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A review on teratronics: from present state to future

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Teratronics is an interdisciplinary field of Opto-and Microelectronics embracing the important features of high-speed digital signal processing, high-frequency electronics, and optics and photonics. This is one of the significant challenging fields of solid state physics and technology with the new domains of electronics industry and research. This review outlines the different field of application of terahertz wave in security, medical imaging, chemical and biological sensing and highly emerging field of wide-band telecommunications along with the development of active and passive devices. Discussion encompasses from the founding concept of THz electronics to the development and future scopes. Content of this article will also include the new aspects of terahertz technology with their present contenders in the field of security and telecommunication. Dialogue for the newly evolved devices such as nano-ring and disk transistor along with stacked quantum dots systems also included to provide a novel glimpse for deep and underlying fundamental physical mechanism. All these topics will provide a critical supervision for further innovative stages in this field.

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1. Introduction

Terahertz (THz) electromagnetic radiation lies in the frequency interval of 0.3-10 THz, is the highly futuristic and broad science and technological domain of interests. It occupies a band between the infrared and microwave region. Recent research and development with new initiatives has been reached to the significant level in this area and current maturity pushed the application of THz in many unexpected area of technology compared to well-developed are of microwave and optical frequencies. In the last few decades, solid-state device for electronic and photonics applications in THz region have been prominently explored; as a result this has become more advanced for possible implementation in numerous applications, such as Teratronics, (i.e., Terahertz + Electronics). However, this multi-disciplinary field of Opto-and Microelectronics still needs breakthroughs to embrace the features of optics and photonics, high-frequency electronics, and high-speed digital signal processing. Last century was largely devoted to the astronomy and spectroscopy, which addressed as sub-millimeter or far-infrared development. Thanks to the finale decades era for the expansion of coherent source of terahertz for spectroscopy application, which was prolonged quickly and traces to many other areas from basic science to real time applications.

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Now the application is extended to the solar cell development for material optimization and also envisioned for the future generation airport safety scanner. Along with it, this filed is emerging for our daily life application such as communication, dermatology, oral healthcare, food quality control and smart railways system. However, new developments are also on track and increasing day by day making more diverse to this field. By this point as an emerging field of science and technology for interdisciplinary arena, technologist and researchers have proposing the roadmaps to help future directions and identify the extensiveness of devolvement and also to point out the challenges and opportunities. One of the most promising areas of research and development of the current is focused on the THz band for transformational progresses in communication, imaging and transport system etc. for the advancing our social life. Therefore, the fusion of technological need with researches efforts are working together for promising technologies, to reveal the distinctive properties and novel applications of THz waves.

Terahertz waves (T-rays) shows extraordinary properties of nonionizing, noninvasive, and ability to penetrate non-conducting materials. Their properties and behavior are governed by the Maxwell equations similar to any EM wave; however, uniqueness comes from their location in the spectrum where the electronics and optical devices fail to respond against them. Factually, T-rays are very hard to deal because to invisibleness and lack of guiding component in contrast to the popular region of research: optics and electronics. That's why it took the long time to harness this EM region. Moreover, the conventional photonics and electronics devices do not found compatible for high terahertz frequencies [1].

Such as, electronics drift diffusion is responsible for electronic device function and quantum excitation and depopulation of electron is responsible for photonics device function. But most of RF sources are not capable to generate large GHz signal. T-rays photon energy is comparable to phonon, which may also a restriction over THz devices. Lack of suitable design and materials with low loss and dispersion guiding tools for t-rays is another hindrance in the development of THz technology.

Present progress in terahertz technology has led many millstones for the different types of terahertz equipment accessible in the market with bid for miscellaneous arenas. In spite of, Terahertz shares a minor slice of electromagnetic spectrum, which offers untapped possibilities and can be realize form ability to read a book without opening uncover the pages. In this regard, surprising finding has been made by Albert Redo-Sanchez and his colleagues by lookup many hidden signature from painting, Sacrifice to Vesta with THz imaging setup without disturbing the painting's surface as shown in Fig. 1. Therefore, THz systems has been established itself as strong tool for creating the pictures and transmit them without touching the objects, which is not possible by a single EM wave because visible light only create a photograph and further need radio waves to transmit. Radiation of 1 THz shows a period of 1 ps, 300 μm wavelength, magnetic field of 0.7 Tesla, and energy of 4.1 meV with corresponding temperature of 47.6 K, which might be able to make the signature of fastest phenomenon.

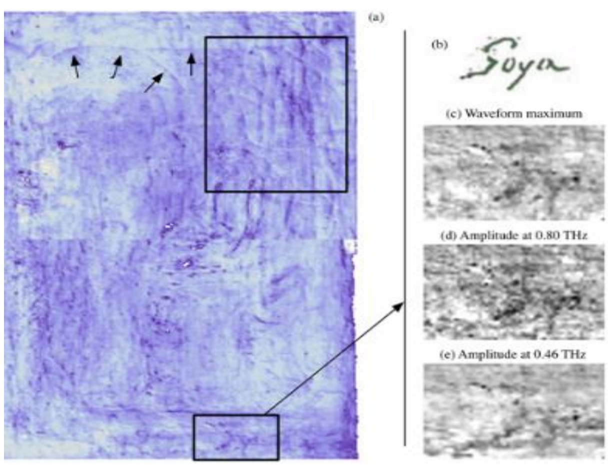

Fig. 1. Finding a hidden text by THz imaging [3].

A potential development in terahertz technology has been made by scientists to enable new applications by shrinking electron gun to matchbox size as a high-quality source of electrons. This might a breakthrough to drive X-ray free-electron lasers in compact way. The main concept to utilize terahertz radiation in place of radio-frequency is just because of shorter wavelength to shrink the device size upto millimetre range from size of a car [4].

One of most life changing invention of our planet can be addresses as integrated circuit technology, which has drastically changed social structure in many ways such as communication, computation and information technology, and health-care. In this direction, many researchers have been proposed the complex VLSI circuits using the existing fabrication processes for making them attractive candidates for THz monolithic integrated circuits with the next generation of technology. Researchers at the Karlsruhe Institute of Technology proposed different surface plasmon polaritons (SPPs) waveguide to propagate the optical signal along metal-insulator interfaces for a future generation “light-on-a-wire” age. Calzadilla et al. [5] presented different structures of nano-lasers at THz frequencies which were compatible with the CMOS technologies along with THz monolithic integrated photonics circuit by Melikyan et al. [6]. Si based microelectronics THz sources have also been demonstrated a lot of potentials with novel concept of strained germanium micro-bridges for THz integrated photonics circuits.

There are a lot of quotes have been stated to explain the beauty of T-rays: “The no-man’s-land between optics and electronics” and “heat rays of great wavelength”. It has to be speculated that since the inception of our universe 98% of all photons emitted lies in the THz-far IR spectrum of EM wave. This fact may give some extent of importance of terahertz study by scientific community in astronomy, spectroscopy and remote sensing. The high cost of instrumentation for THz technology was limited to laboratory for research filed; however, recent years development have made possible this technology for wide spread use. This era has also been a rebirth of new dynamic research concern in this area and interests have been become twofold by the basic finding along with novel applications. The mature development has become a hard foundation for future technological advancement and research also approaching towards a wide-ranging technical discipline. Terahertz technology has already made great progress in medical diagnosis especially early skin cancer detection, DNA sequencing, security screening, global environmental monitoring, quality control and ultra-fast wireless communication. Most of future technology depends on the new materials systems for cost reduction with integrated single chip. Silicon is widely accepted in this regard for competing technology with capability of high integration, well established process mechanism and unmatched performance for CMOS technology. However, efficiency and power consumption may lead towards the other technology along with higher frequencies operation, which depends on III-V group based devices. Therefore, the area of THz technology reflecting a bright future of research and development, where technology is still ‘sparse’ with electronics and optics complements especially in solid state compact systems.

If anybody believing the intentions to see the T-ray superhero may have to wait a little more for the development of high intense source in this region. Further, there is scope of handheld devices for medical diagnosis with a way to miniaturize the technology and put terahertz in the palm of our hand. There has a chance in our life to see cell phones like device by the capability to read documents without disturbing them with the future terahertz technology. Therefore, this review provides the beginning of the history of THz research, then recapitulates up-to-date THz wave generation and detection methods with the advances in this field. The objective of this article is to deliver a synopsis of THz photonics and electronics rather than converging on precise area. It brings together the basics of THz and advanced applications along with the future aspects those can transform the near and-term perspective. Manuscript have expectation to support readers for the glimpse of fundamentals of THz technologies with the valuable reference and tries to shade light systematically on the THz sciences, technologies, and applications along with the future demand of THz technologies.

2. Overview of Terahertz Generation AND Detection

After learning the basic knowledge of terahertz and before moving to the application section, it is quite suitable to familiarize the generation and detection process of THz. There are many methods and concepts have been well established to generate THz radiation such as photoconductive (PC) antennas, semiconductor surfaces with built-In field, Photo-Dember Effect by ultrashort optical signals, or nonlinear optical process, Electro-optical Sampling. Detection of THz radiation has also become a mature technology by variety of concept based on Thermal, photoconduction and heterodyne techniques. Therefore, this section will deliver an insight to some major facts and figures for generation and detection. For a long time, this region of EM spectrum was considered as “THz gap” because of the lack of efficient sources and detectors. The starting efforts have been made to fill this gap by using technology present for the nearby regions of microwaves and infrared until the new concept of quantum cascaded systems and change plasma oscillations. However, there are many THz high power sources have been evolved by using free electron lasers (FELs) and synchrotrons. These setups are highly expensive and bulky with the use of electron accelerators and undulator along with alternating magnetic fields. Backward wave oscillator is also trivial comrade of this family. In this series, some gas lasers, p-germanium (p-Ge) lasers and quantum cascade lasers (QCLs) also have been introduced with much compact size and user friendly and limited tenability. There commercial applications have been hindered with cryogenic operation. However, the high power compact sources with good efficiency and room operation is still in demand along with the large frequency coverage. For the detection point of view, they basically work a transducer to transform an absorbed signal into the suitable usage. An electromagnetic signal has a characteristic in the form of energy, amplitude and a phase. Detection function might be classified in two ways: coherent and incoherent. If the detection takes place in coherent form then it will record phase and amplitude both. However, only amplitude detected comes in the incoherent category. Therefore, this section further provides the details of few major concepts for achieving this goal.

2.1. Terahertz Generation

2.1.1. Photoconductive Antenna

Application of photoconductors for THz generation is a very fundamental and frequent approach. The designed Photoconductive (PC) antenna with large aperture can be good choice to generate THz waves by photocarriers induced by impinging ultrafast laser pulses as shown in fig. 2 with typical concept. A standard antenna array comprises the couple of metallic electrodes coated on semiconductor substrate with a certain gap (from cm to mm), which a matter of design. The high intense ultrafast laser pulses basically used to induce free carriers in the substrate, which store energy in form of electric field. Switching of optical pulses controls this electric energy in the reservoir and releases through the THz pulses, perpendicular to electrode lines. Switching of applied voltage across the electrodes mentions the polarization of the THz wave. Bias field across the electrode gap also controls the free carriers. Some requirements are necessarily fulfilled such as substrate should short life time, high carrier mobility and high break down voltages. The photonic excitation energy has to be greater than substrate’s material band-gap; however, this can be neglected by using the multiphoton absorption concept.

2.1.2. Built-In Field in Semiconductor

Nature of the surface of semiconductor is slightly different from the bulk in terms of covalent bond of free orbitals known as dangling bond, which affects the electrical properties greatly. The difference in fermi level induces the band bending in energy bands on the surface, which reflects in the form of built-in filed as shown in figure 2a. Generally, this band bending occurs in upwards manner for n-type semiconductors and vice a versa for p-type. This surface field creates the carrier drift between bulk material and surface until the equilibrium and creates a depletion layer just like p-n junction. With incidence of ultrafast optical pulses, a photo current generated with motion of electron and hole in opposite direction across the depletion layer. The switching of photo induced current, known surge current, is responsible for the generation of THz pulses just like in a PC antenna.

A special case of this concept is also considered by the use of narrow band gap semiconductor, where built-in field seems to be very weak may also use for THz generation with ultrafast laser pulses through the photo-Dember effect as shown in Figure 2b&c. Here, the large difference in mobility of electron and hole is responsible for asymmetric distribution of carriers with the optical excitation and able to create dipole oscillation successfully to generate the THz pulses.

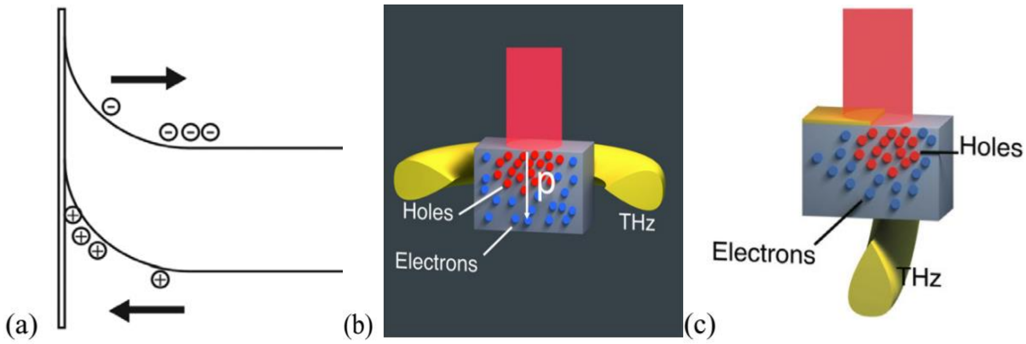

Fig. 2. (a) Band bending at the surface of a semiconductor; Geometry of (b) convectional photo-dember effect; (c) lateral photo-Dember [7].

2.1.3. Optical Rectification

Terahertz wave generation from optical rectification is a second-order phenomenon with nonlinear properties, which truly depend on martial dependent process with the advantage of broad spectral bandwidth. Typically, process took place in the electro-optical (EO) crystals by the optical excitation of femtosecond laser pulses via difference-frequency generation. This takes place between the two frequency components of excitation pulse, which governs by numerous physical aspects. However, Phase matching between wave vectors is the most important factor to control the nonlinear process for optical rectification. Only phase matching between the wave contributing to optical rectification process leads to maximum energy conversion coefficient for THz Waves generation due to long interaction length.

2.1.4. Quantum Cascade Lasers

QCLs, a class of laser based conventional semiconductor, works on intersubband transitions in a superlattice hetrostructures, which is quite different from the conventional interband transitions based semiconductor lasers. QCL is unipolar in contrast to the interband lasers that radiates by the recombination of electron–hole pairs with in the material band gap. A typical intersubband transition in a superlattices periodic series of varying material composition. It has to be noticed that carriers are annihilated during the optical transitions in a conventional semiconductor laser. Conversely, intersubband transition based lasers have a beauty to reuse an electron for another intersubband transition through the tunneling into the next structure. A QCL is known as a device to use a single electron for causing the emitting multiple photons. Hence the cascade structure of QCL makes them highly efficient to achieve higher quantum efficiency than conventional semiconductor laser. The varying high electric potential by injection current inside the superlattice structures along the thickness induces the splitting of energy level and increases the probability of electrons to the different energy states in the device. This condition becomes suitable for mid-infrared to terahertz intersubband transition. Additionally, the change of layer thickness may provide the possibility for tuning emission wavelength with the same material system. One of the exciting properties of QCLs is to allow a material system with poor optical properties even with indirect bandgap materials such as silicon. However, the change of momentum does not have any role change in intersubband transitions.

2.1.5. Plasma Wave Field Effect Transistors

The transistor and laser have most significant invention of the scientific community in respect of transforming our social life with the introduction of advanced telecommunication technology and handheld electronic gadgets. From a long time transistor has been only considered as a component of integrated circuits. However, four decades back, Gornik and Tsui have been presented a new role for transistor as source of infrared radiation by subbands transitions including a uncommon confined oscillations of electron plasma [8]. Further, Deng and Shur have extended this concept of plasma oscillation for terahertz radiation with Si field effect transistors; just like shallow water wave with some extraordinary requirements for device (i.e. nanoscale sized gate, high carriers mobility and longer momentum relaxation time) [9]. This concept basically depends on the instability state of conduction which was firstly demonstrated by wnap et al with HEMT structure. Further, this has been extended for strained Si MOSFETs with sub-40 nm gate length for suppressing the attenuation of plasma oscillation [10, 11]. When the change plasma oscillations begins, cavity boundaries of the source/drain acts like a resonator for the growth through the successive back and forth oscillation just like a laser cavity. Hence, these oscillating charges continued to emit photon corresponding frequency to charge plasma oscillation. An asymmetric boundary conditions of a typical source/ drain electrode of nanoscale transistor might be helpful for further growth of oscillations in channel region: an active region of the plasma wave device, which conditions might be attained by keeping the short circuit condition at the drain along with open circuit condition at the source. A broad and incoherent THz emission expected in the perpendicular plane of conduction. Recently, this D-S theory has been reached to a new domain with proposal of terahertz transistor for monochromatic and coherent emission [11]. This is expected to be achieving by incorporating an optical cavity in the direction of emission. A transistor laser structure has been designed with a plasma wave strained-Si channel FET and vertical photon oscillation cavity by using quasi-periodic distributed Bragg reflector (DBR). This device has been made realistic applications of monolithic THz coherent source for Teratronics.

2.2. Terahertz Detection

Last few decades have been witnessed the fast development of THz detectors to enhance the switching and sensitivity, which is also a major cause of opening the THz gap. The actual terahertz range has defined slightly by the overlapping with microwave techniques and IR regions. Therefore, some concepts of detection for THz belong to the extension of present microwave and IR technology to cover the whole range just like heterodyne and thermal based system. Technology for THz is developing day by day with new concepts and designs; therefore, this chapter will focus some major principles as follows:

Thermal detection

Thermal detectors are basically the combination of the two units: one is for THz absorption and other is transducer. This transducer is design to respond against the temperature change in the absorption unit. This mechanism also divided into three categories name as bolometers, pyroelectric detectors and Golay detector [12]. They are categorized based on some physical changes in materials, bolometers used to measure the change in electrical resistance with the change in temperature, the change in in-built electrical charge with respect to temperature observed in pyroelectric detectors, however, Golay detector uses a very complex sensitive gas cell thermometer to measure the expansion. Thermal detection concept is very basic and easy to use with limitation towards the low THz frequencies and bulk designs. Interesting feature is the ability to cover large spectral range and fast response with superconducting and semiconducting electron bolometers.

2.2.1. Direct Photodetection

Historically, direct photodetection has come in picture for visible and near infrared region. The development for longer and shorter wavelengths started for new direction of optoelectronics with the interests in UV and THz range. However, The THz photodetection is the most recent development with hindrance of much lower energy of photon after the long efforts with the optics and electronics components [13]. The main hard wall faced for the longer wavelength side is the role of polar optical phonons especially with THz region (~300µm wavelength). So recording the response of an individual photons has become is tough task, which works on the optical transition between shallow impurity. The magnificence features is the faster response with the sharp cutoff of frequency. However, THz photodetectors typically works with liquid helium temperature to circumvent thermal ionization issue and easily employed towards 10 THz frequency. Therefore, using these detectors for 1–10 THz range is really a fundamentally unnatural with the focus of new advanced technical issues that are highly significant for future THz technology. However, it may useful with attractive device physics with deep heritages in the mid-infrared region.

Rectifiers: Rectification in the THz region are simply the high-frequency versions of microwave or mmW spectral regions. In these, currents are induced at the radiation frequency and, by a nonlinear voltage current relationship in the device, a DC component, related to the amplitude or power of the AC input, is obtained. There are some real difficulties to extend the rectification to higher frequencies due to increase losses with the combination of resistive, capacitive, and inductive components [14]. However, point contact Schottky diodes found compatible for the operation beyond 3 THz but limited in terms of sophisticate and reliability for numerous applications. Progress in extending planar diode structures to higher frequencies has been steady, and relatively low-loss detectors are now available to above 1 THz. More advanced rectification system are proposed based on utilization of superconducting materials such as photon-assisted tunneling in superconductor–insulator–superconductor devices with limited used at quite low temperature. Therefore, room temperature and broad operation frequency range are still open for future innovation in terahertz range.

Plasma-Wave Detectors: The channel of a typical nanosized field effect transistor can work as cavity to start the plasma oscillation by maintaining the asymmetric boundary conditions at the cavity ends [15]. This phenomenon can be used for the detection of THz wave along the emission with certain experimental conditions. Hence a high electron mobility transistor may leads to resonant THz emission or detection by avoiding the overdamping of plasma oscillations. However, low carrier mobility transistor might also be useful for detection by just recognizing the plasma density perturbation made by incident THz pulses.

3. THz Technology in Security and Aerospace Industry

The risk of terroristic activities for the civil and military security are becoming more and more severe problem. THz detection of explosives is emerging as one the most appealing technologies, although, operational devices are strongly limited with the availability of sensors and sources especially size, complexity with specific application, and cost effectiveness. Generally, airport X-rayed checkpoints requested to remove (put off) the shoes and other thick accessories to avoid any unwanted harmful items. To avoid this exercise, the focus is increasing to develop new technologies for security screening such as terahertz based system. The resistance in the development of THz technologies use up to now are to be ascribed as “Terahertz Gap”. However, recent decades development for high power room temperature reliable sources and low coat highly sensitive detectors may able to fill this gap. The enough radiation power of solid state sources form microwave side to photonic side are braking the limitation over the many applications. The development of hand-held sensors for detection for THz are opened new dimensions in this field. The continued advancement for present designs and new growth techniques for the devices may allow better operating conditions along with improved performance.

The main requirement of smart detection of any explosive and unwanted items should be fast and effective for high level of security specially at airports, railway or coach stations with excellent sensitivity and lowest wrong alarm rate to reduce panic situation. A traditional methods at security checks follows the wiping of carry-on baggage/laptop computers etc.. The future requirement of standoff detection along with specific of each and every items moved the direction of research towards exploring the electromagnetic spectrum, particularly from infrared to terahertz radiation. The terahertz radiation has found unique properties which are advantageous for security applications with capability of penetrating non-conducting materials, but unlike X-rays it is non-ionizing. Fig. 3 shows the identification of hidden objects by THz imaging. The beauty of short pulses EM waves are to form 3D radar-like imaging along with the collection of corresponding spectroscopic features like as finger-print. A sensitive issue of using THz is privacy, because of imaging the naked body.

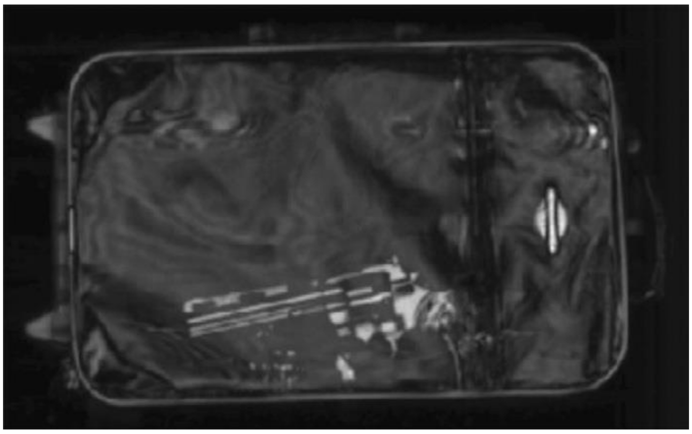

Fig. 3. Digital image of a hidden objects through THz image [17].

The extraordinary advantage for security of using THz is because of unique intermolecular vibrations signature for most of materials. Therefore Terahertz technology along with non-ionizing property established as a powerful tool for screening and identifying different chemicals and materials even hidden under clothing which are tough to detect using backscatter X-ray many times. The high resolution THz 3D imaging are useful for radar technology. Hybrid IR-THz systems are also gaining interests for security applications with innovative technologies multi-domain applications.

The terahertz waves also shown full potential in the field of nondestructive industrial level quality control for emerging technologies. The inspection of materials development for automotive and aviation industries are the key point of the reliability of product and varies with the specific application with different frequency ranges of terahertz systems. The volume inspection and high-resolution are expected on industrial scale which are highly dependent of associated electronic and optical component. The reliability of the designed systems also becoming challenging field of interests with the highly robust and variant industrial environments. Fig. 4a shows a typical view over the state-of-the-art terahertz technology for the inspection of industrial quality. Red location and air gaps are considered as the defects location in the test sample. Polytetrafluoroethylene (PTFE) and paper inlays were positioned at different depths of the sample on top of the honeycomb core structure. Fig. 4b shows the captured terahertz image with clear indication and exact locations of at the precisely intended positions with 150 GHz. Figure of merit of different THz system indicated in Fig. 6c by plotting detection rate with different mode of exposure (from the top and bottom).

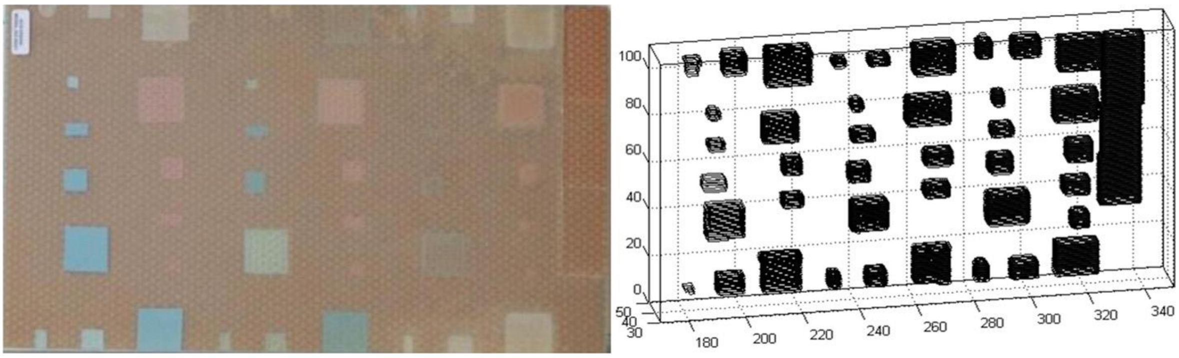

Fig. 4. Sandwich reference sample with honeycomb structure. Left: Photo of the sample, right: 3D representation of the detected faults for measurements at 150 GHz. [17].

4. THz Technology for Imaging, Sensing and Communications

The last few decades have been focused on the development of THz imaging and sensing system for higher resolution. Terahertz waves can generate 2D images like X-ray with an additional advantage of nonionizing nature which provides a large degree of harmless impact to the receiver. Medical imaging of cancerous tissues by using terahertz waves are currently under investigation. Early detection is really challenging and can make a difference between life and death of patient. Basically terahertz spectroscopic techniques differentiate a cancer cell based on the difference in water absorption since water shows intense absorption of the terahertz [18]. Except it, terahertz radiation also used to investigate many biomolecules based on different vibrational band involving hydrogen and other species. Controlling the THz wave polarization provides and additional advantage in the medical imaging system. It is very tough task to differentiate cancer and healthy tissue in normal pathology image. Following THz images demonstrates clear identification of structure, complexity along with the heterogeneity among transgenic and xenograft tumors, which is quite difficult task because of reduced fibro and fatty tissues during degradation of healthy tissue.

Remote sensing is method for acquisition of distanced information by the transmission of EM wave, which might be promising tools for faster way of transfer signal by using spectroscopic technique. Current scenario of using broadband terahertz detection for remote sensing has been developed in many way by using coherent wave even from many meters distance. The developed method has revealed a promise to minimised the absorption by water vapor and directionality of optical signal. A typical schematic developed recently has been for THz based remote sensing, which exploits fluorescence induced by gas plasma generated by the interaction of laser wave and target material. THz for remote sensing became an important gap in the EM spectrum astronomy for excellent ability to acquire the information of galaxy and stars formation and transmit into the space. It also provides wide range of spectral lines useful for astronomy phenomena's. More specifically, It also embraces a unique spectral signatures for different atoms, and ions just like molecules as discussed above which develops a decent comparative understanding for each and every received signal in different time frames from space. The examination of THz remote sensing delivers the excellent scientific information from their unique signatures for different species and further development is still underway to get high- resolution spectra for future better direct detection systems [19, 20].

Terahertz spectrum are also gaining interest for wireless communication application day by day with innovation of different sources and detectors to achieve good bandwidth for data transmission. Transmission ability at 542 GHz of terahertz WIFI up to 100 Gbit/s has been achieved with limitation of 30 feet distance. However, a typical terahertz with high frequencies have support much larger transmission bandwidth and improved data rates which is not explored so much previously. Interestingly the low atmospheric loss window also has been recognized from 200 GHz to 300 GHz for maintaining longer distance transmission with reduced attenuation of signal [21, 22]. Furthermore investigations are also expected for harsh weather conditions. The down-converted received signal passes through MMIC technology passes through the electro-optical (E/O) conversion and photonic network are also required for a typical arrangement.

5. New Trends for Terahertz Technology

Metamaterial: Metamaterials are most innovative subject of interest for future technology with the unique properties and widespread applications. These synthetic materials can be designed for many novel electromagnetic behaviour with insulators and metals. Terahertz metamaterials are a new class of artificial materials which can control terahertz radiation to realize new phenomena that cannot be obtained with natural materials. Typically, high loss of THz with conventional optical materials with lenses and other systems has been observed with optical devices. Recently, researchers have actively stimulated towards terahertz metamaterials just after the demonstration in microwave region. The development in this direction is moving with very fast speed with the designing as absorbers, lenses, switches, modulators, sensors, as well as phase-shifting and beamsteering devices by considering the importance of THz waves. The fast operation with broad bandwidth of THz metamaterials device and systems along with fine adjustment of operational frequency are needed for versatile application. Additionally, the flexible and screen printed functionality with metamaterials and metadevices are also in demand wearable application. Few effort for passive meta component of terahertz application have also been developed through electric, magnetic, or electromagnetic engineering for antireflection and resonance frequency tuning. An ultimate graphene based hybrid metamaterial with electrically controlled active devices (TFETs) also demonstrated as shown in fig. 5 a. The flexible property also submerged for this application by PDMS substrate though fishnet metamaterials. Optical probe tunability for THz metamaterials demonstrated experimental as shown in fig. 5 c with the transmission spectra of the sole-CW (pink), SRR-pair (orange), and the EIT metamaterial sample (olive). The insets shows structural variation of geometry in sole-CW, SRR-pair, and the EIT metamaterial from left to right, respectively.

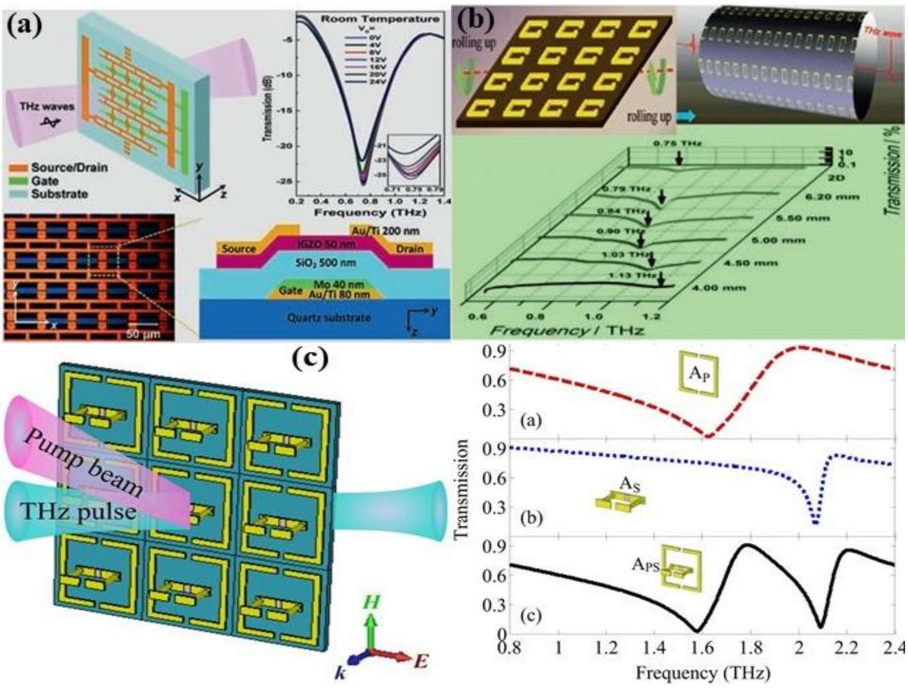

Fig. 5. a. Electrically tunable THz metamaterials [23], b. Flexible THz metamaterials on PDMS substrate [24], c. Optically tunable THz metamaterials [25].

Quantum dots: Quantum dot (QD) is an atom-like artificial material system to configure their energy levels for a particular application. This type of nano-sized material are expected to confined carrier in all spatial dimensions. Since invention, most of scientific and technological field have been successfully implemented QDs such as diode lasers, amplifiers, saturable absorbers, photovoltaic devices and biosensors. Every application enjoys its special distinctive properties even for THz also such as short charge carrier lifetime, which is critical for the actual action of a photoconductive devices. However, the demand of compact tunable terahertz sources are of great interest with the direct electrical control and an efficient room temperature operation along with the integration opportunities on a chip. Therefore, the application of QDs are quite expected to remove the limitations of photoconductive antennas such as confined optical wavelength pumping range and thermal breakdown. The unique carrier dynamics of QDs semiconductors supposed to break these boundaries by efficient room temperature optical-to-terahertz signal conversion.

In this series, The InAs QDs implanted defect-free GaAs crystal layers over a distributed Bragg reflector (DBR) based active region has demonstrated for photoconductive antenna to harness the excellent carrier mobilities across for effective optical-to-THz signal conversion along with lower threshold of optical pump energies as shown in Fig. 6. This innovative idea also pave the way towards the development of all-QD on-chip integrable THz systems. This proof-of concept experiments are also demonstrated higher optical pump damage thresholds due to QDs integration and potentially agrees with the future invention of a highly efficient, ultrafast devices without any compromise with carrier mobility, gain, THz materials.

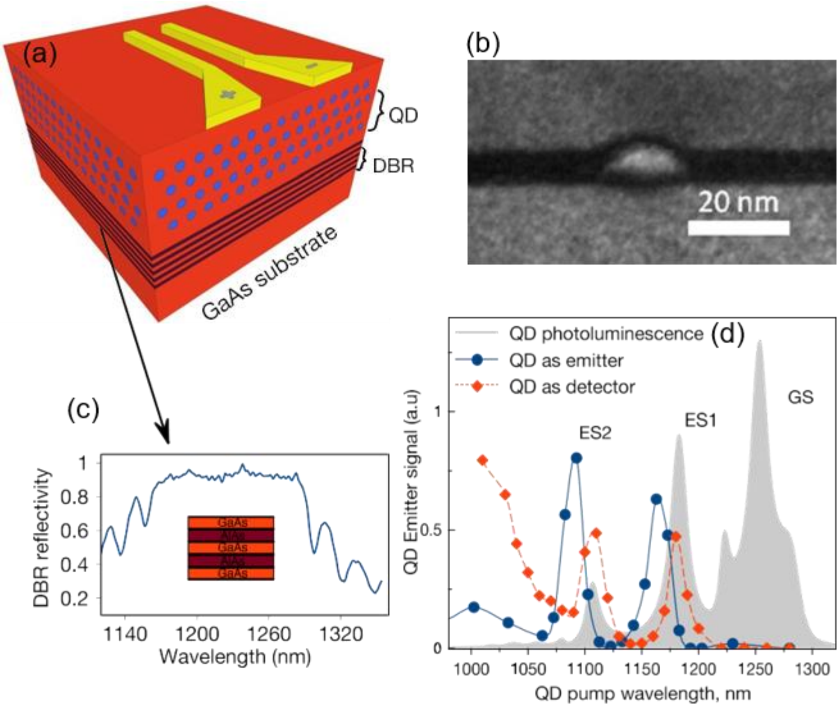

Fig. 6. (a) Quantum dot based designed device structure of photoconductive antenna; (b) QD representation through cross-section TEM; (c) Distributed Bragg reflector reflectivity with schematics; (d) wavelength dependencies of QD sample THz signals and recorded by detector (blue) and emitted by crystal surface and recorded by QD detector (red), ground state (GS), first excited state (ES1), second excited state (ES2). Photoluminescence spectrum corresponding to GS and ES [26].

Nano-ring Transistor: Nanoscale sized transistor are effectively demonstrated and implemented as THz source and detector based on resonant as well as nonresonant concept of charge plasma oscillations. Being as a strong contender in imaging technology, THz has shown boundless potential applications with the exceptional assets of THz wave in the form of many innovative physical phenomenon. In this continuation, the plasmon based THz detection gained much attention much attention for real-time THz imaging. Afterthought, silicon based FETs including plasmonic concept have been attracting researchers for meaningful on chip multi-pixel array detectors, which is really close to the level of commercialization. The development in this direction are becoming essential to utilize the advantage of above both concept for lower cost and highly integrable application with already established CMOS technology. The conventional submicron Si FETs has been utilized for the detection of THz waves with the integration of large-size antennas of quarter- or half-wavelength THz. This type of design is limited with input impedance mismatching and the feeding loss. These issues have been resolved by the asymmetric and low-impedance design of a FET along with in-plane integrated antenna which significantly enhanced the performance by focusing on considering the impedance matching. The newly proposed idea for this field is related to nano scaled transistor with ring-shaped asymmetric design [27]. The innovative transistor works itself as a circular antenna for high-performance plasmonic THz detector. This is most eligible design of plasmonic monolithic THz active antenna which includes transistor and antenna in a single device also called as “trantenna”.

6. THz for Semiconductor Industry

Semiconductor industry is the backbone of current technological era which touched the every part form high end application to conventional one. Therefore reliability of the complex systems as well an individual device need to be tested before the launching of product. Terahertz wave also established itself in this area to test wafer scale defects with matured THz spectroscopy and imaging techniques. Semiconductor industry of ICs and solar cells are actively implemented for wafer analysis based on time-domain spectroscopy systems, the fusion of fiber technology has been upgraded to this application with microprobes for getting high-resolution in near-field imaging through non-destructive and non-contact mode. Automated online inspection with THz technology is already about to develop for future semiconductor chip industry. Thanks to the good reflective nature of THz with metals and doped semiconductors are able to perform online inspection of packaged integrated circuits at microscale by sheet resistance distributions. The direct access to the near-field properties with THz related to charge-carrier of semiconductors can also be demonstrated by using transmittance spectrum with picosecond temporal resolution which provides the new dimensions to the terahertz based systems.

7. THz for Our Daily Life

Dermatology: The development in the THz research has already opened many new areas application as discussed along our daily life also such as Dermatology, Oral healthcare, Quality Control, and smart Rail Mobility. Terahertz spectroscopy and imaging system develops a new understating for biological molecules because of the unique interaction mechanism of THz with the each different kind of tissue [28]. Particularly, THz-skin tomography has been developed a lot because of used for noncontact and non-invasive inspection of skin burn injuries and cancerous tissue etc.; The Evaluation of Skin Hydration by just monitor the water content by just checking the absorption level of THz. Time-domain THz spectroscopy (TDTS) analysis was found to be effective for hemodialysis of human skin. The future perspectives for this application still need to be explored due to structural complexity and molecular heterogeneity along with complex biologic phenomenon of THz radiation. Several skin models are developing to resolve the THz response to skin specially to point out exact information about the diseases selectively in term of location and differentiable to avoid any risk of molecular side effect.

Oral healthcare: X- ray is the leading imaging technique used in dentistry to monitor cavities and plan treatment for braces, dentures, extractions, and implants. Because of the highly ionizing and damaging nature, terahertz imaging have boundless alternative for dental diagnosis. Teeth contains relatively lower water compare other tissues, hence which makes THz imaging more convenient with pulsed imaging system to detect cavities as well as erosion. 2D and 3D THz imaging might be carried out in pulsed or continuous mode and analysis possible in spatial and frequency domains including real- time terahertz color scanning [29]. The water content interference for THz imaging can be minimizes by just heating the teeth samples and furthermore effect can optimized by the different frequencies. The effect of different frequencies can be visible in fig. 8 by comparing the visible light image and different THz frequency image.

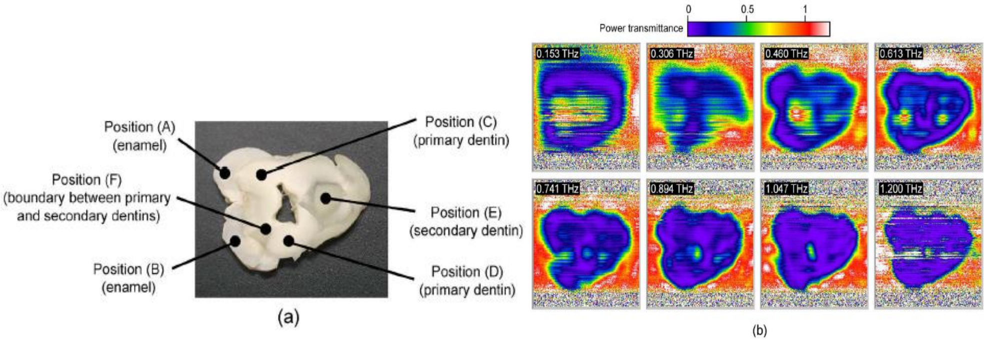

Fig. 7. Human tooth image to recognize cavity with visible and terahertz: (a) Specimen of sliced human tooth; (b) THz images of specimen with different frequencies [29].

Smart Rail Mobility: A much efficient and green transportation of rail traffic is mandatory for the coming era with the ability of smart mobility where different demand such as infrastructure, trains mobility with higher safety, and lower costs need to be fulfilled. Continuous high-data rate wireless connectivity with high bandwidth is required. Only THz based communications systems can fulfill these requirement for smart rail mobility with expected 100 GHz to form high-gain directional antenna beams. This high data rate application requirements might be fulfilled the demand of on-board HD video surveillance which is essential for safety and security along with the on-board passengers necessity for real-time web browsing, video conferencing, video broadcast [30, 31]. A complexity of a integrated tracking system for safe operation information also required a high data rate communication system to share critical voice and signal, online train route and equipment performance. Future driverless system also additionally required the extra dynamic journey information for all passengers and control system via multimedia. Further, different communication scenarios also need to tested to overcome all challenges with optimized bandwidth requirements to explain link between the train and the infrastructure. Every point need to be focused uniquely and find respective solution such as wireless link between access points in the wagon and the transceivers of passenger equipment and interwagon wireless network to avoid complexity of wiring.

8. Conclusion

The notable advancement of the THz electronics has been witnessed by few last couple of decades from basic concept of generation, detection and manipulation radiation to novel advanced application. Being as small leap of electromagnetic spectrum, the THz application is leading to increase for industry as well as research. This chapter tried to review these applications form technological to basic life. After all these, researchers also trying to develop a complex artificial intelligence system based on terahertz radiation for early warning a normal infection and epidemic situation. THz imaging also integrated with the robotic system to investigate more complex issues. Therefore, THz might be going to be a highly anticipated field of interests for more advance society and need more attention to develop.

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