

УДК 535

## Характеристики поглощения в одномерном фотонном кристалле на основе графена

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С целью исследования характеристик поглощения одномерного графенового фотонного кристалла методом матрицы перехода теоретически и численно проанализировано поведение моды TE в диапазоне от 300 до 1000 нм. Проанализированы параметры, влияющие на характеристики поглощения: угол ввода излучения, структура фотонного кристалла, число слоев графена, показатель преломления дефектного слоя. Показано, что поглощение в графене может быть существенно увеличено путем формирования микрорезонатора Фабри–Перо в дефектном слое фотонного кристалла. Пиковым значением, положением и шириной полосы поглощения можно управлять путем изменения указанных выше параметров фотонного кристалла. Результаты работы открывают новые возможности применения фотонных кристаллов.

**Ключевые слова:** фотонный кристалл, графен, матрица переноса, коэффициент поглощения

## Absorption characteristics of one-dimensional graphene photonic crystals

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Submitted 06.10.2020

DOI:10.17586/1023-5086-2021-88-03-03-09

In order to study the absorption characteristics of one-dimensional graphene photonic crystal, the TE wave of 300–1000 nm was analyzed theoretically and numerically based on the transfer matrix method. The effects of incident angle, the structure of the photonic crystal, the number of graphene layers and the refractive index of the defect layer on the absorption characteristics are analyzed. The results show that the absorption of graphene can be greatly improved by using the micro Fabry–Pérot cavity formed by the defect layer of the photonic crystal. The peak, the position and the bandwidth of the absorbance can be adjusted by changing the above-mentioned parameters of the photonic crystal. This study provides a way to expand the application of photonic crystals.

**Keywords:** photonic crystal, graphene, transfer matrix, absorptivity.

**OCIS codes:** 140.3300, 220.3620, 260.5430

### INTRODUCTION

In 1987, Yablonovitch and John respectively proposed the concept of photonic crystal [1, 2]. Because of its periodic structure, electromag-

netic wave in some frequency bands can not be propagate in the photonic crystal, resulting in photonic band gap. If a defect layer is introduced into the photonic crystal, a propagation

electromagnetic wave mode with narrow spectrum can be generated in the band gap, similar to the impurity level in the forbidden band of a doped semiconductor, and the propagating electromagnetic wave in the band gap will produce a local light enhancement effect in the doped layer [3]. These characteristics make photonic crystal an ideal tool to control electromagnetic wave propagation according to our wishes. In recent years, photonic crystals have been widely used in the fabrication of micro resonators, efficient zero threshold lasers, wide-band mirrors, ultra narrow filters and optical waveguides [4, 5].

In 2004, Novoselov and Geim prepared graphene [6] by mechanical stripping method. Because of its zero gap energy band structure, strong ductility, good conductivity, fast response speed and high mobility, graphene has become the research focus in recent years. Theoretical calculation shows that only 2.3% of white light can be absorbed by single-layer graphite [7], which greatly limits the application of graphene in the photoelectric equipment. However, because graphene has the thickness of the atomic layer, it is almost completely transparent under the visible light, and has very good flexibility and ductility, it's application will be a great improvement of photoelectric devices.

In recent years, some researchers have combined graphene with photonic crystals, expecting to use the special structure of the photonic crystal to increase the light absorbance of graphene [8–13]. Ning *et al.* found that the light absorbance of the photonic crystal with this structure is much higher than that of the single graphene sheet [14]. Wu *et al.* designed a metal graphene photonic crystal to make the peak absorbance of light wave reach nearly 95% [15]. In this paper, a cavity structure is formed in the 1D photonic crystal with graphene defect layer in the middle of the cavity. Because the light wave is reflected back and forth in the Fabry–Pérot cavity [16], it can improve the light absorbance of the graphene thin layer and realize the perfect absorption of light in theory. On this basis, the relationships between the absorption characteristics and the structure and some parameters of the photonic crystal are discussed, and nearly perfect absorbance is obtained in a compact 1D photonic crystal containing a graphene layer.

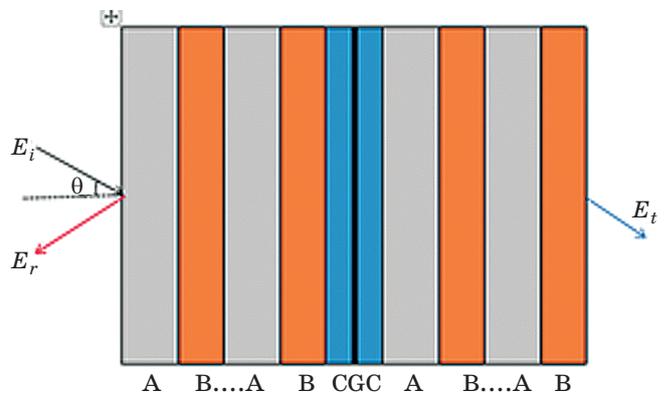
## PRINCIPLE AND MODEL

In this paper, the defect layer is used as the cavity in the middle of the photonic crystal, and the graphene layer is inserted in the middle of the defect layer. When light enters the cavity, it is repeatedly reflected between the mirrors on both sides of the defect layer, so that the photon is strongly localized in the cavity. Because every reflected light passes through the graphene layer, the absorption of light by the graphene is greatly improved. Based on this theoretical consideration, a model is designed as shown in Fig. 1. Medium C is inserted into the photonic crystal with periodic arrangement of A and B, and graphene layer G is embedded in the middle of C to form the defect layer of the photonic crystal, *i.e.* the formula for the structure under consideration can be expressed as  $(AB)^N CG_g C(AB)^M$  in Fig. 1. Here,  $N$  is the number of periods of the photonic crystal before the defect,  $M$  is the number of those after the defect, and  $g$  is the number of graphene monolayers.

According to the definition of absorption coefficient, a general equation can be derived when light is normally incident on a slab of medium

$$\frac{4\pi k}{\lambda} = -\frac{1}{nd} \ln \left[ \frac{I}{I_0} \frac{1}{1-R} \right]. \quad (1)$$

In Eq. (1),  $k$  is the absorption coefficient,  $n$  is the actual refractive index, and  $d$  is the thickness of the medium,  $\lambda$  is the wavelength.  $I$  is the transmitted light intensity,  $I_0$  is the



**Fig. 1.** The dielectric materials A and B are arranged periodically, and medium C and graphene G. The electric field  $E_i$  is incident at  $\theta$  angle, reflecting the electric field  $E_r$ , and transmitting the electric field is  $E_t$ .

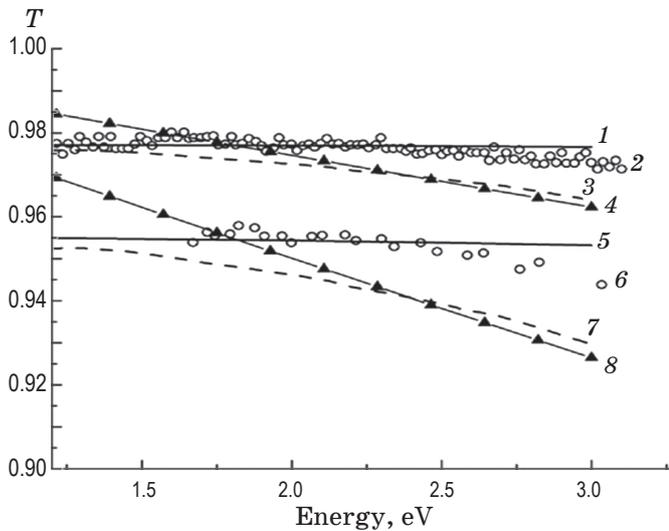
incident light intensity, and  $R$  is the fraction of reflected light. For graphene, its reflectivity  $R$  is negligible, and  $I/I_0 \approx (1 - \pi\alpha)$  [7], where  $\alpha$  is the fine structure constant. So Eq. (2) can be reduced as

$$k = -\frac{\lambda}{4\pi n d_g} \ln(1 - \pi\alpha) \equiv C_1 \frac{\lambda}{n}, \quad (2)$$

where, considering as usual the graphene thickness  $d_g = 0.34$  nm,  $C_1 \approx 5.446 \mu\text{m}^{-1}$ .

In Ref. [17], the measured spectra were compared with the fitting curves to find the best  $n$  value that can reproduce the experimental data, as shown in Fig. 2. It can be seen from the figure that the fitting curve is in good agreement with the experimental results when  $n = 3.0$ . Therefore, the complex refractive index of graphene in the visible light range can be obtained

$$n_g = 3 + (1/3)iC_1\lambda. \quad (3)$$



**Fig. 2.** In Ref. 17, the experimental or theoretical transmittance ( $T$ ) spectra of single-layer graphene and double-layer graphene are shown in the figure. Curve 1 is the theoretical value of single-layer graphene when  $n = 3.0$ ,  $k = C_1\lambda/n$ , curve 5 corresponds to the result of double-layer graphene; curve 2 is the experimental observation result of single-layer graphene transmittance by Nair *et al.*, curve 6 corresponds to the result of double-layer graphene; curve 3 is the result of Johnson and Dresselhaus using the three-dimensional band model. The calculation result of graphene, curve 7 corresponds to the result of double-layer graphene; curve 4 is the theoretical value when  $n = 2.6$ ,  $k = 1.3$ , curve 8 corresponds to the result of double-layer graphene.

In this paper, we consider incident TE wave. According to the theory of optical films [18], the relationship between the electromagnetic field components parallel to the interfaces on both sides of the interface of the  $i^{\text{th}}$  single-layer film is

$$\begin{bmatrix} E_i \\ H_i \end{bmatrix} = M_i \begin{bmatrix} E_{i-1} \\ H_{i-1} \end{bmatrix}, \quad (4)$$

where  $E_i$ ,  $H_i$  are the electric field and magnetic field components at the interface between the  $i^{\text{th}}$  and the  $(i + 1)^{\text{th}}$  layers, and

$$M_i = \begin{bmatrix} \cos\beta_i & -i\sin\beta_i / P_i \\ -iP_i \sin\beta_i & \cos\beta_i \end{bmatrix},$$

$$\beta_i = \frac{2\pi}{\lambda} n_i d_i \cos\theta_i,$$

$$P_i = n_i \sqrt{\frac{\epsilon_0}{\mu_0}} \cos\theta_i,$$

$\lambda$  is the incident wavelength,  $d_i$  is the thickness of the  $i^{\text{th}}$  layer,  $n_i$  is its refractive index,  $\epsilon_0$ ,  $\mu_0$  are the permittivity and permeability in vacuum respectively, and  $\theta_i$  is the light propagation angle in the  $i^{\text{th}}$  layer. In the graphene layer, the angle  $\theta_i$  is complex, the above formulation is still applicable. In theory, there are two ways of dealing with a graphene sheet [19–20]: one is to consider it as a two dimensional plane with surface conductivity  $\sigma_g$ , the other is to regard it as a thin layer of medium with permittivity  $\epsilon_g = 1 + i\sigma_g/(\omega\epsilon_0 d_g) = n_g^2$ , and they are consistent with each other due to negligible thickness of graphene compared with thicknesses of dielectric layers. For a photonic crystal with  $N$  layers, we have

$$\begin{bmatrix} E_N \\ H_N \end{bmatrix} = M_N M_{N-1} \dots M_2 M_1 \begin{bmatrix} E_0 \\ H_0 \end{bmatrix} = M \begin{bmatrix} E_0 \\ H_0 \end{bmatrix}, \quad (5)$$

$$M = \begin{bmatrix} A & B \\ C & D \end{bmatrix},$$

where,  $M$  is the transfer matrix of the photonic crystal. In Fig. 1, the incident electric field is  $E_i$ , the reflected electric field is  $E_r$ , the transmitted electric field is  $E_t$ , and the transmission coefficient is

$$t = \frac{E_t}{E_i} = \frac{2P_0}{AP_0 + BP_0 P_{N+1} + C + DP_{N+1}}. \quad (6)$$

The transmittance is  $T = |t|^2$  and both sides of the one-dimensional periodic structure shown in Fig. 1 of the model are air, so we have  $P_0 = P_{N+1}$ .

The reflection coefficient is

$$r = \frac{E_r}{E_i} = \frac{AP_0 + BP_0P_{N+1} - C - DP_{N+1}}{AP_0 + BP_0P_{N+1} + C + DP_{N+1}}, \quad (7)$$

the reflectance is  $R = |r|^2$ , and the absorbance is  $A = 1 - T - R$ .

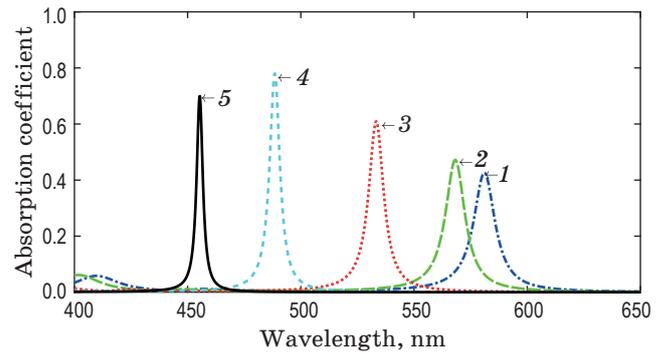
## RESULTS AND ANALYSIS

In the following, the refractive indices of the dielectric layers are taken as  $n_a = 1.5$ ,  $n_b = 3.0$ , and the thickness is  $d_a = 100$  nm,  $d_b = 50$  nm, so  $n_a d_a = n_b d_b$ , that is, the optical thickness of the two dielectric layers is the same. The refractive index of the defect layer is taken to be  $n_c = 1.3$ , and the thickness is  $d_c = 50$  nm. The absorption characteristics of the structure are calculated when the electromagnetic wave with wavelength between 300 and 1000 nm is incident. The numerical results and analysis are given in the following from the viewpoints of different angle of incidence, periodic structure, number of defect layers, refractive index of the defect layer.

### INFLUENCE OF INCIDENT ANGLE ON ABSORPTION CHARACTERISTICS

Let  $N = 2$ ,  $M = 4$ ,  $g = 1$ , the incident angle  $\theta$  is set in the range of  $0-80^\circ$ , increasing by  $20^\circ$  in turn. The absorbance of the TE wave is calculated, and the results are shown in Fig. 3.

It can be seen from Fig. 3 that the photonic crystal has obvious absorption peaks for the incident light waves of all angles, and the absorption peaks are all in the visible light band. Moreover, along with the increase of the incident angle, the absorption peak of the photonic crystal increases first and then decreases, the position of the absorption peak moves to the short wavelength direction, and the secondary absorption peak in the short wavelength side increases with the incident angle. We can see from the figure that the maximum absorption peak value of the structure occurs at an incident angle between  $40$  and  $80^\circ$ . Numerical result shows that, when the incident angle  $\theta = 73^\circ$ , the maximum absorption peak value reaches  $97.55\%$  at wavelength  $464$  nm, which is  $42.4$  times of the light absorbance of



**Fig. 3.** Construct an  $(AB)^2CG_1C(AB)^4$ -type photonic crystal. When the incident angle  $\theta$  is in the range of  $0-80^\circ$  and increases by  $20^\circ$  in turn, the absorption coefficient of TE wave is calculated. Curve 1 is the absorption coefficient at  $\theta = 0^\circ$ , curve 2 is the absorption coefficient at  $\theta = 20^\circ$ , curve 3 is the absorption coefficient at  $\theta = 40^\circ$ , curve 4 is the absorption coefficient at  $\theta = 60^\circ$ , curve 5 is the optical absorption coefficient at  $\theta = 80^\circ$ .

single graphene sheet in natural state. In the micro Fabry–Pérot cavity formed by graphene and the defect layer, the longer the distance of wave propagation is, the greater the absorptivity of light wave is. When the incident wave changes from normal incidence to oblique incidence, it will inevitably lead to the change of the propagation distance of light wave in the cavity structure, so it will lead to the change of absorption peak value, and the incident angle will have an impact on the phase difference of light wave propagation. When the incident angle changes, the position of absorption peak will also change.

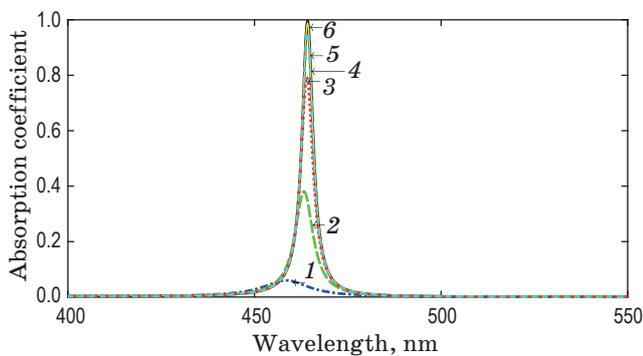
### INFLUENCE OF PERIODIC STRUCTURE ON ABSORPTION CHARACTERISTICS

Now let us set  $g = 1$ ,  $n_c = 1.3$  and the incident angle  $\theta = 73^\circ$  while maintaining  $N = 2$ , for  $M = 2, 3, 4, 5, 6, 7, \text{etc.}$ , the absorbance calculated for the TE wave is displayed in Fig. 4.

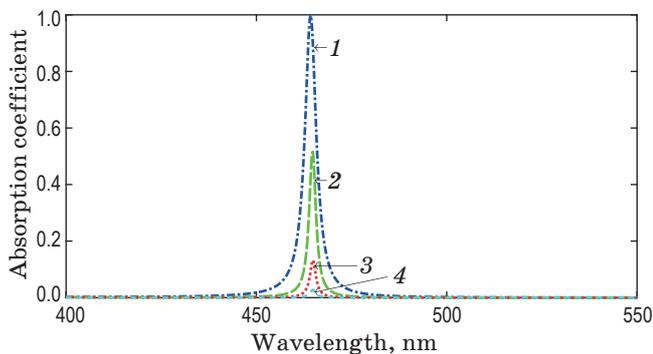
It can be seen from Fig. 4 that with the increase of the period number  $M$  behind the defect layer, the peak value of the absorbance of the photonic crystal tends to grow. The peak value is only  $13.55\%$  when  $M = 2$ , and it becomes  $99.65\%$  when  $M = 7$ . The absorbance of the photonic crystal is greatly improved, the position of the absorption peak moves slightly to the long wave direction with the increase of  $M$ , and finally stabilized at  $464$  nm. When  $M$  is increased

further, it is found that when  $M \geq 8$ , the absorbance reaches a saturation value of 99.89%. In the case of keeping other structures unchanged, increasing the number of periods behind the defect layer will increase the probability that the transmitted light wave will be reflected back to the cavity, leading to an increase in the absorbance of the graphene layer.

If we set  $g = 1$  and incidence angle  $\theta = 73^\circ$ , when  $M = 8$ , and  $N$  is taken as 2, 3, 4, 5, etc. respectively, the calculated absorptivity of the TE wave is shown in Fig. 5.



**Fig. 4.** When incident angle  $\theta = 73^\circ$  and other conditions remain unchanged, the absorption coefficient of TE wave with different periods  $M$  is calculated. Curve 1 is the absorption coefficient at  $M = 2$ , curve 2 is the absorption coefficient at  $M = 3$ , curve 3 is the absorption coefficient at  $M = 4$ , curve 4 is the absorption coefficient at  $M = 5$ , curve 5 is the optical absorption coefficient at  $M = 6$ , curve 6 is the absorption coefficient at  $M = 7$ .



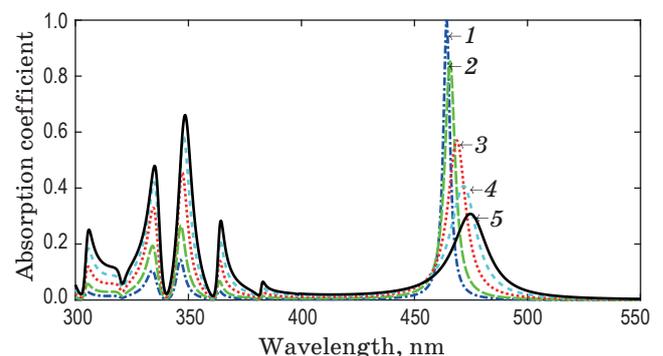
**Fig. 5.** Incident angle  $\theta = 73^\circ$ , and other conditions remain unchanged, the absorption coefficient of TE wave with different periods  $N$  is calculated. Curve 1 is the absorption coefficient at  $N = 2$ , curve 2 is the absorption coefficient at  $N = 3$ , curve 3 is the absorption coefficient at  $N = 4$ , curve 4 is the absorption coefficient at  $N = 5$ .

It can be seen from Fig. 5 that with the increase of the number of periods  $N$  in front of the defect layer, the peak value of the absorption of the photonic crystal for the incident light wave shows a significant decreasing trend. When  $N = 2$ , the absorption rate is 99.89%, when  $N = 3$ , the absorption rate has dropped to 51.54%, and when  $N = 4$ , the absorption rate is only 13.27%. When the value of  $N$  is increased further, the absorbance of light waves by photonic crystals becomes negligible. If there are too many periods before the defect, it will increase the probability that the light wave is reflected, which will also lead to the decrease of the absorbance of graphene. Therefore, we can see that when the periodic structure of the photonic crystal is changed, the light absorption of graphene will be greatly affected.

#### THE EFFECT OF THE GRAPHENE LAYER ON ABSORPTION PROPERTIES

First, let us consider the influence of the number of thin layers of single-layer graphene on the absorption characteristics. Let the parameters  $N = 2$ ,  $M = 8$ , the incidence angle  $\theta = 73^\circ$ , and the number of layers of graphene  $g = 1, 2, 4, 6$ , and 8 respectively, the absorbance of the TE wave is computed and the result is displayed in Fig. 6.

As shown in Fig. 6, when the number of graphene monolayers in the defect layer increases, there are obvious changes in the absorption bandwidth in the range between 450 and 500 nm



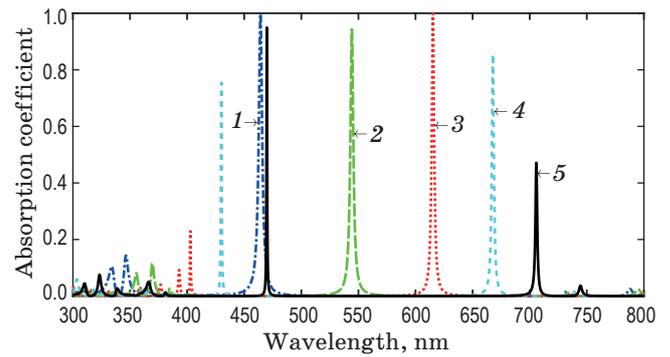
**Fig. 6.** When the incident angle  $\theta = 73^\circ$  and the period number  $N = 2$ ,  $M = 8$ , the number of graphene layers  $g$  changed, the absorption coefficient of TE wave was calculated. Curve 1 is the absorption coefficient at  $g = 1$ , curve 2 is the absorption coefficient at  $g = 2$ , curve 3 is the absorption coefficient at  $g = 4$ , curve 4 is the absorption coefficient at  $g = 6$ , curve 5 is the absorption coefficient at  $g = 8$ .

for the absorption peak and in the position of the absorption peak. When  $g = 1$ , the absorption peak appears at 465 nm, and the peak value is 99.89%. With the increase of the number of thin monolayers of graphene, the absorption peak becomes lower, the absorption peak moves towards the long wave direction, and the absorption bandwidth also becomes wider. At  $g = 8$ , the absorption peak appears at about 475 nm, the peak value is 30.77%, and the absorption band width is obviously wider than that for  $g = 1$ . In the short wave range, a series of absorption peaks appear with the increase of graphene monolayers. As graphene is a kind of lossy dielectric with complex dielectric constant, with the increase of graphene monolayers, the total thickness of graphene increases, and the damping of plasma wave on graphene surface increases, resulting in the increase of half width and reflectivity, so the bandwidth increases. As the number of layers increases, the reflection increases, so the absorption decreases. In addition, with the increase of the number of graphene monolayers, the resonant mode of the microcavity has a red shift, which makes the spectrum of the enhanced photoelectric field red shift, so the main absorption peak moves to the long wavelength direction, and the interaction between graphene layers makes the absorption of the short wave increase.

### INFLUENCE OF REFRACTIVE INDEX OF DEFECT LAYER ON ABSORPTION CHARACTERISTICS

Taking  $N = 2$ ,  $M = 8$ ,  $g = 1$  and increasing the refractive index of the defect layer from 1.3 to 0.5, we calculate the absorbance of the TE wave, and the result is shown in Fig. 7.

It can be seen from Fig. 7 that with the increase of the refractive index of the defect layer, the absorption peak position of the photonic crystal generally moves to the long wave direction, and with the increase of the refractive index, the main peak in the long wave range becomes smaller, and the secondary peak in the short wave range becomes larger. When  $n_c = 2.3$ , the maximum absorbance of the photonic crystal is 99.95% at 615 nm, while at  $n_c = 3.3$ , the secondary peak of the absorbance exceeds the main peak. The results show that the refractive index of the defect layer has an obvious effect on the optical absorption of the photonic crystal.



**Fig. 7.** When the incident angle  $\theta = 73^\circ$ , the period number  $N = 2$ ,  $M = 8$ ,  $g = 1$ , and the refractive index  $n_c$  of the defect layer changed, the absorption coefficient of TE wave was calculated. Curve 1 is the absorption coefficient at  $n_c = 1.3$ , curve 2 is the absorption coefficient at  $n_c = 1.8$ , curve 3 is the absorption coefficient at  $n_c = 2.3$ , curve 4 is the absorption coefficient at  $n_c = 2.8$ , curve 5 is the absorption coefficient at  $n_c = 3.3$ .

### CONCLUSION

In summary, graphene-containing  $(AB)^N CG_g C(AB)^M$ -type photonic crystals is studied, and the TE wave absorption characteristics of one-dimensional photonic crystals is analyzed from several aspects, such as changes in incident angle, periodic structure, the number of graphene monolayers, and refractive index of defect layers. It is found that with the increase of the incident angle, the absorption peak of the photonic crystal increases first and then decreases, and the position of the absorption peak moves to the short wave direction; with the increase of the period number behind the defect layer, the peak value of the absorption increases, while with the increase of the period number of the photonic crystal before the defect layer, the peak value of the absorption increases. When the number of graphene monolayers in the defect layer varies, the absorption peak value, the peak position and the absorption bandwidth have obvious changes; the refractive index of the defect layer also has a great influence on the absorption characteristics. Based on the conclusion, in designing the absorbing device with the photonic crystal containing graphene, we can get the nearly perfect absorbing characteristics of the photonic crystal device by adjusting the above parameters properly.

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