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# Effects of waveguide layer on reflection spectrum characteristic of two-dimensional photonic crystal

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**Abstract:** The two-dimensional(2D) photonic crystal(PC) was constructed with the substrate of $SiO_2$ and the surface coating medium of $TiO_2$, and rigorous coupled-wave analysis (RCWA) theory was used to analyze the optical propagation property of 2D PC. The effects of the lattice period, refractive index and thickness of waveguide layer on optical properties of 2D photonic crystal were analyzed. Analysis results show that: While the lattice period and thickness of the waveguide layer are constant, with the increase of refractive index of waveguide layer, the reflective peak wavelength value (PWV) appears red shift, and there is a good linear relationship between above two. When the refractive index of waveguide layer is constant, photonic crystal reflection PWV increases with the increase of thickness or lattice period, the linear relationship between the two and PWV is in certain range. The non-uniform characteristic of surface adsorbing medium is obtained by analyzing the spectrum of non-uniform distribution of surface adsorbing medium of 2D PC.

**Key words:** photonic crystal; rigorous coupled wave analysis; peak wavelength value; waveguide layer

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# 波导层介质对二维光子晶体反射光谱的影响

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**摘　要:** 构建了基底介质为 $SiO_2$、表面覆层介质为 $TiO_2$ 的二维光子晶体,采用严格耦合波法分析了二维光子晶体的窄带光学传输特性。分析了二维光子晶体的晶格周期、波导层的折射率及厚度对其反射光谱的影响。分析结果表明:当光子晶体的晶格周期和波导层介质厚度为常数时,随着波导层介质折射率的增大,光子晶体的反射峰值波长红移,且波导层折射率与反射峰值波长呈线性关系。当光子晶体波导层介质折射率为常数时, 波导层厚度增大或光子晶体晶格周期的增大都会引起光子晶体反射峰值波长增大,但这两个参数与反射峰值波长只是在一定的变化范围内为线性关系。此种结构的二维光子晶体覆层表面吸附分布不均匀的介质时, 通过分析光子晶体的呈现光谱可获得其表面吸附介质的不均匀特性。

**关键词:** 光子晶体; 严格耦合波; 峰值波长; 波导层

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## 0 Introduction

The photonic crystal is an ordered structure of artificial optical material which is composed of two or more materials of different refractive indices according with a certain cycle in the space. PC structure has a photonic energy band[1-2], which is similar with electronic energy band of semiconductor crystals. There is band gap between energy bands, also known as forbidden band, so that the frequency of the electromagnetic wave falls in the band gap cannot continue to propagate in PC[3-5]. A variety of new devices can be designed and produced based on PC, such as PC waveguides, PC lasers, and PC optical switch[6-8].

The interaction between incident electromagnetic field of PC and waveguide layer[9] can be enhanced by the composing parameter of waveguide layer medium and the surface structure of PC. The RCWA theory is used to analyze the optical propagation property of 2D PC in this paper[10]. When a beam of optical waves incident on the surface of 2D PC, it will produce a narrowband reflected wave. The drift of narrowband reflection PWV results in the change of composing parameter of waveguide layer medium. The effects of lattice period, thickness and refractive index of waveguide layer medium on the reflection spectrum characteristic of 2D PC are analyzed. The effects of parameters change of waveguide layer medium on the PWV and wavelength drift are discussed. When the composing parameters of waveguide layer medium are determined, the reflective PWV is changing with the change of surface adsorption medium concentration of PC. If the surface adsorption medium is uniform, the reflective PWV of each region are the same. And if it is non-uniform, the reflective PWV is different. The reflective PWV of each region reflects the characteristic of medium distribution, i.e. the distribution characteristics of the reflective index of surface adsorption medium of different regions. Therefore, a new type of photonic crystal biosensor can be achieved by a reasonable design of PC structure[11].

## 1 Structure model of 2D PC

The RCWA theory is an exact solution method for solving Maxwell's equations, which is widely used to accurately calculate the diffraction properties of electromagnetic waves in periodic structure, and it can be used to accurately analyze the holographic grating and surface relief grating structure. The accuracy of the solution depends on the series of Fourier series expansion; the series of Fourier series expansion takes 15 in this paper. The structure of PC is shown in Fig.1, the refractive index of the substrate is 1.45, the refractive index of waveguide layer is **n**, thickness is **d**, lattice periodical is $\Lambda$, depth of groove **h**=170 nm, and filling ratio is 0.5. Depositing a medium with high refractive index and its thickness of 100 nm, refractive index is 2.25. The medium of each layer is non-magnetic material, the relative magnetic permeability $\mu_r \approx 1$, and the materials are lossless dielectric.

When the beams at vertical incidence, the magnetic field can be written as

$$\overrightarrow{\mathbf{H}_{inc}} = e^{-j\mathbf{k}_0 \mathbf{n}_I (\sin\theta \mathbf{x} - \cos\theta \mathbf{z})} \tag{1}$$

Where $\mathbf{k}_0 = 2\pi/\lambda_0$, $\lambda_0$ is the incident wavelength; $\mathbf{n}_I$ is the refractive index of incident region; $\theta$ is the incident angle. The total magnetic field of incident region can be written as

$$\overrightarrow{\mathbf{H}_I} = \overrightarrow{\mathbf{H}_{inc}} + \sum_i \mathbf{R}_i e^{-j(\mathbf{k}_{xi} \mathbf{x} - \mathbf{k}_{I,i} \mathbf{z})} \tag{2}$$

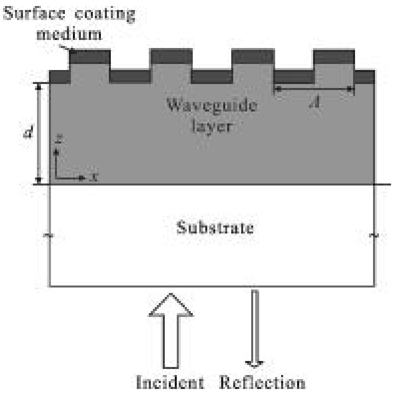

Fig.1 Structure of photonic crystals

The magnetic field of transmission region as

$$\overrightarrow{\mathbf{H}_{II}}=\overrightarrow{\mathbf{H}_{inc}}+\sum_i \mathbf{T}_i e^{-j[\mathbf{k}_{xi}\mathbf{s}+\mathbf{k}_{II,i}(\mathbf{z}-\mathbf{h})]} \tag{3}$$

Where $\mathbf{R}_i$ is the amplitude of the i level reflected wave magnetic field of incident region and $\mathbf{T}_i$ is the amplitude of the i level transmitted wave magnetic field of transmission region. **h** is the depth of groove, $\mathbf{k}_{xi}$, $\mathbf{k}_{I,i}$ and $\mathbf{k}_{II,i}$ are the wave vectors respectively obtained by Floquet:

$$\mathbf{k}_{xi}=\mathbf{k}_0[\mathbf{n}_I\sin\theta-(\lambda_0/\Lambda)\mathbf{i}] \tag{4}$$

$$\mathbf{k}_{I,i}=\begin{cases}+\mathbf{k}_0[\mathbf{n}_l^2-(\mathbf{k}_{xi}/\mathbf{k}_0)^2]^{1/2} & \mathbf{k}_0\mathbf{n}_l>\mathbf{k}_{xi}\\ -j\mathbf{k}_0[(\mathbf{k}_{xi}/\mathbf{k}_0)^2-\mathbf{n}_l^2]^{1/2} & \mathbf{k}_{xi}>\mathbf{k}_0\mathbf{n}_l\end{cases} \quad l=I,II \tag{5}$$

In grating region, Fourier expansions of the relative dielectric constant can be written as

$$\varepsilon_r(\mathbf{x})=\sum_i \varepsilon_{ri}(\mathbf{x})e^{j\frac{2\pi}{\Lambda}ix} \tag{6}$$

Fourier expansions of the electric field and magnetic field can be expressed as

$$\overrightarrow{\mathbf{E}_g}=\sum_i\{\mathbf{S}_{xi}(\mathbf{z})\hat{\mathbf{x}}+\mathbf{S}_{zi}(\mathbf{z})\hat{\mathbf{z}}\}e^{-jk_{xi}x} \tag{7}$$

$$\overrightarrow{\mathbf{H}_g}=-j\left(\frac{\varepsilon_0}{\mu_0}\right)^{\frac{i}{2}}\sum_i \mathbf{U}_{yi}(\mathbf{z})\hat{\mathbf{y}}e^{-jk_{xi}x} \tag{8}$$

Where $\varepsilon_r$ is the distribution function of the relative dielectric constant in grating region; $\mathbf{S}_i$ and $\mathbf{U}_i$ are respectively the amplitude of the i level electric and magnetic fields in grating region; $\varepsilon_0$ and $\mu_0$ are respectively permittivity and permeability of vacuum.

The equations(6)-(8) into the following Maxwell equations

$$\nabla\times\overrightarrow{\mathbf{E}_g}=-j\omega\mu_0\overrightarrow{\mathbf{H}_g} \tag{9}$$

$$\nabla\times\overrightarrow{\mathbf{H}_g}=-j\omega\varepsilon_0\varepsilon_r\overrightarrow{\mathbf{E}_g} \tag{10}$$

Eliminate $\mathbf{H}_{gz}$, coupled differential equations can be obtained as follows

$$\frac{\partial\mathbf{H}_{gy}}{\partial\mathbf{z}}=-j\omega\varepsilon_0\varepsilon_r(\mathbf{x})\mathbf{E}_{gx} \tag{11}$$

$$\frac{\partial\mathbf{E}_{gx}}{\partial\mathbf{z}}=-j\omega\mu_0\mathbf{H}_{gy}+\frac{\partial\mathbf{E}_{gx}}{\partial\mathbf{x}} \tag{12}$$

The coupled differential equations can be solved by putting the boundary condition into equations(11), (12). The reflection coefficient and transmission coefficient of PC can be respectively expressed as

$$\mathbf{DE}_{ri}=\mathbf{R}_i\mathbf{R}_i^*\mathrm{Re}\left(\frac{\mathbf{k}_{I,zi}}{\mathbf{k}_0\mathbf{n}_I\cos\theta}\right) \tag{13}$$

$$\mathbf{DE}_{ti}=\mathbf{T}_i\mathbf{T}_i^*\mathrm{Re}\left(\frac{\mathbf{k}_{II,zi}}{\mathbf{n}_{II}^2}\right)/\left(\frac{\mathbf{k}_0\cos\theta}{\mathbf{n}_I}\right) \tag{14}$$

## 2 Effects of transmission characteristic of waveguide layer

The effect of the change of refractive index of waveguide layer, thickness and lattice periodical on narrowband reflection characteristic is analyzed by using RCWA.

### 2.1 Effects of the refractive index of waveguide layer

The structure of PC is shown in Fig.1, keeping the other parameters constant, taking **d**=300 nm, $\Lambda$=550 nm, effects of the change of refractive index on the reflection spectrum being studied. The reflection spectrum of different refractive index of waveguide layer medium can be simulated by using the established model in Fig.2.

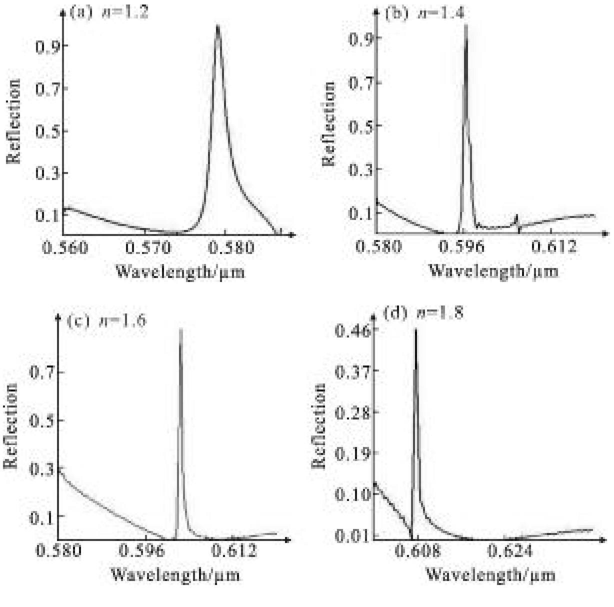

Fig.2 Reflective spectrum of different refractive index

As shown in Fig.2, the band gap of the reflection spectrum varies with the refractive index of waveguide layer varies. The width of band gap is larger, reaching about 5 nm when the refractive index is small as **n**=1.2. The band gap of the reflection spectrum decreases to about 2 nm with the increase of refractive index of waveguide layer. The highest reflection efficiency of PC appears at **n**=1.2 to **n**=1.6, exceeding 90%. The band gap properties is better at this time, also it is easier to be observed in the experiment.

The relationship between the refractive index of waveguide layer and the PWV is shown in Fig.3. The reflective PWV appears red shift with the increase of the refractive index of waveguide layer, and there is a good linear relationship between the above two.

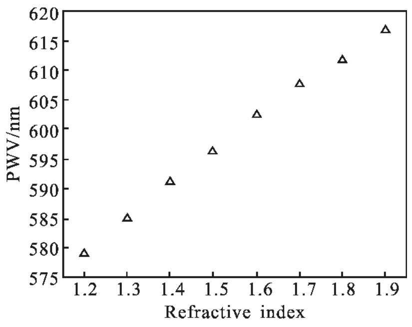

Fig.3 Relationship between PWV and refractive index of waveguide layer

## 2.2 Effect of thickness change of waveguide layer

Keeping the structure of PC constant, the effect of thickness of waveguide layer on reflection spectrum is studied. The relationship between the different thickness of waveguide layer and the PWV can be obtained by taking **d** respectively 300 nm, 500 nm, and 700 nm. As shown in Fig.4.

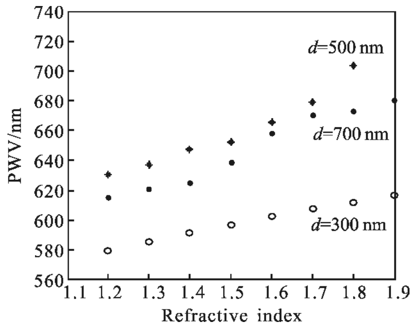

Fig.4 Relationship between PWV and thickness of waveguide layer

It has been shown in Fig.4 that a small change of the refractive index and thickness of waveguide layer generates the PWV drift. When the refractive index of waveguide layer is constant, there is a maximum PWV at **d**=500 nm and a minimum PWV at **d** =300 nm, with the thickness of waveguide layer increases from 300 nm to 500 nm, **ΔPWV** increases from 53.7 to 147, increased by 93.3, while **ΔPWV** decreases from 147 to 92.6 as the thickness of waveguide layer continuing increase to 700 nm, **ΔPWV** reduced by 54.4, which shows that the continuing increase of thickness cannot bring the increase of change rate of PWV. The thickness keeping constant, the PWV increases with the increase of the refractive index of waveguide layer medium, and keeps a linear relationship between above two within certain range.

## 2.3 Effects of lattice period of waveguide layer

Keep the structure of PC constant, takes the thickness of waveguide layer **d**=500 nm, and the lattice period $\Lambda$ respectively as 500 nm, 550 nm, 600 nm, the relationship between the different lattice period of waveguide layer and the PWV can be obtained in Fig.5.

As shown in Fig.5, the PWV drifts toward the long-wavelength with the increase of refractive index of waveguide layer, and a linear relationship between the two. As the equation (6) shown that when the lattice period $\Lambda$ is changing, the dielectric constant distribution of the periodic structure of PC is changing, and then the reflection efficiency of PC is changing. In the case of the same refractive index of waveguide layer, Fig.5 shows that the PWV increases with the increase of the lattice period of waveguide, the **ΔPWV** drifts from 55.4 to 147 when $\Lambda$ varies from 500 nm to 550 nm, increased by 91.6, but the **ΔPWV** drifts from 147 to 90.8 while $\Lambda$ varies from 550 nm to 600 nm, reduced by 56.2, this indicates that

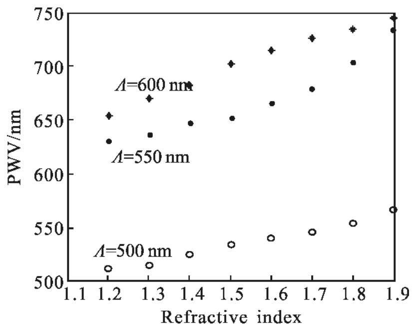

Fig.5 Relationship between PWV and lattice period of waveguide layer

simply increase the lattice period of waveguide layer cannot bring about the increase of the change rate of PWV.

## 3 Conclusions

The effects of lattice period, thickness and refractive index of waveguide layer of 2D PC on reflection spectrum properties have been analyzed by RCWA theory. Results indicated that keep the other parameters constant, the PWV drifts toward the long-wavelength with the increase of thickness, refractive index and lattice period of waveguide layer, moreover with linear relationship. The change rate of PWV is the highest with in certain range while **d** is 500 nm, $\Lambda$ is 550 nm. Therefore, the optical properties of 2D PC can be optimized by choosing appropriate parameters of waveguide layer, thereby providing a certain reference for the fabrication of PC biosensor.

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