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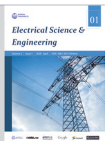

REVIEW

Terahertz (THz) Generator and Detection

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ABSTRACT

In the whole research process of electromagnetic wave, the research of terahertz wave belongs to a blank for a long time, which is the least known and least developed by far. But now, people are trying to make up the blank and develop terahertz better and better. The charm of terahertz wave originates from its multiple attributes, including electromagnetic field attribute, photon attribute and thermal attribute, which also attracts the attention of researchers in different fields and different countries, and also terahertz technology have been rated as one of the top ten technologies to change the future world by the United States. The multiple attributes of terahertz make it have broad application prospects in military and civil fields, such as medical imaging, astronomical observation, 6G communication, environmental monitoring and material analysis. It is no exaggeration to say that mastering terahertz technology means mastering the future. However, it is because of the multiple attributes of terahertz that the terahertz wave is difficult to be mastered. Although terahertz has been applied in some fields, controlling terahertz (such as generation and detection) is still an important issue. Nowadays, a variety of terahertz generation and detection technologies have been developed and continuously improved. In this paper, the main terahertz generation and detection technologies (including already practical and developing) are reviewed in terms of scientific and engineering principles, in order to provide a systematic and up-to-date reference for researchers in terahertz field.

1. Introduction of Terahertz (THz) Wave

In the electromagnetic spectrum, a band between microwave and infrared is called terahertz (THz), as shown in Figure 1. In fact, the definition for standard range of terahertz wave is still controversial. Now most researchers accept the definition of 0.1-10 THz, which corresponds to the electromagnetic wave with the wavelength range of 3 mm-30 μm (1 THz = 10^{12} Hz, corresponding to the wavelength of 300 μm) [1]. The photon energy of THz wave is small, and the photon energy of 1 THz is 4.14 meV. Due to the lack of effective technical means to generate and detect terahertz wave, this band is called "terahertz gap" for a long time. Terahertz radiation exists everywhere in nature, but the absorption of terahertz wave by the atmosphere of the earth (especially polar molecules in atmosphere such as water) is also very strong, resulting in the weak terahertz signal intensity in nature [2]. Terahertz waves have a wide range of applications, and the schematic summary as shown in Figure 2.

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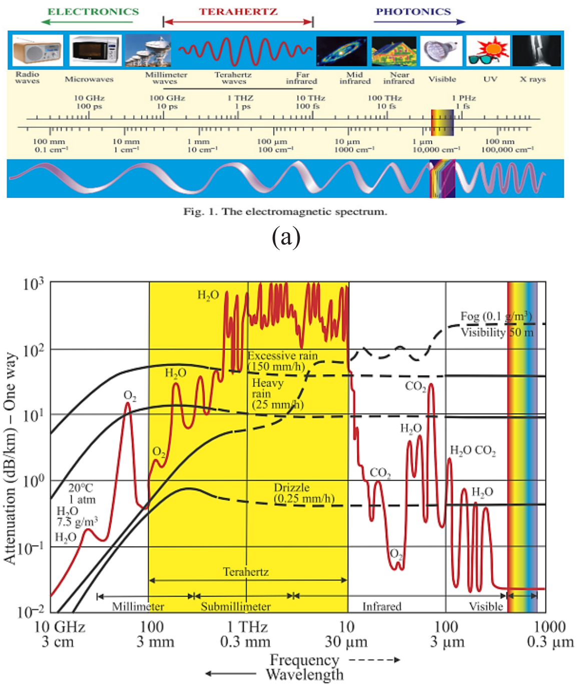


(a)

(b)

Figure 1. (a) The position of THz in electromagnetic spectrum, and (b) the atmosphere induced attenuation from visible to radio frequency range [2]. Copyright © 2011 SEP, Warsaw

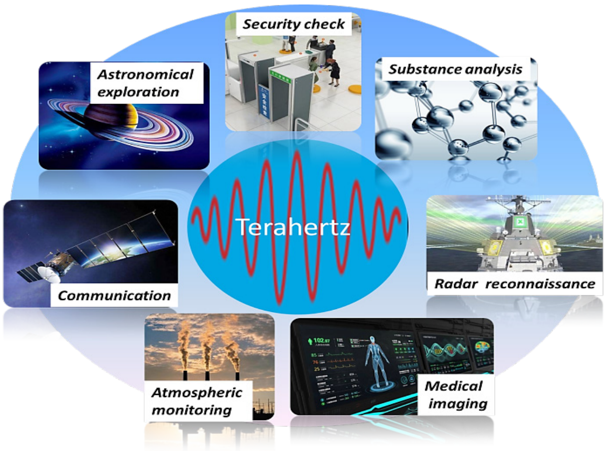
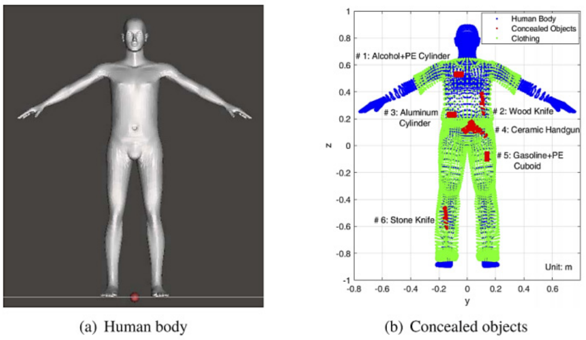


Figure 2. The wide application range of THz

Substance detection and analysis [3-5]: the vibrational and rotational energy levels of many molecules, lattice vibrational phonons of some crystals, and the oscillatory motion of biomolecules are in terahertz band. According to the analysis of terahertz spectrum of these substances, we can obtain the complex structure inside these substances.

Atmospheric environment monitoring [6-8]: terahertz remote sensing technology can be used to detect the information of atmospheric environment, including water vapor, cloud layer, ozone content and temperature in the atmosphere. In addition, chlorine, sulfur, nitrogen and other elemental compounds have independent characteristic absorption spectrum in terahertz band. Hence, using this special sensitivity, we can monitor the atmospheric environment through terahertz remote sensing, and timely understand the development of environmental problems such as pollution gases, ozone holes and other harmful human survival. Terahertz remote sensing also has the unique advantage of all-weather observation, and has an important application prospect in the research fields of atmospheric composition detection and environmental monitoring.

Security check [9-11]: the photon energy of terahertz wave is very low (1 THz is about equivalent to 4.14 meV), which will not cause ionizing radiation and is safe for human body. Compared with microwave, the wavelength of terahertz wave is smaller and the imaging spatial resolution can be higher. Furthermore, many toxic and harmful substances or dangerous explosives have unique "terahertz fingerprint spectrum" characteristics in terahertz band, so terahertz technology also has great potential in the field of public security, which can be applied to the active and passive detection and identification of concealed drugs, pistols, knives, explosives and other contraband in airports, stations, subways and other occasions. Figure 3 shows the practical application of THz security check, and some dangerous things such as pistol and knife, can be seen.



(a) Human body

(b) Concealed objects

Figure 3. The THz security check images [9]. © 2020 Optical Society of America

Medical imaging [12-14]: terahertz wave does not interact with nonpolar molecules so that terahertz has a good penetrability for nonpolar molecules. However, the absorption of terahertz wave by water molecules is very strong. Different water content of biological organs with different characteristics leads to their different absorption and reflection efficiency of terahertz wave. Meanwhile, a variety of biological components such as protein and fat

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possess different radiation-absorbing. Hence, it can take advantage of these characteristics to do terahertz imaging, and biological organs can be easily judged with high sensitivity. Figure 4 shows the THz image of brain cancer, it can be seen that the results of terahertz imaging directly reflect the severity of brain cancer.

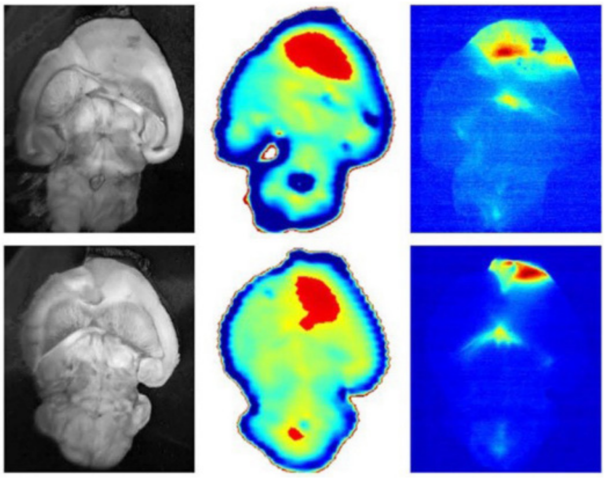

Figure 4. THz images (middle part) show brain cancer [14].

Terahertz communication [15-18]: according to Shannon formula, the channel capacity of electromagnetic wave is directly proportional to its bandwidth. Compared with the existing wireless communication technology, terahertz band has a higher frequency, so it can obtain a larger signal transmission bandwidth. The absorption of THz wave in the atmosphere is very strong, but there are still several small absorption windows in the low-frequency THz band, including 0.15 THz, 0.23 THz, 0.34 THz, 0.67 THz and 0.85 THz, which makes THz can be applied to the atmospheric short-range secure communication. In 2019, the World Radiocomunication Conferences (WRC-19) clearly points out that the total 137 THz bandwidth resources of 275-296 GHz, 306-313 GHz, 318-333 GHz and 356-450 GHz bands can be used for fixed and land mobile service applications without restrictions. In the future, terahertz technology is expected greatly in those fields such as the internet of things, 6G communication, and space communication.

Astronomical exploration [19-21]: according to statistics, about half of the photon energy and 98% of the photon number in the universe fall in the terahertz band. Terahertz is an important band for cosmic observation, especially for understanding the early evolution of the universe. Compared with infrared and visible bands, terahertz wave has a stronger ability to penetrate interstellar dust, which is of great significance for astronomical observation and research. At present, many countries have launched or are launching astronomical exploration plans in terahertz band. Among them, the Atacama Large Millimeter/Submillimeter Array (ALMA), and the European Herschel and Planck Space Telescopes, etc., are more successful and useful for observing the background radiation of the universe, and have been successfully used, as shown in Figure 5.

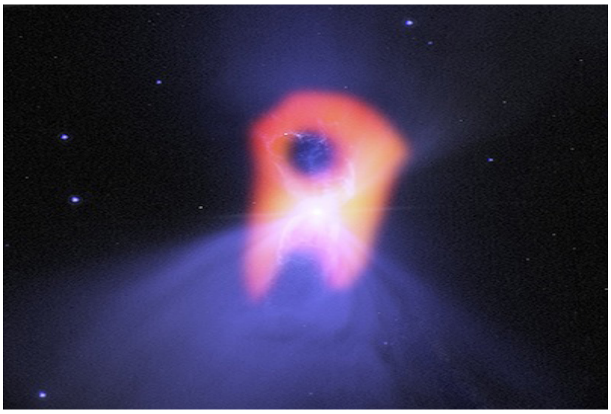

Figure 5. ALMA detects "Boomerang Nebula" that has only 1 K temperature, using THz wave. Copyright ©2013 ALMA

Terahertz radar [22-24]: still, it is difficult for microwave radar to directly obtain the full-scale measurement data of large-scale targets. At present, it is a feasible scheme to use the scaled model of the target (the small-scale target model) to derive the full-scale results of the target from the high-frequency measurement results. However, for super large targets such as aircraft carrier and large aircraft, it is still difficult to measure their scaled model size in microwave frequency band. Thus, we need a larger scaling and a higher measurement frequency band. Terahertz has a high measurement frequency band and can meet the measurement requirements of large-scale target and large-scale scaled model. Nowadays, terahertz radar is the high technology that every country wants to seize. Radar cross section area (RCS) in terahertz radar technology plays an important role in target recognition and imaging, and means the physical quantity of the echo intensity produced by the target under the radar wave irradiation, as shown in Figure 6.

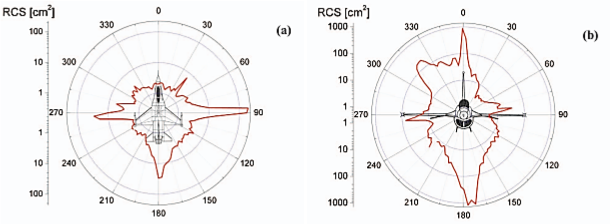

Figure 6. Terahertz radar obtains (a) polar and (b) azimuthal RCS information of the aircraft fighter F-16 model [24]. Copyright ©2010 Optical Society of America

2. THz generation Technology

Table 1. The THz generation technologies and some features

Technology	Duration	Coherence	Section
Femtosecond pulse laser excited photoconductive antenna	Pulse	Incoherent	2.1.1
Femtosecond pulse inducing the optical rectification of nonlinear optical crystal	Pulse	Incoherent	2.1.2
Electron accelerator (bremsstrahlung and synchrotron radiation)	Pulse	Coherent	2.1.3
Optical mixing based on semiconductor materials	Continuous	Incoherent	2.2.1
Difference frequency and optical parametric amplification based on nonlinear crystal	Continuous	Incoherent	2.2.2
Laser (P-type Ge laser, free electron laser, far-IR gas laser, quantum cascade laser)	Continuous	Coherent	2.2.3
Backward wave oscillator	Continuous	Incoherent	2.2.4
Microwave frequency multiplication	Continuous	Incoherent	2.2.5

In order to control terahertz, terahertz radiation generation is an important issue. The generation of terahertz radiation benefits from the development of ultrafast optics, nonlinear optical crystal material technology and micro-nano processing technology. According to the duration of THz radiation, they can be divided into THz pulse radiation and THz continuous radiation. Due to the feature of frequency and time, they can be divided into time-domain THz radiation and frequency-domain THz radiation. Further, relying to the coherence, the radiation generator also can be divided into coherent THz or incoherent THz. In this review, we discuss them from the perspective of duration of THz radiation. The technology for generating terahertz radiation is summarized in Table 1.

2.1 Generation of Pulsed THz Radiation

2.1.1 Femtosecond Pulse Laser Excited Photoconductive Antenna

The most common way to generate terahertz radiation is to use photoconductive antenna [25-26], as shown in the Figure 7. Coplanar two electrodes are evaporated on one side of semiconductor materials (such as GaAs), and two electrodes are connected to DC bias voltage. Because of the difference of electrode gap size, the electrode gap which is far less than THz wavelength is called small aperture photoconductive antenna (SAPA), and the electrode gap which is far greater than THz wavelength is called large aperture photoconductive antenna (LAPA). A femtosecond laser pulse (with a wavelength of 800 nm) is used to excite the semiconductor materials between the electrodes to obtain photo-generated carriers (mainly electrons) that will accelerate and attenuate under bias voltage to radiate electromagnetic pulses. Because the carrier lifetime of the semiconductor material used is sub-picosecond, the electromagnetic pulse radiated is also sub-picosecond, which just falls in the terahertz wavelength range. Shorter femtosecond pulse can obtain higher frequency THz wave.

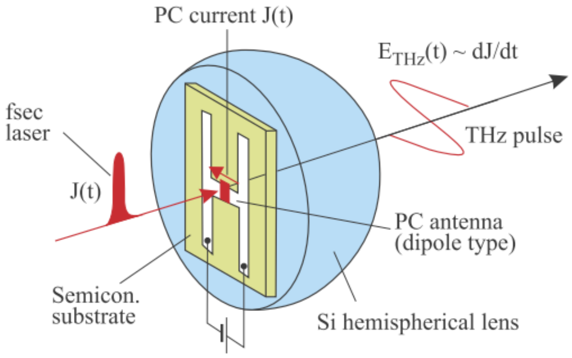

Figure 7. The schematic process of femtosecond pulse laser excited photoconductive antenna inducing THz [2]. Copyright © 2011 SEP, Warsaw

The radiation and propagation mechanisms of THz pulse to free space are in accordance with the electric dipole radiation model. The space THz radiation field of small aperture photoconductive antenna E_{THz} can be expressed as follows:

$$\boldsymbol{E}_{THz}=\frac{\mu w}{4\pi}\frac{\sin\theta}{r}\frac{d}{dt_r}\left[I_{PC}\left(t_r\right)\right]\hat{\theta} \quad (1)$$

Where μ is the vacuum magnetic permeability, w is the spot size of femtosecond laser beam, θ is the angle between the terahertz radiation direction and the plane of the material irradiated by the femtosecond laser, r is the radiation distance, t_r is the time delay from terahertz radiation to a certain point in the space with distance r, and I_{PC} is the photocurrent. In addition, because the THz wavelength is larger than the aperture size, the THz radiation direction is seriously scattered, hence the collimating lens (high resistance silicon material) is generally integrated on the back of the device. The terahertz signal generated by the small aperture photoconductive antenna is low in intensity, but low in heating, and can work stably for a long time. For high power terahertz pulse generation, large aperture photoconductive antenna is needed. The large aperture photoconductive antenna has a large stimulated area, also needs high DC bias voltage and amplified femtosecond laser pulse. The spatial radiation field E_{THz} of large aperture photoconductive antenna can be expressed as:

$$\boldsymbol{E}_{THz} = -\frac{\mu A}{4\pi}\frac{E_b}{z}\frac{\frac{d\delta(t)}{dt}}{\left[\frac{\delta(t)Z_0}{1+\sqrt{\varepsilon}}+1\right]^2} \tag{2}$$

Where A is the photoexcited area, E_b is the bias electric field, z is the THz radiation distance, δ (t) is the surface conductivity at the time of t, $Z_0 = 377\ \Omega$ means the impedance in the free space, and ε is the dielectric constant of the material. Although the large aperture photoconductive antenna has high terahertz output power, it is not easy to work stably for a long time due to its high heating.

2.1.2 Femtosecond Pulse Inducing the Optical Rectification of Nonlinear Optical Crystal

The interaction of optical field and nonlinear optical crystal (such as ZnTe) makes the electric polarization of nonlinear optical crystal. When the light intensity is weak, the electric polarization intensity P is directly proportional to the optical field, which is a linear optical effect. However, when the light intensity is too high, the nonlinear optical effect will be excited. At this time, the electric polarization intensity and the optical field intensity are not in direct proportion. The optical rectification belongs to the second-order nonlinear optical effect [27]. The total polarization $P^{(2)}$ caused by the optical rectification is proportional to the applied light intensity I, which is expressed as:

$$P^{(2)} = 2\varepsilon_0 x^{(2)} \,|\, E_0 \,|^2 \propto I \tag{3}$$

Where $\chi^{(2)}$ is the second-order nonlinear optical susceptibility corresponding to the optical rectification process. E_0 is the amplitude of incident light field. Considering the rectification polarization caused by femtosecond optical pulse, the incident optical field pulse E(t) is set as:

$$\boldsymbol{E}(t) = E_0(t)e^{-i\omega t} \tag{4}$$

Where ω is the light angle frequency. As shown in Figure 8, the nonlinear polarization P(t) of the optical rectification will reappear the envelope of the optical pulse, and the final THz field E_T can be obtained by resolving the relationship of E_T and P(t) the spectral bandwidth radiated is about the reciprocal of the optical pulse time. Because the optical pulse time is in the category of 10-100 fs, that is to say, the radiation spectral bandwidth is sub-picosecond, thus the femtosecond pulse optical rectification can generate THz pulse. Ideally, the propagation speed v_T of terahertz pulse is the same as that of optical pulse v_o. At this time, the terahertz radiation field E_T propagating along the z-axis is expressed as:

$$E_T = Cl[1-4a(t-\frac{z}{v_0})^2\exp[-2\mathrm{a}(t-\frac{z}{v_0})^2] \tag{5}$$

Where C is a constant, l is the transmission length of terahertz in the crystal, and a is the angle between the light field and terahertz field. It should be pointed out that the expression of terahertz radiation field is different for different nonlinear optical crystals and different polarizing crystal planes of the same optical crystal. Furthermore, the propagation speed of terahertz and optical pulse is difficult to be the same in fact. Coupled with the linear absorption of crystal, the real representation of terahertz radiation field is very complex.

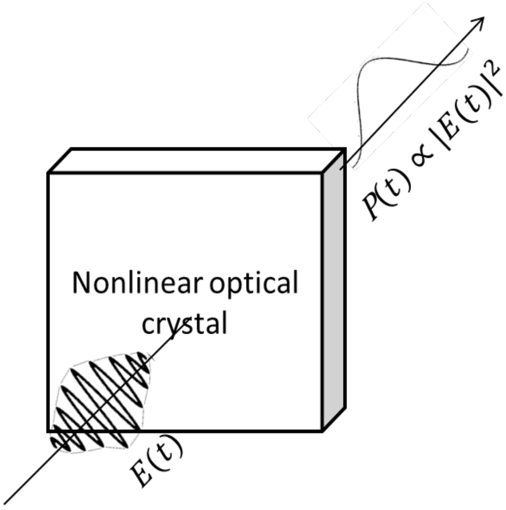

Figure 8. The schematic for femtosecond pulse excited nonlinear optical crystal inducing the optical rectification

2.1.3 Electron Accelerator (Bremsstrahlung and Synchrotron Radiation)

The THz radiation produced by photoconductive antenna and nonlinear crystal is incoherent. The electron accelerator provides a solution for the generation of coherent terahertz radiation. The principle is as shown in the Figure 9. When femtosecond pulse light is incident to semiconductor material surface (such as GaAs) or photocathode electron cavity, it will generate sub-picosecond electron beam that will be further accelerated to 10-100 meV (become relativistic electron) through linear particle accelerator. If the electron beam bombards the metal target at this time, the coherent terahertz radiation will be produced when the electron decelerates rapidly, which is called bremsstrahlung (Figure 9a) [28]. On the other hand, if the electron beam deflects through the magnetic field to make a circular motion, then the radiation coherent terahertz wave is called synchrotron radiation (Figure 9b) [29], and the terahertz radiation power generated by synchrotron radiation can be as high as 20 W. After the electron beam is accelerated, its size is close to radiation wavelength. The emission of a single electron is superimposed in the same phase, so the total THz radiation power is greatly improved.

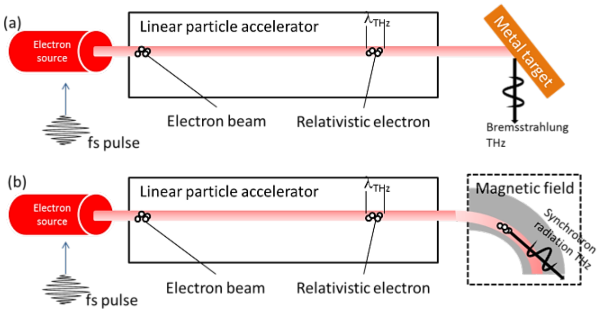

Figure 9. The schematic (a) bremsstrahlung and (b) synchrotron radiation

2.2 Continuous THz Radiation Generation

2.2.1 Optical Mixing based on Semiconductor Materials

As shown in Figure 10, the structure of optical mixing device is similar to that of photoconductive antenna in Section 2.1.1. The main materials in optical mixers are low temperature growth GaAs (LT-GaAs) with high electron mobility and short lifetime [30]. The metal electrode is generally made into interdigital electrode, with the logarithmic antenna structure of outward spiral, and can also be made into dipole photoconductive antenna structure. The excitation source uses two different frequencies (w_1, w_2) in the wavelength range of 800-850 nm. Beat frequency light is received by the metal antenna and mixed in an optical mixer. The frequency after mixing is located in the terahertz band, which is the two-photon frequency difference $w_T = w_1 - w_2$. This method is also called optical heterodyne down conversion. By enlarging the excitation area and irradiating the area continuously with high power laser, the THz radiation power can be increased. In addition, the THz radiation power of the device can also be increased by using semiconductor heterojunction instead of LT-GaAs.

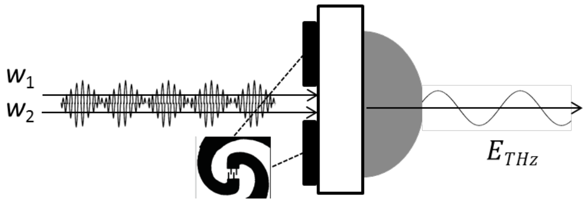

Figure 10. The schematic structure of optical mixing device.

2.2.2 Difference Frequency and Optical Parametric Amplification based on Nonlinear Crystal

As shown in Figure 11, when two beat frequencies (w_1, w_2) of different frequencies are incident into a nonlinear crystal, the difference frequency $w_T = w_1 - w_2$ located in the terahertz band is produced, which is caused by the second-order nonlinear optical effect of the crystal [31]. The optical rectification effect enables the generated difference frequency continuous wave (nonlinear polarization reappear the envelope of two difference frequencies), similar to that in 2.1.2 Section. In most nonlinear crystals, GaSe has the best effect, and other crystals such as quartz, $LiNbO_3$, gap and DAST have also been proved to be available. If a pumping photon w_P is transformed into two photons (w_i, w_T) with lower energy, and the sum of the two photons is the same as the energy of w_P photon (that is, $w_P = w_i + w_T$), which involves the case of optical parametric amplification [32]. As shown in Figure 12, the w_i is called idle frequency photon, and w_T is in terahertz band. When the wave vector of photon meets $k_P = k_i + k_T$, both idle frequency light and terahertz light can be amplified. $LiNbO_3$ is the core material of optical parametric process, and the wavelength of pump light is generally 1.064 μm. By changing the angle between the pump light and the idle light, the terahertz frequency can be continuously adjustable.

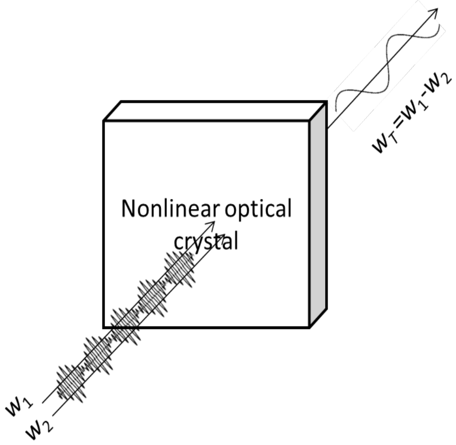

Figure 11. The schematic THz generation based on difference frequency through nonlinear crystal

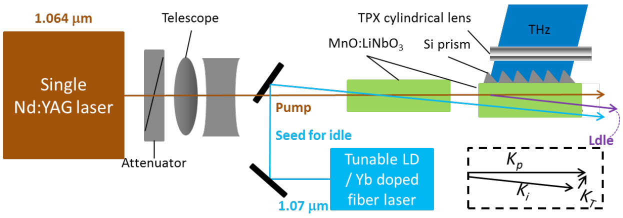

Figure 12. The schematic THz optical parameter generator

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2.2.3 Laser (P-type Germanium Laser, Free Electron Laser, Far Infrared Gas Laser, Quantum Cascade Laser)

One of the most important characteristics of laser is to obtain large output gain through resonant cavity. ***P-type germanium laser*** [33]: P-type germanium (Ge) is generally realized by doping beryllium. When an orthogonal magnetic field is applied, a four level system will form in P-type germanium, as shown in the Figure 13(a). At low temperature (< 40K), the applied electric field is strong enough to complete a particle number inversion between the light hole (LH) state and the heavy hole (HH) state. At this time, the hole in the high energy state will emit an optical phonon w_{op} and complete the transition to the low energy state. The THz wave occurs when the hole accumulated in the stable Landau level transits to the lower LH state. ***Free electron laser*** [34]: similar to synchrotron radiation, free electron laser also use electron accelerator. As shown in the Figure 13(b), the electrons are accelerated to near the speed of light (i.e. become relativistic electrons), and then enter the resonant cavity. The resonance is in the magnetic field array with alternating magnetic poles, which is called Wiggler magnetic array. The electrons do sinusoidal oscillation to emit coherent terahertz radiation in the magnetic field, and the terahertz laser beam produced is amplified in the resonant cavity for many times. The biggest disadvantage of free electron laser is that it takes up a lot of space and costs a lot. ***Far infrared gas laser*** [35]: the gain material in the resonant cavity can be some gas molecules, such as CH_3F, CH_3OH and CH_2F_2. The pump source uses generally CO_2 gas laser. If electrons transition among the rotational energy levels of these gas molecules, they can radiate terahertz waves. ***Quantum cascade laser*** [36]: the core of quantum cascade laser is to construct periodic structure alternation superlattice, which is different from the conventional semiconductor in which the mission of electron is terminated after only one transition from high energy level to low energy level. The cascade structure makes the electron enter the next cycle after one transition, and each transition can produce the same frequency THz radiation, as shown in the Figure 13(c). A typical quantum cascade laser belongs to a three-level system. The terahertz radiation transition occurs between the third and the second levels. Then, by adjusting the applied bias electric field, the first level of the previous period is consistent with the third level of the next period. At this time, the first level electrons of the previous period will be injected into the third level of the next period for reuse.

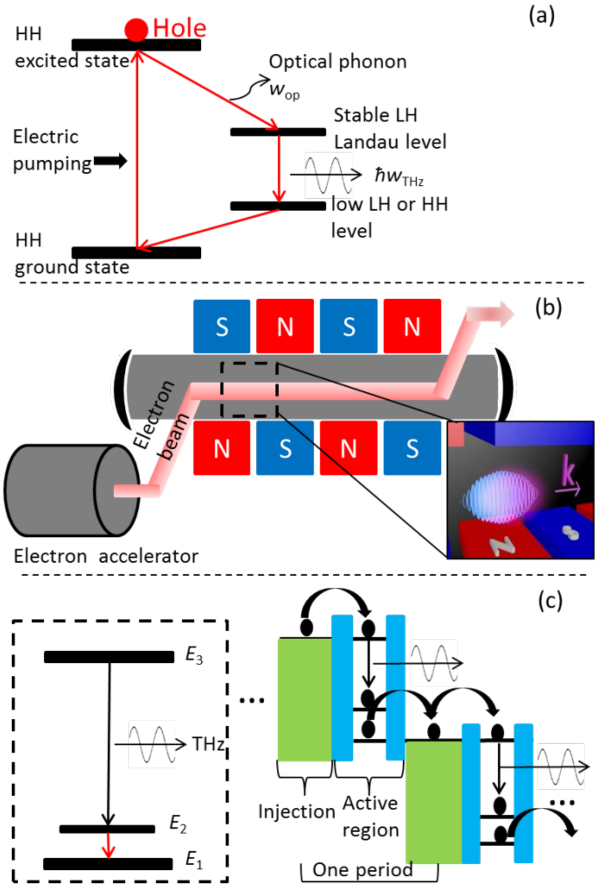

Figure 13. (a) A four level system in P-type Ge under an orthogonal magnetic field, (b) the schematic free electron laser, and (c) the schematic principle of quantum cascade laser

2.2.4 Backward Wave Oscillator

The backward wave oscillator consists of an electron vacuum tube, a group of calibration magnet, and a metal gate, as shown in the Figure 14. Under high voltage, the cathode emits electrons to move towards the anode. The two magnets with different polarity are located at the two ends of the vacuum tube, respectively, which provides a strong magnetic field. The function of the magnetic field is to bunch the electrons and avoid the loss of energy caused by the electrons hitting the tube wall. The metal gate has a comb like structure, and its function is to slow down the electron in the process of moving. The change of electron velocity radiates terahertz electromagnetic wave [37]. The move direction of electromagnetic wave is opposite to the move direction of electron beam, and electromagnetic wave increases in intensity, so it is called backward wave oscillation. Finally, terahertz radiation is longitudinally output to free space. Backward wave oscillation structure requires the equipment to be precise enough. Its magnet

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takes up most of volume. The terahertz output wavelength is determined by the electronic speed, so by changing the electronic speed under applied voltage conditions, it can be adjusted at 0.5-1.5 THz, and the continuous wave output power can reach 1 mW.

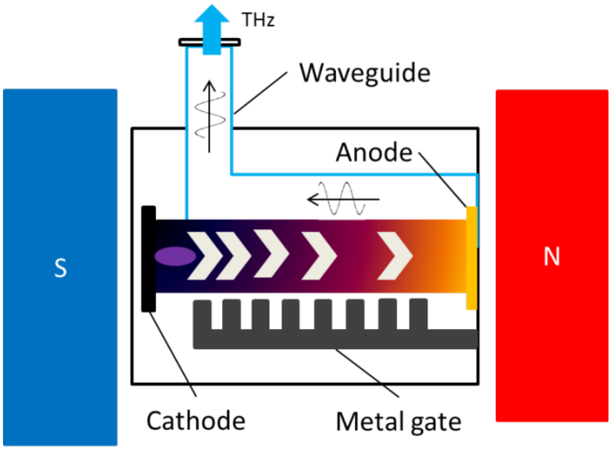

Figure 14. The schematic principle of backward wave oscillator.

2.2.5 Microwave Frequency Multiplication

Microwave frequency multiplication technology is the product of pure electronics technology [38]. The microwave source includes Gunn oscillator and tunnel diode. When it is connected with the resonator, the DC electric signal can be converted into AC microwave signal. Then, the microwave signal is input into the frequency multiplier to generate THz wave. The core of the frequency multiplier is the Schottky barrier diode (mainly composed of Au and GaAs), as shown in the Figure 15. Microwave frequency doubling is similar to the generation of light wave harmonics in nonlinear crystals. Microwave frequency multiplier can be cascaded, so a microwave can be multiplied many times to form a higher frequency terahertz wave, but the wavelength cannot be adjusted continuously, and the higher the frequency has the faster the output power decays.

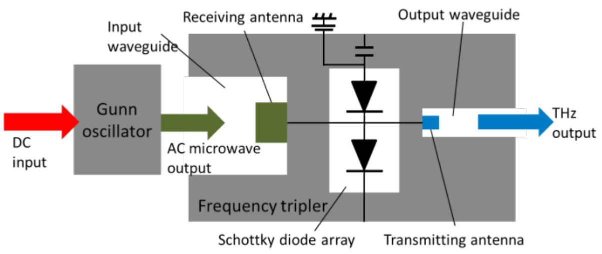

Figure 15. A schematic principle for THz generation by triple frequency of microwave

3. THz Detection Technology

Nowadays, the development of terahertz detectors with high response, easy to use, easy to integrate and low cost has become a research hotspot and focus in this field. Terahertz wave is between microwave and infrared, and it has the particularity of electricity and optics, so there are abundant ways to detect terahertz in as summary in Table 2.

Table 2. The THz detection technologies and some features

Technology	**Attribute based**	**Detection coherence**	**Section**
Photoconductive antenna detector	Electromagnetic field	Incoherent	3.2.1
Electro optical sampling and optical rectification	Electromagnetic field	Coherent	3.2.2
Nonlinear mixing and difference frequency detector	Electromagnetic field	Incoherent/ coherent	3.2.3
Glow discharge detector	Electromagnetic field	Incoherent	3.2.4
Surface plasmon detector	Electromagnetic field	Incoherent	3.2.5
Golay detector	Thermal effect	Incoherent	3.2.6
Bolometer	Thermal effect	Incoherent	3.2.7
Thermoelectric detector	Thermal effect	Incoherent	3.2.8
Pyroelectric detector	Thermal effect	Incoherent	3.2.9
Barrier detector	Photonic property	Incoherent	3.2.10
Electron bound state transition detector (quantum well detector)	Photonic property	Incoherent	3.2.11

Considering the characteristics of terahertz as electromagnetic field, terahertz detection can be realized. Terahertz electric fields cause electronic motion, such as photoconductive antenna detectors. Terahertz electric field induces polarization of materials, and produces a series of changes, such as electro-optical sampling and optical rectification. In addition, the interaction between THz electric field and some substances can excite the surface plasma of substances, which will cause the change of electrical signal, so as to realize THz detection, such as surface plasma detector.

Considering the thermal effect of terahertz, many detection techniques have been created. When some materials are irradiated by electromagnetic wave, they will produce thermal effect, that is, the increase of temperature after absorbing the energy of incident electromagnetic wave will cause the change of physical characteristics such as resistivity, volume or spontaneous polarization intensity. Through the measurement of these changes, the terahertz thermal detector can detect the terahertz wave. Because the detection process is only related to the thermal energy of the incident electromagnetic wave, the terahertz

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thermal detector has a wide range of response frequency, which can generally cover all terahertz bands. Common THz thermal detectors include Golay detector, bolometer, pyroelectric detector and thermoelectric detector.

The optical properties of terahertz are also used. Among the photodetectors, semiconductor based intrinsic photodetectors are usually used to detect ultraviolet to infrared light. However, because the terahertz photon energy is far less than the intrinsic forbidden band width, it is difficult to detect via the transition of electrons between the intrinsic bands. Photodetectors working in terahertz band usually use the non-intrinsic transition, in-band transition and sub-band transition effects of materials. Due to the interference of thermal radiation from any object in background, these detectors need to work in deep and low temperature environment, such as some barrier detectors and quantum well detector.

3.1 Detector Performance Evaluation Index

Frequency range: that is, the effective frequency range that the terahertz detector can detect. No matter what the THz detector is a narrow-band or a wide-band, users need to know whether the THz detector is effective or invalid for a certain frequency range. ***Noise:*** THz detectors are used in most environments with a variety of inherent current signals. These effects come from temperature, vibration, humidity, ambient light and other electromagnetic radiation, etc., and itself factors of detector materials such as impurities, lattice vibration, electronic motion, etc. All these current signals can be called noise. Ideally, the detector does not have any noise, which makes the detected THz signal very satisfactory. But in fact, noise is inevitable. If the noise is not handled well, it will seriously affect the terahertz detection. The main indicators related to noise are signal-to-noise ratio (SNR) and normalized detectivity (D^*). The signal-to-noise ratio (SNR) represents a proportional relationship between the noise and the THz signal. The normalized detectivity is expressed as: $\boldsymbol{D^*} = \sqrt{A \times \Delta f} \,/\, NEP$, where A is the effective detection area of the device, Δf is the amplifier bandwidth, and NEP is the noise equivalent power which is defined as the incident light power at the unit signal-to-noise ratio. The higher the D^* means the better the detectability. ***Responsivity:*** the responsivity is divided into voltage responsivity and current responsivity, which are the voltage (V) and current (I) signal under unit THz radiation power P and expressed as $\mathrm{d}V/\mathrm{d}P$ and $\mathrm{d}I/\mathrm{d}P$ respectively. At the same time, there is also a frequency response, which is expressed as $R(f) = R_0/[1+(2\pi f\tau)^2]^{1/2}$. $R(f)$ is the response at the frequency f, R_0 is the response at the frequency 0, τ is the response time of the detector which is determined by the material and external circuit. Other indicators include polarizability and coherence.

3.2 The Main Types of THz Detectors

3.2.1 Photoconductive Antenna Detector

The photoconductive antenna described in Section 2.1.1 can not only generate terahertz radiation, but also be used to detect terahertz radiation [2]. The detection principle is opposite to the production principle, as shown in the Figure 16(a). When the photoconductive antenna detects terahertz, the electrode does not need to be biased, but it needs to connect an ammeter to detect the current. Terahertz wave is incident to semiconductor material through one side of silicon lens of photoconductive antenna, and carriers are produced when femtosecond laser irradiates to one side of electrode of semiconductor material. Terahertz can be detected when the carriers are drove by terahertz electric field and generates a current signal. However, it should be pointed out that the detected photocurrent signal is not a copy of the terahertz waveform, but is determined by the incident terahertz field and the surface conductivity together. Therefore, to obtain the final terahertz amplitude signal, a complex mathematical deconvolution operation is necessary. The most typical application of generation and detection based on photoconductive antenna is to construct terahertz time domain system (THz-TDS), as shown in the Figure 16(b).

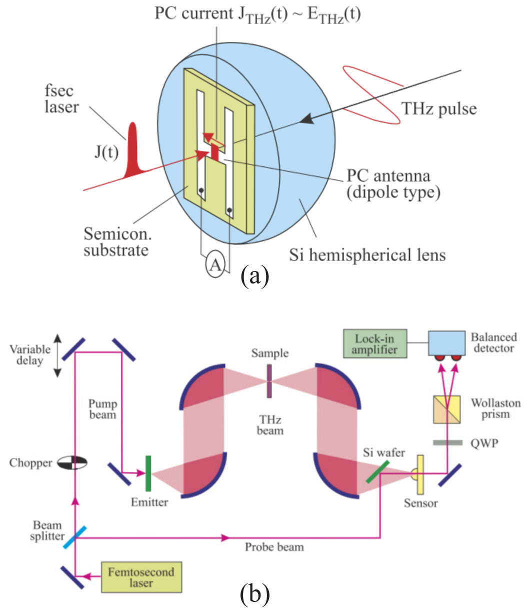

Figure 16. (a) The schematic photoconductive antenna detector, and (b) the schematic picture of THz-TDS [2]. Copyright © 2011 SEP, Warsaw

3.2.2 Electro Optical Sampling and Optical Rectification

The terahertz signal detected by the photoconductive antenna is still the intensity signal, but the electric field phase and other information cannot be determined. A good solution based on free space electro-optic sampling is proposed [39]. The basic mechanism of electro-optical sampling is the Pockels effect, which is closely related to the optical rectification. In practical application, the process is as follows. As shown in Figure 17, terahertz wave and optical pulse (here optical pulse as a probe pulse) pass through the electro-optic (EO) crystal together. When there is no terahertz pulse, the polarization direction of the linearly polarized optical pulse does not change. After passing through a 1/4 wavelength plate, probe pulse turns into a circularly polarized light. The Wollaston prism decomposes subsequently the circularly polarized light into two vertical components with the same light intensity. The balance photodetector will eventually fail to detect the radiation intensity. However, if a terahertz pulse is incident on the EO crystal, the field induced birefringence will cause the probe pulse to produce elliptical polarization, which will be further converted into an elliptical polarization similar to circular polarization after passing through a quarter wavelength plate. Then, the elliptically polarized light is decomposed into two vertical components with different intensities by the Wollaston prism, which eventually causes the balance photodetector to detect the intensity difference. The intensity difference is proportional to the amplitude of terahertz field and also can reflect the phase information.

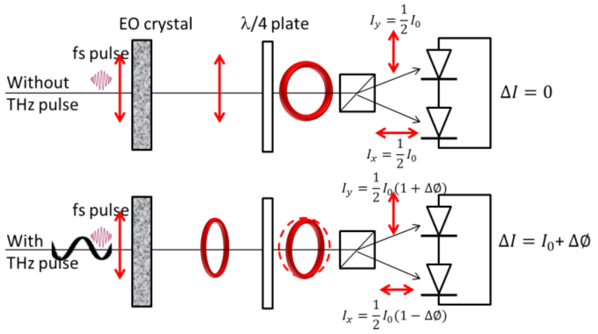

Figure 17. The typically schematic principle of EO sampling in free space

3.2.3 Nonlinear Mixing, Heterodyne and Difference Frequency Detector

As shown in Figure 18, THz radiation with frequency w_S is combined with reference frequency w_O (the reference frequency is generated by a local oscillator (LO) with definite frequency and power) [40]. THz radiation and reference radiation are combined in a nonlinear mixer, which induces a frequency sum (w_S+w_O) and a frequency difference (w_S-w_O). The latter means the down-conversion of THz signal, which usually falls in the microwave range. Subsequently, it can be detected indirectly by a mature detector (such as the microwave detector based on Schottky barrier diode). The difference frequency detection method can also be used for coherent detection of THz radiation of continuous wave, and can also determine the phase. Scanning the local oscillator signal can reappear the THz wave.

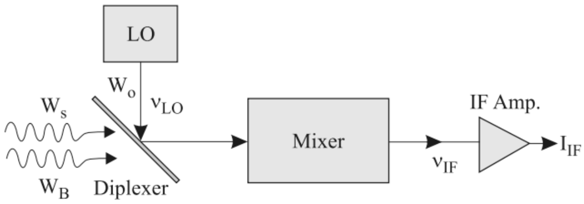

Figure 18. The schematic principle of nonlinear mixing and difference frequency detector (w_B is background radiation) [2]. Copyright © 2011 SEP, Warsaw

3.2.4 Glow Discharge Detector

Terahertz radiation hits the gas plasma (i.e. that in the commercial neon tube) that thus is heated by the inverse bremsstrahlung effect in the negative glow region, resulting in the increase in the ionization of the gas plasma [41]. At this time, the current flowing and the brightness in the tube will increase at the same time, and these phenomena can be monitored. On the one hand, the current in the neon tube is operated in the "normal" or "abnormal" range, and then, the current change is tested to determine the terahertz radiation. On the other hand, due to different brightness, optical technology is also utilized to monitor the brightness of the tube to determine terahertz radiation.

3.2.5 Surface Plasmon Detector

When the matching conditions of the incident terahertz wave vector and the materials' surface plasma wave vector are satisfied, and the matching conditions of the terahertz frequency and the materials' surface plasma frequency are satisfied, terahertz field can interact with the surface plasmon of materials to excite the surface plasma wave of materials. This interaction can be detected by designing appropriate device structures, such as field effect transistors (FET), as shown in Figure 19(a) [42]. In recent years, with the development of new materials and micro-nano technology, the surface plasmon detection method has been brought into full play and has a bright future. The surface

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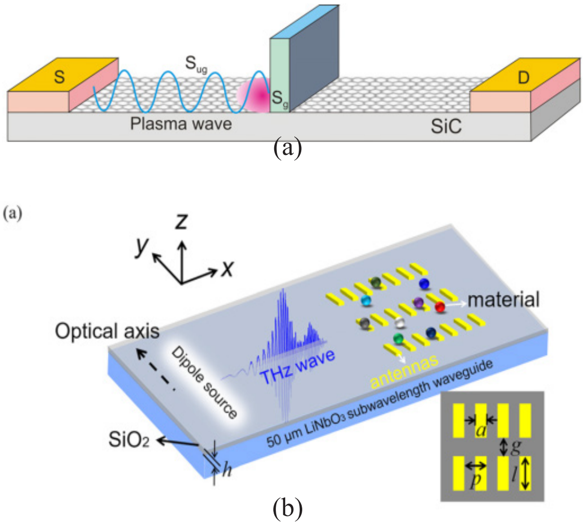
plasmon detector has the advantages of fast response, high detection, high sensitivity and gate voltage control.

A variety of material systems have been used to prepare THz detection devices based on the principle of plasmon resonance, such as high electron mobility transistors based on III-V family materials and graphene two-dimensional materials. Compared with many other types of room temperature terahertz detectors, these devices achieve higher detection sensitivity and faster response speed. At the same time, their preparation process is compatible with the current common semiconductor production process, which is conducive to the practical and commercial development of the devices.

Meanwhile, the artificial metamaterials (metasurfaces) structures are one of the emerging research hotspots in recent years [43], which are usually composed of periodic arrangements of meta-atoms that size is less than or equal to a specific wavelength. By studying the structure design of metamaterials, the terahertz wave can be modulated or absorbed. As shown in Figure 19(b), metamaterials are expected to use in various kinds of surface plasmon detectors, further improving the detection efficiency of THz [44].



(a)

(b)

Figure 19. (a) The FET surface plasmon detector [42], and (b) the use of metamaterials in THz sensing [44]

3.2.6 Golay Detector

Golay detector is one of the most common terahertz gas detectors, which is often used for astronomical detection and infrared band detection. As shown in the Figure 20, the core part of Golay detector is a closed gas chamber. The one wall of the chamber is equipped with a radiation absorber, and the other wall of the chamber is a flexible mirror. When terahertz irradiates, the radiator absorbs the heat of the terahertz wave. As heat builds up, the gas expands. This makes the flexible mirror deform, and then the probe beam deflect and terahertz is detected indirectly. The device can work at room temperature with low cost, low energy consumption, no wavelength selection, but it has a slow response and is easy to be interfered by its own thermal fluctuation, external radiation and vibration.

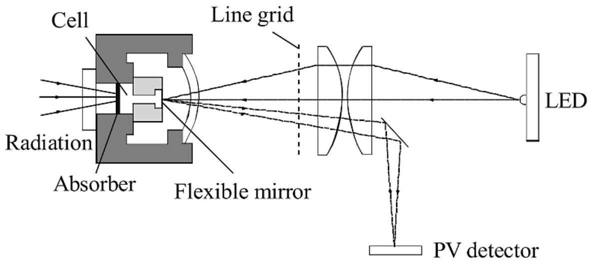


Figure 20. The schematic principle of Golay detector [2]. Copyright © 2011 SEP, Warsaw

3.2.7 Bolometer

Bolometer is another common terahertz thermal detector [1], including semiconductor bolometer, hot electron bolometer (HEB) and transition-edge sensor (TES) bolometer based on superconducting phase transition. The working principle of bolometer can be summarized as follows: when the device absorbs the energy of electromagnetic radiation, the lattice temperature or electron gas temperature of the photosensitive element in the device changes, resulting in the change of the conductivity or the electrochemical property of the photosensitive element, and then the electrical signal that can be detected is generated. The detectivity of this device is high, but it needs to work at very low temperature.

3.2.8 Thermoelectric (photo-thermoelectric) Detector

As shown in Figure 21, thermoelectric detector uses Seebeck effect to realize terahertz detection, which is generally made of two different materials as electrodes or the same material but different diameters. Further, photo-thermoelectric detector based on photo-thermoelectric effect emphasizes the thermal radiation characteristics of light [45]. Because of the difference of Seebeck coefficient, the temperature difference between two different electrode materials or the ends of different diameters of the same material will produce the potential difference. The medium receiving thermal radiation are various (such as graphene we are familiar with). Thermoelectric detector has the advantages of small size, durability and low price,

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but generally it has slow response, high noise and poor sensitivity.

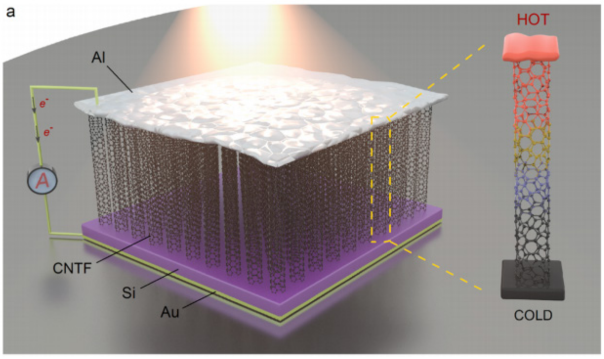

Figure 21. The THz thermoelectric detector based on Al-carbon nanotube-Au system [45]. Copyright © 2019 American Chemical Society

3.2.9 Pyroelectric Detector

Pyroelectric detector is based on pyroelectric material [46]. Pyroelectric materials can show spontaneous polarization, and the degree of polarization is usually related to temperature. When the heat of THz wave is absorbed by the pyroelectric material, the temperature of the material increases, which will change the electric field on the upper and lower surfaces of the material. Usually, the pyroelectric material is usually inserted into the capacitor as a medium. As a results, the THz can be monitored by test the change in electrical performance of capacitor. Pyroelectric materials can work at room temperature and have compact and simple structure. But the noise is strong, the response is slow, and the sensitivity is still low.

3.2.10 Barrier Detector

By constructing devices with electronic barriers, the most common ones are Schottky diodes [1], and other ones are tunnel diodes, superconductor-insulator-superconductor or superconductor tunnel junctions. As shown in Figure 22, the terahertz field acts on one side of the barrier, and the electron gains energy across the barrier, which makes the device obtain current signal. Because the diode can operate under zero bias voltage, it can effectively reduce the device noise, and the response speed is faster when detecting terahertz at room temperature. However, because the potential barrier is a certain value, the electron must obtain the corresponding energy in order to effectively transition, which makes the device often work in the narrow band and cannot realize the wideband detection.

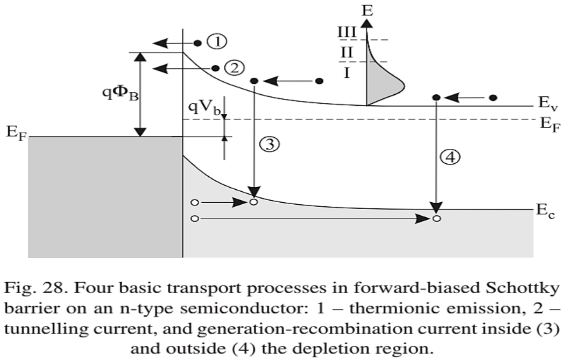

Figure 22. The schematic principle of Schottky barrier THz detection [2]. Copyright © 2011 SEP, Warsaw

3.2.11 Electron Bound State Transition Detector

At low temperature, electrons combine with atoms that supply electrons, and electrons in certain bound states can absorb terahertz photons and transition to high energy states. The device can be realized by doping the intrinsic semiconductor to building a quantum well [47,48], as shown in Figure 23. Terahertz light makes the electrons on the impurity bound state transition to the unbound state. Affected by the well parameters, the quantum well detector belongs to a narrow band, but by adjusting the transition energy between sub-bands, the detection frequency range can be widened. These devices have fast detection response, but low quantum efficiency and need low temperature environment.

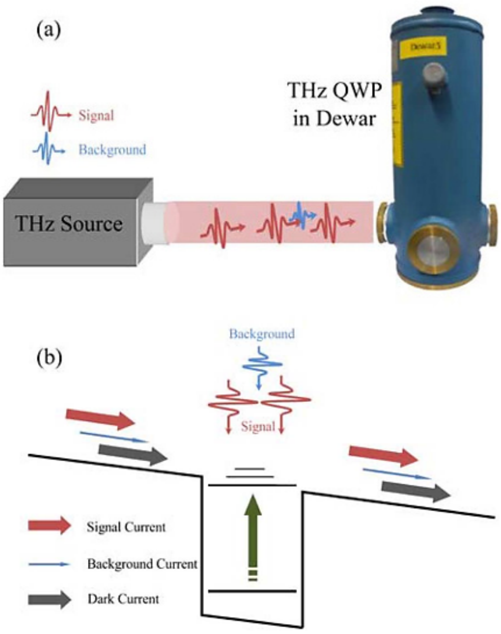

Figure 23. The schematic THz quantum well detector [47]. Copyright © 2015 IEEE

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4. Forward

Today, terahertz generation and detection technologies have achieved a prosperous development, but there are still many problems. Traditional terahertz generation technologies, such as those based on photoconductive antenna and electro-optic crystal, are difficult to achieve high output power. Although electron accelerator, laser and backward wave oscillator have been applied to the terahertz generation field and obtained improved output power, these devices are precise and huge, which lead to the high cost of terahertz generation. On the other hand, many kinds of detection technologies have been developed, but these methods have their own limitations. Traditional detection technology based on terahertz thermal effect is always difficult to detect terahertz efficiently and accurately. With the development of new material technology and micro-nano technology, the technologies of detecting terahertz by means of electromagnetics and photonics seems to be more and more popular, especially the surface plasmon detection technology that is completely based on the new material and advanced micro-nano machining technology, has a broad development space. In general, although the development of terahertz generation and detection technology still has a long way to go, with the progress of industry and science, it is believed that the engineering and theoretical bottlenecks restricting terahertz generation and detection will be solved.

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