Optical tunable multifunctional slow light device based on double monolayer graphene grating-like metamaterial

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Abstract

A very simple optical tunable device, which can realize multiple functions of frequency selection, reflection and slow light, is presented at the investigation. The proposed device is constructed by a periodic grating-like structure. There are two dielectrics (graphene and silicon) in a period of the equivalent grating. The incident light will strongly resonate with the graphene of electrostatic doping, forming an evanescent wave propagating along the surface of graphene, and this phenomenon is the surface plasmon. Under constructive interference of the polaritons, a unique plasmonic induced transparency phenomenon will be achieved. The induced transparency produced by this device can be well theoretically fitted by the bright and dark mode of optical equivalent cavity which can be called coupled mode theory. This theory can well analyze the influence of various modes and various losses between the function of this device. The device can use gate voltages for electrostatic doping in order to change the graphene carrier concentration and tune the optical performance of the device. Moreover, the length of the device in y-direction is will be much larger than the length of single cycle, providing some basis for realizing the fast tunable function and laying a foundation for the integration. Through a simulation and calculation, we can find that the group index and group delay of this device are as high as 515 and 0.257 picoseconds (ps) respectively, so it can provide a good construction idea for the slow light device. The proposed grating-like metamaterial structure can provide certain simulation and theoretical help for the optical tunable reflectors, absorbers, and slow light devices.

1. Introduction

For a long time, the electrical-based materials have been the main integration units of various chips. However, this structure is obviously limited by the material, that is, the so-called physical limit [1, 2]. Among various devices, optical integrated chip may be a good alternative [3, 4]. As an oscillating electromagnetic field with certain frequency, amplitude and phase, the polarization state of light can characterize the selectivity in different propagation directions. The ideal optical integrated chip does not need any electronic unit, but it cannot be achieved at present. For example, the photodetector we often encounter combines the used of electric chip. In addition, according to the change of corresponding light intensity, it can monitor the internal properties of light such as phase. The photodetector play an important role astronomy, remote sensing, quantum optics, and so on [5–8].

The integration of photodetectors involves complex and huge optical and electrical systems, including polarizers, photo-electric signal conversion, and so on. Therefore, it is urgent to find a method to reduce the integration area. After many years of research, optical surface plasmonic metasurface provides a revolutionary method to reduce the floor area of the system. The development of optical integration
technology with metasurface can not only minimize the manufacturing and component cost, but also realize the functions with great potential applications. Surface plasmonic metamaterials and metasurface provide fascinating ways to control and monitor light [9–11]. Therefore, the research on surface plasmon is becoming more and more popular. From metals in the previous decade to two-dimensional materials which can be represented by graphene in recent years, the research on surface plasmon is also becoming more and more intense [12–18].

Graphene, a two-dimensional material, was successfully prepared ten years ago [19–24]. At that moment, the research upsurge of two-dimensional materials has also been opened. Initially, researchers only studied the electrical properties of this latest material, but since researchers found that this latest material also has very good optical properties, there are more and more studies on its optical effects. For example, in various aspects such as photodetectors and solar cells, the optical effects of graphene play a great role.

In the optical properties of graphene, it is proved that the monolayer graphene can excite surface plasmon polaritons, bringing great application prospects and development prospects for the integrated thickness of devices. Moreover, the monolayer graphene can also control the carrier concentration by electrostatic doping, and it not only offers higher efficiency than chemical doping, but also provides excellent ideas for researchers. Among such many methods, plasmon induced transparency obtained by surface plasmon polaritons is an attractive way to achieve outstanding functions. At present, a variety of optical devices based on graphene surface plasmon polaritons have been realized, such as a series of optical modulator, optical reflectors, optical sensors, slow light devices and so on [25–30].

In this paper, we have designed a very simple equal-distance graphene ribbon-based grating-like structure. The graphene in the grating-like structure is distributed in two layers. One layer is located on the upper surface of substrate dielectric (silicon) and the length of this graphene band in one period of the grating-like structure is small. The other layer is distributed in the middle of substrate dielectric and the length of this graphene band of this layer in one period is long. Compared with the plasmonic graphene-based waveguide structure [31] and the metal–graphene-based metamaterials [32], our proposed structure can obtain a tunable PIT effect by a simpler structure. Moreover, the performance of this simpler device is much higher than that reported in the discrete patterned structure [33].

Due to the constructive interference produced by graphene-based surface plasmon polaritons, this structure can obtain an optically induced transparency very well. In this structure, due to the electrostatic doping, the monolayer graphene has a high carrier concentration, and the electrons in the lower layer of graphene can well resonate with the incident light under the condition of high concentration, and then it should be regarded as a bright mode. Because the electrons in the lower monolayer graphene have absorbed most of the incident energy, the upper graphene layer can only be passively excited by the surface plasmon polaritons excited in the upper layer, and then it can be a dark mode. Some constructive interference between the dark and bright modes would have happen, leading to an apparent plasmonic induced transparency phenomenon. Because the monolayer graphene involved in this device is a continuous plane (this device is a two-dimensional structure and extends infinitely along y-direction, or the length in y-direction is much longer than the ones in x- and z-directions), we can operate well during the electrostatic doping. The carrier concentration and Fermi energy of graphene can be changed directly by adjusting the voltage of the electrode. The Fermi energy of graphene can be controlled by changing the voltage. Then an external tuning of this graphene-based devices can be obtained, laying a foundation for the integration of devices. In addition, due to the dispersion of graphene, we also have found that the slow light performance of this device is very excellent. Through calculation and simulation, we can see that the slow light coefficient (group index) of this device is as high as 515 and the group delay can reach to 0.257 ps (picosecond), and this performance can provide a good construction idea for slow light devices. This silicon–graphene grating-based device can provide certain simulation and theoretical help in the optical reflectors, absorbers and slow light devices.

2. Structure and theoretical model

As shown in figure 1, the two monolayer graphene are located on the upper surface of silicon and the middle of silicon, respectively (where the dielectric constant of silicon is 11.9 and that of air is 1.0). Besides, the two graphene bands are all at the center of each periodic unit. One layer is located on the upper surface of substrate dielectric (silicon) and the length of this graphene band in one period of the grating-like structure is small. The other layer is distributed in the middle of substrate dielectric and the length of this graphene band of this layer in one period is long. The grating constant is equal to the period length, that is, the grating constant $g_1 = 1400$ nm. The height of the device $h = h_{g1} + h_{g2} = 150$ nm. Where, $l_{g1} = 400$ nm, $l_{g2} = 1200$ nm, $h_{g1} = 50$ nm, $h_{g2} = 100$ nm. The numerical data in our work are achieved by the finite-difference time-domain method (FDTD). A periodic boundary conditions in our device is chosen
in the $x$-direction, and the perfectly matched layers is set at the $z$-direction. Moreover, compared with the $x$ direction of this device, the $y$ direction of this device is a single form and can be considered as infinite, so we can use the two-dimensional model to analyze the phenomenon of this device in order to reduce the calculation time.

In this device, compared with the ordinary grating structure, the two-dimensional material graphene is placed on the boundary, greatly changing the current density of the boundary in grating. Therefore, when incident light is placed on the top of this grating, the incident photons with a certain energy can excite surface plasmon polariton, and then a good surface plasmon induced transparency phenomenon can be obtained. Moreover, in this structure, there is an incomparable advantage for the simple change of carrier concentration. The carrier concentration which can affect the Fermi energy of graphene can be controlled by electrostatic doping. At this time, we can directly add the gate voltage to achieve an excellent tuning effect and control the transparency phenomenon.

With the aid of gate voltage (as shown in figure 1(a)), the carriers of the upper and lower layers of graphene can obtain an active concentration range. At this time, if a terahertz light wave is incident from above the grating (along the negative direction of the $z$-axis), the graphene in the lower layer can be preferentially resonated by the incident light to produce surface plasmon polaritons, and this layer plays the role of a bright mode. The upper graphene can be indirectly excited by the polaritons generated by the lower layer to achieve the effect of a dark mode. The polaritons generated between the bright and dark modes can lead to an excellent plasmon induced transparency effect, as shown in figure 2(a) (transmittance) and figure 2(b) (absorbance $= 1 −$ transmittance $−$ reflectance). The higher the voltage, the higher the carrier concentration, and then the higher the Fermi energy of graphene. At this moment in time, the resonance frequency of transparency can also be changed, resulting in a blue shift of resonance frequency. Also, the photons should require higher energy. That is, it can result in a blue shift, as shown in figure 4.

Of course, in order to analyze this phenomenon, we first need to know the optical parameters of those material. As mentioned above, we have used three materials, namely silicon, air, and graphene. The dielectric constant of silicon is 11.9 and that of air is 1.0. In this paper, the dielectric constant of these two materials is set to a fixed value. Furthermore, our device operates in the terahertz band and room temperature. The Fermi energy of monolayer graphene could be experimentally modified from 0.2 eV to 1.2 eV after applying an appropriate bias voltage [19, 34–36]. Thus, we can reasonably assume that the Fermi energy of graphene is 0.80 eV to 1.00 eV under electrostatic doping. At present, $E_F \gg \hbar \omega$, $k_B T$, $E_F$, $\hbar$, $\omega$, $k_B$, $T$, respectively, are Fermi energy, reduced Planck constant, angular frequency of incident light, Boltzmann constant, temperature. Therefore, we can use a Drude-like model to describe the optical conductivity of graphene [35, 37], as follows:

$$\sigma = \frac{ie^2 E_F}{\pi \hbar^2 (\omega + i\tau)^{-1}},$$

(1)

here, $e$ is the electron charge and the carrier relaxation time $\tau$ can conform the following equation:

$$\tau = \frac{\mu E_F}{e v_F^2}.$$  

The Fermi velocity ($v_F$) and carrier mobility ($\mu$), respectively, are 1.00 m$^2$ (V s)$^{-1}$ and 10$^6$ m s$^{-1}$.
As mentioned above, graphene can obtain a tuning advantage through electrostatic doping. We can preset the electrodes of device, and then we can dominate the Fermi energy in the way of changing the gate voltage to change the resonant frequency of the device. Thus, we can realize an excellent tuning function by this method. Therefore, the device can realize the function without changing the geometric parameters compared with other structured tuning structures. This construction method is predicted to offer some basis foundation of realization of integrated devices, so that it can achieve the effect of using circuits to control functions, and then it can realize practical functions such as photoelectric detection. In addition, the voltage modulation relationship of graphene is as follows [38, 39]:

\[
E_F = \frac{\hbar v_F}{\pi \varepsilon_0 \varepsilon_d V_g d_s},
\]

(2)

here, \(\varepsilon_0\), \(\varepsilon_d\), \(V_g\), \(d_s\) are respectively the permittivity of free space and dielectric, the applied gate voltage, the distance between graphene monolayer and electrode location. This relationship can provide us with the theoretical basis of electrostatic doping. In this paper, the length in \(y\)-direction of each period in the device will be much longer than that in the \(x\)- and \(z\)-direction, that is, we can regard the graphene monolayer as a complete graphene band in the \(y\)-direction. It also provides a good convenient basis for the electrostatic doping. Moreover, compared with those discontinuous patterned graphene-based structures, this device is easier to realize the tuning function and is easier to obtain in the manufacture of device.

3. Results and analysis

In order to better describe the phenomena by theoretical description and data fitting, we need to use the optical equivalent cavity coupled mode theory (CMT) [40, 41]. In this theory, we can regard the bright and dark mode as two optical equivalent cavities: \(a_1\) and \(a_2\) (\(n = 1, 2\), representing the optical bright and dark modes), respectively. The electric field component of incident light can be regarded as a time harmonic field, which can be expressed in complex form as: \(E(r, t) = E(r)e^{-i\omega t}\). At this time, the propagated and generated polaritons between \(a_1\) and \(a_2\) modes in this resonance phenomenon can be equivalently represented as shown in figure 2(c). Thus, we can respectively express \(a_1\) and \(a_2\) as the complex amplitudes of the optical modes. Here, \(A_{1 \pm}^{\text{in(out)}}\) and \(A_{2 \pm}^{\text{in(out)}}\) denote the incident or outgoing energy of bright and dark mode. The superscript \(\text{in}\) denotes the incident energy and \(\text{out}\) denotes the outgoing energy.
The subscript $+$ denotes the positive propagating energy and $-$ denotes the negative propagating energy. Moreover, $\gamma_m = \omega_m/(2Q_m)$ is the external loss and $\gamma_0 = \omega_0/(2Q_0)$ is the internal loss. Where, $\omega_m$ is the resonant angle frequency in the optical bright and dark mode. $Q_m$ and $Q_0$, respectively, are the quality factor relating to external loss and internal loss of the bright and dark modes. Those quality factors also should satisfy the following relationship: $1/Q_m = 1/Q_{on} + 1/Q_{in}, \mu_{21}^2(\mu_{21})$ is the coupling coefficient between the bright and dark modes. Therefore, we can easily describe the equations of the resonant cavities as follows:

$$
\begin{pmatrix}
\gamma_1 - i\mu_{12} \\
-\mu_{12} \gamma_2
\end{pmatrix}
\begin{pmatrix}
a_1 \\
a_2
\end{pmatrix}
= 
\begin{pmatrix}
-\gamma_1^{1/2} \\
0
\end{pmatrix} 
\begin{pmatrix}
\delta_1 \\
\gamma_2^{1/2}
\end{pmatrix}
\begin{pmatrix}
a_1^+ \\
a_2^+
\end{pmatrix}.
$$

(3)

Here, $\gamma_n = i(\omega - \omega_n) - \gamma_m - \gamma_0$ ($\omega$ is the angular frequency of incident source).

According to the conservation of energy, the following relations between the incoming and outgoing energy of the bright and dark modes would be obtained as follows:

$$
A_{in}^{out} = A_{1+}^{out} e^{i\varphi}, \\
A_{1-}^{out} = A_{2-}^{out} e^{i\varphi},
$$

(4)

$$
A_{in}^{out} = A_{1+}^{out} - \gamma_0^{1/2} a_n, \\
A_{1+}^{out} = A_{2-}^{out} - \gamma_0^{1/2} a_n \quad (n = 1, 2).
$$

(5)

Here, $\varphi$ is phase differences between the two optical resonant bright and dark modes. Moreover, if the excitation energy only propagates from the positive direction (i.e., $S_{12}^{in} = 0$), thus, through the above equation (equations 3–5)), we can obtain the transmittance coefficient ($t$) and reflectance coefficient ($r$) about this optical plasmonic system:

$$
t = \frac{A_{2+}^{out}}{A_{1+}^{in}} = e^{i\varphi} + \left(\gamma_0 \gamma_2 e^{i\varphi} + \gamma_1 \gamma_0 \gamma_2 e^{i\varphi} + (\gamma_0 \gamma_1 \gamma_2)^{1/2} e^{2i\varphi} \chi_1
+ (\gamma_0 \gamma_1 \gamma_2)^{1/2} \chi_2 \right) \left(\gamma_1 \gamma_2 - \chi_1 \chi_2\right)^{-1},
$$

(6)

$$
r = \frac{A_{2-}^{out}}{A_{1+}^{in}} = \left(\gamma_0 \gamma_2 + \gamma_1 \gamma_0 \gamma_2 e^{i\varphi} + (\gamma_0 \gamma_1 \gamma_2)^{1/2} \chi_1 e^{i\varphi}
+ (\gamma_0 \gamma_1 \gamma_2)^{1/2} \chi_2 e^{i\varphi} \right) \left(\gamma_1 \gamma_2 - \chi_1 \chi_2\right)^{-1}.
$$

(7)

The relevant coefficients are as follows: $\chi_1 = i\mu_{12} + (\gamma_0 \gamma_1 \gamma_2)^{1/2} e^{i\varphi}$, $\chi_2 = i\mu_{21} + (\gamma_0 \gamma_1 \gamma_2)^{1/2} e^{i\varphi}$. Then, we can obtain the transmittance ($T = |t|^2$), reflectance ($R = |r|^2$) and absorbance ($A = 1 - T - R$) of the entire system for the optical tunable slow light device according to this optical equivalent cavity CMT.

The plasmon polaritons excited by the incident light can locally propagate at the monolayer graphene. Besides, the equivalent dielectric constant of graphene will be much larger than that of the substrate (silicon), thus we simplify the calculation method of propagation constant for simpler calculation. In this paper, we take the propagation constant of monolayer graphene as follows [42–44]:

$$
\beta = \kappa_0 \sqrt{\varepsilon_{Si} - \left(\frac{2}{\sigma_g \kappa_0}\right)^2},
$$

(8)

where, $\beta, \kappa_0, \varepsilon_{Si}$, and $\sigma_g$ are the propagation constant, the wave number in free space, the intrinsic impedance in free space, the relative dielectric constant of silicon, and the conductivity of graphene, respectively. Thus, the effective refractive index is equal to the effective refractive index divided by the propagation constant: $n_{eff} = \beta/k_0$. The internal loss quality factor of the plasmonic modes can be achieved by follows equation: $Q_i = \text{Re}(n_{eff})/\text{Im}(n_{eff})$. Moreover, the total quality factor can be obtained by the following equation: $Q_e = f/\Delta f$ (f and $\Delta f$ respectively are resonant frequency and full width at half maxima). Thus, by the relationship $(1/Q_m = 1/Q_{on} + 1/Q_{in})$, we can get the value of the external loss quality factor ($Q_{on}$). The real part and imaginary part with frequency are shown in figures 3(a) and (b) in different Fermi energy. Figures 3(c) and (d) are the resonant frequency and the value quality factor with the Fermi energy. Then the value of each $Q_m$ can be obtained according to the resonant frequency, and the quality factor values are clearly classified as follows: $Q_{11} = (4.32, 4.26, 4.18, 4.09, 4.01), Q_{12} = (3.52, 3.48, 3.41, 3.35, 3.18), Q_{21} = (22.10, 24.26, 26.51, 28.79, 31.16), Q_{22} = (33.29, 36.49, 39.77, 43.17, 46.64)$ as $E_g = (0.80 \text{ eV}, 0.85 \text{ eV}, 0.90 \text{ eV}, 0.95 \text{ eV}, 1.00 \text{ eV})$ in this graphene-based grating-coupled metamaterial structure, respectively. The values of these parameter are shown in figures 3(c) and (d).

Through the above parameters, we can use equations (6) and (7) to obtain the theoretical fitting transmittance ($T$) and reflectance ($R$) of the device, as shown by the red dot lines in figure 4. It can be seen that the theoretical fitting results are in good agreement with the numerical results. The simulation curves
Figure 3. (a) The real parts part with frequency in different Fermi energy. (b) The imaginary part with frequency in different Fermi energy. (c) The resonant frequency of the device at different Fermi energy. (d) The value quality factor of the device at different Fermi energy.

Figure 4. (a) and (b) The blue shift phenomenon caused by the change of Fermi energy. The blue lines are the simulation data and the red dot lines are the CMT fitting result. (blue solid line) match the theoretical curve (red dotted line) very well, and it can also show that our theory is successful established.

From figure 4(a), we can see that the resonant frequency has a blue shift with the increase of the Fermi energy of the monolayer graphene. We can know that the electrons in graphene need higher energy to be excited with the increase of Fermi energy, meaning that the energy of incident light will be higher. Thus, the
Figure 5. (a) and (b) Slow light effect the optical tunable slow light device based on silicon–graphene grating metamaterials.

whole transparency phenomenon will blue shift. The Fermi energy of graphene can be tuned by electrostatic doping, and electrostatic doping can be provided by adding gate voltage. The adding voltage provides a very convenient method for external regulation and provides an idea for subsequent integrated optoelectronic circuits. We can also select some needed frequency or wavelength through this device, that is, this device realizes a good selection function. In figure 4(b), we can see that the reflectance of this device will be greater than 90%. This high reflectivity also provides an optical reflection function for the structure. Moreover, the simple external regulation property not only makes the device have a high selectivity, but also provides a modulator and reflector.

Due to the dispersion of graphene, we have found that this device also has a very good slow light performance. According to the above described CMT, we can obtain a transmission coefficient, and then obtain the phase change of the light vector passing through the device. Finally, the values of group index \( n_g \) and group delay \( \tau_g \) can be achieved [45, 46]:

\[
\tau_g = \frac{d\theta}{d\omega}, \quad n_g = c \frac{dk}{d\omega} = \frac{c}{h_g} \tau_g,
\]

where \( c \) is the speed of light in vacuum, \( h_g \) is the thickness of the whole device (i.e., \( h_g = h_{g1} + h_{g2} = 0.15 \mu m \)), and \( \theta \) is the phase change.

From figure 5, we can see that the evolution relationship between group index, group delay and phase change and frequency under different Fermi energy in this device. We can find that strong dispersion occurs at the transparent window, thus the slow light coefficient and group delay change sharply. This can provide a theoretical simulation basis for the design of slow light devices. In addition, it can be seen from figure 5 that the maximum values of group index and group delay will increase with the increase of Fermi energy, and the frequency at the peak position will also blue shift. Through calculation and simulation, we can see that the slow light coefficient (group index) and group delay of the device are as high as 515 and 0.257 ps, respectively. At this time, the device can provide a good construction idea for the multi-functional slow light device, such as slow light modulator or slow light reflector and so on.

4. Conclusion

In conclusion, a tunable multifunctional slow light device with simple structure is designed in this paper. The device is constructed by two graphene monolayer grating-like metamaterials. One of graphene monolayer is on the upper surface of silicon substrate and has a small length, and the other is on the middle position of silicon and has a long length. The lower graphene in this device can be directly excited by incident light, and the resulting surface plasmon polaritons acts as a bright mode. The upper graphene can
be indirectly excited by the surface plasmon polaritations excited by the upper graphene, acting as a dark mode. The constructive interference between the bright and dark modes can lead to an obvious optical plasmonic induced transparency phenomenon. Besides, we can set an external gate in this device, and then the carrier concentration and conductivity of graphene can be regulated by the gate voltage. Thus, the Fermi energy of graphene can be regulated, and finally it can achieve an effect of voltage regulation. Moreover, the length in the y-direction of this device is much larger than the length of the device. Therefore, we can operate well to obtain a very good external tuning effect of this graphene-based device, and it can lay a foundation for the integration of the device. In addition, through calculation and simulation, we find that the group index and group delay of this device are as high as 515 and 0.257 ps respectively, providing a good construction idea for the slow light effect. This graphene-based grating structure can provide some theoretical and simulation help for the optical reflectors, absorbers, slow light device, and so on.

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Disclosures

The authors declare no conflicts of interest.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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