

# Double Narrow Notch Spectral Filter Design Using Waveguide Grating on Metal Substrate

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## Abstract

A double narrow notch spectral filter design using planar dielectric grating diffraction coupled resonant thin dielectric waveguide on metal substrate is numerically studied in this article. Due to excitation and coupling of guided resonance mode in thin dielectric waveguide layer and surface plasmon mode on the interface between the waveguide and the metal substrate, double deep and narrow reflection spectrum dip can be obtained. This physical explanation is confirmed by the momentum matching conditions of resonance and the field distribution calculation. As an example, double notch filter design with full width half maximum less than 2 nm centered at 549 nm and 651 nm is presented.

## Keywords

Surface Plasmon Mode, Guided Resonance Mode, Notch Filter

## 1. Introduction

Guided-mode resonance (GMR) within narrow parameters (such as wavelength, incidence angle, and polarization states) is a type of grating anomaly effect that is observed in thin waveguide film [1]. Waveguide grating structures containing diffractive grating layers and homogenous waveguide layers are beneficial for excellent narrow-band optical filters [2] [3] [4] [5] [6]. Narrowband spectral filters are crucial for signal detection systems such as Radar tracking [7] and bio- and gas-sensors [8]. Meanwhile, surface plasmon polaritons (SPPs) are electromagnetic surface waves propagating along with metal-dielectric interfaces caused by electron density oscillations. SPPs can be excited by p-polarized light through an attenuated total reflection (ATR) type arrangement or a grating so that the transverse component of the incident beam wave vector matches the wave vector of SPPs [9] [10]. In this paper, we introduce a thin dielectric wave-

guide layer into the conventional grating-excited SPR device. The evanescent diffractive-order waves diffracted by the grating layer are coupled into the waveguide layer to excite the guided resonance and surface plasmon resonance in the same structure. We apply this concept in the study of double-notch filter design. This physical explanation for double spectral notch filter is investigated by analyzing the momentum matching conditions and the distribution of near field.

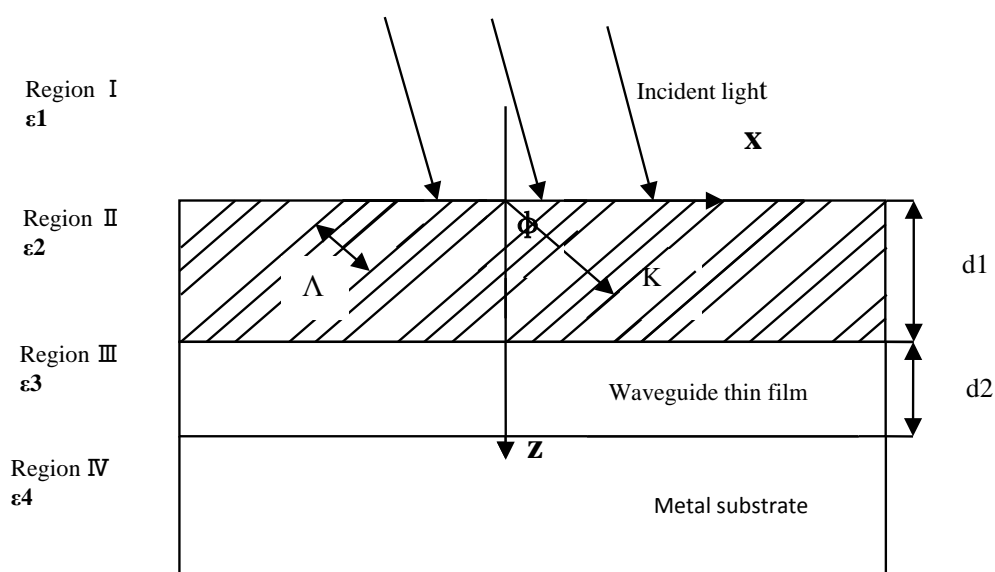
## 2. Proposed Structure for Double Spectral Notch Filter

The proposed double spectral notch filter is illustrated in **Figure 1**. It is basically a grating-SPR setup with a waveguide layer inserted. The lossless planar dielectric grating [11] [12] is characterized by a periodical medium. The relative permittivity can be depicted by

$$\varepsilon_2(x, z) = \varepsilon_{avg} + \Delta\varepsilon \cos[K(x \sin \phi + z \cos \phi)] \quad (1)$$

where  $\varepsilon_{avg}$  is the average permittivity and set to be 2.25,  $\Delta\varepsilon$  is the amplitude of the sinusoidal permittivity and set to be 0.33. The grating slant angle  $\phi$  is to be  $\pi/2$ , and  $K = 2\pi/\Lambda$ , here  $\Lambda$  is the grating period. The period of the grating is fixed at  $\Lambda = 400$  nm.

The Drude model is adopted to simulate the substrate Ag film in region IV with plasmon frequency  $\omega_p = 1.37 \times 10^{16}$  rad/s and the collision frequency  $\gamma = 7.29 \times 10^{13}$  rad/s [13]. A waveguide layer is sandwiched between the top of the planar grating and the metal substrate. The refractive index of waveguide layer is chosen to be  $n_3 = 1.5$ . The planar grating height  $d_1$  and the waveguide layer thickness  $d_2$  are chosen to be 100 nm and 40 nm, A  $p$  polarized collimated beam with central wavelength  $\lambda$  illuminates the grating with an incident angle  $\theta = 10^\circ$ . The incidence wavelengths we are interested in the visible light range from 390 nm to 760 nm.



**Figure 1.** Schematic diagram of double notch filter structure.

### 3. Numerical Calculations and Discussions

Firstly, the rigorous coupled-wave analysis (RCWA) method [11] [12] is used to calculate the reflection characteristics. **Figure 2** shows the reflection spectrum including double deep and narrow reflection dip observed in the visible spectral range. The reflection curve exhibits evident filtering property at the two dips. The reflection dips are deep and the reflectance both reaches 3%, very close to zero. The reflection response exhibits Lorentzian shape at the resonant wavelength of 549 nm and 651 nm. It is found that the FWHM of two dips resonance wavelength is less than 2 nm. Although, the two resonant modes have the same shape and nearly the same deep depth, the resonant conditions are not the same. The coupling condition can be calculated from the well-known grating equation [14]

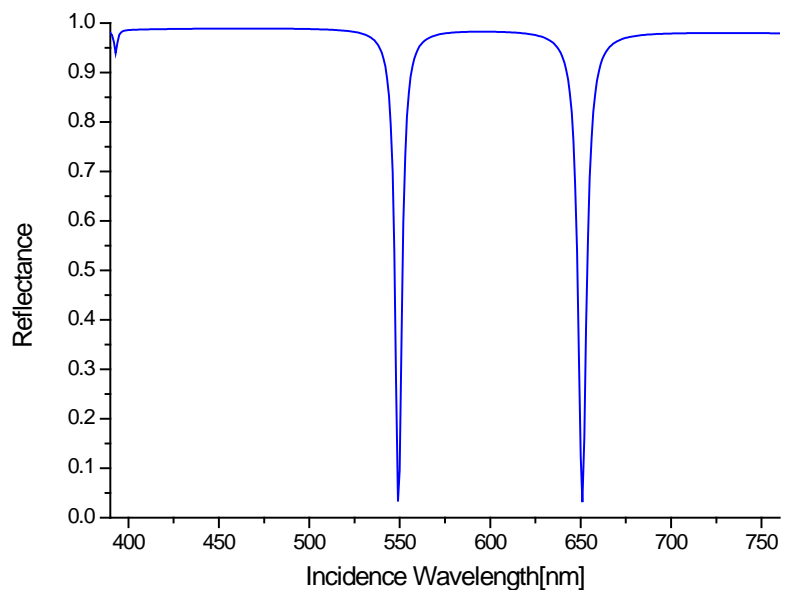
$$n_{eff} = n_c \sin \theta + m \frac{\lambda}{\Lambda} \quad (2)$$

where  $n_{eff}$  is the effective refractive index of the guided mode or the SPP mode,  $n_c$  is the refractive index of the cover layer (air in the schematic shown in **Figure 1**),  $\theta$  is the coupling angle,  $m$  is the diffraction order,  $\lambda$  is the wavelength in free space, and  $\Lambda$  is the grating period.

Treating the grating structure as a homogenous layer using effective refractive index theory, the effective average refractive index of the grating layer to a first-order approximation can be written as [15]

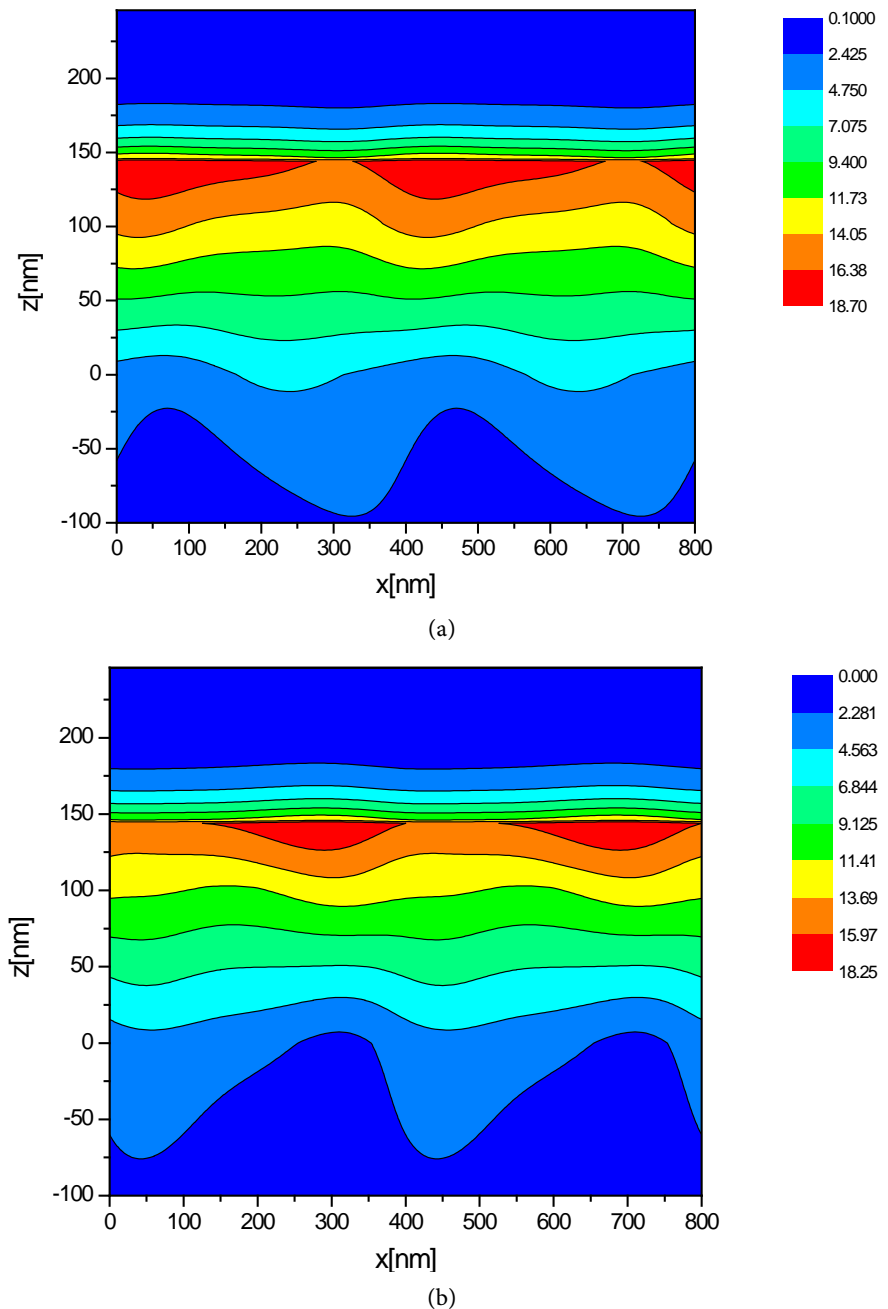
$$\frac{1}{\varepsilon^{gr}} = \frac{f}{\varepsilon^A} + \frac{1-f}{\varepsilon^B} (TM) \quad (3)$$

where  $f$  is fill factor of material  $A$  in a grating period. The grating is composed of materials with the relative permittivity  $\varepsilon^A$  and  $\varepsilon^B$ . According to the above Equation (3), the effective refractive index of the planar grating in the proposed structure is 1.54.



**Figure 2.** The computed 0th order reflection spectrum.

Using Equation (2), the resonant wavelength of waveguide mode is inferred to be excited at 546.8 nm. And the resonant wavelength in the calculated spectra is shown at 549 nm in **Figure 2**. It is that the wave vector of the first diffracted order beam matches that of one guided mode, coupling occurs. GMR effect will occur if the evanescent diffractive-order waves diffracted by the grating layer are coupled into the waveguide mode that can be propagated in the waveguide layer. Field distributions of  $|H_z|$  at the incident wavelength of 549 nm are depicted in **Figure 3(a)**. It is found that the excitations of resonant modes emerge in the



**Figure 3.** (a) Field distributions of  $|H_z|$  at 549 nm; (b) Field distributions of  $|H_z|$  at 651 nm.

waveguide layer and the magnetic fields are sharply confined to the dielectric waveguide layer. The field of other regions is evanescent gradually. It is no other than the guided resonances in the dielectric layers.

On the other hand, the other dip at 651 nm meets the resonance condition of the surface plasmon resonance. The relative permittivity of silver film at 651 nm is  $21.3731 + j0.563291$ . So the effective refractive index of surface plasmon polaritons is 1.46112. The resonant wavelength of surface plasmon resonance mode estimated is 653.8 nm by the wave vector of the first diffracted order beam matching that of surface plasmon resonance mode. The near field distributions of  $|Hz|$  at the incident wavelength of 651 nm are depicted in **Figure 3(b)**. The magnetic field is sharply confined to the interface between the Ag substrate and the dielectric layer due to the excitations of SPPs.

#### 4. Conclusion

In this paper, we introduce a thin dielectric waveguide layer into the conventional grating-excited SPR device. The evanescent diffractive-order waves diffracted by the grating layer are coupled into the waveguide layer to excite the guided resonance and surface plasmon resonance in the same structure. Double deep and narrow reflection spectra dips can be obtained. This physical explanation is confirmed by the momentum matching conditions of resonance and the field distribution calculation. As an example, double notch filter design with full width half maximum less than 2 nm centered at 549 nm and 651 nm is presented.

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#### Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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