Introduction of Perfect metamaterial absorber

1 Introduction of absorbing layers

An absorber is a kind of device in which all incident radiation is absorbed. That is to say, all wave actions such as reflection, transmission, scattering, and other light propagation are impossible. The most typical EM wave absorber is so called Salisbury screen\cite{1} which is developed by the well known scientist W. W. Salisbury as a basic example of the resonant absorber. Such a device consists of two layers, a resistive sheet to absorb EM wave and a metal plate to reflect the wave\cite{1}.

As reference \cite{2} summarized, another similar absorber device is Jaumann absorber in which has more than one resistive sheet are placed $\lambda_d/4$ in front of the mental ground plate in order to achieve a broadband response.\cite{3} Circuit Analog absorber also have more than one resistive sheet to achieve absorption at high incidence angle\cite{4,5} and over broad bands\cite{6}.

Another two type of resonant EM wave absorber are Dallenbach layer employs consists of a homogeneous layer in front of mental plate\cite{2}; Crossed Grating absorber uses a reflective metal plate with an etched shallow periodic grid\cite{7,8}.

2. Introduction of Metamaterial Perfect Absorbers (MPA)

Metamaterials are artificial structural materials composed of metals and dielectrics arranged in a periodic way. Owing to its tailored property, e.g., permittivity and permeability, metamaterials have been found many applications such as invisibility cloak \cite{9-12}, sub-wavelength imaging \cite{13, 14}, perfect lens \cite{15,16} and perfect absorber\cite{17-39}.

The most famous metamaterial perfect absorber unit cell is so called three layered structure, which consists of two metallic layers, one ground plane and a varied shaped electric ring resonator (ERR) separated by a dielectric layer. The ERR on the top of the dielectric layer couples strongly to uniform electric field of the incidence wave, but weakly to magnetic field, providing frequency dependent electric response $\varepsilon(\omega)$. The magnetic field of incident waves will penetrate the space between the ERR and back metallic ground plane, leading to a frequency dependent magnetic response $\mu(\omega)$. One can tuned the effective $\varepsilon(\omega)$ and $\mu(\omega)$ through adjusting the dimension of the ERR, back ground plane and the space gap between them. Thus realize the perfect impedance matching between the absorber and free space and minimize the reflection near to zero. Simultaneously, by varying the imaginary part of the material permittivity to achieve large loss and minimize the transmission near to zero. The resulting absorption $A$, is calculated $A(\omega)=1-R(\omega)-T(\omega)$, where $R(\omega)$ is the refrection and $T(\omega)$ is the transmission, approximately equal to zero.

Generally, when electromagnetic wave incident the boundary between metal and
dielectric layer and satisfy the surface electromagnetic wave (SEWs) propagation conditions which write as \( k_1 = k_0 \), where \( k_1 \) is the real part of the wave vector parallel to the surface some SEWs propagate along the surface. In optics the surface wave are termed surface plasmon wave because there exists an interaction between the free electron in the metal layer and the electromagnetic waves. These surface waves propagate but they are damped too and we have to determine how they propagate and how they are damped. The last term play the most important role when we dealing with absorbers.

The way that SEWs propagates can be determined from the so-called dispersion characteristic, the key parameter being the velocity of the waves propagating along the surface \( k_1 = k_0 + i k_2 \) and the propagate length is described as \( L_p = 1/2 k_2 \) \([40]\) which characterise the penetration intensity of the SEWs or plasmon decays by \( 1/e \). If \( k_2 \) is carefully selected, the SEWs be in form of loss, and \( L_p \) is perfectly matched \( k_1 = k_0 \), so as to reduce the reflection and transmission and reach to nearly unit absorption.

To analyze the absorption feature, one most important concept is the operation bandwidth characterized by the full wave at half maximum (FWHM), which defined as \( \text{FWHM} = \frac{\Delta f}{f_0} \times 100\% \), where \( f_0 \) is the centre frequency of the incident wave of the absorption spectrum, \( \Delta f = f_2 - f_1 \), is the frequency gap when the absorption reduce to half of the maximum value.

3 State of the art in terms of absorbance and fractional bandwidth, thickness.

Since the first metamaterial (MM) perfect absorber is demonstrated by N. I. Landy et al \([17]\), numerically and experimentally, which consists of three layers, operated at microwave, science, including the design, analysis and experiment of MM absorber, grow rapidly at microwave \([17-26]\), THz \([29,30]\), infrared \([27,28,29,31-35,38]\) and visible \([36,37,39]\) wavelength with varied structure.

In case for the absorber operated in the microwave region, the general method is to build split ring resonators (electric field coupled (ELC)) connected to a split-wire (the magnetic coupling required a more complicated arrangement, and thus in order to couple to the incident \( \mathbf{H} \)-field, we needed flux created by circulating charges perpendicular to the propagation vector.). In a word, the absorber cell mainly contents two elements, of which one responds to the electric-field the other responds to the magnetic field.

Then multiple of such units are arranged orderly onto a substrate. For modifying and optimizing the absorption properties, such as the absorption ratio and the location of the absorption peak, the respond to polarized wave and incident wave with arbitrary angular, firstly one have to carefully choose material for fabricating the
absorber unit, and then the shape (ring or quadrate) with proper structure parameters such as length, height and the gap between these two elements, and the last work is how to compile this elements.

Fig. 3.1 shows the absorber unit cell with a ring shape and a quadrate shape. Experimentally can achieve an absorption of 88% which have a little error compared to the simulation results, and the authors explained that due to fabrication errors.

Ref. [20] demonstrated a perfect absorber using non-magnetic metamaterials, which functions as a “black body” and be able to effectively absorb incident waves from all directions. The unit cell used here consists of an I-shaped unit and an ELC resonator illustrated in Fig.3.2. Based on this unit cells, the mainly difference from the other metamaterial absorber is that this absorber is formed by orderly compiling these I-shaped unit and ELC resonators into a ring disc, thus all the incoming wave with all direction and be effectively trapped and consequently spirally travels inside the disc as shown in Fig.3.2.

Fig. 3.1 Electric resonator, magnetic resonator, unit cell and results of a metamaterial perfect absorber.\(^{(17)}\)

Fig. 3.2 Unit cell and the electric field distribution at resonance frequency 18GHz\(^{(20)}\)
Aside from the mainstream idea of arraying those absorber units into a two dimension plate, Ref.[18] demonstrated an 3-dimension absorber based on a cubic with three absorber units on each surface, of which the unit cell is formed by combining an electric resonators with a magnetic resonator, but not the split-wire mentioned above. The unit cell and result are show in Fig.3.3.

![Fig. 3.3 unit cell of 3-dimension and the absorption spectrum](image)

Comparing with the absorbers operating in microwave band, the typical unit cells used for constructing the infrared absorbers are with a cross shaped geometries [29, 30] and the detail structures are show as Fig. 3.4. As a development from this type of cells, Ref[31] Fig. 3.4 shows a H shaped nanoresonator, based on which a narrow band, polarization-independent absorptivity of >90% over a wide ±50 angular range centered at mid-infrared wavelengths of 3.3 and 3.9 μm was achieved.

![Fig. 3.4 simulation structure of cross unit cell and low-magnification field emission scanning electron microscope image and the experimental and simulation absorption results](image)

The other method for realizing IR absorb is by generating surface plasma using a so called Plasmonic metamaterials (MMs). Generally, a narrow band absorber(NBA) is fabricated by sandwiching an array of plasmonic strips[28]/patches[27] by a thin dielectric spacer from a ground plate, show in Fig.3.5 and the absorb ratio at the peak can be up to nearly 100%. For expanding the absorb band, one can combining several
NBAs with their absorption peaks being close to each other\textsuperscript{28}. Apart from the approach based on plasmonic material used above, Kamil Boratay Alici and etc. demonstrated a polarization independent absorber utilizing both electrical and magnetic impedance matching at the near-infrared regime, the half absorption width of which is as large as 893nm, and when the incidence angles is up to 60° respecting to the surface of the plane, the absorption still remains more than 70%.

Fig. 3.5 Geometry of the sample and measured and simulated absorbance spectra \textsuperscript{27,28}

As another wave band, visible wavelength has attracted much attention in recent years. Similar to the mechanism exploited in infrared absorbers, the Plasmonic material is also widely used for realizing visible light absorb. Developing from grating configuration, Koray Aydin and etc. proposed a visible light absorber consisting of a metal–insulator–metal stack with a nanostructured top silver film composed of crossed trapezoidal arrays, whose absorption ranges from 400nm~700nm, covering the entire visible spectrum. On the other hand, Peng Zhu and L. Jay Guo also realized an absorber with the same absorption range and an average absorption of more than 80\% by designing the dispersion and geometry of a Cu/Si3N4/Cu stack\textsuperscript{36}. Show as Fig. 3.6(left).

Additionally, a perfect black absorber operating in visible regime was also demonstrated by using the Plasmonic material, but different from the stripe and cross structure used in the above approaches, the nanocomposite-SiO$_2$-Gold film-Glass substrate multi-layers structure designed in this work is relatively simple and cost effectively.\textsuperscript{39} Show as Fig.3.6(right).

In conclusion, the absorbers operating at microwave regime mainly constructed by orderly arraying a great deal of unit cells that generally formed by electric resonators with cut wire or magnetic field resonators and, each of the unit cell with certain structure parameters could provide an absorption peak. Different from the
mechanism utilized in the microwave absorbers, plasmonic materials are intensively used for realizing a broadband absorption in infrared and visible regime. Additionally, the absorption properties (bandwidth, absorptivity, location of the absorption peak or band) greatly depend on the fixed material of the metamaterial and the structure of the unit cells. Considering that the effective permittivity $\varepsilon(x)$ and permeability $\mu(x)$ of the metamaterial can be independently changed by modifying the geometry of its unit cell, it is possible to realize an efficient absorption in different frequency bands with perfect absorption ability by designing unit cells with an optimized structure using a material with perfect electro-magnetic properties respecting to a target operating wave band$^{[25]}$.

![Fig. 3.6 Geometry of the sample and measured and simulated absorbance spectra $^{[36,39]}$](image)

Generally, a single SRR type absorber exhibits one corresponding absorption peak. So it’s reasonably to suppose that multi-absorption peaks can be achieved by combining multi-SRR units with different resonance peaks together.

Based on the former mechanism mentioned above, a three absorption bands absorber were realized by adjacently placed multiple unit cells, which comprises an electric ring resonator and a pair of crossed wires imprinted on the opposite faces of a dielectric substrate, with different resonant resonances together. As shown in Figure 3.7, three types of resonances were placed together as a unit and the corresponding resonances are shown in Figure.3.7(left).$^{[23]}$
Beside the proposal for achieving multi-peaks absorption, Jingping Zhou and etc.\cite{26} have proposed a metamaterial absorber based on a cross-circular-loop resonator, of which the absorption effect can be easily altered from single-band to dual-band by adjusting the positions of the shorted stubs inside the loop. Show as Fig. 3.7(right).

When it comes to the absorption bandwidth of the absorber, one can also extend it by overlapping multi-SRRs with multiple absorption peaks, but the frequency peak differences among each SSR should not be big. Ref. \cite{24} shows an absorber constructed by overlapping multiple ELC and SRR layers show as Fig. 3.8(above). A maximum absorption of 99.9% at 2.4 GHz with a relative broad half maximum bandwidth (700MHz) was achieved, which was contributed by the different resonances provided by multiple elements. Additionally, the resistors embedded in the metamaterial structure effectively lower the Q factor.

Fig. 3.8 broad band absorption structure and results\cite{24,29}

Based on the interference theory that is also used in Ref. \cite{29}, a metamaterial absorber with a multilayered SRRs structure was numerically demonstrated to be with an ultra broad band absorption of 60Hz, ranging from 0Hz to 70Hz with a bandwidth
of absorptance >90%, which is originated from the destructive interference of the reflection wave based on the anti-reflection formed by the SRR and substrate together, but not the intrinsic electromagnetic resonance loss. Show as Fig. 3.8( below) In contrast to the perfect absorber realized by exploiting the coherent effect of among SRRs, herein the resonance was mainly used for providing an optimal refractive index for forming the destructive interference, rather than for realizing an effective absorber by itself with its insufficient loss[21].

Similar to the method of combining multi-absorber units with single absorption peak for realizing multiband absorption, a microwave[25] and infrared[32] rization-independent absorption with an width band and an absorption of nearly 7GHz and more than 90%, respectively, was realized by an pyramids structure formed by periodically overlapping 20 metal-dielectric quadrangular frustum layers. Show as Fig. 3.9, in the left is operated at microwave, in the right one is operated at infrared wave.

![Fig. 3.9 pyramid structure for broad band absorber and results](image)

4 Optimization of PMA

Although lots of works about PMA explored the very affirmative results of high absorbance with broad band spectrum, it is a perpetual issue to optimize the PMA. For one thing to reach to unit absorption under the condition of perfect impedance matched determined by the thickness and loss tan of the absorber. One the other hand, in order to achieve broad band absorbance through designing multiresonance in planar and stack structure[23-26,29,30,32] or useing broadband periodic structure like grating[27,28,36].

Additionally, operation flexible is another significant element, including polarization independence, broad incidence angle, and selected waveband. There are three kinds of method to realize polarization independence by appealing to repeat of unit cells[20,41,42]; by utilizing an asymmetric unit cell[26], by using chiral metamaterials[43].

5 Conclusion and prospects

As conclusion, we have experimentally design a perfect electromagnetic absorber using BST cube with high permittivity. The experiment results show great agreement with the simulation we have done before, and the absorptive very close to 100% with FWHM around 4% at Mie resonance frequency. It is notably that the
absorption characters are significantly influenced by the lattice period, space gap and loss tangent. In other word, we can optimize the BST absorber through adjusting the geometry and BST local properties.

6 References

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