Invited Paper

Progress of terahertz vacuum electronic radiation sources

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Abstract: Terahertz wave is located between microwave millimeter waves and light waves, which has unique characteristics, such as good transmissivity, security. The terahertz waves can be widely used in many fields, such as military and civil areas. In many applications, the high performances of terahertz sources are the keys points. Various sources can generate THz waves, optics, semiconductors and vacuum electron devices (VEDs). Among the three types of THz sources, VEDs with the characteristics of high power and high efficiency is highlighted and focused. In this paper, the progress of VEDs is introduced, and some developing trends are described.

Keywords: Terahertz waves, Traveling wave tube, Backward wave oscillator, Gyrotron, Free electron laser

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1. Introduction

Terahertz (1 $THz=10^{12}$ Hz) wave [1], [2] refers to the electromagnetic wave with a frequency of 0.1~10 *THz*, located between microwave millimeter wave and light wave, and in the transition area from macro-electronics to micro photonics. Early terahertz has different names in different fields. It is called far infrared in the field of optics, and submillimeter wave in the field of electronics [3]. Its position in the electromagnetic spectrum is shown in Fig. 1.1

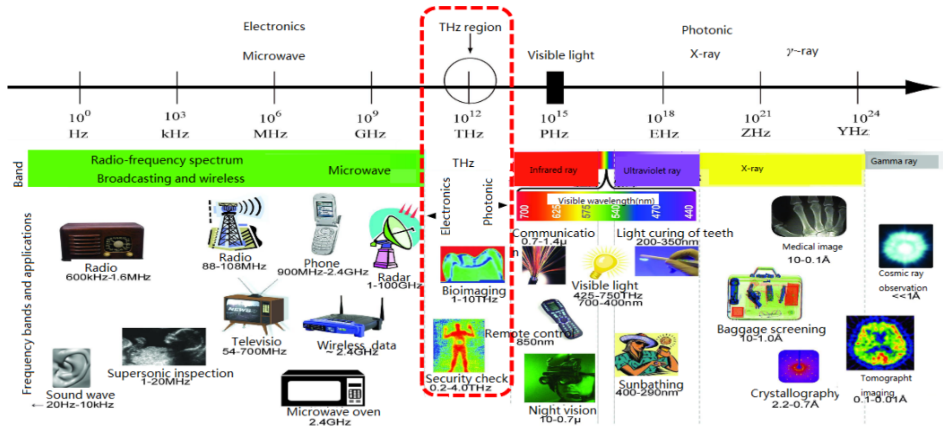


Fig. 1.1 Terahertz wave in the electromagnetic spectrum

In recent years, terahertz science and technology have been highly concerned in the world. In 2004, the United States listed the terahertz as one of the top ten technologies that would change the world in the future. In January 2005, Japan established terahertz technology as the first of the "top ten key strategic objectives of national technologies" to be developed in the next decades. In November 2005, the Chinese government specially convened the 270th "Xiangshan Science and Technology Conference", invited influential academicians, experts and scholars in the field of terahertz research to discuss the development status and trends of terahertz science and technology at home and abroad, and formulated the development strategy of terahertz technology in China.

2. Characteristics of terahertz waves

The terahertz wave between microwave and light waves in the electromagnetic spectrum has the following characteristics [4]:

(1) Good transmissivity

Terahertz has good penetrability to many dielectric materials and nonpolar materials. It can represent perspective imaging of concealed objects, effectively complements X-ray imaging and ultrasonic imaging technology, and achieve high-resolution non-destructive testing in security inspection or quality inspection.

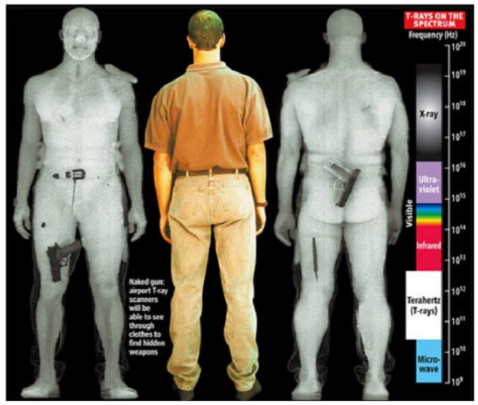


Fig. 2.1 Terahertz Safety Detection

(2) Security

The terahertz photon energy is 4.1 meV, which is only $1/10^7$~$1/10^8$ of the X-ray photon energy. Terahertz radiation will not cause photoionization and damage the tested materials. It can be applied to the in vivo inspection of the human body or other biological samples, and can easily extract spectral information such as refractive index and absorption coefficient of samples.

(3) Water absorption

Water has strong absorption of terahertz radiation. Because the water content in tumor tissue is obviously different from that in normal tissue, the interface between normal tissue and tumor can be determined by analyzing the water content in the tissue.

(4) Transient

The typical pulse width of terahertz pulse is in the order of picosecond. It is convenient to study time-resolved spectra of various materials, including liquids, gases, semiconductors, high-temperature superconductors, ferromagnets, etc. Moreover, the interference of background radiation noise can be effectively suppressed through sampling measurement technology.

(5) Coherence

The coherence of terahertz originates from its coherent generation mechanism. Terahertz coherent measurement technology can directly measure the amplitude and phase of the electric field, so as to conveniently extract the optical parameters of samples, such as refractive index, absorption coefficient, extinction coefficient, dielectric constant, etc.

(6) Fingerprint spectrum

Most of the vibrational and rotational energy level transitions of polar molecules and biomacromolecules are in the terahertz band, so there is abundant physical and chemical information in the terahertz band. According to its fingerprint spectrum, terahertz spectral imaging technology can not only distinguish the shape of objects, but also obtain the physical and chemical properties of substances, providing the relevant theoretical basis and detection technology for anti-drug, anti-terrorism, explosive disposal, etc.

(7) Large bandwidth

Compared with microwave and millimeter waves, terahertz wave has a shorter wavelength and broader bandwidth, higher image resolution, and greater capacity for data transmission, which can obtain clearer contour and fretting characteristics of targets. It is also the preferred frequency band for future 6G wireless communication.

3. Progress of vacuum electronics terahertz sources

There are many methods to generate terahertz wave radiation, including (1) semiconductor terahertz source; (2) Terahertz generator based on photonics; (3) Terahertz radiation source using free electrons (including small and medium power terahertz linear beam vacuum device, high-power gyrotron and free electron laser); (4) Terahertz radiation source based on high energy accelerator. Different types of terahertz radiation sources have their own characteristics and advantages, which are also suitable for different application needs [5].

This section mainly introduces the low power [6] and high power [7] vacuum electronics terahertz sources.

3.1 Low power terahertz source of vacuum electronics

In terahertz vacuum electronic devices, there is a size effect between operating wavelength and physical size. The size characteristics decrease with the decrease of the operating wavelength. At the same time, the output power decreases with the decrease of beam power. Among the linear beam devices, there are mainly terahertz traveling wave tubes(TWT), backward wave tubes(BWO), extended interaction klystrons and oscillators, klystrons and Smith Purcell devices [8][9][10].

(1) Terahertz traveling wave tube

Traveling wave tube (TWT) is a VED that realizes a small signal amplification function by continuously modulating the velocity of electron beam. The electron beam interacts with the advancing electromagnetic wave field in the slow wave circuit. In the slow wave circuit with 6~40 wavelengths, the electron beam continuously transfers kinetic energy to the electromagnetic wave signal, so that the signal can be amplified and has the characteristics of high gain and large bandwidth.

TWT is widely used in radar, electronic countermeasure, communication and other fields as the core device of electromagnetic wave power amplification. The core of TWT is slow wave circuit, also known as high-frequency structure. Its main forms are helix, coupling cavity and folded waveguide structure. The high-frequency structure of helix has a wide frequency band and large output power. It has been used in microwave and millimeter bands. The helical TWT has poor thermal dissipation capacity due to the existence of clamping rods, which limits the increase of its power, while the coupled cavity TWT has stronger thermal dissipation capacity due to its all-metal structure so that it can obtain larger output power. Coupled cavity slow wave structure has all metal characteristics and has advantages in thermal dissipation, which leads to large power capacity. However, its metal sealing will enhance dispersion and decrease the bandwidth of TWT. Therefore, it is necessary to find a balance between power and bandwidth. However, when helix and coupled cavity slow wave structures develop towards high frequency, they are limited by their own structures and are difficult to be used in submillimeter wave and terahertz frequency devices. Compared with helix and coupled cavity slow wave structure, folded waveguide can overcome this limitation and is widely used in submillimeter wave and terahertz wave [11]。

Folded waveguide slow wave circuit is a kind of all metal periodically loaded waveguide, which is generally composed of bent waveguides on the electric field surface and serpentine lines arranged in a certain period along the axis direction, as shown in Fig. 3.1. The folded waveguide high-frequency structure is not only easy to realize in processing, but also has the following advantages in terahertz frequency band [12], [13]: (1) Low manufacturing cost; (2) Solid structure; (3) High power capacity; (4) Simple structure of input and output signal transition section is simple; (5) Wide working frequency band; (6) Compatible with micro fabrication technology (MEMS). It has been widely used in millimeter wave VED, especially in terahertz band.

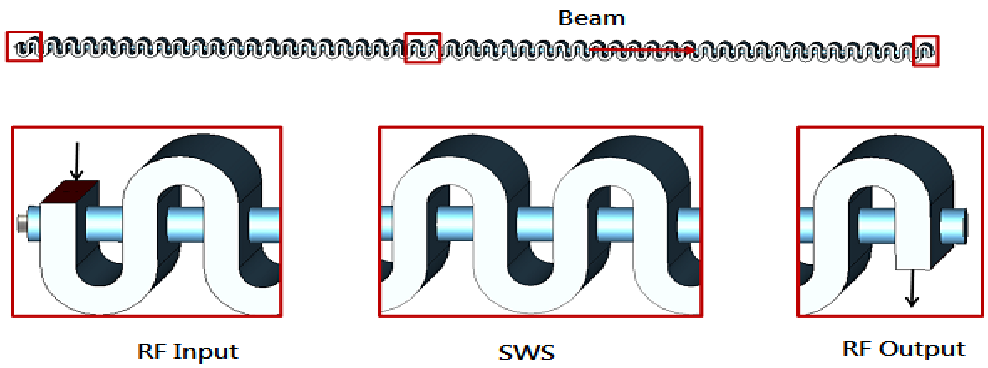


Fig. 3.1 High Frequency Structure of Folded Waveguide

Since Northrop Grumman Company (NG) developed 40~50 *GHz* TWT with folded waveguide in 1987, its output power has reached 300 *W*, and the folded waveguide has become a research hotspot for high-frequency interaction system of millimeter wave and terahertz VED. In 2003, the University of Wisconsin carried out a 560 *GHz* oscillator simulation and prepared folded waveguide circuits using LIGA technology. It is believed that the micro method can be applied to folded waveguide circuits, making the micro method for developing high-frequency structures an important way [14]. In 2007, NG Company successfully prepared the folded waveguide high-frequency structure using deep reaction ion etching technology and applied it to the terahertz TWT with the center frequency of 0.638 *THz*, and the output power reached 16mW. In 2008, a 0.656 *THz* TWT was developed, with an output power of 52 *mW* and a gain of 15 *dB*. NG developed 0.85 *THz* folded waveguide TWT [15] from 2012 to 2013, with operating bandwidth of 15 *GHz*, output power of 141 *mW* and gain of 26.5 *dB*. C.D. Joye of the US Naval Laboratory developed a 220*GHz* folded waveguide high-frequency structure through UV-LIGA technology. In 2014, it was successfully applied to the terahertz TWT, and achieved signal output with bandwidth greater than 15 *GHz* and peak power greater than 60 *W*. In 2021, the Academy of Aeronautics and Astronautics of the Chinese Academy of Sciences developed 220 *GHz* TWTs with a peak power of 61 *W*, a bandwidth of 5 *GHz* and a continuous wave of 27 *W* and bandwidth of 6 *GHz* respectively. The Institute of Beijing Vacuum Electronics Research Institute(BVERI) has carried out the development of 220 *GHz* TWT, and achieved the output of 50 *W* peak power and 20 *W* continuous wave respectively.

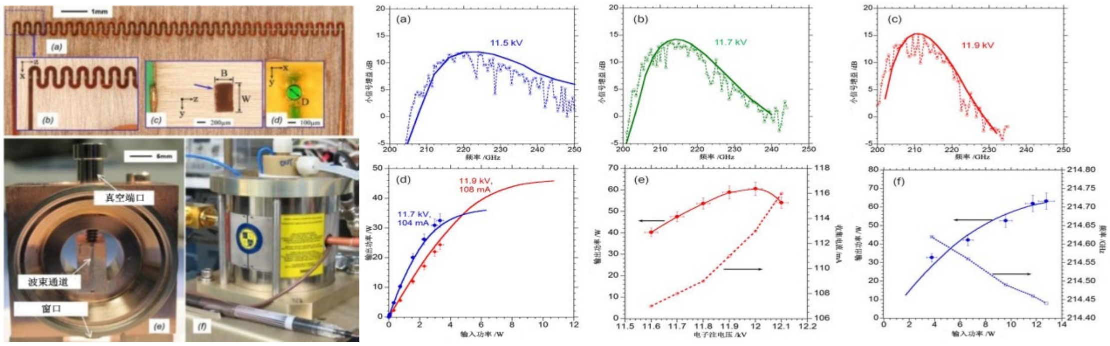
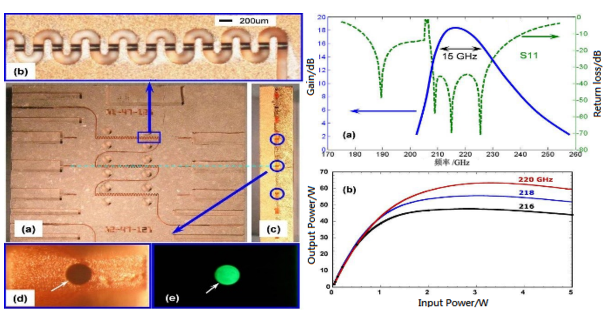


Fig. 3.2 0.22*THz* Traveling Wave Amplifier Developed by US Naval Laboratory

To improve the output power, Khanh Nguyen, et al. of the US Naval Laboratory, carried out research on cascaded folded waveguide high-frequency structure TWT. This method significantly improves the output power and increases the working bandwidth. The research results were reported in the vacuum electronic conference for four consecutive years (2010~2013), which caused a strong response. It is considered that this method is an effective way to expand the working band of terahertz devices and improve the power output. In 2012, NG Company of the United States used five circular electron beams to drive five independent folded waveguide structures [16]. It achieved a high power output of devices through power synthesis at the end of high-frequency structures. When the voltage is 19 *kV* and the current is 250 *mA*, the signal output with an operating frequency of 214 *GHz* is realized, and 56*W* power output is obtained with a bandwidth of 5 *GHz*. In 2015, Yan [17], [18] proposed a multi-beam folded waveguide traveling wave amplifier, which uses power distribution in the excitation section and power synthesis in the output section. It can achieve 95.5 *W* power output with a bandwidth of 5 *GHz* at 0.14 *THz*.



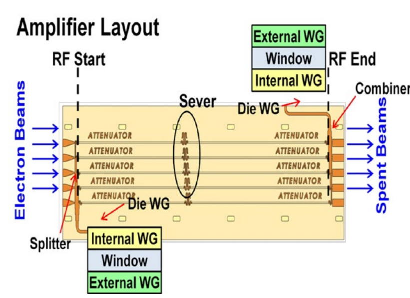
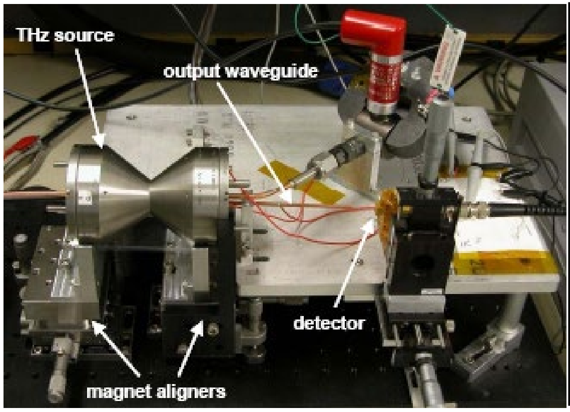


Fig. 3.3 Cascaded circuit of 0.22*THz* Fig. 3.4 Cascaded slow wave circuit of 5 beam synthesis



PARAMETER	Source #3
Power @ window	52 mW
Frequency	0.656 THz
Gain	~15 dB
Cathode voltage	9.9 kV
Pulse length	0.05 – 1.0 ms
Repetition rate	≤30 Hz
Duty cycle, max.	3 %
Axial field	10 kG
Emission current	4.6 mA
Collector current	2.1 mA
Beam transmission	46 %
Interaction efficiency	0.4 %
Source efficiency	0.2 %

Fig. 3.5 Test Site and Experimental Parameters of Terahertz Source

Tab. 3.1 Research Results of THz Folded Waveguide Traveling Wave Amplifier

Frequency/THz	0.22(multi-beam)	0.22(single beam)	0.64	0.67	0.85	1.03
Cathode voltage/kV	19.8	11.7	9.7	9.6	11.4	12.1
Electron beam (mA)	277	105	4.8	3.1	2.8	12.1
Saturated Gain(dB)	28.5	14	22	17	22	20
Peak Power(Mw)	55.5	68	259	71	39	29
3dB band	4.5	15	15	15	15	5
Operation ratio(%)	--------	-------	10	0.5	11	0.3

Another method to increase the output power and expand the frequency band is to drive the cascaded folded waveguide high-frequency structure by multiple electron beams. This structure is mainly studied by NRL. First, they conducted a preliminary study in Ka-band. The simulation results show that the method can significantly improve the output power and increase the bandwidth. Therefore, they extended this structure to 0.22 *THz* folded waveguide traveling wave amplification, as shown in Fig. 3.6. By this method, the output power of the device and the bandwidth of the frequency band are improved.

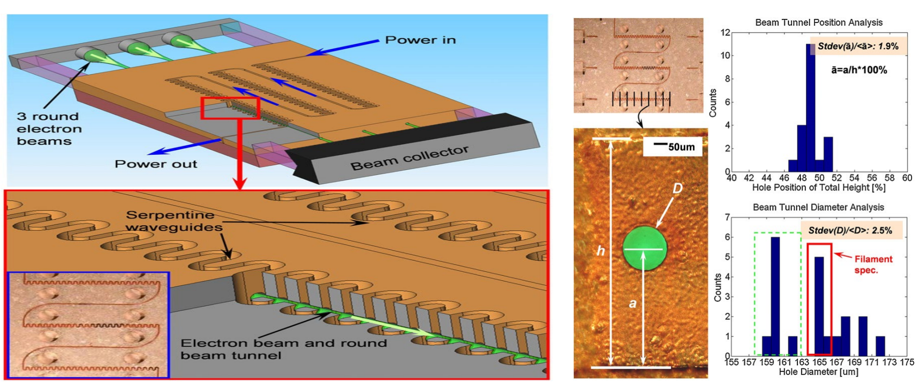


Fig. 3.6 Three beams cascaded folded waveguide high-frequency structure developed by NRL

The Institute of Electronics of the Chinese Academy of Sciences has proposed a folding waveguide device [19] for traveling wave amplification with backward wave excitation. The amplifier uses a folding waveguide backward wave oscillator (FW-BWO) as the excitation source to stimulate a folding waveguide traveling wave amplifier with a working frequency of 216 *GHz*. Research shows that the output power of 96 *W* is finally obtained, and the design length of the entire circuit is only about 1cm. At the same time, theoretical and simulation studies on power synthesis and distribution are also carried out, as shown in Fig. 3.7. With this method, the output power of the device can be increased by 3 *times*. As shown in Fig. 3.8, the output power of the device can be increased to 2.5 *times* under the same electron beam power condition.

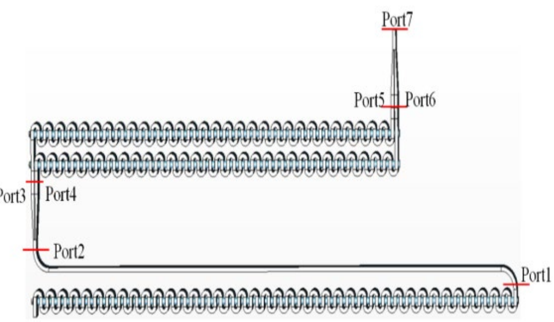


Fig. 3.7 Preliminary design of power synthesis and distribution structure

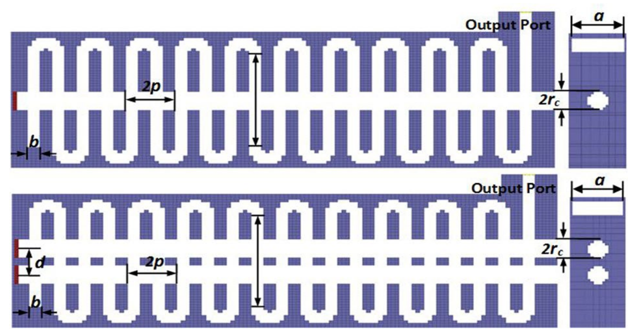


Fig. 3.8 Double electron beam 0.22THz folded waveguide oscillator

In the research of width band sheet beam terahertz TWT, the University of California, Davis, is in the leading position [20]. By breaking through the key technology of shaping and stable transmission of the ribbon electron beam, as well as the technical difficulties in the preparation of the energy transfer window, a 0.22 *THz* band beam TWT with a peak power greater than 100 *W* and a bandwidth greater than 5 *GHz* has been developed.

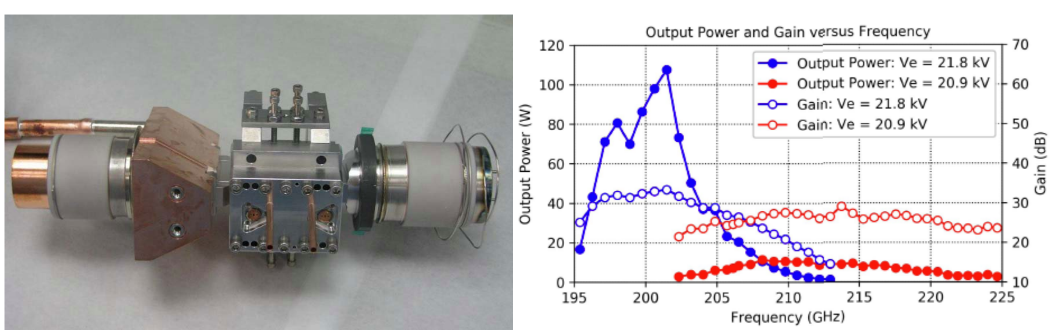


Fig. 3.9 0.22 *THz* Band Beam TWT

In 2020, Pan and co-authors from the State Key Laboratory of Vacuum Electronics Science and

Technology of Beijing Institute of Vacuum Electronics used high-speed milling machines to process the improved folded waveguide high-frequency circuit, and realized the development of G-band T-TWT with a continuous wave output power of 20*W* [21]. In order to eliminate the band edge instability caused by 20 *kV* high voltage beam, a folded waveguide circuit with corrected circular curvature is used to enable the device to work in continuous wave mode, and periodic permanent magnets are used to achieve compactness. CVD diamond chips are used in input and output RF windows to minimize TWT losses and VSWR. The peak power of the G-band pulse TWT sample tube is 20 *W*, the 3 *dB* bandwidth is 7.6 *GHz*, the saturation output power is greater than 15 *W*, and the saturation gain is greater than 32 *dB*.

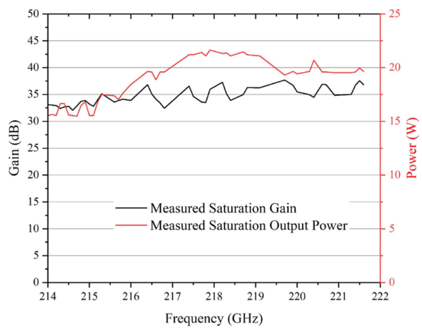


Fig. 3.10 Output Power Curve

Fig. 3.11 Photo of traveling wave tube sample tube

In 2021, the G-band TWT [22] developed by the unit will work in the 10 *GHz* band and use a folded waveguide slow wave structure, PPM focusing continuous system, a first stage step-down collector and a diamond energy transmission system. For this sample tube, the frequency multiplication link is used to connect the isolator as the front stage push. The directional coupler and PM5 power meter are used to test the output power and gain. The test results show that the output power is more than 10 *W* in the nearly 11 *GHz* bandwidth, the whole tube gain is more than 30 *dB*, and the efficiency is more than 4%. The tube works continuously and stably.

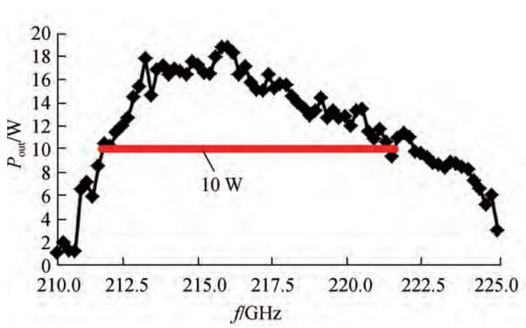


Fig. 3.12 Output Power Curve

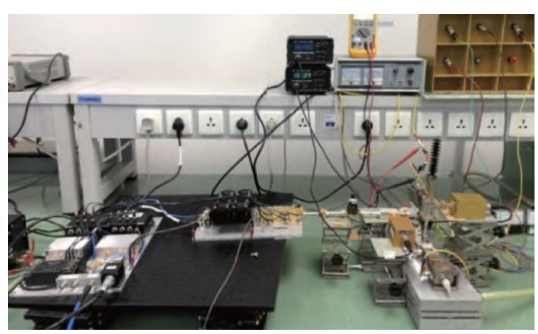


Fig. 3.13 Sample Tube Test Photo

In the same year, the unit developed a compact periodic permanent magnet focused beam pulse G-band 50 *W* TWT [23], which combines three methods: setting the operating point near the cut-off frequency, using a folded waveguide slow wave structure with improved circular bending, and using phase velocity gradient technology to improve the working performance of the tube. The thermal test results show that when the beam voltage is 24.25 *kV* and the beam current is 59 *mA*, the output power of the TWT is greater than 50 *W*, and the electronic efficiency and gain are greater than 3.5% and 35 *dB* respectively at the 3.6 *GHz* bandwidth.

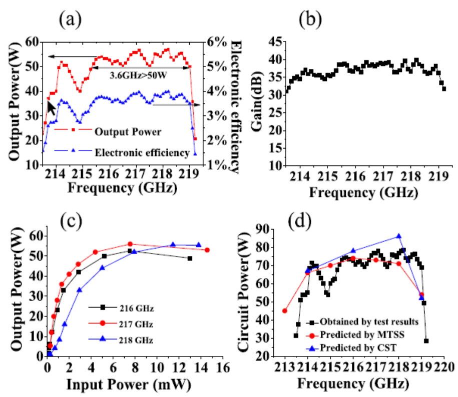


Fig. 3.14 Thermal Test Results of TWT

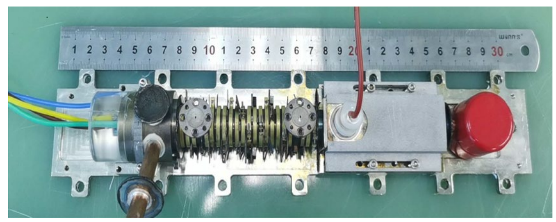


Fig. 3.15 Traveling wave tube sample tube

In 2021, Gao Luanfeng, et al. of the University of Electronic Science and Technology of China, proposed a spindle shaped slow wave structure suitable for band beam, and designed a 340 *GHz* band beam TWT based on the spindle shaped slow wave structure [24]. The maximum output power is 12.3 *W*, the gain is 30.9 *dB*, the electronic efficiency is 2.16%, and the 3 *dB* bandwidth is larger than 45 *GHz* and the gain within the bandwidth is greater than 28 *dB*. The comb type slow wave structure is deeply studied from three aspects of theory, simulation and experiment. The designed Ka-band three-beam integrated comb type TWT achieves the maximum output power of 132.8 *W*, electronic efficiency of 5.12%, and gain of 41.2 *dB* in 32-36 *GHz*. When the input power of G-band three-beam integrated comb type wave tube is 20 *mW*, the maximum output power is 13W, the gain is 28.1 *dB*, and the electron efficiency is 3.7% at 230 *GHz*. The maximum output power, gain, and electron beam efficiency are greater than those of G-band single beam comb type TWT. In addition, a new type of beam wave interaction mechanism based on the feedback loop is studied, and a 140 *GHz* dual channel folded waveguide forward-backward-feedback amplifier is designed. Compared with the single beam TWT, the saturated input power of the feedback loop based forward-backward-feedback amplifier is reduced by 75%, and the gain is increased by 12.4*dB*. Compared with the traditional BWO, the starting current of the feedback loop is reduced by 44.4%.

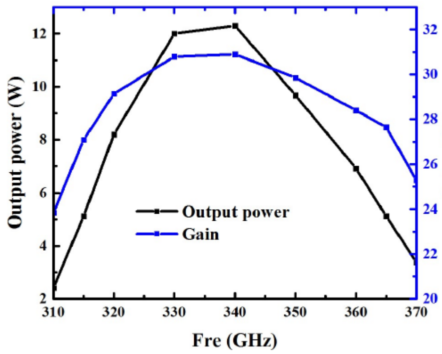


Fig. 3.16 Spindle TWT Output Power

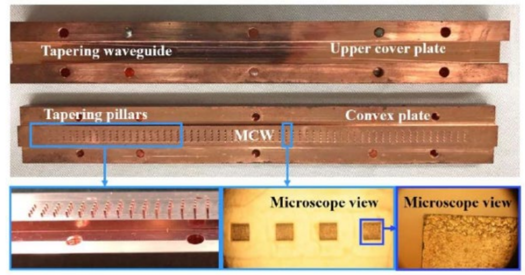


Fig. 3.17 Detailed drawing of multi-beam integrated comb type slow wave structure

In 2021, Yang Zhenxin et al. designed a band electron beam staggered double grid TWT [25] operating at 850 *GHz*. The calculation results show that under the conditions of voltage of 30 *kV* and current of 0.12 *A*, the maximum output power obtained at 850 *GHz* is 5.3 *W*, the corresponding gain is 16.28 *dB*, and the electronic efficiency is 1.6%. In addition, a cylindrical electron beam folded waveguide TWT operating at the same wavelength is designed. The calculation results show that the maximum output power is 0.86 *W* at 860 *GHz*, the corresponding gain is 16.3 *dB*, and the electron efficiency is 1.6%.

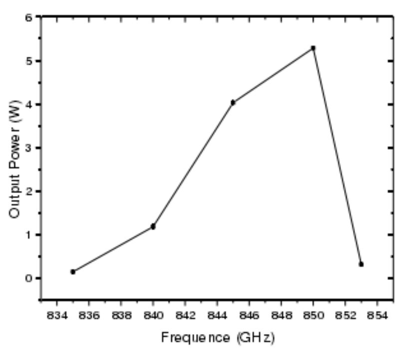


Fig. 3.18 Output power of 850*GHz* staggered double grid TWT at different frequencies

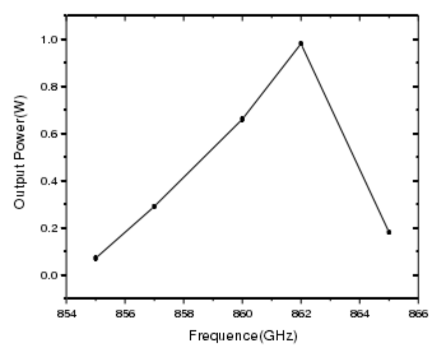


Fig. 3.19 Output Power of 850*GHz* Folded Waveguide TWT at Different Frequencies

In 2021, Yi Jiang, et al. of the Institute of Applied Electronics of the Chinese Academy of Engineering Physics, designed, manufactured and tested a 220 *GHz* CW folded waveguide TWT with 30 *W* output power for terahertz application systems [26]. The design and fabrication of the TWT include folding waveguide circuit, electron gun, periodic permanent magnet system, coupling window and thermal management structure. The test results show that when the beam current is

20.5 *kV* and 52.4 *mA*, the output power is 16 *W* and the corresponding bandwidth is 7 *GHz* in the range of 213~220 *GHz*. At the frequency of 217 *GHz*, the maximum power and the corresponding gain are 30 *W* and 31.2 *dB* respectively. The above results show that the folded waveguide slow wave structure of the sample tube has great potential for manufacturing continuous wave high output power THz devices.

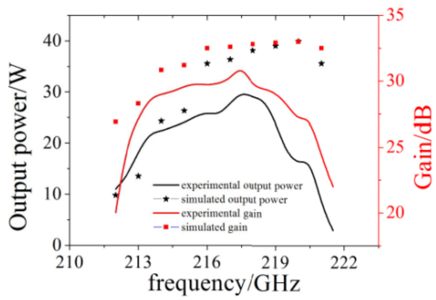


Fig. 3.20 Experimental Results of TWT Output Power and Gain

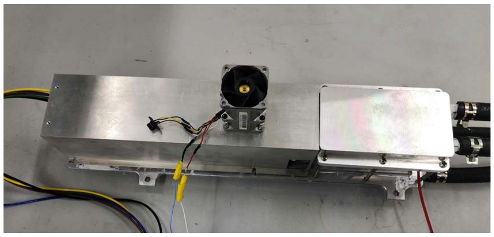


Fig. 3.21 Photo of Folded Waveguide TWT

In 2020, Ningjie Shi, et al. of the State Key Laboratory of Vacuum Electronic Science and Technology, University of Electronic Science and Technology of China, proposed a scheme to improve the gain and power of THz TWT by using an extended interaction cavity [27]. The scheme combines the slow wave structure and multi gap resonator to realize the complementary mixing of traveling wave and standing wave components, thus providing a compact circuit length. For the electron beam with a voltage of 21 *kV* and a current of 200 *mA*, Zeng Yiwei has a maximum of 42.22 *dB*, a 3 *dB* bandwidth of 6.5 *GHz*, and the length of the entire circuit is only 38 *mm*. For the output power of 11.25 *mW*, it is estimated that the continuous wave peak power is 187.5 *W* at 220*GHz*, corresponding to 4.47% of the electronic efficiency.

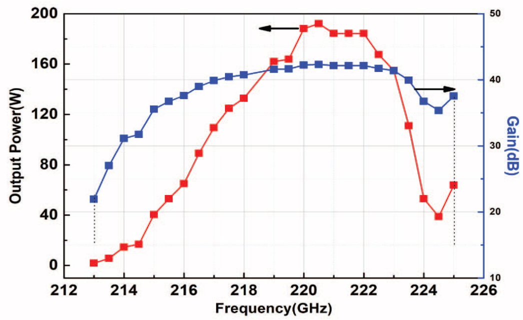


Fig. 3.22 Output Power and Gain of Three cavity TWT

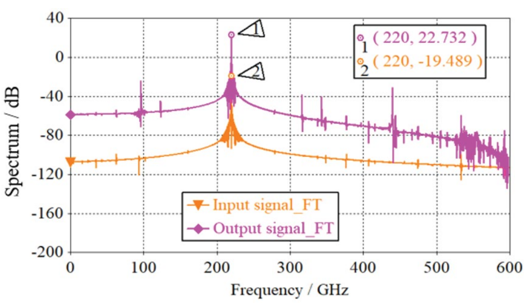


Fig. 3.23 Spectrum of input signal and output signal of two slow wave structures of three cavities traveling wave tube

In 2020, Liu Wenxin and others from the Aerospace Information Innovation Research Institute of the Chinese Academy of Sciences studied and manufactured G-band folded waveguide TWT [28]. The slow wave structure is the critical component in determining the performance of TWT. The theoretical bandwidth of folded waveguide slow wave structure is greater than 40 *GHz*. In the simulation experiment, the output power is about 34 *W* when the input power is 28 *mW*. The output power of the TWT amplifier developed by the project team is 17 *W* when the working voltage is 16.7 *kV* and the current is 65 *mA*. The working ratio during the test is 10%. The gain of the TWT amplifier is 24 *dB*.

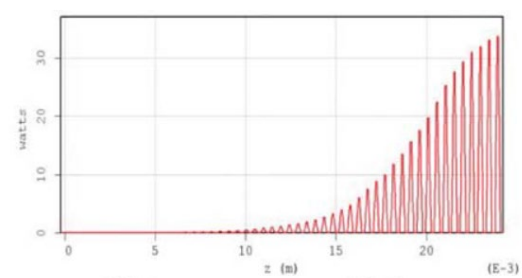


Fig. 3.24 Relation between output power and axial distance

Fig. 3.25 Prototype of THz TWT Amplifier

In 2021, to achieve high power, high gain and wide bandwidth, the unit proposed a terahertz TWT cascade scheme [29]. The G-band TWT had two cascaded amplifiers. The output wave of the first TWT was used as the input of the second TWT, and the two TWTs used folded waveguides and made through computerized digital control as the interactive circuit. Using an electron beam with a voltage of 17 *kV* and a current of 71 *mA*, the sample tube was tested at a frequency of about 0.22*THz*. The peak power of more than 60 *W* and the average output power of 12 *W* was obtained. The duty cycle was 20%, the gain was about 30 *dB*, and the bandwidth was more than 6 *GHz*. The average power bandwidth gain product in the designed spectral range reached the highest value in history. This newly developed THz TWT will have broad remote radar and communication systems applications.

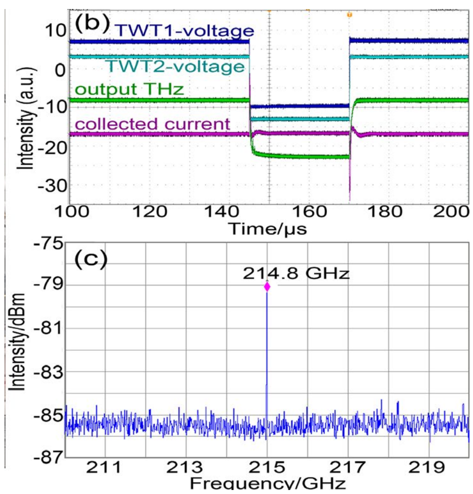


Fig. 3.26 Measurement Waveform and Output Signal Measurement Spectrum of TWT in Operation

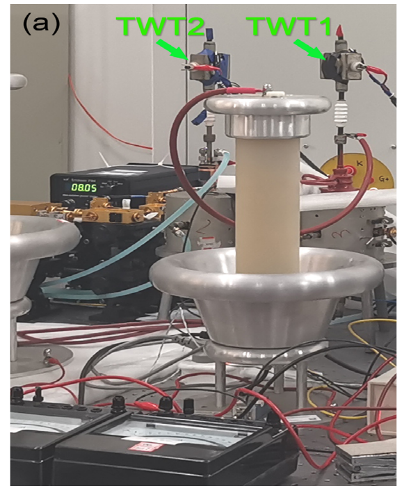


Fig. 3.27 Photos of experimental device

In 2021, R. Yang et al. of the same unit conducted research on T-shaped TWT based on flat top sinusoidal waveguide slow wave structure 1 *THz*, and made some devices [30]. Its saturation output power is 720 *mW*, and the corresponding gain is 28.57 *dB*. In addition, to reduce the transmission loss of the high-frequency structure, the input and output structures are designed, and a transition structure is proposed to convert the waveguide into a standard rectangular waveguide. The simulation results show that the reflection coefficient of this new transmission system is less than 20 *dB*, and the loss of the transition structure with input and output waveguides is 2.45 *dB* and 1.68*dB* respectively. The above research shows that the micromachining technologies such as depth reflection ion etching can be used to manufacture 1 *THz* sine wave guided TWTs.

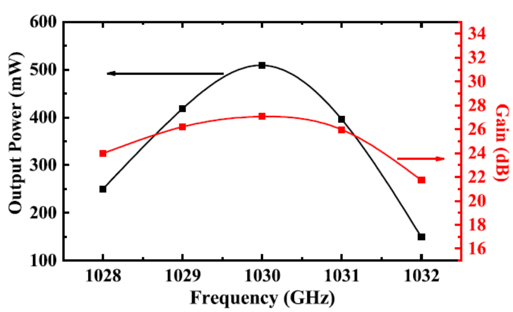


Fig. 3.28 Changes of Output Power and Gain with Frequency

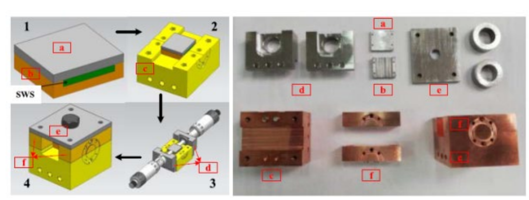


Fig. 3.29 Slow wave structure and metal components

The University of Electronic Science and Technology of China proposed the sinusoidal waveguide slow wave structure TWT, researched the band beam TWT using the unique characteristics of the sinusoidal waveguide [31], and carried out the design research on the 220*GHz*, 670 *GHz* and 1.03 *THz* TWTs. In the frequency range of 0.2 *THz*~0.25 *THz*, hundreds of watts of power output is achieved, and the device gain reaches 37 *dB*.

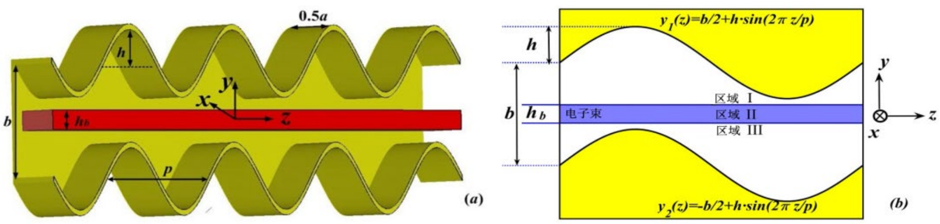


Fig. 3.30 Terahertz Sine Wave Guided Traveling Wave Tube

2. Terahertz BWO

Compared with TWT, the group velocity of electron beam in BWO is opposite to the phase velocity. The group velocity $V_g<0$ and the phase velocity $V_p>0$, the operating frequency can be adjusted by electrical tuning, and the output waveguide is set at the electron injection port. At present, the international successfully developed and productized THz BWO is mainly the Russian ISTOK Company, which has developed 100 *GHz*~1.03 *THz* BWO with output power reaching milliwatt level. BWO developed by another Microtech company, with milliwatt output power, has been applied in imaging systems.

Terahertz BWO has also been studied in China. Northwest Nuclear Technology Research Institute researched surface wave terahertz backward wave tube, and fabricated micro high-frequency structure using UV-LIGA technology. At 340 *GHz* working frequency, it realized a power output of 100 *milliwatts*.

3. Terahertz extended interaction devices

Extended interaction devices mainly include extended interaction klystron (EIK) and extended interaction oscillator (EIO). At present, many international research institutions are carrying out EIK research: CPI Canada Branch, Thales Company in France, Seoul University in South Korea, etc. CPI Canada is a world leader in the research of millimeter wave high-power distributed effect klystron. Due to the progress in manufacturing technology, high-frequency circuit and electronic optical design, the operating frequency of distributed effect klystron has been expanded to 700 *GHz*. The EIK developed by CPI Canada has been widely used in airborne and spaceborne communication systems, imaging radars, rain and weather radars, surveillance and tracking radars, missile borne radars and millimeter wave electronic countermeasure systems.

The 220 *GHz* continuous wave extended interaction klystron developed by CPI Canada Branch has a pulse output power of 10 *W* and a gain of 23 *dB*. At the 2007 International Conference on Infrared Millimeter Wave and Terahertz, CPI reported EIO with a tunable operating frequency of 220 *GHz* [32]. When the voltage is 11 *kV* and the current is 105 *mA*, the average power is 6 *W*, with 2% mechanical tuning capability. At the same time, the 280 *GHz* pulse EIO developed by CPI Company has an output power of 30 *W*. At present, the 220 *GHz* EIK pulse output power developed by the Aerospace Information Innovation Research Institute of the Chinese Academy of Sciences is greater than 100 *W* and the bandwidth is greater than 400 *MHz*.

4. Terahertz Smith-Purcell devices

Smith-Purcell (SP) type THz FEL has become an important method to develop THz devices. SP effect is an essential physical phenomenon discovered in 1953 by Steve Smith and Edward Purcell in experiments in 1953, and considered as an essential THz radiation source. When an electron beam flies close to the surface of an open periodic metal grating, it will stimulate electromagnetic wave radiation. Then this phenomenon is called SP radiation [33], as shown in Fig. 3.31. However, this radiation is incoherent spontaneous radiation, and the radiation power is minimal.

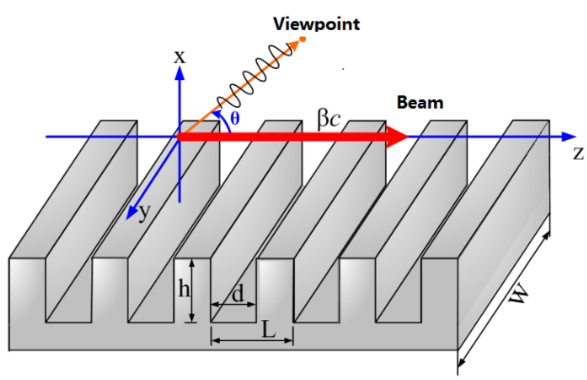


Fig. 3.31 SP Radiation Diagram

In 1998, J Urata et al. used the scanning electron microscope to generate a continuous electron beam with high brightness to make it pass through the grating surface, and observed the phenomenon of SP superradiation in the experiment, providing a new direction for the study of SP radiation [34]. The experimental structure is shown in Fig. 3.32, and the period used in the experiment is 173 μm. The metal grating of m is used as the interaction structure, the electron beam energy is 20~40 *keV*, and the operating frequency of the device is 0.3~1*THz*. Superradiation is a kind of coherent radiation with much higher power than spontaneous radiation. The principle of superradiation is to use the interaction of grating surface wave and electron beam to make the electron beam cluster to produce periodic electron beam clusters. When the periodic electron beam cluster passes through the grating surface, it will produce coherent radiation in a certain direction, that is, SP superradiation. The condition for generating superradiation is that the electron beam current exceeds a certain critical current, which is called the starting current to ensure the electron beam clustering and the generation of periodic electron beam clusters. This super radiation phenomenon based on SP effect has aroused extensive research interest of scientists and high attention of the government. It is one of the more active research fields in the world at present, and is expected to develop into a compact, adjustable, high power terahertz radiation source.

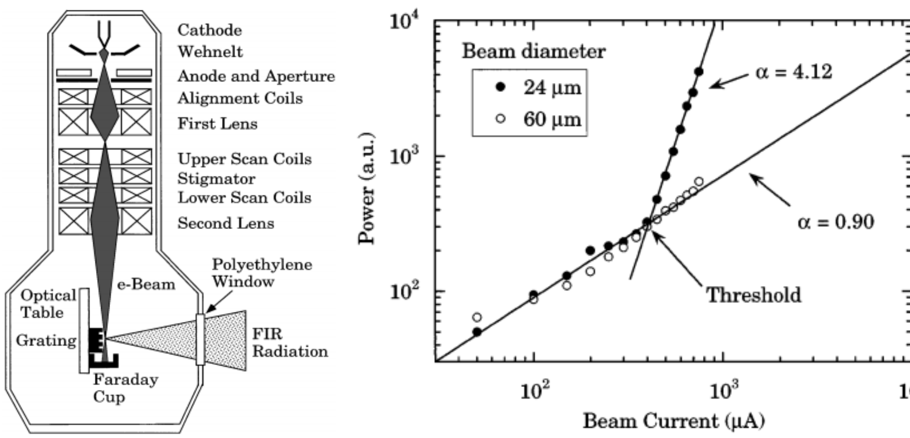


Fig. 3.32 Dartmouth College Experimental Structure and Output Power Diagram

In 2002, *Nature* magazine reported that the Jefferson Laboratory (JLab) used a pre- modulated electron beam to generate a terahertz source [35], which attracted extensive attention from scientists all over the world. In 2004, Vanderbilt University conducted a free electron laser experiment based on SP effect [36]. The experimental structure is shown in Fig. 3.33. In the experiment, the grating period is 0.25 *mm*, and the radiation wave frequency is 0.3~1 *THz*.

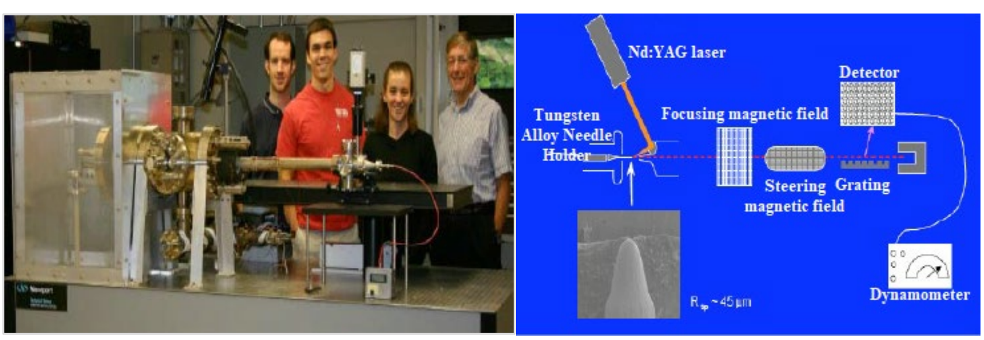


Fig. 3.33 Vanderbilt University Experimental Device Diagram and Schematic Diagram

In 2005, MIT used a linear accelerator to generate electron clusters with a frequency of 17.14*GHz*, a pulse width of 1ps, and an electron beam energy of 15 *MeV* (each cluster charge is

4.67 pC) [37]. A step grating with a period of 1 cm was used as the high-frequency structure, and coherent SP radiation terahertz wave with a frequency of integral times of the repetition frequency of the electron beam cluster was measured. In 2006, the terahertz band SP coherent radiation signal was successfully measured using the same parameter electron beam cluster to make it move close to the 2.54 *mm* step grating.

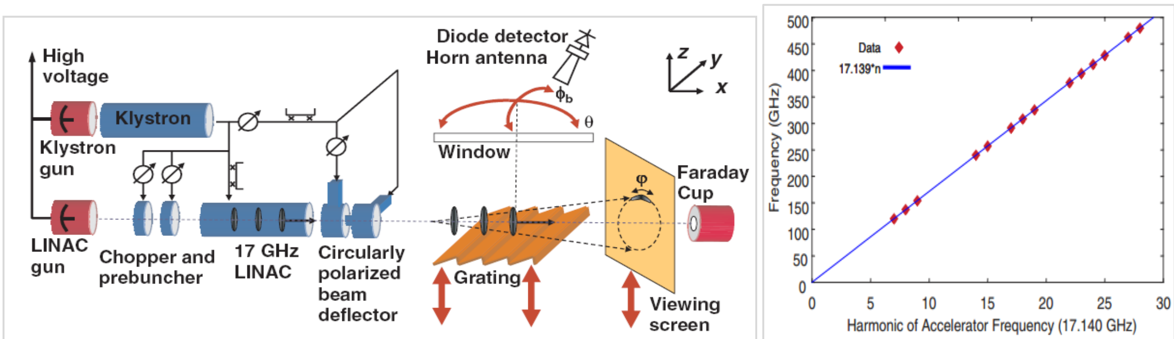


Fig. 3.34 Schematic Diagram and Signal Spectrum of MIT Experiment

In 2007, Professor G.S. Park[38], a Korean scholar, proposed to use the double electron beam model to generate terahertz radiation through beam wave interaction, as shown in Fig. 3.35, which is the double electron beam model and dispersion curve.

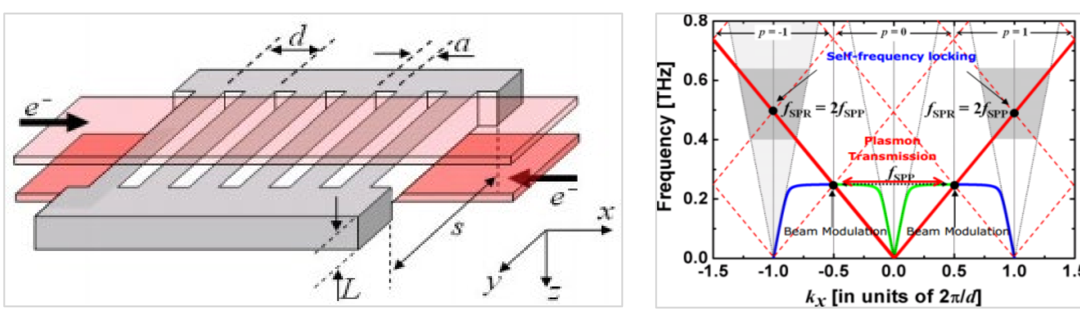


Fig. 3.35 Double electron beam model and dispersion curve

In China, the University of Electronic Science and Technology of China has done a lot of theoretical and experimental research on the three mirrors quasi optical system based on SP effect. In 2001, Professor Chen Jiayu carried out the SP effect oscillator experiment based on the metal periodic grating [39]. The experimental device is shown in Fig. 3.36, and the radiation with the operating frequency of 73.8~112 *GHz* and the peak power of tens of kilowatts is obtained

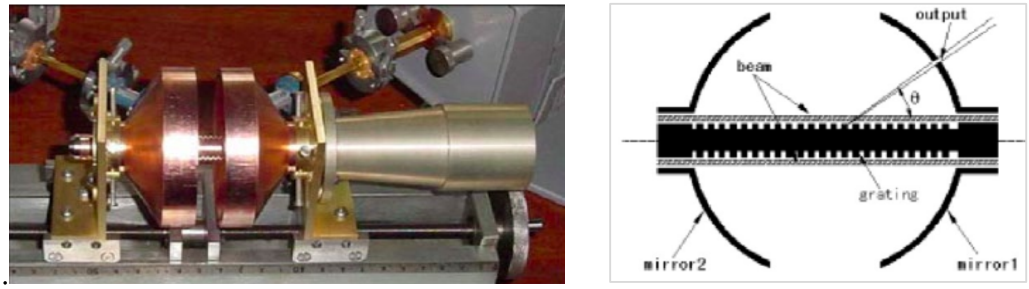


Fig. 3.36 Experimental Diagram and Schematic Diagram of SP Oscillator of University of Electronic Science and Technology of China

The Institute of Electronics of the Chinese Academy of Sciences has researched dielectric loaded terahertz devices and developed the Smith-Purcell three-dimensional dielectric theory of dielectric loaded terahertz gratings [40]. To more accurately calculate the growth rate of SP devices, it has developed a second-order small quantity method for calculation, which improves the accuracy and accuracy of the growth rate calculation. Peking University has conducted relevant research on SP devices of surface plasma, which provides a strong theoretical basis for developing broadband tunable terahertz radiation sources. Tsinghua University used ultrashort electron beam to generate terahertz radiation in Smith-Purcell grating, which was published in *Applied Physics Letters*.

5. Terahertz klystron

Terahertz klystron can produce milliwatt power output, and its operating voltage is low (usually only tens to hundreds of volts), so no magnetic field is required. Because of its many advantages, it has become a hot research topic in the terahertz field.

As shown in Fig. 3.37, terahertz klystron is composed of a high emission current density cold cathode, a high-frequency resonant cavity, a bunching gate, a reflective cavity, an output waveguide, a transmission coupling structure, etc. To make this kind of klystron work stably, it is absolutely necessary to have a cathode that can emit extremely high current density[41].

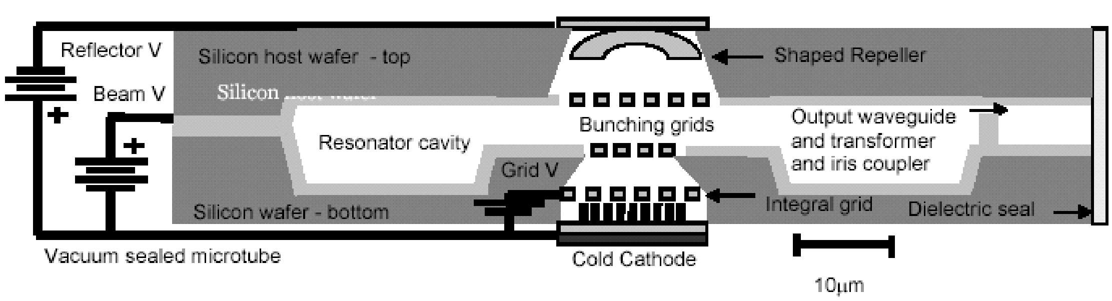


Fig. 3.37 Terahertz Reflex Klystron

The working principle of the THz reflection klystron is similar to that of the traditional reflection klystron: electrons generated by the cathode pass through a pair of clustered metal grids in the resonant cavity, and then directly enter the reflective cavity. At this time, the electrons enter a drift region. As a result of the negative reflector of the reflection cavity, electrons are reflected and returned along the original path. If the injection current fluctuates randomly, the oscillating electromagnetic field in the cavity will also fluctuate, which will cause the fluctuation of the potential difference between the clustered grids and establish an alternating electric field between them. When electrons pass through the resonant cavity, this alternating electric field accelerates the electrons passing through the positive half cycle and decelerates the electrons passing through the negative half cycle, that is, the electrons are velocity modulated, as shown in Fig. 3.38.

When the electrons enter the drift region, the velocity modulation will be converted into the density modulation, so the electrons will cluster, as shown in Fig. 3.39[42]. After the clustered electrons are reflected, if they return to the resonant cavity at an appropriate time (the potential of the upper grid is positive), the power will be transferred to the resonant cavity. At the same time, the clustering of electrons will be strengthened, and the tube will spontaneously oscillate at the frequency point of the resonant cavity, and part of the oscillating power will be output outside the tube through the waveguide transmission device. It is worth pointing out that the energy supplied to the cavity by the electron beam must be sufficient to compensate for the energy loss of the cavity and the power coupled to the external load.

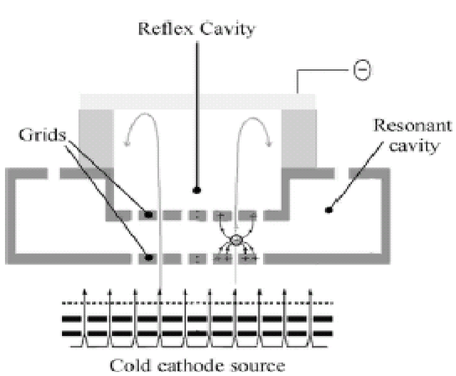


Fig. 3.38 Working principle diagram of terahertz klystron

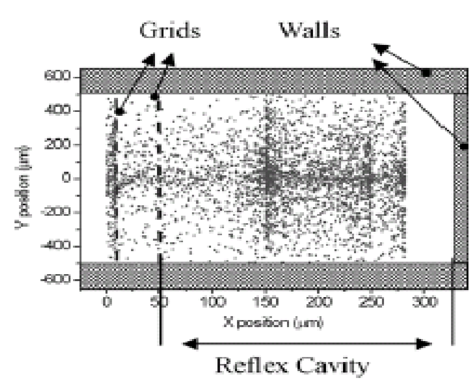


Fig. 3.39 Clustered electrons in the reflecting cavity

3.2 Large size high power of vacuum electronics terahertz source

1. Terahertz gyrotron

The mechanism of electron cyclotron resonance stimulated radiation was first proposed by Australian astronomer Tevez in 1958. At the same time, Kapalov, a former Soviet scholar, also independently proposed a new concept of the interaction between the cyclotron electron beam and electromagnetic waves, taking into account the relativistic effect. In 1965, Hirshfield of Yale University in the United States fully confirmed this mechanism in experiments, thus laying a theoretical foundation for the development of gyrotron. In recent years, the United States, Russia, Germany, Japan and other countries have made great progress in gyrotron research. Gyroklystron has the advantages of high power, high gain, high efficiency, stable performance and a certain bandwidth. It is mainly used in denial weapons, ITER programs, nuclear magnetic resonance, radioactive material telemetry, radar imaging and other fields.

Fig. 3.40 is the schematic diagram of gyrotron oscillator and amplifier developed by MIT for dynamic nuclear polarization/nuclear magnetic resonance (DNP/NMR). The gyrotron used by MIT's first DNP/NMR operates at proton NMR frequencies of 5Tesla, 140 *GHz* and 210 *MHz*[43].

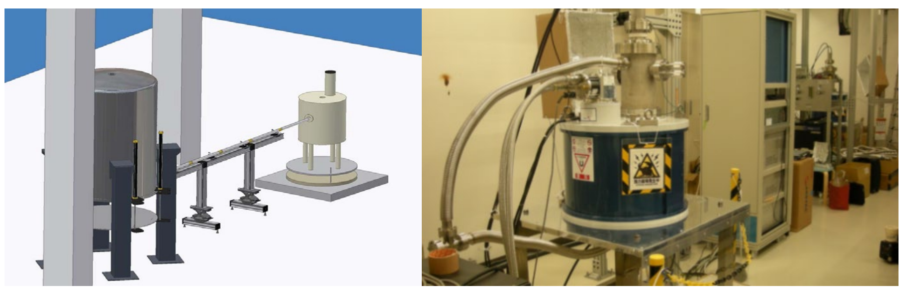


Fig. 3.40 Gyrotron Device Developed by MIT for DNP/NMR

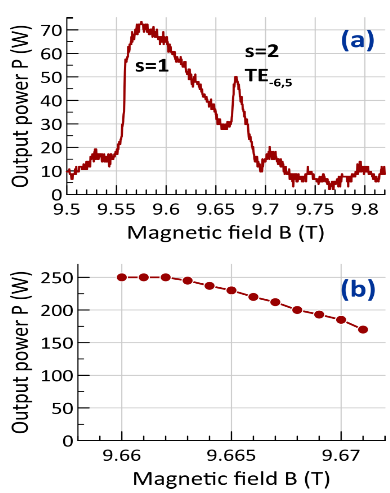


Fig. 3.41 Output RF power as a function of voltage and electron beam current

Fig. 3.42 Photos of gyrotron (located in low-temperature magnet) and experimental device

In 2021, Mikhail Yu Glyavin and others from FSBSI Federal Research Center, Institute of Applied Physics, Russian Academy of Sciences designed, manufactured and tested a 250 *W* terahertz continuous wave second harmonic gyrotron working in 10 *T* liquid nitrogen free superconductor [44]. Gyrotron tubes are based on the interaction between electrons rotating in an external magnetic field and fast waves excited in a smooth waveguide near the cut-off point. They have no slow wave structure and can utilize electron beams with energy lower than 100 *keV*. Therefore, they are much more compact than free electron lasers. The working voltage of the gyrotron is 15 *kV*, the beam current is 0.6 *A*, the frequency of 0.526 *THz* coherent continuous wave radiation is generated, the output power is 250 *W*, and the efficiency is 2.7%.

The University of Electronic Science and Technology of China (UESTC) has developed a double beam gyrotron, which operates in TE_{02}/TE_{04} mode, with a working frequency of 0.11/0.22 *THz*, a magnetic field of 4.2 Tesla, a voltage of 40 *kV*, a current of 5 *A*, and a power of 20 *kW*. The UESTC has also developed A 220 *GHz* gyrotron with an 8 T pulse magnet has been designed, constructed and operated in UESTC. TE_{03} mode is selected as the operation mode, which is less susceptible to the mode competition. Experimental results show the output power is achieved 11.5 *kW* with efficiencies of 12.8%, and the frequency is between 219.6 *GHz* and 234.2 *GHz*.[45]

Fig. 3.43 Double beam gyrotron developed by UESTC

The 12th Research Institute of China Electronics Science and Technology Corporation (CETC 12th) adopts a double anode magnetic control injection electron gun, which operates in TE22,6 mode. Under 68 *kV* voltage and 28 *A* current conditions, it has obtained 430 *kW* power output, with a resonant frequency of 140.2 *GHz* and an efficiency of 22.6%[46].

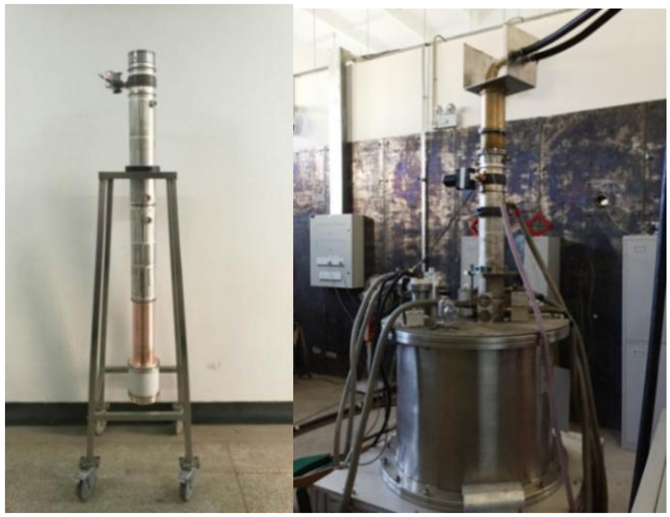


Fig. 3.44 Gyrotron

2、Terahertz free electron laser

Free Electron Laser (FEL) is a high-power, tunable coherent radiation source that uses relativistic high-quality electron beams oscillating in a periodic magnetic field as the working material. Its physical basis is the stimulated scattering of electromagnetic waves by moving free electrons. Since electrons are not bound by atoms as they are in ordinary lasers, they are "free", so they are called free electron lasers. Because FEL has the advantages of continuously adjustable frequencies, high power, narrow linewidth, good directivity, and strong polarization, it is possible to achieve a high-power ideal terahertz source with full coverage in the terahertz band on the same device. Therefore, FEL is the most promising high-power tunable coherent light source in this band.

In 1970, J.M.J. Madey of Stanford University began to study the first named "free electron laser". In 1976, L.R. Elias and others completed the FEL amplification experiment for the first time using the superconducting linear accelerator of Stanford University [47]. In 1977, Deakin et al. carried out a similar experiment in the mode of oscillator operation [48]. The potential characteristics and advantages of FEL were quickly recognized by scientists, which effectively have promoted the development of FEL experiments worldwide. At the same time as the early experimental work, various theoretical research work has also come out.

Since 1985, the development of FEL has been significantly influenced and promoted by the SDI program, and there has been a research boom in FEL in the world since then. France, Russia, Britain, Germany, China, Japan, the Netherlands and other countries have carried out work in this regard [49], [50], [51]. It has an attractive application prospect in civil and military applications such as communication, radar, plasma heating.

The major international FEL user devices in the infrared terahertz band include FELIX in the Netherlands, FELBE [52] in Germany and Novo FEL in Russia. Among them, the peak power of Novo FEL in Russia to generate terahertz wave reaches *MW*, and the average power reaches 500 *W*, while the average power of FELBE in Germany reaches 65 *W*. THz produced by FEL device is mainly used in the research of material science, physics, chemistry and biology. Table 3.2 shows the basic parameters of the Dutch FELIX device. The device has a large universal width and can achieve terahertz signal output in the range of 0.2 *THz*-100 *THz*. The pulse energy is 0.5-30 microfocus. The main working mode is TEM00 mode, and the signal polarization is linear polarization. The user device can realize spectral characteristics analysis such as gas molecular spectrum, biomolecular spectrum, cluster and ion spectrum (chemistry), nonlinear time-resolved spectrum under low temperature and/or strong magnetic field.

Tab. 3.2 Basic parameters of FELIC

Beam parameters	Value
Spectrum width [cm^{-1}]	6.6 - 3500 cm (0.2 - 100THz)
Tunable ability[%]	200 – 300
Pulse structure	5μs, 10 Hz / 1000 or 25 MHz or signal pulse
Pulse energy[μJ]	0.5 – 30
Micro duty cycle	Transform limits
FEL mode	TEM_00
Polarization mode	Line polarization

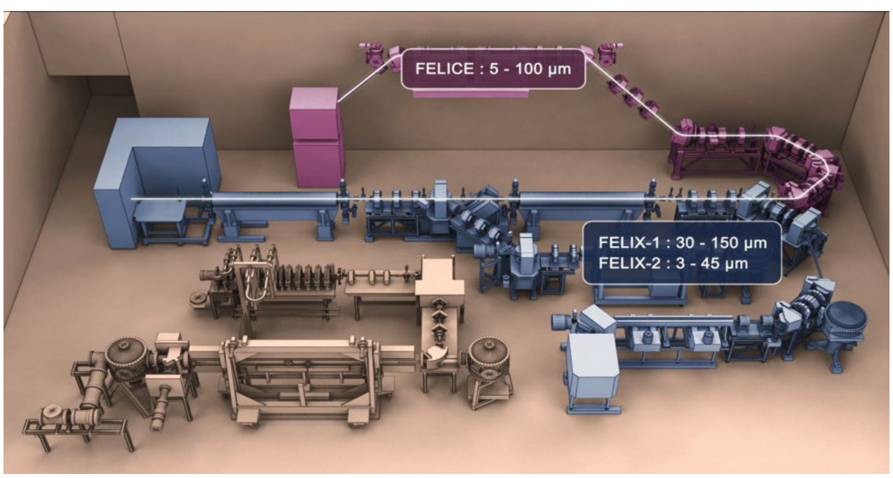


Fig. 3.45 Basic installation of FELIX, Netherlands

FELBE [53]is the most perfect long wavelength light source device in the world, which uses superconducting linear accelerator. The device can be used as X-ray source, positron source, Thomson γ Source, white light neutron source, etc. FELBE in Germany has undergone two transformations. For the first time, FEL1 achieved 7.5 *THz*-60 *THz* signal output, with an average power of 44 *W* and a pulse width of 0.7-4 *ps*. For the second FEL2, the characteristic spectrum of 1.2 *THz*-16.7 *THz* is achieved, the maximum average power is 65 *W*, the pulse energy is 5 *μJ*, and the pulse width is 1-25 *ps*.

Tab. 3.3 Basic parameters of FELBE

Parameters	**FEL1(U37)**	**FEL2(U100)**
Characteristic spectrum	7.5-60THz	1.2-16.7THz
Average power	≤44W	≤65W
Pulse width (min.)	0.7-4ps	1-25ps
Pulse width (max.)	3.4μJ	5μJ
Peak field strength	3MV/cm	600kV/cm
Bandwidth	0.4-3.4%	0.4-2%
Repeat rate	13MHz	13MHz

NovoFEL [54]of Russia is the highest average power infrared terahertz FEL device in the world. As shown in Fig. 3.46, the device has the function of energy recovery at room temperature. After three stages of upgrading and reconstruction, the energy gain of the main accelerator of the system can reach 10 *MeV*, the beam cluster charge energy can reach 1.5 nanocoulombs, the normalized emittance of the beam is 20 *mm*. *m*rad, the maximum repetition frequency is 90.2 *MHz*, the output signal frequency can be 1.25 *THz*-60 *THz*, and the average power can reach 500 *W*. The main beam parameters are shown in Table 3.4. It has the functions of single pulse high-resolution spectrum, low temperature and strong magnetic field conditions, combustion and detonation conditions, biological research conditions, imaging and holographic imaging.

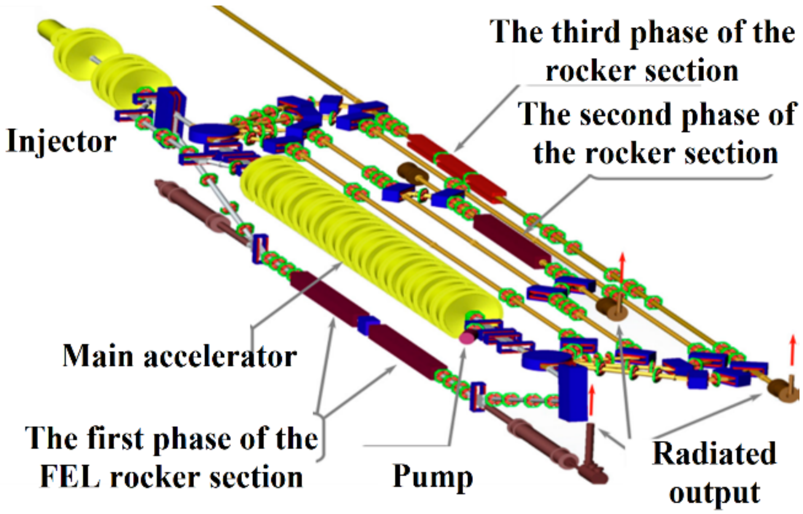


Fig. 3.46 NovoFEL in Russia

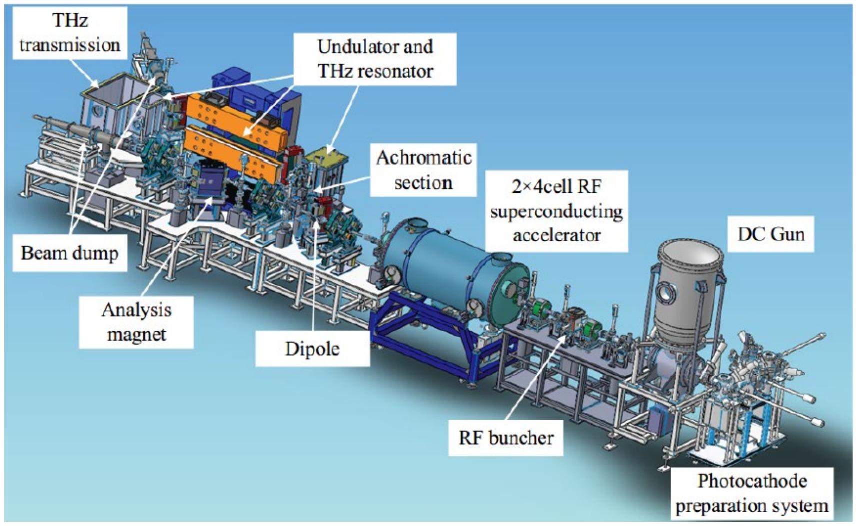
Tab. 3.4 Basic beam parameters of NovoFEL

Inject energy (MeV)	2
Main accelerator energy gain (MeV)	10
The amount of bundle charge (nC)	1.5
Normalized emissivity (mm.mrad)	20
Max. repetition rate (MHz)	90.2

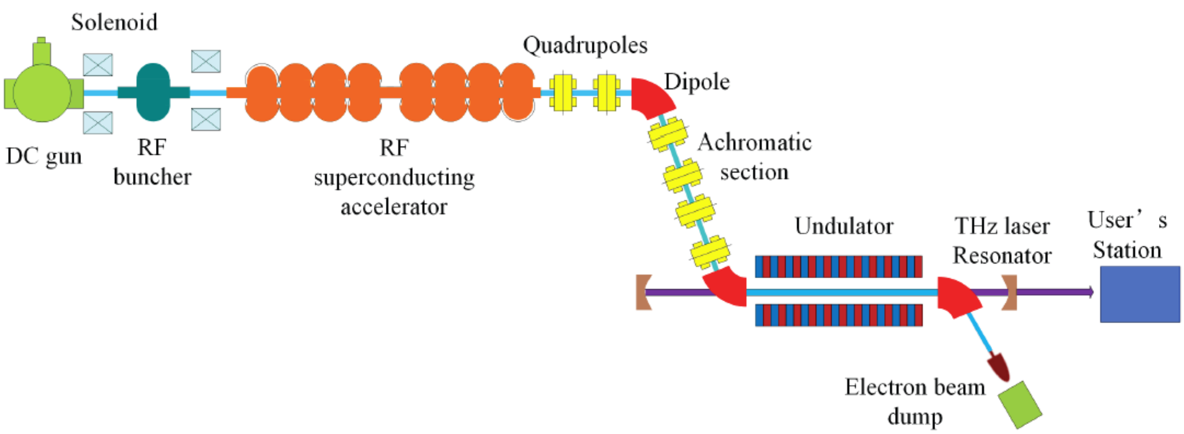
Tab. 3.5 Radiation parameters of NovoFEL

Stage	First	Second	Third
situation	2003	2009	building
Wavelength (μm)	90-240	30-90	5-30
Duty cycle	0.2-2%	0.2-1%	0.1-1%

The first terahertz FEL device (CTFEL)[55] independently developed in China was saturated and put into operation in Chengdu at the end of 2017, marking that China's terahertz technology has officially entered the FEL era. The CTFEL device operates stably at three frequency points of 1.99 *THz*, 2.41 *THz* and 2.92 *THz*. The average power is more than 10 *W*, and the maximum power is 17.9 *W*;/. The peak power of the micro pulse is more than 0.5 *MW*, and the maximum is 0.84 *MW*. By adjusting the electron beam energy and the wiggler magnetic field strength, the output frequency can be continuously adjustable.



(a)



(b)

Fig. 3.47 CTFEL facility (a)The Layout (b) Block diagram

As a new type of coherent strong terahertz light source, terahertz FEL with high average power and high peak power has essential applications in materials, biomedicine and other fields. Through systematic research on the interaction mechanism of strong terahertz wave and new materials, the biological response mechanism of THz electromagnetic radiation and DNA interaction, we have found the physical laws and experimental phenomena under strong terahertz wave environment. It provides a theoretical basis for new experimental research methods and new device design and development.

4. Conclusions

In this paper, the characteristics of THz waves are introduced, and the main application fields are described. The THz wave can be generated by many types of THz sources. Among the THz generating sources, the VED has important advantages, and the progresses of TWT, BWO, EIK/EIO, SP devices and reflex klystron are described. Furthermore, the large size and high power gyrotron and FEL are also described. From the development of many types of THz sources, it can be seen that the high power, width band, high efficiency and high stability of THz sources are highly focused on the main direction.

Acknowledgment

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