Waveguide Thickness Effects on the Sensitivity of Lamellar Grating Waveguide Sensor with TE-Polarization Incidence

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Abstract: This paper has studied the effects of waveguide thickness on the sensitivity of the sub-wavelength Lamellar grating waveguide sensor with TE polarization incidence. The variation of guided modes and the sensitivity of fundamental mode are also investigated. The calculation results show that the thicker waveguide layer will induce more guided modes. Comparing the spectrum sensitivity of fundamental mode of different waveguide thickness, the peak shift of the thinner waveguide layer is larger than the thicker one's. In other words, thinner waveguide layer is a better selection for the use of sensor.

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Keywords: waveguide thickness, Lamellar grating, biosensor, sub-wavelength, full wave half maxima (FWHM)

1. Introduction

At present, photonic crystal devices possess many fantastic features which have widely been applied to pharmaceutical discovery, environmental testing, label-free DNA, protein, and so on. [1,2,3,4] Because of the spectrum filtering characteristics, sub-wavelength photonic crystal could only allow a very sharp transmission or reflected spectrum while white light incidence. As biomolecules or cells attached on the surface of the sensors, the effective index of sensor refraction would be altered; the peak wavelength would be shifted simultaneously. Based on this principle, we can detect the change of the materials on the surface of sensor.

Lamellar grating is a simple 1-dimension photonic crystal and has been widely used in the field of waveguide sensors. Lamellar grating waveguide sensors can not only reduce the energy loss but also simplify the process of fabrication. [5]

In this article, we have discussed wavelength spectrum characteristics affected by waveguide layer with TE polarization incidence in order to understand the relationship between waveguide thickness and sensitivity. Moreover, we do not only investigate the wavelength peak shift, but also discuss the full wavelength half maxima (FWHM) of the resonant optical modes in order to review the instinct physics of sensitivity of the sensors.

2. Analysis methods and materials

Because the convergence and stability of the rigorous coupled wave analysis (RCWA) method has been improved, this method has commonly been utilized to solve scattering problem of photonic crystal. [6] RCWA technique is relatively simple and straightforward. [7] It also possesses very fast convergence to solve diffraction questions, so it becomes widely used on thicker or surface relief gratings. It is a non-iterative, deterministic technique utilizing a state-variable method that converges to the proper solution without inherent numerical instabilities. [8] The accuracy of the solution solely depends on the number of terms in space-harmonic expansion; the conservation of energy is always satisfied. [9]

For the silicon-on-insulator (SOI) materials based sensors, a sub-wavelength grating can be created by the combination of single crystal silicon with silica (SiO_2) or other low index materials, such as SU-8 polymer. [10] Because the surface area of the nanosized SiO_2 particles in the thick film could increase the surface enzyme loading, it leads to high performance of the biosensor. [11, 12]

3. Energy band of thinner structure

The proposed structure is composed of grating layer and waveguide layer, which is a simple resonant sensor. Fig. 1 shows the scheme of such a sensor that consists of Lamellar grating and a waveguide layer surrounded by air (n_{air} = 1). The simulation parameters are designed as followings: the refractive index of grating and waveguide ($n_g = n_{WG} = 1.55$), the periodic of grating (Λ=0.5μm), filling factor (F= 0.5), the thickness of grating d_g and waveguide d_{WG} are set as 100nm. In addition, we set a homogeneous thin film layer to replace the bio donor and acceptor attached layer; the refractive index and thickness of thin film are defined as n_f =1.334 and d_f. Filling factor is defined as the ratio of the high refractive index material of grating.

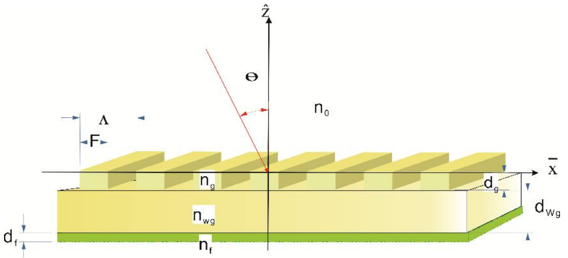

Figure 1. The proposed structure has grating and waveguide layer, a simple resonant sensor.

The reflected spectrum energy band introduced by variable incidence angle is illustrated as figure 2. Referring to figure 2(a), it is obvious that only single resonant mode exists in normal incidence. The energy gap (forbidden band) is about 0.1 under normal incidence. Besides, it will separate as two reflective optical modes, while using the inclined incidence (θ > 0°). Figure 2(b) shows high and low resonance mode spectrum versus different incidence angle (θ) such as θ = 0° , 1° , 2° , 6° .

The spacing of resonance modes will become larger as the incidence angle increases. Furthermore, the lower frequency (longer wavelength) mode still remains higher reflectance (R > 99.5%) than the higher frequency (shorter wavelength) mode, even if the incidence angle (θ) is 6° .

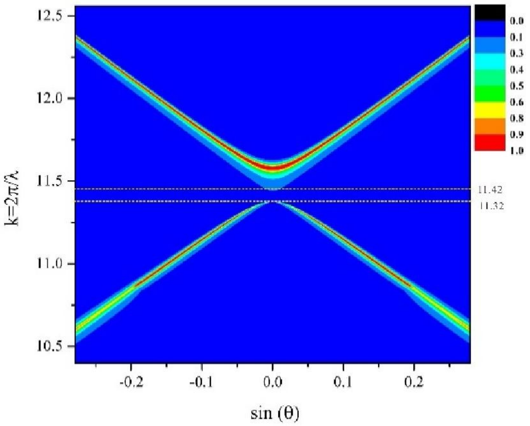

Figure 2(a) The energy band of Lamellar grating waveguide layer, as $d_g = 100$nm, $d_{WG} = 100$nm.

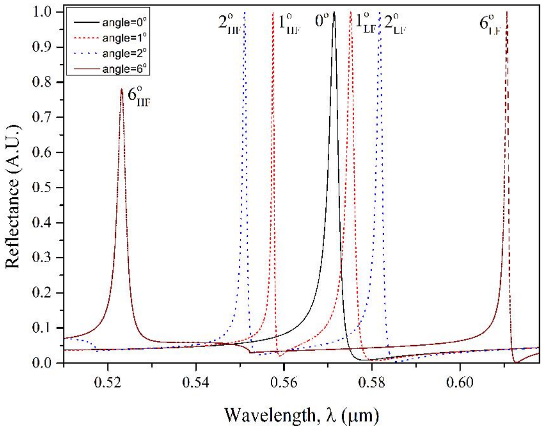

Figure 2(b) shows the high and low resonance mode spectrum versus different incident angle (θ), such as θ = 0° , 1° , 2° , 6° .

3. Reflection spectrum of different thickness of Lamellar grating

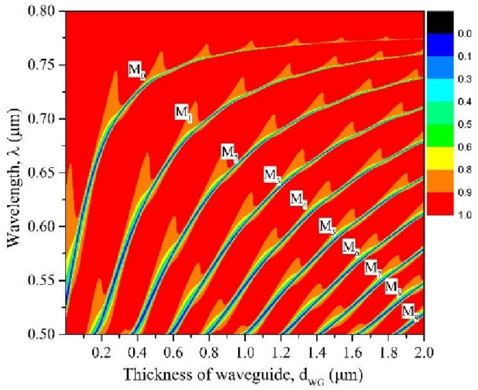

Figure 3(a)

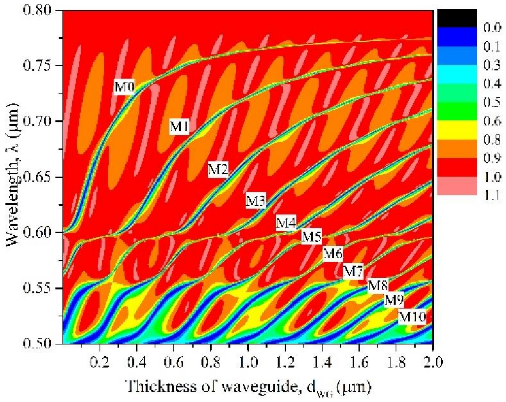

Figure 3(b)

Figure 3. Transmittance spectrum of the increasing thickness of waveguide (d_{WG}). Figure 3(a) Transmittance wavelength spectrum vs. d_{WG} under $d_g = 100$nm. Figure 3(b) Transmittance wavelength spectrum vs. d_{WG} under $d_g = 1000$nm.

The simulation of the increasing thickness of waveguide (d_{WG}) effects are plot as Fig.3 (a) and (b). The thinner grating layer (i.e. d_g=100nm), the transmittance of the increasing waveguide thickness presents more like a generally homogeneous waveguide layer. The thicker grating possesses stronger modulation strength, it will make the modes closer to threshold condition (Λ=500nm) and these modes will be deformed more greatly. It is interesting that the peak wavelength (λ_P) of the fundamental mode (M_0) has shifted 108nm (from 482nm to 600nm) as d_g is from 100nm to 1000 nm, its profile can still be recognized very easily. Comparing the Fig.3 (a) and (b), the high order modes are deformed by the increased d_g.

The reflected spectrum is the reverse of the transmitted spectrum when the resonance condition is satisfied. It explicitly reveals that the fundamental mode (M_0) still remains high reflectance ($R > 99\%$).

4. Sensitivity affected by waveguide thickness

To prove the validity of our simulations, the 100nm grating layer has been used for three different waveguide thickness, d_{WG}=100nm, 500nm and 1000nm. Thin film of the refractive index n_f = 1.334 is used statistically instead of the bio donor and acceptor layer. The fundamental mode peak shift and its FWHM have been selected for advancing comparison of the sensitivity of these different waveguide thickness (d_{WG}) sensors.

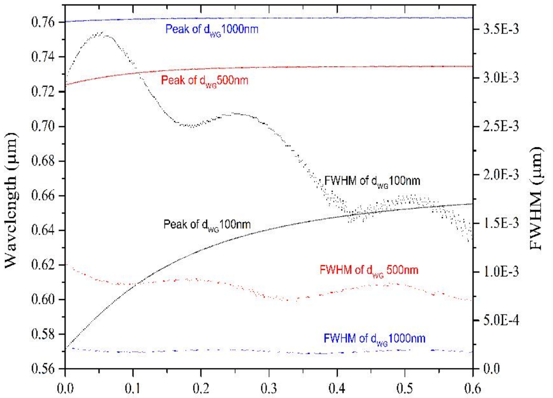

Figure 4. Wavelength peak shift and their FWHM of different waveguide thickness of sensors. The black, red and blue lines and square dot are respectively referring to the sensors under d_{WG}=100nm, 500nm and 1000nm.

Figure 4 illustrates the wavelength peak shift and FWHM variation as the thin film layer increases from 0 to 1000 nm for different waveguide layer thickness (d_{WG}=100nm, 500nm and 1000nm) sensors. The peak shift of the thinnest waveguide (d_{WG}=100nm) is larger than the thickest one's (d_{WG}=1000nm). For example, the peak shift ($\delta\lambda$) of the thin film layer increases from 0 to 100nm. $\delta\lambda_{100nm}$= 610.5-573.2 is 37.3 nm for d_{WG}=100nm; $\delta\lambda_{1000nm}$= 761.96-759.95 is 2.01 nm for d_{WG}=1000nm. It is difficult to recognize the peak shift of the thicker waveguide layer; on the contrary, it is very simple to recognize the thinner waveguide one.

5. Conclusion:

In this article, we have discussed the effects of waveguide thickness on sub-wavelength Lamellar grating waveguide sensor. Referring to the calculation results, we have found that the fundamental mode peak shift of thinner waveguide layer is larger than the thicker one. That is, the sensitivity of thinner waveguide and grating layer possesses the higher sensitivity. On the other hand, even though the FWHM of the thinner waveguide layer varies more sharply than the thicker one, the thinner waveguide layer is still a good option for Lamellar waveguide sensor.

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