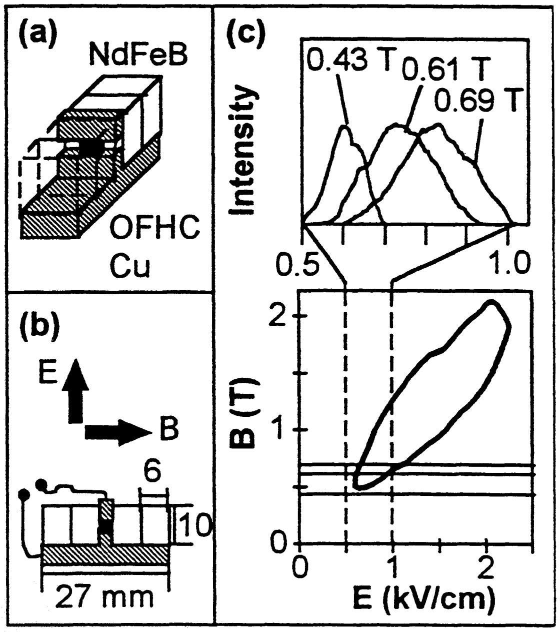

Figure 2: (a) set-up of a 27 mm^3 Ge:Be laser cube with 2 pairs of NdFeB permanent magnets and OFHC copper heat sinks, (b) cross-section of laser set-up in crossed electric and magnetic fields in the Voigt configuration, (c) Ge:Be laser radiation as a function of the electric and magnetic field was found in the area enclosed by the thick line using a tunable superconducting magnet. Horizontal lines indicate magnetic fields of 0.43 T, 0.61 T and 0.69 T reached with 1, 2 and 3 pairs of permanent magnets, respectively. The measured intensities were normalized.

The electric contacts and heat sinks were made from oxygen-free high-conductivity copper (OFHC) to improve cooling. The necessary condition of crossed electric and magnetic fields for Ge laser operation is naturally achieved by using the self-attractive force of the magnets aligning themselves perpendicularly to the electric contacts (Fig. 2(a),(b)). The radiation was detected in the Voigt configuration perpendicular to the magnetic field. Figure 2(c) shows the Ge:Be laser radiation as a function of the electric field for each permanent magnet configuration. For comparison, the active laser area as a function of electric and magnetic fields using a tunable superconducting magnet was measured. With the superconducting magnet we detected the laser radiation in the direction of the magnetic field in the Faraday configuration.

III. Ge:Be laser operated in a closed-cycle He refrigerator

Permanent magnets allow LHe-free operation of Ge lasers at temperatures up to 20 K. Therefore, we were able to demonstrate laser operation in a closed-cycle He refrigerator [10]. Figure 3 gives an overview of the experimental set-up used to investigate the Ge:Be laser cube in the closed-cycle machine. The cooling power of the CTI-Cryogenics cryocooler limited the minimum temperature to 14.3 K without electric excitation of the laser crystal.

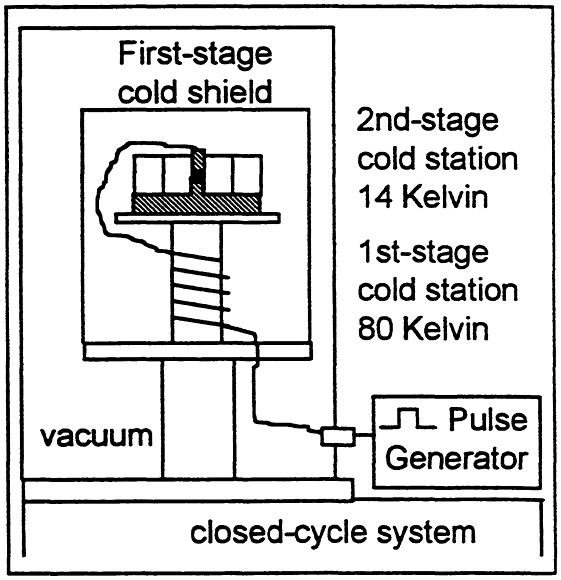

Figure 3: Permanent magnet laser set-up mounted in a closed-cycle machine. The machine specifications allowed a minimum temperature of 14.3 K on the 2nd-stage cold station. The electric pulse for excitation of the laser crystal was delivered by a pulse generator with variable pulse duration and repetition rate.

The laser crystal was excited by an electric field pulse. The laser radiation was directed through four windows made of black polyethylene, Teflon (PTFE) and TPX (poly 4-methyl pentene-1) onto a Ge:Ga photodetector [11] in a LHe-cryostat (Fig. 4(a)). The detected laser signal was observed directly on a digital oscilloscope.

The experiments with 1, 2 and 3 pairs of permanent magnets show an increase of laser intensity with magnetic field accompanied by an increase of the limiting laser temperature up to 20 K (Fig. 4(b)). The duty cycle for the Ge:Be laser cube in the closed-cycle machine reached values of up to 0.03% in comparison to 0.6% in LHe because of the limited cooling power of 0.5 W which raised the second-stage cold station temperature to 20 K. Modern closed-cycle machines can reach 4.2 K at a heat input of 1 W and 10 K at a load of 10 W which corresponds to the maximum dissipated electrical power of our best laser crystals in LHe.

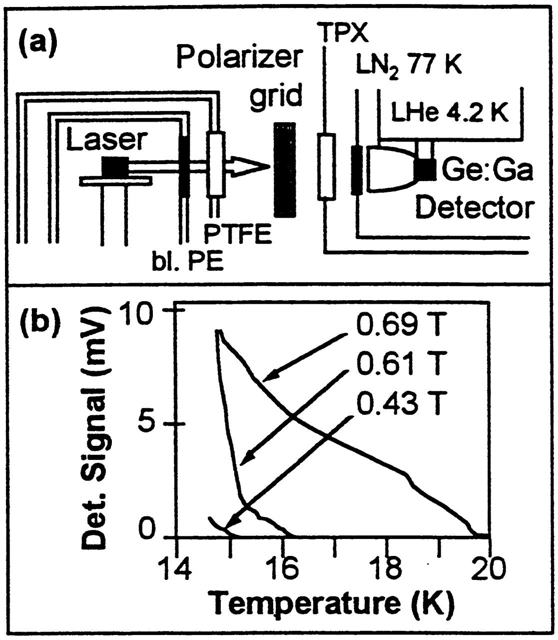

Figure 4: (a) Experimental set-up for measuring the polarization of the Ge:Be laser and temperature dependencies. (b) Laser intensity as a function of temperature and magnetic field.

IV. Polarization of the Ge:Be laser in Voigt configuration

The polarization was measured by introducing a rotating grid polarizer in the air-gap between the closed-cycle machine and the detector cryostat (Fig. 4(a)). The measured signal intensity passing the polarizer grid deviated from the theoretical curve of linear polarization due to the non-ideal polarizer (Fig. 5). With a 2.5 THz emission line of a gas laser with a Brewster window resulting in 100% linear polarization, we reproduced the same curve as measured with the Ge laser. The result is in accordance with theory for emission in the Voigt configuration which imposes quantum mechanical selection rules for linear polarization. In addition, the polarization is directed parallel to the magnetic field indicating the involvement of cyclotron resonance transitions [3]. We measured the emission in the Faraday configuration with the table-top LHe-cryostat. The polarization was found to be elliptical.

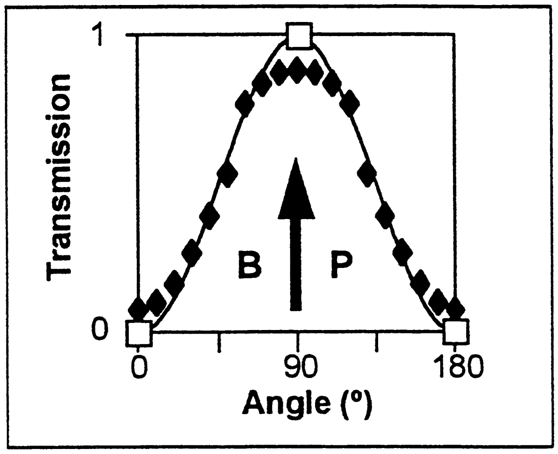

Figure 5: Polarization of the Ge:Be laser radiation. An ideal polarizer is defined by the open squares and the calculated function. Diamonds show the measured signal intensities indicating linear polarization P parallel to the magnetic field B.

V. Summary and conclusions

We have demonstrated that Ge lasers can meet the requirements of local oscillators for future THz heterodyne receivers. They feature linearly polarized radiation, a single mode tunability from 1 to 4 THz with narrow line widths, LHe-free operation in a closed-cycle machine with permanent magnets, and a high duty cycle of 2.5%. In the desired continuous wave mode the homogeneous Ge laser transition will result in single mode operation only defined by the quality and stability of the external resonator.

Further improvement of the laser geometry, the doping level, the cooling environment, the use of external resonators with mesh outcouplers and the application of uniaxial stress will reduce the total applied power and improve the heat dissipation. Careful crystal and surface preparation including crystal growth, contact formation and materials characterization might enable us to design a crystal with which we may reach the ultimate goal of continuous wave operation with mW output power.

Hot electron bolometers require only μW pumping power and operate in the same temperature range as Ge lasers [12]. Therefore, a future heterodyne receiver might consist of an array of hot electron bolometers integrated with a p-Ge laser in a standard table-top cryostat or closed-cycle machine.

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