Handbook of Laser Technology and Applications
Lasers Design and Laser Systems
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Terahertz Lasers

Publication details
Taiichi Otsuji
Published online on: 24 Jun 2021

Accessed on: 28 Dec 2023

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Terahertz Lasers

Taiichi Otsuji

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50.1 Introduction

Exploitation of the terahertz (THz) electromagnetic resources is the fundamental need to envision real-world future smart society based on innovative information and communication technology (ICT) [1]. However, the THz region is yet to be well explored due to substantial physical limitations for both electron devices such as transistors and photonic devices such as lasers [1] (Figure 50.1). Then therefore, the development of compact, integrated, room-temperature operating novel solid-state THz laser devices is the critical demand for the brighter future society [2]. Among broad aspects and varieties of laser physics and device technology, THz frequency range constraints their applicability due to its low photon energy (on the order of meV to 100 meV) comparable to or rather weaker than the thermal energy at room temperature (~26 meV). Photon emission via interband radiative direct transitions of electrons in general semiconductor materials having bandgap energies above 100 meV does not meet the requirement for the THz lasers. Therefore, the THz lasers utilize the transitions of electrons in various fine structures of the energy bands such as absorption lines of gas molecules in gas lasers like He-Ne [3], CO₂ [4], and HCN [5], subbands where the degenerated states are split by spatial confinements in quantum wells in quantum cascade lasers (QCLs) [6,7], valence bands for heavy/light holes in p-Ge lasers [8–10], and Landau levels split by the application of magnetic fields in Landau lasers [11]. Another limiting factor is a so-called “phonon decoherency.” The coherency of THz photons is easily broken in solid-state materials by the phonon scattering caused by thermally excited lattice vibrations (acoustic phonons) and/or electromagnetically excited lattice vibrations (optical phonons). To cope with this critical limit in the solid-state THz lasers, decrease of the operating temperature is a straightforward way. In fact, most of the currently existing solid-state THz lasers can only operate at cryogenic temperatures whose thermal energies are below the THz photon energies [1]. The THz p-Ge lasers are so-called inter-valence-band (IVB) transition-type THz lasers and exploit the direct transition of holes between the light hole (LH) valence band and the heavy hole (HH) valence band under high electric and magnetic fields to emit rather intense THz photons under cryogenic temperatures below ~20 K [8–10] (Figure 50.2). The THz QCLs are the most successful, industrialized current-injection-type laser devices that could be integrated into a single microchip and serve rather high wall-plug efficiency although still suffering

FIGURE 50.1 Maximum output power of various solid-state oscillators and light sources versus frequency. QCL, Quantum cascade laser; BWO, Backward-wave oscillator; RTD, Resonant tunnelling diode; UTC-PD, Uni-traveling carrier photo-diode; TUNNETT, TUNNElling transit-time diode; IMPATT, 1M Pact ionization avalanche transit-time diode; Gunn, Gunn diode; MMIC, Microwave monolithic integrated circuit. The left wing is the area of electron devices whose frequency response is substantially limited by the electron transit time \( \tau \) and parasitic resistance-capacitance (RC) time constant, resulting in inverse triple power of frequency dependence of the output power. The right wing is the area of photonic laser devices whose frequency response is substantially limited by the phonon decoherency originated from the thermal energy \( k_B T \) (\( k_B \) is the Boltzmann constant and \( T \) is the absolute temperature). There still exists a technological gap in the THz range.
from the phonon decoherency [7,12,13]. The Landau lasers need external magnetic fields to split the degenerated Landau levels [11]. It is performed in THz p-Ge lasers as one lasing mode [9]. Due to their cryogenic temperature operation and the needs of external magnetic field, the physical size and volume of the THz Landau lasers as well as p-Ge lasers are large so that they could not have been well industrialized so far. New trends with graphene-based THz lasers have been recently emerging [11,14–17], and some experimental demonstrations have been reported in the last 3 years [18,19].

Historically, the CO2 gas laser with optical pumping is the most popular among the THz lasers and is operable at room temperature, thanks to the gas nature free from the phonon decoherency so that it is well matured among broad industrial and military applications [20] (Figure 50.3). The CO2 laser needs large physical volumes and consumes high power due to intense optical pumping so that it never be integrated into a tiny chip. On the other hand, free-electron lasers are a different type of THz lasers that does not utilize the interband direct transitions of photon emission but utilize the bunching of accelerated free electrons via periodically modulated resonant electromagnetic fields [21], providing high-energy coherent THz radiation in a gigantic synchrotron radiation system [22–24]. Semiconductor Raman lasers are the other optical-pumping-type THz solid-state lasers that do not utilize the interband transitions of photon emission but the stimulated Raman scattering in non-linear-optic semiconductor crystals [25]. Their quantum efficiencies are quite low (~10^-3), suffering from high pumping threshold intensity and preventing room temperature operation.

In the following subsections, first, fundamental physics and substantial and/or technological constraints are described. Then, the THz QCL is described as the most industrialized current-injection-type compact solid-state THz laser devices in detail. Finally an emerging THz laser device technology based on graphene is described.

**50.2 Fundamental Physics and Constraints**

Laser is the abbreviation of “Light Amplification by Stimulated Emission of Radiation.” The substantial feature of the laser that is never obtained from any natural light sources is the coherency that is attributed to the action of the “stimulated” photon emissions. A pertinent material that gives an optical gain, which is called a gain medium, is prepared first. Its operation mechanism consists of (i) generation of incoherent spontaneous photon emission as a seed of the laser light and (ii) transformation of the incoherent spontaneous emission to the...
coherent stimulated lasing operation. The process is further broken down into the following four steps. First, carriers are optically or electrically excited to make transition from an equilibrated low energy level to an upper energy level. This is called optical or electrical pumping. Second, thanks to the pumping the population of carriers between the adjacent two energy levels that allow the direct transition of electrons becomes “inverted.” That is, the population of carriers at the upper energy level becomes larger than that of the lower energy level. In case of optical pumping, a four-level energy band system is generally utilized to obtain carrier population inversion efficiently. In the four-level system, electrons are first launched from the lowest level (called the ground level) to the highest level (called pumping level) by the pumping (Figure 50.5). The electrons excited to the pumping level are transferred soon to the second highest level (called the upper level) via fast indirect transitions where electrons are stacked for a while to increase their population. The electrons at the upper level recombine with holes at the secondly lower level (called the lower level) via direct transition. The electrons transit to the lower level is then evacuated to the ground level via fast indirect transition. Due to the relatively long life time of electrons at the upper level and the fast transition from the lower level to the ground level the population of electrons between the upper and lower levels can be “inverted” as long as electrons are sufficiently pumped. This is the situation of “carrier population inversion” that is the fundamental condition to enable the lasing operation.

**FIGURE 50.5** A four-level THz laser system. First electrons at the lowest level called “ground level” are optically or electrically pumped to the highest excited level called “pumping level.” The electrons momentarily make fast non-radiative transitions to the second highest level called “upper level.” The life time of electrons at the upper level is relatively long, and the electrons recombine with holes in the next lower level called “lower level” via direct radiative transitions to emit THz photons whose energy coincides with the band-gap between these two levels in a certain rate. The electrons transited to the lower level are momentarily evacuated (depopulated) to the ground level via fast non-radiative transitions. Due to the relatively long life time of electrons at the upper level and the fast transition from the lower level to the ground level the population of electrons between the upper and lower levels can be “inverted” as long as electrons are sufficiently pumped. This is the situation of “carrier population inversion” that is the fundamental condition to enable the lasing operation.

**FIGURE 50.6** Fabry–Perot type laser cavity. Cross-sectional schematic (upper) and its frequency response (lower). THz photons are spontaneously generated from the gain medium inside the cavity. The photons emitted along the cavity direction can travel in a round-trip way between Mirror-1 and Mirror-2 with stimulating photon emission in every round-trip cycle, resulting in amplification of the photons by stimulated emission of radiation, that is the laser action. The lasing coherent photons are output from Mirror-2 having a bit low reflectance $R_2$. The spontaneously generated photons that are not directed along the cavity are spread outside the cavity to stray, resulting in ASE noise factor.
photon emission becomes a noise factor with respect to the main signal part of the coherent stimulated emission, which is called as an amplified spontaneous emission (ASE) noise. The signal-to-noise ratio of the stimulated coherent emission to the spontaneous incoherent emission is determined by the quality factor or the finesse of the laser cavity as well as by the level of carrier population inversion. The ASE noise causes fluctuations of the intensity and frequency of laser signal, giving rise to the fluctuation of laser output power. Thus the ratio of the fluctuation of optical power to the average optical power, which is called as relative intensity noise (RIN), is frequently utilized to characterize the noise performance of the laser.

Due to the broadening of the energy bands including the upper and lower levels originated from the quantum-mechanical uncertainties, the spontaneously emitted photons have a specific spectral width corresponding to the broadening. If no laser cavity is incorporated, the incoherent ASE is only obtained and its spectral width is rather broad. The laser cavity is a fundamental element to obtain the stimulated photon emission enabling the laser operation with spectral narrowing. When the facets of the solid-state laser mesa structure generally having mm’s long are cleaved, they work as high reflectance mirrors. Thus, the main body of the laser structure itself works as a Fabry–Perot cavity. Due to its long cavity size with respect to the THz photon wavelength, multiple higher harmonic frequency resonant modes of the cavity may fall in the optical gain spectral range, resulting in multi-mode lasing. The lasing spectral width becomes narrower dramatically than that for the ASE according to the quality factor, Q, or the finesse, F, of the cavity that is determined by the reflectance of the mirrors, \( R_1 \) and \( R_2 \).

\[
F = \frac{\Delta_{\text{FSR}}}{\delta_{\text{FWHM}}} = \frac{\pi \sqrt{R_1 R_2}}{1 - \sqrt{R_1 R_2}} \tag{50.1}
\]

where \( \Delta_{\text{FSR}} \) is the free spectral range and \( \delta_{\text{FWHM}} \) is the spectral linewidth of each resonant mode in full-width value at a half maximal intensity \([26]\). \( \Delta_{\text{FSR}} \) is the frequency difference between adjacent resonant modes, correspondingly the fundamental resonant mode frequency \( f_0 \),

\[
\Delta_{\text{FSR}} = f_0 = c/2\sqrt{\varepsilon L_c} \tag{50.2}
\]

where \( \varepsilon \) is the dielectric constant of the internal cavity, and \( L_c \) is the cavity length. For simplicity, assuming \( L_c = 1 \) mm, \( \varepsilon = 10 \), and the reflectance of the two mirrors of 0.7 and 0.85, respectively, \( \Delta_{\text{FSR}} = f_0 \sim 47 \) GHz and \( F \sim 10.6 \). Then the spectral line width \( \delta_{\text{FWHM}} \sim 4.5 \) GHz. When the optical gain spectral width is 200 GHz at a central peak frequency of 3,000 THz (3000 GHz), this cavity gives multi-mode lasing at ~2.906, ~2.953, 3.0, 3.047, and 3.094 THz. To obtain a single-mode lasing, the THz laser needs a micro-size cavity whose feature size (electrical length) coincides with the THz photon wavelength of the order of 10s–100s of micrometres.

As is implemented in general laser diodes (LDs) in visible or infrared frequencies, the distributed feedback (DFB) cavity is a practical structure to make the single-mode lasing in THz QCLs \([12]\) (Figure 50.7).

The THz lasers are characterized by various aspects of performances like the quantum efficiency (QE), the wall-plug efficiency, the maximal output radiation power, the threshold injection current, the threshold operating temperature, the spectral purity (spectral linewidth), the RIN, as well as the physical volume. The QE of electrically (current-injection) pumped lasers is defined as the ratio of the emission rate of photons to the pumping rate (injection rate) of electrons, whereas the QE of optically pumped lasers is defined as the ratio of the emission rate of photons to the pumping rate of photons. 100% or unity of the QE is the idealistic lossless case in a single event of the laser action. An electron can be recycled to contribute to make the cascade of photon emissions in case of electrically pumped lasers like QCLs, the total QE is multiplied by the number of the cascade so that it could well exceed “1.” The wall-plug efficiency is the energy conversion efficiency of electrically pumped lasers that is defined as the ratio of the laser output power to the total consumed electric power.

Higher QE as well as higher wall-plug efficiency needs higher optical gain given by higher pumping efficiency and higher level of carrier population inversion. Generally, in case of electrical pumping, the electrons are injected to the upper level (states) for the radiative direct transition of photon emission from much higher initial levels (states) that are not responsible for the direct transitions. The transition from the initial level(s) to the upper level is performed via non-equilibrium electron energy relaxation dynamics associated with acoustic/optical phonon scattering as well as impurity scattering. The probability density of transition between the two states from the initial state to the final state is given by the Fermi’s golden rule in good accuracy \([26]\). If there are other levels (states) near the upper level, the injected electrons may reach these levels (instead of the upper level), which reduce the injection efficiency. Such a stray leakage of undesirable electron transitions to the other

![FIGURE 50.7 A subbands diagram for a QW having a thickness d (left) and a band diagram for a multiple-QW’s superlattices (right) demonstrating an operation of intersubband THz photon emission.](image-url)
surrounding levels (including the lower level) becomes significant in the THz frequency range due to overlapping the electron wave functions among these levels and also due to its weak photon energy comparable to or smaller than the optical phonon energy of the substance as well as the thermal energy. Also, there is non-zero probability of non-radiative transition via phonon and/or plasmon scattering that does not contribute to photon emission. The ratio of the number of electrons successfully reaches the upper level and contributes to the direct transition to the lower level to the number of total injected electrons is defined as the injection efficiency.

Electrons at the upper level recombine with holes at the lower level via direct radiative transitions to emit photons. This process is the normal route to get spontaneous THz photon emission. To constantly keep the photon emission via the direct transition, sufficiently large number of electrons must be injected at the upper level, and at the same time, sufficiently large number of unoccupied vacant states must be preserved at the lower level. This means the electrons recombined with holes at the lower level must be evacuated (depopulated) to the other energy level(s) as fast as possible. Otherwise, the recombined electrons are piled up in the lower level so that the population of electrons at the lower level increases, preventing population inversion. Thus, depopulation of electrons at the lower level is another key to maintain a high level of population inversion.

50.3 THz Quantum Cascade Lasers

As is described in former Fundamental Physics and Constraints section, to obtain the THz spontaneous emission in a solid-state semiconductor material, transitions of electrons in various fine structures of the energy bands. The THz QCL exploits the intersubband direct transition of electrons in QWs where the degenerated states are split into the subbands by its spatial confinement effect (Figure 50.8). For a simplest case with an infinitely deep potential well and a parabolic band dispersion, the subband energies (measured from the bottom of the conduction band) is given by

$$E_n = \frac{n^2 \hbar^2}{2md^2}$$

where $d$ is the thickness of the well and $n$ is the quantum number of the subband level. The THz QCL consists of a cascading stack of intersubband THz laser units based on multiple QW superlattices and incorporates a pertinent laser cavity structure. The intersubband THz laser unit consists of an electron injector section, a spontaneous photon emission section, and an electron depopulation (swept-out) section. The electron depopulation section works as the electron injector section of the successive unit. Such a cascading stack of the laser units emit incoherent THz photons via intersubband transitions of electrons in a cascading manner. Thanks to the laser cavity installed in the QCL, it eventually gives stimulated emission of coherent photon radiation.

The idea for the QCL was first discovered by Kazarinov and Suris in 1971 [27]. When a dc electric field is applied along an $n$-type doped multiple QW superlattices (MQW-SLs) structure so as to align the ground subband level in the $(n-1)$-th MQW-SL to the second subband level in the $n$-th MQW-SL, an electron at the ground subband in the $(n-1)$-th MQW-SL is driven to quantum-mechanically tunnel to the second subband level in the $n$-th MQW-SL, allowing direct

---

**FIGURE 50.8** Concept and principle of operation for the QCL. As cascading waterfalls (upper) cascading quantum-mechanical electron falls (centre) can be configured by using multiple-QW superlattices (MQW-SLs) under application of a dc electric field (lower).
radiative transition to the ground subband level in the $n$-th MQW-SL to emit a THz photon whose energy coincides with the intersubband gap energy (Figure 50.8). Then the electron at the ground subband in the $n$-th MQW-SL is driven to tunnel to the second subband level in the $(n+1)$-th MQW-SL, allowing direct radiative transition to the ground subband level to emit another THz photon again. Such a series of (i) injection of electrons (from the ground subband in the $(n-1)$-th MQW-SL to the second subband in the $n$-th MQW-SL), (ii) intersubband transition to emit THz photons, and (iii) depopulation of the electrons at the ground subband in the $n$-th MQW-SL to the $(n+1)$-th MQW-SL, is taken place $N$ times in a cascading manner over the entire MQW-SL's structure. If the structure includes $N$ cascade of the unit, a single electron can contribute to emit $N$ photons, resulting in dramatically high QE. The QCL operation was first experimentally demonstrated in the mid-IR range using a GaInAs/AlInAs heterostructure material systems by Faist et al. in 1994 [6].

After 8 years passed since the first QCL worked in the mid-IR range, Kohler, Tredicucci, and their colleagues succeeded in the first THz QCL operation using a GaAs/AlGaAs heterostructure material system in 2002 [7]. As is described in former subsections, the weak THz photon energy of the order of 10’s meV comparable to the environmental thermal energy, lattice phonon energy, and uncertainty (broadening) of electron wave function deteriorate the carrier injection efficiency as well as the population inversion due to the phonon decoherency as well as the thermal back filling. Thus, the THz QCLs generally operate at temperatures lower than the phonon-limiting temperatures. The difficulties in carrier injection to the upper level and in carrier depopulation from the lower level have been resolved by introducing novel quantum-mechanical physics with smart superlattices structures. The first operation of THz QCL was performed by introducing a so-called chirped superlattice structure into the carrier depopulation section in which the width of the QWs and barrier layers are designed to be chirped so that the minibands become flat bands under application of an operating fixed dc electric field [7] (Figure 50.9a). In such a situation, the electrons are injected to the ground level of the lowest miniband via longitudinal-optical- (LO-) phonon scattering, making radiative direct transition of THz photon emission to the topmost level of the miniband in the next carrier depopulation section. Then the electrons are depopulated to the ground level of the lower miniband via LO-phonon scattering in a recursive manner. This type of the THz QCLs utilizes LO-phonon scattering to organize the carrier depopulation from the topmost level of the upper minibands to the ground level of the lowest miniband thanks to its ultrafast relaxation rate. However, it is hard to exclusively interact the LO phonons with the electrons in the upper levels of minibands. Thus the electrons in the ground level of the lowest minibands (working as the upper level of direct radiative transition of electrons) are also scattered by the LO phonons, deteriorating the injection efficiency and the level of population inversion. The bound-to-continuum type THz QCL has been then developed in which an independent upper level is prepared just after the chirped superlattices section so as to improve the injection efficiency [28] (Figure 50.9b).

The resonant phonon depopulation (RPD) type THz QCL has been developed to cope with aforementioned LO-phonon issue [29] (Figure 50.9c). The RPD THz QCL introduces a new carrier depopulation mechanism in which a LO-phonon-assisted resonant tunnelling QW section is introduced just after the lower level of the THz photon emission section instead of the chirped superlattice minibands. In the LO-phonon-assisted resonant tunnelling QW, the level of the final state to which electrons transit is designed to be lower by the LO-phonon energy than that of the initial state (the lower level of the prior THz photon emission section). Therefore, the electrons at the initial state are assisted by the LO-phonon scattering to make the quantum-mechanical resonant tunnelling to the final state. In this regard, the electrons approaching the initial state just after radiative transition of THz photon emission can be exclusively depopulated via LO-phonon-assisted resonant tunnelling, resulting in improved higher levels of injection efficiency and population inversion than those for the other types of the THz QCLs. Thanks to the RPD mechanisms, this type of the QCLs demonstrate record-operating threshold temperatures in the wide THz frequency range with rather high output power approaching the level of 100’s mW.

The early stage of the THz QCLs has incorporated Fabry–Perot cavity configured by the QCL mesa with the cleavage facets, resulting in multi-mode lasing (due to its mm-order long cavity length) with rather high output power [7,30]. To obtain a single-mode lasing, DFB cavity has been implemented in various structures [29,31–33]. The other critical limiting factor that strongly attenuates the emitted THz photons in THz QCLs is Drude free-carrier absorptions along the waveguide antenna structure. The Drude optical conductivity $\sigma(\omega)$ of a medium having a density of carrier $n$ is given by

$$\sigma(\omega) = \frac{e^2 n \tau}{(1-i\omega\tau)} + \frac{e^2 n \tau}{1 + \omega^2\tau^2} + i \frac{e^2 n \omega \tau}{1 + \omega^2\tau^2},$$

(50.3)

where $\tau$ is the electron momentum relaxation time. The real part of $\sigma(\omega)$:

$$\text{Re}[\sigma(\omega)] = \frac{e^2 n \tau}{1 + \omega^2\tau^2},$$

(50.4)

gives the loss factor of free-carrier absorption. In general semiconductors, the $\tau$ value stays on the order of 10s of femtoseconds ~sub-picoseconds at temperatures 100–300 K. Thus, in mid-IR or higher frequency range where $\omega \tau \gg 1$, the free-carrier absorption can be well suppressed. On the other hand,
Terahertz frequency range holds optical absorption becomes significant. How to suppress the free-carrier absorption in waveguiding the THz photon to the freespace radiation becomes a critical issue in the THz QCLs.

The standard QCL device structure consists of the active laser mesa on a base semiconductor substrate and the top metal electrode layer. The metal layer works as a high reflectance mirror to the THz radiation whereas the base substrate is made with a semiconductor whose refractive index should be lower than the mesa area in order to confine the THz photon field into the active mesa region of the gain medium, then minimizing the free-carrier absorption loss. However, in reality, the fraction of the reflective indices between the mesa area and the substrate could not be set largely due to material constraint, resulting in poor THz photon field confinement and suffering from the free-carrier absorption loss. To reduce the free-carrier absorption losses, two types of waveguiding structures, the semi-insulating surface plasmon (SISP) waveguide [7,29] and the metal-metal (MM) waveguide [34,35], have been proposed. In the SISP waveguide structure, a heavily doped layer is introduced to the bottom of the mesa that can totally cut off the THz photon field, and the THz photons are attracted to the surface plasmon at the vicinity of the heavily doped layer. The base substrate gets a certain level of penetration of the evanescent modes of THz photons. To minimize the free-carrier absorption in the substrate, a semi-insulating substrate is utilized [29]. On the other hand, the MM waveguide is configured by transferring the mesa structure onto a metal-coated substrate. Then both the top and the bottom surface are covered by metal layers. Thanks to the highly reflectance mirror effect of the metal layers, the THz photon field is completely confined into the mesa area, resulting in dramatic reduction of the waveguide loss [35].

The lasing frequency in the THz QCLs is substantially limited by the LO-phonon Reststrahlen band of the material. The GaAs/AlGaAs material systems are the most popular for use in THz QCLs. Their lasing operation is inhibited at the frequencies between 5 and 12 THz due to the LO-phonon scattering of GaAs-based materials. GaN-based material systems are suffering from the free-carrier absorption loss. To reduce the free-carrier absorption losses, two types of waveguiding structures, the semi-insulating surface plasmon (SISP) waveguide [7,29] and the metal-metal (MM) waveguide [34,35], have been proposed. In the SISP waveguide structure, a heavily doped layer is introduced to the bottom of the mesa that can totally cut off the THz photon field, and the THz photons are attracted to the surface plasmon at the vicinity of the heavily doped layer. The base substrate gets a certain level of penetration of the evanescent modes of THz photons. To minimize the free-carrier absorption in the substrate, a semi-insulating substrate is utilized [29]. On the other hand, the MM waveguide is configured by transferring the mesa structure onto a metal-coated substrate. Then both the top and the bottom surface are covered by metal layers. Thanks to the highly reflectance mirror effect of the metal layers, the THz photon field is completely confined into the mesa area, resulting in dramatic reduction of the waveguide loss [35].

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To date, the THz QCLs have covered the spectral range from 1 to 6 THz. Maximum operating temperature has been aggregated close to 200 K [37]. With regard to output power, a single state-of-the-art THz QCL could provide 1 W peak power in pulsed mode [38] and over 130 mW in CW mode [39] at 10 K heatsink temperature.

Optical parametric oscillation (OPO) [40] and optical rectification (OR) [41] using non-linear susceptibility in non-linear optic materials are other optical-pumping-type principles of THz coherent emission. Different frequency generation (DFG) is one type of OR that serves CW THz radiation [42,43]. When a mid-IR QCL is pumped with dual mid-IR laser lights whose frequency differs by the order of THz, the different frequency component of the incident dual laser beams is generated via OR due to non-linear optic effects of the gain media in the QCL, giving rise to another type of THz QCLs [12,44–47]. It is noted that this DFG THz QCL is not a simple current-injection type but a mixture of optically pumped and current-injection-pumped THz QCL, providing ~2 mW peak power in pulsed operation modes [47] and μW level average power in CW (continuous wave) operation modes [48]. This DFG THz QCL can only serve room-temperature operation and wide frequency tunability among semiconductor laser sources.

### 50.4 Graphene-based THz Lasers

Graphene, a monolayer of sp²-bonded carbon atoms in a honeycomb crystal lattice, has attracted considerable attention due to its unique carrier transport and optical properties since it has been discovered [49]. The conduction band and the valence band of graphene take symmetrical conical shape and contact each other at the K and K’ point (Figure 50.10). Electrons and holes in graphene hold linear dispersion relation with zero bandgap, resulting in extraordinary features like massless relativistic Dirac fermions with back-scattering-free ultrafast transport [50] as well as the negative-dynamic conductivity in the THz spectral range under optical or electrical pumping [13,15,51].

When the intrinsic graphene is optically pumped with a photon energy $\hbar\Omega$, where $\hbar$ is the reduced Planck constant and $\Omega$ is the angular frequency of the photon, interband transitions lead to the generation of “hot” photoelectron-photohole pairs in the distance equal to the photon energy at above and below the Dirac point for the electrons and holes, respectively (Figure 50.11). At room temperature, these photo-excited “hot” electrons and “hot” holes are quasi-equilibrated with the low-energy conduction electrons and valence holes around

![Graphene lattice and band structures](image-url)

**FIGURE 50.10** Graphene lattice and band structures. Graphene is a monolayer sp²-bonded carbonaceous honeycomb lattice crystal. The energy band at the Brillouin zone edge, K and K’ points, takes conical and symmetric linear dispersion for conduction and valence bands touching each other.
the Dirac point at the ultrafast timescale of tens of femtoseconds due to the carrier–carrier scattering resulting in the quasi-Fermi distribution [15,52] (Figure 50.11). As a result, the quasi-Fermi level of electrons and holes split and shift \textit{below} and \textit{above} the Dirac point, respectively. At the same time, the high-energy electrons and holes lose their energy by emitting optical phonons. Thus the quasi-Fermi distribution, which is originally widely spread in the energy space, gets concentrated around the Dirac point. This results in a rapid recovery of the quasi-Fermi level on a picosecond time scale [52]. After the energy relaxation via the optical phonon emissions, the non-equilibrium electrons and holes may lose their energies via the “interband” optical phonon scattering, impurity/disordered scattering, as well as the acoustic phonon scattering, or they recombine. Compared to the aforementioned “intraband” optical phonon scattering, these scattering and recombination processes have much longer relaxation times. Therefore, the non-equilibrium carriers are piled up around the Dirac point if the pumping intensity is sufficiently high. This is the carrier population inversion, in which the quasi-Fermi levels for electrons and holes shift \textit{above} and \textit{below} the Dirac point, respectively (Figure 50.11). The Auger-type three-particle scattering processes are theoretically forbidden in the ideal graphene [53], but they might dominate in the disordered low-quality graphene and/or under an intense pumping leading to significant many-body effects [54]. Thus, the Auger-type scattering is recognized as a killer of the carrier population inversion [55]. However, the carrier population inversion in the THz frequency range has been experimentally observed in prolonged long time more than 1 ps after a rather intense pumping with a high photon energy (~1.5 eV) picosecond laser pulses even at room temperature in high-quality epitaxial graphene [56]. This result encouraged us to explore the creation of the graphene THz lasers/amplifiers.

Optical pumping suffers from a significant heating of the electron-hole plasma suppressing carrier population inversion. However, in case of the optical pumping with sufficiently low photon energies, the electron-hole plasma can be cooled down. Recently a rigorous theoretical modelling and calculation of the Auger scattering rate, including many-body effects of Coulomb interactions, reveal that the Auger scattering is substantially suppressed when carrier temperature is maintained at or below room temperature [57]. In this regard, current injection pumping is the idealistic way to suppress the carrier heating decreasing the pumping threshold because the pumping energy could be of the order of millielectron volts in a graphene p-i-n junctions structure [15,51]. A dual gate p-i-n structure using a dual-gate graphene-channel field-effect transistor (DG-GFET) has been proposed as a simplest current-injection THz graphene laser structure (Figure 50.12) [51]. The gate biasing ($V_g$) controls the injection level, whereas the drain bias ($V_{ds}$) controls the level of population inversion. To minimize the undesired tunneling current lowering the injection efficiency, the distance between the dual gate electrodes should be sufficiently long. The conductivity profiles calculated for the typical dimensions and applied bias conditions demonstrate the advantage of current-injection pumping compared to the optical pumping. The optical conductivity of graphene channel under the gates and drain biases is given by:

\begin{equation}
\sigma_{\omega} = \sigma_{\omega}^{\text{intr}} + \sigma_{\omega}^{\text{inter}},
\end{equation}

\begin{equation}
\sigma_{\omega}^{\text{intr}} = \frac{e^2}{2h} \exp \left( \frac{eV - 2eV_g - V_{ds}}{2k_B T} \right) \sinh \left( \frac{\hbar \omega eV_{ds}}{2k_B T} \right),
\end{equation}

where $\sigma_{\omega}^{\text{intr}}$ and $\sigma_{\omega}^{\text{inter}}$ are the intraband and interband component of the conductivity, respectively; $e$ is the elementary charge; $\varepsilon_F$ is the Fermi energy reflecting the carrier doping level by applying $V_g$; $\tau$ is the carrier momentum relaxation time; $k_B$ is the Boltzmann constant; and $T$ is the temperature [51]. $V_g$ determines the carrier injection level and the corresponding $\varepsilon_F$ , whereas $V_{ds}$ determines the level of the population inversion (the amount of shifting the quasi-Fermi levels of electrons and holes). When the carrier momentum relaxation time is rather long ($\tau = 2.0$ ps) and carrier injection level is pertinent at $V_g = 1.0$ V, an even weak $V_{ds}$ produces a net gain (negative conductivity) in a wide THz frequency range (Figure 50.13a). The situation dramatically changes when the value of $\tau$ becomes short (down to 0.1 ps); in this case, the net gain almost disappears (Figure 50.13b). As a consequence, the high-quality graphene having a picosecond-order value of $\tau$ is mandatory to obtain a net gain in the THz range. It is noted that the maximal available negative conductivity is limited below $e^2/(4\hbar)$ corresponding to the interband absorption coefficient ($\alpha = \pi e^2/(\hbar c) \approx 2.3\%$) of monolayer graphene [50].
Recently the DG-GFETs incorporating a DFB-type internal cavity have been reported demonstrating world-first observation of single-mode lasing from GFETs at 5.2 THz at 100 K [19] (Figure 50.14). The graphene used in the GFETs is non-Bernal-stacked a few layers of high-quality graphene synthesized by the thermal decomposition of a C-face 4H-SiC substrate. The GFET was fabricated using a standard photolithography and a gate stack with a SiN dielectric layer, providing an excellent intrinsic field-effect mobility exceeding 100 000 cm² V⁻¹ s⁻¹ at 300 K. A pair of toothbrush-shaped gate electrode was patterned to form a DFB cavity in which the active gain area and corresponding gain coefficient were spatially and periodically modulated. The THz single-mode lasing was observed at around 5.2 THz with a linewidth of 31 GHz under pertinent complementary DG biases (Vg1 = −Vg2 = ±1.0 V). A different sample with the identical design on the same wafer exhibited an amplified spontaneous broadband emission ranging from 1 to 7.6 THz at 100 K with a maximal emission power of 80 µW. Such a variation stems from a poor THz photon field confinement and resultant weak gain overlapping. Numerical analysis well reproduces such a variation when a wide fraction of the carrier momentum relaxation time of graphene carrier under weak gain overlapping conditions is assumed [19]. Improvement on the gain overlapping by introducing a plasmonic waveguide for dense THz photon field confinement as well as on the cavity quality factor by increasing the number of the DFB periods, and the DFB modulation depth will lead to more intense lasing at higher temperatures approaching 300 K [19].

Introduction of graphene plasmon dynamics is a promising way to dramatically increase the THz net gain and QE of the GFET lasers due to the extremely slow-wave nature (by two orders slower than the speed of light) of the graphene plasmons [58,59]. Once THz photons couple with the graphene plasmons, photons may propagate along the population-inverted graphene as plasmon polaritons having the plasmon velocity so that the interaction between the THz photons and graphene carriers is dramatically enhanced in proportion to the ratio of the speed of photon to that of plasmon, well exceeding the aforementioned quantum-mechanical limit of 2.3% per layer of graphene [60]. A giant gain enhancement of up to 50 times as high as that without graphene plasmons has been experimentally observed in the THz range [61] (Figure 50.15).
Graphene plasmon instability is another promising physics to promote giant amplification. When a dc current flows along the graphene channel in a GFET structure, plasma waves are excited as perturbative collective electron density waves and propagate onto the current flow. Since the electron density is spatially modulated (highest density at the ungated region at the source side, medium and chipped densities under the gate region, and lowest density at the ungated and depleted region at the drain side). This spatial charge density modulation spatially modulates the characteristic impedance. When the plasma wave travels forward to the drain side on the drift flow, its effective velocity is the sum of the plasma velocity $v_d$ and the drift velocity $v_{ds} + v_{dr}$. It approaches the end of the gated region at the drain side, reflecting back to the source side in response to the high impedance boundary (due to the carrier depletion in ungated region at the drain side). The backward plasma wave propagates slowly with its effective velocity $s - v_d$, giving rise to compression of the wave with increase in the charge density $\delta n$, reflecting increase in the gate potential $\delta V_g$ correlated via gate capacitance $C_g$ as $\delta V_g = -e\delta n/C_g$ (Figure 50.16). Since the reflection at the source side end is almost equivalent to the one at the short-terminated end (due to highly dense electron concentration at the ungated region at the source side), preserving the energy and inverting the phase, every round-trip gives an increment of the gate potential $\delta V_g$, resulting in self-oscillation of plasmons at the resonant frequencies with the temporal period equal to the round-trip delay time or its $N$-th division ($N$ is an integer). This is called Dyakonov–Shur instability, a Doppler shift-type instability [62]. Such a spatial charge density modulation also modulates the electron drift velocity spatially in order to preserve the current continuity along the channel. This velocity modulation causes bunching of electrons and plasma waves, giving rise to self-oscillation of plasmons. This is called Ryzhii–Satou–Shur instability, a transit-time-type instability [63]. There are several other types of plasmon instabilities like Cherenkov-type [64] and/or plasmonic-boom-type [65]. The self-oscillation of plasmon instability is a free-running oscillation whose quality factor is given by the quality factor $Q$ of the graphene plasmons which is defined by the ratio of the electron momentum relaxation time to the round-trip delay time. In general, assuming a round-trip delay time of 0.2 ps (corresponding self-oscillation frequency of 5 THz) and a momentum relaxation time of 2 ps (practically obtainable in graphene electrons), the $Q$ becomes 20, giving rise to rather broadband emission. Thus, the emission itself could not serve high coherency, but the emission of the free-running oscillation could work as a mean of amplification of stimulated emission of incoming coherent radiation like an output radiation of a THz DFB-DGGFET laser whose radiation frequency falls in the emission spectral range. This function is equivalent to those in semiconductor laser amplifier as well as optical fibre amplifier in which the spontaneous broadband emission is locked to the injected coherent radiation from a laser, outputting an amplified incoming laser signal. Recently, frequency tunable coherent THz light amplification up to 9% gain at 300 K by current-driven plasmon instabilities produced in GFETs has been experimentally demonstrated [66]. Integration of the graphene THz laser transistor and graphene plasmonic amplifier would be a possible way towards room-temperature operating current-injection pumped intense THz graphene laser device.
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50.5 Conclusions

This chapter described the physics and technology of THz laser devices. First wide variety of THz lasers was overviewed, and their fundamental physics and constraints were discussed. Then attempt was focused on QCLs as currently industrialized current-injection pumping-type integrated solid-state THz lasers. The key technology to enable coherent intense THz lasing is maximizing the electron injection efficiency, minimizing phonon decoherency including thermal back-filling, and minimizing the waveguiding losses. Tremendous efforts have been made improving the operating threshold temperatures as well as output powers, still suffering from the phonon limit of $k_BT$. Study on graphene-based THz lasers has been emerging due to its extraordinary carrier transport and optoelectronic properties. Recent experimental demonstration of single-mode THz lasing even at a low temperature and a weak emission intensity is encouraging the scientific community to proceed further getting steps ahead towards room-temperature intense THz lasing.

REFERENCES


