Metamaterial as a Resonant Absorber

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Abstract: ***Resonant absorbers are used to ensure that all resonant light is neither reflected nor transmitted but is turned completely into heat and get absorbed. From transmission line theory resonant absorbers which depends on the material's way to interact with wave at particular frequency. Resonant absorbers are also called as quarter wavelength absorbers. Absorber design is an impedance match problem. MTM with its strong EM responses is used for designing a resonant absorber. MTM are material with negative value of permeability and permittivity made up of periodic array of magnetic inclusion. These properties are derived from their precisely designed structure. Metamaterials are unique material's which exhibits negative index of refraction. Metamaterials are used as cloaks, miniature antennas, concentrators and so on. MTM based absorber is best suited for THZ regime (Far-IR region). Design of a metamaterial based resonant absorbers providing absorption of EM wave at resonance frequency is discussed.***

Keywords: Metamaterials, impedance, reflectance, transmission

1. Introduction

Electromagnetic wave is an electromagnetic disturbances originated by one charged body travel out with velocity of light in free space. EM wave interact with any material in three ways:

1) Absorption (A)
2) Reflection (R)
3) Transmission (T)

For an EM wave following relation shows relation among absorption, reflection and transmission:

$A+R+T = 1$
$A= 1- T- R$

If T=0 and R=0 then A = 1. Hence absorption of wave will occur when T and R both are equal to zero [1] [2].

2. EM Absorber-Type

According to Boston college physicist Willie J. padilla, "Light can be reflected as in a mirror. It can be transmitted as with window glass or it can be absorbed and turned into heat. Hence absorber is a device which transmission and reflection of wave becomes zero and incident wave completely get absorbed at operating frequency.

2.1 Type of EM Absorbers

1) Resonant Absorber (Absorption of wave is frequency dependent and narrow-banded)
2) Broadband absorber (Absorption of wave is frequency independent and takes place over large frequency range).

2.1.1 Resonant Absorber

Resonant absorbers are those devices in which absorption of wave is dependent on frequency and absorption is due to resonance are called as resonant absorber. A system is said to be in resonance when frequency of incident force on to the system is equal to the natural frequency of the system and makes electrons to vibrate with maximum amplitude then state of resonance said to be occur [3].

In resonant absorber, absorption takes place only at resonance frequency (frequency at which resonance of a system is achieved), that is why resonant absorbers are called as narrow band absorbers. There are various resonant absorber, some of them are as follow [4]:

- Salisbury screen
- Jaumann absorber
- Dallenbach layer
- Crossed grating absorber
- Circuit Analog absorber

In simple microwave absorber, resistive sheet (resistance of 377 ohm) is used in the order to achieve impedance matching condition to make reflection equal to zero and a metallic backing is used to make transmission equal to zero. The minimum distance between resistive sheet and metallic backing is $\lambda 0/4$ and distance may vary according to the absorber performance.

Applications and limitations of EM resonant absorber:

Applications:
- To reduce the radar cross-section
- To reduce EMI.
- To shape antenna pattern.
- Cavity Resonance Reduction.
- Near field absorber.

Main flaws of resonant absorber are:
- Thickness (minimum thickness is $\lambda 0/4$ which makes these absorbers bulkier).
- Practical implementation of these resonant absorbers is limited to microwave frequency range (up to 30GHz). Hence not suitable for THz-gap (0.1THz – 10THz).
- Metallic backing is used for avoiding power transmission through the absorbers, which may be disadvantages in stealth applications

- These absorbers have very less control over absorption properties [5].

Due to flaws mentioned above, these absorbers are not suitable for many applications. These flaws are overcome by metamaterial based resonant absorbers.

3. Metamaterial

EM metamaterials are manmade material with exotic properties that are not found in nature. These properties are simultaneous negative permittivity and permeability, negative index of refraction, left hand rule and backward waves. Phenomenon of negative index of refraction was first shown by Victor Veselago, a Russian physicist in his research that if a material has both ε and μ simultaneously negative then refractive index (n) will also be negative according to the relation n = $\sqrt{\epsilon\ \mu}$ [6]. These responses and properties of metamaterial completely depend on dimension and structure of metamaterial. Metamaterial exhibit these properties only at resonance frequency. It is possible to attain desired resonance frequency by varying dimensions of metamaterial elements [7].

Metamaterials are designed by using two metamaterial elements. One generates desired electric response and other generates desired magnetic response.

3.1 Metamaterial Elements

Specifically, there are four combination methods.

1) SRR and metal wires.
2) SRR and CSRR.
3) Slot line and metal wire.
4) Slot line and CSRR.

SRR (split ring resonator) and Slot line generates magnetic response, CSRR (complementary split ring resonator) and metal wire generates electric response. Split ring resonator was the first magnetic inclusion used to design metamaterial to generate negative permeability at desired frequency [6]. Desired resonance frequency can be attained by varying dimensions of split ring resonator as shown in equation given below, where ω is resonance frequency, A is lattice constant and W, D and R are geometric parameters[7]

$$\omega = \frac{3Aco^2}{\pi ln\frac{2WR^3}{D}}$$

3.2 Metamaterial best suited as resonant absorber

Metamaterial is used in various applications like in superlenses, electromagnetic cloaking devices, miniature antennas, concentrators and so on[8][9]. Among those EM wave absorber have drawn considerable attention. One limitation of metamaterial is inherently high losses associated with resonant structures. However, this limitation of metamaterial can be a problem in other applications of metamaterials but it is very beneficial when we talk about metamaterial absorber, since more the losses more will be absorption. Second reason which makes metamaterial best suited for resonant absorber is it's THz operability. As it is difficult to design THz devices because THz materials lack in magnetic response and by using metamaterial, resonant absorber can be designed which works at THz region [10]. There is no need to use reflection sheet and metallic backing in case of metamaterial absorber which makes size small [12].

3.3 Theory

(a) Fresnel equation

Fresnel equation tells us about the proportion of field being reflected and transmitted from the incidence field. Here incident electric and magnetic fields are symbolized as $\mathbf{E}_i$ and $\mathbf{H}_i$ respectively, reflected electric and magnetic fields are symbolized as $\mathbf{E}_r$ and $\mathbf{H}_r$ respectively, transmitted electric and magnetic fields are symbolized as $\mathbf{E}_t$ and $\mathbf{H}_t$ respectively [12].

ηo (impedance of vacuum) = $\frac{E_0}{H_0} = \sqrt{\mu_0/\epsilon_0} = \sqrt{\frac{4\pi\times10^{-7}}{\frac{1}{36\pi\times10^{9}}}}$ = 377Ω

η_1 (impedance of medium) = $\frac{E_1}{H_1} = \sqrt{\mu_1/\epsilon_1}$

$$\eta_1 = \frac{E_i}{H_i},\ \eta_1 = \frac{E_r}{H_r} \text{ and } \eta_2 = -\frac{E_t}{H_t} \qquad (1)$$

According to continuity of tangential components of $\vec{E}$ and $\vec{H}$.

$$E_i + E_r = E_t \qquad (2)$$

$$H_i + H_r = H_t \qquad (3)$$

From (1) and (3)

$$\frac{E_i}{\eta_1} - \frac{E_r}{\eta_2} = \frac{E_t}{\eta_2} = \frac{E_i + E_r}{\eta_2}$$

Coefficient of reflectance R is defined as ratio of incident electric field to that of reflected electric field.

R = $\frac{E_r}{E_i} = \frac{\eta_2 - \eta_1}{\eta_1 + \eta_2}$

If medium 1 is vacuum then we can consider $\eta_1 = \eta_s$

$$\therefore R = \frac{\eta_2 - \eta_s}{\eta_s - \eta_2} \qquad (4)$$

Hence when impedance of medium 2 is equal to the impedance of medium 1 then reflection will be '0'.

From equation (1)

$E_i + E_r = E_t$

Divide both sides by E_i

$$\frac{E_i}{E_i} + \frac{E_r}{E_i} = \frac{E_t}{E_i}$$

$$1 + \frac{E_r}{E_i} = \frac{E_t}{E_i}$$

$$\frac{E_t}{E_i} = 1 + \frac{\eta_s - \eta_2}{\eta_s + \eta_2}$$

$$since\ T = \frac{E_t}{E_i}$$

∴ T = $1 + \frac{\eta_2 - \eta_s}{\eta_s + \eta_2}$

On solving above

$$\text{We get, } T = \frac{2\eta_2}{\eta_2 + \eta_s} \qquad (5)$$

From above equation it is clear impedance matching of two mediums will not lead to zero transmission. Incident radiation can still transmit through medium.

(b) Drude - Lorentz model

By using Drude-Lorentz model one can describe the frequency dependence of dielectric permittivity as sum of multiple resonance lorentzian functions. In other words it describes the material's response [13].

$$\vec{r}(\omega) = \frac{-q\,\vec{E}(\omega)}{\varepsilon_0\, m_e\,(\omega_0{}^2 - \omega^2 - j\omega\Gamma)}$$

The above shown relation describes the displacement in terms of deriving EF and Lorentz parameter. Here $\vec{r}(\omega)$ is position vector and $\varepsilon_0\, m_e\,(\omega_0{}^2 - \omega^2 - j\omega\Gamma)$ are called as Lorentz parameters. Lorentz polarizability α(ω): It is a constant value which relates the applied electric field and offset charge.

$$\alpha(\omega) = \frac{q^2}{\varepsilon_0\, m_e\,(\omega_0{}^2 - \omega^2 - j\omega\Gamma)}$$

$\chi(\omega)$ is the susceptibility of a dielectric which has only one resor

$$\chi(\omega) = \frac{N\alpha(\omega)}{\varepsilon_0} = \frac{N q^2}{\varepsilon_0\, m_e\,(\omega_0{}^2 - \omega^2 - j\omega\Gamma)}$$

Where N is number of atoms per unit volume, ω_0 is natural frequency, ω is resonance frequency, Γ is damping factor, m_e is mass of electron ($m_e = 9.10938188 \times 10^{-31}$ kg), q is charge on electron ($q = = 1.60217646 \times 10^{-19}$ C) and ε_0 is permittivity of free space ($\varepsilon_0 = 8.854187176 \times 10^{-12}$).

$$\chi(\omega) = \frac{\omega_p{}^2}{\varepsilon_0\, m_e\,(\omega_0{}^2 - \omega^2 - j\omega\Gamma)}$$, where ω_p is plasma frequency.

Relative permittivity is expressed in terms of susceptibility as follow:

$$\varepsilon(\omega) = 1 + \chi(\omega)$$

$$\bar{\varepsilon}(\omega) = 1 + \frac{\omega_p{}^2}{(\omega_0{}^2 - \omega^2 - j\omega\Gamma)}$$

Real and Imaginary parts of permittivity are as follow:

$$\varepsilon'(\omega) = 1 + \frac{\omega_p{}^2(\omega_0 - \omega^2)}{(\omega_0{}^2 - \omega^2)^2 + \omega^2\Gamma^2}$$

$$\varepsilon''(\omega) = \frac{\omega_p{}^2(\omega\Gamma)}{(\omega_0{}^2 - \omega^2)^2 + \omega^2\Gamma^2}$$

$\varepsilon'(\omega)$ and $\varepsilon''(\omega)$ are real and imaginary parts of permittivity and imaginary part of permittivity is related to loss. If $\varepsilon''(\omega)$ is zero, then loss will also be zero.

Refractive index and impedance tells us what actually is happening to the wave.

$$\bar{n} = n + j\kappa$$

Where $\bar{n}$ is complex refractive, n is real part of refractive index (called as ordinary refractive index) and 'κ' imaginary part of refractive index is called as extinction coefficient which is responsible for decay.

$$r(\omega) = \frac{1 - n(\omega) - j\kappa(\omega)}{1 + n(\omega) + j\kappa(\omega)}$$

$r(\omega)$ is amplitude of reflection coefficient.

3.4 Discussion of various metamaterial absorbers

First metamaterial based absorber was proposed by N.I Landy in 2008. This metamaterial absorber consisted of two MM resonators, which were separated by dielectric. This single unit cell consisted of ERR (electric ring resonator) and CW (cut wire), separated by dielectric with dimensions a1 = 4.2, a2 = 12, W = 3.9, G = 0.606, t = 0.6, L = 1.7, H = 11.8 as shown in figure 1(a), 1(b) and 1(c). Electric response was created by combining center of ERR with CW and desired magnetic response is created by varying geometry of CW and thickness of dielectric. Simulation was performed in time domain solver of CST microwave studio. Simulation of single unit cell of metamaterial absorber showed minimum reflection of 0.01% at resonance frequency 11.65 GHz, transmission is minimum near resonant frequency and is approximately 0.9%. Hence best absorption of approximately 99% at 11.65 GHz as shown in figure 2 [14].

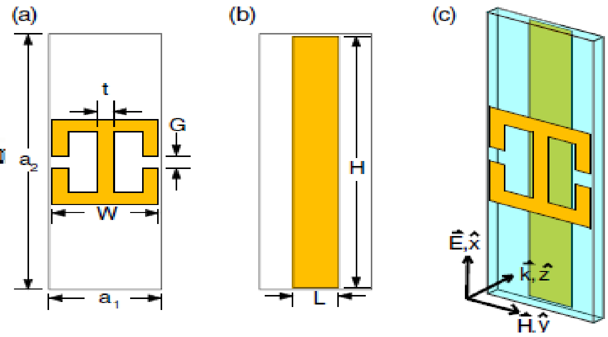


Figure 1: Electric resonator (a) and cut wire (b). The unit cell is shown in (c) with axes indicating the propagation direction. Figure adapted from Physics Review letters [14]

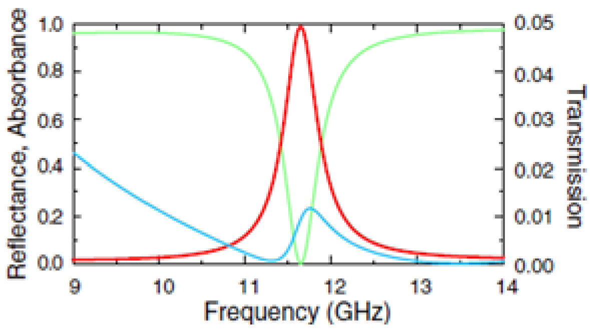


Figure 2: Simulated metamaterial perfect absorber. Reflectance (green color), transmission (blue color) and absorption (red color). Figure adapted from Physics Review letters [14]

H.Tao *et al* perposed a metamaterial based absorber consisted of two layers separated by dielectric. Top layer was of SRR (split ring resonator) and bottom layer wasof contineous metallic film with dimensions in µm (a=36µm, b= 25.9, c= 10.8, g= 1.4, w= 3, t1= t2= 8) ασ shown in figure 2(a). SRR creats effective permittivity and metallic film creats permeability. Minimum reflactance was achieved by matching impedance and transmission derived was T = exp(-2n2dk) = exp (-αd), where d is sample thickness, α is absorption coefficient and n2 is imaginary negative refractive index[15].

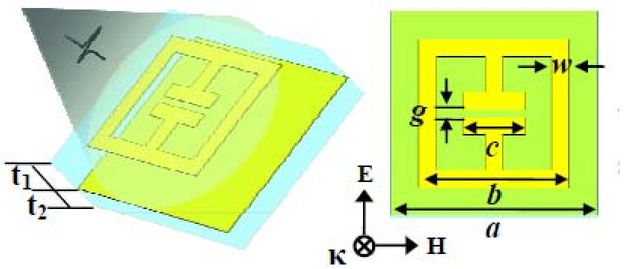


Figure 3: Metamaterial absorber. Figure adapted from [15]

Simulation of given design took place in CST microwave studio. Results of simulation shows absorption as function of frequency for TE and TM radiation at various incidence angles. Results reveal with increase in incidence angle, absorption remains large for TE case and is 0.89 at 50^0. For the TM case, the peak absorption is greater than 0.99 for all angles of incidence shown in figure 3(a) and 3(b).[15]

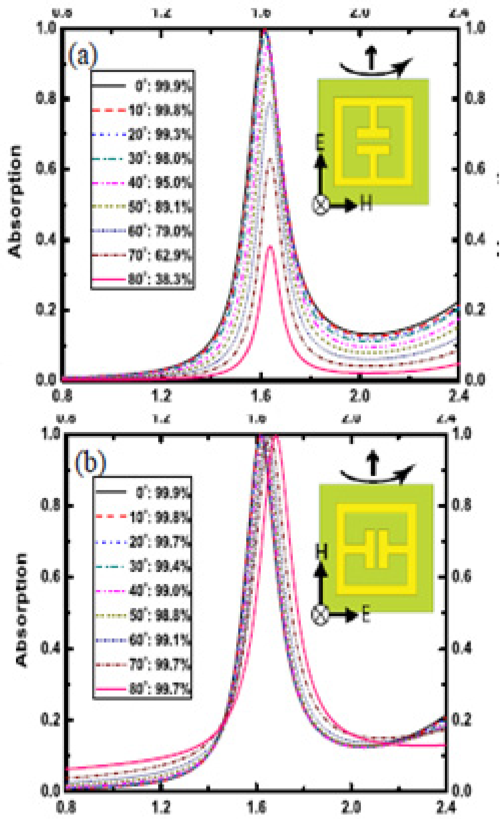


Figure 4: Simulation results of absorption as function of frequency at various incidence angles for TE (a) and for TM (b). Figure adapted from [15]

H.tao *et al* designed and simulated a metamaterial absorber that works for THz regime in 2009. ERR(electric ring resonator) and CW(cut wire) were used as metamaterial elements, separated by dielectric with dimensions as unit cell is 34μm wide and 50μm in length, line width of gap of ERR is 3 μm.

Side length of square electric resonator is 30 μm, the side length of cut wire is 48 μm and width of cut is 4 μm . Thickness of the electric ring resonator and cut wire is 200 nm. ERR generates desired electric response and by varying geometery of CW and dielecric substrate desired meganetic response can be generated as shown in figure. Simulation results showed absorption of 98% at 1.12 THz. Results reveals that transmission is less for entire range of frequency and reflectivity is high for entire range, except for 1.125 THz which is of 2% [16]. According to results derived, absorption is strong for light polarized in x direction and poor for light polarized along y direction.

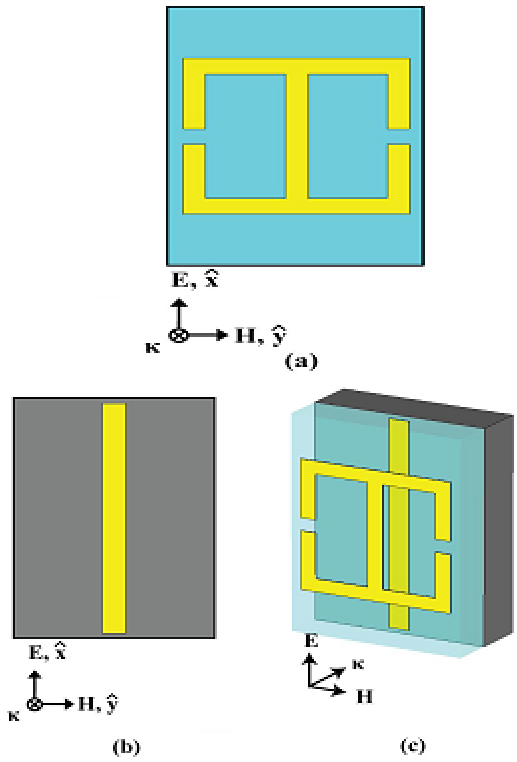
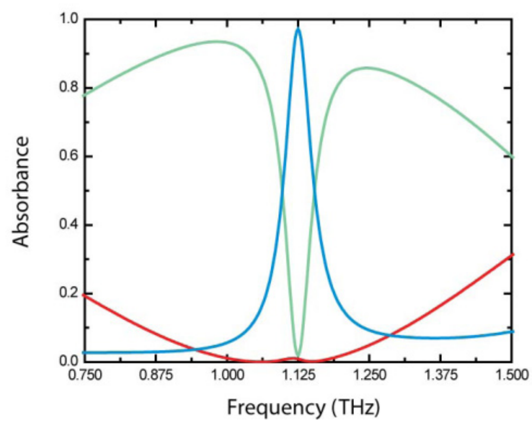


Figure 5: (a) Electric resonator (b) Cut wire (c) Single unit cell showing the direction of propagation of incident EM wave. Figure adapted [16]



(d) The absorption (blue) yields a value of 98% at 1.12 THz, reflection (green) and transmission (red) both at normal incidence. Figure adapted from [16]

A metallic back plane-less metamaterial absorber design was proposed by Hongmin Lee in 2012. Single unit cell of metamaterial layers separated by a dielectric spacer is placed parallel to direction of propagation. Metamaterial elements used to generate electric and magnetic responses are OCSRR and SRR respectively with geometrical dimensions a= 7.4mm, b=7mm, w= 3.2mm, h= 6.4mm, l= 6mm, d= 0.3mm and g= 0.4mm. Time domain solver of CST microwave studio is used for simulation. Results show maximum absorbance peak 93% and 94% at 2.848 GHz and 3.236 GHz, respectively. Results indicate that absorption does not homogeneously occur in MTM unit cell [11].

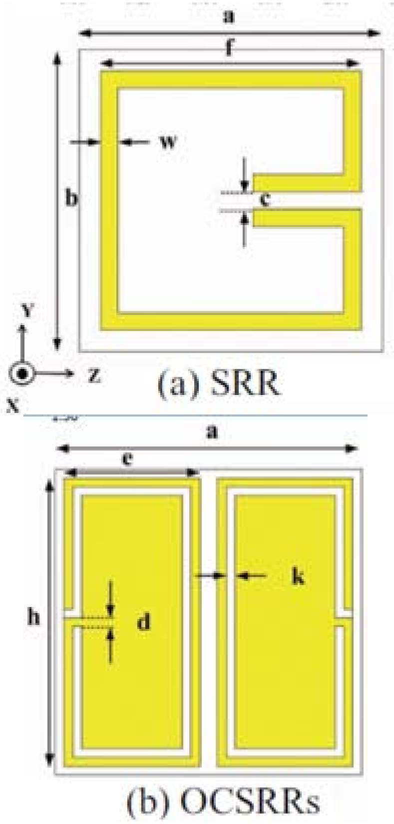


Figure 6: (a) SRR and (b) OCSRR. Figure adapted from [11]

Simulation of a single unit cell metamaterial absorber using commercial software COMSOL multiphysics shows insensitivity to incident polarization and propagation. Metamaterial structure consisted of ERR and ground plane separated by a dielectric filler as shown in figure 7.

Results showed 99.6% absorption. Results derived after rotating structure about the axis of propagation revealed that neither the absorption nor the frequency of resonance change significantly. Device was tested at various incidence angles of propagation and from results it is clear that at normal incidence angle absorption is 99.4% - 99.6% at 0.84 THz and with variation in angle of incidence absorption changes to 94% - 98.7% with shift in resonance frequency up-to 0.03THz as shown in figure 9.

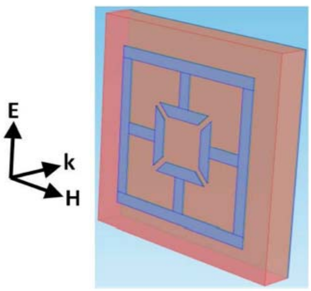


Figure 7: Unit cell of THz absorber. Figure adapted from [17]

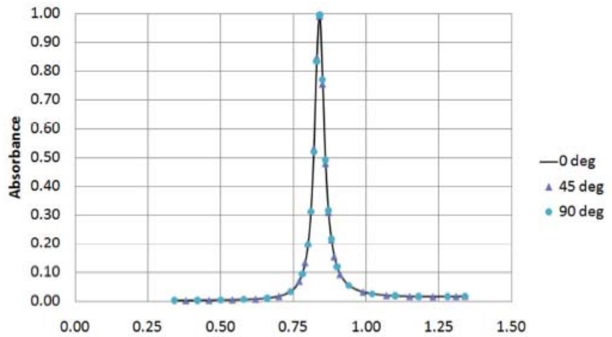


Figure 8: Absorption spectra for various Polarization angle. Figure adapted from [17]

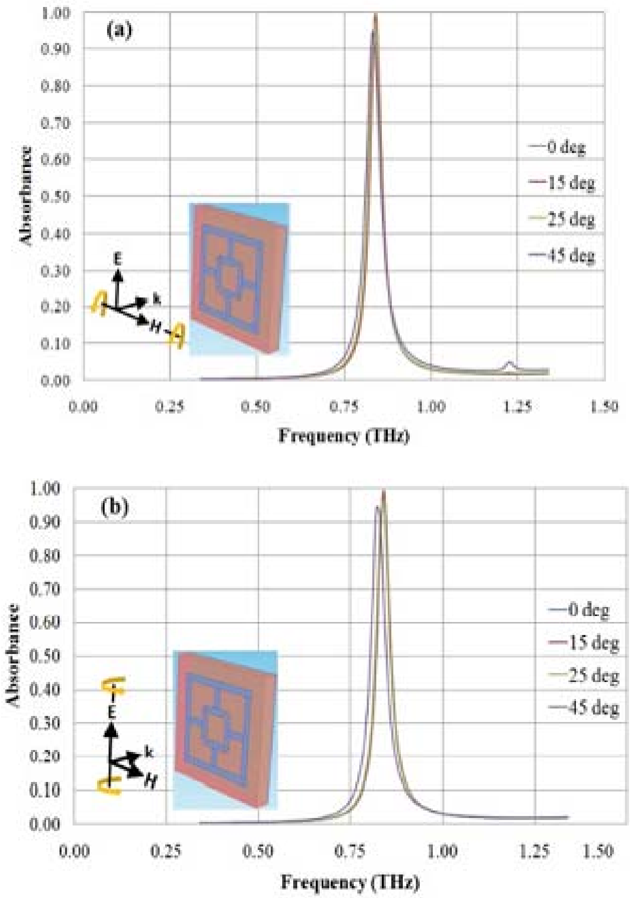


Figure 9: Absorption spectra for incident angles rotation about (a) MF (b) EF. Figure adapted from[17]

4. Conclusion

We presented in this paper different simulatons done to design and generate absorption ratio. It can be easily concluded that metamaterial absorber are of particular importance at THz frequencies, where it is difficult to find naturally occuring materials with strong absorption. Absorption can be derived at desired frequency range and most importantly just only by varying dimensions of metamaterial absorber, targeted frequency range can be achieved. Metamaterial structures are scalable to operate over most of the elecromagnetic spectrum. Absorbers with polarization independency and incidence angle independency can also be realized. Such metamterial absorbers may find number of applctions ranging from active element in thermal detector to THz stealth technology.

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