Integrated Tunable Distributed Feedback Reflection Filter Based on Double-Layer Graphene

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Abstract. A silicon waveguide integrated electrically tunable distributed feedback grating device based on double-layer graphene is proposed and analysed by mode coupling theory and finite element simulation method. The theoretical results show that with the graphene fermi energy level change from 0.5 eV to 0.8 eV, the center wavelength of TM mode reflection spectrum shifts from 1.55 μm to shorter wave by 3.9 nm, and the center wavelength of TE mode reflection spectrum shifts from 1.89 μm to shorter wave by 4.8 nm. The graphene electrically tunable distributed feedback grating device may have potential application in the integrated tunable wavelength selection device.

Keywords: Distributed feedback, Reflection filter, Graphene

1 Introduction

In modern optoelectronics, periodic distributed feedback[1] (DFB) structure plays an important role. It has been used in modern optical communication and optoelectronics core devices such as distributed feedback lasers[2] and fiber grating filters[3]. In recent years, waveguide integrated distributed feedback Bragg grating has been widely studied as one of the effective ways to realize integrated wavelength selection and dispersion compensation functional devices. Most of the existing tunable distributed feedback devices[4] adopt the methods of temperature adjustment or mechanical adjustment, and the tuning speed is relatively slow.

With the emergence of graphene with excellent photoelectric characteristics, graphene-based high-speed electrically tunable devices is widely studied. Graphene has a very high electron mobility (about $15000 \text{cm}^2/(\text{V} \cdot \text{s})$), making the speed of graphene-based electro-optic modulation devices up to 500 GHz theoretically. In addition, the density of carrier states in the graphene band near the Dirac point is very low, so its fermi energy level can be significantly adjusted with a low applied voltage[8]. Integrating graphene into the dielectric waveguide structure and changing the fermi energy level of graphene can adjust the transmission characteristics of the waveguide mode. In this paper, we propose an electric tunable silicon waveguide integrated distributed feedback filter based on
double-layer graphene. By changing the gate voltage of graphene, the operating wavelength of the filter can be effectively adjusted. Using mode coupling theory[9-12] and finite element simulation method, we analyse the transmission, polarization, and electrically tunable characteristics of the distributed feedback filter we proposed.

2 Structure description and principle introduction

2.1 Structure description

The structure is shown in Figure 1, (a) (b), SiO2 is used as the substrate, above it is a Si waveguide with a width of 500nm and a height of 220nm. And then a graphene-Al2O3-graphene period structure constitute a grating covering the Si waveguide. The thickness of graphene-Al2O3-graphene is 0. 34nm-10nm-0. 34nm. The grating period is P and the total grating length is L. The double-layer graphene constitute a capacitor and can be electrically gated, So that the Si waveguide do not require doping, which can reduce the transmission loss. Besides both the upper and lower graphene can be electrically gated. Under the same gate voltage, the ability of regulating the transmission characteristics is larger than that of single-layer graphene[13].

2.2 Principle introduction

First of all, we use the model coupling theory to analyse the above structure. When the waveguide mode passes through the grating, it diffracts a series of harmonics. The harmonics may couple with each other. The coupling equation can be expressed as[14]

\[ i(K + 2\pi p / a \mp \beta_0)\chi_p^+ = \pm i \sum_{n} k_p^{\pm} \chi_n^+ + \sum_{n} k_p^{\pm} \chi_n^- \]

where K represents the Bloch wave number and a represents the grating period, p is determined by the current mode, \( \beta_0 \) represents the propagation constant of the waveguide mode, \( \chi_p^{\mp} \) represents the mode expansion coefficient, and the superscript \( \pm \) represents the mode propagation direction. \( k_p^{\pm} \) Denotes the coupling coefficient. The superscript indicate that the two coupling modes are in the same direction or the reverse direction. The subscripts indicate the coupling coefficient order. The first part on the right side of the equation represents the coupling between two co-directional transmission modes, and the second part represents the coupling between two reverse transmission modes. Since the thickness of graphene is only 0. 34nm, its disturbance to the waveguide mode is negligible, so it can be regarded as a weak periodic coupling system. In a weak periodic coupled
system, the strongest mutual coupling is the between forward zeroth harmonic \(X_0^+\) and the reverse negative primary harmonic \(X_1^-\). In our paper, we only consider this two harmonics, and then the coupling equations can be simplified to

\[
\begin{align*}
(K - \beta_0) X_0^+ &= k_0^+ X_0^+ + k_1^- X_1^- \\
(K - 2\pi l a + \beta_0) X_1^- &= k_1^+ X_0^+ + k_0^- X_1^- 
\end{align*}
\]  

(2)

And

\[
\begin{align*}
k_m^{\pm}(z) &= \frac{i\omega}{2} \int ds \text{Re}\left[ e^i \cdot (E_{z,\beta} \times H_{z,\beta}^*) \right] \\
k_m^{\pm}(z) &= \frac{i\omega}{2} \int ds \text{Re}\left[ e^i \cdot (E_{z,\beta} \times H_{z,\beta}^*) \right]
\end{align*}
\]  

(3)

\[
C_m = \frac{1}{a} \int dz \Delta \varepsilon_r(z) e^{-i\frac{2\pi m z}{a}}
\]  

(4)

where \(E\) and \(H\) represent the electrical and magnetic field of the eigenmode of the waveguide without grating structure, respectively. The eigenmode filed of the waveguide can be obtained by finite element simulation method. \(\Delta \varepsilon_r(z)\) represents the change of relative permittivity in the transmission direction. Suppose that only forward mode is excited in the waveguide, which means the boundary condition \(X^+(z = 0) = 0\). Under this boundary condition, we solve the mode coupling equation (2) to obtain the change in mode expansion coefficient along the propagation direction. And the reflectivity can be express as

\[
T(z = 0) = \left| \frac{\chi^+(z = 0)}{\chi^+(z = 0)} \right|^2
\]  

(5)

When the gate voltage is changed, the fermi energy level of graphene changes, and the optical conductivity and relative dielectric constant of graphene changes accordingly, thereby changing the coupling coefficient and the reflectivity of the grating. In this paper, the optical conductivity of graphene is derived using the random phase approximation model under local limit[15]

\[
\sigma_m = \sigma_{intu}(\omega) + \sigma_{inter}(\omega)
\]  

(6)

\[
\sigma_{intu}(\omega) = \frac{2e^2k_BT}{\pi\hbar^2} \frac{i}{\omega + i\epsilon} \ln \left[ 2\cosh \left( \frac{E_f}{2k_BT} \right) \right]
\]  

(7)

\[
\sigma_{inter}(\omega) = \frac{e^2}{4\hbar} \left[ \frac{1}{2} + \frac{1}{\pi} \text{arctan} \left( \frac{\hbar\omega - 2E_f}{2k_BT} \right) - \frac{i}{2\pi} \ln \left( \frac{(\hbar\omega + 2E_f)^2}{(\hbar\omega - 2E_f)^2 + 4(k_BT)^2} \right) \right]
\]  

(8)

where \(\omega\) is the electromagnetic wave frequency, \(k_B\) is the Boltzmann constant, \(T\) is the temperature, \(\hbar\) is the modified Planck constant, \(\tau\) is the transit time, \(E_f\) is the graphene fermi energy level. Figure 2 (a), (b) show the real part and imaginary part of optical conductivity of graphene for different wavelength and different fermi energy level, respectivley. It can be seen that the influence of the fermi energy level on the conductivity...
of graphene is an order of magnitude greater than the influence of the wavelength, and the change is obvious when the fermi energy level is greater than 0.4 eV. Therefore, changing the graphene fermi energy level can effectively adjust the conductivity of graphene in a large range, and then adjust the relative permittivity of graphene.

**Figure 2.** (a) Graphene conductivity changes with wavelength (under Fermi energy level 0.5 eV); (b) Graphene conductivity changes with fermi energy level (with wavelength 1500 nm).

### 3 Research result

First, we calculate the propagation constant of the waveguide when there is no graphene grating and the change of the coupling coefficient with wavelength for different fermi energy levels with graphene grating as shown in Figure 3 (a) and (b), respectively. It can be seen that $\beta_0, k_0^+, k_1^-$ all decrease gradually with increasing wavelength. And the higher the graphene fermi energy level, the smaller the coupling coefficient $k_0^+, k_1^-$. Changing the fermi energy level from 0.5 eV to 0.8 eV, and the change of the coupling coefficient is about two orders of magnitude smaller than the propagation constant, which belongs to weak coupling.

**Figure 3.** (a) The variation of the propagation constant with wavelength when there is no grating; (b) The variation of the coupling coefficient with wavelength when there are different fermi energy levels with graphene grating.

Suppose that the center operating wavelength of TM mode is 1550 nm. First, according to the conditions that the grating period $a$ should satisfy $|\beta_0 + k_0^+ - \frac{\pi}{a}| = 0$, we determine that the grating period is about 490 nm. Taking 500 cycles, the reflection spectrum of TM and TE modes and the corresponding central wavelength of the reflection spectrum change with graphene fermi energy level are shown in the figure below.
Figure 4. (a) The change of system reflectance with graphene fermi energy level in TM mode. The curves from right to left are the corresponding spectra of fermi energy level 0eV, 0.5−0.8eV; b) The change of system reflectance with graphene fermi energy level in TE mode. The curves are the corresponding spectra of the fermi energy level of 0eV, 0.5−0.8eV; (c) with the fermi energy level changes, the center wavelength of the reflection spectrum changes.

As shown in Fig. 4 (a), in the TM mode, when the graphene fermi energy level changes from 0.5eV to 0.8eV, the center of the reflection spectrum of the system shifts by 3.9nm toward the short wavelength. From the spectrum center formula $\Delta = \beta_0 + k_0^+ \cdot -\frac{\pi}{a} = 0$, we can see that as the fermi energy level increases, the decrease of $k_0^+$ is significant, and the corresponding $\beta$ should increase, that means the center wavelength shifts to a shorter wavelength, which is consistent with our results. In addition, the reflection bandwidth becomes narrower as the Fermi energy level rises. The reason is that the zeroth coupling coefficient changes with the Fermi energy level is greater than that of the first order coupling coefficient with the Fermi energy level (Figure 3. (b)). In the TE mode, when the graphene fermi energy level changes from 0.5eV to 0.8eV, the center of the reflection spectrum of the system shifts to 4.8nm toward the short wavelength, and the reflection bandwidth also becomes narrower as the fermi energy level increases.

4 Conclusions

In summary, we propose a silicon waveguide integrated electrically tunable distributed feedback grating device based on double-layer graphene. The Si waveguide do not require doping, which can reduce the transmission loss; at the same time, both the upper and lower graphene can be electrically regulated, so the regulation range is larger than monolayer graphene. The reflection filter characteristics of the distributed feedback grating we designed is analyzed by the mode coupling theory and finite element simulation method.
The theoretical analysis results show that when the graphene fermi energy level is adjusted from 0.5eV to 0.8eV, the center wavelength of TM mode reflection spectrum shifts from 1.55um to shorter wave by 3.9nm, and the center wavelength of TE mode reflection spectrum shifts from 1.89um to shorter wave by 4.8nm. The graphene electrically tunable distributed feedback grating device we proposed may have potential application in the integrated tunable wavelength selection device.

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