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Trend of Terahertz in Metamaterials

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Abstract — Interest in engendering, identifying and deploying terahertz (THz) waves by using either photonic or electronic properties of the material in THz frequencies is still challenging part, where the metamaterials open a path to bridge the so-called "THz gap". Terahertz radiation (T- rays) will provide opportunities on the growth of metamaterials which have the enormous electromagnetic properties present in it. With the concept of negative permittivity and permeability find a new artificial material named metamaterials has all the properties which are not available in nature started finding out a wide range of the structures in all the dimensions reviewed in terms of their concepts, an area of use and its applications. Terahertz metamaterials in the field of science and technology would provide excellent growth which leads to advance the research by controlling the electromagnetic fields desired for the implementation and fabrication. This paper recalls the properties of metamaterials and provides a wide view for their demonstrated applications and takes it to the next generation of Terahertz frequencies & devices. The review includes the various structures of metamaterials used in terahertz domain and the power sources used which are beyond the infrared and microwave region.

Keywords — Laser, Metamaterials, Split Ring Resonator, Spectroscopy, Terahertz

I. INTRODUCTION

It is much eager to notice that the concept of "Metamaterial" by without knowing its principle of physics and the property of light present in it which are available in earlier centuries. The best example for metamaterial (MM) is the Lycurgus cup- roman nanotechnology, which is exhibited in the British Museum dated around the 4th Century are shown in Fig. 1. The cup is made up of ruby glass with gold nanoparticles merged in it. The Property of the light scattering over the cup proved the principle of metamaterials is present in the cup, by showing it in green color under day light, i.e., reflected light and turns to reddish color when the light passes through it, i.e., transmitted light. The analysis also confirmed by using Mossbauer spectroscopy [1]. Although many researchers have made a major number of reviews and attempts in the field of metamaterials to exhibit its properties to its next level of revolution still they are facing some challenges during fabricating it has a device with its unique exotic effects such as negative refraction [2 – 4], negative refractive index [5 – 7] invisibility cloaking [8, 9], super lens [10], and more, which made the need of metamaterials extend to its next decade. Metamaterials are the one which has artificially structured with its nonexistence properties which are not available in nature [11 – 14]. To govern the electromagnetic fields these artificial structures could be used in a way, which were early unprecedented.

Fig. 1 Lycurgus Cup (British Museum; 4th century) *[1]*.

It is much more useful to have a glance about the concept of metamaterials with its historical record which made the following researchers to do much more adequate research in this area towards the day to day change in technology. While viewing the groundwork for research in the area of metamaterials, three beautiful works realized the need of metamaterials and becomes a milestone in the field of modern metamaterials. The first work was done by V. G. Veselago's in 1968 to analyse both negative permittivity and permeability of artificial materials in a theoretical manner over the naturally available materials and proved that none of the natural material doesn't have this property in the same frequency range. Moreover, he quoted that this kind of materials are possible which exhibits the significant properties not like thereof any identified materials by providing changes in electromagnetic phenomena [15]. Veselago's work was demonstrated experimentally first by D. R. Smith et al. in 2000 at the microwave regime forms the “left handed materials” with negative refraction phenomena [16]. The work done by Pendry over a perfect lens made easy to understand negative refraction of artificial materials by filling the gap in existing applications with novel metamaterials [17]. All three papers have initiated the path of research over the metamaterials research field which were especially focused on the negative refractive index medium and left handed materials. It has been found during late 1990s that mainly two structures were prescribed for the design of metamaterials: The structure with negative-ε/positive-μ is called a thin wire (TW) structure in the form of an array, by predicting an effective plasmonic response at GHz range [18], while the structure with positive-ε/negative-μ is named as a split ring resonator (SRR) which exhibits a magnetic resonance [19]. Then the third basic metamaterial element was introduced lately will be an alternative for SRR’s which has the electric LC-resonator (ELC) [20] with its electric resonance. In Fig. 2, shows the structures mainly used for metamaterials in various regime. Day by day there is a rapid development in the area of metamaterials which has exclusive properties which are nowhere found in the natural materials. It made as an important phenomenon for the terahertz (THz) devices were still an initial stage of research are carried out when compared to the infra-red and microwave range of frequencies.

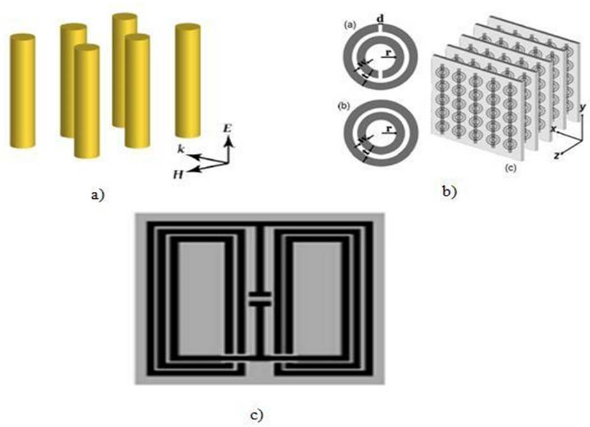

Fig. 2 a) Thin wire, b) SRR with various types *[19]*, c) ELC *[20]*.

Corresponding from 100 GHz to 10 THz is the THz regime for the electromagnetic (EM) spectrum (1 THz = 1012 Hz, where 1 THz belongs to 300 μm in wavelength and 4.1 meV of photon energy) [21], [22]. This region, lies below the visible & IR frequencies and above the microwave frequencies, so alternatively named as the far-IR region, as shown in Fig. 3. An electromagnetic response which has been derived from their sub-wavelength structure leads to manipulating its waves in THz radiation and gives the path to so many novel applications, including THz devices like switches, sensors, detectors, modulators…etc. with its electrical properties and optical properties which has been derived from proposed metamaterials. Today’s metamaterial research got extended far beyond where exhibiting the tailored electromagnetic properties at higher frequencies, which includes THz gap.

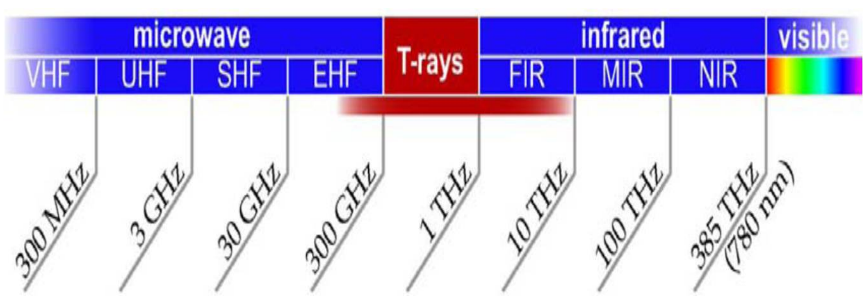

Fig. 3 Terahertz wave in the electromagnetic spectrum [25].

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II. A PATH TO TERAHERTZ

Peter H. Siegel in 2002 gave a vast idea about the terahertz technology in the form of its components and applications in the area of terahertz radiation, terahertz imaging and more, which makes easier understanding to initiate some basic research by the followers includes the field of metamaterials [23]. Technologies for THz generation, detection and processing are analysed clearly with its fields and its applications [24] are used to examine the metamaterial research. In terahertz technology, the Terahertz-Time-Domain-Spectroscopy (THz–TDS), Far-Infrared-Spectroscopy (FIRS) and Quantum-Cascade-Lasers (QCL) play a vital role. Metamaterials is the major area focused mainly, where it tuned to operate in the THz regime for real-world applications. Some of the major power sources used in THz range have been described in Fig. 4. Micromachining techniques and nanotechnology has created a path of terahertz metamaterials in various emerging applications.

In THz-TDS, one can measure the refractive index of a medium, as well as the power absorption and the real & imaginary parts of the complex dielectric function for metamaterials [26 – 29]. Terahertz range has several advantages like low loss dielectric materials, which makes easier in the fabrication using Ultra Violet (UV) lithography. In the future more metamaterials with its remarkable anisotropic properties get into introduced, where it can be polarization-resolved by using THz–TDS as an important tool for its characterisation [30 – 32]. By using, the interaction of laser and photoconductor in an optical heterodyne conversion the amplitude and the phase of the terahertz component are studied [34]. After six years of development, in the entire terahertz range terahertz quantum-cascade lasers can deliver milliwatts which are of continuous-wave coherent radiation in nature [33, 35]. Zero-index terahertz quantum cascade laser shows its excellent performance over the active photonic metamaterials at the terahertz frequency range [36].

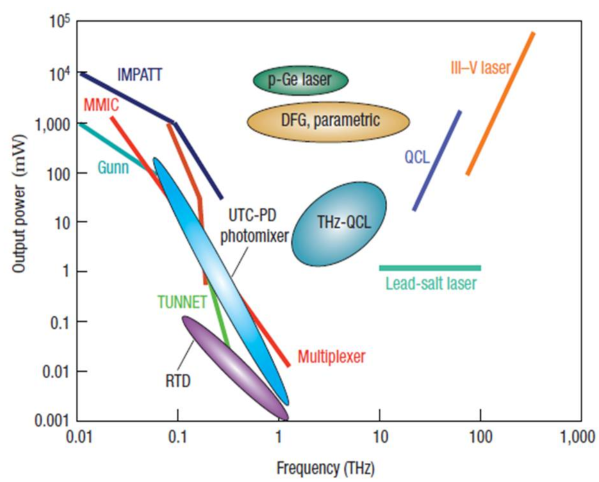

Fig. 4 THz emission power in terms function of frequency *[25]*.

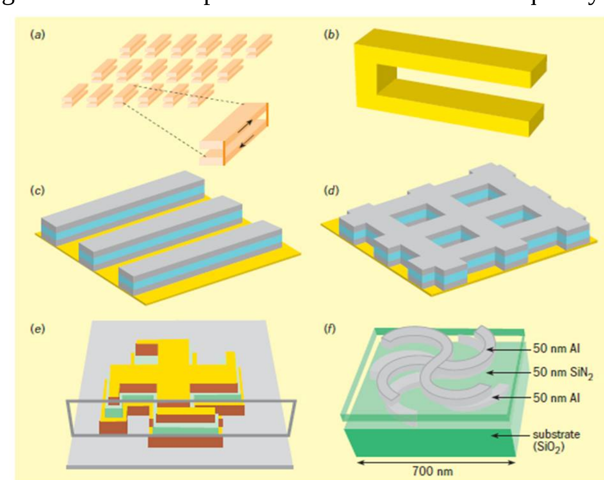

Fig. 5 Types of meta-atoms in various shapes and sizes: (a) nanorods, (b) U-shaped structure, (c) nanostrips, (d) fish-net structure, (e) and (f) chiral structures *[63]*.

During the last decade, theoretical designs and experiential demonstration have been made to build metamaterials with various types of sub-wavelength resonators, for example, metallic TWs [37 – 39], Swiss rolls [40 – 43], rods & crosses in pairs [44 – 51], fishnet like structures [52 – 55], and SRRs [56 – 62]. All the types which are mainly used for THz applications of metamaterial are clearly shown in Fig. 5 with their corresponding shapes and sizes. Among the structures, SRRs are highly symmetric in structures and having finite element modelling which is capable of providing sub-wavelength and sensitivity to metamaterials which includes major designs and applications of THz with its strongest response [64 – 70]. Afterwards, various designs of SRRs were presented as shown in Fig. 6 [71].

Main motivation behind the design of SRRs were used for magnetic responses [72]. If the time-varying magnetic field normally polarized to the SRRs plane above the resonant frequency, it will result in an out of phase or the negative magnetic-response by inducing circulating currents within the ring [73]. In THz this prospective limitation of SRRs could be used as the magnetic response and the magnetic field desires to be erect to the SRR plane in the higher frequencies if coupling is fully induced with magnetic field [72]. However, the EM waves are commonly instance typical to the planar SRR structure with its magnetic field lying on the SRRs plane, which won't excite the direct magnetic resonance in nature [73]. Non-linear properties of the magnetic metamaterials was observed using SRR where the power-induced shift varies for the magnetic response and simultaneously it varies the resonance frequencies, where it supports more in higher frequencies range [74, 75].

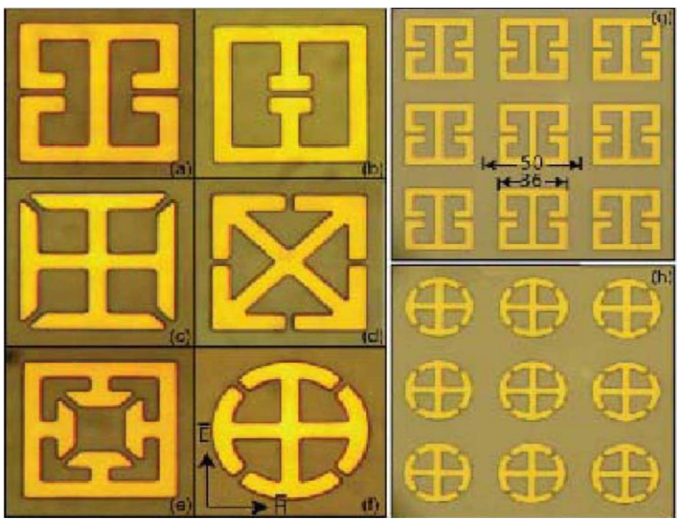

Fig. 6 Various kinds of SRR metamaterials designs *[71]*.

Nonetheless, T. J. Yen et al demonstrated the first THz MM experimentally in 2004, shows a robust magnetic response nearby 1 THz, utilising a single planar layer from the double SRRs array [76]. Over an ellipsometer the MM sample was kept and measured in a Transverse Electric (TE) configuration in 30° as an angle of the incidence for the magnetic response excitation which are off-normal as shown in Fig. 7. To eliminate the electric field coupling fully SRR gap side was associated parallel by the electric field. Similar calculations have been made over single SRRs where it shows a good magnetic response especially at mid-IR (100 THz) [63] and a near-IR (200 THz) regime [77], as shown in Fig. 8. It was achieved by cutting down the SRR size and for easy way for fabrication marginally compact the structure it.

III. ROLE OF STRUCTURES IN TERAHERTZ

Current IC (Integrated Circuits) fabrication and technologies are very suitable for producing planar terahertz metamaterials by matrix embedded of a few micrometres which is minimal in geometric nature. Most of the terahertz metamaterials account for these technologies which has been reported yet now (see Fig. 8, as an example). Over a single wafer large number of small size of MMs were fabricated, where it leads to economy in range, made many metamaterial devices could accommodate in a single wafer. Terahertz metamaterials have shown to have increasingly important applications. It is observed that more terahertz devices based on metamaterials will be developed in the near future.

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Most of the cases, MMs based THz devices outdo their conventional counterparts has been proved. However, their performance is limited only to a narrow spectral band which is not suitable to the broadband terahertz systems due to their resonance properties. The value of terahertz metamaterials will be enhanced largely if frequency tunability or broadband schemes can be incorporated. In Fig. 9. gives the vast information of THz metamaterials with their technique and process involved. The substrate chosen having the capability of changing substrate properties for active and dynamic control in the metamaterial devices like a Schottky diode structure and an eSRR array [78]. It added greater flexibility and made metamaterials to be promising one for practical application at THz frequencies. This made metamaterials based terahertz devices can extend it working frequencies into broadband range.

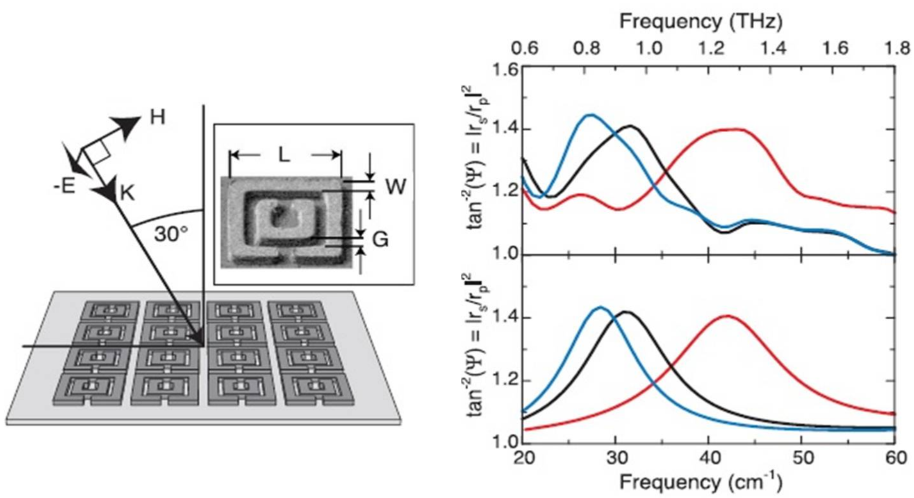

Fig. 7 30° off-normal incident wave using an ellipsometer with different geometrics by magnetically coupled SRRs *[76]*.

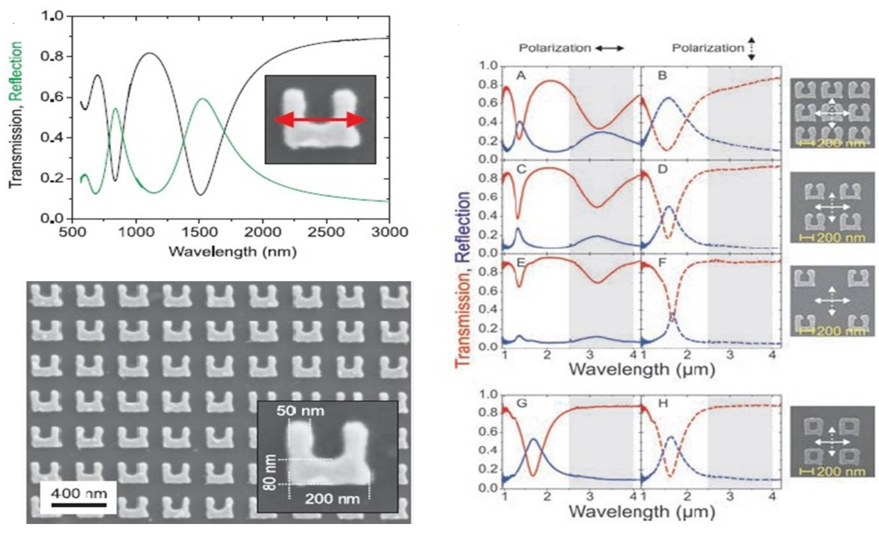

Fig. 8 Magnetic MMs at (a) 100 THz (mid-IR) [63] and (b) 200 THz (near-IR) *[77]*.

As the development of terahertz technology, the metamaterials will play an important role to control and manipulate terahertz waves. Using multilayer electroplating technique it is easy to fabricate complex 3D metamaterials over the silicon, flexible Polyimide, and broadside-coupled SRRs also easily extendable to other numerous structures has been reported recently [81]. The gaps near the split rings will tune the resonance strength of the metamaterials where the substrate of SRR results in the photoexication of it carries where the combination decides the range of THz finally. In case of Schottky diode metamaterials array and substrate together enables the THz modulation by transmitting on the existing devices.

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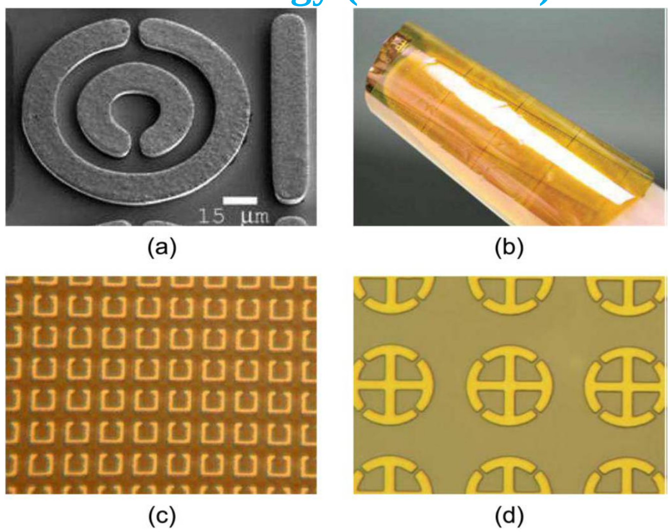

Fig. 9. Different THz metamaterials developed using lithography & deposition processes. These patterns are of micrometres in the order of metamaterials shows the robust personalised electromagnetic retorts at THz frequencies. (a) Using a ring-wire structure obtained Negative Index Metamaterials (NIM) *[64]*. (b) Embossed micro SRRs in free-standing polyimide substrate *[79]*. (c) Using Polyimide substrate fabricated an array of SRRs *[80]*. (d) GaAs mounted with Polarization-invariant eSRRs *[69]*.

Variation in materials and their structures by using some numerical solutions with many attempt of the fabrication process with range from simple to some proposed techniques will make the range of extension on the applications where the recent technology playing a vital role in it. One of the best examples was designed by G. Kenanakis et al. with three existing structures are 807˚ per wavelength in GHz and 417˚ per wavelength in optical frequencies of optical activity with negative index on it [83]. So, they optimize this problem and extend their work by comparing it in both theoretical and practical implementation over Polyimide substrate where they succeeded which made to introduce two more structures by using chiral materials with inspired SRR's. The corresponding structures have the optical activity, which is larger than 300˚ per wavelength in THz regime is a challenging one where they succeeded both in left hand and right hand composite based devices with the negative refractive index response. Large optical activity and huge chirality in metamaterials made the manipulation of THz components with the control of the light polarization and also achieved in micro-nano mechanical systems. Different structures of metamaterials are used in sensing and detecting band gaps near the microwave and THz region [84, 85].

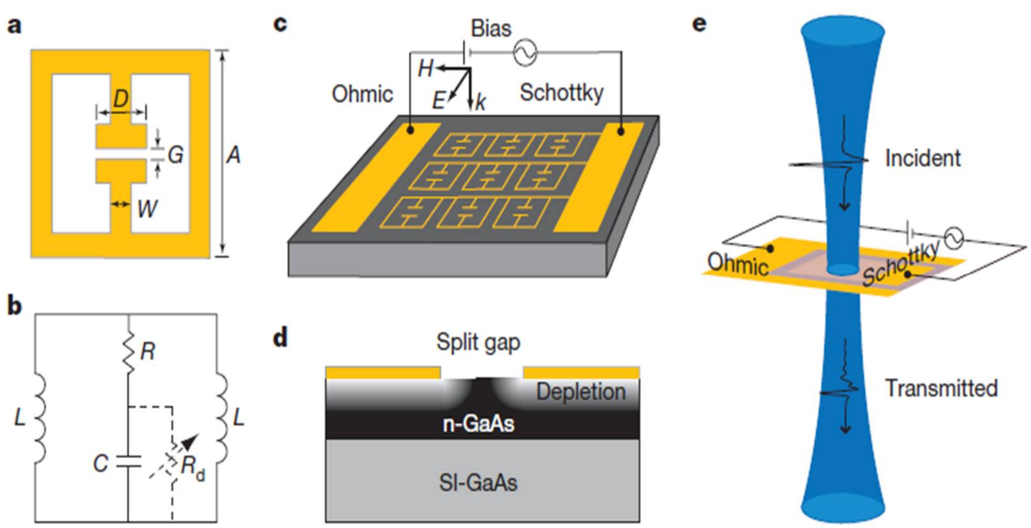

Fig. 10. Schematic view of the active THz metamaterial device. a, Structural view of THz metamaterial switch/modulator

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with its geometry and dimensions. b, RLC model of the chosen metamaterial element. c, Patterned metamaterial elements with a dimension of 50 mm to form a planar array of 535 mm^2. d, Substrate and the depletion region model near the split gap, where the free charge carrier density is indicated by the gray scale. e, THz transmission measurements on a fabricated device an experimental view. *[82]*

Theoretically proven wire arrays and ferrite films shows a negative permittivity and negative permeability in the metamaterials assassinate at microwave and further development made with the available techniques combing novel concepts for metamaterials to achieve an -8 dB bandwidth at 2.4 GHz for -0.5 dB transmission peak by using $Lu_{2.1}Bi_{0.9}Fe_5O_{12}$ (LuBiIG) films and Silver (Ag) films coated over a Gadolinium Gallium Garnet (GGG) substrate. The work proposed by Y. J. Huang et al. also proved that it will have the applications in THz antenna designs and in the sub-millimetre wave with low loss [86].

An anisotropy, which is available naturally has wide applications in tradition ranging from beam splitters, filters to isolators with the realization of hyper lenses, negative refraction and cloaking ... etc. But, achieving the same in the terahertz domain is much more difficult so the artificial anisotropic media is induced by the newly framed Maltese-cross pattern made by W. M. Zhu et al. as shown in the Fig. 11 [87]. It is achieved with the help of Microeletromechanical System (MEMS) actuators by adapting metamaterials into it where it creates the new opportunities and development especially in terahertz devices [87].

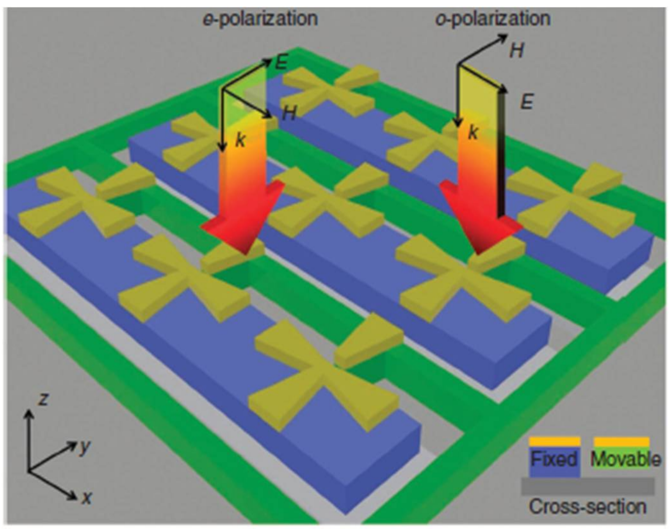

Fig. 11. Experimental configuration of Maltese-cross metamaterial. Four trapezoid metal strips in a single unit cell, out of one is connected to the movable frames connected with the comb-drive actuator (green). The rest of the unit cell is attached on the isolated islands (blue) mounted on the substrate. *[87]*

The Maltese-cross metamaterials array have been broken into four symmetry, which induce the anisotropy in the THz spectral region. It is fascinating, to observe that the transmission and phase spectra of Maltese-cross metamaterials array has been designed with the unit cell of 28×28 mm^2 to operate from 1 to 5 THz range. The e-polarized incidence and o-polarized incidence with the electric field are the key point in this work. With the help of electric split ring resonators and cantilever beam reconfiguration made a technical bonding of MEMS with metamaterials in the transmission spectra of 0.21 THz. Corresponding e-polarization and o-polarization was obtained by numerical solution where it provided electric potential voltage in its schematic structure. Nanostructure used in metamaterials upgrading the electrical potential from terahertz to an optical range using the low cost technique of nanoimprint and high-resolution complementary metal–oxide–semiconductor (CMOS) fabrication technique, in a result they are useful for low energy and high contrast applications with megahertz bandwidth in micro power levels [88].

IV. RECENT DEVELOPMENT IN TERAHERTZ

In the wide range of applications and manufacturing techniques metamaterials becoming unexpected in an emerging area of developments, where the research is mainly focused more on the desiring worldwide applications ranging up to the visible range. The detailed view of 3D THz metamaterials ranging from micro to nano during its manufacturing facilities work has been discussed

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by H. O. Moser et al. with various interesting and preferred evidence, experimenting it in the range of microwaves to the visible one [89]. In electromagnetic metamaterials negative refraction is the key to develop the double-negative properties with high resolution microscopy attenuated by Sub-wavelength resolution imaging in the experimental path [89]. As mentioned earlier about the various structures it can easily identify that fishnet structure plays a unique role, especially in terahertz frequencies with the improved multiband where a desirable 3D metamaterials has been made with all forms of lithography techniques ranging from photo lithography to 3D primary pattern generation. The hidden electromagnetic properties could be verified by various numerical analysis especially shows the negative permeability, permittivity, transmittance, S-parameter and refractive index in an independent electromagnetic wave for various THz frequencies. By doing, some modification in the fishnet structure the 3D metamaterials could be extended to the infra-red and optical frequencies and the corresponding results were pointed out evidently by Q. Du et al. after doing the clear experimental demonstration [90].

To attenuate SRRs in three dimensional (3D) is the challenging task, achieving magnetic responses is not easy as in the terahertz planar metamaterials. But by multilayer electroplating, K. Fan et al. achieved and also proved a very strong magnetic response using THz-TDS system adapted in the range from 1 to 1.3 THz. With this successful technique made 3D metamaterials to develop more novel devices in THz range. The new path and new technology leads to many success by doing more research and produce many interesting devices in the THz regime with their corresponding applications [91, 92]. Photonics and metamaterial devices have always bonding in nature, which enhances the growth of photonics in the name of metamaterial (devices) and vice versa. As of like metamaterials, photonics devices should show a good performance in THz range, which is again a big challenge for all domain researchers varies from physicists, chemists or engineers in the research of terahertz applications. Like anisotropic mode here polarization has to derive from electromagnetic waves, by transmitting the signal along with its valuable information without changing not even its basic properties. So N. K. Grady et al. created a way with the ultrathin form which realises near-perfect anomalous refraction in the relevant terahertz regime [93].

It was predicted that both the linear polarization and near perfect anomalous refraction found to be difficult at THz frequency technically through numerical simulation, even though by solving some fabrication issues too which is a real challenge over THz range. Polarization sensitive tunability of the incident waves in THz waves was proposed by F. Ma et al. by changing the deflected shape of curved cantilever beams over a tunable THz metamaterial simultaneously in an array of eSRR unit cells [94]. Electrostatic actuation mechanism was used to change the height of the cantilever beams. Conducting metal line was used to connect the individual eSRR unit cells electrically in order to connect the entire eSRR array. By using strong transmission spectra, reconfiguration of the cantilever beams for eSRRs was achieved at the transmission spectra at 0.21 THz for the e-polarization, whereas the transmission spectra remains practically unchanged for σ-polarization. The observed polarization sensitive could be used for the development of THz polarimetric devices in polarization sensitive and insensitive technique. The unit cells of eSRR arrays with T-shaped cantilevers of SEM images are shown in Fig. 12 [95].

Recent works of terahertz metamaterials have enhanced to the Plasmon Induced Transparency, (PIT) which is polarization independent over here. In general, PITs are polarization dependent and highly sensitive to split it without changing its behaviour, where c-SRRs played a huge role in THz frequencies. The polarization of light, sensors, Electromagnetically Induced Transparency (EIT) effect can be achieved by using coupled radiative-dark plasmonic mechanism in 2008 by S. Zhang et al. [96] numerically shown in various applications [97, 98]. EIT like effect in a symmetric planar metamaterials was achieved by A. Ourir et al. in THz range with the help of destructive Fano interference between the first two modes of an array for Multi-Gap Split Ring Resonators (MSRRs) deposited over a thick silicon substrate [99]. A polarization-independent transmission have been achieved due to four fold symmetry properties of planar thin film material in the structure. High group index values are also achieved in both vertical and horizontal polarization over the THz spectral range using these metamaterials. Specific transmission band in the THz range makes this perfect for the slow light applications and easily adaptable in the infra-red & optical range too. Polarization insensitive multiband THz metamaterial absorber was designed by F. Hu et al. with four narrow band high absorptivities of 98%, 97%, 98% and 97% at 0.8 THz, 1.27 THz, 2.21 THz and 3.09 THz, respectively [100]. This found to be an alternate for sensitive polarization of multiband absorber used previously more [100]. By changing the geometrics of the absorber and its thickness, the position of the each and every absorption peak can be tuned. The absorption of metamaterials whose dielectric layers moulded in semiconductor (SiO_2 and Si) substrate have the average efficiency of absorptivity with 95% at 3.7 THz [101].

J. Zhu et al. demonstrated ultra-band THz metamaterial absorber with polarization insensitive, wide angle measurements using array

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of truncated pyramid structure. The unit cell in the structure was made up of metal-dielectric multi-layer composite [102]. In this each sub layer behaving as an effective waveguide, producing a large absorptivity above 80% from 0.7 to 2.3 THz. The maximum measurement angle used here is 40°, achieved full width absorption at half maximum is of around 127%. Compare to earlier report values for THz frequencies this is much greater with high practical feasibility. This device was much more useful in microbolometer element sensor of THz imaging. X. Chen et al. proposed and investigated thin-film polarization insensitive multiband THz metamaterial absorber and reveals that multi-band absorption of 89%, 98% and 85% absorptivities at 0.72 THz, 1.4 THz and 2.3 THz, respectively [103]. More than 60% absorption with its incident angles over a wide range of THz waves lead to many applications. Polarization independent characteristics for multiple resonances was demonstrated by P. Pitchappa et al. using micromachined reconfigurable metamaterial in terahertz spectra region [104]. MEMS based Reconfigurable Metamaterial (MRM) was proposed by placing symmetrically eight microcantilevers at the corner to form an octagon shape. Switching range proposed here is of 0.16 THz and 0.37 THz. Modulation could be improved by optimising the metal layer thickness up to 80% at 0.57 THz. To incident THz waves with electric field, along x- direction (TE mode) and y- direction (TM mode) would be polarization independent one for ELC resonance and dipolar resonance at all states of actuation. Isotropic proposed MRM was fabricated using CMOS compatible process with improved switching performance, repeatable operations, high yield fabrication process is an ideal for THz applications [104].

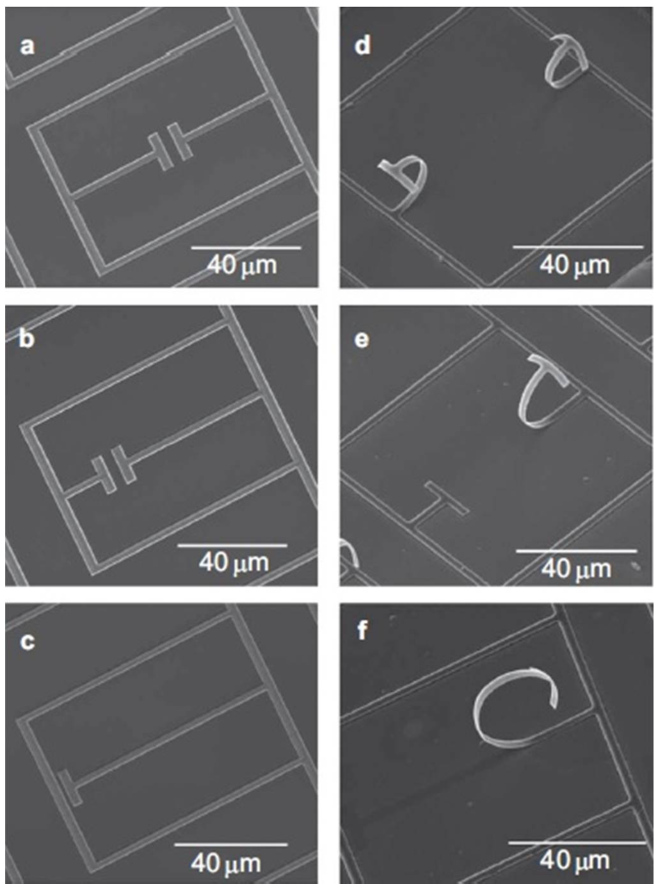

Fig. 12. SEM images of T-shaped cantilevers attached with unit cells of the eSRR01, eSRR02 and eSRR03 arrays: (a–c) non-released and (d–f) released, respectively. *[95]*

Using an electrostatic MEMS actuator and electrical dipole resonator array F. Hu et al. demonstrated dynamically tunable THz metamaterial absorber [105]. Electrical dipole resonance is the cause for absorption and shows a tunable performance on need. Applying very low voltage of 20 V, the centre frequency of modulation and the amplitude reaches 10% and 20%, respectively for the finite integral technique used. Samples were fabricated on the silicon substrate by adapting surface micromachining technique during the fabrication process. The Scanning Electron Microscopy (SEM) of the fabricated samples are shown in the Fig. 13 [105].

The experimental and simulation results shown a good agreement and could be capable for wide applications in THz regime. THz-TDS system was used to characterize the modulation performance by measuring its reflection spectra. The proposed dynamically tunable devices can be working across a broad frequency range, includes microwave and infra-red.

MEMS Plays a vital role in the recent decades by adapting reconfigurable metamaterial in terahertz applications. Micromachining technique is the key factor in that surface micromachining is desirably usable and easily adaptable one to any substrates like silicon, quartz, etc. for tunable THz filter applications. Z. Han et al. used this principle to incorporate THz switchable filter and modulator over a low loss quartz substrate by incorporating RF-MEMS (Radio Frequency Micro Electro Mechanical Systems) capacitor with SRRs [106]. THz-TDS system was used to conform the tunabality of SRR resonance and controlled electrostatically by RF-MEMS capacitor to achieve THz transmittance. A high contrast switching performance was enhanced here at 480 GHz as 16.5 dB due to high transparency and low loss of quartz as a substrate. MEMS-SRR was found to be the high-contrast switch in a specified THz frequency, where it supports dynamic modulation measurement too. The arrayed cluster of MEMS-SRR switch type cantilever could be used to develop tunable grating plate or Fresenel zone plate is a sub-module of terahertz optics [106]. THz wavelength lies in the sub-micrometer regime makes ease to produce the materials using standard photolithography process by adapting metamaterial concept in it. Scarcity of passive and active components in THz regime leads to do more research on this area which made N. born et al to enhance and demonstrate metamaterials with ultrahigh angular sensitivity towards the angle of incidence [106]. It is depicted by them first by optimise the angular sensitivity of strongly interacting asymmetric Double Split Ring resonator (aDSR) metasurface and applied the concept to the multiband metamolecule i.e., with multiple Fano resonances [107]. The sensitivity of detector arrays could be enhanced by the high angular sensitivity with the concept of metamaterials in THz range between 0.44 and 0.55 THz.

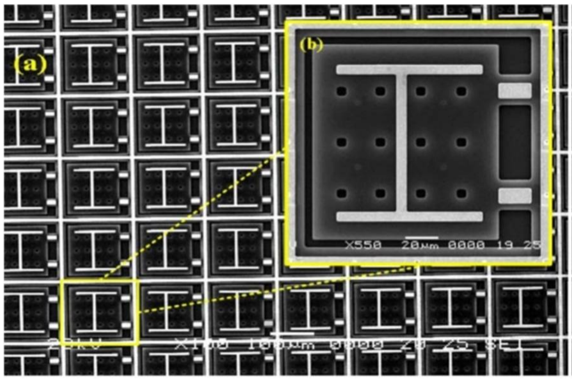

Fig. 13. SEM Images a. the array and b. a unit cell. *[105]*

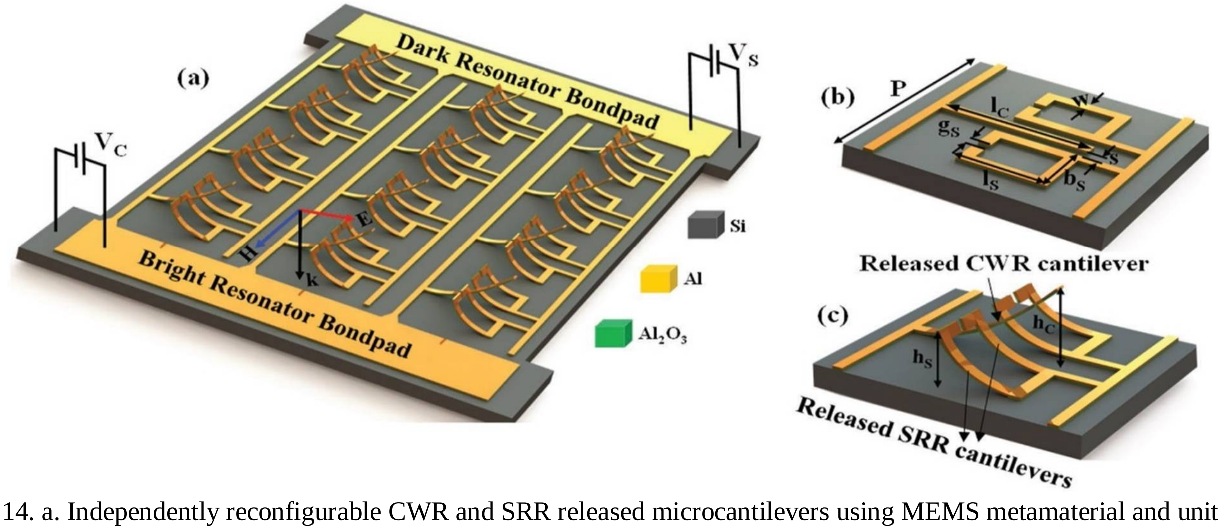

Fig. 14. a. Independently reconfigurable CWR and SRR released microcantilevers using MEMS metamaterial and unit cell of metamaterial with both CWR and SRR microcantilevers in b. OFF states and c. ON states, respectively *[110]*

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If the SRR's were incorporated with liquid crystals (LC) tunable terahertz absorber exploits the critical coupling between periodically arranged patch resonators and external field as discussed by G. Isic et al. [108] . It has been shown by them that the device having above 23 dB in display modulation depth, low operating voltages and 15% more than of spectral tuning. Critical coupling phenomenon exploded with simple electrode allows an effective switching in LC molecules with reduced line defects. Most of the coupling mechanisms are passive in nature, which fails to control the dynamic mode coupling in plasmonic metamaterial arrays. X. Su et al. [109] demonstrated the dynamic mode coupling, which was not used extremely yet. Metallic concentric rings comprised in hybrid metal semiconductor metamaterial connected with silicon (Si) bridges. By modifying, the photodoped carriers the dielectric function of silicon was studied that triggers the coupling characteristics between metallic resonators. Active and ultrafast way of the dynamic mode coupling was demonstrated by enabling reconfigurable metamaterials has opened the opportunities for active imaging, active sensors, filters, modulators and active polarization rotation devices in THz regime [109]. To observe the polarization of the incident THz electric field parallel to the photosensitive Si islands here using an Optical-Pump Terahertz-Probe (OPTP) system was illustrated here. Recently proposed EIT for THz MEMS metamaterial by P. Pitchappa et al. schematic diagram is described in Fig. 14 with an array of Cut Wire Resonator (CWR) placed with SRRs to give sharp transmission peak [110]. In Fig. 15, the optical microscope and SEM of both CWR and SRR microcantilevers in OFF state is shown [110].

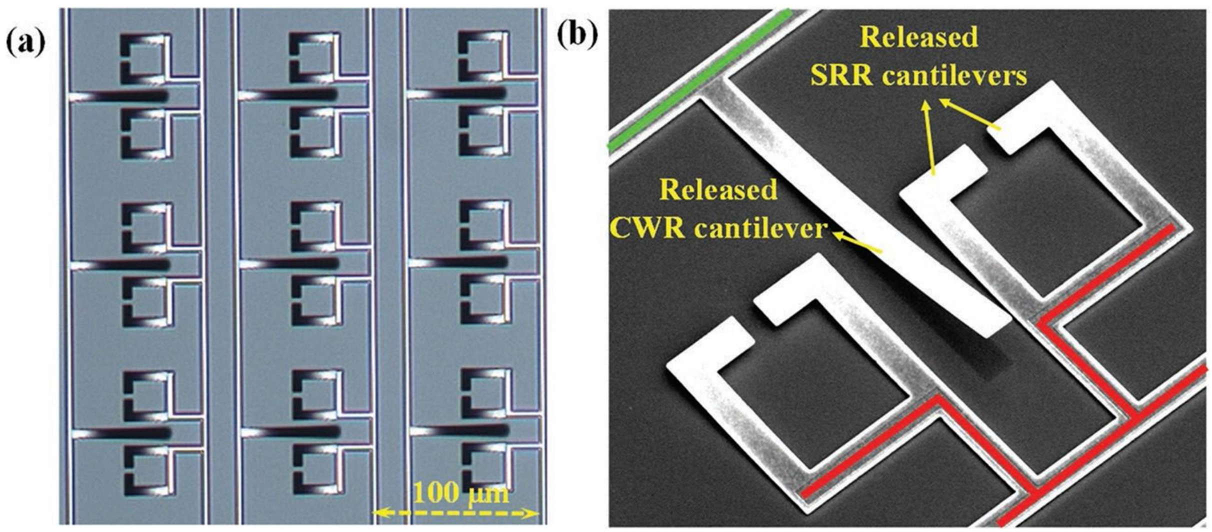

Fig. 15. a) Fabricated MEMS metamaterial an optical microscope image and b) SEM image of fabricated unit cell of metamaterial with both CWR and SRR microcantilevers in OFF state *[110]*

V. CONCLUSION

In the last two decades notable research progress have been carried and achieved in the upcoming field of THz science and technology. But, still there are large restrictions which limits the fruitful applications in this regime. To sort out this issue artificial electromagnetic materials, i.e., in the form of SRR's should incorporate with semiconducting or dielectric substrate to develop novel devices with achievable tunability in THz region. The Metamaterials structures, which performs well in THz devices has been discussed and some of the cases deal beyond THz frequencies to the visible range. Due to their resonant nature, most of the metamaterial devices found to be operated in narrow spectral band region, which made to take much efforts on them to make it into working devices with tunable frequency and functionality with multiple/broadband favoured for applications employing Continuous Wave (CW) THz sources/detectors. This has potential applications in the long resonant lifetime's measurement, radiation signatures with reference free, and total internal reflection attenuated sensing based on the THz spectrum. The operation and execution of THz Metamaterials made a prominent ability for evolving applications in the EM Spectrum relevant region technologically. Three dimensional (3D) Metamaterials and anisotropic media start emerging which may rapidly boost the various applications of terahertz spectrum. Newly admired fabrication techniques, advancement in the near-field characterization and novel concepts in designing metamaterial ensure a lead to widely essential over the time of last five years has given a path for THz based metamaterials. Certain additional fundamental advances within the next decade combined the implementation of Metamaterials into real-world THz applications. Merging the concepts of electronics and optics with all sorts of emerging fields as open a wide path to so many devices in the terahertz region ranging from cloaking, absorbers, modulators, bolometers, antennas, filters, lens etc. A detailed view of all possibilities of making THz metamarials is discussed in detail manner till current scenario.

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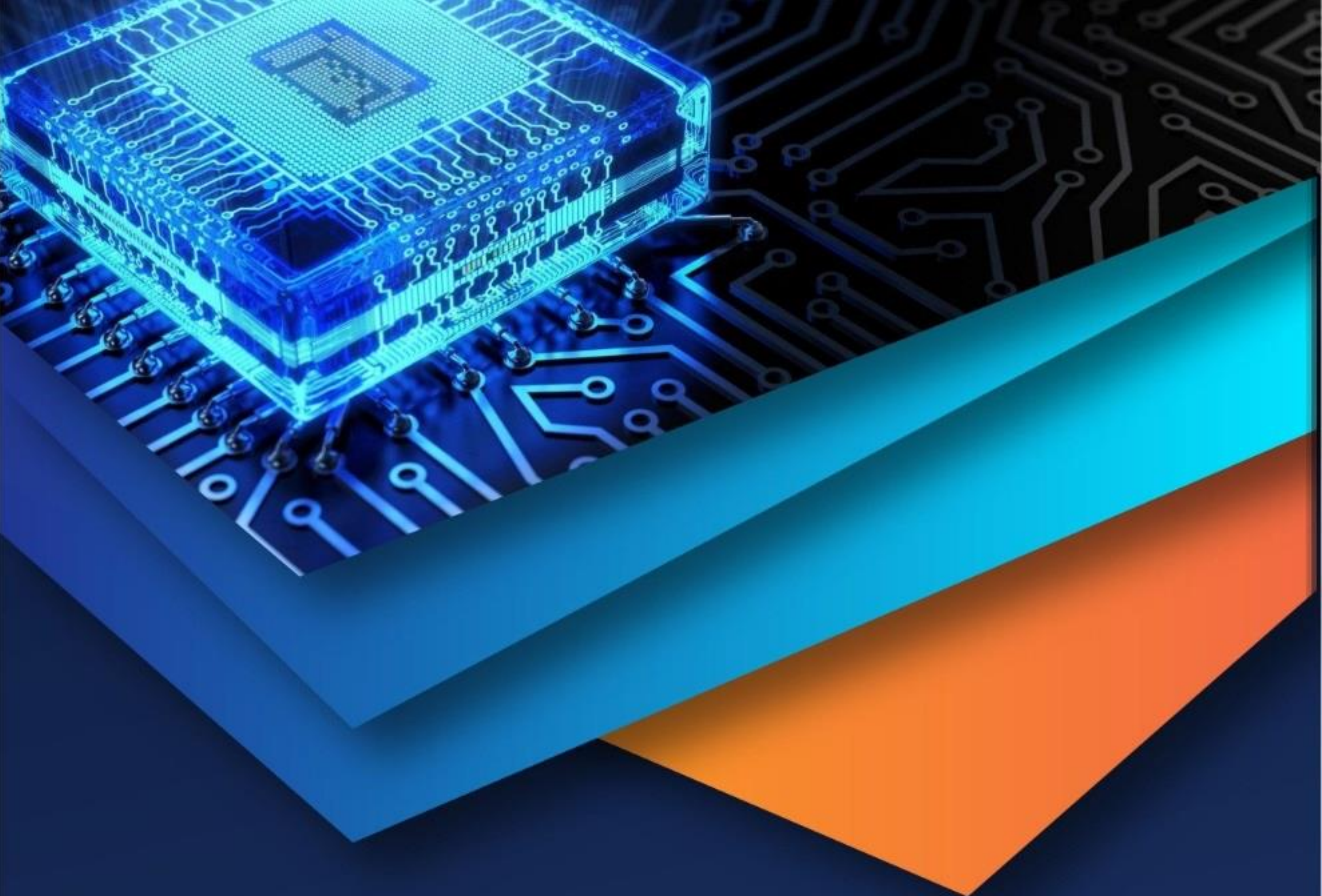

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