TUNABLE p-Ge LASER

IN THE FREQUENCY RANGE FROM 1 TO 4.5 THz

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ABSTRACT

We have studied the pulsed p-type Ge laser to build a tunable local oscillator source for the THz frequency range. We have used the heterodyne technique to reveal the fine structure of the emission spectrum on the MHz scale that was only resolved on the GHz scale. The heterodyne measurements using a ring gas laser as local oscillator and a Schottky diode as mixer revealed an absolute line width of the p-Ge laser of 25 MHz due to heating of the active Ge sample. Self mixing of the p-Ge laser modes gives a line width which is only determined by the pulse length and can be as small as 0.9 MHz. The emission is broad band but it can be confined in one laser mode, concentrating the total power by using a lamellar grating in high orders. The pulse duration is in the order of 10 µs while the repetition rate can reach a few tens of Hz which results in a low duty cycle. We present some ideas to improve the laser performance and to reach continuous wave operation.

INTRODUCTION

We have used a heterodyne receiver for many years on the Kuiper Airborne Observatory (NASA) to study rotational transitions of molecules in starforming regions. The receiver signal and laser beam are overlaid in a Martin-Puplett type diplexer and directed onto a Schottky diode. The resulting intermediate frequency is improved by low noise amplifiers and can be analyzed by an acousto-optical spectrometer which resolves a 1 GHz band simultaneously with 1 MHz [1]. Due to the limited bandwidth of those amplifiers, it is necessary to find a laser transition close to the signal frequency.

In the present receiver we use an optically pumped, continuous wave, ring gas laser as the local oscillator that can be filled with different laser gases, e.g., CH_2F_2 and CH_3OH, which generate laser radiation on discrete frequencies. A further improvement of the device would be a tunable laser source based on a semiconductor especially if space qualifications have to be fulfilled. This could open new possibilities in astronomical observations [2] and also for atmospheric research [3]. The only possible material in the THz frequency range with reasonable output power is the far infrared pulsed p-type Ge laser.

The p-Ge material can operate in various configurations as a laser source and is already intensively studied since its invention in 1984 [4,5,6]. Recently, the p-Ge laser has been considered as a useful tool for spectroscopy due to the wide tuning range [1,7]. We would like to concentrate here on the p-Ge laser in crossed electric and magnetic fields in the Faraday configuration meaning the radiation detection and the resonator longitudinal axis are in the direction of the magnetic field.

p-Ge LASER MECHANISM

The crystals are normally cut and polished in a rectangular shape. The surfaces are parallel within 30" so that the crystal can already operate on internal reflection modes in a Fabry-Perot cavity due to the high refractive index of Ge ($n_{Ge} \approx 4$). Typical lengths of the samples are between 30 and 60 mm and cross sections vary between 3x4 and 6x8 mm^2. The acceptor doping concentration which allows laser action covers a range of nearly two orders from $6x10^{12}$ cm^{-3} up to $5x10^{14}$ cm^{-3} [6].

There are two processes which provide laser action. The first involves intervalence band (IVB) transitions between the light and heavy hole bands where the magnetic field is in the range of 0.25-2.5 T. In the second type a higher magnetic field 1.5-4.5 T separates the bands significantly into Landau levels, and then cyclotron resonance (CR) lasing transitions within the light hole band occur. The essential difference between the two is that in the CR mode a single line is produced while IVB transitions can give a multiline output.

To obtain IVB lasing it is necessary to induce an inversion between the light and heavy hole bands, and the first requirement is a lattice temperature below 20 K which is achieved by immersing it into liquid Helium at 4.2 K. Then acoustical lattice scattering is negligible and optical lattice scattering is not possible. Excitation by a high electric field between 0.33 and 3.5 kV/cm then accelerates holes above the optical phonon energy leading to strong backscattering into the valence band. The electric field of 0.33 kV/cm defines the onset of heavy hole streaming motion. If at the same time a magnetic field is applied, the light holes can be 'trapped' into an orbit where the maximum energy is always less than the optical phonon energy of 37 meV, while at the same time the heavy holes exceed this energy and scatter by a 4% chance into the light hole band. Thus, a situation is created where the lifetime of the light holes (upper laser level) is much longer than that of heavy holes (lower laser level) and inversion is produced. This results in an emission in the range of 1-4.5 THz [8].

In the CR mode the inversion which is built up between the light hole levels is even more sensitive to the heavy hole motion, so that a specific crystallographic orientation of the applied fields has to be taken into account. The CR line is tunable by the magnetic field in the frequency range from 0.9-2.7 THz due to the CR transition frequency $e \cdot B/(2 \cdot \pi \cdot m) = B\,[T] \cdot 0.6$ THz, where e is the electron (hole) charge, m the light hole effective mass which is a factor of 22 smaller than the free electron mass, and B the magnetic field. The output power within the pulse is less than 0.3 W [9].

The IVB laser has an output power of 1-10 W and is homogeneously broadened [10]. This allows the concentration of the total power in one frequency forced by an external resonator condition [11].

While the crystals are long in one direction, the easiest way to mount the sample in a homogeneous magnetic field is in Faraday configuration although the Voigt configuration seems to be preferable for laser emission [12]. For this configuration a larger bore superconducting magnet is used and the radiation is detected perpendicular to the magnetic field axis. An easier way to mount the sample in this configuration would be two permanent magnets which could be laid onto the side faces of the crystal. The magnetic field can then be tuned by varying the spacing between the two magnets. Although this method is restricted to low magnetic fields it might be useful for applications. In the following we concentrate on the IVB laser.

MODE FINE STRUCTURE OF THE p-Ge LASER

We have used grating spectroscopy to analyze the laser spectrum on the GHz scale, the heterodyne system to study in detail the emission characteristics on the MHz scale, and we measured frequency tunability, frequency and amplitude stability and line width.
The first attempt to measure the line width by self (homodyne) mixing of the p-Ge laser modes in a Schottky diode [13] revealed a small mixing product line width in the order of 10 MHz which was spaced by 633 MHz due to the cavity length of the laser. This can be easily calculated by $c/(2 \cdot n_{Ge} \cdot L)$, c velocity of light, n_{Ge} refractive index of Ge and the crystal length L. This encouraged us to think of a narrow line source in the order of the acousto optical spectrometer resolution which we use in the heterodyne receiver. Later we have shown by using a Schottky diode that the homodyne line width is only pulse length dependent, e.g., the smallest line width was achieved with a full width at half mean of 900 kHz for a 3.7 μs long laser pulse [14].
By using mesh outcouplers which were developed for the gas laser [15], we were able to increase the IVB laser emission range in respect to the parameters E and B, electric and magnetic field, which is an indication for a high quality cavity [16].

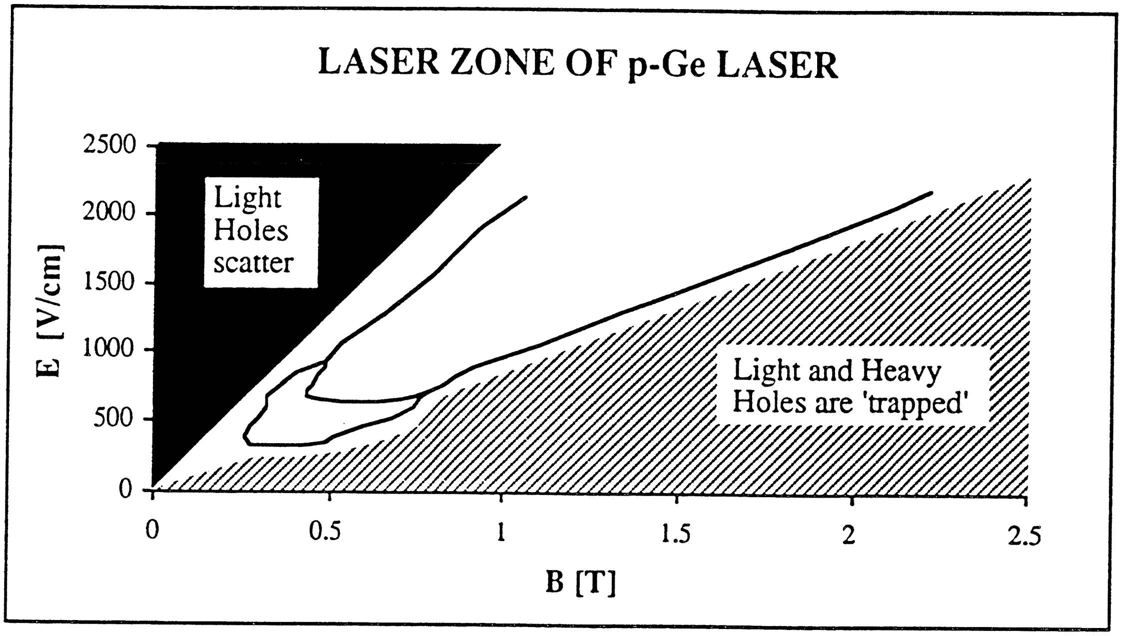

Fig. 1: IVB laser emission zone of a Ga doped Ge laser for different electric and magnetic fields. The sample size is 35x7x5 mm^3 with a Ga acceptor concentration of 7×10^{13} cm^{-3}. The electric field E is applied in the [1-10] direction and the magnetic field B in the [110] direction. The line in-between areas divides a low frequency emission part around 1.5 THz and a high frequency part above 2.5 THz. The frequencies 1.5-2.5 THz are absorbed by the impurity transitions in the C and D lines of Ga. Due to the sensitivity of the Ge photoconductive detector which we used, those parts can be easily separated by there intensity and there time dependence during the laser pulse. For higher electric fields the laser zone is closed, usually around 2.5 T and 3.5 kV/cm. The lower electric field value of 0.33 kV/cm defines the onset of heavy hole streaming motion.

In the heterodyne mixing experiment we have shown that the absolute line width of a laser mode is about 25 MHz due to sample heating during the applied voltage pulse. The heating changes the optical length of the sample so that all laser modes move in the same

direction. Therefore the homodyne mixing experiment cannot sense this temperature effect while difference frequencies do not change. As a result only pulse length limited line widths are measured. This suggests an extremely narrow emission line if stable temperature conditions are fulfilled or in continuous wave operation where an equilibrium temperature can evolve. The relative mode frequency positions for different resonators follow closely the calculated values [17]. Tunability of the emission is possible by shifting the apparatus function of a lamellar grating in high orders across the resonator mode pattern. Due to the homogeneously broadened medium the total power can be concentrated in one single line [11,17].
In addition we started preliminary heterodyne experiments to study the CR laser (in cooperation with W. Heiss, TU Wien) which has a line width of 6 GHz resolved by a tunable detector with the same resolution [9]. This line width should consist of several finer modes on the MHz scale spaced in the order of one GHz due to the sample size.

FUTURE IMPROVEMENTS

While the orbits of heavy and light holes are centered at the drift velocity E/B, we find the necessary condition for inversion and trapping of light holes in a semiclassical approach. The maximum energy is reached when the velocity of the holes is 2E/B, and for the light holes this has to be lower than the optical phonon energy E_{op} = 37 meV. The light hole effective mass $m = 0.046m_e$ and the heavy hole effective mass $M = 0.35m_e$, m_e free electron mass, have a ratio of $M/m \approx 7.6$.

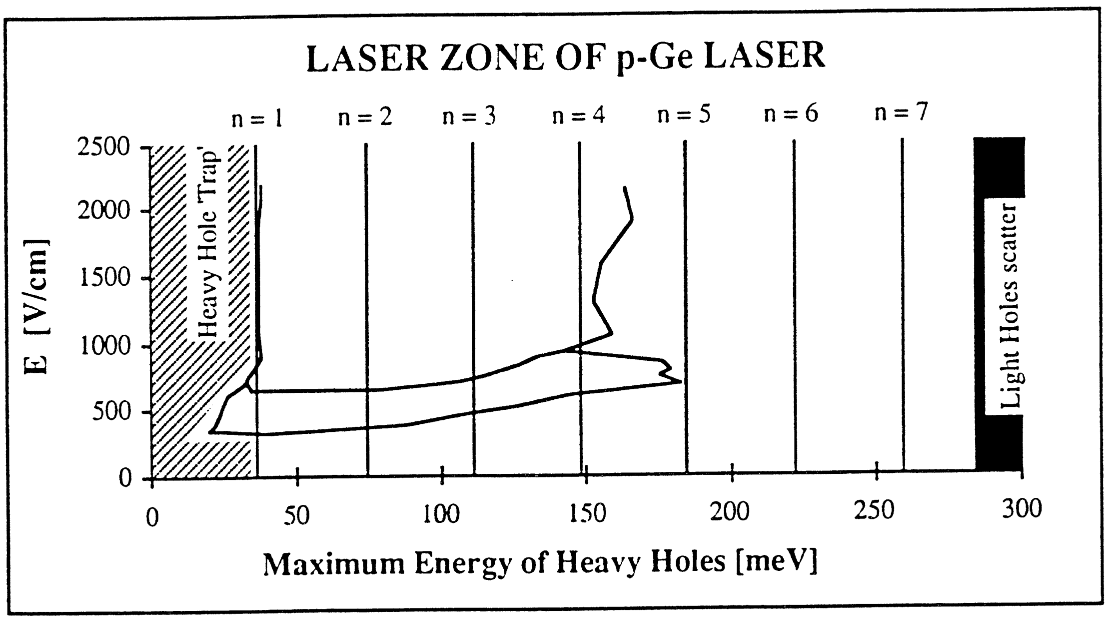

Fig.2: Laser zone of p-Ge laser from Fig.1. The maximum heavy hole energy follows from 2E/B. Clearly the emission is not found below E_{op} = 37 meV, except for high magnetic and low electric fields. The reason might be a different heavy hole mass while in a more exact approach the total electric field in the crystal is made up by the applied field and a Hall component which can change the direction of the total field versus the crystallographic axis. The maximum gain is usually found between 74 meV and 111 meV, close to 74 meV (9.7 meV for light holes). Emission can be found up to n = 4, e.g., 148 meV. Light holes are below 37 meV if heavy holes are below 280 meV.

If the energy of the light holes is less than 37 meV, or E/B < 2.7 kV/(cmT) = 2.7×10^5 m/s, the heavy holes can still scatter not only by emission of one optical phonon but up to seven optical phonons. We find that the laser power peaks if the maximum energy of the heavy holes is equal to $n \cdot E_{op}$ or E/B = $(\sqrt{n}) \cdot 0.96$ kV/(cmT), where n = 1,2,3,4.
The maximum at n = 1 is very rare while the stream of heavy holes is not infinitely thin but already broadened by the scattering. Therefore some heavy holes have closed orbits below the optical phonon energy so that they are lost for populating the light hole band via this scattering mechanism. Especially with further reduction of E/B below 0.96 kV/(cmT) the lasing is not possible because all heavy holes stay below 37 meV. We find clear maxima for n = 2 and 3 which corresponds to E/B = 1.36 kV/(cmT) and 1.67 kV/(cmT) with the highest peak in most cases close to n = 2 (more exactly at E/B = 1.42 kV/(cmT) which is also found in Monte-Carlo simulations [6]). We propose that in this picture the shift is due to the doping itself. If we calculate the maximum light hole energy for E/B = 1.36 kV/(cmT), we obtain 9.7 meV while for E/B = 1.42 kV/(cmT) we obtain 10.5 meV.
In the emission spectrum of the p-Ge laser it was found that impurities play an important role especially by self-absorption due to transitions between the impurity ground state and excited impurity states [18,19]. In an absorption spectrum the transitions can be recognized as several narrow lines labeled A, B, C, D, E, G. The result is the absence of emission lines in the IVB laser range of 1.6-2.1 THz because of strong absorption at the B, C and D transitions. Recently, additional proof has been given with a Tl-doped crystal which differs drastically in these transitions [20].
The transitions for Ga, the most commonly used acceptor in p-Ge lasers, correspond to energies of 9.8 meV, 9.2 meV and 8.4 meV (B, C and D). This leads to a reduction of the light hole population due to impurity scattering and hole capture when the pumping from the heavy holes into the light hole band at 74 meV is most efficient. In this respect, one improvement of the p-Ge lasers could be the introduction of group II acceptors or deep level acceptors. While we found that laser radiation can be detected with group III acceptors (so far we tested Ga, Al, Tl), this might be a major step forward to a continuous wave laser. Our experience showed also that the crystal performance varied drastically from crystal to crystal, e.g., a 50 mm long sample which should have a higher gain operated in a smaller range of E and B values than a 35 mm long sample although the preparation and the doping level were the same. Due to the low level of doping we assume an inhomogenity of doping across the sample and also different compensation levels.
Therefore we would like to use Neutron Transmutation Doping (NTD) of isotopically engineered Ge which is already used to fabricate Ge bolometers. This method enables a control of the compensation ratio and a statistical distribution of the doping atoms [21]. In addition we will change the usually used method of forming ohmic contacts for p-Ge lasers. Diffusing of Al or In into the crystals lateral surfaces will be substituted by implantation of Boron ions which are also used as low noise contacts for Ge bolometers or Ge photoconductors [21,22].
The main problem for a useful device in time-limited experiments on satellites or in airplanes is the pulsed operation. Preliminary experiments have shown that the repetition rate is mainly determined by the input energy of the applied electric field. The field heats the crystal adiabatically resulting in a hot crystal of about 20 K when laser action breaks down. High repetition rates produced a lot of He gas which in our experiments led to a local heating of the superconducting magnet and quenching. We believe that a He gas cloud covers the surface of the sample and limits the repetition rate. We have used superfluid liquid helium at 2 K to increase the repetition rate but this resulted in no major

improvement possibly still due to the local gas cloud attached to the sample. Otherwise we found a reduction in the pulse peak power and a reduced pulse length down to 70% compared to 4.2 K [23]. This seems to be in agreement with a better performance of the p-Ge lasers in 4.2 K liquid helium if the repetition rate is increased and the lattice mean temperature rises slightly above 4.2 K. This is probably connected to a higher mobility of the carriers.

In a more detailed study for different p-Ge lasers, we show that the electric input power P is connected to the geometry of the sample [24]. The power P can be easily calculated by $P = U \cdot I \cdot \Delta t \cdot f$ with the applied voltage U, the current I through the sample, the applied voltage duration Δt and the repetition rate f. The current is a result of the acceptor concentration N_a and the drift velocity E/B. The latter tends to saturate at 1/2 of the velocity which corresponds to heavy holes with an energy of $E_{op} = 37$ meV ($v_{op} = 1.9 \times 10^5$ m/s) . With several measurements of different laser crystals, we found a very accurate relation to determine the current through the crystal: $I = A \cdot N_a\, e \cdot E/(2 \cdot B)$, where A is the ohmic contact area. We assume that it is possible to design a continuous wave laser by using the high quality cavity based on a lamellar grating with a mesh outcoupler and by using our results about the electric input power and crystal geometry which already increased the duty cycle due to a high repetition rate by an order in comparison to reported values [6].

CONCLUSION

Due to the high output power, the single mode operation possibility, the tunability over a wide frequency range from 1 to 4.5 THz and the narrow spectral width of the laser modes on the MHz scale, this laser will be a very useful spectroscopic source. If continuous wave operation is possible, then the device will be also usable in space applications, e.g., as the local oscillator in a heterodyne spectrometer. In addition the fine tunable source can lead to an exchange of Schottky diode mixers by Ge photoconductors which are not practical with gas lasers due to there small bandwidth of a few tens of MHz.

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