Dynamic Tunable Plasma-Induced Transparency of Periodic Images Of Graphene Nanoribbons

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Abstract. Metamaterials are synthetic special structural units, usually in the wavelength or subwavelength range. When the incident light is coupled with the structural element, the free electrons on the surface can generate surface plasmons under the periodic drive of electromagnetic wave. In this paper, we mainly study the transparency of dynamically adjustable plasma-induced periodic graphical graphene nanoribbons. This paper discusses the geometric parameters that affect the variation of PIT. The gap distance $G$ and the disc moving distance $S$ can change the coupling strength of the light and dark modes, and the variation of coupling strength can adjust the transparency and frequency band width of PIT window. The Fermi energy of graphene can be changed by adjusting the electrical conductivity of graphene, and the change of Fermi energy can also regulate the PIT effect.

1. Introduction

Since the beginning of the 21st century, with the breakthrough development of optoelectronic information technology, traditional optoelectronic devices and optical devices have played an increasingly important role in people's lives in order to meet the growing needs of people. However, there is a significant problem that the production cost of traditional optoelectronic devices is high. Size remains the same with and can flexibly control gradually can't satisfy people's needs, in this situation, the electromagnetic metamaterials due to its special magnetic properties, can change the size, periodic unit geometry structure or filling materials, and many other ways to achieve a perfect advantages of flexible control of electromagnetic waves, Electromagnetic metamaterials have attracted extensive attention and more thorough research [1]. A typical example is people's research on the metamaterial. As a two-dimensional planar metamaterial, the most important advantage is that the electromagnetic wave wavelength of metamaterial response is smaller than its thickness. This reflects the special advantage of the thin thickness of metamaterials. Secondly, the metamaterials extended by the metamaterials have excellent electromagnetic properties, using its special advantages can achieve the performance of traditional optoelectronic devices even better than the traditional devices. Third, metasurface is also very flexible in adjusting phase, polarization mode and amplitude while achieving the effect of traditional optoelectronic devices. For this reason, more and more researchers have designed many functional devices using metasurface, which also promotes the breakthrough progress in the field of micro/nano optical devices [2-3].

In the early stages of Plasmon Induced Transparency (PIT) development, where designs are usually composed of metal elements, inherent ohmic losses are unavoidable [4]. Therefore, the tunability of the PIT transparent window can only be achieved by changing the geometric parameters. This suggests that once the structure has been manufactured, it is difficult to adjust its transmittance without
remanufacturing. It hinders the development of quality factor (FOM) and slow light effect [5]. In order to overcome these limitations and reduce radiation losses, graphene has attracted a lot of attention due to its unique electromagnetic properties. It can enhance surface plasma, reduce transmission loss and improve carrier mobility. More importantly, the conductivity can be dynamically adjustable by adjusting the gate voltage, and then the non-contact regulation of the transmission spectrum can be realized [6]. So far, different types of graphene structures have been studied, such as waveguide resonators, cut-line resonators, split-ring resonators, etc. [7].

In this paper, the classification, application and electromagnetic properties of metamaterials are taken as the starting point to introduce graphene in detail, and the physical mechanism behind the realization of plasmon induced transparency based on metamaterials and its development status are analyzed in depth.

1.1. Based on Graphene Plasma Induced Transparency

1.1.1. Optical Properties of Graphene. After the discovery of the world, because of its two-dimensional material unique mechanical, thermal, electrical, optical and other properties and highly respected by all walks of life. The third-order nonlinear polarizability of graphene is 10-7 esu, the light damage threshold is several orders of magnitude higher than silicon, and the thermal conductivity is 36 times higher than silicon dioxide. These valuable characteristics together make graphene excel in optical applications [8-9]. At present, the common preparation method is to use chemical vapor deposition to grow graphene on the surface of silicon substrate, but to achieve industrial mass production needs to be improved.

Graphene has a transmittance of about 97.7% over a wide spectral range, so it can be said that it has almost no absorption of incident light. Another important nonlinear feature of graphene is that the third-order nonlinear polarizability can be as high as 10-7 esu. Graphene is an excellent candidate material in some fields where high third-order nonlinear polarizability is used to perform triple frequency wavelength conversion [10].

Graphene can support two types of SPP waves. When the real part of the dielectric constant of graphene is greater than 0, it is a normal dielectric material, and it only supports transverse electromagnetic surface waves, that is, TE mode. When the real part of the dielectric constant is negative, graphene behaves as metallic (the dielectric constant of the metal is less than 0), and the SPP in this case is only in TM mode [11-12]. The SPP wave dispersion equation of TM mode can be expressed as:

\[ k_{sp} \approx \frac{\hbar^2}{4\varepsilon_0 E_F} (\epsilon + 1) \omega (\omega + \frac{i}{\tau_s}) \]  

Apart from qualitative differences in electron dispersions (linear Dirac cones versus the usual parabolas), the field characteristics of the ion in graphene look very similar to surface plasmas in metals. The binding degree of SPP surface waves in graphene can be written as:

\[ \frac{\lambda_{sp}}{\lambda_0} \approx \frac{4\alpha E_F}{\epsilon + 1} \frac{\omega}{\omega_h} \]  

Generally we use graphene, is the gold properties, use it for graphene than precious metals, has more advantages in stimulating SPP wave, from SPP in terms of the wave characteristics, graphene inspire SPP have longer propagation length and larger mode spot diameter, and the wave number of SPP broad in free space excited wave number SPP, wavelength is small, this binds the SPP better than precious metals. But the most important advantage is that graphene's conductivity changes with its chemical potential, making it easier to modulate.

In recent years, graphene-based tunable Pit and Pia effects have attracted a great deal of attention because the Fermi level and conductivity of graphene can be dynamically adjusted by manipulating chemical doping, static gate voltage and magnetic field, for example, it has been shown that the tunable Pit effect can be realized in graphene planar metamaterials, graphene waveguide coupled
cavities, single-layer graphene band gratings (GRG), double GRG and multilayer graphene metamaterials layered by dielectric space. Although the required PIA effects can be obtained in the plasma structures described above, the relatively complex device design poses a significant challenge in the manufacturing process. It is worth noting that in the plasma structure consisting of a single graphene layer and a silicon-based diffraction grating, the excitation of surface plasmon plasmons (SPPs) with low propagation loss and high binding was observed on the surface of the graphene layer. Therefore, it would be an effective method to excite the SPP on the graphene layer by using the metal diffraction grating in the dielectric waveguide coupled metal grating structure, which provides a new method for realizing the PIT effect. Obviously, tunable PIA effects and low complexity dielectric waveguide layer structures are expected to be obtained in graphene metal gratings.

1.1.2. PIT Effects Based on Graphene In order to control photons as if they were electrons, a basic approach is to limit the transmission of light by using a structural size smaller than the wavelength of the incident photon, thus confining the light to a certain region. The specific method is to use a probe tip with a size smaller than the wavelength to illuminate the surface of the plasma structure in the near field range. Due to the small size of the probe tip, the light irradiated from the probe tip will contain the component of the electromagnetic wave vector larger than the surface plasma vector, so that the matching of the wave vector can be realized and the surface plasma can be generated.

Graphene-based metamaterials can be designed autonomically, manually, through subwavelength surfaces and periodic and quasi-periodic subwavelength model arrays, so that the unit size of their properties can be much smaller than the radiation wavelength. In addition, due to the small energy loss and large dispersion of graphene materials, a careful balance is needed when designing graphene surface plasma models.

In this paper, we propose a parallel coplanar metamaterial structure of three graphene strips, and obtain the Pit spectra in the near terahertz band by means of bright mode-bright mode coupling. In the metamaterial structure, both the long and short strips can be excited independently by incident light, and transparent Windows can be observed when the two lengths of strips are placed in parallel. The resonant frequency of the spectrum can be adjusted by optimizing the metamaterial structure and changing the Fermi energy level of graphene.

The simulation is performed by the CST’s time domain solver, where the computational domain is truncated by the perfect matching layer in the Z direction, and periodic boundary conditions are used to truncate the unit structure in the XY plane. In the simulation process, the adaptive meshing technique is used to deal with the boundary and geometric shape of the structure, and good convergence of the results can be obtained. Port boundary must be set before simulation test with simulation software.

The port boundary condition provides the S parameter for post-processing. The reflectivity and transmittance of the metamaterial structure can be obtained easily and quickly by using the S parameter. The transmission coefficient is an important index representing the transmission property of light in metamaterials. Since the absorption rate A of metamaterials is determined by the transmission coefficient and reflection coefficient, the formula is as follows:

\[
A = 1 - |S_{11}|^2 - |S_{21}|^2
\]

(3)

S11 said port 11 of the reflection coefficient of incident light, |S11|^2 for reflectance;
S21 of port 1 and port 2 said the incident light transmission rate, |S21|^2 for transmittance.

Then the transmittance is:

\[
|S_{21}|^2 = 1 - A - |S_{11}|^2
\]

(4)

CST Microwave Studio, a finite-difference time-domain method simulator based on time-domain boundary conditions in the X and Y directions, was used to study the S21 parameters to study the PIT effect.
The graphene unit structure proposed in this paper consists of a disk and two side bars. The thickness of the substrate is 300nm and the relative dielectric constant is 1.5. The radius of the graphene disc R is 500nm, the length L and width W of the graphene side strips are 1um and 200nm respectively, and the thickness of the graphene is D=0.35. In addition, the distance between the disc and the sidebars and the downward movement distance of the disc are g and s, respectively. The dimensions of the substrate structure in the x and y directions are fixed at 2um and 1.8um, respectively. Planar waves incident vertically along the Z direction and are polarized along the x axis.

2. Simulation Experiment

2.1. Finite Difference Time Domain Method

Finite difference time domain method (FDTD) is a method to derive the electromagnetic field distribution by calculating the time domain. It can solve the electromagnetic wave of TM mode and the electromagnetic wave of TE mode. Finite difference time domain method is a process to obtain the electromagnetic wave distribution by calculating the time domain. Finite difference time domain method has been widely used in almost all fields of electromagnetic field calculation, some electromagnetic field simulation software is based on this method to evaluate the electromagnetic wave calculation.

2.2. CST of Simulation Software

CST is a 3D electromagnetic field simulation software suite based on the finite-difference time-domain method, which covers the entire electromagnetic frequency band, and can provide complete high frequency algorithm for the whole electromagnetic wave in the time domain and frequency domain. In this paper, all the related calculation and simulation of graphene surface plasma are simulated by CST Microwave Studio software. Before the design, the design module must be selected first, such as the selection of periodic structure module. Then enter the main interface to build the model for simulation calculation.

Frequency domain problems can be used to calculate electromagnetic fields in both single and multiple frequencies. It is a professional tool for 3D electromagnetic wave simulation of high frequency components. Its unparalleled performance makes it the first choice for leading R&D departments. CST Microwave Studio can quickly and accurately analyze high frequency devices, providing quick insight into the electromagnetic behavior of high frequency designs. With the variety of solver technologies available, users have the flexibility to respond to a wide range of applications. In addition to the widely available time domain solver and frequency domain solver, CST Microwave Studio offers more solver modules for specific applications. The extraction of filters and parameters used to import specific files enhances design possibilities and saves time.

3. Simulation Results and Discussion

3.1. Permeability Spectra of Different Gap Distances in Cell Model

| g (nm) | 12  | 13  | 14  | 15  | 16  | 17  |
|--------|-----|-----|-----|-----|-----|-----|
| 100nm  | 1   | 0.92| 0.53| 0.82| 0.78| 1   |
| 150nm  | 1   | 0.96| 0.71| 0.92| 0.78| 1   |
| 200nm  | 1   | 0.98| 0.85| 0.97| 0.99| 1   |
As shown in Table 1 and Figure 1, obviously observed that with the increase of the gap distance $g$, transparent window in the transmission intensity and width is less, and transparent window occurred red shift move to the wavelength change direction (PIT), it is proved that the clearance distance $g$ can affect the coupling strength, and with the increase of $g$, bright patterns and dark mode coupling between intensity gradually weakened.

When the Fermi energy is constant, with the decrease of the gap distance $g$, the coupling strength of the bright and dark modes gradually increases, the frequency band width of PIT gradually expands, and the transmittance of the PIT transmission peak gradually increases. The transparency and band width of the PIT window can be adjusted by adjusting the size of the gap distance $G$.

3.2. Effects of Graphene Thickness Change on PIT Projection

As shown in Figure 2, with the increasing thickness of graphene, the transmission intensity and width of the transparent window almost remain unchanged, while the PIT window shifts, indicating that the
increase of graphene thickness does not affect the coupling strength, but only the resonant frequency of the light and dark modes. Adjusting the chemical potential energy of graphene may cause the change of the bonding strength.

4. Conclusion
The excellent electromagnetic properties of graphene, which are different from those of common materials, open up a new path for the research of metamaterial devices with metamaterial functions and provide new ideas for the design of multifunctional metamaterial devices. In this paper, the dynamic tunable properties of graphene plasma-induced transparent structure metamaterials were studied based on graphene plasma-induced transparent structure. In this paper, a plasma structure with light and dark mode is constructed, which is composed of disk (dipole resonance) and side bars (four-level resonance). The optical effect of PIT is simulated by CST software, and the structural parameters affecting the PIT effect are studied. There are still more fields for us to explore about the optical response of metamaterials, such as using other metamaterials combined with plasmon resonance, such as sulfide, vanadium dioxide and other materials, to realize the application of optical devices with more performance.

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