Modelling & Simulation of Terahertz Perfect Absorber for various incidence angle

A PROJECT REPORT

SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENT FOR THE AWARD OF THE DEGREE OF

MASTER OF SCIENCE

IN

PHYSICS

Submitted by

Nilesh Kumar Gupta

(Roll No. 2K19/MSCPHY/08)

Under the Supervision

of

Dr. Yogita Kalra

&

Dr. Kamal Kishore

DEPARTMENT OF APPLIED PHYSICS

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road Delhi -110042

May -2021

DEPARTMENT OF APPLIED PHYSICS

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

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I hereby certify that the work, which is presented in the Project entitled "**Modelling & Simulation of Terahertz Perfect Absorber for various incidence angle"** in fulfilment of the requirement for the award of the Degree of Master of Science in Physics and submitted to the Department of Applied Physics, Delhi Technological University, Delhi is an authentic record of my/our own, carried out under the supervision of Dr. Yogita Kalra & Dr. Kamal Kishore. The work presented in this report has not been submitted and not under consideration for the award for any other course/degree of this or any other Institute/University.

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2K19/MSCPHY/08
M.Sc., Physics

DEPARTMENT OF APPLIED PHYSICS
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road Delhi -110042

SUPERVISOR CERTIFICATE

I hereby certify that the Project Dissertation titled "**Modelling & Simulation of Terahertz Perfect Absorber for various incidence angle**" which is submitted by Nilesh Kumar Gupta, Roll No. 2K19/MSCPHY/08, Department of Applied Physics, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Science, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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NILESH KUMAR GUPTA

ABSTRACT

Because of the developed fabrication and simulation technologies, the need for a perfect absorber that must be very thin and flexible is continuously increasing. There is a particular interest in developing a resonant metamaterial absorber by designing of refractive index n(ω) and impedance Z(ω) through which near unity absorption can be obtained at wide angle of incidence. Here I present a design and analysis of metamaterial perfect absorber for its response in frequency range of 0.6 THz to 1.4 THz through computer simulation using COMSOL Multiphysics 5.5. We tested the absorber's reaction to transverse magnetic and transverse electric polarizations at varied angles of incidence. It is important to note that our absorber was just 8 μm thick, that is it is highly flexible. I showed an absorptivity of 0.99 at 0.97 THz.

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LIST OF ABBREVIATIONS

PIM	Positive index materials
THz	Terahertz
FE	Finite element
TE	Transverse electric
TM	Transverse magnetic

CHAPTER 1

INTRODUCTION

1.1. BIRD'S-EYE VIEW OF METAMATERIAL

"The important thing is not to stop questioning" Albert Einstein once said. Indeed, in 1968, a Russian physicist named Victor Veselago's scientific curiosity led to the discovery of an entirely new field of modern optics: metamaterial optics. How light waves will interact with materials normally depends on two parameters, permittivity (ε) and magnetic permeability (μ) both of which are independently used in Maxwell's equations. The Refractive index of a medium is defined by their product as $n = \sqrt{(\pm \varepsilon\mu)}$. Generally, the refractive index and dielectric permittivity of transparent materials are greater than or equal to 1 and magnetic permeability $(\mu) \approx 1$. By changing the chemical composition of the material, the refractive index can be altered to some extent. Though, the refractive index is typically greater than one (for air) and less than four (for silicon). Veselago tried to find whether or not ε and μ for some material can be simultaneously negative, which will lead us to a negative refractive index. The idea that a negative refractive index can be obtained by creating subwavelength composites in which effective permittivity and permeability can be controlled independently brought us the motivation for metamaterial research.

Meaning of meta in Greek is 'beyond', so the interest behind research in metamaterials is to design an artificial material which has properties that are beyond of that found in nature. Modifying refractive indices and having control on distribution of spatial refractive index are not possible earlier without the discovery of metamaterial technology. Because of these artificial structures antiparallel phase and energy velocities, backward phase-matched nonlinear wave interactions, negative refractive index, magnetism in optics, and clocking phenomena are made possible. Metamaterials are made of periodic structure of unit cell called meta atoms. Metaatoms provides us the unprecedented opportunity for modeling the material's properties.

Optical metaatoms are artificially made structures with dimensions that are smaller than the wavelength of light. By changing that dimensions and other characteristics of meta atoms desired magnetic and electric properties in materials can be achieved. In this way a new type of optical materials is developed which are not found in nature, including positive index materials (PIM) with nearly any μ and ε, so called near zero refractive index materials, negative refractive index materials. Recently negative refractive index materials have been designed which shows negative index of refraction at a short wave length of 580 nm i.e. in visible range. Although in 2-D metamaterials many unnatural physical properties have been showed despite this bulk structure are required for many practical applications. In recent time, designing of 3-D metamaterials at optical frequencies have made considerable progress.

A metamaterial is a kind of material that is designed artificially to have such properties which are not found in materials occurring naturally. They are made by the repetitive arrangement of small unit cells. These unit cells are made of materials like metals and plastics. Metamaterials having exceptional optical properties had changed the entire world of optical science and engineering in the last few years. The science-fiction-like idea of super-resolution imaging and optical cloaking is made possible to bring to the science laboratories with the discovery of metamaterials, and further promises to bring it to the arena of our day-to-day life. The advancement in experimental and theoretical procedures capable of studying optical activity on a variety of scales, from nanometer through micrometer to even larger scale of metamaterial devices is a hallmark of the modern era of optical metamaterials.

Metamaterial allows us to control the impedance of material in such a way that cannot be easily achieved with naturally occurring materials. This idea of engineering refractive index and impedance provides us with the opportunities to manipulate electromagnetic radiation in new ways. Antennas, absorber superlens, and cloaking systems are only a few examples, with many more to come in the coming years.

1.2. TERAHERTZ RADIATION

In the electromagnetic spectrum the region between $0.1 - 10 \times 10^{12}$ Hz frequency is called as terahertz gap. Terahertz region has wide opportunities for advanced research in area of security, communications, medical etc.

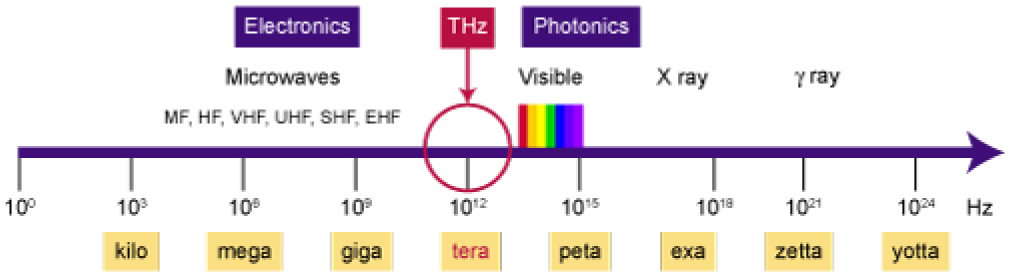

Figure 1.1 Terahertz Radiation within the Electromagnetic Spectrum

Terahertz region lies in between of infrared and microwaves region. Because of its non-ionizing property despite having small wavelength it is ideal choice for applications in imaging and communication along with many others. Image Source: https://sites.google.com/a/ferroix.net/notedevitn/the-terahertz-gap

Since electromagnetic radiations in terahertz region can penetrate most of the non-polar, non-metallic materials, also they are non-ionizing. Because of this property, terahertz radiations can be used in food inspections, advanced security scanners, medical diagnosis, etc. The ability of terahertz radiation for nondestructive inspection and evaluation is evident in large range of materials including human tissue which shows spectral characteristics.

The most important considerations for imaging in terahertz region is small thermal (background) radiation in the terahertz range and absence of sensitive detectors and powerful sources. Until recently high cost of existing sensors and sources prevented the wide usage of terahertz imaging systems. Recently developed quantum cascade terahertz lasers and metamaterial-based terahertz perfect absorbers has made possible modelling of compact imaging systems. In this thesis we will discuss such metamaterial-based terahertz absorbers because of which applications of terahertz frequency region has potentially increased.

Metamaterial absorbers compromises of two or more that two materials which are arranged in repetitive manner that are capable of absorbing terahertz radiations.

The properties found in metamaterials are different from their constituent materials. And because of their ability to be regulated for specific terahertz frequencies they are used in detectors. Fabry-Perot resonance, plasmonic near-field effect, resonant circuit model, etc. are few mechanisms through which behavior of metamaterial absorbers have been explained. Because of the complex and periodic structure of metamaterials, finite element (FE) method is the most suitable method for modelling metamaterials. For using metamaterial absorbers in sensor applications, absorbers must absorb the incident radiation of wavelength of our interest efficiently. Planer metamaterials also known as perfect absorbers have near unity absorption in a particular frequency range.

CHAPTER 2

STRUCTURE AND DESIGN

In last few years, researchers around the globe had shown a considerable interest in developing a resonant metamaterial absorber by designing of n(ω) and Z(ω) through which near unity absorption can be obtained [10-12]. This can be done by simultaneously reducing the transmission and reflectivity through impedance matching. This was experimentally demonstrated at microwave and terahertz frequency range [10-12]. Other methodologies have been theoretically presented to extend these ideas to wide angle of incidence at higher frequencies along with maintaining unity absorption for application purpose [13-15].

While this resonant absorber was designed for working at terahertz frequencies, where it is not easy to find a strong absorber, but this will also work well at any frequency of electromagnetic spectrum. With continuous-wave sources like a quantum cascade laser or a thermal detector, these absorbers will be employed as a coating material to eliminate spurious reflections. Initially an absorption of 0.70 at 1.3 THz was achieved [11]. Later a polarization insensitive design was made, which showed an absorption of 0.65 at 1.15 THz [12].

I have theoretically presented a resonant metamaterial with an absorptivity of 0.99 at 0.97 THz through computer simulation in a commercial program COMSOL Multiphysics 5.5. In contrast to previous designs, [11,12] the current design has several important benefits. The current design is on a highly versatile polyimide substrate with a total thickness of 8 μm, allowing it to be wrapped around items as small as 6 mm in diameter, allowing it to be used in nonplanar applications. We also show that this metamaterial absorber works for both transverse electric (TE) and transverse magnetic (TM) arrangements for a large range of incidence angles using simulation. At last, the bottom layer of the absorber is made up of a continuous metal film, which simplifies the manufacturing process because it eliminates the need for precise layer alignment in this two-layer structure.

According to A = 1 – T – R, in order to increase A (absorptivity), we need to decrease T (transmittivity) & R (reflectivity). As showed [12], impedance matching with free space is realized (i.e., $Z = Z_0$ giving R = 0), the transmission becomes $T = \exp(-2n_2dk) = \exp(-\alpha d)$, where k is free space wave vector, d is sample thickness, n_2 is imaginary part of refractive index, and α is absorption coefficient. Thus, through impedance matching we can get a transmission that is controlled by the losses in the slab of d thickness. Effective refractive index (n_2) of metamaterial depends on $\varepsilon(\omega)$ and $\mu(\omega)$. So, to design a resonant metamaterial absorber we need to optimize $\varepsilon(\omega)$ and $\mu(\omega)$ such that at the required frequency Z must be equal to Z_0, with n_2 as large as possible. The absorption finally arises from losses within the dielectric slab and metal.

In our metamaterial absorber, a dielectric spacer is sandwiched between two metallic layers. On top layer, an array of split-ring resonators is present, which determines $\varepsilon(\omega)$. And at the bottom a continuous metallic layer is present so that the incident magnetic field creates a circulating current in between top and bottom layers. Although there is a strong coupling between the top and bottom layer, to get the condition discussed in the previous paragraph, geometry has to be finely tuned. By using full-wave electromagnetic simulation an optimized design is achieved.

Our optimized design is shown in figure 1. On the top layer [Fig. 1(a)], there is an array of cross resonators. These resonators are made of Copper (Cu) with a thickness of 200 nm. The dimensions of the cross resonators are: unit-cell (a) = 100 μm, side length (l) = 90 μm, line width (w) = 10 μm. The top and bottom metallic layers are separated by an $8\mu m$ thick spacer layer. At bottom a Copper (Cu) film is used as impedance boundary condition.

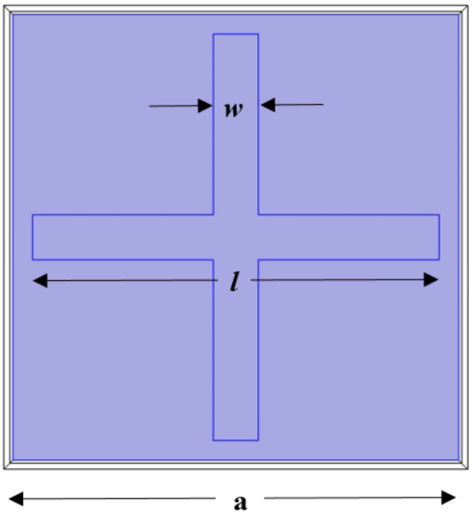

Figure 2.1 Cross resonator unit cell

Figure 2 shows the optimized structure that was obtained through computer simulations using a commercial program COMSOL Multiphysics 5.5. We have used frequency domain solver where the portions of metamaterial absorber made of gold (Au) were designed as lossy gold with a frequency independent conductivity of 4.09107 S/cm. By using the experimentally determined value of polyimide, we have deigned this $8\,\mu m$ thick spacer layer. We have used a frequency independent permittivity of $\tilde{\varepsilon} = \varepsilon_1 + i\varepsilon_2 = 2.88 + i0.09$ and corresponding loss tangent is $\tan(\delta)$ = $\varepsilon_2/\varepsilon_1$=0.0313.[20] By obtaining transmission coefficient and reflection coefficient, we calculated absorption using A = 1 – R – T = 1 – S_{11}^2 - S_{21}^2. In our design S_{21} is zero for entire frequency values because of the ground plane, which is also expected. The optimized structure shown in Fig. 1 was created by varying the dimensions of the SRR and the dielectric spacer thickness while simulating radiation at normal incidence. At the design frequency of 0.97 THz, the optimized parameters produced the lowest reflection.

CHAPTER 3

MODELLING AND SIMULATION

3.1. BACKGROUND

I have created a virtual model of metamaterial presented in figure using finite element (FE) method. Unit cell of the model is shown in figure. Entire simulation process compromises of various steps viz. making unit cell, applying appropriate physical boundary conditions, obtaining absorptions values for various frequencies and for various angle of incidence. We will have a detailed discussion of these processes below.

3.2. UNIT CELL GEOMETRY

My design consists of a Cu ground plane at bottom and Cu cross resonator at top. The top and bottom metallic layer is separated by a polyimide substrate. Medium above the cross resonator is air from which incoming wave is coming. The thickness of substrate is 8 µm. Substrate maximizes absorption characteristics. The important

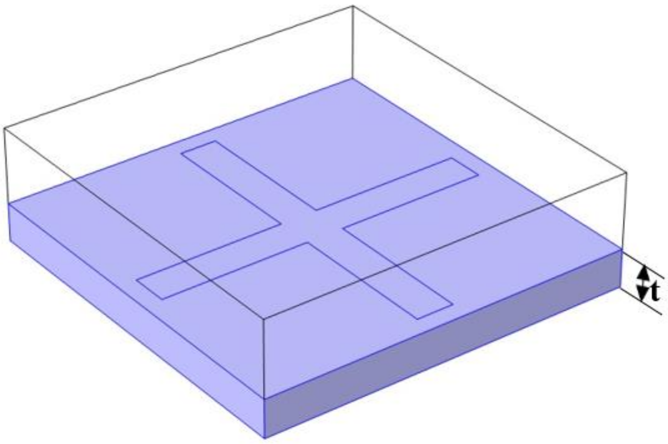

Figure 3.1 Perspective view of the absorber unit

application of this design is its integration with thermal sensors. It is important to note that my structure was just 8 μm thick to minimize the thermal capacitance.

Thermal capacitance of an object is directly proportional to it volume. Operation speed of absorber can be maximized by using a thin dielectric because of its smaller volume. Simulation and extraction of parameters can be done in relatively less run time by using the periodic nature i.e. repeated unit cell. Figure above shows both polyimide substrate and Cu metallic regions. The empty space above the unit cell is air.

3.3. UNIT CELL PHYSICS

3.3.1. ELECTROMAGNETIC WAVE EQUATION

As told earlier, unit cell consists of Cu and polyimide and surrounding medium is air. Every material used is provided with its required electromagnetic property. So that COMSOL can solve wave equations for each node of mesh. If medium does not contain any initial current and charge also conductivity cannot be neglected for such medium electromagnetic wave equation is given by

$$\frac{\nabla \times (\nabla \times \vec{E})}{\mu_r} - k_0^2\left(\varepsilon_r - \frac{j\sigma}{w\varepsilon_0}\right)\vec{E} = 0 \quad (1)$$

here σ is the conductivity, ε_r is the permittivity and μ_r is the relative permeability.

Since conductivity of polyimide and air is negligible, the loss depends only on imaginary part of ε_r therefore COMSOL solves the below equation

$$\nabla \times (\nabla \times \vec{E}) - k_0^2\varepsilon_r\vec{E} = 0 \quad (2)$$

To reduce the computing effort, these conditions can be put in the model. On comparing both the equations (1 & 2) we got relative permeability could be one. Hence the complex refractive index can be given by this equation

$$\varepsilon_r = (n - ik)^2 \quad (3)$$

Here n is the real part and k is the complex part. For the simulations done in this research, initially n is taken to be 1.9 and k to be 0.02. Obtaining S parameters is THz region of electromagnetic spectrum is possible because of the resonant characteristic of metamaterial which allows us to fit experimental results with finite element simulations.

3.3.2. BOUNDARY CONDITIONS

Because of the periodic nature of our design, periodic boundary condition will be used to simulate the unit cell. Further simplification can be done in this structure, because this metamaterial structure will be used for sensing and imaging, the incident field will be nearly normal and because of this reason perfect electric boundary conditions on faces perpendicular to electric and perfect magnetic boundary conditions for faces that are perpendicular to magnetic field can be used. Figure below shows a schematic diagram of unit cell simulated.

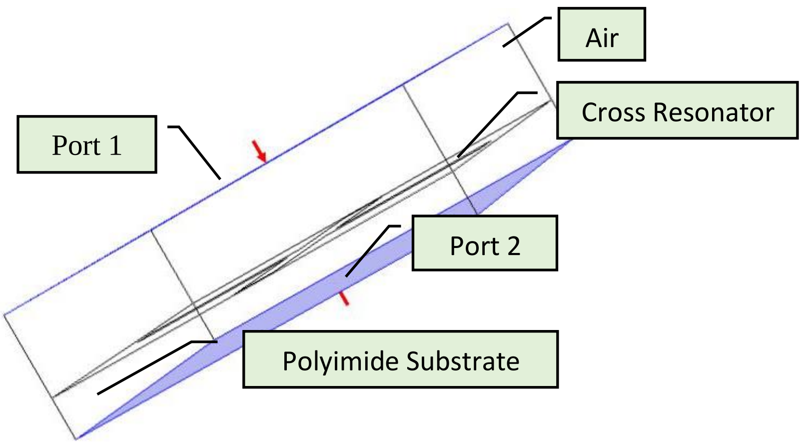

Figure 3.2 Representation of a COMSOL Simulation

3.3.3. INPUT POWER

We use 1 watt (W) of input power at Port No. 1 shown by red arrows in figure. By using 1 watt of input power we can determine normalized absorption by calculating power dissipation on the metamaterial unit cell. An easy way of determining absorption was to calculate the reflected power back at port 1. Because transmission is not there, absorption can be determined by

$$A = 1 - abs(S_{11})^2$$

where $abs(S_{11})^2$ is the reflected power on Port 1 in Figure.

While meshing at the boundaries of different metamaterial layers, extra attention is given in order to ensure that the critical boundary conditions were designed correctly. We have used physics-controlled mesh at each layer horizontally and sweep function was used to create meshing in vertical directions in each unit cells. Below figure shows the example of meshed unit cell.

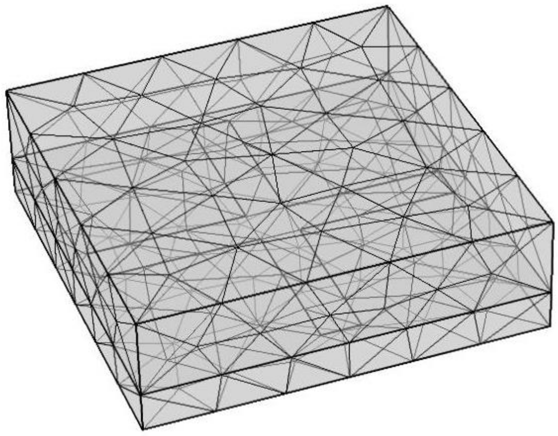

Figure 3.3 Schematic of Unit Cell Meshing

3.3.4. EVALUATION

We simulate the particular unit cell over 0.6 THz to 1.4 THz frequencies that was focused for the expected resonance on the unit cell. The duration of simulation depends

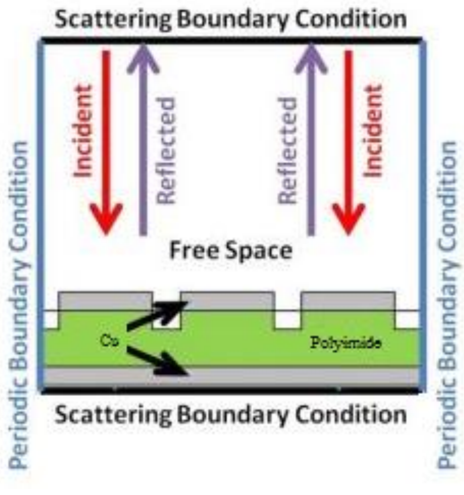

Figure 3.4 Schematic of Reflection and Transmission

on frequency step size and mesh sizes. In this project simulations time was around 2-3 minutes. These simulations generally used for the parametric sweep.

3.3.5. MESHING

By meshing we generate set of nodes on each regions or layers of the unit cell. Generally, the minimum size of mesh was kept smaller that one fifth of wavelength used. In our simulations we have used frequency of maximum 1.4 THz and corresponding wave length is 214 µm ($\lambda = c/f$), here c is the speed of light and f is the frequency. We use physics-controlled mesh to speed-up simulation process. The absorption in each of the unit cell was then calculated using integrated resistive losses.

CHAPTER 4

SIMULATED RESULTS & ANALYSIS

4.1. RESULTS OBTAINED FROM SIMULATIONS

Table at Appendix 1 shows the absorption of our optimized structure as a function of frequency for TE & TM mode for different angle of incidence ranging from 0^0 to 80^0.

Figure 4.1 shows the absorption of our optimized structure as a function of frequency for TE & TM mode for different angle of incidence ranging from 0^0 to 80^0.

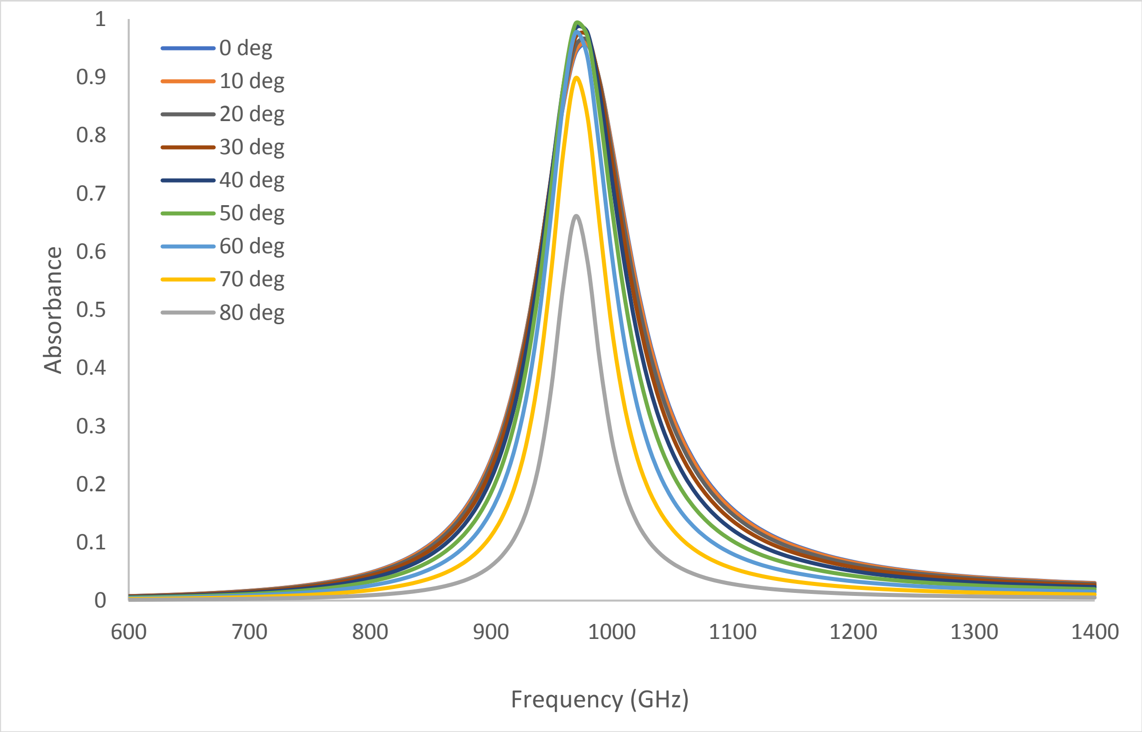

Fig. 4.1 (a) For TE Mode

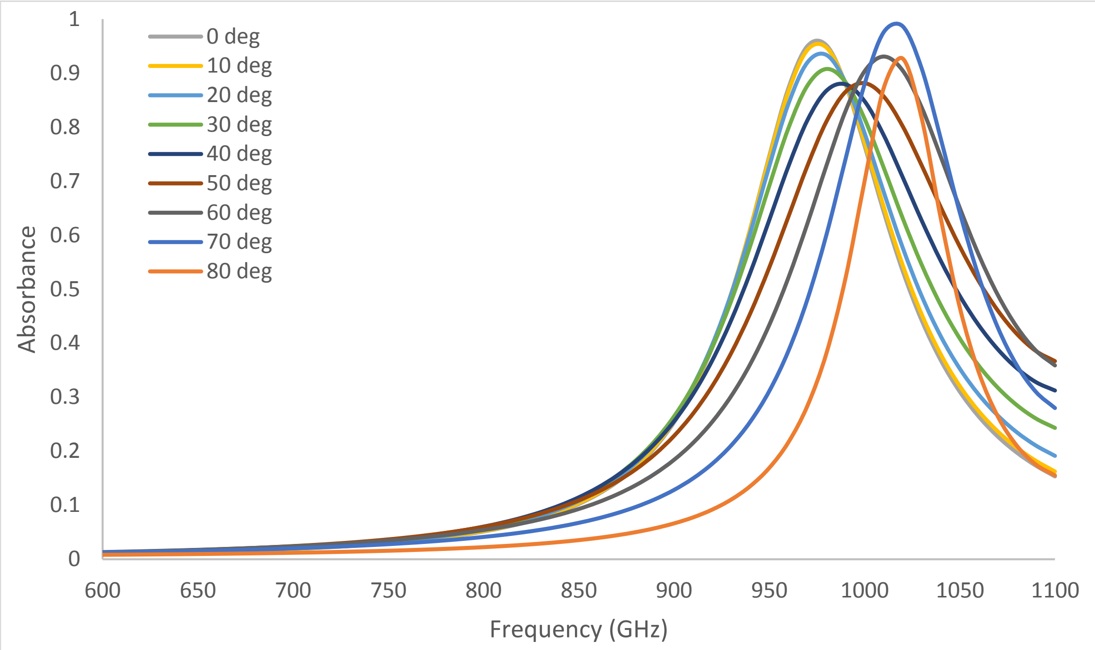

Fig. 4.1 (b) For TM

Figgure 4.1 Absorptivity as a function of frequency at various angle of incidence obtained from simulations. The labels for the curves show the angle of incidence.

4.2. ANALYSIS OF RESULTS OBTAINED FROM SIMULATIONS

Table 4.1 below shows the peak absorptivity for various angle of incidence and corresponding frequency at which peak absorptivity is obtained.

Table 4.1: Peak absorptivity at various angle of incidence and corresponding frequency.

Angle of incidence	TE Mode		TM Mode	
	Peak Absorptivity	Frequency (THz)	Peak Absorptivity	Frequency (THz)
0^0	0.95558024	0.980	0.95160476	0.980
10^0	0.95772212	0.980	0.94741486	0.980
20^0	0.96376862	0.980	0.93355288	0.980
30^0	0.97149195	0.980	0.90759603	0.980
40^0	0.98374892	0.970	0.87925683	0.990
50^0	0.99208072	0.970	0.8813674	1.000
60^0	0.97651934	0.970	0.93059653	1.010
70^0	0.89808674	0.970	0.98682066	1.020
80^0	0.66085225	0.970	0.92701894	1.020

Figure shows the absorption of our optimized structure as a function of angle of incidence for TE & TM mode.

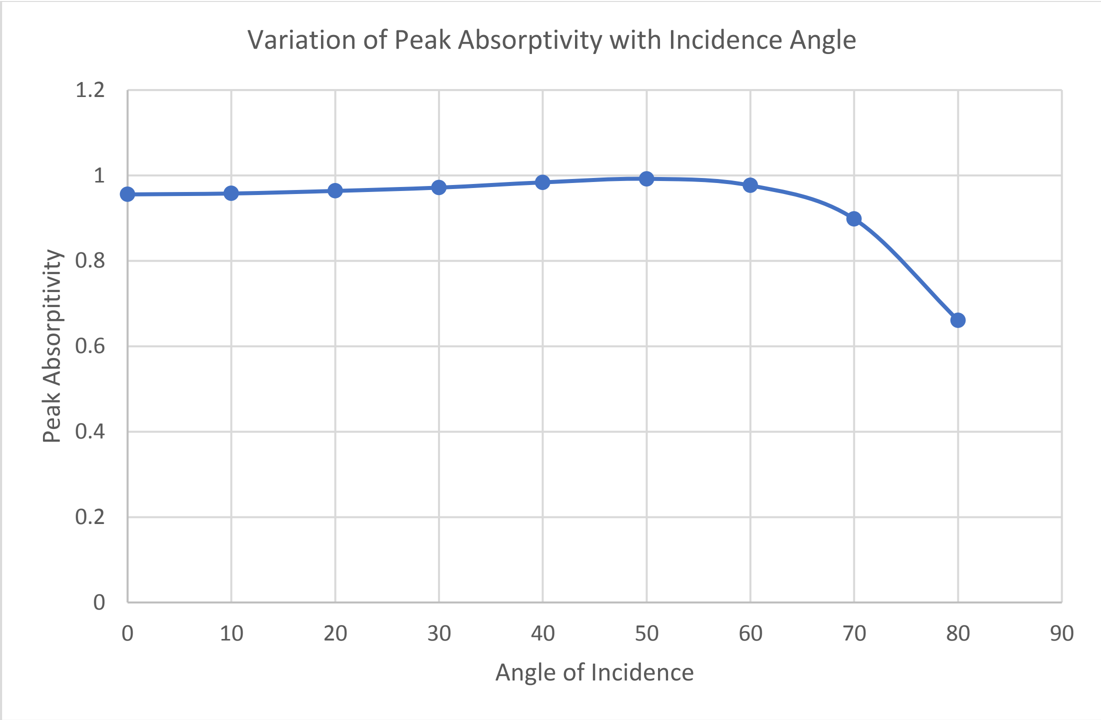

Figure 4.2 (a) For TE

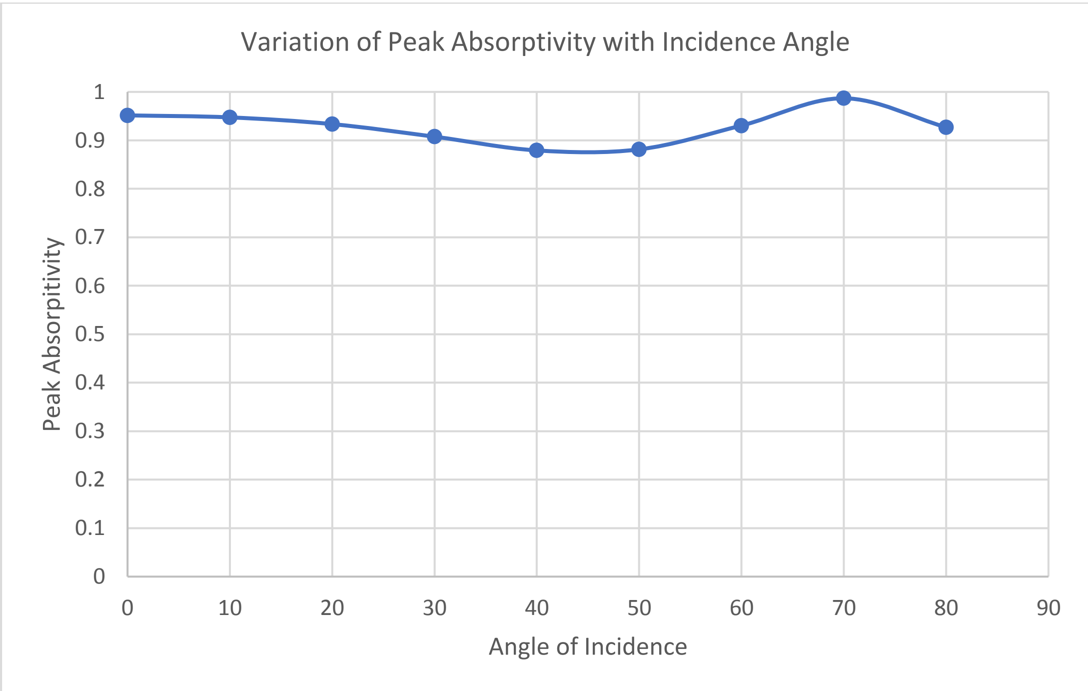

Figure 4.2 (b) For TM

Figure 4.2 Variation of Peak Absorptivity with angle of incidence

Peak absorption of 0.95 was obtained for TE mode at normal incidence. As angle of incidence increases, the peak absorptivity remains large i.e. 0.99 at 50^0. After this there is rapid decrease in value of peak absorption with the increasing angle of incidence. This is because at larger angle of incidence, incident magnetic field is not able to circulate currents between the two metallic layers. There is also a small frequency change of 10 GHz from 0^0 to 80^0. For TM mode, peak absorption at normal incidence is 0.95 and it increases with increase in angle of incidence to 0.98 at an angle of incidence 70^0. In this mode, magnetic field does not efficiently drive circulating currents is between two metallic layers at near normal angle of incidence. The frequency change for TM mode is 10 GHz from 0 to 80^0. These results show that this MM absorber operates quit well for wide angle of incidence for TE mode. For TM mode this work well at larger angle of incidence only.

CHAPTER 5
CONCLUSION

In summary we have designed a highly flexible perfect absorber that shows an excellent absorptivity of 0.99 at 0.97 THz frequency and normal angle of incidence. Also, this absorber works good for large range of angle of incidence for both Transverse electric and Transverse Magnetic mode. This kind of perfect absorbers may have variety of applications from terahertz stealth technology to thermal detectors.

APPENDIX 1

RESULTS OBTAINED FROM SIMULATIONS

Table below shows the absorption of our optimized structure as a function of frequency for TM mode for different angle of incidence ranging from 0^0 to 80^0.

Table A1.1 Absorbance in TE mode at various frequencies for Incidence angle 80^0, 70^0, 60^0

Incidence Angle=80^0		Incidence Angle=70^0		Incidence Angle=60^0	
Frequency (GHz)	Absorbance	Frequency (GHz)	Absorbance	Frequency (GHz)	Absorbance
600	0.001418324	600	0.00277683	600	0.00403954
610	0.00152796	610	0.00299215	610	0.00434833
620	0.001639626	620	0.0032121	620	0.00466861
630	0.001763072	630	0.00345434	630	0.00502072
640	0.001899962	640	0.00372209	640	0.00540931
650	0.00205206	650	0.00401884	650	0.00583939
660	0.002221389	660	0.00434858	660	0.00631671
670	0.002410309	670	0.00471595	670	0.00684799
680	0.002621606	680	0.00512642	680	0.00744107
690	0.002858591	690	0.00558646	690	0.00810524
700	0.003125227	700	0.00610375	700	0.00885152
710	0.003426278	710	0.00668753	710	0.00969309
720	0.003767514	720	0.00734892	720	0.01064582
730	0.004156199	730	0.00808536	730	0.01172909
740	0.004577791	740	0.0089454	740	0.01296586
750	0.005086129	750	0.00993345	750	0.014373
760	0.005673958	760	0.01107487	760	0.01601292
770	0.006358068	770	0.01240157	770	0.01791633
780	0.007159447	780	0.01395364	780	0.02013953
790	0.008105248	790	0.01578252	790	0.02275444
800	0.009230683	800	0.01795471	800	0.02585359
810	0.010582098	810	0.02055728	810	0.02955755
820	0.012221386	820	0.02370585	820	0.03402537
830	0.014232499	830	0.02755621	830	0.03946987
840	0.0167313	840	0.03232192	840	0.04618025

850	0.019880941	850	0.03830135	850	0.05455654
860	0.023916686	860	0.04592036	860	0.06516261
870	0.029186957	870	0.05580055	870	0.07880856
880	0.036183469	880	0.0688674	880	0.09670178
890	0.045820227	890	0.086569	890	0.12059858
900	0.059429047	900	0.11115226	900	0.1532143
910	0.079330642	910	0.14627502	910	0.19872773
920	0.109618544	920	0.19796635	920	0.26355595
930	0.1577145	930	0.27604702	930	0.3570595
940	0.236967514	940	0.39515302	940	0.49063468
950	0.36597332	950	0.56797864	950	0.6683893
960	0.543128728	960	0.77290618	960	0.86063868
970	0.660852248	970	0.89808674	970	0.97651934
980	0.582555755	980	0.83107665	980	0.93325915
990	0.413245346	990	0.64622517	990	0.77329948
1000	0.278400478	1000	0.46945704	1000	0.59580484
1010	0.192197868	1010	0.34056858	1010	0.45105082
1020	0.138423682	1020	0.2530805	1020	0.34493535
1030	0.103866599	1030	0.19375856	1030	0.26918939
1040	0.080728035	1040	0.15263153	1040	0.21483117
1050	0.064593768	1050	0.1232966	1050	0.17514046
1060	0.052920752	1060	0.10175819	1060	0.14553153
1070	0.044247199	1070	0.08554293	1070	0.12296
1080	0.037552816	1080	0.0730957	1080	0.10543755
1090	0.032555993	1090	0.06332121	1090	0.09157365
1100	0.028523077	1100	0.05554664	1100	0.08046208
1110	0.025255849	1110	0.04923927	1110	0.07141932
1120	0.022580285	1120	0.04406328	1120	0.06397667
1130	0.020364935	1130	0.03977001	1130	0.05778815
1140	0.018515966	1140	0.03618004	1140	0.05260159
1150	0.016963196	1150	0.03315929	1150	0.04822806
1160	0.015627765	1160	0.0305633	1160	0.0444691
1170	0.014422539	1170	0.02823163	1170	0.04110327
1180	0.013432379	1180	0.0261539	1180	0.03810504
1190	0.012464378	1190	0.0243729	1190	0.03549626
1200	0.01163972	1200	0.02279478	1200	0.03318452
1210	0.010958712	1210	0.02141588	1210	0.03119897
1220	0.0103132	1220	0.02019789	1220	0.0294386
1230	0.009746672	1230	0.01913363	1230	0.02786785
1240	0.009268738	1240	0.01815356	1240	0.02645939
1250	0.008805096	1250	0.01727481	1250	0.02520502
1260	0.0083961	1260	0.01648321	1260	0.02405362
1270	0.008099806	1270	0.01576777	1270	0.02300974

1280	0.007713305	1280	0.01511913	1280	0.02206027
1290	0.007429105	1290	0.0145294	1290	0.02119368
1300	0.007138838	1300	0.01399133	1300	0.02039791
1310	0.006891124	1310	0.01352068	1310	0.01966216
1320	0.006653728	1320	0.01310076	1320	0.01899392
1330	0.00644199	1330	0.01280207	1330	0.01844601
1340	0.006283297	1340	0.01236619	1340	0.01796844
1350	0.006156152	1350	0.01203411	1350	0.01752293
1360	0.005944289	1360	0.0116473	1360	0.01696255
1370	0.005771223	1370	0.01133351	1370	0.01649822
1380	0.005620369	1380	0.0110442	1380	0.01607578
1390	0.005485889	1390	0.010787	1390	0.01569429
1400	0.005364144	1400	0.01053786	1400	0.01534509

Table A1.2 Absorbance in TE mode at various frequencies for Incidence angle of 50^0, 40^0, 30^0

Incidence Angle=50^0		Incidence Angle=40^0		Incidence Angle=30^0	
Frequency (GHz)	Absorbance	Frequency (GHz)	Absorbance	Frequency (GHz)	Absorbance
600	0.0051638	600	0.00611465	600	0.00686697
610	0.00554872	610	0.00655727	610	0.00735306
620	0.00595801	620	0.00704152	620	0.00789637
630	0.00640755	630	0.00757314	630	0.0084928
640	0.00690314	640	0.00815889	640	0.00914977
650	0.0074511	650	0.00880607	650	0.00987534
660	0.00805866	660	0.00952311	660	0.01067884
670	0.00873429	670	0.01031987	670	0.01157116
680	0.00948787	680	0.01120787	680	0.01256506
690	0.01033106	690	0.01220069	690	0.01367556
700	0.01127771	700	0.01331443	700	0.01492045
710	0.01234433	710	0.01456825	710	0.01632091
720	0.01355075	720	0.01598516	720	0.0179023
730	0.01492103	730	0.0175929	730	0.01969514
740	0.01648412	740	0.01942515	740	0.02173652
750	0.01827601	750	0.0215231	750	0.02407156
760	0.02034091	760	0.02393752	760	0.02675578
770	0.02273157	770	0.02673135	770	0.02985805
780	0.02552633	780	0.0299835	780	0.03346414
790	0.02880709	790	0.03379358	790	0.03768223
800	0.03268665	800	0.03828867	800	0.04264979
810	0.03731124	810	0.04366735	810	0.04854327
820	0.04287253	820	0.05008773	820	0.05559158
830	0.04962511	830	0.05785686	830	0.06409504
840	0.05791194	840	0.06735288	840	0.07451318

850	0.06820244	850	0.07908837	850	0.08727683
860	0.08114981	860	0.09376785	860	0.10316436
870	0.09767754	870	0.11237266	870	0.12318006
880	0.11911171	880	0.136286	880	0.1487178
890	0.14744641	890	0.16747564	890	0.1817226
900	0.18544025	900	0.20885325	900	0.22490091
910	0.23731863	910	0.26422251	910	0.28194635
920	0.30909374	920	0.33900898	920	0.35768302
930	0.40864749	930	0.43957981	930	0.45711142
940	0.54361017	940	0.57079757	940	0.58336908
950	0.71263933	950	0.72834443	950	0.73080596
960	0.88573305	960	0.884692	960	0.87463053
970	0.99208072	970	0.98374892	970	0.96852737
980	0.96954058	980	0.9763736	980	0.97149195
990	0.83979039	990	0.87242748	990	0.88684691
1000	0.6767194	1000	0.7268653	1000	0.75689156
1010	0.53066541	1010	0.58618713	1010	0.62331334
1020	0.41612505	1020	0.46936584	1020	0.50741149
1030	0.33043943	1030	0.37834227	1030	0.41398907
1040	0.26692273	1040	0.30889843	1040	0.3409909
1050	0.21949365	1050	0.2559821	1050	0.28440317
1060	0.18355629	1060	0.21529983	1060	0.24033935
1070	0.1558204	1070	0.18353055	1070	0.20557361
1080	0.13405649	1080	0.158362	1080	0.17797297
1090	0.11671949	1090	0.13820388	1090	0.15550163
1100	0.10272359	1100	0.12181997	1100	0.13726434
1110	0.09129404	1110	0.10839483	1110	0.12227283
1120	0.08185691	1120	0.09727504	1120	0.1098202
1130	0.0739892	1130	0.08798086	1130	0.09938872
1140	0.06738105	1140	0.08016089	1140	0.09059954
1150	0.06180087	1150	0.07355374	1150	0.08317092
1160	0.05700969	1160	0.0678886	1160	0.07680261
1170	0.05272929	1170	0.06282722	1170	0.07109961
1180	0.04891038	1180	0.05829437	1180	0.06597376
1190	0.04557649	1190	0.05432741	1190	0.06148287
1200	0.04266466	1200	0.05085825	1200	0.05746338
1210	0.0400315	1210	0.04770879	1210	0.05402927
1220	0.03778229	1220	0.04502546	1220	0.0509761
1230	0.03577198	1230	0.04262647	1230	0.04824831
1240	0.03396731	1240	0.04047268	1240	0.04580061
1250	0.03234102	1250	0.03853175	1250	0.04359542
1260	0.03087046	1260	0.0367766	1260	0.04161329
1270	0.02955411	1270	0.03521011	1270	0.0398138

1280	0.02833849	1280	0.03376688	1280	0.0381764
1290	0.02722849	1290	0.03245059	1290	0.03668377
1300	0.02621242	1300	0.03125264	1300	0.03532467
1310	0.02528171	1310	0.03010491	1310	0.03410098
1320	0.02443485	1320	0.02909503	1320	0.03288357
1330	0.02366968	1330	0.02818564	1330	0.03185213
1340	0.02306895	1340	0.0274769	1340	0.03103218
1350	0.02249437	1350	0.02674028	1350	0.03014377
1360	0.02174939	1360	0.02584327	1360	0.02915003
1370	0.02114556	1370	0.02512382	1370	0.02834288
1380	0.02059823	1380	0.02447339	1380	0.02761209
1390	0.02010385	1390	0.0238924	1390	0.02695722
1400	0.01964899	1400	0.02335281	1400	0.02634633

Table A1.3 Absorbance in TE mode at various frequencies for Incidence angle of 20^0, 10^0, 0^0

Incidence Angle=20^0		Incidence Angle=10^0		Incidence Angle=0^0	
Frequency (GHz)	Absorbance	Frequency (GHz)	Absorbance	Frequency (GHz)	Absorbance
600	0.00730562	600	0.00774873	600	0.007834982
610	0.00786381	610	0.00827489	610	0.008384416
620	0.00844303	620	0.00888659	620	0.009005614
630	0.00908064	630	0.00955784	630	0.009687398
640	0.00978484	640	0.01029682	640	0.010438012
650	0.01056432	650	0.01111232	650	0.011266842
660	0.01142904	660	0.0120146	660	0.012184133
670	0.01239047	670	0.01303829	670	0.013202225
680	0.01346208	680	0.01415587	680	0.014334908
690	0.01465972	690	0.0154035	690	0.015599681
700	0.01607865	700	0.01680081	700	0.017015819
710	0.01758414	710	0.01837116	710	0.018607144
720	0.01928311	720	0.02014246	720	0.020401815
730	0.021208	730	0.02214829	730	0.022433637
740	0.02339813	740	0.02442926	740	0.024744198
750	0.02590134	750	0.02703475	750	0.027382775
760	0.02877637	760	0.03002531	760	0.030410236
770	0.03209587	770	0.03347574	770	0.033903119
780	0.03595027	780	0.037479	780	0.0379539
790	0.04045325	790	0.04215173	790	0.042680725
800	0.04574893	800	0.04764152	800	0.048231988
810	0.05202179	810	0.05413682	810	0.054797301
820	0.05951037	820	0.06188058	820	0.062582843

830	0.06852641	830	0.07118921	830	0.071979786
840	0.0794819	840	0.08247897	840	0.083371016
850	0.09292754	850	0.09630325	850	0.097312235
860	0.10960724	860	0.11340498	860	0.114546049
870	0.13051325	870	0.13476776	870	0.136076922
880	0.15703974	880	0.16182235	880	0.163269399
890	0.19109185	890	0.19640353	890	0.197972382
900	0.23526978	900	0.24103144	900	0.242664994
910	0.29303025	910	0.2989998	910	0.300562567
920	0.36865293	920	0.37428722	920	0.376018462
930	0.4664195	930	0.47082245	930	0.472045444
940	0.58840006	940	0.59002775	940	0.590195151
950	0.72840187	950	0.72556461	950	0.724492605
960	0.86376644	960	0.85607634	960	0.853411025
970	0.95424636	970	0.94460365	970	0.941289139
980	0.96376862	980	0.95772212	980	0.955580239
990	0.89207472	990	0.89356683	990	0.893886291
1000	0.7738837	1000	0.78232376	1000	0.784947085
1010	0.64677879	1010	0.65952952	1010	0.663622916
1020	0.53266112	1020	0.5470717	1020	0.551696958
1030	0.43847648	1030	0.45285222	1030	0.457413141
1040	0.36358704	1040	0.37707627	1040	0.381274313
1050	0.30482454	1050	0.31706259	1050	0.320804162
1060	0.25862094	1060	0.26948606	1060	0.272846711
1070	0.22177283	1070	0.23137969	1070	0.234442922
1080	0.19212235	1080	0.20070205	1080	0.203523523
1090	0.16814049	1090	0.17587996	1090	0.178429742
1100	0.14858159	1100	0.15556485	1100	0.157858134
1110	0.13245723	1110	0.13877381	1110	0.140865714
1120	0.11902609	1120	0.12476634	1120	0.12668976
1130	0.10774662	1130	0.11299229	1130	0.114774363
1140	0.09822213	1140	0.10305046	1140	0.104710992
1150	0.09016228	1150	0.0947023	1150	0.096194446
1160	0.08343114	1160	0.08749512	1160	0.088883411
1170	0.07724307	1170	0.08102532	1170	0.082309535
1180	0.07162185	1180	0.07526171	1180	0.076378797
1190	0.06676622	1190	0.07013345	1190	0.071225386
1200	0.06251005	1200	0.06564125	1200	0.066642269
1210	0.05875488	1210	0.06168302	1210	0.062531188
1220	0.05542014	1220	0.05812413	1220	0.058975002
1230	0.05244417	1230	0.05498773	1230	0.05580507
1240	0.04977457	1240	0.05217622	1240	0.052961202
1250	0.04736989	1250	0.04964557	1250	0.050398635

1260	0.04519647	1260	0.04735924	1260	0.048082278
1270	0.04322576	1270	0.04528678	1270	0.045980029
1280	0.04143374	1280	0.04340248	1280	0.044068113
1290	0.0398	1290	0.04168469	1290	0.042325341
1300	0.03830768	1300	0.04011509	1300	0.04073469
1310	0.03694401	1310	0.03867847	1310	0.039288316
1320	0.0357067	1320	0.0373414	1320	0.037968076
1330	0.03456261	1330	0.03618688	1330	0.036734909
1340	0.03363318	1340	0.03520381	1340	0.035758988
1350	0.03267782	1350	0.03425473	1350	0.034801283
1360	0.03157434	1360	0.03314817	1360	0.03366189
1370	0.03072928	1370	0.03222739	1370	0.032642437
1380	0.02994653	1380	0.03137777	1380	0.031805386
1390	0.02922063	1390	0.03060116	1390	0.031026249
1400	0.0285467	1400	0.0298849	1400	0.030302808

Table below shows the absorption of our optimized structure as a function of frequency for TM mode for different angle of incidence ranging from 0^0 to 80^0.

Table A1.4 Absorbance in TM mode at various frequencies for Incidence angle of 80^0, 70^0, 60^0

Incidence Angle=80^0		Incidence Angle=70^0		Incidence Angle=60^0	
Frequency (GHz)	Absorbance	Frequency (GHz)	Absorbance	Frequency (GHz)	Absorbance
600	0.00824092	600	0.01242425	600	0.01324674
610	0.008465581	610	0.01296687	610	0.01396882
620	0.00873378	620	0.01354041	620	0.01473636
630	0.00902649	630	0.01415989	630	0.01556849
640	0.009346052	640	0.01483032	640	0.01647347
650	0.009695144	650	0.01555731	650	0.01745925
660	0.010076773	660	0.01634725	660	0.01853581
670	0.010494581	670	0.01720741	670	0.01971312
680	0.010952447	680	0.01814609	680	0.02100407
690	0.011455055	690	0.01917284	690	0.02242279
700	0.012007767	700	0.02029866	700	0.02398718
710	0.012616809	710	0.02153629	710	0.02571541
720	0.013289437	720	0.02290055	720	0.02763033
730	0.014034051	730	0.02440873	730	0.02975869
740	0.014860936	740	0.02608124	740	0.03213171
750	0.015781632	750	0.02794203	750	0.03478572
760	0.016826095	760	0.03001958	760	0.03776617
770	0.017978833	770	0.03234799	770	0.04112429
780	0.01927662	780	0.03496802	780	0.04492376

790	0.02074393	790	0.03792919	790	0.04924085
800	0.022410827	800	0.04129153	800	0.05416823
810	0.024314264	810	0.04512882	810	0.05982059
820	0.026500186	820	0.04953221	820	0.06633784
830	0.029026271	830	0.05461538	830	0.07389434
840	0.031965802	840	0.06052144	840	0.08273197
850	0.035413234	850	0.06745199	850	0.09308269
860	0.039492057	860	0.07560639	860	0.10531335
870	0.044365235	870	0.08530306	870	0.1198682
880	0.050249834	880	0.09693943	880	0.13731698
890	0.057440141	890	0.11104224	890	0.15839068
900	0.066350808	900	0.12831776	900	0.18403072
910	0.077531355	910	0.14972422	910	0.21544479
920	0.091824637	920	0.17658488	920	0.25417128
930	0.110453363	930	0.21067394	930	0.30203379
940	0.135256285	940	0.25445934	940	0.36116929
950	0.169064962	950	0.31123114	950	0.4336504
960	0.216266376	960	0.38514286	960	0.52071099
970	0.283681363	970	0.48068137	970	0.62111767
980	0.381190328	980	0.60055425	980	0.72860269
990	0.519851495	990	0.7402612	990	0.82941176
1000	0.699085786	1000	0.87898515	1000	0.90317303
1010	0.871219784	1010	0.97526052	1010	0.93059653
1020	0.927018941	1020	0.98682066	1020	0.9049784
1030	0.81683665	1030	0.90887512	1030	0.83668127
1040	0.632117461	1040	0.77924247	1040	0.74571595
1050	0.466591112	1050	0.64227018	1050	0.65068833
1060	0.34619979	1060	0.52311253	1060	0.56344834
1070	0.264381719	1070	0.4289835	1070	0.4893115
1080	0.210068013	1080	0.35887014	1080	0.43006568
1090	0.175220737	1090	0.30987593	1090	0.38629244
1100	0.155234542	1100	0.27990376	1100	0.35881849
1110	0.148620378	1110	0.26929107	1110	0.35042027
1120	0.157405737	1120	0.28229111	1120	0.36759006
1130	0.188565213	1130	0.32911947	1130	0.42257726
1140	0.255544843	1140	0.42554755	1140	0.53084187
1150	0.367568411	1150	0.57327763	1150	0.6857067
1160	0.475497979	1160	0.70261289	1160	0.80824581
1170	0.475899046	1170	0.70596603	1170	0.80638357
1180	0.394697509	1180	0.6111127	1180	0.71457968
1190	0.315322067	1190	0.50747675	1190	0.61155463
1200	0.261184646	1200	0.42911257	1200	0.52917638
1210	0.22805957	1210	0.37600602	1210	0.4693227

1220	0.209490685	1220	0.34151238	1220	0.42655092
1230	0.201215663	1230	0.31995356	1230	0.39545836
1240	0.200856689	1240	0.30735755	1240	0.3719196
1250	0.207333899	1250	0.30094388	1250	0.3529314
1260	0.220234584	1260	0.29857702	1260	0.33633174
1270	0.239598336	1270	0.29856804	1270	0.32061946
1280	0.26550018	1280	0.29924977	1280	0.3047585
1290	0.297676483	1290	0.29914843	1290	0.28852618
1300	0.334674722	1300	0.29701111	1300	0.27174836
1310	0.372826218	1310	0.29195858	1310	0.25464613
1320	0.405648349	1320	0.28361782	1320	0.23758073
1330	0.424903077	1330	0.27215019	1330	0.22093818
1340	0.424179763	1340	0.25814982	1340	0.2050493
1350	0.402850561	1350	0.2425006	1350	0.19015397
1360	0.3664336	1360	0.22593486	1360	0.17639313
1370	0.323039028	1370	0.20934271	1370	0.16382287
1380	0.279510678	1380	0.19331219	1380	0.15243442
1390	0.23986238	1390	0.17822619	1390	0.1421767
1400	0.205664683	1400	0.16430634	1400	0.13297385

Table A1.5 Absorbance in TM mode at various frequencies for Incidence angle of 50^0, 40^0, 30^0

Incidence Angle=50^0		Incidence Angle=40^0		Incidence Angle=30^0	
Frequency (GHz)	**Absorbance**	**Frequency (GHz)**	**Absorbance**	**Frequency (GHz)**	**Absorbance**
600	0.01256425	600	0.01152897	600	0.01046764
610	0.01332655	610	0.01215443	610	0.01120212
620	0.01414858	620	0.01295044	620	0.0119478
630	0.01504483	630	0.01392637	630	0.01276774
640	0.01602514	640	0.01488356	640	0.0136688
650	0.01709929	650	0.01593632	650	0.0146621
660	0.01827951	660	0.0170974	660	0.01575819
670	0.01957825	670	0.01838044	670	0.01697367
680	0.02101154	680	0.0198025	680	0.01832397
690	0.02259707	690	0.02138285	690	0.01982907
700	0.02435742	700	0.02314554	700	0.02150786
710	0.02631579	710	0.02511655	710	0.02342235
720	0.02850152	720	0.02732815	720	0.02553563
730	0.03094905	730	0.02981863	730	0.02792254
740	0.03369903	740	0.03263361	740	0.03062924
750	0.03679916	750	0.03582737	750	0.03371136
760	0.04030935	760	0.03946769	760	0.03723771

770	0.04429779	770	0.04363392	770	0.04129115
780	0.04884977	780	0.04842527	780	0.04597494
790	0.05406831	790	0.0539632	790	0.05141698
800	0.06007926	800	0.06039797	800	0.05777736
810	0.06703943	810	0.0679183	810	0.06525858
820	0.07514123	820	0.07675952	820	0.07411731
830	0.08462549	830	0.08721967	830	0.08468264
840	0.09582207	840	0.09967706	840	0.09737935
850	0.10906158	850	0.11464975	850	0.11276024
860	0.1248474	860	0.13269581	860	0.13154863
870	0.14378983	870	0.15463758	870	0.15470511
880	0.16666126	880	0.18148909	880	0.18341547
890	0.19442996	890	0.21452648	890	0.21929134
900	0.22829569	900	0.25531781	900	0.26433264
910	0.26970223	910	0.30569261	910	0.32092166
920	0.32030021	920	0.36757578	920	0.39156215
930	0.3816757	930	0.44241929	930	0.47809251
940	0.45500019	940	0.53027296	940	0.57993259
950	0.54001759	950	0.62793835	950	0.6911665
960	0.6335826	960	0.726885	960	0.79744273
970	0.72796329	970	0.81248252	970	0.87662905
980	0.81028805	980	0.86734466	980	0.90759603
990	0.86523208	990	0.87925683	990	0.88340617
1000	0.8813674	1000	0.84820912	1000	0.8157368
1010	0.85727386	1010	0.78575337	1010	0.72568622
1020	0.80193656	1020	0.70772126	1020	0.63187834
1030	0.72932867	1030	0.62735366	1030	0.54541349
1040	0.65215718	1040	0.5528203	1040	0.47083785
1050	0.579076	1050	0.48776729	1050	0.40884202
1060	0.51460017	1060	0.43318207	1060	0.35832492
1070	0.46040964	1070	0.38862242	1070	0.31758156
1080	0.41715401	1080	0.35356365	1080	0.28525278
1090	0.38549492	1090	0.32793601	1090	0.26051571
1100	0.36678109	1100	0.31238529	1100	0.2431639
1110	0.36451828	1110	0.30947167	1110	0.23408363
1120	0.38612061	1120	0.32518691	1120	0.23616911
1130	0.44526564	1130	0.3718897	1130	0.25650942
1140	0.55880207	1140	0.46851319	1140	0.30856744
1150	0.71586123	1150	0.61339201	1150	0.40128656
1160	0.82582107	1160	0.71533206	1160	0.48074961
1170	0.80847181	1170	0.68800123	1170	0.46319317
1180	0.71876193	1180	0.60243583	1180	0.39832628
1190	0.62879086	1190	0.52987726	1190	0.34639138

1200	0.5606014	1200	0.48376378	1200	0.3162236
1210	0.51261127	1210	0.45906359	1210	0.30315286
1220	0.47873214	1220	0.44948309	1220	0.30325316
1230	0.45343105	1230	0.44994795	1230	0.31474038
1240	0.43237923	1240	0.45592113	1240	0.33733989
1250	0.41235234	1250	0.46257273	1250	0.371466
1260	0.39119268	1260	0.46459786	1260	0.41696635
1270	0.36784243	1270	0.4570922	1270	0.47074325
1280	0.3422855	1280	0.43729128	1280	0.52301877
1290	0.31521412	1290	0.40585721	1290	0.5561933
1300	0.28795361	1300	0.36682739	1300	0.55151509
1310	0.26152674	1310	0.32507473	1310	0.50564983
1320	0.23680471	1320	0.28478824	1320	0.43487332
1330	0.21431297	1330	0.24848753	1330	0.36029572
1340	0.19426314	1340	0.2171602	1340	0.29475792
1350	0.17663922	1350	0.19079848	1350	0.24206452
1360	0.16128349	1360	0.16889691	1360	0.20130351
1370	0.14796568	1370	0.1507888	1370	0.17013406
1380	0.1364337	1380	0.13581782	1380	0.14623884
1390	0.12644769	1390	0.12340194	1390	0.12774889
1400	0.11779023	1400	0.11305205	1400	0.1132665

Table A1.6 Absorbance in TM mode at various frequencies for Incidence angle of 20^0, 10^0, 0^0

Incidence Angle=20^0		Incidence Angle=10^0		Incidence Angle=0^0	
Frequency (GHz)	Absorbance	Frequency (GHz)	Absorbance	Frequency (GHz)	Absorbance
600	0.00979823	600	0.00946451	600	0.009327335
610	0.01049715	610	0.01007324	610	0.009872178
620	0.01119731	620	0.01074315	620	0.010528592
630	0.01196583	630	0.01147731	630	0.011248377
640	0.01281059	640	0.01228392	640	0.012039879
650	0.01374169	650	0.01317239	650	0.012912246
660	0.01477014	660	0.01415371	660	0.013876455
670	0.01591007	670	0.01524059	670	0.014944723
680	0.01717687	680	0.01644799	680	0.016131979
690	0.01858906	690	0.0177937	690	0.0174553
700	0.0201674	700	0.0192985	700	0.018935926
710	0.02193863	710	0.02098733	710	0.020597504
720	0.02393377	720	0.02288951	720	0.022469502
730	0.0261893	730	0.02504093	730	0.024586891
740	0.02874982	740	0.02748469	740	0.026992052

750	0.03167084	750	0.0302728	750	0.029736384
760	0.03501657	760	0.03346952	760	0.032884095
770	0.03887041	770	0.03715413	770	0.036512326
780	0.04333291	780	0.04142513	780	0.040718607
790	0.04853145	790	0.04643595	790	0.045625129
800	0.05462644	800	0.05228554	800	0.051385889
810	0.06181884	810	0.05919942	810	0.058238411
820	0.07036983	820	0.06743339	820	0.066347343
830	0.0805578	830	0.07732009	830	0.076090169
840	0.09292727	840	0.08929604	840	0.087900334
850	0.10800803	850	0.10393982	850	0.102355995
860	0.12656699	860	0.12202518	860	0.120231299
870	0.14962433	870	0.14459536	870	0.142573511
880	0.17853819	880	0.17306321	880	0.170806701
890	0.21511158	890	0.20933665	890	0.206861123
900	0.2616876	900	0.25599888	900	0.253324465
910	0.3211682	910	0.31619526	910	0.313543286
920	0.39675421	920	0.39370392	920	0.391459136
930	0.49110223	930	0.49183775	930	0.490664741
940	0.60383985	940	0.6108517	940	0.611617429
950	0.7274292	950	0.74273957	950	0.746404305
960	0.84252028	960	0.86507837	960	0.871561439
970	0.91955965	970	0.94277693	970	0.949889262
980	0.93355288	980	0.94741486	980	0.951604759
990	0.88277949	990	0.88077316	990	0.879731262
1000	0.78925371	1000	0.77203514	1000	0.766050535
1010	0.68096159	1010	0.6535772	1010	0.644306435
1020	0.5774658	1020	0.54500022	1020	0.534217051
1030	0.48754782	1030	0.45359287	1030	0.442443839
1040	0.41314712	1040	0.37963879	1040	0.368723033
1050	0.35298776	1050	0.32075724	1050	0.3103112
1060	0.30474742	1060	0.27398158	1060	0.26404457
1070	0.26602948	1070	0.23655922	1070	0.227081324
1080	0.23501227	1080	0.20643726	1080	0.197303599
1090	0.21047523	1090	0.18213471	1090	0.173211314
1100	0.19138186	1100	0.16246086	1100	0.153389684
1110	0.1775795	1110	0.14663883	1110	0.137051622
1120	0.16970362	1120	0.13425583	1120	0.123472349
1130	0.17013293	1130	0.12542766	1130	0.112144788
1140	0.18431923	1140	0.12109626	1140	0.10273342
1150	0.21848737	1150	0.12269863	1150	0.094990234
1160	0.2549511	1160	0.12663317	1160	0.088335202
1170	0.2478813	1170	0.12077472	1170	0.081775404

1180	0.2136808	1180	0.10776192	1180	0.075542843
1190	0.18529933	1190	0.09654557	1190	0.070240762
1200	0.1678045	1200	0.08856333	1200	0.065595897
1210	0.15846061	1210	0.08287446	1210	0.061578428
1220	0.15535542	1220	0.07911298	1220	0.057994488
1230	0.15752856	1230	0.0767421	1230	0.054897743
1240	0.1651637	1240	0.07567586	1240	0.052126949
1250	0.17944354	1250	0.07603486	1250	0.049635281
1260	0.20283695	1260	0.07817953	1260	0.047386013
1270	0.2397991	1270	0.08284835	1270	0.045348348
1280	0.29795736	1280	0.09149206	1280	0.043496804
1290	0.38919234	1290	0.10709963	1290	0.041809572
1300	0.52564752	1300	0.13640377	1300	0.040267749
1310	0.69136595	1310	0.19656944	1310	0.038854577
1320	0.7836973	1320	0.33743961	1320	0.037557677
1330	0.69670144	1330	0.68557496	1330	0.036387392
1340	0.51732849	1340	0.97066098	1340	0.035534468
1350	0.36458333	1350	0.5369755	1350	0.034699094
1360	0.26217899	1360	0.26432977	1360	0.033507128
1370	0.19669229	1370	0.15620959	1370	0.032542735
1380	0.15413612	1380	0.10738962	1380	0.031730516
1390	0.12553086	1390	0.08186007	1390	0.030980477
1400	0.10559136	1400	0.06690992	1400	0.030287583

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LIST OF PUBLICATION OF CANDIDATES' WORK

Modelling & Simulation of Terahertz Perfect Absorber for various incidence angle

Nilesh Kumar Gupta*
Department of Applied Physics, Delhi Technological University, Main Bawana Road, Delhi, 110042, India
*nileshgupta3636@gmail.com

Abstract: Because of the developed fabrication and simulation technologies, the need for a perfect absorber that must be very thin and flexible is continuously increasing. There is a particular interest in developing a resonant metamaterial absorber by designing of refractive index n(ω) and impedance Z(ω) through which near unity absorption can be obtained at wide angle of incidence. Here I present a design and analysis of metamaterial perfect absorber for its response in frequency range of 0.6 THz to 1.4 THz through computer simulation using COMSOL Multiphysics 5.5. We tested the absorber's reaction to transverse magnetic and transverse electric polarizations at varied angles of incidence. It is important to note that our absorber was just 8 μm thick, that is it is highly flexible. I showed an absorptivity of 0.99 at 0.97 THz.

Keywords: Perfect absorber, Resonant metamaterial, Refractive index, Impedance, COMSOL Multiphysics, Transverse magnetic, Transverse electric, Flexible, Absorptivity.

1. Introduction

"The important thing is not to stop questioning" Albert Einstein once said. Indeed, in 1968, a Russian physicist named Victor Veselago's scientific curiosity led to the discovery of an entirely new field of modern optics: metamaterial optics. How light waves will interact with materials normally depends on two parameters, permittivity (ε) and magnetic permeability (μ) both of which are independently used in Maxwell's equations. The Refractive index of a medium is defined by their product as n =√ (± εμ). Generally, the refractive index and dielectric permittivity of transparent materials are greater than or equal to 1 and magnetic permeability (μ) ≈ 1. By changing the chemical composition of the material, the refractive index can be altered to some extent. Though, the refractive index is typically greater than one (for air) and less than four (for silicon). Veselago tried to find whether or not ε and μ for some material can be simultaneously negative, which will lead us to a negative refractive index.

The idea that a negative refractive index can be obtained by creating subwavelength composites in which effective permittivity and permeability can be controlled independently brought us the motivation for metamaterial research [1-3]. A metamaterial is a kind of material that is designed artificially to have such properties which are not found in materials occurring naturally. They are made by the repetitive arrangement of small unit cells. These unit cells are made of materials like metals and plastics. Metamaterials having exceptional optical properties had changed the entire world of optical science and engineering in the last few years. The science-fiction-like idea of super-resolution imaging and optical cloaking is made possible to bring to the science laboratories with the discovery of metamaterials, and further promises to bring it to the arena of our day-to-day life. The advancement in experimental and theoretical procedures capable of studying optical activity on a variety of scales, from nanometer through micrometer to even larger scale of metamaterial devices is a hallmark of the modern era of optical metamaterials.

Metamaterial allows us to control the impedance of material in such a way that cannot be easily achieved with naturally occurring materials. This idea of engineering refractive index and impedance provides us with the opportunities to manipulate electromagnetic radiation in new ways. Antennas, absorber superlens, and cloaking systems are only a few examples, with many more to come in the coming years [4-9].

2. Theory

In last few years, researchers around the globe had shown a considerable interest in developing a resonant metamaterial absorber by designing of n(ω) and Z(ω) through which near unity absorption can be obtained [10-12]. This can be done by simultaneously reducing the transmission and reflectivity through impedance matching. This was experimentally demonstrated at microwave and terahertz frequency range [10-12]. Other methodologies have been theoretically presented to extend these ideas to wide angle of incidence at higher frequencies along with maintaining unity absorption for application purpose [13-15].

While this resonant absorber was designed for working at terahertz frequencies, where it is not easy to find a strong absorber, but this will also work well at any frequency of electromagnetic spectrum. With continuous-wave sources like a quantum cascade laser or a thermal detector, these absorbers will be employed as a coating material to eliminate spurious reflections. Initially an absorption of 0.70 at 1.3 THz was achieved [11]. Later a polarization insensitive design was made, which showed an absorption of 0.65 at 1.15 THz [12].

I have theoretically presented a resonant metamaterial with an absorptivity of 0.99 at 0.97 THz through computer simulation in a commercial program COMSOL Multiphysics 5.5. In contrast to previous designs, [11,12] the current design has several important benefits. The current design is on a highly versatile polyimide substrate with a total thickness of 8 μm, allowing it to be wrapped around items as small as 6 mm in diameter, allowing it to be used in nonplanar applications. We also show that this metamaterial absorber works for both transverse electric (TE) and transverse magnetic (TM) arrangements for a large range of incidence angles using simulation. At last, the bottom layer of the absorber, made up of a continuous metal film is used as impedance boundary condition, which simplifies the manufacturing process because it eliminates the need for precise layer alignment in this two-layer structure.

According to A = 1 – T – R, in order to increase A (absorptivity), we need to decrease T (transmittivity) & R (reflectivity). As showed [12], impedance matching with free space is realized (i.e., $Z = Z_0$ giving R = 0), the transmission becomes $T = \exp(-2n_2dk) = \exp(-\alpha d)$, where k is free space wave vector, d is sample thickness, n_2 is imaginary part of refractive index, and α is absorption coefficient. Thus, through impedance matching we can get a transmission that is controlled by the losses in the slab of d thickness. Effective refractive index (n_2) of metamaterial depends on $\varepsilon(\omega)$ and $\mu(\omega)$. So, to design a resonant metamaterial absorber we need to optimize $\varepsilon(\omega)$ and $\mu(\omega)$ such that at the required frequency Z must be equal to Z_0, with n_2 as large as possible. The absorption finally arises from losses within the dielectric slab and metal.

In my metamaterial absorber, a dielectric spacer is sandwiched between two metallic layers. On top layer, an array of split-ring resonators is present, which determines $\varepsilon(\omega)$. And at the bottom a continuous metallic layer is present so that the incident magnetic field creates a circulating current in between top and bottom layers. Although there is a strong coupling between the top and bottom layer, to get the condition discussed in the previous paragraph, geometry has to be finely tuned. By using full-wave electromagnetic simulation an optimized design is achieved.

3. Models in numerical simulations

My optimized design is shown in figure 1. On the top layer [Fig. 1(a)], there is an array of cross resonators. These resonators are made of Copper (Cu) with a thickness of 200 nm. The dimensions of the cross resonators are: unit-cell (a) = 100 μm, side length (l) = 90 μm, line width (w) = 10 μm. The top and bottom metallic layers are separated by an 8μm thick spacer layer. At bottom a Copper (Cu) film is used as impedance boundary condition.

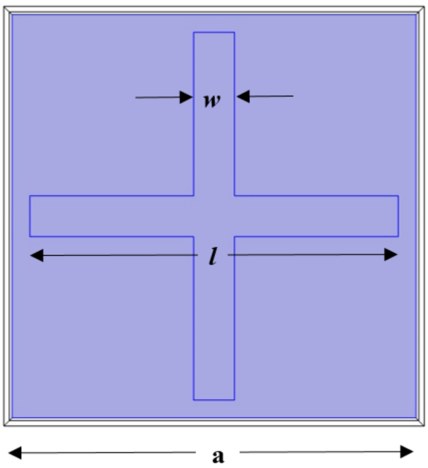

Fig. 1 (a)

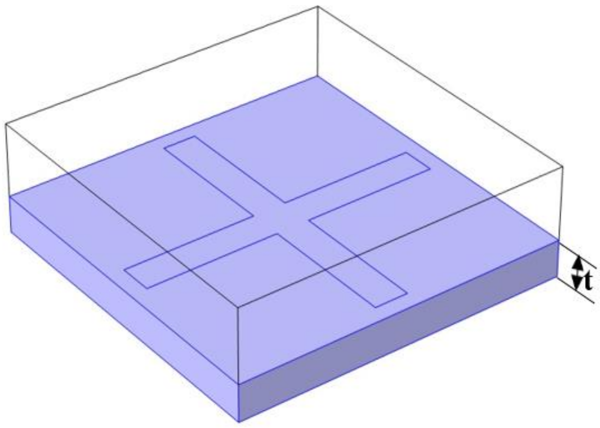

Fig. 1 (b)

Fig. 1 Terahertz perfect absorber. (a) Split ring resonator unit cell (b) Perspective view of the absorber

Figure 1 shows the optimized structure that was obtained through computer simulations using a commercial program COMSOL Multiphysics 5.5. We have used frequency domain solver where the portions of metamaterial absorber made of Copper (Cu) with a frequency independent conductivity of 5.998×10^7 S/m. By using the experimentally determined value of polyimide, I have deigned this 8 μm thick spacer layer. I had used a frequency independent permittivity of $\tilde{\varepsilon} = \varepsilon_1 + i\varepsilon_2 = 2.88 + i0.09$ and corresponding loss tangent is $\tan(\delta) = \varepsilon_2/\varepsilon_1$=0.0313.[20] By obtaining transmission coefficient and reflection coefficient, I calculated absorption using A = 1 – R – T = 1 – S_{11}^2 - S_{21}^2. In my design S_{21} is zero for entire frequency values because of the ground plane, which is also expected. The optimized structure shown in Fig. 1 was created by varying the dimensions of the cross resonator and the dielectric spacer thickness while simulating radiation at normal incidence. At the design frequency of 0.97 THz, the optimized parameters produced the lowest reflection.

4. Result and Discussion

Figure 2 shows the absorption of our optimized structure as a function of frequency for TE & TM mode for different angle of incidence ranging from 0^0 to 80^0.

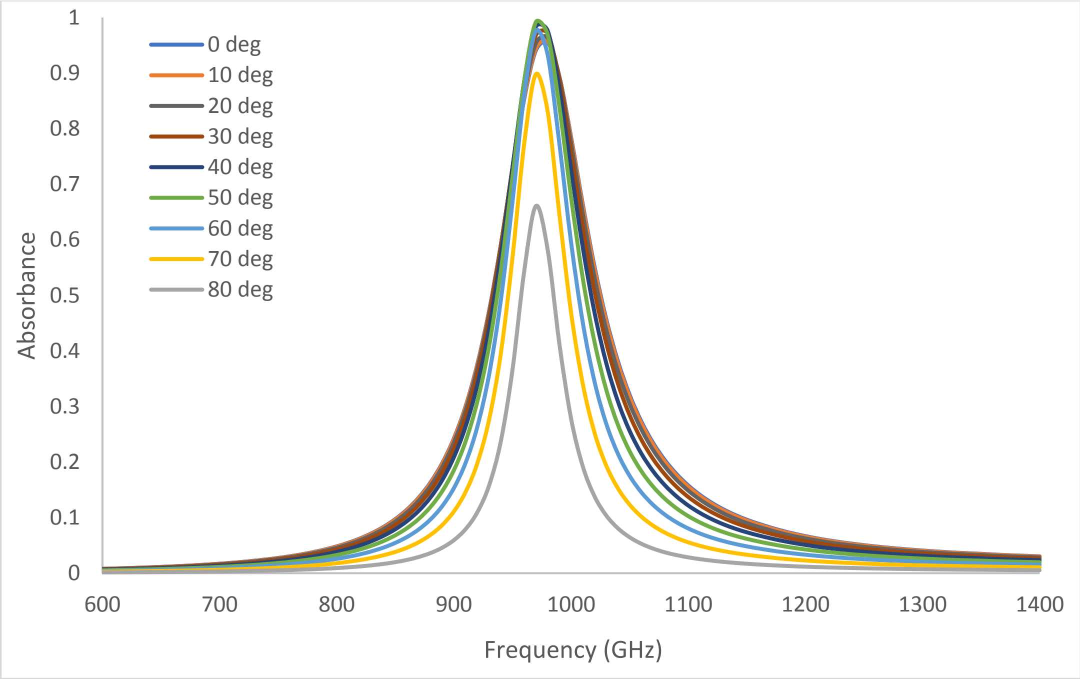

Fig. 2(a) For TE Mode

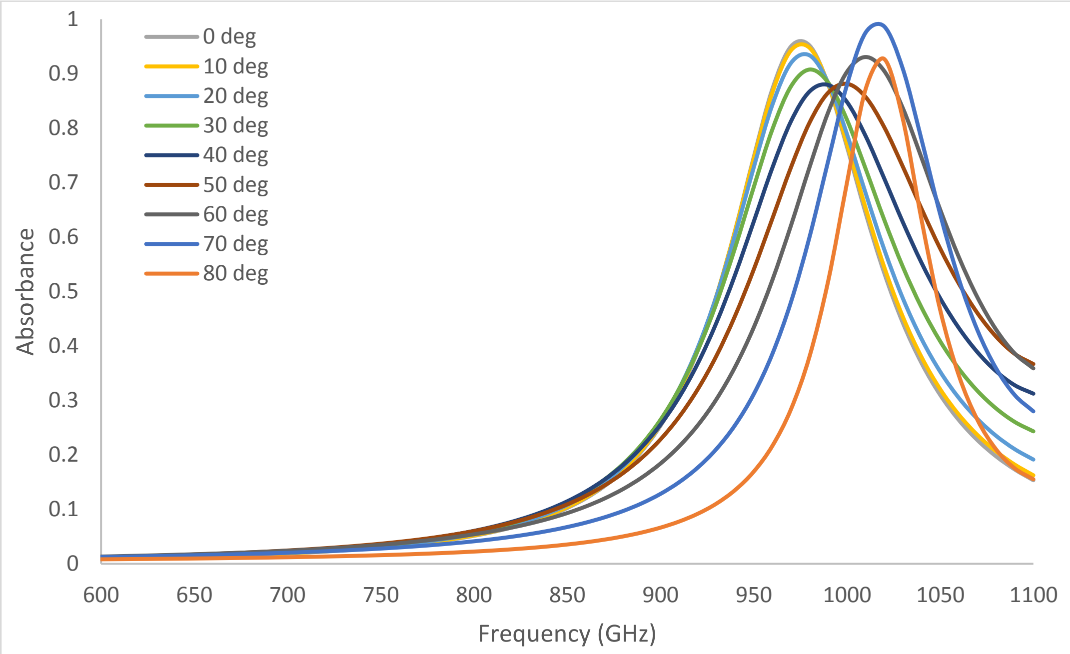

Fig. 2(b) For TM Mode

Fig. 2 Absorptivity as a function of frequency at various angle of incidence obtained from simulations. The labels for the curves show the angle of incidence.

Table 1 below shows the peak absorptivity for various angle of incidence and corresponding frequency at which peak absorptivity is obtained.

Table 1: Peak absorptivity at various angle of incidence and corresponding frequency.

	TE Mode		TM Mode	
Angle of incidence	Peak Absorptivity	Frequency (THz)	Peak Absorptivity	Frequency (THz)
0^0	0.95558024	0.980	0.95160476	0.980
10^0	0.95772212	0.980	0.94741486	0.980
20^0	0.96376862	0.980	0.93355288	0.980
30^0	0.97149195	0.980	0.90759603	0.980
40^0	0.98374892	0.970	0.87925683	0.990
50^0	0.99208072	0.970	0.8813674	1.000
60^0	0.97651934	0.970	0.93059653	1.010
70^0	0.89808674	0.970	0.98682066	1.020
80^0	0.66085225	0.970	0.92701894	1.020

Peak absorption of 0.95 was obtained for TE mode at normal incidence. As angle of incidence increases, the peak absorptivity remains large i.e. 0.99 at 50^0. After this there is rapid decrease in value of peak absorption with the increasing angle of incidence. This is because at larger angle of incidence, incident magnetic field is not able to circulate currents between the two metallic layers. There is also a small frequency change of 10 GHz from 0^0 to 80^0. For TM mode, peak absorption at normal incidence is 0.95 and it increases with increase in angle of incidence to 0.98 at an angle of incidence 70^0. In this mode, magnetic field does not efficiently drive circulating currents is between two metallic layers at near normal angle of incidence. The frequency change for TM mode is 10 GHz from 0 to 80^0. These results show that this MM absorber operates quit well for wide angle of incidence for TE mode. For TM mode this work well at larger angle of incidence only.

5. Conclusion

In summary we have designed a highly flexible perfect absorber that shows an excellent absorptivity of 0.99 at 0.97 THz frequency and normal angle of incidence. Also, this absorber works good for large range of angle of incidence for both Transverse electric and Transverse Magnetic mode. This kind of perfect absorbers may have variety of applications from terahertz stealth technology to thermal detectors.

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