Chapter 1

Theoretical background of metamaterials and its applications

1.1. Introduction to metamaterials

Electromagnetic metamaterials are periodic arrays of sub-wavelength dimensional structures that can be optimized to engineer the constitutive electromagnetic parameters of the medium such as permittivity, permeability, effective impedance and refractive index [1-3]. Due to the sub-wavelength size of the metallic pattern, the incident electromagnetic wave does not acknowledge the structure as a combination of periodically arranged unit cells rather it will treat the whole structure as a homogenous medium having an effective value of permittivity and permeability. To some extent, this is possible when the effective size of the unit cell is much smaller than the wavelength of the incident electromagnetic field. Numerically, if l is the length of the unit cell and λ is the wavelength of the incident electromagnetic wave then according to the homogeneity principle $l << \lambda$.Usually the minimum requirement for a medium to be called as homogeneous is $l < \frac{\lambda}{4}$. Under this condition, refraction and reflection become the predominant phenomenon leaving out diffraction and scattering [4]. An illustration of the metamaterial concept through the homogeneity principle is shown in Fig. 1.1. Each red square can be treated as a unit-cell which forms a composite material under periodic configuration. If we consider the material under the incidence of an electromagnetic wave, then the size comparison between the material and the wavelength of the incident wave decides that how much of the information one can resolve about the internal structure. If the wavelength of the incidence electromagnetic [EM] wave is of the order of or less than the size of the material, then the wave acknowledges the whole material as a combination of small unit cells. On the contrary, if the wavelength of the incident EM wave is longer than the size of the material, then the wave sees the whole structure as a homogeneous medium, as evident from Fig. 1.1. Consequently, rather than analyzing the whole structure as a combination of structured geometry, we can average the property of the material as a whole through constitutive medium parameters such as effective permittivity $\varepsilon_{eff}(\omega)$ and effective permeability $\mu_{eff}(\omega)$. The constitutive medium parameters are important because they are the only medium parameters used in Maxwell's equations that govern electromagnetic and optical wave propagation [5].

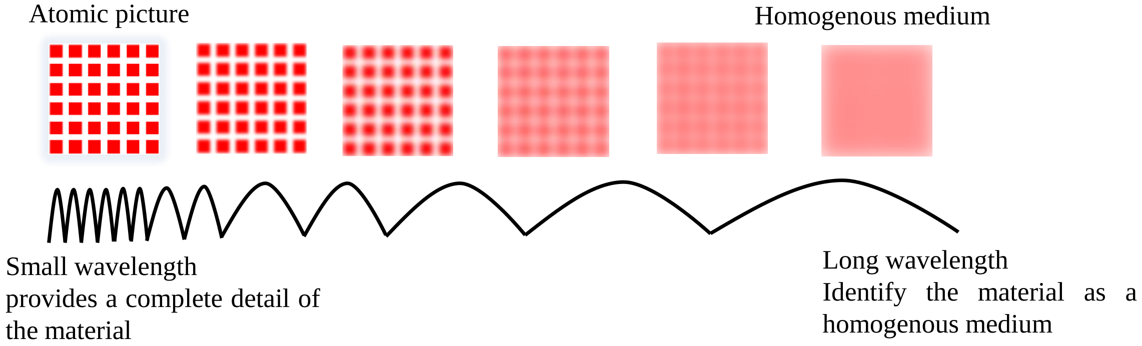


Fig. 1.1 Homogeneity principle in metamaterial.

1.1.1. Introduction to metasurfaces

Metamaterial and metasurface belong to the same class of artificially designed structures. However, there is a slight difference between the two terminologies. If we consider metamaterial as a bulk array of resonating metallic structures, then metasurfaces are planar array of resonating metallic structures. More technically, metasurfaces are the 2-D analogue of metamaterial. Most of the functionalities which can be realized using a metasurface can also be realized using metamaterial [6-8]. Despite that metasurface is preferred over metamaterial mainly due to the three reasons.

1.) Metasurface can be integrated well with planar electronics systems due to its ultrathin nature.

2.) It is tough to analyze bulk metamaterial at high frequencies such as Terahertz (THz) or Infrared.

3) Bulk metamaterials involve the propagation of electromagnetic waves for a substantial distance leading to undesirable losses. On the contrary, due to ultrathin thickness, metasurface shows a better ability to control electromagnetic waves as compared to metamaterial.

The structural arrangement of meta-atoms in metamaterial and metasurface designs are separately shown in Fig. 1.2(a) and Fig. 1.2(b) respectively.

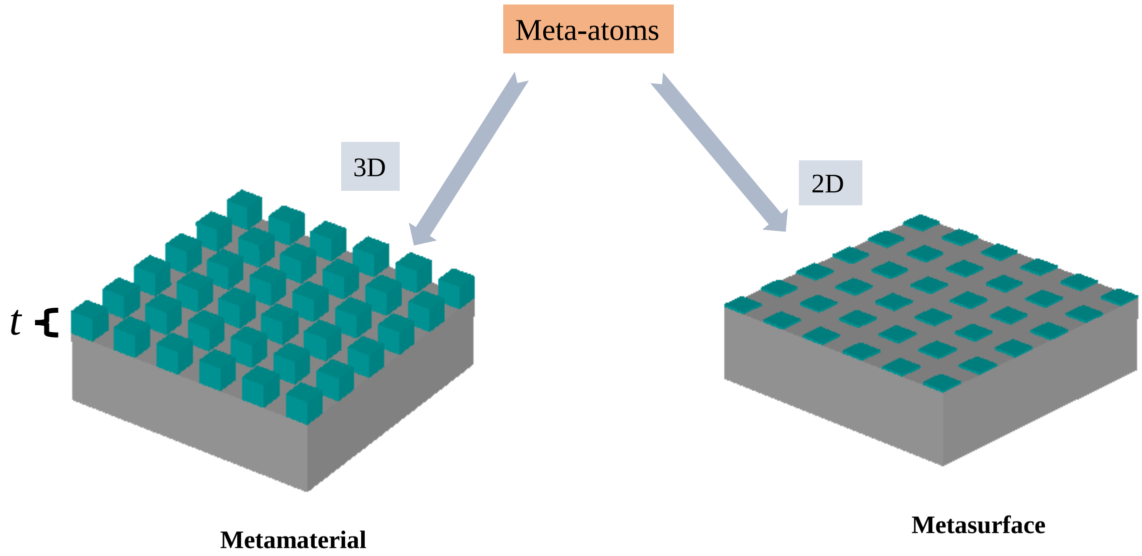


Fig. 1.2. (a) Meta-atoms having finite thickness: metamaterial (b) meta-atoms having ultra-thin thickness: metasurface

1.2. Drude-Model characterization of metals at optical frequencies

In this section, we will understand the modification needed in the property of metals at high frequency applications. Most of the metamaterial structure comprises metals in the unit cell. The Drude free electron model provides a more realistic model of metals than the conventional conductor model, as at high frequencies the inertial effect due to the finite electronics mass becomes important. In metals, the valence electron is loosely bound to the nucleus and thus ready to become free to pursue random motions inside the metal. The response of metal for an incident electromagnetic wave largely depends on the overall movement of free electrons (represented as "N") that moves against the positive ion core. Drude model is a classical approach that considers material to be a gas of free electrons distributed among the arrangement of relatively heavy positive ions. The combination of the negatively charged gas of free electrons and positive ion core makes the medium neutral and the medium can be categorized as plasmas. The two major assumptions of Drude model are:

1.) In the absence of electromagnetic wave, the electrons move in a straight path in between collisions. The effect of electron-electron and electron-ion interaction is ignored.

2.) The mean free time between the collision (τ) is independent of the electron's velocity and position.

The probability of collision per unit time, also called collision frequency is mathematically expressed as $\gamma = (\frac{1}{\tau})$. When a time harmonic electromagnetic field ($E_o e^{-j\omega t}$) is incident on the metal, then it will accelerate the electron as long as the electric field is applied. The relation between these two forces can be mathematically written as:

$$m\frac{d^2x(t)}{dt^2} = qE \quad (1.1)$$

Where m and q represents effective mass and charge of the free electron respectively and E is the electric field applied. This equation signifies that, once we apply an electric field across the electrons, the electrons undergo acceleration in response to the applied electric field. If we put this in Newton's first law of motion, i.e., $v = u + at$, the equation implies that the velocity of electrons will keep increasing as long as the field is applied. In practice, this equation is missing something. During the movement, the electron collides with other electrons directly or indirectly. The higher the velocity of the electrons, the sooner they will collide with other electrons. So, it signifies that there is some form of resistive term present, that is preventing the movement of the electrons. Accordingly, equation. 1.1 will then be modified as

$$m\frac{d^2x(t)}{dt^2}+m\gamma\frac{dx(t)}{dt}=qE \tag{1.2}$$

Here γ represents the damping constant. The first term of the equation represents inertial force and the second term represents the loss due to the collision of electrons. The term on the left side of the equation represents the force due to the applied electric field. Solving the differential equation will yield the displacement *x(t)* of the electron from its initial position, mathematically related as:

$$x(t)=-\frac{q}{m}\frac{1}{\omega(\omega+i\gamma)}e^{(-j\omega t)} \tag{1.3}$$

The total dipole moment per unit volume, also known as polarization density can be calculated as $P=Nqx(t)$, where *N* is the density of free electron, *x(t)* is the displacement of the electron from its initial position and *q* is the charge of an electron. The relation between applied electric field and electric displacement is given by:

$$D=\varepsilon_o E+P \tag{1.4}$$

$$\text{where, } P=-\frac{Nq^2}{m}\frac{1}{\omega(\omega+i\gamma)}$$

Putting the value of *P* in equation. 1.4, the relative permittivity of metallic material is computed as provided in equation. 1.5.

$$\varepsilon(\omega)=1-\frac{\omega_p^2}{\omega(\omega+i\gamma)} \tag{1.5}$$

Here, ω_p is the plasma frequency at which the electrons gas oscillates, equated as:

$$\omega_p=\sqrt{\frac{Nq^2}{mq_o}} \tag{1.6}$$

The plasma frequency of metals lies in the range of visible to ultraviolet frequency because for most metals, free electrons (*N*) are in the order of $10^{23} cm^{-3}$. Up to plasma frequency (ω_p) dielectric constant is negative and has a large magnitude of imaginary part, which means that metals offer complete shielding for the electromagnetic wave. The same metal behaves as an ordinary dielectric medium above ω_p by offering a positive value of dielectric constant. Here in Table 1 we have listed the plasma frequency f_p and collision frequency γ of some of the most commonly used metals.

Table 1: Plasma frequency and collision frequency for metals

Metals	**Plasma frequency (f_p)**	**Collision frequency (γ)**
Gold (A_u)	2175 THz	6.5 THz
Silver (A_g)	2175 THz	14.1 THz
Aluminium (Al)	3570 THz	17.5 THz

1.3. Waves at the interface of two medias

When the EM wave is incident on the interface of two media, then either the wave can be transmitted, refracted, reflected, scattered or get absorbed inside the medium. If the surface roughness of the interface is much less than the characteristics wavelength, then the surface scattering becomes so minimum that it can be ignored. Consequently, the incident wave will be either reflected ($R(\omega)$), transmitted ($T(\omega)$) or absorbed ($A(\omega)$). According to Kirchhoff's law, the relation between these three phenomena at a media interface must follow the relation shown in equation 1.7 [9-10].

$$A(\omega) = 1 - T(\omega) - R(\omega) \tag{1.7}$$

The complex transmission and reflection coefficient can be calculated by using Maxwell's boundary condition at the media interface. By properly applying field continuity equation at the two media interfaces, one can get the proper idea of amount of reflection, transmission or absorptions experienced by the incident plane wave. The reflection and transmission of electromagnetic wave between the two media is described by Fresnel's equations which says that when the light strikes the interface of two media having two different values of refractive indices, then both reflection and refraction of light occurs. Fresnel equation mathematically deduced the relation between reflected wave's electric field to incident wave's electric field and transmitted wave electric field to the incident wave electric field for both type of polarizations i.e., transverse electric (TE) and transverse magnetic (TM). If a plane wave is incident obliquely on a planar interface at an angle θ_{in}, then the reflectance for TE and TM polarizations will be given as equation. 1.8 and 1.9 respectively.

$$r_{TE} = \frac{\mu_r \cos\theta_{in} - \sqrt{\mu_r \varepsilon_r - \sin^2\theta_{in}}}{\mu_r \cos\theta_{in} + \sqrt{\mu_r \varepsilon_r - \sin^2\theta_{in}}} \tag{1.8}$$

$$r_{TM} = \frac{\sqrt{\mu_r \varepsilon_r - \sin^2\theta_{in}} - \varepsilon_r \cos\theta_{in}}{\sqrt{\mu_r \varepsilon_r - \sin^2\theta_{in}} + \varepsilon_r \cos\theta_{in}} \tag{1.9}$$

Here ε_r and μ_r are the relative permittivity and permeability of media 1 (μ_1, ε_1) and media 2 (μ_2, ε_2) respectively. For the media interface of air and dielectric, when the wave is incident normal to the interface, then the reflectivity equations will be modified as:

$$r = \frac{1 - \sqrt{\mu_r \varepsilon_r}}{1 + \sqrt{\mu_r \varepsilon_r}} \tag{1.10}$$

The equation. 1.10 can be further modified in terms of the characteristics impedance of medium 1 and medium 2, where the term characteristics impedance implies the ratio between the electric and magnetic fields in that medium. equation. 1.11 shows the modified equation of reflectance where $Z_1 = \sqrt{\frac{\mu_o}{\varepsilon_o}}$ and $Z_2 = \sqrt{\frac{\mu_o \mu_r}{\varepsilon_o \varepsilon_r}}$.

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{1.11}$$

The term characteristics impedance implies the ratio between the electric and magnetic fields in that medium. In equation. 1.11, Z_1 is the characteristic impedance of medium 1 i.e., air and Z_2 is the characteristics impedance of medium 2 i.e., dielectric. From the equation of reflectance in equation. 1.11, it can be clearly observed that to achieve zero reflection i.e., $r = 0$, the impedance of medium 2 (Z_2) should be equal to the intrinsic impedance of medium 1 i.e., air (Z_1). This can only be possible when the real part and imaginary part of permittivity and permeability should be equal to each other ($\mu_r = \varepsilon_r$). Unfortunately, it cannot be possible by any natural material, therefore one has to look for artificially designed structures for controlling the values of permittivity and permeability.

1.4. Electromagnetic wave absorbers

A device that can absorb the incident electromagnetic wave is called as electromagnetic wave absorbers. They have a wide range of applications in solar harvesting, heat sensing and energy conversion devices working in the frequency range from microwave to visible. In the microwave frequency region, they are widely used for military applications such as reducing the radar cross section and antennas applications. In THz frequency region, they can be used for biological imaging, spectroscopy, high band communications and some non-ionizable medical diagnosis. At infrared frequencies an electromagnetic absorber can be used for sensing, detection and thermal imaging applications. At visible frequency region, the efficiency of solar cells can be improved by using electromagnetic absorbers which can meet the overgrowing demand of energy nowadays. Though these devices are used for different applications at different frequency spectrums, however, one thing that is common in all these devices is the presence of absorbers as an integral part of the system. In the next sections, we will briefly describe the evolution of electromagnetic absorbers from initially designed Salisbury screen to recent advances in metamaterial absorbers.

1.4.1. Conventional electromagnetic wave absorbers

The first concept in the design of electromagnetic wave absorbers was proposed by Winfield Salisbury in 1940s [11]. It was one of the first concepts to reduce the radar cross section area by designing an artificial radar absorbent material. Salisbury screen is based on the same concept of optical antireflecting coating used on the surface of camera lenses. Salisbury screen consists of three layers. The first layer consists of a thin resistive screen, the middle layer is a low loss dielectric (air) layer of quarter wavelength thickness and the third layer at the bottom is a continuous metallic plate. The schematic of the Salisbury screen illustrating all the wave phenomena is shown in Fig. 1.3 below.

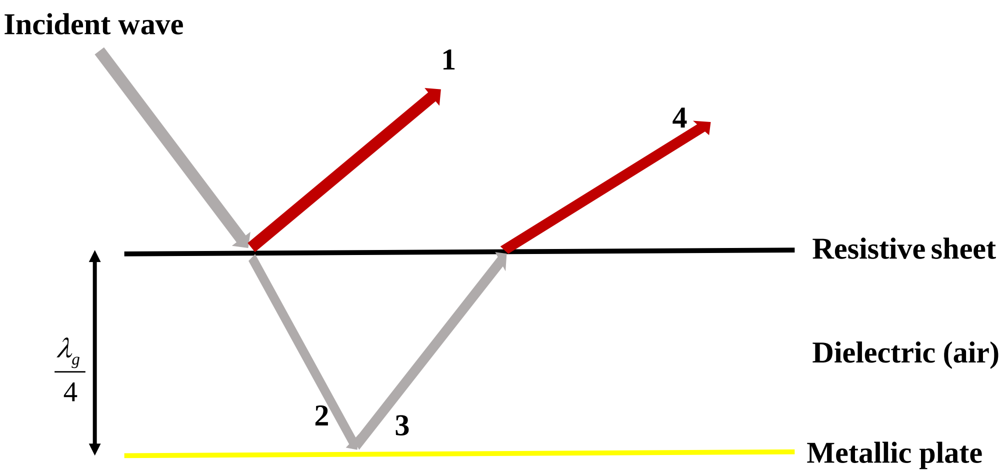


Fig. 1.3. Schematic of the Salisbury screen

When the electromagnetic wave (let say radar wave here) strikes at the top of the resistive screen, it splits into wave 1 and wave 2, as shown in Fig. 1.3. Since wave 2 travels an extra distance of $\frac{\lambda_g}{2}$ as compared to wave 1, it experiences an additional 180^0 phase shift. Finally, the two waves i.e., wave 1 and wave 4 undergo destructive interference due to out of phase and thus cancel out each other. Therefore, no energy gets reflected back to the radar and it perceives as the device has absorbed all the incident waves. Nevertheless, the two major limitations of Salisbury screen are its larger thickness and low bandwidth. The quarter wavelength size of the dielectric makes the design thick at low frequency region. As the operating principle depends on the quarter wavelength dielectric thickness, the device can be used only for single band operating frequency. The limitations of narrow bandwidth in Salisbury screen was later on solved by Jaumann absorbers [12]and Dallenbach absorbers [13], but on the cost of increased thickness due to stacking of layers.

1.4.2. Circuit analog absorbers

The designed structure of circuit analog absorbers (CA) is very similar to the Salisbury screen or Jaumann absorber [14]. Only difference is that instead of resistive sheet on the top, it uses a metallic patch of different shapes. Therefore, instead of making the top layer as a complete resistive sheet, the CA absorber has a reactive top layer. The resistance of the patch itself can be modelled as a resistor, the length of the patch can be modelled as an inductor and the gap between the two patches can be modelled as a capacitor. Therefore, the structure can be modelled as a combination of R, L and C. The frequency of operation is decided by the resonance of the RLC circuit (not by the distance between the top and bottom layers). The terminology circuit analog is due to the fact that the top metallic patch of the structure can be modelled as an equivalent circuit with an effective value of inductance, capacitance and resistance. The behavior of CA absorber is quite different than that of Salisbury screen or Jaumann absorbers, when the incident EM wave has off-resonance frequency. In the CA absorbers, the rear metal plate behaves like inductance whereas the top metallic patches behave like capacitance. If the frequency of the incident EM wave is lower than the resonant frequency, then the middle layer becomes inductive. Therefore, the overall admittance of the structure is the sum of the admittance of the top metallic patch and the rear metal. The combination of these two admittances leads to the cancellation of the reactive part of the combined admittance leading to very small reflectance. Similarly, if the frequency of incident EM is higher than the frequency of resonance, then the role of the metallic patch at the top and rear metal patch gets interchanged, resulting in an identical response. In a nut-shell, we can conclude that despite having the same quarter wavelength size middle layer, a CA absorber offers a larger bandwidth than Salisbury screen and Jaumann absorber.

1.4.3. Metamaterial/Metasurface based perfect absorber

Metamaterial based absorbers are similar to CA absorbers. However, unlike CA absorbers (quarter wavelength dielectric), a metamaterial absorber consists of dielectric layer much smaller compared to the wavelength of the resonance. Most of the metamaterial based absorbers comply of three different layers [15-17]. The top layer is a metasurface while the bottom layer consists of complete metallic plate. The metasurface layer comprises of periodic arrangement of subwavelength size metallic pattern where each metallic pattern is termed as a unit cells. The top and bottom metallic layers are separated by a layer of dielectric of subwavelength thickness. Each of these layers play a different role in the realization of a metamaterial based absorber. The top layer is responsible for deciding the frequency of resonance in the structure. The bottom layer acts like a metallic reflector, which suppresses any transmission from the structure. The dielectric layer in the middle simply provides a space for the wave to stay and get absorbed. Since the bottom layer reflects the wave incident on it, it can be interpreted as a short circuit offering zero impedance. The dielectric layer in the middle simply provides a space for the wave to stay and get absorbed. It is believed that in order for the wave to stay and get absorbed the dielectric layer should have enough space. This can be easily done by choosing high dielectric constant material, because such materials (η) can reduce the thickness (d) while maintaining the electric path length (ηd). A dielectric material usually has a very small value of loss tangent and this loss tangent is usually enough for the wave to get absorbed while travelling inside the dielectric material.

The two different types of losses that leads to absorption in a metamaterial absorber are 1) dielectric loss and 2) ohmic loss. Because a metamaterial absorber structure consists of metallic patch and dielectric, there might be a possibility that the absorption in the structure may be dominantly due to ohmic loss or may be due to the dielectric loss. Sometimes even both losses are responsible equally in the absorption process. In the first metamaterial absorber proposed by Landy et al., the dominant absorption was due to the dielectric loss. They theoretically investigated the origin of absorption in the structure and found that a weak energy dissipation was found on the metallic surface, whereas a large dissipation was seen in the inner dielectric layer. In the microwave range, the ohmic loss is very low due to the fact that metals are highly conductive with little losses; however, as the frequency increases, the ohmic loss starts dominating over the dielectric loss and we can say that beyond infrared frequency range the dielectric loss becomes weaker and weaker and eventually we can even neglect the dielectric loss at higher frequencies [18].

1.5. Single-layer effective medium model for the realization of perfect absorption

The Single-layer effective model considers the whole metamaterial structure as a single layer having an effective value of permittivity ε_{eff} and permeability μ_{eff} which can be retrieved from the complex reflection and transmission coefficients of the structure. The amount of absorption in a structure can be mathematically calculated by the equation $A(\omega)=1-|R(\omega)|-|T(\omega)|$, where, $|R(\omega)|$ and $|T(\omega)|$ are the reflectivity and transmissivity and $A(\omega)$ is the absorptivity in the structure. For the perfect absorption of electromagnetic waves, there must be minimum reflectivity (ideally $|R(\omega)|=0$) and minimum transmissivity (ideally $|T(\omega)|=0$) from the structure. Due to the presence of metallic plate at the bottom, the total transmission from the structure is zero ($|T(\omega)|=0$). For minimum reflection, impedance matching is required which can be achieve when the impedance of the structure becomes equal to the intrinsic impedance of the air. The intrinsic impedance of air and the characteristics impedance of structure can be mathematically calculated from equation. 1.12 and equation. 1.13 respectively.

$$\text{Intrinsic impedance of air} = Z_1 = \sqrt{\frac{\mu_o}{\varepsilon_o}} \tag{1.12}$$

$$\text{Characteristics impedance of structure} = Z_2 = \sqrt{\frac{\mu_o \mu_r}{\varepsilon_o \varepsilon_r}} \tag{1.13}$$

If we artificially optimize the top metallic pattern of the metasurface, such that $\varepsilon_r = \mu_r$, then according to equations. 1.12 and 1.13, impedance Z_1 becomes equal to Z_2. Under such condition, the total reflection from the structure represented as $r = \frac{Z_2 - Z_1}{Z_2 + Z_1}$ becomes zero leading to perfect absorption in the structure. Conventionally, it is not possible for any natural material to achieve the impedance matching condition with air. Only metamaterial allows us to tune the constitutive medium parameters of the structure artificially to realize the impedance matching with ease.

The design of a metamaterial structure typically consists of a metal-dielectric metal trilayer pattern which shows strong electromagnetic field enhancement due to the mutual interaction between the top and bottom metallic layers. When the top and bottom layers are brought in close proximity to one another, then their mutual interaction induces a symmetric high frequency hybrid mode with in phase electric field oscillation between the top and bottom metallic plates normal to the axis (Fig. 1.4(a)) and an antisymmetric low frequency hybrid mode with out of phase electric field oscillation between the top and bottom metallic plate (Fig. 1.4(b)). The in phase electric field is characterized by an electric dipole whereas the out of phase electric field give rise to magnetic dipole. Due to the time varying electric field the electric dipole oscillates, giving rise to electric resonance, whereas the formation of antiparallel surface currents signifies the occurrence of magnetic resonance in the structure. The combined effect of electric and magnetic resonances together gives at the same frequency results to absorption in the structure.

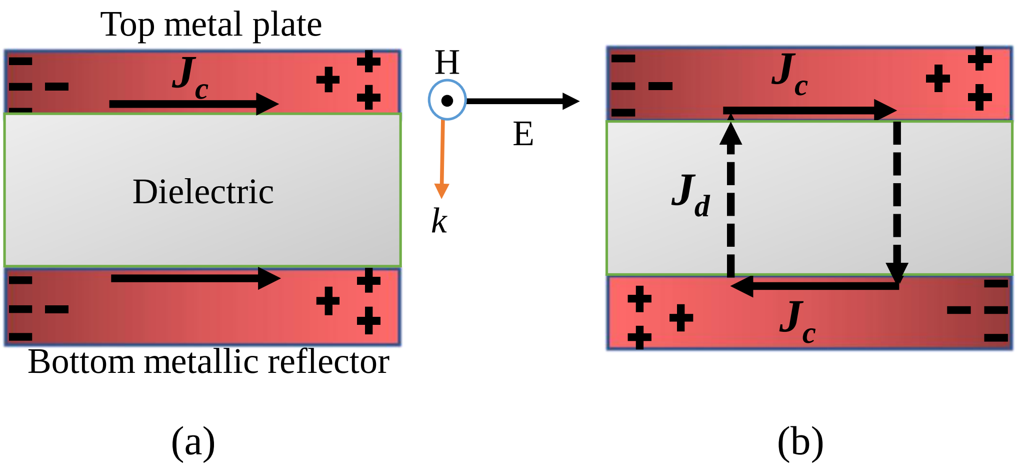


Fig. 1.4. Charge and current orientation of the (a) electric dipole resonance and (b) magnetic dipole resonance.

1.5.1. Three-layer effective model for perfect absorption

This model is also known as multiple interference model which is based on Fabry-Perot (FP) resonance**.** The absorption characteristics are based on the multiple reflection interference phenomena. Unlike the single-model theory, this theory considers metamaterial structure as a combination of three distinct layers. The reflection and transmission characteristics of the whole structure can be obtained by multiplying the reflection and transmission coefficient of each layer [19-21].

To understand the absorption mechanism, a schematic diagram showing the multiple reflection and transmissions at each layer of the metamaterial structure is shown in Fig 1.5. When the wave is incident on the top of the metasurface layer then some part of the wave will undergo reflection whereas rest of the wave enters inside the dielectric layer. The wave which has enters into the dielectric layer will undergo multiple reflections inside the dielectric in between the top and bottom layers

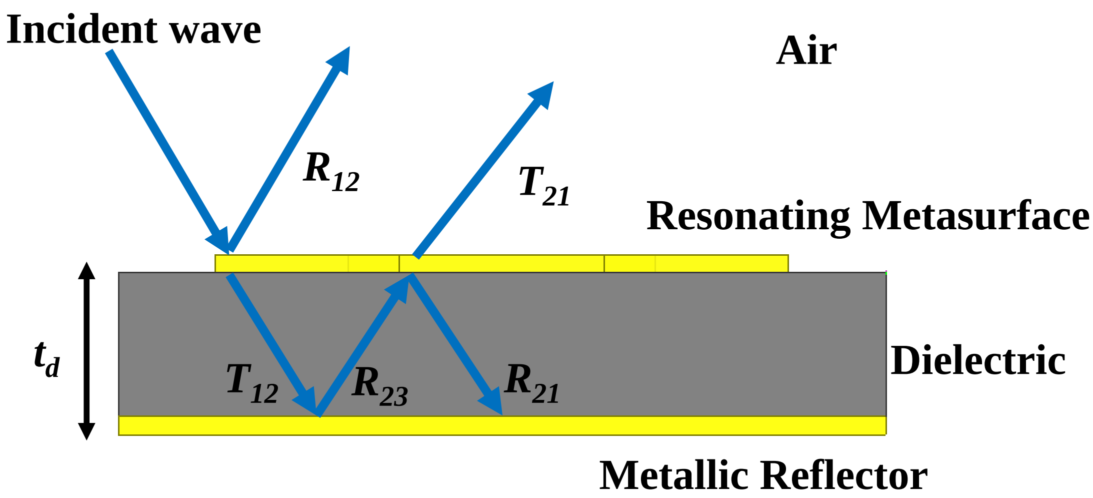


Fig. 1.5. Multiple reflections and transmission at each layer of metamaterial

The overall reflection from the structure will then be the multiplication of reflection and transmission of each layer, mathematically given in equation. 1.14:

$$r_{rstructure} = \frac{R_{12} + \alpha R_{23} e^{2i\beta}}{1 - R_{21} R_{23} e^{2i\beta}} \tag{1.14}$$

where R_{12} and R_{21} are the reflection of the top metasurface layer from the top side (air) and bottom side (dielectric) respectively. R_{23} is the reflection from of the bottom metallic reflector. σ is the constant numerically equal to $T_{21}T_{12} - R_{12}R_{21}$, where T_{12} and T_{21} are the transmission coefficient of the top metasurface layer form the top side (air) and bottom side (dielectric) respectively. β is the total phase change experienced by the wave when it travels inside the dielectric, mathematically equal to $\beta = \eta \times k \times d$, where η signifies the refractive index of the dielectric material, k is the propagation vector and d is the thickness.

One of the conditions to make perfect absorption in a structure is to have zero reflection. From equation. 1.14, the two conditions which makes zero reflection from the structure are:

Amplitude condition: $R_{12} = |\alpha R_{23}|$ (1.15)

Phase condition: $\theta = \phi(R_{12}) - \phi(R_{23}) - \phi(\alpha) - 2\beta = (2n+1)$, where $|n|$=0,1.. (1.16)

A zero reflection signifies that the wave incident on the top of the structure completely enteres into the structure. The wave thereafter undergoes multiple reflections between the top and bottom metallic plates and in this way, they interfere with each other. In this process, if the waves interfere in such a way that they satisfy equation. 1.17, then they establish Fabry-perot (FP) resonance inside the dielectric cavity. The condition for FP cavity resonance:

$$\varphi = \phi(R_{21}) + \phi(R_{23}) + 2\beta = 2m\pi, |m| = 0,1.. \quad (1.17)$$

When $\varphi = 2m\pi$, the wave which undergoes multiple reflection inside the cavity will interfere constructively, resulting standing wave resonance inside the structure, which leads to absorption.

1.6. Metamaterial absorber with a transmission band (RASORBER)

A perfect absorber plays a major role in stealth technology by reducing the radar cross section [22-23]. However, in some applications, despite absorbing a particular band of frequency, we need to transmit another band of frequency to communicate with other remote devices. Therefore, it is required that the structure should absorb a particular frequency band while transmitting another band of frequency. Such structures are also termed as rasorbers which is an absorber with a transmission band. A figure illustrating the two applications is shown in Fig. 1.6.

Earlier a lot of research has been carried out on the design of metamaterial based rasorbers for microwave frequency range. Most of them used distributed passive elements such as resistors, inductors and capacitors to switch the bands of operation [24-25]. However, the need of vias for the realization of distributed inductors makes the fabrication challenging and thus restricts this method for being used. Later on, rasorber based on active elements were proposed, which consist of diodes such as PIN diode and varactor diode for the switching purpose between the transmission and absorption band [26-27], as shown in Fig. 1.7.

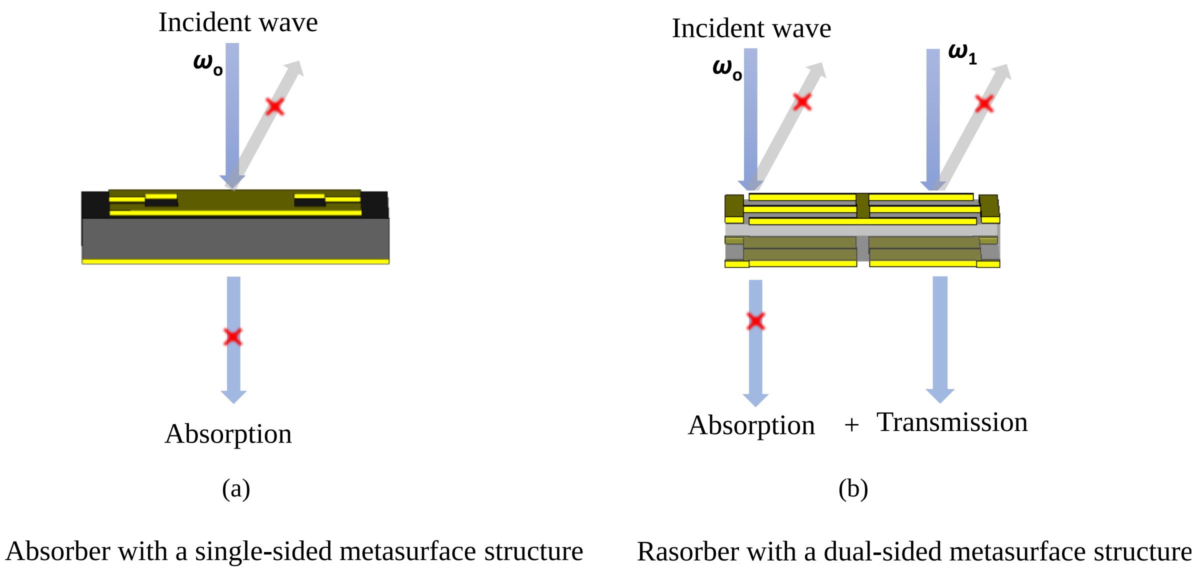


Fig. 1.6. Single sided metasurface structure working as an (a)absorber and (b) rasorber.

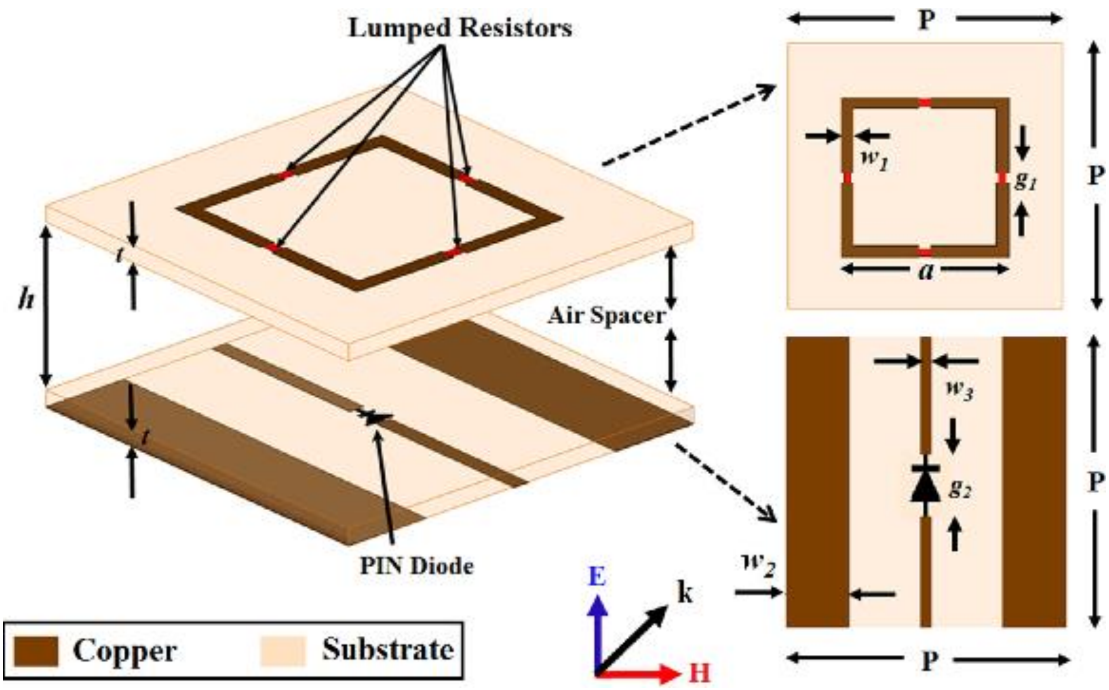


Fig. 1.7. Reconfigurable rasorbers based on PIN diodes (reproduced from [26]).

The top layer acts as a resistive sheet with an appropriate value of the lumped resistors. The bottom layer consists of PIN diode, which can switch its state of operation under suitable biasing voltage across it. The role of the bottom layer in switching the state of operation is explained with the help of an equivalent circuit model for both ON and OFF states of the PIN diode, as shown in Fig. 1.8. It is inferred from Fig. 1.8(a) that when the PIN diode is in the ON state, the circuit does not resonate due to the absence of any capacitance, thus acting as a complete reflector. On the contrary, in the OFF state, the diode offers a capacitance into the equivalent circuit, making it a parallel resonance circuit that offers a high impedance value which leads to transmission of energy from the structure.

The main issue with the design of rasorbers based on passive or active elements are.

1) Realization of elements such as resistance, inductance, diodes are not feasible at very high frequencies such as THz or infrared frequencies.

2) It makes the device direction sensitive and thus can limit the directional efficiency of the device.

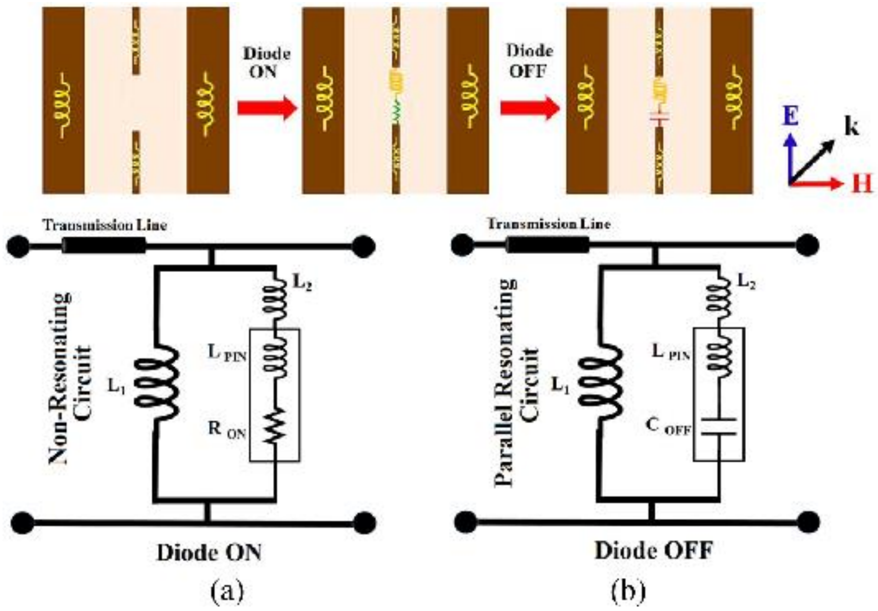
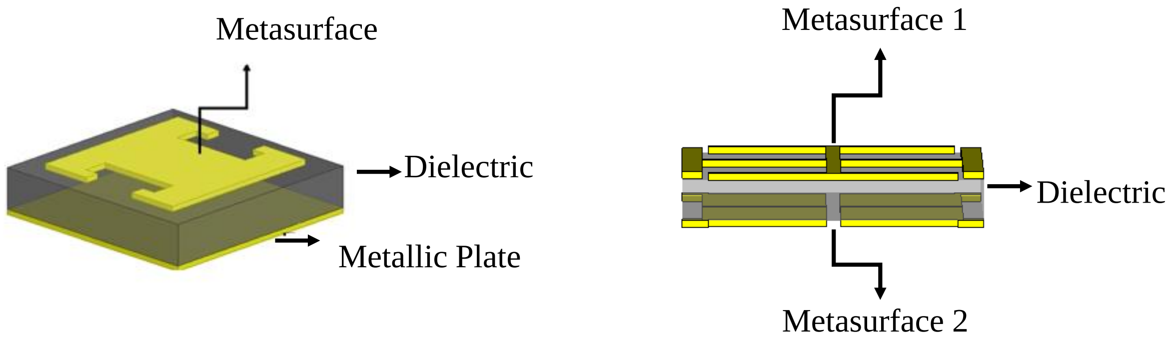


Fig. 1.8. Equivalent circuit representation of the bottom Frequency selective surface for various biasing states of PIN diodes. (a) Diode on. (b) Diode off (reproduced from [26]).

1.7. Dual-sided metasurface structures

A dual-sided metasurface structure can solve all the issues arising due to the active and passive elements in the design of rasorbers. For the design of absorbers, the most common configuration comprises a three-layered structure where the top layer is a metasurface layer consisting of metallic patterns, the middle layer is the dielectric, while the bottom layer is a continuous metallic plate. Such structures consisting of metasurface on only one of its layers and continuous metallic plate at the other are called single-sided metasurface structures. On the other hand, a dual sided metasurface structure consists of metasurface on both sides of the dielectric layer i.e., at the top and bottom metallic layers. Fig. 1.9(a) and Fig. 1.9(b) show the structural comparison between a single-sided metasurface structure and a dual-sided metasurface structure. From Fig. 1.9(b), it is well depicted that in the dual-sided metasurface structure, the bottom metallic plate of single-sided metasurface layer (Fig. 1.9(a)) has been replaced by a layer of metasurface at the bottom which makes them competent for multifunctional and/or bidirectional applications.



(a) (b)

Fig. 1.9. Structural design of a (a)Single-sided metasurface design and (b) bi-directional metasurface design.

1.8. Emerging trends in the metamaterial absorbers

In the year 2008, Landy et al. firstly proposed the design of metamaterial-based absorber operating in the microwave frequency region []. The unit cell consists of a dielectric layer sandwiched in between the electric ring resonator at the top and metallic plate at the bottom, as shown in Fig. 1.10. The absorption mechanism is based on the simultaneous excitation of electric and magnetic resonances at the frequency of operation.

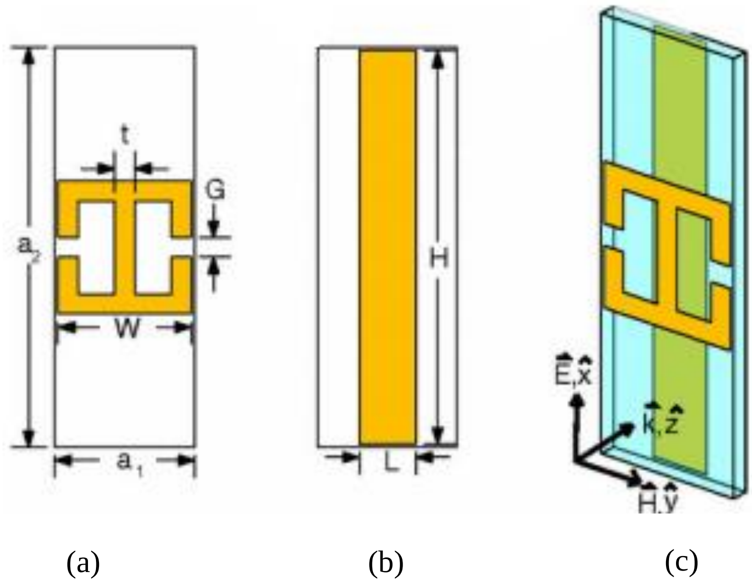


Fig. 1.10. (a) Top layer of the metamaterial structure consisting of an ERR (b) bottom layer consisting of a metallic patch and perspective view of the metamaterial structure (reproduced from [28]).

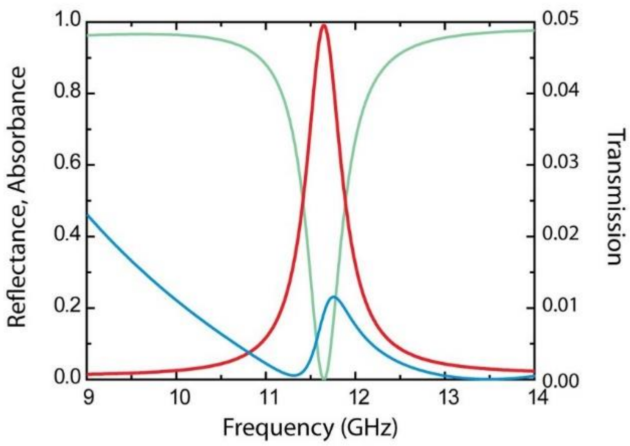


Fig. 1.11. Simulated absorbance for metamaterial perfect absorber design as shown in Fig. 1.10. R(ω) (green), A(ω) (Red) are plotted on the left axis and T(ω) (blue) is plotted on the right axis (reproduced from [28]).

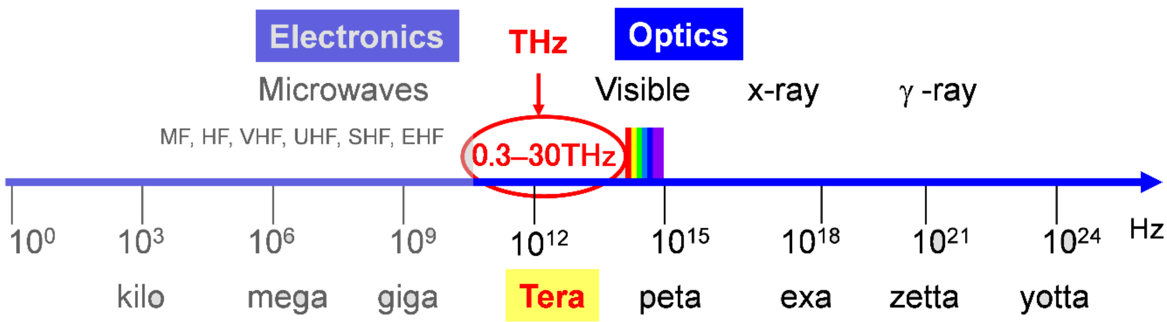
The simulated absorptivity response reaches to a maximum of 96% at frequency 11.5 GHz, as shown in Fig. 1.11. The design and fabrication of the structure was done on FR4 epoxy using printed circuit board (PCB) technology. Experimentally they found that the absorptivity equal to 88%. Further, the authors also investigated the loss mechanism in the structure and found that the loss is mainly due to the dielectric loss in the structure and that also beneath the resonating structure.

Metamaterial structure's deign can be scaled up or down to operate the device ranging from microwave to optical frequency region [29-30]. The other important aspect is to study the property of the material at that frequency. For an example, for metal characterization at THz frequencies, Drude model is required. Similarly, the selection of the dielectric is extremely important as the dielectric constant is dispersive in nature. Therefore, it is also required to have a good knowledge of the material characterization at different frequencies. One of the works has been done in [31], where the device which was operating in the microwave frequency region was scaled down to operate in the THz frequency region. The absorption mechanism is the same i.e., simultaneous excitation of electric and magnetic resonances. The simulated absorptivity response suggests that the structure operates at 1.12 THz with an absorption of 98% and the fabricated response offers an absorptivity of 70% at 1.3 THz. The discrepancy between the two results is said to be different since the dielectric deposited was of less thickness than the optimized one.

The first successful experimental demonstration of downscaling paves the way for the researchers to extend these ideas to higher frequencies such as THz, Infrared. The first metamaterial absorber operating in the infrared frequency region was proposed by [32]. The structure was a three layered, where the top layer was a cross structure consisting of gold, bottom layer was a metallic plat and in between that there was a dielectric layer of Al_2O_3. The structure achieved an absorptivity of more than 97% at 50 THz. The thickness of the metallic layer was more than the skin depth of gold at that frequency, so that there is no transmission from the structure.

Another work on metamaterial perfect absorption was carried out at infrared frequency in [33]. The structure consists of a circular shaped periodically arranged metallic pattern at the top and at the bottom. For the dielectric layer ZnSe was selected, whose properties at the desired frequency was taken from the experimental result of [34]. The work further studied the role of metallic thickness on the absorptivity response and found that with decrease in the thickness of the gold layer, the absorption decreases, owing to the fact that the arrangement of charge on the top gold structure does not reflects properly at the bottom metallic plate due to finite skin depth.

1.9. Terahertz technology and its applications



Terahertz (THz) radiation is also known as submillimetre radiation consisting of electromagnetic waves in the frequency region 0.3 THz to 3 THz (International Telecommunication Union). However, the upper level is arbitrary and can sometimes consider the frequency range till 30 THz. Development in science and technology based on terahertz radiation has gained momentum in last three decades. Till the last century, terahertz radiation was referred as sub-millimetre waves or far infrared waves and was mostly considered for astronomical applications. Since the development of laser-based terahertz generation in the early 1990s, the field of THz has rapidly grown from generation to real world applications.

THz radiation is essentially electromagnetic waves and therefore exhibits all the characteristics of electromagnetic waves such as interference, diffraction, polarization etc. However, THz radiation is often considered to have particle nature which helps one to understand the interaction of these waves with matter. Some of the areas where THz metamaterial devices can find potential applications are briefly discussed below.

Communications:

It is difficult to transmit THz waves through cables, but they can be transmitted easily through the free space. Diffraction is weaker than microwave waves due to which collimated beam having small diameters can be formed. However, THz communication is not possible for long distance communication because the water vapour present in the atmosphere can strongly absorb THz waves [35].

Imaging

In imaging applications, THz wave has a higher spatial resolution and therefore the image has more depth of field while maintaining the same spatial resolution [36]. Furthermore, THz radiation can penetrate many materials such as paper, plastics, textiles and foams. This can lead to imaging applications for industrial applications in the quality checks of materials. Another application can be in the inspection of space shuttles (after the terrible accident of space shuttle Columbia in 2003) and security inspection of airports.

Biomedicals

THz radiations exhibit extremely low photon energy due to which they emit very low power leading to insignificant heating. Terahertz radiation is non-ionizing, and thus is not expected to damage tissues and DNA, unlike X-rays [37]. Some frequencies of terahertz radiation can penetrate several millimetres of tissue with low water content (e.g., fatty tissue) and reflect back.

Apart from these advantages there are several other applications where THz plays a prominent role are in thermal detection, astronomy, THz material characterization, Non-destructive testing, security and defence etc.

1.10. Motivation

Development in science and technology based on terahertz radiation has gained momentum in last three decades. Till the last century, terahertz radiation was referred as sub-millimetre waves or far infrared waves was mostly considered for astronomical applications. Since the development of laser-based terahertz generation in the early 1990s, the field of THz has rapidly grown from generation to real world applications. There are several real world application areas where THz stand out to be more promising and attractive as compared to microwave frequencies. In the field of imaging THz enables to achieve good spatial resolution required for quality imaging. THz frequency can penetrate clothing, polyethylene, polyester and other types of covers and enclosures made up of various opaque materials. As compared with the microwave, THz radiation has a higher frequency and bandwidth. It has great potential applications in the short-distance high-capacity wireless communications. In imaging applications, THz wave has a higher spatial resolution and therefore the image has more depth of field while maintaining the same spatial resolution. Terahertz radiation is non-ionizing in nature, and thus is not expected to damage tissues and DNA, unlike X-rays. Some frequencies of terahertz radiation can penetrate several millimetres of tissue with low water content (e.g. fatty tissue) and reflect back. Terahertz radiation can also detect differences in water content and density of tissue. Such methods could allow effective detection of epithelial cancer with a safer and less invasive or painful system using imaging.

Considering the promising applications of THz radiations and understanding the paucity of naturally occurring material with useful property at THz frequency, metamaterial becomes one of the best candidates for the design of THz devices. The growing field of terahertz applications includes absorbers, polarization converters, antennas etc.

Metamaterial based perfect absorber can be used for the design of micro-bolometer arrays which has the potential to significantly improve the thermal imaging, chemical and biological sensing capabilities of the device.

In order to establish the mechanism of absorption in a metamaterial absorber, the theory which evolves initially was based on single-layer model where the whole metamaterial structure was modelled as a medium of effective permittivity and permeability. The structure behaves as an absorber only when light is incident from the front side. If the structure is illuminated from the backside there will be a total reflection. Henceforth a fundamental question always remain unanswered, if the structure behaves like a single atom having effective $\varepsilon_{eff}(\omega)$ and $\mu_{eff}(\omega)$, then why there is absorption if the wave is incident from the front side whereas if the structure is illuminated from backside, there is a complete reflection. This asymmetric nature of metamaterial perfect absorber (MMPA) cannot be described by considering the MMPA as a single atom/molecule having effective permittivity and permeability. Also, it was found that with each increment of $n\lambda_g/2$ in the cavity thickness (dielectric layer thickness), the absorption characteristics repeat itself. Ambiguity was found in the direction of surface currents, for some integer values of cavity thickness there was absorption with antiparallel surface currents on the top and bottom metallic layers, whereas for some other integer value, there was absorption even though the surface currents were parallel to each other. This again contradicts the single effective medium theory for which occurrence of anti-parallel surface for perfect absorption is compulsory.

The thesis answers all these discrepancies by explaining metamaterial absorption based on metacavity model which deals with multiple reflection interference model. Instead of treating metamaterial structure as a single model, it has been treated as a three-layer model. The reason for absorption at higher-order cavity thickness along with the reason for parallel and antiparallel surface currents has been well explained through this model. In extension, thesis presents a complete mathematical model of absorption via multiple interferences of waves between the top and metallic bottom plates of the metasurface absorber. The electromagnetic field component of the incident and reflected waves have been used to derive the expression for the total electric and magnetic fields existing inside the dielectric cavity of the metasurface absorber which mathematically explains the formation of standing wave resonance, surface current orientation, and absorption from the expression of the electric and magnetic fields.

For the design of absorbers, the most common configuration comprises of a three-layered structure, where the dielectric layer is sandwiched between the top metasurface layer (consisting of periodically arranged sub-wavelength metallic pattern) and bottom metallic plate. Any such structure consisting of metallic pattern (metasurface) on one of its layers and metallic plate on the other is also termed as single-sided metasurface structure [10-12]. The top metasurface layer determines the frequency of resonance, whereas the bottom metallic plate suppresses any transmission from the structure. However, on the cost of two major limitations,

1) The presence of metallic plate at the bottom makes the device unifuncitonal (Fig. 1(a)). For example: if there is a need to design a device that can absorb one frequency band and transmit other frequency bands, then it is not possible from single-sided metasurface design.

2) The metallic plate at the bottom makes the device direction sensitive (unidirectional) also. For example: the absorber shown in Fig. 1(b) can absorb the wave incidenting from the top but completely reflects the wave when incident from the bottom.

Multifunctionality has been a long-lasting pursuit for the electronic system, specifically if the functions are mutually exclusive from one another. Additionally, apart from offering multifunctionality, if the device is bidirectional too, then it makes the whole system directionally efficient also. Such multifunctional devices are often referred as rasorbers which offers absorption as well as transmission in two separate bands of frequencies [15-16]. Acknowledging the limitation of single-sided metasurface design, a complete mathematical and structural study of dual-sided metasurface structures can open up a broad avenue for the research and development of metasurface based multifunctional or bidirectional optoelectronic devices.

In this regard, the thesis presents an elaborative study on the structural and mathematical analyses of a dual-sided metasurface structure. The work elucidates that the ratio between the resonating wavelength and the structure's thickness plays a deterministic role in switching the mode of application from absorption to transmission or vice versa. Further, the thesis demonstrates the equivalent circuit model (ECM) to study the role of impedance in granting multifunctionality and bidirectionality to such structures.

1.11. Organization of the thesis

The whole thesis has been divided into six chapters with **Chapter 1** belongs to introduction where the basic of metamaterial and its application has been discussed. The overview of metamaterial based absorption along with its different absorption mechanism has been discussed. A literature survey on the emerging trends on metamaterial absorber and rasorber has been provided. The motivation and organization of the thesis have also been mentioned here.

Chapter 2 discusses metamaterial absorber based on three-layer effective model which is based on multiple reflection model. The work demonstrates that the single-layer model of absorption based on antiparallel surface currents has some discrepancies. The first discrepancies is that with each increment of $n\lambda_g/2$ in the cavity thickness (dielectric layer thickness), the absorption characteristics repeat itself despite the fact that the surface currents are parallel. Also a single-layer model based on effective permittivity and permeability cannot answer that why the absorption is from single side only if the whole structure is modelled as a single layer having effective medium parameters. In this chapter we have explained metamaterial absorber based on three-layer model which is based on multiple reflections of waves inside the middle dielectric layer. The occurrence of multiple reflections inside the structure is validated numerically as well as analytically using time-domain analysis using inverse chirp-Z transform technique The theory can well explain the reason for absorption at higher-order cavity thickness and can light up the reason for parallel and antiparallel surface currents has been well explained through this model.

Chapter 3 is an extension of the work done in Chapter 2. It demonstrates the mathematical modelling of the multiple reflection phenomenon occurring inside the dielectric cavity in the form of electric and magnetic fields. The electromagnetic field component of the incident and reflected waves have been used to derive the expression for the total electric and magnetic fields existing inside the dielectric cavity of the metasurface absorber. As a result, it is possible mathematically to elucidates the formation of standing wave resonance, surface current orientation, and absorption in the light of the electric and magnetic fields. The effect of change in the polarization angle of the incident electromagnetic wave on the standing wave pattern and surface current orientation can also be explained through the mathematical model.

Chapter 4 deals with the study of dual-sided metasurface structure which can be a strong candidate for the design of multifunctional devices. In view of this, the paper presents an elaborative study on the structural and mathematical analyses of the frequency response of a dual-sided metasurface structure. It has been found that the ratio between resonating wavelength and the structure’s thickness plays a deterministic role in achieving multi-functionality in such designs. In order to understand the role of bidirectionality in such structures an Equivalent circuit model of a dual-sided metasurface structure has been provided which says that such structures can be made directional insensitive by properly designing the metallic pattern of both the metallic layers. To validate the theory, a bidirectional rasorber has been designed in this work.

Chapter 5 discusses the broadband quasi non-dispersive cross polarization converter (CPC) structure using metasurface for far infrared region. The structure is transmissive in nature, which converts a linearly polarized incident wave to its mutually orthogonal linearly polarized wave over a broad range of frequency maintaining a high polarization conversion ratio (PCR). The fractional bandwidth of 75.6% corresponding to the centre frequency of PCR bandwidth having more than 0.9 PCR value has been realized. The structure is also studied for oblique incidences where it shows wide band polarization conversion up to 45^o for both TE and TM polarized oblique incident waves. The electric field distributions at the top and bottom surfaces of the structure close to the centre frequency of polarization conversion bandwidth indicate the orthogonal rotation of incident linearly polarized wave at the frequency of interest. For the given set of media interface a separate study on polarization conversion through the Brewster angle concept has been carried out simultaneously. The structure exhibits high PCR by maintaining the compactness in thickness (~λ/5) as well as periodicity (~λ/3) compared to the existing polarization converters.

Chapter 6 deals about the conclusion and future scope of the thesis.

CONTENTS

Chapter 2: Frequency and time-domain analyses of multiple reflection and interference phenomena in a metamaterial absorber