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SPECTRAL RESONANT PROPERTIES OF REFLECTED LIGHT FOR METAL DIELECTRIC SUBWAVELENGTH GRATINGS IN VISIBLE REGIONS

РЕЗОНАНСНЫЕ СВОЙСТВА СВЕТА, ОТРАЖЕННОГО ОТ МЕТАЛЛОДИЭЛЕКТРИЧЕСКИХ СУБВОЛНОВЫХ РЕШЕТОК В ВИДИМЫХ ОБЛАСТЯХ СПЕКТРА

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A metal-dielectric grating consists of alternating metal and dielectric materials with period less than single wavelength of visible radiations. Optical behaviors of reflection spectra of this grating for *s*-polarized and *p*-polarized incident white light are studied systematically. For reflected light, it is the *p*-polarized light rather than *s*-polarization shows unusual optical behaviors with characteristics of single-peak spectra, higher peak efficiencies of higher than 75% and lower off-resonant efficiencies. The spectral width of *p*-polarized light with desirable frequency-selective functions is much wider. There exist two resonant areas for *p*-polarizations extending toward each other as filling factors increase, and positions of the resonances are mainly determined by grating periods existing linear relationships between them. For making positions of resonances occur in visible wavelengths, filling factors and grating periods should be respectively designed between 0.5 and 0.6 and between 0.25 and 0.45 μm. The newly observed properties of *p*-polarized lights can be used to exploit novel devices for reflection applications in the fields of optical securities and color filters.

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1. Introduction

Subwavelength structures on the surface of a metal or dielectric film can strongly modify its interactions with electromagnetic fields [1]. This capability of manipulating light via subwavelength gratings has attracted a significant interest in the last decade to investigate its resonant process, properties, and potential applications in various fields e.g. photonics, display devices, etc [2, 3]. Spectral resonances refer to rapid fluctuations in spectral efficiencies of light reflected or transmitted from its minimal value to maximum generally higher than 70% and back again as a function of some physical parameters of such structures (e.g. wavelengths). This property, as one of some distinct optical properties of the structures, can be used to exploit novel optically anti-counterfeiting technologies [4, 5].

Dielectric sub-wavelength gratings for visible wavelengths if designed appropriately can exhibit intriguing spectral resonant characteristics of reflection in *s*-polarization (electric field parallel to grating lines) with a single peak, peak efficiency of almost 100% and spectral width (full width at half maximum) of ~0.01 μm at normal incidence [6]. The reflection peak of this grating will split rapidly apart into double peaks shifting toward shorter and longer wavelengths separately for increasing the angle of incidence, with better potential of applications in optically variable image security fields. The resonances of the grating are considered to result from coupling of externally propagating waves to waveguide modes [7].

Metal subwavelength gratings can also possess unique resonant behaviors, called as extraordinarily optical transmission, if designed, which is suggested to originate from the excitations of (surface-plasmon polaritons) SPPs [8]. There exist vast reports on resonances of metal gratings, up to now, and much progress has also been made with various subwavelength structures, such as arrays of slits and apertures, etc [19, 10], but the vast majority of them only aim to achieve extraordinary transmission and beaming characteristics of light transmitted at specific wavelengths. To our knowledge, the report on reflection spectra resonances of this grating operating in visible wavelength ranges and its applications for producing the effects of color shifts detected by naked eyes to optical security have not been provided so far. So, it is significant to study spectral resonant properties of reflected lights of this grating and its relative applications. In this article, spectral resonant properties of reflection of metal-dielectric gratings have been studied systematically for producing seen color effects. This grating studied with period less than wavelength of visible light consists of alternating metal and dielectric materials and the s-polarized and p-polarized (electric field perpendicular to grating lines) normal incident white lights are considered. In addition, the dependences of grating parameters including filling factors, grating periods and depths on resonances are also simulated. Different from s-polarization (reflection) resonances of dielectric gratings [5, 6], for metal-dielectric gratings, it is p-polarized lights that can produce desired spectral resonant behaviors of reflection if it is designed properly. This feature can be exploited in applications of advanced optical securities with effects of seen color varieties.

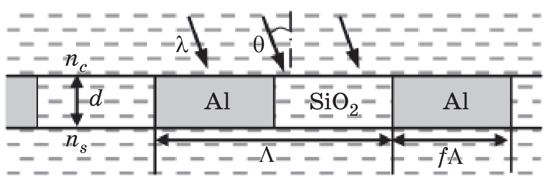

Fig. 1. Cross-sectional configuration of metal-dielectric structures.

2. Metal-dielectric gratings and spectral resonances

The metal-dielectric subwavelength grating under study consists of alternating metal and dielectric materials, as illustrated in Fig. 1. The grating period is denoted by Λ, the depth is denoted by d, and its filling factor referring to the ratio of metal width to Λ is denoted by f. Here, Λ is shorter than wavelengths of visible light (0.38–0.78 μm) for making requirements of subwavelength gratings fulfilled.When a beam of light with wavelength λ at an angle θ impinges the grating (Fig. 1)surrounded by a cover region ofindex n_c and a substrate region of index n_s, owing to excitations of SPPs and cavity resonances [11, 12], some interesting optical properties related to reflection can be obtained. For gratings studied, aluminum and silicon oxide are chosen separately as materials of metal and dielectric and the silicon oxide was assumed to possess a constant refractive index of 1.5 with negligible small loss for visible incident lights. The data for complex refractive indices of aluminum are taken from literature [13] and interpolated for every given wavelength by use of cubic splines. A rigorous coupled wave analysis method [14] is adopted to study optical properties of the grating. Within this method, it is feasible to calculate correctly the spectra of reflection of gratings, 100 spatial harmonic orders are kept and step length of wavelength increasing is 0.001 μm when simulations are performed for s-polarized and p-polarized lights in the case of non-conical diffractions.

To systematically study the spectral resonances of the gratings, based on the considerations of subwavelength gratings for normal-incident visible radiations, we take following grating parameters: $f = 0.5$, $\Lambda = 0.3435$ μm, $n_c = n_s = 1.5$,

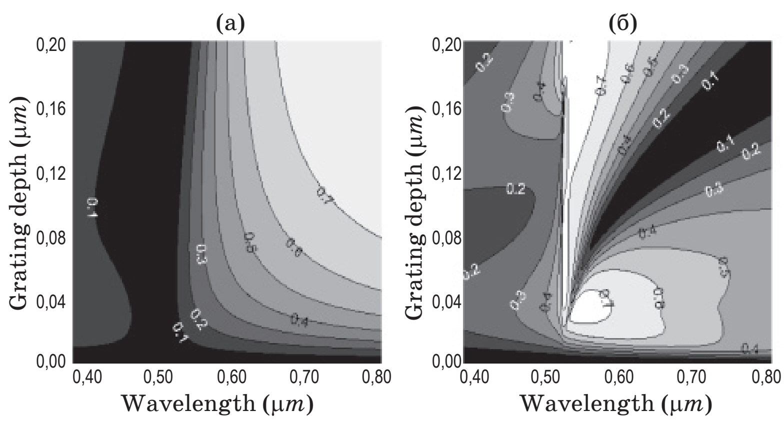

Fig. 2. Contour plots of reflection efficiencies for s-polarized (a) and p-polarized (b) lights when wavelength and grating depth are changed and gray scales are linear in efficiencies.

and d varies from 0 to 0.2 μm. The grey distribution plots of reflection efficiencies as functions of grating depths and wavelengths for s-polarized (a) and p-polarized (b) radiations are shown in Fig. 2. The gray scale of this plot is linear in the efficiency calculated, the whiter region has higher value, and the numbers express the values of efficiency at the positions of the black lines. It is clearly observed from Fig. 2 that the resonant behaviors for s-polarizations and p-polarizations are different. For reflected light, it is the p-polarized light rather than s-polarization that obtains desired resonant behaviorsof spectra with properties of single peak, higher peak efficiency and lower off-resonant efficiency. This single-peak resonance property of the grating can be exploited for colorizing incident white lights through design for grating depths e. g. $d = 0.12$ μm. Moreover, there exist two prominent resonant areas with efficiencies of higher than 70% and their resonant wavelengths are located between 0.50 and 0.55 μm. When d is smaller than ~0.005 μm, efficiencies for s-polarizations and p-polarizations is lower of less than ~10%. This reason is that absorption coefficient κ of aluminum in visible bands is rather higher, ranging from 4.3 to 7.1, and the grating with thickness below λ/κ can be considered transparent. The spectrum for s-polarizations at any grating depth, ranging from 0.05 to 0.20 μm, has not yielded the expected behavior of single-peak resonance, fluctuations of efficiencies at some grating depth e.g. $d = 0.10$ μm and varieties between spectra of different grating depths are both slower. In reality, cavity resonances in dielectric slits of this grating are mainly responsible for reflection resonances of p-polarized lights, because the position of plasma-resonances of aluminum lies near the wavelength of 0.83 μm and its spectral width is quite narrow in visible ranges, too narrow for colorizing incident white lights.

3. Results and discussions

To achieve in-depth understanding of the metal-dielectric gratings, effects of the varying parameters of gratings including f, Λ and d on resonances have been systematically studied. First, effects of f and d on resonances are considered. Figure 3 shows grayscale images of reflection efficiencies for s-polarizations (Figs. (a)–(d)) and p-polarizations (Figs. (e)–(h)) as functions of λ and d for four different filling factors, i. e. $f = 0.3$, 0.4, 0.6, 0.7. From Figs. 2 and 3, it is known that there exist two resonant areas in any one of all the plots of p-polarizations for the grating, spaced distinctly by the line of $d = {\sim}0.1$ μm when $f \le 0.4$ and increasing gradually from its center location of resonances as f increases from

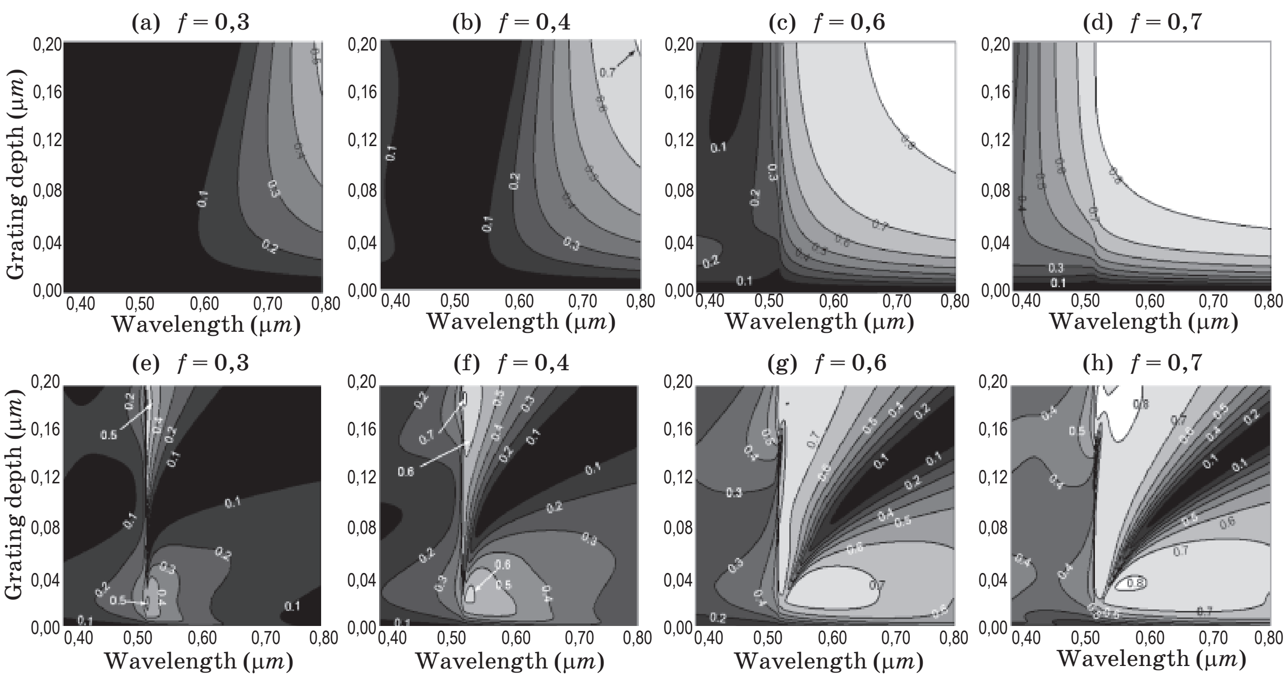

Fig. 3. Contour plots of reflection efficiencies for s-polarized (first lines) and p-polarized (second lines) incident lights as functions of wavelengths and grating depths at different filling factors: $f = 0.3$, 0.4, 0.6, and 0.7, respectively.

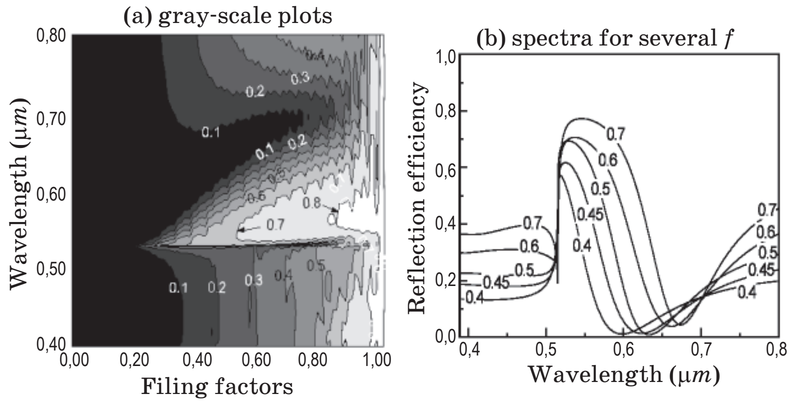

Fig. 4. Reflection efficiencies as functions of wavelengths and filling factors for p-polarizations and $d = 0.12$ μm.

0.3 to 0.7. The upper one of both areas has a long and narrow profile for efficiencies of higher than 70% when $f \geq 0.45$. Compared with spectra for d between 0.14 and 0.20 μm, spectra for d between 0.08 and 0.14 μm with desired shapes have lower off-resonant efficiencies and narrower spectral widths. For the other of both regions, there exists indeed one region with efficiencies of higher than 70% when $f \geq 0.45$ extending as f increases from 0.45, but its spectral width are much wider with a value of greater than 0.2 μm when $f = 0.50$. So, d should be located between 0.08 and 0.14 μm e.g. $d = 0.12$ μm for design of gratings with easily seen saturated color effects. In contrast, spectra of s-polarizations for different filling factors have not obtained desired optical behaviors similar to those of p-polarizations. When f is lesser e.g. $f < 0.3$, efficiencies of spectra at any grating depth e.g. $d = 0.05$ μm have less values for visible radiations because the vast majority of lights transmit directly through the grating. Intensities of lights reflected are wholly enhanced when f increases, however, contour plots for different filling factors are very similar with each other in profile except for different grayscale values. Consequently, it is very hard to make lights of s-polarizations with controlled color effects. Figure 4(a) gives contour plots of efficiencies of reflection as functions of λ and f for p-polarized radiations and $d = 0.12$ μm, and Fig. 4(b) shows curves of spectra extracted from Fig. 4(a) at $f = 0.4$, 0.45, 0.5, 0.6, 0.7. It is easily found from Fig. 4 that efficiencies of gratings for different wavelengths are all lower than 10% when $f \leq 0.35$ and spectral widths of resonances increase as f increases from 0.4. The peak position of spectra shifts toward longer waves when $f$changes from 0.4 to 0.7, with peak efficiency increasing from 60% to 80%, spectral bandwidth extending from 0.03 to 0.2 μm and efficiency of off-resonant wavelengths increasing from 17% to 38%. Therefore, for colorizing incident lights and obtaining bright saturated color aspects, $f$should be designed between 0.5 and 0.6 and then lights reflected will possess desirable spectral bandwidths of ~0.06 μm.

In addition, considering that Λ is a very crucial parameter of designs, it is very necessary to establish the relationship between Λ and λ. The simulation results of the effects of Λ on spectral resonances of this grating for s-polarized lights when $d = 0.12$ μm are shown in Fig. 5. It is shown clearly that for given materials and parameters of the grating, the resonant position or wavelength is primarily determined by Λ, almost a linear function of Λ with a slope of ~ 1.68 in this case. The design for a controlled color hue or resonance location amounts to determining the parameter of Λ. This can be understood as a direct consequence of grating equations [15]. The distinctive p-polarized resonances can be attributed to cavity resonances in dielectric materials

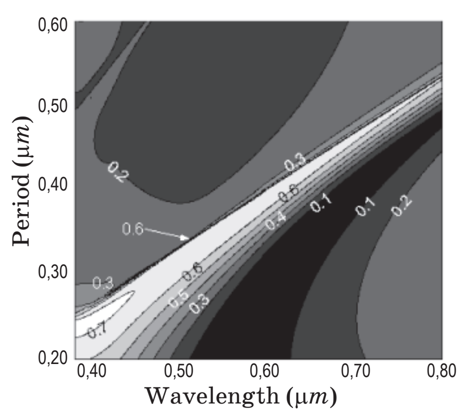

Fig. 5. Effects of grating periods on reflection resonances for $d = 0.12$ μm.

of the grating and excites of SPPs. Moreover, for reflected light, it should be mentioned that the resonant behavior of metal dielectric gratings is completely different from that of dielectric gratings in reflection applications of color changing securities for getting seen color effects [5, 6], because the former is the resonance of p-polarizations and the latter is that of *s*-polarizations. Owing to that the resonant wavelength determines color hue of reflected light and spectral width affects the saturation of the color, the parameter of Λ should be between 0.3 and 0.5 μm when designed for colorizing the grating.

4. Conclusion

Metal dielectric gratings consist of alternating metal and dielectric materials with periods less than wavelengths of visible lights. Characteristics of resonances of reflection spectra and influences of grating parameters (e.g. f, Λ and d) on reflections, for *s*-polarized and *p*-polarized incident white light, are studied systematically. It is found that, for reflected light, it is the *p*-polarized lights rather than *s*-polarization shows unique optical behaviors with characteristics of single-peak spectra, higher peak efficiencies of higher than 75% and lower off-resonant efficiencies, and its spectral width with desirable frequency-selective functions is much wider than that of well-known surface-plasmon resonance. The parameters of d and Λ are very crucial parameters of design of this grating. There exist two resonant areas for *p*-polarizations with centers at both positions of $d = 0.03$ and 0.18 μm extending toward each other as f increases, and the positions of its resonances are mainly determined by Λ existing linear relationships with a slope of ~1.68 between them. The resonance will be greatly strengthened when f increases from a less value e.g. 0.2, with its spectral width increased. For making positions of resonances occur in visible wavelength ranges, the parameters of f and Λ should be respectively designed between 0.5 and 0.6 and between 0.25 and 0.45 μm. The newly discovered properties of *p*-polarizations of this grating different from those of surface-plasmon resonance can be used to exploit novel productions for applications to the fields of securities with seen color changes and color filters. Practically, the design for color hues of the grating such as green, blue, etc. has already determined the parameter of Λ, and designs for other parameters are used mainly to improve its performances or visual effects. For applications by means of reflection resonances of the grating such as optically variable securities, color filters, etc., the *p*-polarized light rather than *s*-polarization should be adopted for colorizing incident white lights in a controllable way.

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