Optics Communications 358 (2016) 140–146

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Fano resonance and tunability of optical response in double-sided dielectric gratings

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A R T I C L E I N F O

Article history:
Received 21 June 2015
Received in revised form
10 August 2015
Accepted 10 September 2015
Available online 21 September 2015

Keywords:
Fano resonance
Double-sided dielectric grating
Rigorous coupled-wave analysis

A B S T R A C T

A tunable resonant doubled-sided dielectric grating (DSDG) structure has been designed for operating in the near-infrared (NIR) wavelength range under transverse electric (TE) polarization. The rigorous coupled-wave analysis (RCWA) is applied to determine the optical characteristics, and the reflection resonance of the grating structure is analyzed by varying their geometrical parameters. The excited sharp Fano resonance (FR) is demonstrated numerically that does not occur in single layer grating. The maximal magnitude of electric field in the spacing layer sandwiched by the gratings is 35 times enhanced compared with incident filed, that dues to the waveguide resonance, which can be excited by a normally incident plane wave in the proposed design. The relationship between structure parameters of DSG and the reflectance spectrum in order to guarantee the appearance of FR in the designed structure is fully investigated. An optical refractive index (RI) sensor with a potential sensitivity of 602.15 nm/RIU is designed based on the proposed structure. The method demonstrated may lead to potential applications for the design of tunable filter or modulator with narrow-band with a wide range of potential applications including telecommunications, optical information processing, and optical sensors.

1. Introduction

Fano resonances (FRs), which is distinguished by an asymmetric line shape or a narrow resonance dip, has been explored widely in various micro/nanophotonic structures and employed for lots of potential applications in the development of chemical or biological sensing, lasing, switching, nonlinear and slow-light devices, and so on [1,2]. FR can be generated from the destructive interference between an overlapping broad resonance with a narrow resonance. Conventional FRs in plasmonic nanostructures have been widely investigated. However, nanostructures made of metal intrinsically suffer from strong Ohmic loss, and saturation effects which limit the quality factor (Q) and spectral contrast under rather small values precluding further performance improvement [3–7]. Very recently, all-dielectric nanostructures exhibiting low-loss scattering and strong magnetic response at visible wavelengths have drawn increasing attention [8,9].

Coupled waveguide grating structure is another compelling approach to generate FRs [10–12]. FR generally originates from the interference between a coherent background pathway and a resonance assisted pathway. A large number of research works have been reported on FR in high-contrast grating (HCG). For example, Zhou et al. designed and demonstrated a GaAs-based high quality resonator to achieve high *Q* value using the FR in subwavelength HCG [13]. Karagodsky et al. presented a simple analytic method to explain the multimode Fabry-Pérot resonance mechanism in resonant HCG [14]. Ahmed et al. provided a coupled mode theory to design and analyze a high-Q HCG resonator with FR [15]. Hu et al. developed a semi-analytical model for the analysis of HCG structures and investigated the FR with the proposed model [16].

Recently, Nghia et al. have used the RCWA method to investigate the optical transmission features of an Au and Ag DSG structure comprising a SiO_2 layer sandwiched between them [17]. The results have shown that the transmission spectrum of the DSG structure in the visible region can be tailored by changing the grating profiles and is insensitive to the angle of incidence. Single layer grating filters offer limited quality factor Q and limited dispersion engineering capabilities for fine-tuning the output spectrum. The DSG offers a flexible way to control the *Q* factor, optomechanical interaction, and resonant wavelengths by varying the gap distance and the alignment between two layers. To our best knowledge, there are no works using FR for the tunability of optical response in the near infrared wavelength range.

In this paper, we study a asymmetric structure, of which each of the two grating layers is periodically corrugated. The configuration is analyzed and its optical reflection in the NIR range is numerically calculated by employing the RCWA method. Geometric parameters (the filling factor, the grating thickness, and the

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http://dx.doi.org/10.1016/j.optcom.2015.09.036
0030-4018/

grating period) and distance between the two grating structures are varied to control the interaction between the modes supported by the structure. Furthermore, we demonstrate that the control of these interactions enables FR and tunable filtering properties of the reflection spectra. Further, the physical origin of FRs is confirmed by plotting electromagnetic fields, and the reflection spectrum of the DSDG is examined at different angles of incidence. Finally, the change in the resonance curve caused by the change in the refractive index of surrounding materials is considered.

2. Structure profile and numerical method

Fig. 1(a) shows a schematic illustration of the proposed DSDG structure considered in this study. Its reflection properties are numerically studied using the RCWA in the NIR spectrum ($1.5\ \mu m < \lambda < 1.7\ \mu m$). The DSDG consists of two titanium dioxide (TiO_2) single-layered gratings with thicknesses h_1 and h_2 placed in air and separated by a silicon dioxide (SiO_2) layer with a thickness t. Each grating has the form of a slit array with a period $\Lambda = 1.09\ \mu m$, the grating widths $w_{1,2} = \Lambda f_{1,2}$, the filling factor $f_1 = 0.6$, $f_2 = 0.3$, the grating thickness $h_1 = 0.23\ \mu m$, $h_2 = 0.345\ \mu m$, and the dielectric thickness is set to $t = 0.255\ \mu m$ for ease of fabrication and a support as base for DSGs. It is also noted that the geometric parameters are compatible with current fabrication techniques such as electron-beam lithography (EBL), plasma enhanced chemical vapor deposition (PECVD) and lift-off method. The potential fabrication process can be implemented through depositing a 255 nm SiO_2 layer and alignment markers are deposited on the polished Si substrate by PECVD technology. The top layer TiO_2 grating of the designed structure is defined by EBL in a PMMA (poly(methyl-methacrylate)) resistant layer and then developed, following by TiO_2 deposition and lift-off; in the next step, the membrane is released with the wet etch of Si substrate and the lower surface of SiO_2 is polished; on the lower surface of SiO_2, the bottom layer TiO_2 grating is fabricated by the same method [18,19].

As an electromagnetic modeling tool, we apply the RCWA method [20,21], which is based on a Fourier modal decomposition of the fields inside a transversely periodic structure and is a well-established technique for analyzing subwavelength periodic gratings. Using this method, we investigate the optical performance characteristics shown in Fig. 1(b). We assume that this structure is infinitely long in the x direction and all simulation results are normalized to the incident light power. The validity of our numerical method is confirmed by comparing the results with those obtained from the finite-difference time-domain (FDTD) method. The electromagnetic wave is incident on this structure with the electric field polarized along the grating lines (TE polarized light) normally.

A light beam is coupled into the light guide by a grating if the propagation angle of the mth diffraction order (usually $m = 1$) is $\theta_m \geq \theta_{tot} = \arcsin(1/n)$, where θ_m is the angle between the light ray and the surface normal of the grating, θ_{tot} is the critical angle of total internal reflection, and n is the refractive index of the light guide (in this article we will use $n = 1.446$ corresponding to SiO_2 material). The refractive index of TiO_2 can be described using a two term Sellmeier dispersion equation $n^2(\lambda) = 1 + \frac{A\lambda^2}{\lambda^2 - B}$, where $A = 4.316$, $B = 3.846 \times 10^4\ nm^2$, and λ is the wavelength in vacuum (in nm) [22].

In view of FR, the pure DSDG-induced eigen-modes and the pure cavity eigen-mode play the roles of the discrete level and quasi-continuous mode, respectively. The grating diffraction in the horizontal direction x could form the optical Bloch states. With the normally incident light, the grating induced Bloch states at the Γ point (where the transverse wave vector is zero) are discrete. The Fano line shape in Fig. 1(b) is the result of coupling between the quasi-continuous cavity mode and the discrete grating-induced Bloch level at the Γ point [20]. The line-width of the resonance reaches the minimum at 1.6027 μm, where the corresponding Q factor can be calculated as $Q = \lambda/\Delta\lambda = 1238$ (λ is a resonant wavelength of the FR and $\Delta\lambda$ is defined as the difference of the frequency at transmission peak and dip).The properties of top and bottom SGs are also shown in Fig. 1(b), most of the light is reflected.

In order to interpret the FR more clearly, we plot the absolute y component of electric field distribution ($|E_y|$) of the grating array for a unit cell at resonance. Fig. 2 depicts the field pattern at the wavelength of 1.6027 μm. In the spacing layer between the TiO_2 gratings, there exists strong electric field confinement. Accompanied by the high Q-factor, the maximal electric field intensity in the structure is about 1125 times of the intensity of incident electric field. Generally speaking, the field enhancement effect is a natural result of the waveguide resonance, and the waveguide mode can be excited by a normally incident plane wave. Obviously, this physical origin of FR can be employed to design filters, polarizers, or plasmonic sensors as demonstrated.

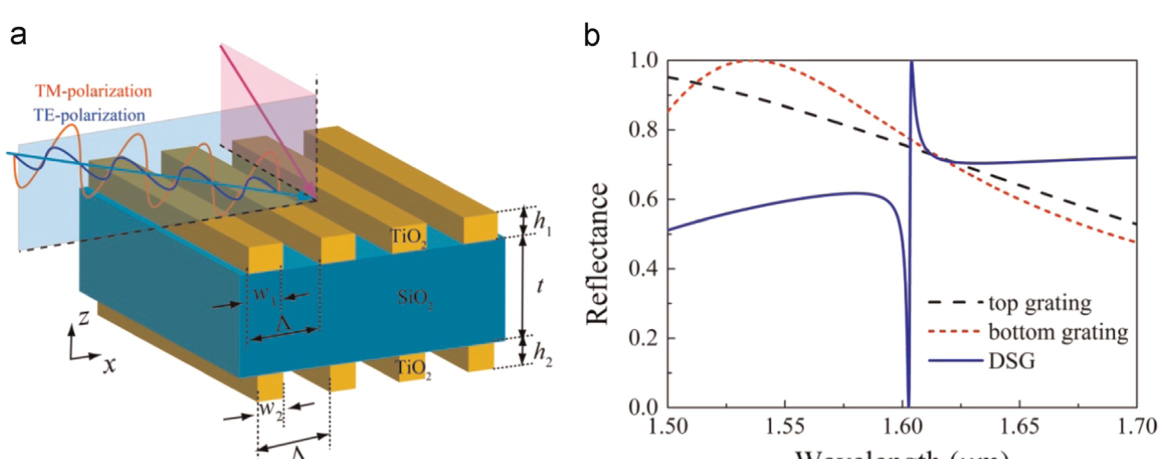

Fig. 1. (a) Schematic illustration of TiO_2 DSDG structure with grating period Λ, grating thicknesses of the first and second layers h_1 and h_2, respectively, SiO_2 thickness t, and filling factor of the first grating and the second grating f_1 and f_2, respectively.