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REVIEW - ATOMS, MOLECULES AND OPTICS

Prospects of a terahertz free-electron laser for field application

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Abstract

Free electron lasers (FELs) have been highly anticipated as a new light source since they were developed in the 1970s because of their perfect wavelength tunability and high power potential. Various types of FELs have been developed over a wide range of wavelengths from mm waves to X-rays, and many technological advances have been made for devices and applications. In particular, X-ray free-electron lasers (XFELs), the fourth-generation synchrotron, have made a great contribution to the deep understanding of matter and nature. However, there have been relatively few advancements in industrial technology using FELs; for example, an FEL has not yet been directly used in the field. High-power light sources in the terahertz (THz) wavelength range are in high demand in industry and the field but have not been properly developed. The FEL is the most powerful light source in the THz range, and although the size of these FELs is still large, they have the spectral range with the greatest potential for industrial or field applications. This study examines the potential of compact THz FEL technology to meet market needs. The current status of various elements of the FEL is reviewed, and the prospects of a possible FEL system are described by combining these elements. An FEL system with an average power of 1 W operating in the THz center wavelength range of 300–600 μm is expected to be realized in an FEL with a size of 1.5 m × 2 m.

Keywords Free-electron laser · Microtron · Terahertz · Compact FEL · THz FEL · Waveguide-mode FEL · Undulator

1 Introduction

Free electron lasers (FELs) convert the kinetic energy of a relativistic electron beam into light energy by using a periodic magnetic field structure called an undulator [1–4], which can, in principle, generate light of any wavelength. Because the gain medium of the FEL is a high-energy electron beam, there is no limit to the output resulting from the deterioration of the medium, which is advantageous for generating ultra-high power. However, FELs require electron accelerators, which are generally large, costly to develop, and technically complex. During the Cold War, both the United States and the Soviet Union chose the free-electron laser as the optimal laser weapon to shoot down opposing intercontinental ballistic missiles. However, few attempts have been made to develop a new FEL in the wavelength range at which conventional lasers operate. Until now, FELs have been mainly developed, and play a role, in the terahertz (THz) and X-ray ranges, where conventional lasers cannot emit light efficiently [5–14]. In this spectral range, FELs are the most powerful and superior light sources.

The early history of FEL development begins with vacuum electronics for radio-frequency (RF) generators. This technology, which uses an electron beam in a vacuum to generate high-power RF waves, developed rapidly during World War II. In the 1950s, Motz et al. conducted research on the generation of radiation by injecting fast electrons of MeV-class energy into an undulator [15, 16]. However, with the development of semiconductors, vacuum electronic device technology has lost its development momentum. The laser was first developed in the early 1960s, and since then, remarkable technological advances have been made. Madey et al. published the results of an FEL developed in the form of an amplifier in 1976, and the following year, they first announced the results of an oscillator-type FEL under the title of "First Operation of a Free-Electron Laser" [17, 18].

After these developments, FELs using various types of accelerators in a very wide spectral range, from millimeter waves to X-rays, were created. FELs with short-wavelength

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ranges of visible and ultraviolet (UV) have been developed using storage-ring accelerators, and infrared (IR) or far-infrared (FIR) FELs have been developed using linear accelerators (LINACs); numerous application research results have been produced with FEL user facilities [19]. Although storage-ring FELs challenge shorter-wavelength lasing, the first X-ray FEL (XFEL) was realized using a LINAC [12]. XFELs serve as fourth-generation radiation sources [12–14] and are state-of-the-art tools for studying materials with intense coherent X-ray pulses with femtosecond duration. The emergence of XFELs coincides with the declining diversity of FELs. For example, in Japan, many FELs using various types of accelerators were actively developed in the 1980s; however, the number of FEL devices in operation has recently decreased sharply, and hardly any additional development plans are being announced. This trend is considered to be due to the large device size and high cost of FELs and means that FELs do not have economic feasibility in terms of photon cost. Nevertheless, plans have been made to utilize large, high-power FEL devices for industrial or military purposes, which include a plan to develop an FEL as a future EUV light source for semiconductor production [20].

Among all electromagnetic waves, the THz waveband has a relatively high photon cost. Most light sources still have a weak output power in the center wavelength range of 1–3 THz, or conversely, accelerator-based THz sources are too large. While a high demand exists for new technologies, such as security inspection, medical imaging, and remote monitoring devices using THz waves, THz sources that meet the needs of the market have not yet been developed. The FEL is the most powerful light source in the THz wavelength range. If the output is more than 1 W, it can be used for real-time imaging or remote sensing in the field [21]. An FEL device with a moderate output power (~ 1 W) can be realized with a rack size and can be used for applications in the field.

In this study, we focus on the problem of developing small-scale FELs in the terahertz wave range. First, the operation principle of the FEL and the development history of compact THz FELs are briefly reviewed. Through this, accelerators, undulators, and waveguide-mode resonators suitable for small-scale FELs are compared and analyzed. Finally, this paper is concluded by introducing the concept behind and prospects for a compact THz FEL device that can be constructed in the near future.

2 Basic principles of an FEL

As shown schematically in Fig. 1, the FEL is a device that converts the kinetic energy of an electron beam into light energy. If energy is to be transferred from the electron beam to the electromagnetic wave, the electrons should have a velocity component parallel to the electric field of the electromagnetic wave. A device with an alternating magnetic field, called an undulator or wiggler, causes the electron beam to oscillate perpendicular to the direction of travel. As shown in Fig. 2, when a high-energy electron beam supplied from an electron accelerator passes through a magnetic field designed to alternately change in polarity, it oscillates in a plane perpendicular to the magnetic field due to the Lorentz force. Most undulators are made with an alternating magnetic-field period (λ_w) of several cm, and the total length is usually a few m. Electrons moving along a curved trajectory in an undulator emit light; when an electron moves

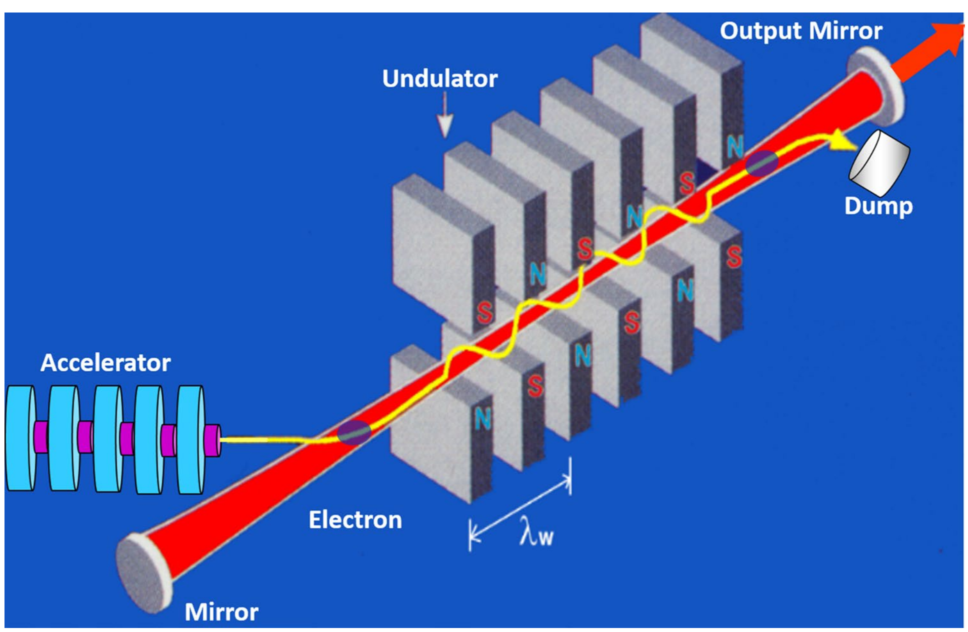


Fig. 1 Schematic of a free-electron laser oscillator consisting of an electron accelerator, undulator, and optical resonator

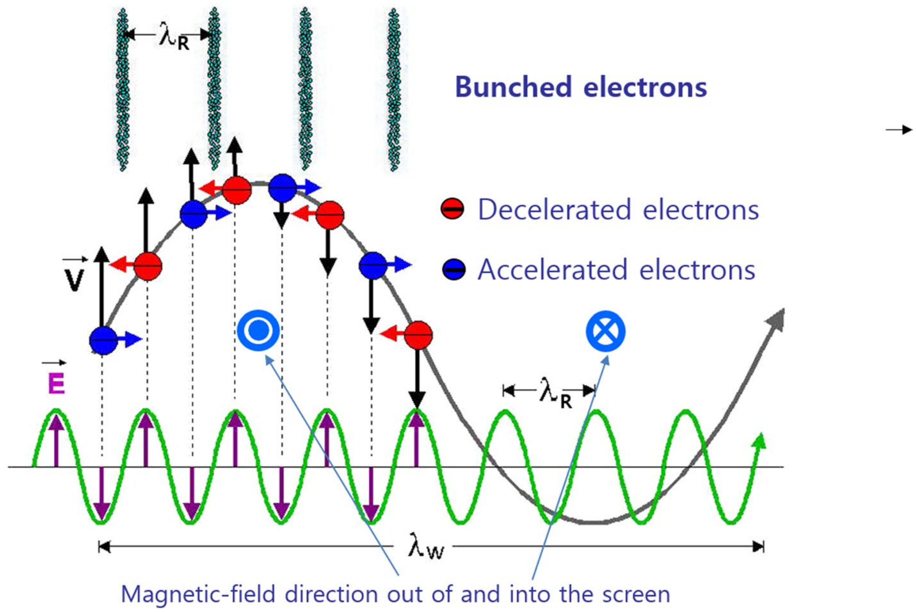


Fig. 2 Schematic diagram explaining the process of bunching an electron beam through interaction with the undulator magnetic field and electromagnetic wave

at a speed close to that of light, the light is focused in the direction of the electron beam. In addition, the wavelength of the emitted undulator radiation (λ_R) satisfies,

$$\lambda_R \cong \frac{\lambda_w}{2\gamma^2}\left(1+\frac{K^2}{2}\right), \tag{1}$$

where γ is Lorentz factor and K ($\cong 0.934 B_w \lambda_w$) is the undulator deflection parameter (B_w is the on-axis peak magnetic-field strength of the undulator). Moreover, the emitted undulator radiation has maximum power owing to the resonance of the phases between the electromagnetic wave and the wiggling electron. For example, an electron beam with an energy of 100 MeV has a γ-value of approximately 200, and the wavelength of the undulator radiation is approximately 500 nm with an undulator period of 2 cm. As seen from the resonance condition, if the energy of the electron beam is sufficiently high, it can produce radiation with a short wavelength such as the wavelength of X-rays.

In an FEL, undulator radiation is amplified by the periodic bunching of the electron beam due to the interaction of electromagnetic waves in the undulator. When the electron beam is incident on the undulator, the initial spatial distribution of the electron beam is close to uniform, and the phase of the undulator radiation emitted from the electrons on each curved trajectory is arbitrary. In this case, the output power of the radiation is the arithmetic sum of the light emitted by individual electrons. However, the electron beam periodically gathers in a very small space owing to the resonant interaction between the electron beam and the radiation while it propagates through the undulator's magnetic field; accordingly, the radiation power becomes proportional to the square of the number of electrons. The radiation power generated from the bunched electron beam is much higher than that generated from a uniformly distributed electron beam. If the electric-field strength and phase of the electromagnetic wave generated from an electron passing through the undulator are A and φ_k, respectively, the total power of the radiation generated from N_e electrons is as follows:

$$P = \left|\sum_{k=1}^{N_e} A e^{i\varphi_k}\right|^2. \tag{2}$$

When the electron beam is not bunched, as shown in the upper part of Fig. 3, the phase of the radiation emitted from each electron is random; therefore, the total radiation power is proportional to the number of electrons, which corresponds to the spontaneous emission power P_{SE} of the FEL:

$$P_{SE} = \left|\sum_{k=1}^{N_e} A e^{i\varphi_k}\right|^2 = A^2\left|\sum_{k=1}^{N_e} e^{i\varphi_k}\right|^2 \approx A^2 N_e. \tag{3}$$

However, if the electron beam is well bunched, as shown in the lower part of Fig. 3 and the period of the bunches is the same as the radiation wavelength, the phase of the radiation emitted from each electron is the same; therefore, radiation output is proportional to the square of the number of electrons, which corresponds to the lasing power P_{FEL} of the FEL:

$$P_{FEL} = \left|\sum_{k=1}^{N_e} A e^{i\varphi_k}\right|^2 = A^2\left|\sum_{k=1}^{N_e} e^{i\varphi_0}\right|^2 \approx A^2 N_e^2. \tag{4}$$

The ratio of power enhancement in the FEL is closely related to the number of electrons satisfying the coherent

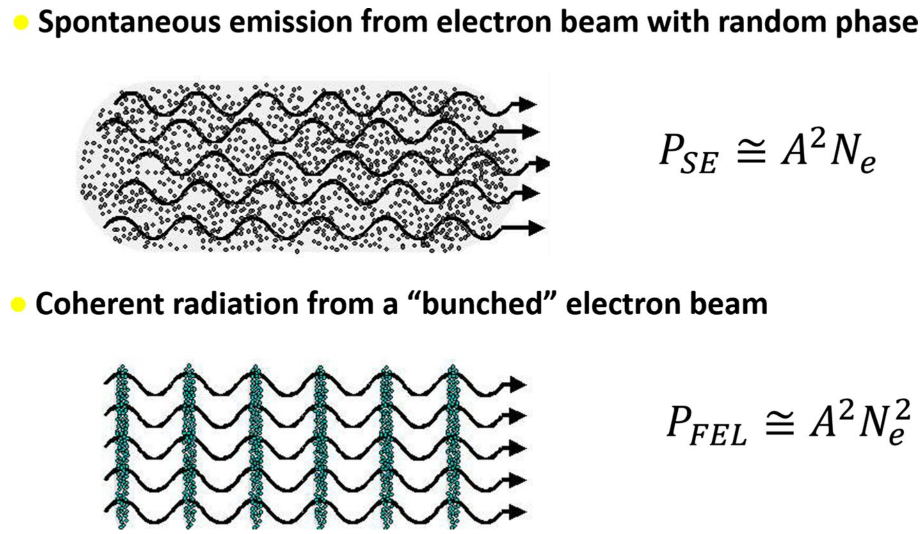


Fig. 3 Schematic explaining the output power of spontaneous emission emitted in random phases from electrons (upper part), and coherently enhanced FEL radiation from a bunched electron beam, where the FEL power is stronger than the spontaneous emission power by approximately the number of electrons (lower part)

condition owing to the bunching process. Electrons are negatively charged particles; therefore, when they are gathered in a small space, they exert a strong repelling force. Because of this repulsive force, the bunching process reaches its limit, and in the start-up process of lasing, the FEL power reaches saturation after while the power no longer increases. In general, FEL oscillators operating in the pulse mode exhibit excellent spatial and temporal coherence. In XFELs, which are typical FEL amplifiers, the spatial coherence of the radiation is excellent while its temporal coherence is not very good.

3 Sub-systems for compact THz FELs

3.1 Accelerator

As seen in Eq. (1), the electron beam energy required for FEL lasing in the vicinity of 300 µm, which is the terahertz center wavelength, is approximately 3–5 MeV. If this level of electron beam energy is to be generated, a large-scale electrostatic accelerator is required; therefore, a small-scale THz FEL using an electrostatic accelerator is very difficult. However, this energy range can be obtained with a small RF accelerator. When the accelerator size, economic feasibility, and the electron beam current required for FEL oscillation are considered, the most common S-band RF accelerator is an appropriate choice for a compact THz FEL for field applications.

Many S-band RF accelerator-based FELs are composed of DC thermionic guns and LINACs [22, 23]. The accelerators are used in conjunction with the prebuncher cavity or buncher cavity to shorten the electron beam pulses produced by the thermionic gun. The FELs using these accelerators can generate stable, high-output laser beams in the infrared and the THz ranges; however, the FELs are complicated and large. Some of them have been operated as user facilities [19]. The Compact Advanced Terahertz Source (FEL-CATS) at the ENEA laboratories in Frascati, Italy, is a device modified from this configuration to realize a small-scale THz FEL [24–26]. In this FEL, a pulsed electron beam with a duration of 5–10 µs from a DC thermionic triode gun is directly incident on an S-band LINAC, producing a ~ 3-MeV electron beam modulated by the RF wave. An optimal coherent enhancement condition for the undulator radiation is obtained using a phase-matching device (PMD). This accelerator is a highly compact device with a length of ~ 1 m, and the overall size of the FEL is merely 2.4 m.

Recently, plans have been made to develop THz FELs using S-band RF guns [27–30]. RF guns can directly generate a bright electron beam with the energy required for THz generation without additional accelerating cavities. An electron beam with a relatively wide energy spread is extracted when a thermionic cathode is used for the RF gun. The energy spread of the electron beam should be reduced with a dogleg-type beamline or alpha-shaped magnet for FEL lasing, which increases the overall size of the FEL device. An FEL based on a photoelectron RF gun requires an ultrashort-pulse laser system and additional components such as a harmonic generator that converts the laser wavelength into UV and a device for synchronizing the repetition rate of the laser pulse and the RF phase. If the FEL is to be operated as an amplifier, a magnetic chicane is necessary to further compress the electron beam and, hence, obtain a high peak current [31]. The reader should note that the size of an RF-gun-based FEL is not small and that the configuration of the subsystem is complex.

The microtron is a circular RF accelerator. The classical microtron has a very simple structure with a single-cell accelerating cavity equipped with a thermionic RF gun inside both a dipole magnet that generates a uniform magnetic field and an extraction tube that extracts the electron beam by shielding the magnetic field, as shown in Fig. 4. The energy of the electron beam is sequentially increased as it repeatedly passes through the RF cavity. The kinetic energy of the electrons obtained while passing through the accelerating cavity depends on the strength of the magnetic field; it is commonly approximated as the rest mass of the electron, ~ 0.5 MeV. In this case, an electron beam with an energy of 3–5 MeV can be obtained with 5–10 turns, and the outer diameter of the entire microtron accelerator can be as small as 50–60 cm. The biggest advantage of the microtron accelerator is that it can use a magnetron as an RF generator. Compared to a klystron-based RF system composed of an RF master oscillator, a solid-state RF amplifier, and a klystron amplifier, the magnetron is a simple high-power oscillator with a very small size. In addition, the pulse modulator, which is the driving power supply, has a much lower voltage (~ 50 kV) compared to that of a klystron system (~ 150 kV); therefore, a magnetron can be made small and at a low price. A downside of the magnetron is that the RF frequency is not stable.

The RF frequency must be an integer multiple of the frequency at which light travels back and forth in the FEL resonator; that is, the RF frequency must be stable within a certain range. The frequency of the magnetron is determined by the Q value of the magnetron cavity and the magnitude of the current and the voltage of the modulator. When other variables are constant, the frequency depends directly on the current in the modulator. For this study, the dependence of the magnetron's frequency on the current was 200–300 kHz/A, and the frequency change in the THz FEL had to be stable within approximately 200 kHz to maintain FEL lasing during a macropulse with a duration of ~ 5 μs. If a modulator pulse waveform with a constant current value is used, the RF pulse with a stable frequency can be obtained from

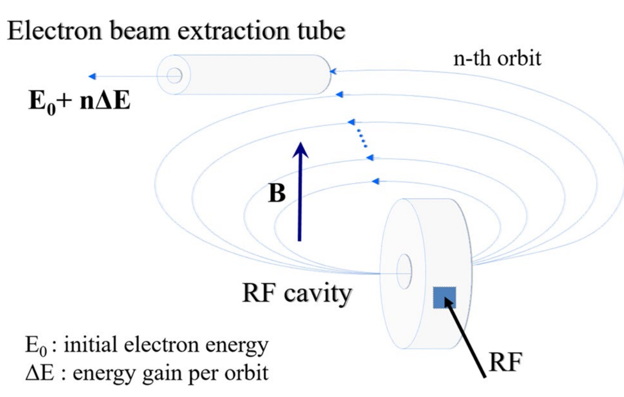


Fig. 4 Schematic layouts of a classical microtron having an RF cavity and extraction tube in a uniform magnetic field

the magnetron. However, in a thermionic RF gun, electrons that do not satisfy the RF phase for acceleration within the macropulse return to the cathode and heat it due to back bombarding. The temperature of the cathode gradually increases, which causes the emission current to continuously increase within the electron macropulse. Because this continuously increasing emission current within the macropulse results in additional cavity loading, the accelerating current decreases during the macropulse. As a way to compensate for the electron beam's decreasing accelerating current, the output power of the RF pulse should be increased by approximately 9% during the macropulse [32]. In other words, pulse shaping should be performed artificially so that the modulator pulse current has a slope that increases by ~ 10 A during the pulse. This driving method is the same for LINACs using thermionic RF guns. As a result, the frequency of the RF pulse changes to approximately 1 MHz within the macropulse; therefore, FEL oscillation cannot be sustained.

A method of solving this problem without an additional RF component was found. When the RF pulse with a stable frequency is injected into the magnetron from the outside, the high-power RF pulse of that frequency is amplified with the seeding frequency. This is known as the frequency-pulling effect. The required RF pulse power was approximately 2 MW. In general, a power of 100 kW or more is necessary to effectively cause the frequency-pulling effect. If an additional master oscillator and RF power amplifier such as klystron are used, the device becomes complex and increases in size and price. In this study, part of the RF pulse reflected from the microtron RF cavity was allowed to return to the magnetron without using an additional RF generator. The Q-value of the microtron cavity was approximately 10^4, which is approximately 10 times larger than that of the magnetron cavity. In other words, it had a narrow resonance width of ~ 100 kHz. In general, the RF pulse generated by the magnetron passes a circulator or Faraday isolator so that the return rate is 10^{-4} or less. However, approximately 10% of the reflected RF pulse was allowed to reach the magnetron in this study. A schematic diagram of the RF system is shown in Fig. 5. By stabilizing the temperature of the RF cavity at 0.1 °C, the resonance frequency change was stabilized within several kHz. The attempt to couple the magnetron with the microtron RF cavity was successful. When the magnetron was connected to a passive-matched load, the frequency change during the macropulse was approximately 700 kHz. However, when operated while coupled with the microtron RF cavity, the maximum change value was reduced to 200 kHz [33]. When the RF power of the magnetron is increased to enhance the returning RF power, the frequency change could be reduced to within 50 kHz [33]. In other words, a stabilization condition that maintained the

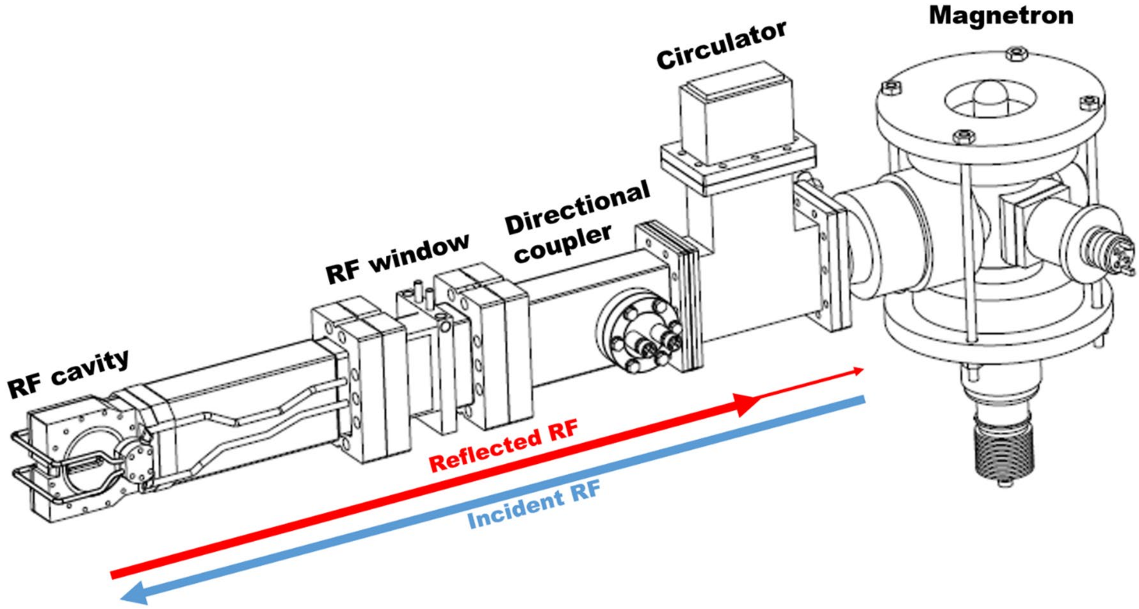


Fig. 5 Schematic of the RF system from the magnetron to the RF accelerating cavity of a microtron. The arrow indicates the direction of flow for the reflected RF wave and its thickness shows approximately the relative strength of the RF wave

FEL oscillation by only using an isolator with poor performance is possible. The microtron generated a high-quality electron beam suitable for FEL oscillation with a low energy spread and emittance.

3.2 Undulator

Permanent magnet (PM) undulators generally have a stronger magnetic field than electromagnetic (EM) undulators. The magnetic field strength is controlled by mechanically varying the gap between the PM undulators to change the radiation wavelength. Usually, the mechanical structure controlling the gap is large and complex; hence, this type of undulator is difficult to use in a compact THz FEL. An alternative is to use a method that varies the period without adjusting the magnetic field strength [34, 35]. For a planar structure, this method was first proposed by Vinokurov et al. [34]. A structure that controls the period in a helical PM undulator was devised and demonstrated [35]. However, using the undulator directly in an FEL is difficult because further technical improvements, such as removing the residual magnetic field, are still needed.

EM undulators have the advantage of high magnetic-field precision and the magnetic field strength can be easily adjusted by applying current. However, the magnetic field strength is relatively low. There is a hybrid-type PM-assisted EM undulator that simultaneously constructs a strong magnetic field strength and has the capacity to easily adjust the magnetic field strength. This undulator was first proposed by Halbach in 1986 [36]. Subsequently, this undulator was developed by optimizing the magnetic structure and was then applied to a THz FEL for the first time [37]. The basic operating principle of this structure is shown in Fig. 6, and the conceptual structures of the EM, hybrid PM, and hybrid EM undulators are shown in Fig. 6a–c, respectively. The role of the PMs in the hybrid EM undulator is to eliminate the magnetization saturation in the iron poles of the undulator, which is caused by the strong electromagnetic field. The effective magnetic flux in the iron poles is very low because the field generated by the PMs is in the direction opposite that generated by the EM. The permeability of pure iron is maintained at a high value, such that the magnetic field produced by the EM undulator can be effectively transmitted to the undulator gap. In case (a), without a PM, a strong magnetic field cannot be transmitted to the undulator gap owing to the magnetic saturation in the iron poles. In the hybrid EM undulator shown in Fig. 6c, a strong magnetic field strength can be obtained and controlled by adjusting the current applied to the EM undulator. A coil that needs to pass a high current of more than 1 kA must have a channel containing cooling water and its cross-sectional area can be as large as several cm^2. Installing the bent coil in a zigzag shape is impossible because the undulator period is only 2–3 cm. To solve this problem, Halbach proposed the structure shown in Fig. 7. If the iron poles are periodically tilted to face each other according to the magnetic field direction, thick coils can be installed in a straight line. Figure 8 shows the cross-sectional shape of the hybrid EM undulator. In this structure, a periodic magnetic field distribution can be realized even with straight coils. As described above, the PMs

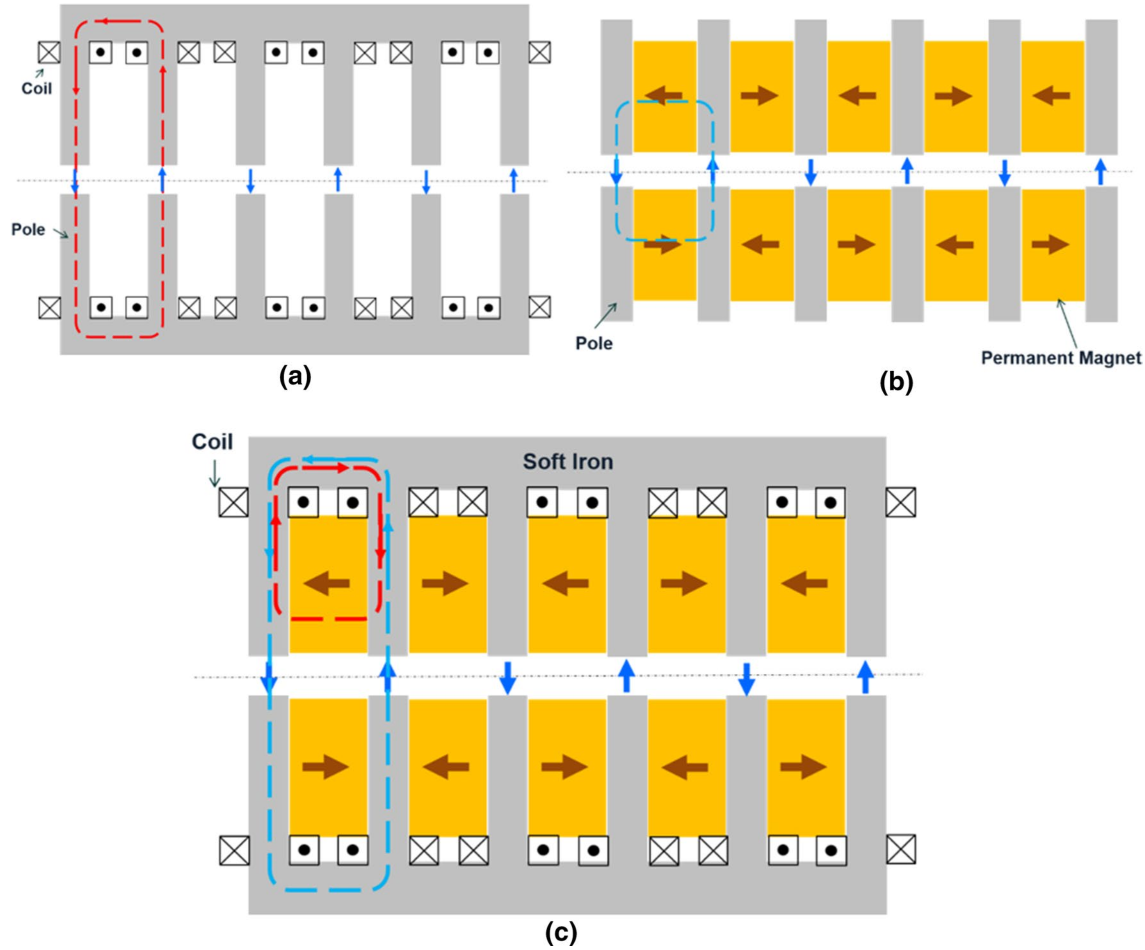
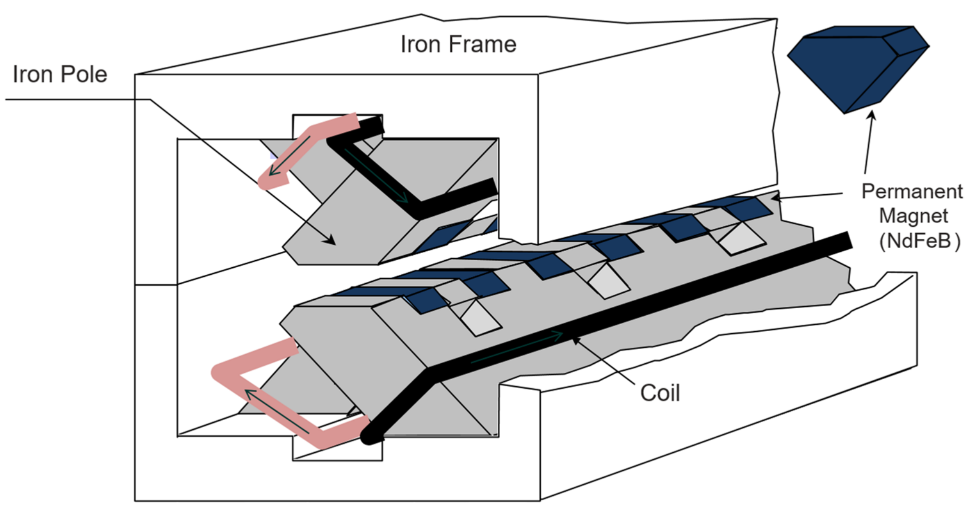


Fig. 6 (**a**) Layout of an EM undulator, (**b**) hybrid PM undulator, and (**c**) hybrid EM undulator by combining the EM and the hybrid PM undulators

Fig. 7 Schematic of a hybrid EM undulator consisting of two pairs of poles facing each other periodically with PMs between them



between the iron poles cancel the magnetic saturation in the iron pole and effectively transfer the magnetic field generated by the strong current to the undulator gap. An undulator with a strong magnetic field strength of up to 6.8 kG and a wide variable range of 40% was successfully developed. The undulator had a precise magnetic field distribution and

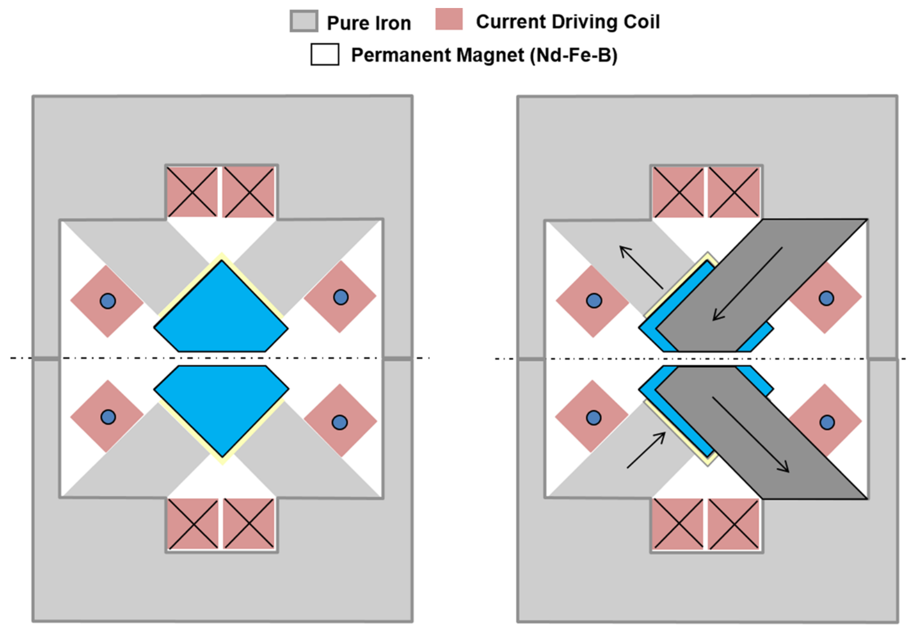


Fig. 8 Schematic showing a cross-sectional view of the hybrid EM undulator at (**a**) a PM and at (**b**) a pole

was much cheaper than hybrid PM undulators because of its simple structure and easy fabrication.

3.3 Waveguide-mode oscillator

The small-signal gain of the FEL is inversely proportional to the effective cross-sectional area of the radiation mode in the resonator [38]. The power density or electric field strength must be increased to increase the interaction between the electron beam and the radiation. That is, if the cross-sectional area of the mode is reduced under the same conditions, the interaction increases, and lasing can be performed more effectively. In the case of long-wavelength radiation such as waves in the THz range, the cross-sectional area of the free-space mode is large owing to the diffraction limit. The cross-sectional area of Gaussian-mode radiation with a wavelength of ~ 300 μm is approximately 300 mm^2 at full width at half maximum (FWHM) for a 1-m-long resonator. A common method of reducing the mode cross-section is to use a waveguide. If a planar undulator is used, a rectangular waveguide or parallel-plate waveguide capable of TE-mode excitation can be utilized as FEL resonator. A rectangular waveguide FEL uses the TE_{01} mode. Because the mode is uniformly distributed in the longitudinal direction of the cross-section, the mode cross-section is not localized at the center. Moreover, a relatively large value of mode loss occurring in the wall of the waveguide in the vertical direction is a disadvantage. As the mode cross-sectional area decreases, the loss increases rapidly. Even with a cross-sectional area of ~ 10 mm^2, a loss of more than 10% occurs in a 1-m-long waveguide. As a solution to this problem, a one-dimensional (1-D) parallel-plate waveguide composed of two parallel metal plates was used for the THz FEL [39]. In this case, under the same conditions, the mode cross-sectional area increased slightly to 15 mm^2; however, the loss was almost negligible. In the case of a two-dimensional (2-D) waveguide, the mode cross-sectional area is determined regardless of the wavelength; however, as the wavelength increases in a 1-D waveguide, the cross-sectional area increases in proportion to the square root of the wavelength, $\lambda^{1/2}$.

A waveguide with a small mode cross-section and low waveguide loss is a key technology for developing a compact THz FEL. In principle, if a waveguide with a very small cross-sectional area and low waveguide loss is developed, the size of the FEL resonator can be significantly reduced. A small cross-sectional waveguide with a low loss is one of the most important elements for reducing the size of the THz FEL. A new waveguide structure was recently devised whose waveguide cross-section resembles that of a human eye. In this structure, the TE mode is localized at the center of the waveguide, and the electric field strength is very low at the walls of the waveguide. A small cross-sectional area of ~ 4 mm^2 was realized in the optimized structure of the eye-shaped waveguide, and it was confirmed that the waveguide was found to have a loss as low as 2.5% at a length of 1 m through an electromagnetic wave simulation.

4 Table-top THz FEL for security inspection

Thus far, the possibility of FEL as a high-output THz generator that can be used in the field has been examined, focusing on key components. In particular, developing a small THz

FEL that is easily manufactured and is economically feasible from the point of view of the entire system is technically very difficult. For this reason, historically, few examples have come close to this requirement. The aforementioned FEL-CATS is a device capable of generating a high-power THz pulse with a length of ~ 2 m, excluding the RF system and modulator. This device is not a typical FEL oscillator that uses coherent undulator radiation from the harmonics component of the RF pulse. Because no mirrors or bending magnets are present in the FEL oscillator, a simpler configuration is achieved. Overall, the conversion efficiency of an electron beam to light is not very low, approximately 0.3%. The radiation of various frequencies corresponding to RF harmonics is generated simultaneously, and the power instability of coherent undulator radiation is considered to be a disadvantage. However, this device can generate THz radiation in the form of a frequency comb, and if developed as an energy recovery type system, a high-power continuous wave (CW) operation is also possible. In the field of science and technology, it has great potential as a new type of high-power THz light source. A device with a similar structure that, instead, uses an RF photoelectron gun and a chicane compressor is being developed at Kyoto University [31]. This uses coherent radiation in the THz range, which is generated when a bunched electron beam with a high-peak current passes through the undulator. It is a very useful tool for time-resolved pump and probe research using THz, IR, and UV light.

An oscillator-type FEL is more suitable for generating laser light with a stable output and tunable wavelength. We devised an FEL using a mesh mirror as an out-coupling mirror downstream of the undulator, which allows most electrons to be directly injected into the undulator without additional bending magnets. The electron beam's transmittance in the mesh mirror is approximately 90%. The THz output generated through the mesh mirror is emitted at a holed mirror through which the electron beam passes. In the upstream undulator, a metallic water-cooled mirror plays the role of an electron beam dump and the oscillator's full mirror at the same time. This is possible because the power of the electron beam in the microtron accelerator is not high. The average electron beam power of the microtron accelerator is just 100 W, which is 1/10 that of a typical LINAC. The method in which the electron beam is incident on the FEL oscillator without bending magnets significantly contributes to simplifying the overall structure and reducing the size. In general, an RF system and its related components account for a large amount of the cost of an accelerator. The magnetron-based microtron accelerator, which is small and inexpensive, is one of the best drivers for compact THz FELs and has notable advantages for field use.

Various types of undulators were developed and checked for compatibility with compact THz FELs. Among them, a hybrid PM undulator was selected for the FEL; this undulator was designed and manufactured with a length of 1 m. Important technological advances that have contributed to reducing the size of the FEL are the design of the eye-shaped waveguide. Although the FEL is small, the energy conversion efficiency of the FEL light from the electron beam can be approximately 1%, which is more than 10 times that of the existing laboratory-scale THz FEL. This is achieved by widening the FEL linewidth and reducing the loss in the resonator. According to recently reported results, the FEL efficiency can be increased by more than 5% by using the dynamic cavity desynchronization method, which adjusts the RF frequency within the macropulse [40, 41]. A new pulse modulator was developed that can freely shape the magnetron's frequency and power. Overall, the energy conversion efficiency of the FEL is hoped to increase, and the average FEL output power is expected to be more than 1 W. With this level of output, a THz scanning image of a person's whole body can be obtained within a few seconds. The target size of the FEL under development is 1.5 m × 2.0 m, including the high-voltage pulse modulator, as shown in Fig. 9.

5 Conclusion

FELs were first developed in the mid-1970s and have made significant progress since; however, their use has been limited to research and development. The main obstacle is the large volume and high cost of the FEL, yet reducing the device size to a portable level does not seem technically feasible. However, if this scale is achieved, it can be used as a THz full-body scanner at airports, ports, and public facilities. This requires innovation and an appropriate combination of

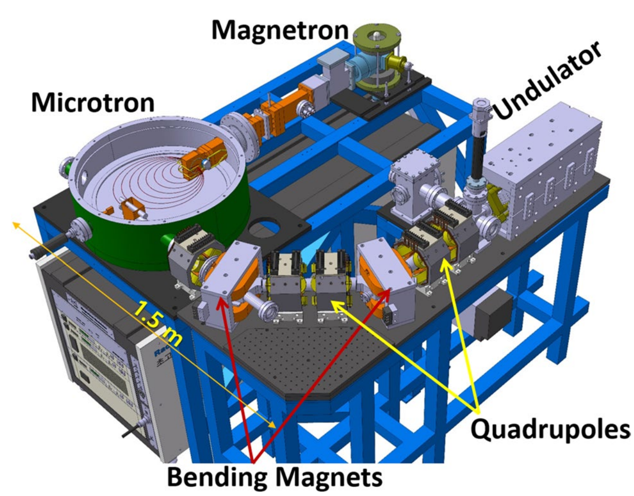


Fig. 9 Table-top THz FEL consists of a microtron accelerator using a magnetron, two 45° bending magnets, five quadrupole magnets, and a hybrid EM undulator. It has a size of 1.5 × 2.0 m[2a]

various technologies. The conclusion obtained through long-term research on a compact THz FEL is that a structure using a small microtron accelerator driven by a magnetron, a hybrid PM undulator with a length of ~ 50 cm, and a wave-guide-mode resonator is required. Small bending magnets and quadrupole magnets, which use both PMs and EMs, are planned for use to reduce the individual size and overall length. Through these efforts, the goal is to make an FEL with a size of approximately 1.5 m × 2.0 m, excluding the control rack. This device uses a coherent THz beam with an average power of ~ 1 W and a tunable wavelength from 300 to 600 μm to acquire real-time security images. Because this FEL can select the optimal transmitted wavelength in the atmosphere, it can be used for the long-distance detection of drones.

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