

6-2 Research and developments on p-type Germanium lasers in the frequency range from 0.1 terahertz to few terahertz

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The recent developments on the p-type Germanium hot-hole laser oscillating in the frequency range from 0.1 terahertz to few terahertz are described in this report. The present stage of development is very close to the practical use as a tunable solid-state coherent sources in millimeter waves and terahertz waves.

Keywords

p-type Germanium, Valence band, Millimeter-waves, Terahertz,

1 Introduction

There are several types of induced emissions (ranging from millimeter waves to terahertz waves) that use p-type germanium semiconductors (p-Ge lasers), including an intervalence band transition type (IVB-type) laser that uses an inverted distribution of the light hole in the valence band with respect to a heavy hole band (1.2 - 4.2 THz), a light hole cyclotron resonance type (LHCR-type) laser that uses the inter-Landau level transition of the light hole (0.9 - 2.7 THz), and a heavy hole cyclotron resonance type (HHCR-type) laser that uses a dimple of the equi-energy surface of the heavy hole band in the $\langle 100 \rangle$ direction of the crystal (0.1 - 0.3 THz)[1][2]. These lasers oscillate in the terahertz frequency range where a compact, stable, and coherent light source is hard to obtain (Fig.1). Furthermore, they have the feature of allowing the oscillation frequency to be swept continuously.

For a tunable light source capable of oscillating in the terahertz range, the free electron laser (FEL) has already been put to practical use, being used in the measurement of physical properties, etc. The FEL is operated in a pulsed manner and can deliver an output in

kilowatts, but the equipment is so large that it must be housed separately. In contrast, at just 18 cm in diameter and 35 cm in height, a p-Ge laser is small enough to be used on an optical bench, although its peak power output in pulsed operation is as low as 10 watts. High expectations, therefore, are held for the laser as a compact, tunable light source in the terahertz range.

2 Oscillation principle of p-Ge laser

The valence band of Ge is composed of the heavy hole band, a light hole band, and a spin-orbit split-off band. Since the spin-orbit split-off band is away from the other two hole bands by about 290 meV at the Γ point, it is filled with electrons, but of the p-type, and does not contribute to conduction. The heavy hole band and the light hole band which contributes to conduction serves as the stage of the p-Ge lasers. The p-Ge lasers amplify and emit the terahertz electromagnetic waves by ingeniously exploiting a peculiar distribution of the hole system that results from interaction between the holes and optical phonon in the valence band of complicated structure in the vicinity of the Γ point. In comparison with a

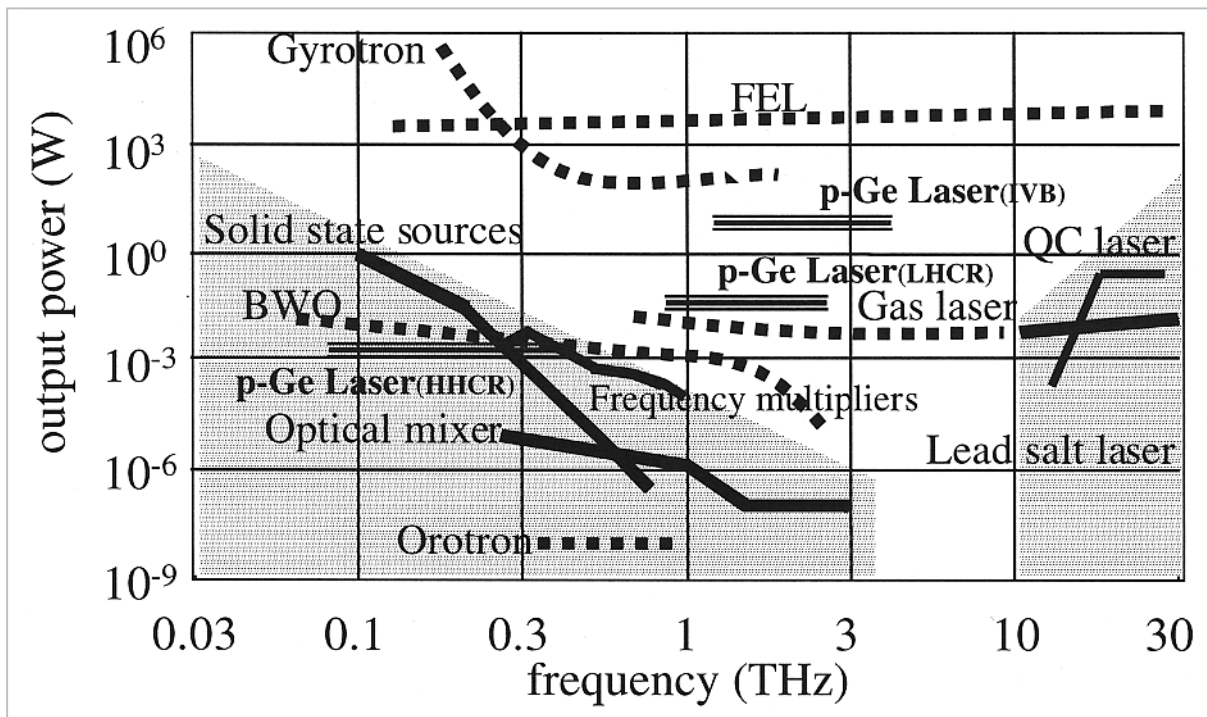


Fig. 1 Fundamental oscillators in the terahertz range

normal semiconductor laser, which is a bipolar device that uses recombination between the electron and the hole at a direct band gap of a semiconductor in which inverted distribution was built up by current injection, the p-Ge laser must be considered a unipolar device. Furthermore, the p-Ge laser uses intersubband optical transitions, and in this respect resembles quantum cascade lasers. The way in which the subband is created, and the way in which the inverted distribution is built up, produce differences in the oscillation mechanism in p-Ge lasers[3].

2.1 Oscillation principle of IVB-type and LHCR-type lasers

A semiconductor with low donor concentration or acceptor concentration cooled to cryogenic temperature (liquid helium temperature, approximately 4.2 K) turns into an insulator, since all carriers are captured by the impurity levels. Even in cryogenic temperature, an electric field of more than a few V/cm ionize almost all shallow impurities (the ionization energy is approximately 10 meV in Ge), and creates a carrier system having the same concentration as that of the shallow

impurity in the semiconductor. There exist the three main scattering mechanisms in a single crystal semiconductor: ionized impurity scattering, acoustic phonon scattering, and optical phonon scattering. In regard to the previously mentioned carrier system, since the impurity concentration is low and the crystal is at a low temperature, the influences of the ionized impurity scattering and the acoustic phonon scattering are relatively small. Fig.2 shows the calculated scattering probability of the heavy hole of a p-Ge with low acceptor concentration at 4.2 K.

The scattering probability differs largely according to whether the energy of the hole is larger or smaller than the energy $\hbar\omega_{op}$ ($= 37$ meV) of the optical phonon. When $\epsilon > \hbar\omega_{op}$ an emission of the optical phonon occurs and hence the scattering time of the hole is very short; When $\epsilon < \hbar\omega_{op}$, the hole can move comparatively freely. In the case where such a hole system is placed in external fields (electric field and magnetic field), when the energy of the hole is increased to $\epsilon > \hbar\omega_{op}$ by acceleration of external fields, the hole emits an optical phonon almost without delay and is scattered into a state of $\epsilon \sim 0$. When electric field

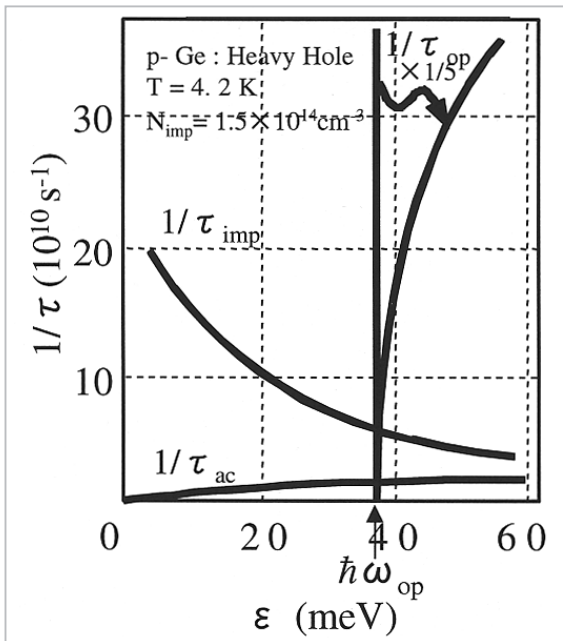


Fig.2 Scattering Rate of heavy holes in p-type germanium

E and magnetic field B, being mutually orthogonal and having appropriate magni-

tudes, are applied to a system in which two kinds of carriers of different effective masses (i.e., the heavy hole and the light hole) exist as the p-Ge, the ways in which both kinds of holes behave in a velocity space are shown in Fig. 3(a).

A circle represented by a dotted curve in the figure indicates a velocity $v_{op}^{lh} = (2\hbar \omega_{op} / m_{lh}^*)^{1/2}$ at which the kinetic energy of the hole becomes equal to the energy of the optical phonon. If there is no optical phonon scattering, the carrier makes a circular motion (cyclotron motion) centered at a point C (0, -E/B) in the velocity space. Denoting the magnetic field strength by $\zeta = v_{op}/(E/B)$, the motion of the carrier can be classified into three categories according to the magnitude of ζ . When $\zeta < 1$, point C is outside the circle $v = |v_{op}|$, and the carrier departs from the origin and moves repeatedly on an arc centered on point C, emitting the optical phonon frequently at the time interval $T_{op} (= v_{op}/(eE/m^*))$, that

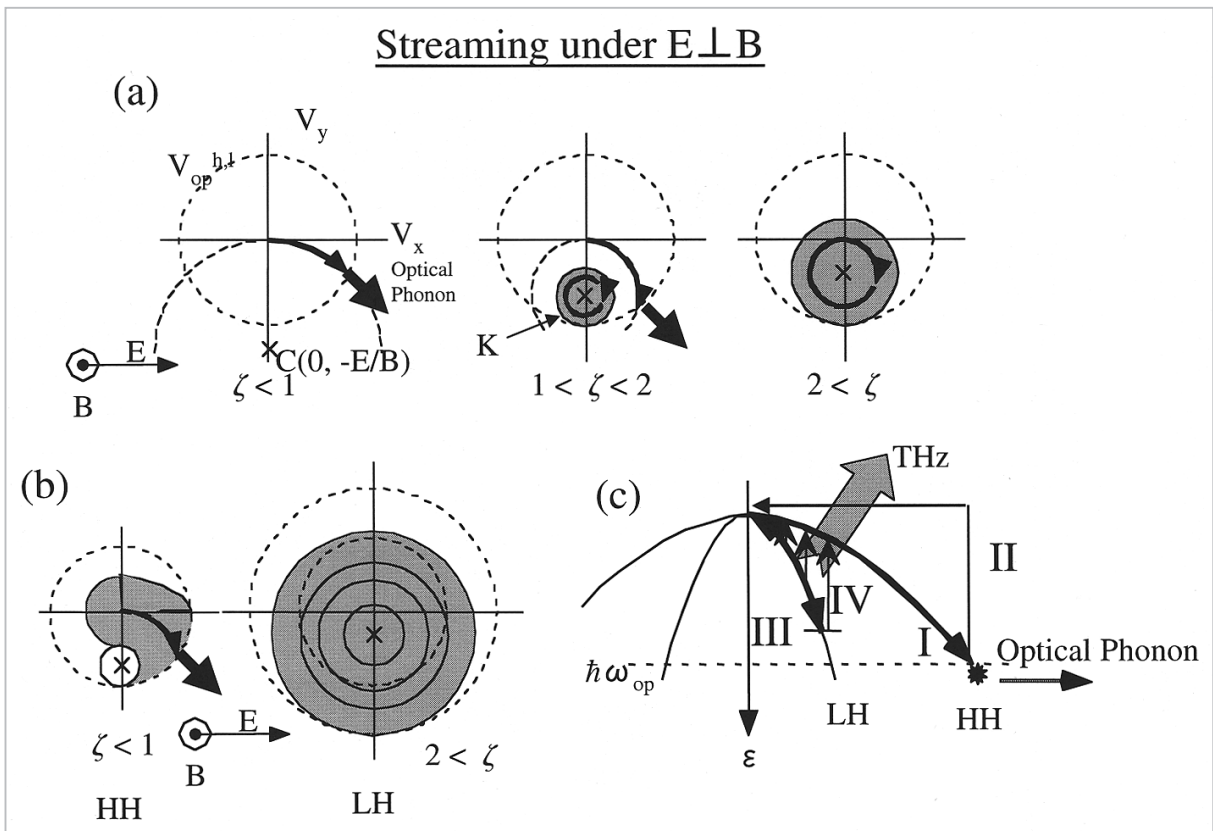


Fig.3 (a) Streaming motion under crossed electric and magnetic fields
 (b) $\zeta < 1$ for heavy hole, $\zeta > 2$ for light hole
 (c) Schematic diagram of the IVB-type laser pumping mechanism

is, it performs what is known as “streaming motion.” When $\beta > 2$, the carrier setting off from the origin makes a cyclotron motion within circular orbit of region K, centered at point C, without reaching the energy $\epsilon = \hbar\omega_{op}$. When $1 < \beta < 2$, which is an intermediate of the above cases, there exists both streaming motion and circular orbit of region K. In p-Ge, the effective masses of the heavy hole and of the light hole are $m_h^* = 0.35m_0$, $m_l^* = 0.043m_0$, respectively, and the v_{op} ratio ($v_{op}^h / v_{op}^l = (m_h^* / m_l^*)^{1/2}$) is about 2.85. Therefore, proper selection of the electric and magnetic field can establish the condition $\beta < 1$ for the heavy hole and at the same time the condition $\beta > 2$ for the light hole (Fig.3(b)). In this case, the heavy hole is performing streaming motion in which the optical phonon is emitted repeatedly with a short time interval of T_{op}^h . On the other hand, the light hole stays in the region K for a comparatively long time while doing the cyclotron motion with a time of $T_{op}^l = (v_{ac}^{-1} + v_{imp}^{-1})$ that was governed by the acoustic phonon and ionized impurity scattering. Whenever scattering occurs, the hole is redistributed into the heavy hole band and the light hole band with a probability proportional to the density of states $m_{h,l}^{*3/2} / (m_h^{*3/2} + m_l^{*3/2})$. Therefore, the longer the time T_{op}^h and the shorter the time interval T_{op}^l , the more the comparatively light hole distribution builds up. If a cooled p-Ge single crystal with low acceptor concentration ($N_a = 0.4 \times 10^{14} - 2 \times 10^{14} \text{ cm}^{-3}$) is subjected to both the electric field ($E = 0.3 - 3.5 \text{ kV/cm}$) and the magnetic field ($B = 0.5 - 3 \text{ T}$), the accumulated light holes in the region K form inverted distribution to the heavy holes. The accumulated light hole makes direct optical transition into the heavy hole band by dipole interaction, and this causes the emission and amplification of terahertz electromagnetic waves ($\hbar\nu < \hbar\omega_{op}$). This is the mechanism of an inter-valence band transition (IVB) type laser. Fig.3(c) shows the pumping mechanism of the IVB-type laser schematically. In process I, the heavy hole is accelerated to the amount of energy $\hbar\omega_{op}$ by both the magnetic field and the electric field, and in process

II, the heavy hole is scattered into the light hole band, emitting an optical phonon. In process III, light holes are accumulated in the region K and are accelerated again to reach a state of higher energy. Following this, in process IV, the light hole undergoes optical transition into the heavy hole band.

Under the same conditions, the inverted distribution between the Landau levels of the light hole builds up and thereby light-hole cyclotron resonance type laser oscillation occurs. In quantum mechanical terms, under mutually orthogonal electric and magnetic fields, the light hole band and the heavy hole band mix with each other to form two new hole bands. The degree of mixture with light hole band and heavy hole band tends to increase with a decreasing energy, and hence, in the Landau level series of the light hole-like band, an energy level with a large component of the heavy hole has a large scattering probability due to the optical phonon. Therefore, the population of the Landau level of the light hole-like band having lower energy decreases, and the inverted distribution between that level and the upper level is built. This is the oscillation mechanism of the LHCR-type laser.

The oscillation region of the IVB-type laser in a plane of electric field bias and magnetic field bias is determined as shown in Fig.4.

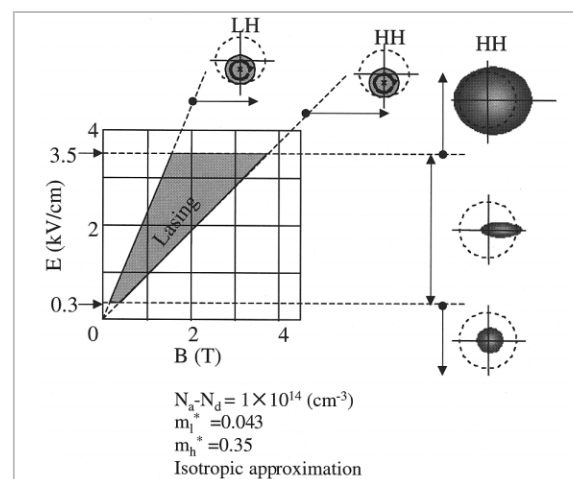


Fig.4 Oscillation region of the IVB-type laser in a plane of electric field bias and magnetic field bias

The strength of the electric field is determined by the necessity that the hole distribution in the velocity space must be bar-like and with strong anisotropy. When the electric field is weak, the holes are scattered by the acoustic phonons and ionized impurities before reaching the energy of the optical phonon and are not able to form the bar-like distribution. Conversely, when the electric field is too strong, since the number of holes that are scattered by optical phonon after entering an energy range larger than $\hbar\omega_{op}$ increase, the bar-like distribution of the holes expands, and hence the oscillation halts. The magnetic field is set to be in the range of a magnitude from where the light hole becomes > 2 to a magnitude where the heavy hole becomes > 2 in a given electric field. In the LHCR-type oscillation, since only the condition that > 2 for the light hole is imposed, it can oscillate in a higher magnetic field than that of the IVB-type oscillation. Fig.5(a) shows actual oscillation regions for the IVB-type, the LHCR-type, and the later-described HHCR-type oscillations. The wave number for each oscillation is shown in Fig.5(b) as a function of the magnetic field.

Since the IVB-type inverted distribution occurs over a continuously wide energy range, the upper and lower edges of this energy range vary according to the magnetic field. However the energy range has a large bandwidth, and the oscillation frequency of the IVB-type laser depends on several conditions, such as resonator structure. For example, if simple lamellar grating is incorporated in the resonator and the depth of the lamellar grating d is changed, the wavelength can be tuned in a range of 83 - 115 μm , i.e., in a frequency range of approximately 1 THz (3.6 - 2.6 THz), with the same electric field and magnetic field biases (Fig.6)[4]. On the other hand, because the LHCR- and HHCR-type are cyclotron resonance oscillations, their oscillation frequencies are proportional to the magnetic field (Fig.5(b)).

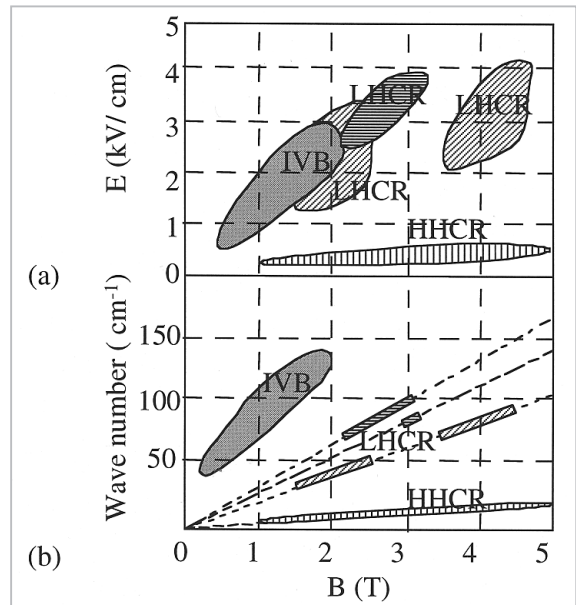


Fig.5 Oscillation region of various type lasers (a) in a E - B plane and (b) in a wave number- B plane

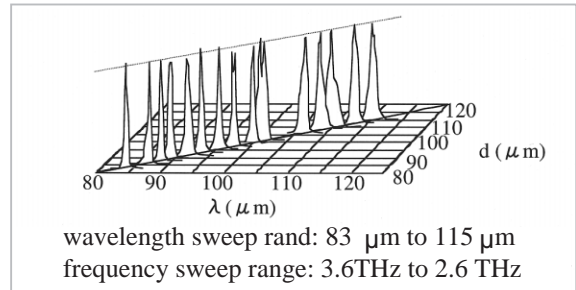


Fig.6 Selection of oscillation wavelength by lamellar grating under the same bias ($B = 0.94\text{T}$, $E = 1.5\text{kV/cm}$)

2.2 Principle of HHCR-type oscillation

It is possible to generate the inverted distribution between Landau levels of the heavy hole, by utilizing anisotropy of the heavy holes of Ge, and obtain pulsed oscillation in a frequency range of 70 - 375 GHz (wavelength = 4.3 - 0.8 mm) with a peak output power of a few milliwatts[3][5][6].

As shown in Fig. 7(a), an equi-energy surface of the heavy hole is a deformed spherical surface that has dimples in six directions equivalent to a $\langle 100 \rangle$ direction. Below, a case where the electric field is applied in the $\langle 100 \rangle$ direction shall be considered. Hereafter, the $\langle 100 \rangle$ direction in which the electric field is applied is referred to as the z -axis. In this case, if a sufficient electric field is applied, there occurs a streaming motion along

the $\langle 100 \rangle$ axis direction. On a wave number plane where the wave number of the hole in the z -axis direction k_z is constant, hole distribution that was developed by the streaming motion can be regarded as inverted distribution. This is because the hole distribution peaks at $k = 0$ and, when k_z is constant, the energy decreases with increasing k , as shown in Fig.7(c). Therefore, the electromagnetic wave having an oscillating electric field parallel to k is amplified. Such a condition is realized in a region where the “longitudinal effective mass” of the hole becomes negative ($d\epsilon/dk < 0$) as shown in Fig.7 (b). Practically, however, it has been made clear by the Monte Carlo method that absorption by the hole whose longitudinal effective mass is positive dominates the amplification and there is no real hope of net amplification[7]. A contrivance for ingeniously separating the absorption by the hole whose longitudinal effective mass is positive and the amplification by the hole whose longitudinal effective mass is negative is the application of a magnetic field (~ 6 T) parallel to the applied electric field[8]. Under this magnetic field, the holes are made

to perform cyclotron motion around the z -axis, but the direction of rotation depends on whether the longitudinal effective mass is positive or negative, that is, the negative hole rotates in a reverse direction to that of the positive hole, i.e., in the same direction as that of the electron. Therefore, if the circular polarization that has a rotating electric field of the same direction as that of the hole having the negative effective mass is entered into the system, amplification surpasses absorption and oscillation becomes possible.

3 Development with a view toward CW oscillation of IVB-type lasers

A single rectangular solid p-Ge crystal that contained the acceptor of $N_a = 0.4 \times 10^{14} - 2 \times 10^{14} \text{ cm}^{-3}$ and had an approximate length of 40 - 60 mm and cross-section of $5 \times 5 \text{ mm}^2$ had been in use for some time after the first realization of the laser. This came from the understanding that a comparatively long crystal was necessary for laser oscillation because the amplification coefficient for light of, for

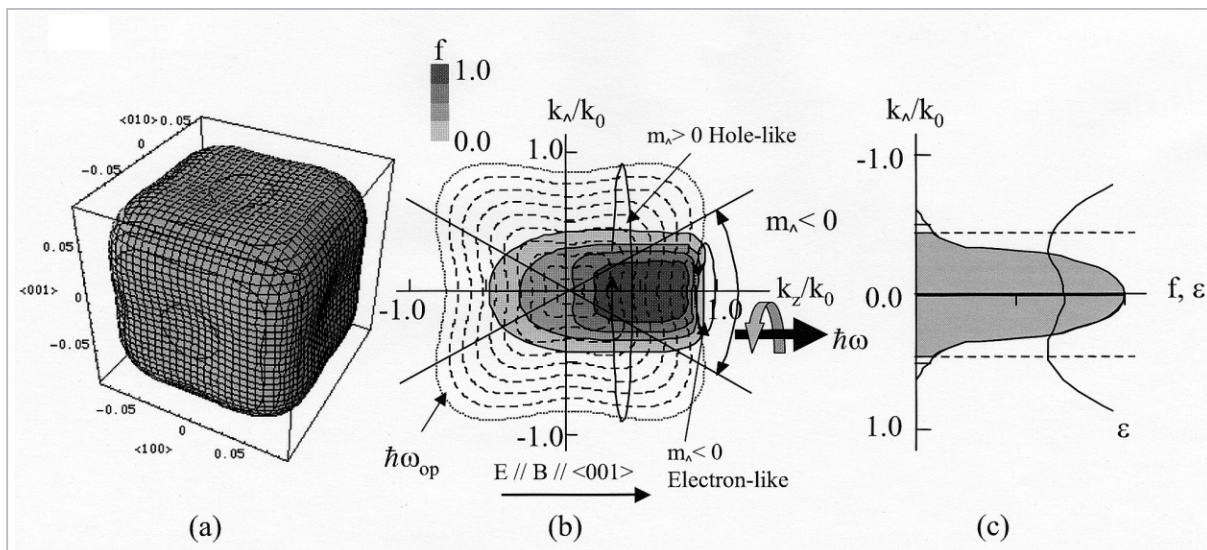


Fig.7 (a) Distorted constant-energy surface of heavy hole ($\epsilon = \hbar\omega_{op}$ (37 meV))
 (b) Showing equi-energy plane of deformed heavy hole (cross-section) and rotational direction of cyclotron motion of heavy hole. In a cone sandwiched between two oblique lines, “longitudinal effective mass (cyclotron effective mass)” becomes negative and the heavy holes make electron-like rotational motions. The portion painted gray shows a distribution of the heavy holes making streaming motion in the $\langle 001 \rangle$ direction
 (c) Distribution function and energy of the heavy hole when the electric field is applied in the $\langle 001 \rangle$ direction. The heavy holes distribute around the k_z axis creating a bar shape where energy is high and form the inverted distribution in a gray-colored range

example, a frequency of 3 THz, was on the order of $\sim 0.02 \text{ cm}^{-1}$. Ohmic electrodes are formed on two mutually opposing side faces of the crystal, and a voltage pulse of 0.15 - 2 kV with a width of 0.3 - 3 μs is applied. The crystal is soaked in liquid helium for cooling, and a magnetic field of approximately 0.5 - 3 T is applied in a direction orthogonal to the electric field. The current reaches 150 - 400 A when the voltage is applied, and consequently input power grows as high as a few hundred kilowatts. Since the output is around 10 W, the energy conversion efficiency is in the order of 10^{-4} - 10^{-5} . Joule heat resulting from the input power warms the crystal, and its temperature exceeds 20 K within a few microseconds. In consequence of the acoustic phonon scattering that is therefore increased, the light hole distribution in region K (Fig.2) decreases and oscillation disappears. This is the reason CW oscillation has not been achieved up to the present time.

For a number of applications, the output may in fact be much smaller, and CW oscillation capability instead of output is thought to afford improved convenience. In such a case, it is important to control the rise in crystal temperature and also the increase in energy conversion efficiency. In light of the present capabilities of mechanical refrigeration machines, if the energy conversion efficiency can be increased so as to be on the order of 10^{-3} , it is likely that a terahertz optical CW light source, with an output of a few milliwatts derived from an input of a few watts, and which is operated at the flick of a switch, will become a reality. When CW operation is realized, the width of an oscillation line, which is nearly governed by Fourier transform of the oscillation pulse width in the pulse operation (not more than 900 kHz at a pulse width of 2.5

μs), becomes narrower, and a chirping problem[9] which causes the oscillation frequency to shift to a lower frequency (by approximately 25 MHz in pulse operation) due to the thermal expansion of the width of a crystal of oscillation line and variation in the dielectric constant.

Hereafter, we will examine miniaturization, uniaxial stress, alteration of acceptor impurity, and application of the Voigt configuration, each of which is considered to be effective in making the laser capable of CW oscillation.

3.1 Miniaturization

Conventionally, a crystal with dimensions of around $60 \times 5 \times 5 \text{ mm}^3$ has been used in the p-Ge laser. If a smaller crystal is used, not only is the amount of heat generation reduced, but cooling efficiency is enhanced because of the increased ratio of (surface area)/(volume), which in turn controls the rise in crystal temperature and suppresses the increase in acoustic phonons scattering. Therefore, there is a possibility that CW oscillation can be achieved by this means alone.

It is important to attach blocks made of oxygen-free copper or the like to act as heat sinks on the electrode of the crystal in order to enhance its cooling efficiency.

Consider a case where a p-Ge crystal that contains Ga as the acceptor at a concentration of $N_a = 1.0 \times 10^{14} \text{ cm}^{-3}$ is used. The minimum electric field at which oscillation occurs is $E = 500 \text{ V/cm}$ ($B \sim 0.18 \text{ T}$). The current density at this time is $J = 100 \text{ A/cm}^2$. Accordingly, the input power density becomes $P = E \times J = 5 \times 10^4 \text{ W/cm}^3$. It is further assumed that the oxygen-free copper blocks are attached to the ohmic electrodes on both side faces of the crystal as heat sink-cum-external electrodes,

Table 1 Improvement in duty cycle by miniaturization

Sample	Size(mm ³)	Heat sink	Stress (kgf/cm ²)	E (kV/cm)	B (T)	V (V)	I (A)	P (kW)	Duty cycle
1	18 × 3.3 × 3.3	no	0	0.64	0.39	214	69	15	3×10^{-5}
2	20 × 3.5 × 3.5	yes	1000	0.46	0.26	165	65	11	1×10^{-4}
3	5 × 1 × 1	yes	1300	0.62	0.39	57.5	5.6	0.3	2×10^{-3}

and these parts are kept at a liquid helium temperature of 4.2 K. However, faces of the crystal other than the electrode planes are ignored, because it is thought that their cooling effect will be small. Furthermore, the thermal conductivity of Ge at low temperatures was assumed to be $K = 0.5 \text{ W/cmK}$. By utilizing the one-dimensional equation of heat conduction, it was found that spacing between the electrodes (d) of the crystal necessary to prevent the temperature at the center of the crystal from exceeding 20 K was $d = 0.36 \text{ mm}$ or less. Table 1 shows an example of improvement in the duty cycle by miniaturization. The uniaxial stress that will be described later was applied to samples 2 and 3. Comparison between samples 1 and 2 shows that the duty cycle was enlarged approximately by an order of magnitude, by virtue of the enhancement of cooling efficiency by the heat sink and the improvement in laser efficiency by the uniaxial stress. From comparison of samples 2 and 3, it was found that the duty cycle was increased approximately by one order, similar to the effect achieved by miniaturization^[10]. However, oscillation was not successfully observed with a sample with dimensions of $5 \times 1 \times 0.5 \text{ mm}^3$ (electrode spacing $d = 0.5 \text{ mm}$), one that was much smaller than sample 3. It is considered that diffraction loss increases rapidly with decreasing crystal cross-section, and hence oscillation cannot be generated.

3.2 Uniaxial stress

Miniaturization is a means of keeping the light hole distribution undiminished by suppressing the increase in the acoustic phonon scattering probability $\propto \omega_{ac}^{-1}$ of the hole. Another means of keeping the light hole distribution undiminished is to suppress the ionized impurity scattering probability $\propto \omega_{imp}^{-1}$. The simplest method of achieving this is to decrease the acceptor concentration, but this in turn entails a decrease in the hole concentration and ultimately decreases the efficiency of the laser.

Regarding the interband scattering caused by the ionized impurity, the smaller the varia-

tion in the momentum associated with the scattering, the larger the scattering probability becomes; therefore, the scattering occurs mainly in the vicinity of Γ point. Uniaxial compressive stress dissolves the degeneracy of the valence band at Γ point (Fig.8) and reduces interband scattering substantially. As a result, it is possible for the ionized impurity scattering probability $\propto \omega_{imp}^{-1}$ to be controlled without reducing the hole density. On the other hand, the application of uniaxial stress adversely influences IVB-type oscillation. When the uniaxial stress becomes large, the separation of the valence band increases accordingly, and the ratio at which heavy holes are converted into light holes by optical phonon scattering decreases. More specifically, the heavy hole does not immediately release the optical phonon after it acquires energy of $= \hbar\omega_{op}$ by the streaming motion, but enters an energy range of $> \hbar\omega_{op}$ to some extent and then emits the optical phonon. Therefore, the heavy hole is scattered into the heavy hole or light hole band, with some energy remaining in it. This is due to the fact that when the separation of the valence band becomes large, the heavy hole cannot enter the light hole band unless it has an amount of energy comparable to the separation of the valence band after scattering. Thus, uniaxial stress has one factor that favors IVB-type oscillation and one that works against it, and it is therefore predicted that there is an optimal stress value. Fig.9 shows the way in which oscillation light intensity in sample 3 ($5 \times 5 \times 1 \text{ mm}^3$) of Table 1 varies depending on the magnitude of the uniaxial stress^[10]. A stressed Ge:Ga detector with sensitivity in 1.5 - 3.75 THz was used here. In the case of zero stress, no oscillation occurred, but it was found that as the stress increased from zero, oscillation light intensity increased, to a peak of 4100 kgf/cm², and then decreased with increasing stress. Furthermore, the minimum electric field required to start the sample oscillating became larger with increasing stress. This phenomenon reflects the fact that with increased stress it is necessary for the heavy

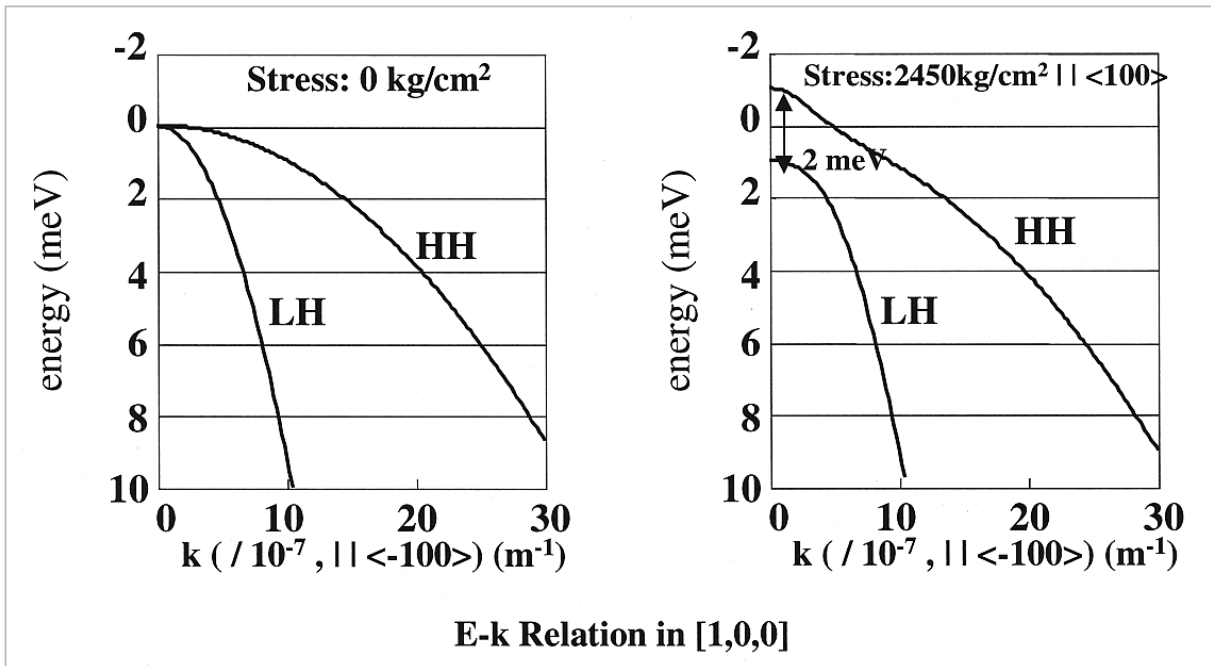


Fig.8 E-k relations in 100 direction in the vicinity of valence band top

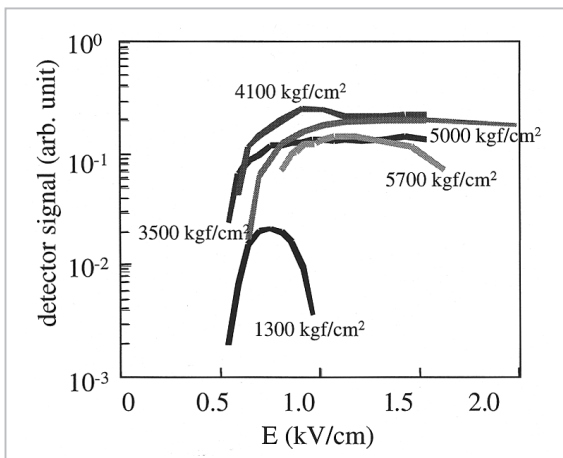


Fig.9 Dependence of the oscillation light intensity on the electric field of sample 3 in Table 1 is shown with a parameter of the magnitude of uniaxial stress

hole to further enter the $> \hbar\omega_{op}$ range, in order to acquire the energy necessary for conversion to the light hole, and hence larger acceleration is needed. This experimental result generally agreed with theoretical calculations, and from these results it was found that the optimal value of uniaxial stress in the case where the crystal contained Ga as the acceptor at a concentration of $N_a = 1.0 \times 10^{14} \text{ cm}^{-3}$ was 3500 - 4100 kgf/cm².

3.3 Alteration of acceptor impurity

Miniaturization and uniaxial stress are improvements via the suppression of non-radiative transition of the light hole in region K. On the other hand, another method for improvement utilizing deep impurity is based on effectively usage of the terahertz light generated by the optical transition of the light hole into the heavy hole band.

Traditionally, impurities with ionization energies as shallow as about 10 meV, such as Al or In, but mainly Ga, have each been used as the acceptor to be added to the p-Ge laser crystal. This is because these shallow acceptor impurities are capable of being ionized almost completely by an electric field on the order of 2 V/cm and yielding free holes of the same concentration as the acceptor concentration. In the case where Ga is used as the acceptor, a frequency range of IVB-type oscillation divides into ranges of 1.0 - 1.8 THz and of 2.1 - 4.2 THz, while in between these there is a non-oscillation range of 1.8 - 2.1 THz. This is thought to be caused by absorption associated with transition between the ground state and the excited state of the acceptor. If the above-mentioned uniaxial stress is applied to the crystal, oscillation occurs even in this

range. This is because the amplification caused by the uniaxial stress exceeds the level of absorption. These shallow acceptor impurities are also considered to be responsible for greatly reducing the efficiency of lasers in the area of oscillation frequency range because they have absorption at a level of 6 - 12 meV [11].

On the other hand, double acceptors such as Be, Zn, Cu, etc., have large ionization energies of 25 meV, 33 meV, and 40 meV, respectively, and the absorption associated with transitions between these ground states and excited states corresponds to larger energies than oscillation energy ranges of the IVB-type p-Ge lasers. Therefore, if these impurities are used, the terahertz light once generated is not absorbed and the efficiency of the laser is thereby improved. Because of the larger ionization energy, these acceptors require larger concentrations than shallow acceptors in order to attain an enough concentrations of free holes required to make the crystal oscillate. However, if the acceptor concentration is too large, the influence of the ionized impurity scattering grows and finally suppresses the oscillation; therefore, it is not necessarily appropriate to suggest that a larger concentration is desirable. The bottom line is that Be-doped crystals delivered the best results [12][13]; the maximum duty cycle so far obtained has been 2.5×10^{-2} , and in this case the impurity concentration was $N_a = 0.2 \times 10^{14} \text{ cm}^{-3}$. In general, efficiency is maximized for an impurity concentration on the order of $N_a = 1.4 - 4.2 \times 10^{14} \text{ cm}^{-3}$, and a duty cycle of $0.01 - 2 \times 10^{-2}$ was achieved with the use of an almost cubic crystal with an approximate length of 3 mm and an electrode spacing of 3 mm. Furthermore, this p-Ge (Be) laser had no region in which oscillation did not occur and was frequency-tunable continuously through a range of 1 - 4 THz.

The p-Ge laser using the above-mentioned double acceptor, such as Be, Zn, or Cu, etc., is that investigated by Bruendermann and his colleagues in a group of Haller, et al. at the Lawrence Berkeley National Laboratory in

California[12][13][14].

3.4 Voigt configuration

The improvement in laser efficiency achieved by application of the Voigt configuration is an improvement based on optical transition probability of the light hole into the heavy hole band and the frequency of emission of the optical phonon $1/T_{op}$ caused by streaming of the heavy hole.

The Voigt configuration is such that the propagation direction of light in a medium crosses perpendicular to the direction of the magnetic field applied to the medium from outside. In comparison, a configuration in which the propagation direction of light is parallel to the direction of the magnetic field is called the "Faraday configuration." In conventional p-Ge lasers, the Faraday configuration was chiefly adopted for the technical reason that a superconducting solenoid and a comparatively long crystal (40 - 60 mm) were used.

The biggest difference in the p-Ge laser oscillation characteristics of both configurations is the state of polarization. A dielectric tensor for a crystal base material and a hole system in a state in which the light holes are accumulated in region K has off-diagonal components as contributions from the hole system. In this case, an allowed vibration in the Faraday configuration is an elliptic polarization, whereas the allowed vibration in the Voigt configuration is a linear polarization whose plane of vibration of the light electric field is either perpendicular or parallel to an external magnetic field. In fact, it has been confirmed that oscillation occurred with such polarizations[15][16].

The plane of vibration of the light electric field is always perpendicular to the external magnetic field in the Faraday configuration. Selection rule and probability for optical transition of the light hole into the heavy hole band vary according to the geometry between the plane of vibration of the light electric field and the external magnetic field. In the case of the linear polarization whose plane of vibra-

tion of the light electric field is parallel to the external magnetic field in the Voigt configuration, the optical transition of the light hole into the heavy hole band accompanies spin-flip [17][18]. The probability of this optical transition grows larger in comparison to a normal case (where the plane of vibration of the light electric field is perpendicular to the external magnetic field)[17]. Actually, LHCCR (Light Hole Combined Cyclotron Resonance) type oscillation accompanied by the spin-flip in the Voigt configuration exhibits oscillation light intensity of the same magnitude as that of the IVB-type oscillation. Since this oscillation occurs in a lower electric field and a lower magnetic field than the LHCR-type oscillation in the Faraday configuration, it is of particular interest from a practical standpoint. It is difficult to compare the oscillation light intensities of IVB-type oscillation in both configurations because conditions other than the configuration may change concomitantly. Nevertheless, it is believed that the oscillation light intensity in the Voigt configuration is ultimately larger from the results of the oscillation light intensity using the p-Ge crystals having various crystal orientations in both configurations[14] - [20] when considering all factors involved.

As previously mentioned, in the case of IVB-type oscillation, the longer the scattering time of the light hole and the shorter the scattering time of the heavy hole T_{op}^h , the more the light hole distribution increases in comparison, and accordingly the degree of inverted distribution increases.

The scattering time of the heavy hole by the optical phonon is $T_{op}^h = (2m_h^* \hbar \omega_{op})^{1/2} / eE$. Because the effective mass of the heavy hole is anisotropic, it should be possible to reduce T_{op}^h by properly choosing the orientation of the crystal along which the electric field is applied, depending on the crystal plane on which the electrode plane is formed. If there is no magnetic field, T_{op}^h can be minimized by forming the electrode on a (100) plane and applying the electric field in the $\langle 100 \rangle$ direction, because the effective mass of the heavy hole in this direction takes on the minimum

value of approximately $m_h^* = 0.28 m_0$ [21].

However, in reality, the hole orbit is bent by the magnetic field, and it is necessary to obtain average effective mass that minimizes T_{op}^h on the bent orbit. The problem here is a Hall field. Under the influence of the Hall field, the direction of the effective electric field in the crystal does not agree with the direction of an externally applied electric field. The Hall field varies in a sample according to the cross-sectional shape of a plane that is perpendicular to the external electric field and magnetic field. When a rectangular solid crystal with a square cross-section is used, a Hall field that is almost of the same magnitude as the applied electric field is generated in the Faraday configuration. Since in the Voigt configuration the influence of the Hall field is small in comparison to that in the Faraday configuration, it is suitable to examine the anisotropic effect of the heavy hole.

When comparing crystals that were cut from the same wafer ($N_a = 1.0 \times 10^{14} \text{ cm}^{-3}$) to a size of around $18 \times 3 \times 3 \text{ mm}^3$ and with different crystallographic orientations, the following orientations appeared to provide the best results: in the Faraday configuration, $\langle 011 \rangle // B \times \langle 0 - 11 \rangle // E \times \langle 100 \rangle$ or $\langle 001 \rangle // B \times \langle 100 \rangle // E \times \langle 010 \rangle$; and in the Voigt configuration, $\langle 111 \rangle \times \langle 0-11 \rangle // E \times \langle -211 \rangle // B$ and $\langle 011 \rangle \times \langle 0 - 11 \rangle // E \times \langle 100 \rangle // B$. However, no clear agreement was found among results obtained by calculation.

Although it is not a laser improvement as such, in the Voigt configuration it is easy to apply a magnetic field on the order of about

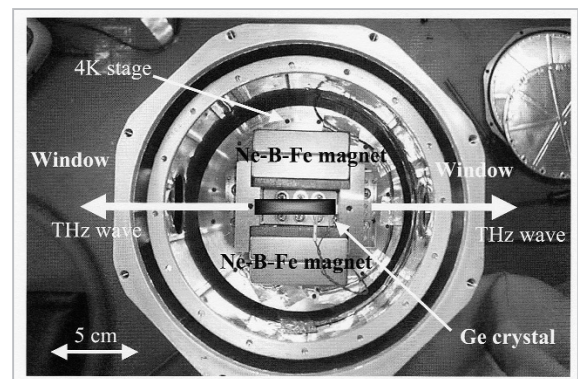


Fig. 10 Photograph of interior of cryostat

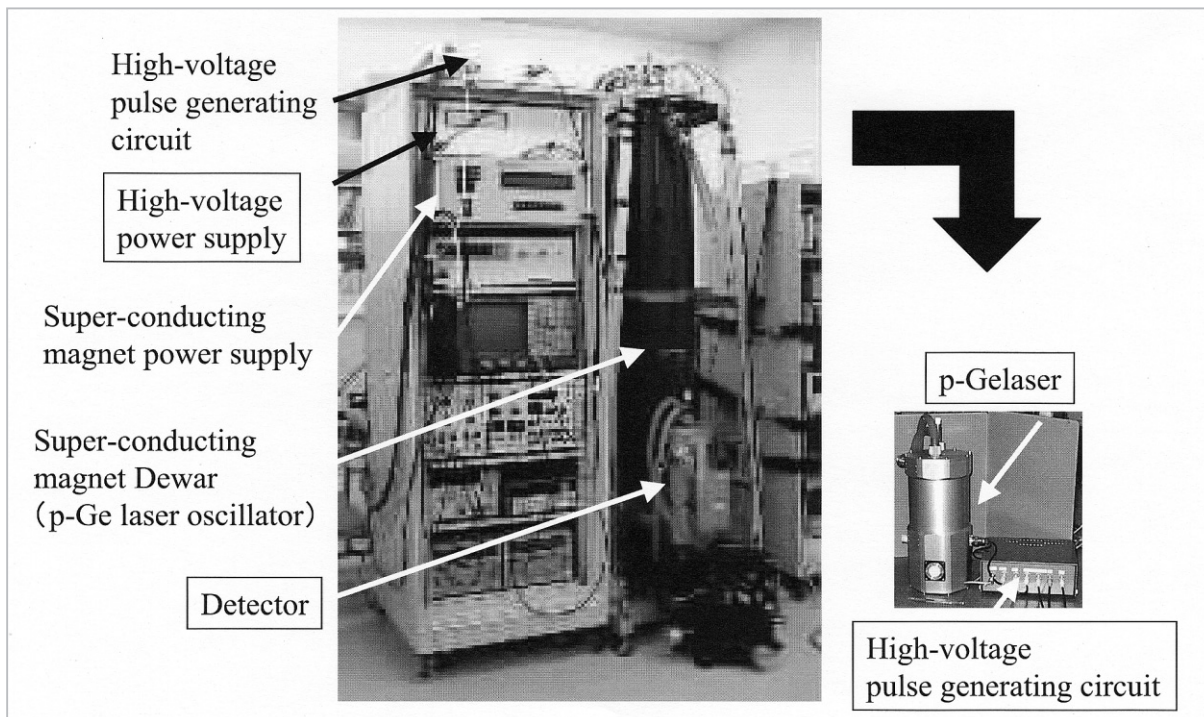


Fig. 11 Miniaturization of system

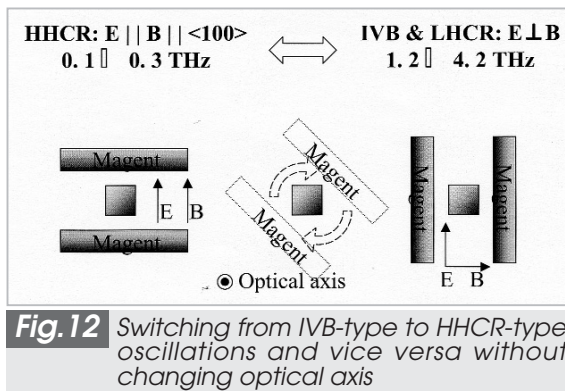
0.5 T by attaching a pair of rare-earth permanent magnets (residual magnetic flux density: about 1.2 T) to the sides of the p-Ge laser rod. In this case, a considerable degree of miniaturization of the laser system becomes possible [22][23] as shown in Figs.10 and 11. Furthermore, if a magnetic circuit called the magic ring is used, then a magnetic field on the order of about 1.0 T can be generated inside the ring. The magnitude of the magnetic field depend on the magnetic material and the outer and inner magnitudes of the ring. If three or more kinds of magic rings (each of which has different dimensions to the magnetic field) are prepared, the whole area of the oscillation region of an IVB-type p-Ge laser can be covered with the magnetic field produced by the magic rings.

4 HHCR-type oscillation in the Voigt configuration

In the HHCR-type oscillation, from the viewpoint of amplifying the circular polarization, a configuration where the propagation direction of the electromagnetic wave in the resonator lies parallel to the direction of the

magnetic field, namely the Faraday configuration, has traditionally been adopted. Therefore, it was necessary to extract the electromagnetic wave generated in the resonator through an electrode in order to apply the electric field, and consequently this introduced various constraints in fabricating a part that serves both as the electrode and also as a mirror for the resonator. Moreover, this configuration has numerous inconvenient points. For example, when the length of the resonator is to be extended in order to achieve sufficient amplification, this causes the spacing between the electrodes to be widened, and consequently the voltage required to attain the same electric field strength increases and the accordingly generated Joule heat multiplies. In many respects it is convenient to adopt the Voigt configuration, for example, when the electrodes and the resonator mirrors can be separated, and when the length of the resonator is extended the spacing between the electrodes does not increase. It has been assumed that since linear polarization in the Voigt configuration is allowed vibration, absorption and amplification caused by holes whose effective masses are positive and negative cannot be

separated. However, this problem was actually solved when a magnetic field was applied and oscillation of the linear polarization also proved possible. In fact, the oscillation in the Voigt configuration was successfully obtained using a crystal with dimensions of $3.3 \times 3.3 \times 18 \text{ mm}^3$ (with an electrode spacing of 3.3 mm) and with Ga concentration of 10^{14} cm^{-3} [24]. The oscillation of a duty ratio of 10^{-3} or more was achieved with this crystal, and under the same considerations as the case of the IVB-type, it is predicted that CW oscillation is possible if the electrode spacing is set at 0.6 mm or less. The Voigt configuration also allows HHCR-type and IVB-type oscillations to be easily swapped, as shown in Fig.12, and so there is merit in the application.



5 Possibility of amplification of a pulse-like terahertz electro-magnetic wave (THz pulse wave) with a p-Ge laser

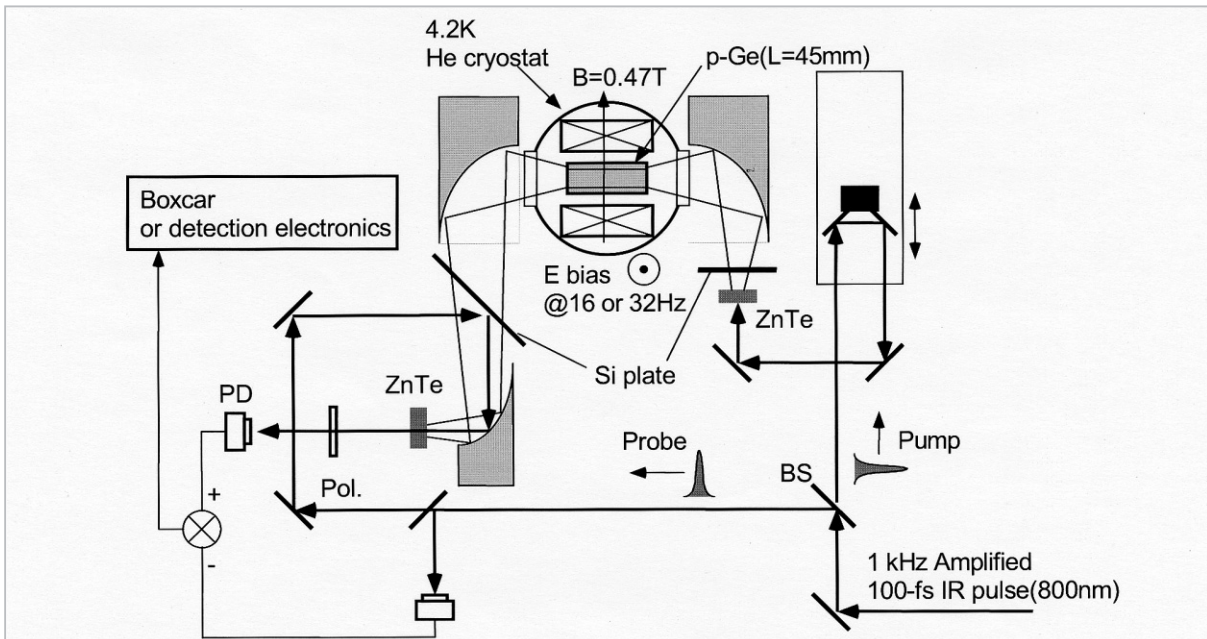
The gain band of the IVB-type p-Ge laser exists within a range of 1.2 - 4.2 THz, and as described above the bandwidth is approximately 1 THz with the same electric field and magnetic field biases[4]. Therefore, it is suitable as an amplifier of a THz pulse wave that contains the broadband frequency components excited by a femtosecond (fs) laser. We tried to amplify the THz pulse wave using the p-Ge laser[25] in cooperation with the CRL Kansai Advanced Research Center, THz group (senior researcher Masahiko TANI et al.). As a THz amplifier, we used a compact desktop THz

light source of Fig. 10 in which a p-Ge single rectangular solid crystal with dimensions of $3.3 \times 3.3 \times 45 \text{ mm}^3$ is mounted on a cold stage so that the optical axis (lying in the longitudinal direction of the crystal) is orthogonal to externally applied electric and magnetic fields.

The arrangement of the experiment is shown in Fig.13. A THz pulse wave generated by irradiating a ZnTe crystal with an fs laser pulse was introduced to a p-Ge crystal, and the transmitted THz pulse wave was focused on another ZnTe crystal. The electric field of the THz pulse wave was detected with the photodiode as a variation in polarization of a reference fs laser pulse due to an electro-optical effect. The waveform of the THz pulse wave was measured while the time delay between the excitation pulse and the reference pulse was varied. We observed large differences in the waveform and in the spectrum of the THz pulse wave in cases where the THz pulse wave was and was not synchronous with the electric field applied to the p-Ge crystal. Two points in particular were noted: frequency components in the vicinity of 2 THz were greatly amplified (Fig.14); and the phase shift spectrum had a macro structure (Fig.15). These results strongly support amplification of the THz pulse wave.

6 Summary and future perspective

As discussed above, if various p-Ge lasers are employed in the ranges of 70 - 375 GHz (HHCR-type) and 1.0 - 4.0 THz (IVB-type, LHCR-type), a considerable portion of the range from 0.1 THz to 10 THz but omitting the 375 - 1000 GHz range, can be covered. It can therefore be said that a set of lasers can be created which are almost continuously tunable in this range. In addition, CW oscillation will be achieved for the various oscillations in the near future. When this occurs, it is expected that output will be between a few tens of microwatts and a few milliwatts, and the line width of oscillation will be from a few kilohertz to a few tens of kilohertz. Since such



[by HOSAKO Iwao, TANI Masahiko, et al. presented at 62nd Annual Meeting of Japan Society of Applied Physics (2001)]

Fig. 13 Pulse-like THz electromagnetic wave amplification experiment

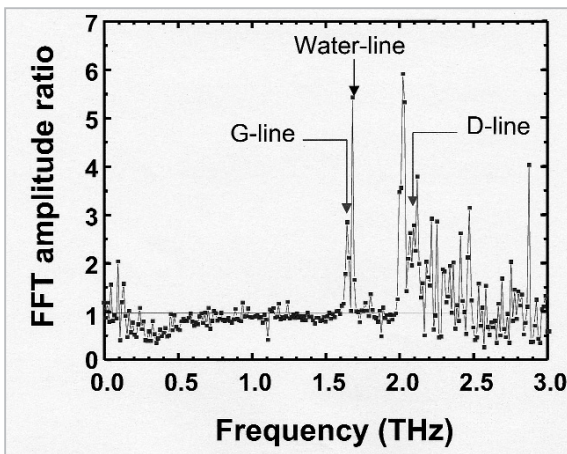


Fig. 14 Transmission spectrum

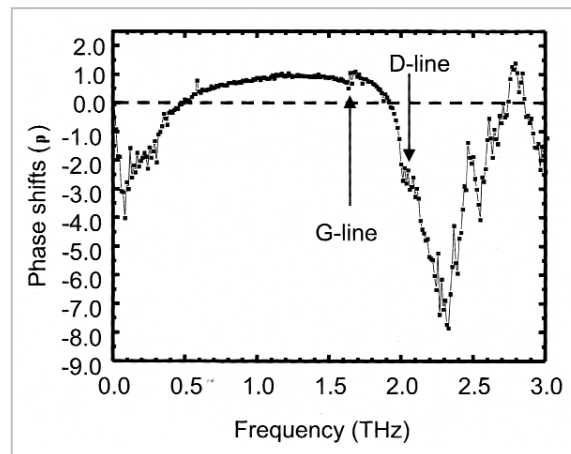


Fig. 15 Phase shift spectrum

output performance is foreseen, if CW oscillation is actually achieved with Ge the laser is guaranteed to take a significant position as the compact, stable tunable terahertz light source.

It is thought that laser oscillation based on any one of the three mechanisms presented in this paper can be applied not only to Ge but also to a single crystal of silicon (Si) that belongs to the same fourth group as Ge. It has been common understanding that because the shallow impurity levels of acceptors in Si are deeper than those of Ge (e.g., 45 meV for Be), complete ionization of the impurity levels is

difficult to achieve, sufficient concentration of free holes cannot be attained, and hence laser oscillation of the Si crystal is more difficult than that of Ge. As mentioned in the paragraph on the efficiency improvement of the IVB-type laser, with the use of Ge, lasers based on impurities having ionization energies of a few tens of meV (e.g., 40 meV for Cu) are becoming possible. In view of this, it is considered that a laser using Si may be feasible. The benefits to be obtained with Si are considered to be as follows: capability of operating at a higher temperature (77K); capability of

operating at a higher frequency than the IVB-type and LHCR-type lasers (about 10 THz); and capability of operating at a higher frequency than the HHCR-type laser (about 1.5 THz).

Conclusion and Acknowledgment

We would like to express our gratitude to Prof. Susumu KOMIYAMA (The University of Tokyo, Graduate school of Arts and Sciences), who kindly offered us advice over a period of many years.

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