A review of Terahertz technology and Metamaterial based electromagnetic absorber at Terahertz band

Darothi Das[1], Kaustubh Bhattacharyya[2], SunandanBaruah[3]
[1,2] Department of Electronics and Communication Engineering, Assam Don Bosco University, Azara. Guwahati
[3]Faculty of Engineering & Technology, Assam down town University, Panikheiti, Guwahati

[1]darothi.das@gmail.com
[2]*kaustubh.bhattacharyya@dbuniversity.ac.in*
[3]sunandan.baruah@adtu.in

***Abstract*: *Terahertz (THz) technology, a new step towards the wireless communication is a recent topic of research. THz radiation has unique properties which make it better than microwaves, infrared, X-rays, etc. These radiations have wide applications in various fields like imaging, spectroscopy, security, biomedicine, sub-millimeter astronomy, in communication, etc. The sources for THz radiation as well as the detectors are the key components within THz communication system, and are still in a developing stage. As in naturally occurring materials, there is lack of good terahertz characteristic, so researchers are moving towards artificial one, i.e., the metamaterial based design. Designing of generators and detectors based on metamaterial for THz radiation is the recent demands in the field of THz communication. Hence, we are focusing on the metamaterial based THz transmitter and receiver. So in this paper, a brief study of the THz technology based on metamaterial has been carried out and presented here.*

***Keywords*:** Terahertz, metamaterial, source, detector.

(Article history: Received: 2nd July 2019 and accepted 10th August 2020)

I. INTRODUCTION

With the rapid growth in the field of communication, one shall always thrive to know more. Nowadays most of the people want a faster communication link without physically interacting each other. So recently the wireless communication system moves towards new technology in the terahertz range [1] [2].
The term "Terahertz" (THz) means one trillion (10^{12}) cycles per second or 10^{12} Hertz. Nowadays, THz is of great interest to physicists and astronomers [3] [4]. The electromagnetic wave within the band of frequencies from 0.3 to 3 THz is designated by ITU as THz radiation, also known a submillimeter wave [3]. The term "terahertz gap" represents the region between the microwaves and infrared light waves [3]. This band of frequencies has broad applications in the field of basic research, in the medical field, security [5] and also of great importance as scientific values is concerned. Hence the THz science and technology play an important role in various area of research [3]. Spectroscopy of materials and non-invasive imaging are the significant properties of THz radiation [4]. Electromagnetic radiation in the THz domain is subject to non-destructive and allows devices and techniques of analysis, thus evaluating the properties of a material without causing damage [4]. The THz frequency has become easy to access during the last two decades due to the immense improvement of emitters and detectors. In this paper, the metamaterial based designs for generation and detection of THz radiation have been discussed. A metamaterial is a device, made from a group of many elements fabricated from composite materials; they have a property that they are not easily found in nature [6]. Metamaterial detectors can absorb the THz radiation at a high speed; they work at a frequency that is in the THz regime, they are less expensive and are not bulky, they work as a multi-pixel array for various applications [7]. Metamaterials are materials whose properties, like permeability and permittivity [8] can be adjusted to its appropriate value. Hence rather than choosing many materials, it is better to select a material whose properties and dimensions can be changed according to the value we want. This criterion is only possible in metamaterial based devices. Also due to the insufficiency of an essential THz

characteristic in naturally occurring materials has driven the work on terahertz metamaterials. Thus, we are concerned with the study of terahertz communication with metamaterials.

A THz frequency band for communication[9] is a very important and valuable underdeveloped frequency resource, which has great potential for high data rate communication [10].As the bandwidth of the THz waves is very high, it is easy to get a data rates of 10 Gbps [11] [12][13] or high with easy modulation techniques. The THz regime is in between microwave at lower frequencies and infrared at higher frequency range and rarely investigated region of electromagnetic spectrum [14].

Since last few years, the smart terrorist attack with concealed explosive has been increasing and becoming a threat to people's life. Hence there is a need for this type of explosive detection and their identification. In this, THz spectroscopy and imaging play an important role. Compared to X-ray with KeV photon energy, the meV energy of THz radiation is not harmful to the human tissue as it is non-ionizing [14]. The THz signal has the penetrability to many non-metallic materials and becomes a unique feature which directs much interesting application towards security [3]. Research in this field is a great initiative for imaging of concealed weapons, concealed explosives detection, detection of illicit drugs, etc. [15] [16]. There are many experiments/projects which are going on in this THz field, and they are showing a good result [17] [18]. That is the reason why the THz technology is in much demand, even though they are in the developing stage.

The sources of THz radiation may be natural or artificial sources. Naturally they are obtained as black-body radiation from materials which have temperature of about 10K [4] and artificial sources of radiation are like the gyrotron, Photo mixing sources, the far infrared laser ("fir laser"), the free electron laser, Quantum cascade laser, and Single-cycle sources used in THz time-domain spectroscopy[19]. As frequency increases, it becomes difficult to generate THz radiation at convenient power [4].Sources, modulators, and detectors are the main reason for the success of THz technologies [8]. For frequencies up to 1 or 2 THz, various sources, and detectors, as well as modulators are now accessible to get a rapid growth in the field of THz technology [8]. Hence, a lot of people are still working to make better sources, detectors [20] and modulator, to make THz communication possible. Some of the recent techniques of generation of THz radiation have been discussed in [21]. In this paper, we are focusing on the fabrication of a highly flexible metamaterial absorber [22] [23].

II. THz SIGNAL

Over the past few decades, THz technology has shown a great accomplishment in many fields [24] [25]. THz signals are showing great potential demand because of its extraordinary nature. Since the range of wavelength in THz signal is decreasing to a shorter wavelength, therefore these THz band is also known as a submillimeter band [4].

THz signal is said to be non-ionizing because of its low energy as compared to other radiating waves. Terahertz radiation has a unique characteristic like penetrability, security, wave-particle duality but, one of the important characteristics is that some of the materials have rare spectroscopic signatures [26] which are very helpful in identifying the explosives, drugs, etc. Terahertz technology is in much demand not only because of its characteristics but also because of terahertz signal has a wide scope in the field of biomedical engineering, material science and engineering, safety and security[5], astronomy, atmospheric research, wireless communication[1] and networking, military applications, spectroscopy, imaging technology etc [3] [21].

In the year 1923, the THz gap concept was first studied by Ernest Nichols and J.D. Tear. Their work was to see the THz radiation both from the microwave side and infrared side [10].

Recently, generation and detection techniques of the THz signal have gained a lot of development in various fields which are discussed in the application part of this paper.

Generation of THz signals with a convenient power level is a significant problem to be solved. Current THz signals sources for research do not give the necessary power levels for the required applications. New quantum-level techniques are needed to work in the IR and visible spectrum. Detectors are perhaps the biggest problem to be solved. Photonic detectors are used by various researchers, but they require cooling. Among various detectors [20], Schottky [27] diode-based heterodyne detectors have a frequency of 3 THz and above [15].

As the scope in the field of THz is increasing day by day, so the field of THz signals being researched at large scale. This is because of the reason that the solutions of many wireless communication systems will be solved by using the terahertz frequency band [1]. So researchers are hoping for a better communication link shortly.

The demand for Terahertz technology is increasing at a high rate due to its various developing techniques like infrared or ultrasound. These radiations have the ability to control, monitor and inspect the infrared and ultrasound techniques. Terahertz radiations are replacing the technologies formicrowave and infrared of the electromagnetic spectrum which are not very safe to use [3] [21].As we have already discussed in the previous section that the THz signal is a part of the electromagnetic spectrum. So, most of its characteristics resemble that of the electromagnetic waves.

One of the important qualities of THz radiation is security. Since the THz waves have energy in the meV, which is very low as compared to the energy of other radiating signals like X-rays whose photon energy is in keV [3]. Radiation at THz frequencies is non-ionizing, so it is safer to use in people [28]. As, this radiation can penetrate through fabrics, hence can be used to detect explosives [5] or other illegal things that are hidden inside people's clothes. So, many of the airports have started using the THz waves in place of X-rays as they are safer than X-rays [4]. Also in various manufacturing, quality control, and process monitoring, these waves can easily inspect the packaged goods.

Terahertz spectroscopy is developing gradually in many fields [2]. It has many applications in the field of imaging, security, manufacturing, communication, sub-millimeter astronomy, etc. Terahertz spectroscopy can identify and check the property of matter, i.e., the THz spectroscopy [26] has a series of information about the material in the THz band. Some materials [29] provide some unique characteristics in the terahertz spectrum. Hence, the THz spectroscopy imaging technology distinguishes between the compositions of materials and also characterizes the morphology of the material [3].

III. THz COMMUNICATION

Wireless communication through THz radiation is a new key to the communication world. Over the recent years, the demand for the wireless network is at a peak because the number of users is increasing. Hence to get a very fast wireless communication and to fulfill the demand of the various users, the data capacity should be improved. Also in a communication system, the signal to noise ratio (SNR) is an important factor. In THz band, as the attenuation is large, so it reduces the SNR ratio. So in the near future, speed of 10 Gb/s [12] [30] or even faster wireless network could be expected. Federici et al. [10] and Kleine–Ostmannand et al. [31] have considered the capability to use the THz signal for future wireless in 100GHz [32] range, i.e., approx. 10THz. A lot of research work is going on to get a faster communication network, which would be possibly in the THz band other than microwave and IR and leads to secured and less attenuation communication [8][10].

In the near future, it can be expected that many indoor wireless communications (WLAN, WPAN) will be through THz technology [14] [8]. There is an organization named Wi-Fi Alliance which has classified the indoor communication system into many categories like wireless displays; in-home distribution of HDTV; rapid uploading and downloading of large files to and from a server etc [14] [8].

D. Britz [33] has counseled a brand new thought referred to as “triple-stack nano cellular architecture", to put three radiosfor cellular, Wi-Fi and THz communications in a mobile handset in parallel. The cellular and Wi-Fi radios offer a broad coverage, however with a slower rate, whereas, the THz communications offers an awfully satisfying result.

Another research in the field of THz communication was done by Koch [34] [35] and Federici [10] towards secure THz communication system.

Few of the devices which are assumed to play an important role in THz communication are as follows:

1. Compound semiconductor transistors are very good for frequency ranging in the higher areas like THz range [14].
2. CMOS [36] and SiGe are not suitable for THz band; the reason is the loss of the base material is very high assumed to be not suitable for THz frequency applications because of the high loss of the base material [14].
3. Schottky barrier diodes (SBDs) are used as a detector for THz signal [37].
4. The photonic devices which are used for fiber optic communication can also be used for detecting the THz signal [14].

There are also some obstacles faced technically by this THz communication link which are:

1. Since the diffraction loss of THz radiations is very high, a beam steering method is required for better THz radio communication. So, for microwaves and infrared, phased-array antenna and optical elements are employed for controlling the direction of the wave [14].
2. Another challenge in this field is the Packaging. The metal packaging would be too large and bulky for operating in the THz wireless systems. So new packaging techniques to overcome the drawbacks of the current one is a new topic of study [14].

So in brief THz communication has a wide application in many fields, though it has some drawbacks also, the studies being continued in the THz frequency band.

IV. THz SIGNAL GENERATION AND DETECTION

The methods by which THz pulses are generated are as follows:

A. SOLID STATE GENERATION: This method was previously studied for the generation of infrared light, by taking into consideration the composition of the semiconductor [38]. But this concept is not suitable for generation signal at the THz band. Some lasers have the property to emit electromagnetic waves but they cannot generate possible THz waves as the semiconductors required for this kind of excitation is unavailable. Another different type of laser has been introduced, but they also have a disadvantage to fit in the THz frequencies. Hence, optical generation method was introduced because of the limitations in solid state generation [21].

B. OPTICAL GENERATION: In this method, a laser is used which is used to generate THz waves. The semiconductor reflects the pulses, which in turn generate the THz signal. In this case, the semiconductor does not emit light; they just refract the light. There are two general approaches to this method. They are Photoconduction and rectification.

1**. PHOTOCONDUCTION**: In this method, THz waves are generated by the use of photoconductive semiconductor [39]. The THz waves generated are better than optical rectification, as the forbidden energy gap can be overcome by exerting a certain amount of energy [21]. When this phenomenon is applied to some semiconductors, current is generated which in turn produces the energy required for radiating antennas.

2. **OPTICAL RECTIFICATION**: This process is also used for the generation of THz waves [21] [40] [41]. Certain semiconductors which are required for this process are now available.

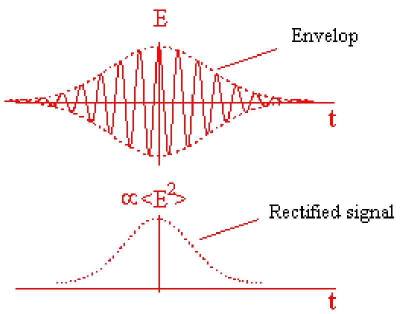

Figure 1.Optical rectification [21]

Figure 1 is an example of optical rectification. It shows the laser pulse before and after it strikes the semiconductor. When the laser pulse strikes the semiconductor voltage is produced, which is proportional to the square of the laser beam. The signal from the laser that is in the THz frequency range is generated is accepted and the remaining signal which are of lower frequencies are rejected.

C. SOURCES OF SEMICONDUCTOR: Bulk electro-optic rectification and ultra-fast charge transport are the two methods by which THz waves can be generated; they are based on some semiconductors**.**

1. Bulk electro-optic rectification: This is a type of optical rectification process[41] but in this case, two laser pulses strike the semiconductor. There is a type of crystal called the nonlinear optical (NLO) crystals, have a property to add the electromagnetic waves or else subtract them. The two types of NLO crystals are sum frequency generation (SFG) or difference frequency generation (DFG) [21]. This method is basically based on the phase matching between the pulses that enter the crystal and the resulting field, i.e., the phase of the THz pulse must match with the phase of the wave pulse. This is not possible to obtain but still is used in some semiconductors [21].
2. Ultra-fast charge transport: This method is in great demand. This method is based on the formation of the electron-hole pair on the semiconductor layer. Here, a laser pulse is used, which have photon energy greater than the band gap of the semiconductor. This causes the formation of the electron-hole pair [21].

DETECTION OF THz RADIATION
Detection of Terahertz signal involves some medium on which the radiation is focused. The generation process is of no use if we do not have a detecting medium. Following are the two methods of detection of THz radiations:
1. Photoconductive Antenna: Mostly the semiconductor used is GaAs [42] [43]. A short laser pulse strikes the antenna, as the photon energy of the laser pulse is greater than the energy gap. Finally, in the conduction band, an electron is created,and in the valence band, a hole is created. Hence, the time delay between the pump and probe pulses are measured [21] [39].
2. Electro-Optic Sampling: Electro-Optic sampling has more advantage than the photoconductive antenna. It was introduced in the year 1995 [21]. The electric field of the terahertz signal will cause a birefringence, which in turn will create an optical polarization of the detected pulse. This change in polarization will be used to find out the amplitude and phase of the THz pulse [42].

V. METAMATERIAL BASED ELECTROMAGNETIC ABSORBER AT THz BAND

For electromagnetic wave absorber metamaterial can be used as a class of metamaterial. Metamaterial absorbers have much more benefits like miniaturization, adaptability, and effectiveness, which are not easily found in ordinary absorbers [44]. Metamaterial based perfect absorber (MMPA) is a perfect example of perfect absorbers [45].Recent years researchers are primarily focusing on the growth of the THz band, with the hope that at this frequency range can solve many problems. Due to the unavailability of efficient sources and detectors, the THz band was not in demand and also not known by many people previously. Recently researchers are come up with the metamaterial based design of absorber in the THz frequency range.
There is a question why terahertz and metamaterial in the electromagnetic spectrum is an outlook in the development process. The main reason behind this is its absorption and reflection spectrums, that is critical for its wide applications including security screening, medical imaging [9], and non-destructive evaluation [7]. Metamaterials are materials whose properties, like permeability and permittivity can be adjusted to its required values. The metamaterial term was introduced by Walser [23]. Metamaterials are materials whose properties, like permeability and permittivity [11] can be adjusted to its required value. Hence rather than choosing many materials, it is better to choose a material whose properties and dimensions can be changed according to the value we want. This is possible in metamaterial based devices. Also due to the insufficiency of an important THz characteristic in naturally occurring materials has driven the work on terahertz metamaterials. In the beginning, this metamaterials were described by a 3D complex which produces a union of many electromagnetic responses that do not found in nature. The major factors by which the metamaterials can be categorized are their structure, the parameters, and the ratio of operating wavelength [7]. These are the characteristics by which one can differentiate the metamaterials from other structures. Hence, a lot of research [7] [23] [46] [47] on metamaterial is being carried out, so the whole system works at THz frequencies.
In this paper, more emphasis is given on the metamaterials that are engineered to operate in the THz band. Since the metamaterial is constructed artificially, so it is easy to understand how the terahertz waves will pass and transmit through a medium [6]. Permeability is the measure of the ability of a material to support the formation of a magnetic field within itself [42]. Naturally occurring materials [29] have a positive value of permeability [23]. A special character of the metamaterial is to achieve a value of permeability zero or negative [7]. The first metamaterial were passive materials, achieves negative permeability at

microwave frequency range. An important achievement was explained by Berry *et al.* on the THz metamaterial [42].Berry et al. have demonstrated a new plasmonic THz antenna which can be used to enhance the photoconductive current. There are different resonators which are the main objects for the metamaterials, for e.g., thin wires, Split Ring Resonators (SRR), electronic Split Ring Resonators (eSRR), etc. They have been formulated for an electric and magnetic response or to get a negative refractive index [48]. It is a known fact that metamaterials can drive the terahertz technology. But the fabrication of metamaterials at this frequency range with the current techniques is a very difficult problem to be solved [23].

At frequency regimes on the far side the THz band, the fabrication of metamaterial scan be very difficult with present technologies. Naturally occurring materials are failed to fulfill the necessity of the THz frequency range applications hence metamaterial covers the gap in the THz band applications. Even though the capability of the metamaterial, in theory, demonstrated that it could operate at any frequency band, but practically there are many disadvantages that may interfere with the performance of metamaterial. Even though the metals and dielectrics are not directly related to the performance of metamaterial, but they play an important role in energy dissipation. Further, most of the research work has been concentrated on the passive metamaterials. The passive properties like geometry, periodicity, etc. of THz technology have been determined by metamaterials [23] [47]. So to overcome some of the difficulties faced by the passive elements, researchers work on the development of active metamaterials [47] [49]. The various methods by which enhancing the design with the laser beam with a varying magnetic field, and applying a dc-biased voltage will open many applications in the field of spectroscopy, THz generation, secure THz communication and also advancement in the field of more sensitive terahertz detection [7].

Most of the metamaterials are within a limited or shorter range, so it is difficult to implement for the applications which require higher bandwidth [23]. A series of solution has been recommended for multi-resonance metamaterials and passive or active resonance-tunable metamaterials to broaden the bandwidth of the THz metamaterial [7] [23].

A metamaterial perfect absorber [50] consists of an array of SRR spaced at a distance above the ground plane and separated by a dielectric [51]. The first metamaterial based absorber was studied by Landy et al. [52], which consisted of three layers; a dielectric and two metallic layers. Through simulation, the absorptivity found to be around 99% at 11.48 GHz, as shown in Figure 2(a) [53]. Here the top layer consisted of an Electronic Ring Resonator (ERR) (dimensions in mm: a1=4.2, a2=12, W=4, G=0.6, t=0.6; cut wire dimensions: L=1.7, H=11.8) which provides along with the ground plane, the electric response by coupling strongly to incident electric field at a certain resonance frequency. The second metal spaced apart from the top layer by a dielectric, consisted of a cut wire in a parallel plane that also contributes to the electric response as shown in Figure 2(b) [51]. Using another similar structure, Landy*et. al.* achieved an absorptivityof 88% (Figure 3(a), 3(b)) [51].

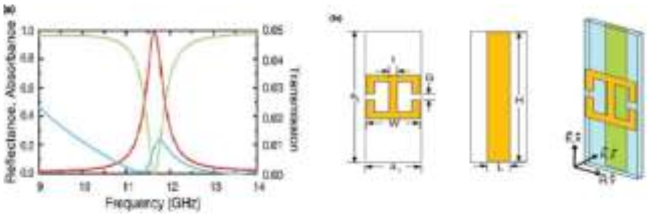

Figure 2(a) Simulated results displaying transmissivity (blue, rightaxes), reectivity (green, left axes), and absorptivity (red, left axes), (b)Unit cell [51].

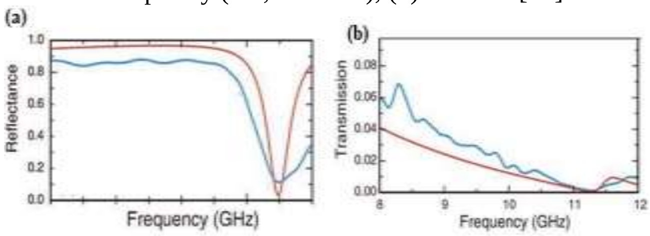

Figure 3: Experimental (blue) and simulated (red) results for reflectivity and transmissivity [51].

The above study conjointly assessed the loss mechanisms within the structure through simulations. It was found that dielectric loss occurring between the two metamaterial layer exceeded the Ohmic loss and was mainly fixe in the center of the metamaterial unit cell just below the strip of the ERR, as shown in Figure 4 [51].

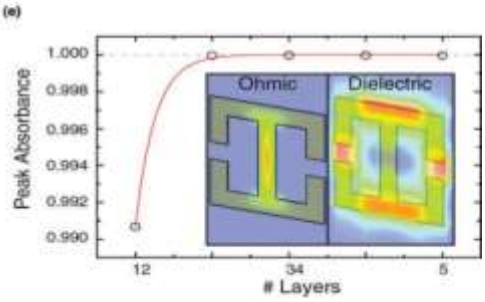

Figure 4Ohmic versus dielectric loss in MPA [51].

Metamaterial perfect absorbers (MPA) [50] [53] which are similar to other metamaterials consists of repeating unit cells and are organized in two or three-dimensional periodic structures. Most of the research is the field of metamaterials is using the software like CST Microwave studio [54], HFSS, [55] and COMSOL multiphysics [56] to know the behavior of the MPA structures before proceeding for actual fabrication.

In the year 2008, Tao *et al*. demonstrated a two-layer metal resonator at 1.3 THz [57] with 70% absorptivity [58] [59], and then he further improved the angle performance of the THz metamaterial absorber. As shown in Figure 5(a) and 5(b), the absorption intensity decreases as the angle of incidence increases more than 30° but there is not much change in the bandwidth. But in case of TM polarization as shown in Figure 5(c) and 5(d), the absorption intensity is less dependent on the angle of incidence until 70° [57]. Many research work has been designed to make the bandwidth of the of the THz absorber better [60] [61]. For example, in 2010 Ye *et al.* demonstrated a three-layered metal-cross structure to urge awfully high band of THz absorption with a 40% of theoretical *Full width at half maximum*(FWHM) [57]. A five-layered unit cell with 200nm thick squared metal films fixed in an insulating matrix at a distance of 4μmalong with lateral lattice is at 95μm is reported by Tao et.al.[58]. By tuning the metal patch width of each layer of the unit cell, a truncated pyramid structure is obtained [62].

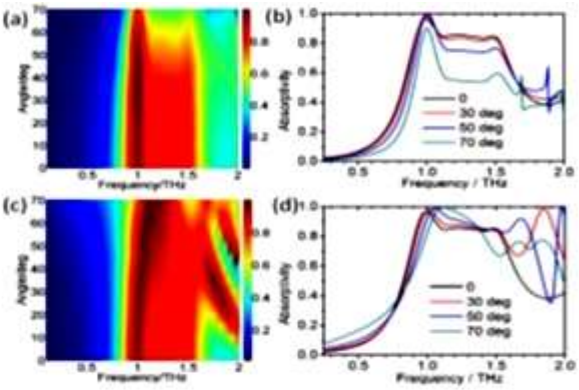

Figure 5:Simulated absorptivity for TE polarization. (b) and (d) for TM polarization. In (a) and (c) the x and y axes represent frequency and incident angle, respectively, and the absorptivity value is represented by different colors. (b) and (d) plot the absorptivity lines at selected incident angles of 0, 30, 50 and 70 degree[57].

In 2008, Chen et al. [22] worked on two metamaterial devices, viz, SRR and eSRR, operating at THz frequencies. The structuresare shown in Figure 6.

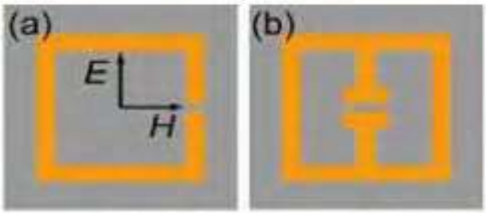

Figure 6: (a) Single split ring resonator (SRR) (b) Electronic split ring resonator (eSRR) [22].

In another reported work, eSRRs were embedded in a conductive n-type GaAs substrate in a Schottky diode configuration as shown in Figure 7[7].Here the substrate and the eSRR are biased by a DC voltage. This is done in order to replenish the depletion region around the split gaps [7]. Once there is no voltage, the gaps are shorted by the conductive doped substrate. As the bias voltage increases, the depletion region is formed, which decreases the conductivity in the gap [7].

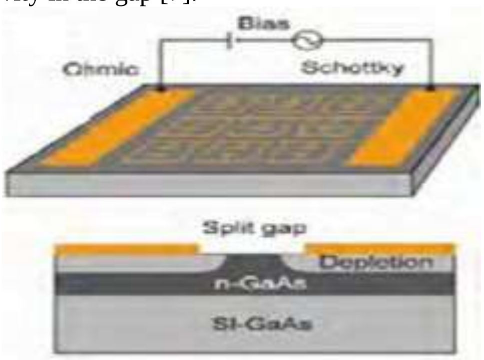

Figure 7: eSSR embedded in a conductive n-type GaAs substrate [7].

In another model, employing a single rectangular SRR, embedded onto a GaAs substrate [7] as shown in Figure 8. Here the THz probes beam (blue color) and femtosecond pump beam (red color) incident on the GaAs embedded metamaterial structure [7].

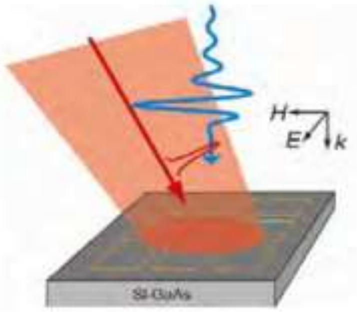

Figure 8. THz probe beam (blue) and femtosecond pump beam (red) incident on the Si-GaAs embedded metamaterial structure [7].

The electron-hole pair generated by the femtosecond pump beam and the THz waves arecouple into thestructure when their electric field vectors are normal to the split gaps of the SRRs substrate. The photo-excited carriers suddenly fill the gaps in the SRRs with dampening their LC resonance [7]. Figure 9 shows some of the SRR at THz frequencies. Figure 9 (a), the LC and dipole resonances are observed in the polarization side. Whereas the dipole resonances was not observed in the other polarization [63]. Next in Figure 9(b), for single SRRs the gap orientation has great effect on the dipole resonance [63]. Figure 9(c) shows eSRRs, which primarily overpower the magnetic response on behalf of a pure electric response and Figure 9(d) shows a four-fold rotational-symmetry eSRRs which are not responsive to polarization [64]. Figure 9(e) shows rectangular eSRRs which enable the dipole resonance frequency to tune [64] [65] to stop the LC-dipole coupling. Figure 9(f) shows THz eSRRs and their complements, and it operates on Babinet's principle[66] [67].

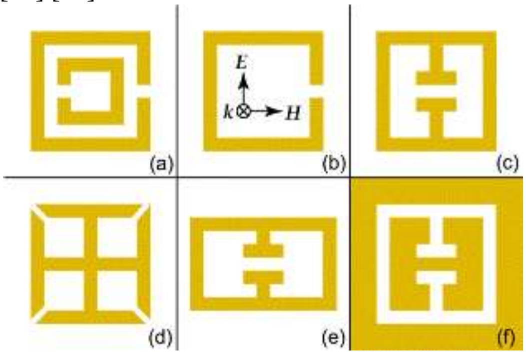

Figure 9. Some SRR variants at THz frequencies. (a) double SRR, (b) single SRR, (c) eSRR, (d) four-fold rotational-symmetry eSRR, (e) rectangular eSRR, and (f) complementary eSRR[63][64][65][66][67].

Recently the technologies which are used for IC fabrication are useful for making a planar THz metamaterial. These planar THz metamaterial are also known as metasurfaces or metafilms, which can be formed by a single metallic layer placed on an insulating substrate. While choosing the types of metals and dielectrics for fabrication purpose, there are few limitations, sometimes thin polymer films stretchable and also transparent to THz can be used for this purpose

[68] [69]. Here semi-insulating substrates can also be used, which will allow to change the conductivity for better performance of the metamaterial [70] [71]. The incident plane waves normal to metasurface cannot produce sufficient magnetism, but this issue can be resolved by taking into consideration an oblique angle of incidence which will allow the part of the magnetic wave to set as an array of SRRs [72][73][74]. When the angle of incidence is applied to an angle to the surface, the SRRs which are fabricated on many glass plates [75] or SU-8 resist [76], they show a negative refractive index. A little more advancement in the design of a double-layer cross-wire structure which is fixed in a thin layer of benzocyclobutene (BCB) is reported in [77].

The concept of transformation optics can be used in many applications of metamaterial [78], for e.g. hyperlenses [79] or invisibility cloak [78]. At THz wavelengths, it is difficult to achieve a 3-D structure. A planar metamaterial can enhance its capacity to 2D by removing from a rigid substrate for e.g. flexible metasurfaces and free-standing S-springs [80]. Moreover, more complication fabrication procedures have been introduced to get 3D structures [81] [82]. Because of the complexity of these techniques, the 3D THz metamaterial is not common.

Further, the magnetic responses are also a topic of concern at THz frequencies. The first research work was an array of planar double SRRs, as shown in Figure 10 which produces a strong magnetic field of about 1THz [73]. Some of the work involving the magnetic resonance concept at 6THz is reported in [72] and of multilayer planar SRRs enclosed in a polyimide film is at [83].

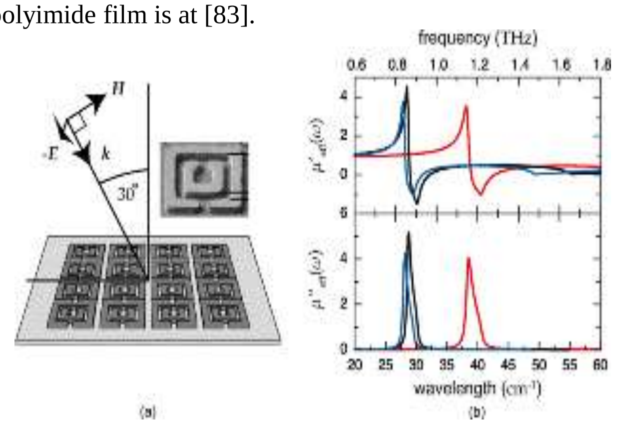

Figure10:Magnetically coupled SRRs (a) theTHz radiation incident on the SRRs at 30° from the normal. (b) The complex magnetic permeabilities of the structures simulated by using different geometries. [73]

Till now, the study on the THz metamaterials are surrounded by negative index metamaterials (NIMs) that have partly or whole negative permeability and permittivity. Any typical structure, at THz frequency does not contain only the wire-ring configuration but they contain advanced NIM structures, like the S-strings, chiral media, etc. Fabrication of NIM that allows electric and magnetic field component to support passband frequencies simultaneously may contain planar SRR and also wires on the same layer. Similar work reported for 2THz in [84] [82] and at 4.92 THz in [76].

So, in brief, we can say that with the scarcity of a powerful terahertz attribute in naturally occurring materials has driven the work on terahertz metamaterials. Metamaterials till now are more concentrated on designing and fabrication part. So in the near future, it is expected that the power of electromagnetic spectrum by metamaterials will be helpful for many THz applications in the field of medicine, security, communication, astronomy etc.

VI. APPLICATION OF THz RADIATION

In recent times, THz technology is a very important field of research. Most of the researchers are carrying out many experiments in this THz range since it has a vast application in this field. Because of its unique applications, most of the countries are accepting the THz signal over other radiating waves like X-rays. THz radiation has some important properties also which unlock the large field of THz application. Few of the properties may include high penetration depth and low scattering combined with good spatial resolution, low photon energy; transmission of information through imaging and unique rotational, vibrational and translational energy of materials in THz range provide information that is generally absent in other radiating waves, etc.

1. Security: As per security is concerned, THz radiation has a very important role. THz radiation has the property to penetrate through materials like fabrics, plastics etc [3] [4]. As THz radiation can penetrate through clothes, it can be used for security screening [85] to detect illegal objects or concealed weapons on people [28].

2. Medical Field: THz imaging is a non-invasive imaging technique. It is a new mechanism which has been introduced recently for medical imaging [9]. This technique uses those frequencies of the electromagnetic spectrum, which can go through several millimeters of the tissue [86] and hence can be used to give the information of the structure. THz imaging is a technique that can be used to detect epithelial cancer [4]. It is much safer than x-rays, which is non-invasive and also non-destructive. Also, THz technology has an important role in dentistry. Earlier X-rays were mostly used to diagnose tooth decay but, they detect it at a late stage whereas terahertz radiation can detect the tooth decay at an early stage, by observing the gradual destruction of enamel at the tooth.

A new technique is known as the THz time-domain spectroscopy [19] and THz tomography use the computer-aided tomography technology to get the information of the images which are not transparent. The result we get from the THz-TDS [87] [88] has much more information than other techniques, as the radiation that is formed from THz-TDS is much larger and is also coherent.

3. Manufacturing: THz technology can be used to inspect the packaged goods. One important example is that they can be used in pharmaceutical industry to detect the impurities in packaged items. Since the quality of the products that are manufactured in pharmaceutical industries are strictly checked, as it has to fulfill the criteria that have been assigned by the regulatory agencies [4]. THz waves have the capability to give both the physical & chemical properties of the product. Also, the THz spectroscopy [89] is used to determine the properties of the various products used in the pharmaceutical industry.

4. Astronomy & atmospheric research: THz technology can be used to study the various research of the space and also used to study the formation of a new star. A wide range of atmospheric molecules can be detected by THz technology. This is helpful for checking and protecting the ozone layer [3] [4].

5. Wireless communication: THz radiation can also be used a short distance wireless communication. The THz range is very wide, so taking that into consideration, we can easily make secure communication links [32]. The THz range can replace the microwave and IR communication links as the THz bandwidth is higher and attenuation is less when the weather is smoky. So, it is possible that Wireless LAN [13] or other combination links will be replaced by THz communication which has a 10Gbps transmission speed [4].

VII. CURRENT STATUS

As the demand for mobile online services is increasing, hence wireless data traffic is increasing exponentially. The increasing demand for a better communication link has created the development of frequency band in the THz band. In the present age, research in this field is a very positive area of development. Terahertz imaging and spectroscopy [88] has proved to be a very promising field of research, as it has many applications in the field of security [90], manufacturing, communication, sub-millimeter astronomy, etc [91]. Till now the equipment's that are used in this field of research are very bulky, this {sometimes becomes very difficult to use in our daily life. So, research is underway to reduce the size of the various sources and detectors of the THz system. This will make the THz systems easy to operate. An important development of the sources of the THz wave is the quantum cascade lasers [92], which have high output power. These lasers will also open many approaches in the detection technology, to get a powerful, less costly and compact THz systems.

In a recent study, an ultrathin tunable THz absorber has been fabricated by integrating Meta atoms and MEMs technology. It is found that the meta-atoms and suspended flat membranes [93]could expand the near-field coupling. Another work was done on a polarization independent metamaterial absorber with the help of graphene wires. After simulation, it was found that if the bias voltage on the graphene wires is tuned, the absorption peak frequency gets fixed in the lower THz frequencies [94]. So, basically this study demonstrates many ways to employ the THz wave with the help of graphene. Similar work carried out by Bing–zhengXu *et al.,* with the help of whole graphene monolayer. The proposed design of THz absorber shows a high absorption for a very high bandwidth [95]. So it is found that with the help of graphene monolayer, it is easy to tune the conductivity of graphene by altering the gate voltage. Many other works based on the graphene-based THz absorber is underway. One such work involves the design of a novel graphene-based tunable broadband absorber. In this work, by adjusting the gate voltage, a broadband from 25.08THz to 44.81THz with the absorption of 90% is achieved [96]. This gate voltage is applied to the graphene for controlling the surface conductivity.

Improvement in the metamaterial research field has given more stress on the chance to design novel devices with unique electromagnetic functionality [97]. Metamaterials are found to operate in narrow spectral band region because of its resonant nature [98], which makes the metamaterial a unique device with properties tunable frequency and functionality with multiple/broadband which are useful for a continuous Wave (CW) THz sources/detectors. In fact, the main criteria of metamaterial are that it has the ability to build materials with the user-designed electromagnetic response at a controlled target frequency. Hence it is an important technology for creating a technologically relevant THz frequency regime. So, a lot of research is being carried out in the field of design, fabrication and, characteristics of metamaterial [99] at THz frequencies.

VIII. STATE OF THE ART

Over the last few years, the Terahertz technology is developing rapidly. It has extended its discoveries and applications in many fields towards the new developments. Particularly metamaterial gives a new way to the group of electromagnetics problems. Recently, the various application of metamaterial w.r.t sensing has gained a lot of advantage, with the growth of metamaterial technology. Hence, our main concern is to design a metamaterial based source and detector in the THz regime and the analysis of the designed structure considering the above-mentioned parameters so that we could propose an efficient structure of source and detector in the THz regime. Another issue related to the development of new and efficient THz sources is the minimum output power; which should be up-to 100mW. Also to reduce the SNR ratio, development is necessary in the field of compact electronically steerable antenna arrays. So, these are few of the problems which are needed to be solved for the fulfillment of a better THz system. Development of his THz technology is a thing that we need to focus on the better performance of electronic devices. Once it will be successful, that can further help us to design a complete set up for THz band communication which can be utilized in the field of medical, security, surveillance.

The research into the metamaterial based terahertz emitter and detector has become a promising paradigm. However due to the practical requirements such as high operating bandwidth, simple structure etc., the progress in metamaterial has yet created the expected impact on research community. Therefore more attention has to be paid towards the development of metamaterial based terahertz emitter and detector, for UWB communication.

IX. CONCLUSION

A detailed study on the THz technology that has been carried out is reported here with primary emphasis on the fabrication part. Terahertz technology has the ability to introduce new opportunities for many applications like imaging, spectroscopy, communications and, materials research etc. Terahertz security screening is developing at an increasing rate. The terahertz technology is very helpful in detecting and identifying objects concealed on people. The terahertz waves are said to be non-ionizing because the energy of the Terahertz waves is very low as compared to other radiating waves. So, many educational institutions, laboratories are investing in terahertz technology for its unique applications. Metamaterials are the artificial structures whose properties are not easily found in nature. As the scope in the field of THz is increasing day by day, so the field of THz signals being researched at large scale. This is because of the reason that the solutions of many wireless communication systems will be solved by using the terahertz frequency band. The demand for Terahertz technology is increasing at a high rate due to its various developing techniques like infrared or ultrasound. These radiations have the ability to control, monitor and inspect the infrared and ultrasound techniques. Terahertz radiations are replacing the technologies for microwave and infrared of the electromagnetic spectrum which are not very safe to use From this generalized concept, the focus of the research and development of metamaterial can be in any quadrant if the proposed artificial structure features the unique electromagnetic properties. To meet the challenges in the field of communication, technologies based on metamaterials can be developed.

Acknowledgement

Author would like to acknowledge the Assam Don Bosco University for providing necessary resources to compile thir paper.

REFERENCES

[1] I. F. Akyildiz, J. M. Jornet, and C. Han, "*Terahertz band: Next frontier for wireless communications,* " Physical Communication, vol. 12, pp. 16-32, 2014.

[2] Shur.M., "*Terahertz technology: Devices and applications,"* Proceedings of ESSCIRC, 13-21, Grenoble, France, 2005.

[3] B. Zhu, Y. Chen, K. Deng, W. Hu, and Z. S. Yao, *"Terahertz Science and Technology and Applications,"* PIERS Proceedings, Beijing, China, March 23–27, 2009.

[4] Ashish Y. Pawar, Deepak D. Sonawane, Kiran B. Erande, Deelip V. Derle, *"Terahertz technology and its applications, "* Published by Reed Elsevier India Pvt. Ltd, Drug invention today Vol. 5, pg. 1 5 7 - 1 6 3, 2 013

[5] W. R. Tribe, D. A. Newnham, P. F. Taday, and M. C. Kemp, "*Hidden object detection, security applications of terahertz technology*," in *Proc. SPIE*, 2004, vol. 5354, p. 55.

[6] Simrat, Jatinder Pal Singh Raina, *"Design, Analysis and Simulation of Metamaterial Electromagnetic Absorber,"* International Journal of Innovative Research in Computer and Communication Engineering Vol. 3, Issue 11, November 2015.

[7] Gabriel Kniffin, *"Metamaterial Devices for the Terahertz Band,"*Portland State University, June 4, 2009.

[8] Michael J. Fitch and Robert Osiander, "*Terahertz Waves for Communications and Sensing,"* Johns Hopkins APL Technical Digest, Vol. 25, No. 4, 2004.

[9] D. Saeedkia, Handbook of Terahertz Technology for Imaging, Sensing and Communications, Cambridge: Woodhead Publishing Limited, 2013.

[10] J. Federici and L. Moeller, *"Review of terahertz and subterahertz wireless communications",* J. Appl. Phys., vol. 107, p. 111101, 2010.

[11] Hirata, A., T. Nagatsuma, T. Kosugi, et al., *"10-Gbit/s wireless communications technology using sub-terahertz waves,"* Proc. SPIE, Terahertz Physics, Devices, and Systems II, Vol. 6772, 67720B, 2007.

[12] Thomas Kürner& Sebastian Priebe, "*Towards THz Communications - Status in Research, Standardization and Regulation,*" Springer Science+Business Media New York 2013, Received: 30 April 2013 / Accepted: 29 July 2013.

[13] T. Kürner, "*Towards Future THz Communications,*" Terahertz Science and Technology, vol. 5, no. 1, pp.11-17, March 2012

[14] Ho-Jin Song, Member, IEEE, and TadaoNagatsuma, Senior Member, IEEE, "*Present and Future of Terahertz Communications,"* IEEE Transactions on terahertz science and technology, Vol. 1, No 1, September 2011.

[15] *"Terahertz (THz) Technology: An Introduction and Research Update,"*High Frequency Electronics, February 2008.

[16]Giles D., *"Terahertz spectroscopy of explosives and drugs,"* Materials Today.2008; 11: 18-26.

[17] R. M. Woodward, V. P. Wallace, R. J. Pye, B. E. Cole, D. D. Arnone, E. H. Linfield, M. Pepper, *"Terahertz pulse imaging of ex vivo basal cell carcinoma," J. Investigative Dermatol.*, vol. 120, no. 1, pp. 72-78, Jan. 2003.

[18]Bradley Ferguson, Xi-Cheng Zhang, *"Materials for terahertz science and technology,"* Nature materials, vol.1, pg. 26-33(2002).

[19] Grischkowsky, D., and Cheville, R. A., "*Limits and Applications of THz Time-Domain Spectroscopy*," in Proc. SPIE—Int. Soc. Opt. Eng.2524, pp. 26–37 (1995).

[20] Van der Weide, D. W., *"Electronic Sources and Detectors for Wideband Sensing in the THz Regime Sensing with THz Radiation,"* D. Mittleman (ed.), pp. 317–334, Springer-Verlag, New York (2003).

[21]Michael R. Boersma, "*An Introduction to Terahertz Electromagnetic Waves Generation, Detection, Properties and Applications,"* Member IEEE.

[22] Hou-Tong Chen, Willie J. Padilla, Richard D. Averitt, Arthur C. Gossard, Clark Highstrete, Mark Lee, John F. O Hara, and Antoinette J. Taylor, *" Electromagnetic metamaterials for terahertz applications. Terahertz Science and Technology,* " 1(1):42–50, March 2008

[23] WithawatWithayachumnankul, Derek Abbott, Fellow, IEEE, *"Metamaterials in the Terahertz Regime,"* IEEE Photonics journal, An IEEE Photonic Society Publication, pp. 99-118, Volume 1, Number 2, August 2009.

[24] Kürner, T. *"Scenarios for the Applications of THz Communciations,"* IEEE 802 Plenary Session, IEEE 802.15 Document 15-11-0749-00-0 thz, Atlanta, (2011).

[25] R. Piesiewicz, T. Kleine-Ostmann, N. Krumbholz, D. Mittleman, M. Koch, T. Kürner: *"Terahertz Characterisation of Building Materials,"* Electronics Letters, 41, 18, 1002–1004, (2005).

[26] Michael C. Kemp, Member, IEEE, *"Explosives Detection by Terahertz Spectroscopy—A Bridge Too Far?",* IEEE Transactions on Terahertz science and technology, Vol.1, No.1, September 2011.

[27] T. Minotani, A. Hirata, and T. Nagatsuma, *"A broadband 120-GHz. Schottky-diode receiver for 10-Gbit/s wireless links*," IEICE Trans. Electron.E86-C, 1501-1505 (2003).
[28] C. Baker, W. R. Tribe, T. Lo, B. E. Cole, S. Chandler, and M. C. Kemp,"*People screening using terahertz technology*," in *Proc. SPIE*, 2005,vol. 5790, pp. 1–10.
[29] B. Ferguson and X.-C.Zhang, "*Materials for terahertz science and technology*," Nature Materials, vol. 1, no. 1, pp. 26–33, September 2002.
[30] Hirata, A., T. Nagatsuma, T. Kosugi, et al., \10-Gbit/s wireless communications technology using sub-terahertz waves," *Proc. SPIE, Terahertz Physics, Devices, and Systems II*, Vol. 6772, 67720B, 2007.
[31] T. Kleine-Ostmann and T. Nagatsuma, *"A review on terahertz communications research,"* J. Infrared, Millim.Terahertz Waves, vol. 32, pp. 143–171, 2011.
[32] T. Kürner, "*THz Communication– Approaching Wireless 100 Gbit/s*," in Proc. International Symposium on Future THz Technology FTT 2012, Nara, Japan, November 2012
[33] D. Britz, *"Evolution of extreme bandwidth personal and local area terahertz wireless networks,"* IEEE 802.15-10/162r0.
[34] M. Koch, *"Terahertz communications: A 2020 vision,"* in Terahertz Frequency Detection and Identification of Materials and Objects, R. Miles, Ed. et al. Dordrecht, the Netherlands: Springer Netherlands, 2007, vol. 19, pp. 325–338.
[35] D. Schurig, J.J. Mock, and D.R. Smith, *"Electric-field-coupled resonators for negative permittivity metamaterials,"* Appl. Phys. Lett. 88, Vol.8, Issue 4, November 2005.
[36] S. Sankaran, M. Chuying, S. Eunyoung, S. Dongha, C. Changhua, H. Ruonan, D. J. Arenas, D. B. Tanner, S. Hill, H. Chih-Ming, and K. O. Kenneth, *"Towards terahertz operation of CMOS,"*Proc. Int. Solid-State Circuits Conf. (ISSCC), 2009, pp. 202–203.
[37] S. Sankaran and K. O. Kenneth, *"Schottky barrier diodes for millimetre wave detection in a foundry CMOS* process*,"* IEEE Electron Devices Lett., vol. 26, no. 7, pp. 492–494, Jul. 2005.
[38] P. Jepsen, R. Jacobsen and S. Keiding, "*Generation and Detection of Terahertz Pulses from Biased Semiconductor Antennas*," *J. Opt. Soc. Am.B*, vol. 13, no. 11, pp. 2424-2436, November 1996.
[39] M. Tani, M. Herrmann, and K. Sakai, *"Generation and detection of terahertz pulsed radiation with photoconductive antennas and its applications to imaging,"* in Measurement Science and Technology, vol 13, pp. 1739-1745.
[40] Y.-S. Lee, T. Meade, V. Perlin, H. Winful, T. B. Norris, and A. Galvanauskas, "*Generation of narrow-band terahertz radiation via optical rectification of femtosecond pulses in periodically poled lithium niobate,"*Appl. Phys. Lett.76, 2505–2507 (2000).
[41] M., Franken, P. A., Ward, J. F., and Weinreich, G., "*Optical Rectification*," Phys. Rev. Lett. 9, 446–448 (1962).
[42] NathanBurford, Magda El-Shenawee, *"Modeling of Plasmonic Terahertz Antennas using COMSOL® Multiphysics"*, IEEE 978-1-4799-7815-1/15/, pp. 2107-2108, 2015
[43] J. N. Heyman, P. Necocleous, and D. Hebert, *"Terahertz emission from GaAs and InAs in a magnetic field,"* in Physical Review, vol 64, 085202.
[44] *Landy NI, et al. (2008-05-21)*"*Perfect Metamaterial Absorber*," *Phys. Rev. Lett. 100 (20): 207402 (2008).*
[45] R. B. Greegor, C. G. Parazzoli, K. Li, M. H. Tanielian, "*Origin of dissipative losses in negative index of refraction materials*," *Appl. Phys. Lett.*, vol. 82, no. 14, pp. 2356-2358, Apr. 2003.
[46] P. H. Siegel, *"Terahertz Technology"*, IEEE Trans. Microw. Theory Tech., vol. 50, pp. 910-928, Mar. 2002.
[47]L. A. Butler, *"Design, simulation, fabrication, and characterizations of terahertz metamaterial devices,"* http://acumen.lib.ua.edu/content/u0015/0000001/0000899/u001500000010000899.pdf
[48] W. J. Padilla, D. N. Basov, and D. R. Smith, *"Negative refractive index metamaterials,"* Materials Today, vol. 9, pp. 28-35, July/Aug. 2006.
[1] [49] H-T Chen, W. J. Padilla, J. M. O. Zide, A. C. Gossard, A. J. Taylor and R. D. Averitt, *"Active terahertz Metamaterial Devices,"* Nature 444, 597–600 (November, 2006).
[50] D. S. Wilbert, M. P. Hokmabadi, J. Martinez, P. Kung, and S. M. Kim, "*Terahertz metamaterial perfect absorbers for sensing and imaging*," Proc. SPIE 8585, 85850Y, 85850Y-6 ("February, 2013).
[51]Claire M. Watts, XianliangLiu , and Willie J. Padilla, *"Metamaterial Electromagnetic Wave Absorbers,"* WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, Advanced Optical Materials.2012, 24, OP98–OP120
[52] N. I. Landy , S. Sajuyigbe , J. J. Mock , D. R. Smith , W. J. Padilla , *"Perfect Metamaterial Absorber,"*Physics Review Letter, Vol. 100, 2008 , , pp. 207-402.
[53] Mohammad ParvinnezhadHokmabadi, David S. Wilbert, Patrick Kung, and Seongsin M. Kim, *"Design and analysis of perfect terahertz metamaterial absorber by a novel dynamic circuit model,"* Vol. 21, No. 14, 15 July 2013.
[54] CST Computer Simulation Technology: www.cst.com/, accessed date: January 2012
[55]ANSYS HFSS:www.ansoft.com/products/hf/hfss/, accesseddate:January 2012
[56] ComsolMultiphysics: www.comsol.com/, accessed date: January 2012
[57] Jianfei Zhu, Zhaofeng Ma, Wujiong Sun, Fei Ding, Qiong He, Lei Zhou, and Yungui Ma, *"High-performance THz metamaterial absorber,"*State Key Laboratory for Modern Optical Instrumentation, 2012
[58] Hu Tao, Nathan I. Landy, Christopher M. Bingham, Xin Zhang1, Richard D. Averitt, and Willie J. Padilla, *"A metamaterial absorber for the terahertz regime: Design, fabrication and characterization,"* Optics Express 7182, Vol. 16, No. 10, 12 May 2008.
[59] Hu Tao, N.I. Landy, Kebin Fan, A.C. Strikwerda, W.J. Padilla, R.D. Averitt, and Xin Zhang, *" Flexible terahertz metamaterials: Towards a terahertz metamaterial invisible cloak,"* Technical Digest – International Electron Devices Meeting, IEDM, 2008.

[60] L. Huang, D. R. Chowdhury, S. Ramani, M. T. Reiten, S. N. Luo, A. J. Taylor, and H. T. Chen, *"Experimental demonstration of terahertz metamaterial absorbers with a broad and flat high absorption band,"* Opt. Lett. 37(2), 154–156 (2012).

[61] T.J. Yen, W.J. Padilla, N. Fang, D.C. Vier, D.R. Smith, J.B. Pendry, D.N. Basov, and X. Zhang, *" Terahertz magnetic response from artificial materials Science,"* 303(5663):1494 – 1496, 2004.

[62] Hu Tao, C. M. Bingham, A. C. Strikwerda, D. Pilon, D. Shrekenhamer, N. I. Landy, K. Fan, X. Zhang, W. J. Padilla, and R. D. Averitt, "*Highly-flexible wide angle of incidence terahertz metamaterial absorber,"* 590 Commonwealth Ave, Boston, Massachusetts, 02215, June 13, 2013.

[63] A. K. Azad, J. Dai, W. Zhang, "*Transmission properties of terahertz pulses through subwavelength double split-ring resonators,*" Opt. Lett., vol. 31, no. 5, pp. 634-636, Mar. 2006.

[64] J. F. O'Hara, E. Smirnova, A. K. Azad, H.-T. Chen, A. J. Taylor, "*Effects of microstructure variations on macroscopic terahertz metafilm properties*", Act. Passive Electron.Compon., vol. 2007, pp. 49691-1-49691-10, 2007.

[65] A. K. Azad, A. J. Taylor, E. Smirnova, J. F. O'Hara, "*Characterization and analysis of terahertz metamaterials based on rectangular split-ring resonators,*" Appl. Phys. Lett., vol. 92, no. 1, pp. 011119-1-011119-3, Jan. 2008.

[66] H.-T. Chen, J. F. O'Hara, A. J. Taylor, R. D. Averitt, C. Highstrete, M. Lee, W. J. Padilla, "*Complementary planar terahertz metamaterials,*" Opt. Express, vol. 15, no. 3, pp. 1084-1095, Feb. 2007.

[67] J. F. O'Hara, E. Smirnova, H.-T. Chen, A. J. Taylor, R. D. Averitt, C. Highstrete, M. Lee, W. J. Padilla, "*Properties of planar electric metamaterials for novel terahertz applications,*" J. NanoelectronicsOptoelectron., vol. 2, no. 1, pp. 90-95, Apr. 2007.

[68] H. Tao, A. C. Strikwerda, K. Fan, C. M. Bingham, W. J. Padilla, X. Zhang, R. D. Averitt, "*Terahertz metamaterials on free-standing highly-flexible polyimide substrates,*" *J. Phys. D Appl. Phys., vol. 41, no. 23, pp. 232004-1-232004*-5, Dec. 2008.

[69] M. Aznabet, M. Navarro-Cia, S. A. Kuznetsov, A. V. Gelfand, N. I. Fedorinina, Y. G. Goncharov, M. Beruete, O. E. Mrabet, M. Sorolla, "*Polypropylene-substrate-based SRR- and CSRR-metasurfaces for submillimeter waves,*" *Opt. Express*, vol. 16, no. 22, pp. 18312-18319, Oct. 2008.

[70] H.-T. Chen, W. J. Padilla, J. M. O. Zide, A. C. Gossard, A. J. Taylor, R. D. Averitt, "*Active terahertz metamaterial devices,*" Nature, vol. 444, no. 7119, pp. 597-600, Nov. 2006.

[71] H.-T. Chen, J. F. O'Hara, A. K. Azad, A. J. Taylor, R. D. Averitt, D. B. Shrekenhamer, W. J. Padilla, "*Experimental demonstration of frequency-agile terahertz metamaterials,*" *Nat. Photon.*, vol. 2, pp. 295-298, 2008.

[72] T. F. Gundogdu, I. Tsiapa, A. Kostopoulos, G. Konstantinidis, N. Katsarakis, R. S. Penciu, M. Kafesaki, E. N. Economou, T. Koschny, C. M. Soukoulis, "*Experimental demonstration of negative magnetic permeability in the far-infrared frequency regime,*" Appl. Phys. Lett., vol. 89, no. 8, pp. 084103-1-084103-3, Aug. 2006.

[73] T. J. Yen, W. J. Padilla, N. Fang, D. C. Vier, D. R. Smith, J. B. Pendry, D. N. Basov, X. Zhang, "*Terahertz magnetic response from artificial materials*", *Science*, vol. 303, no. 5663, pp. 1494-1496, Mar. 2004.

[74] T. Driscoll, G. O. Andreev, D. N. Basov, S. Palit, S. Y. Cho, N. M. Jokerst, D. R. Smith, "*Tuned permeability in terahertz split-ring resonators for devices and sensor,s*" *Appl. Phys. Lett., vol*. 91, no. 6, pp. 062511-1-062511-3, Aug. 2007.

[75] M. Gokkavas, K. Guven, I. Bulu, K. Aydin, R. S. Penciu, M. Kafesaki, C. M. Soukoulis, E. Ozbay, "*Experimental demonstration of a left-handed metamaterial operating at 100 GHz,*" *Phys. Rev. B Condens. Matter*, vol. 73, no. 19, pp. 193103-1-193103-4, May 2006.

[76] B. D. F. Casse, H. O. Moser, J. W. Lee, M. Bahou, S. Inglis, L. K. Jian, "*Towards three-dimensional and multilayer rod-split-ring metamaterial structures by means of deep X-ray lithography,*" *Appl. Phys. Lett.*, vol. 90, no. 25, pp. 254106-1-254106-3, Jun. 2007.

[77] O. Paul, C. Imhof, B. Reinhard, R. Zengerle, R. Beigang, "*Negative index bulk metamaterial at terahertz frequencies,*" *Opt. Express*, vol. 16, no. 9, pp. 6736-6744, Apr. 2008.

[78] D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, D. R. Smith, "*Metamaterial electromagnetic cloak at microwave frequencies*", *Science*, vol. 314, no. 5801, pp. 977-980, Nov. 2006.

[79] X. Zhang, Z. Liu, "*Superlenses to overcome the diffraction limit," Nat. Mater.*, vol. 7, no. 6, pp. 435-441, 2008.

[80] H. O. Moser, J. A. Kong, L. K. Jian, H. S. Chen, G. Liu, M. Bahou, S. M. P. Kalaiselvi, S. M. Maniam, X. X. Cheng, B. I. Wu, P. D. Gu, A. Chen, S. P. Heussler, S. bin Mahmood, L. Wen, "*Free-standing THz electromagnetic metamaterials,*" Opt. Express, vol. 16, no. 18, pp. 13773-13780, Sep. 2008.

[81] D. Wu, N. Fang, C. Sun, X. Zhang, W. J. Padilla, D. N. Basov, D. R. Smith, S. Schultz, "*Terahertz plasmonic high pass filter,*" Appl. Phys. Lett., vol. 83, no. 1, pp. 201-203, Jul. 2003.

[82] B. D. F. Casse, H. O. Moser, L. K. Jian, M. Bahou, O. Wilhelmi, B. T. Saw, P. D. Gu, "*Fabrication of 2D and 3D electromagnetic metamaterials for the terahertz range,*" J. Phys.: Conf. Ser., vol. 34, pp. 885-890, 2006.

[83] N. Katsarakis, G. Konstantinidis, A. Kostopoulos, R. S. Penciu, T. F. Gundogdu, M. Kafesaki, E. N. Economou, T. Koschny, C. M. Soukoulis, "*Magnetic response of split-ring resonators in the far-infrared frequency regime,*" Opt. Lett., vol. 30, no. 11, pp. 1348-1350, Jun. 2005.

[84] H. O. Moser, B. D. F. Casse, O. Wilhelmi, B. T. Saw, "*Terahertz response of a microfabricated rod–split-ring-resonator electromagnetic metamaterial,*" *Phys. Rev. Lett.*, vol. 94, no. 6, pp. 063901-1-063901-4, Feb. 2005.

[85] J. F. Federici, B. Schulkin, F. Huang, D. Gary, R. Barat, F. Oliveira and D. Zimdars*, "THz imaging and sensing for security applications - explosives, weapons, and drugs,"*Semicond.Sci. Technol. 20, S266–S280 (2005).

[86] P. H. Siegel, "*Terahertz technology in biology and medicine*," IEEETrans. Microw. Theory Techn., vol. 52, no. 10, pp. 2438–2447, Oct.2004."

[87] P. Kung and S. M. Kim, *"Terahertz Metamaterial Absorbers for Sensing and Imaging,"* PIERS Proceedings, Taipei, March 25–28, 2013.
[88] X. Yin et al., *"Terahertz Imaging for Biomedical Applications: Pattern Recognition and Tomographic Reconstruction,"* DOI 10.1007/978-1-4614-1821-4 2
[89] KishiT.,*"Terahertz spectroscopy,"* In: Joint 30th International Conference on Infrared and Millimeter Waves; 2005:184.
[90] Murrill, S. R., B. Redman, and R. L. Espinolac, "*Advanced terahertz imaging system performance model for concealed weapon identification," Proc. SPIE*, Vol. 6549, 654902, 2007.
[91] M. C. Kemp, P. F. Taday, B. E. Cole, J. A. Cluff, A. J. Fitzgerald, and W. R. Tribe, *"Security applications of terahertz technology,"* in Proc.SPIE, 2003, vol. 5070, p. 44.
[92] M.F. KIMMITT, "*Restrahlen to T-Rays – 100 Years of Terahertz Radiation,"* Physics Centre, University of Essex, Colchester CO4 3SQ, UK, J Biol Phys. 2003 Jun; 29(2-3): 77–85.
[93] Mingkai Liu, MohamadSusli, Dilusha Silva, Gino Putrino, Hemendra Kala, Shuting Fan, Michael Cole, Lorenzo Faraone, Vincent P. Wallace, Willie J. Padilla, David A. Powell, Ilya V. Shadrivov and MariuszMartyniuk, *"Ultrathin tunable terahertz absorber based on MEMS-driven Metamaterial*," Microsystems &Nanoengineering (2017) 3, 17033, 28 August 2017
[94] Yin Zhang, YijunFeng, Bo Zhu, Junming Zhao, and Tian Jiang, *"Graphene based tunable metamaterial absorber and polarization modulation in terahertz frequency,"* Optics express 22746, Vol. 22, No. 19, 22 September 2014.
[95] Bing–zhengXu, Chang-qingGu, Zhuo Li, and Zhen-yiNiu, *"A novel structure for tunable terahertz absorber based on graphene,"* Optics Express 23806, Vol. 21, No. 20, 7 October 2013.
[96] Ying Zhang, Yan Shi, Chang-Hong Liang, "*Broadband tunable graphene-based metamaterial absorber,"* Optical materials express 3036, Vol. 6, No. 9, 1 Sep 2016
[97] Hou-Tong Chen, Willie J. Padilla, Richard D. Averitt, Arthur C. Gossard, Clark Highstrete, Mark Lee, John F. OHara, and Antoinette J. Taylor. *"Electromagnetic metamaterials for terahertz applications,"*
[98] W. J. Padilla and M. T. Aronsson and C. Highstrete and M. Lee and A. J. Taylor and R. D. Averitt, *"Electrically resonant terahertz metamaterial,"* Theoretical and experimental investigation, Phys. Rev. B 75, 041102(R) (2007).
[99] S. Pradeep Narayanan1, Dr. S. Raghavan, *"Trend of Terahertz in Metamaterials,"* International Journal for Research in Applied Science & Engineering Technology (IJRASET), Volume 4 Issue VI, June2016.

AUTHOR PROFILE

Darothi Das has completed her Master of Technology in Electronics and Communication Technology from Assam Don Bosco University, India. She completed her Bachelor of Engineering in Instrumentation Engineering from Assam Engineering College, Guwahati.

Kaustubh Bhattacharyya is currently serving as an Assistant Professor (Sr.) in the Electronics and Communication Engineering Department of Assam Don Bosco University, India. Prior to this he held research positions at Gauhati University, Assam, India. He completed his Bachelor of Science in Electronics, Master of Science in Electronics Science, Master of Philosophy in Electronics Science and Master of Technology in Electronics and communication Technology from Gauhati University, India in the year 2004, 2007, 2009 and 2012 respectively. His research interest is in high frequency communication and soft computing.

Sunandan Baruah is currently serving as the Dean Faculty of Engineering and Technology, Assam Down Town University, India. Prior to this he held teaching and research positions at Angstrom Laboratories, Uppsala University, Sweden and the Asian Institute of Technology, Thailand. He completed his Bachelor of Engineering from Assam Engineering College, Guwahati and his Master of Engineering and Doctor of Engineering from the Asian Institute of Technology, Thailand. His research interest is in the development of nanomaterials for different applications including sensors, photo-catalysis and solar cells.