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A novel metal/dielectric combined grating structure incorporating optically thin plasma metals with the properties of controllably polarization and spectral filtering

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ABSTRACT

A novel metal/dielectric hybrid grating structure incorporating ultrathin plasma metals and intercross-cascaded dielectric gratings is proposed, characterized by owning the capacities of freely design of resonance and flexibly controls of filtering and polarization, for TE- and TM-polarized lights. Its distinctive resonant behaviors in reflection and transmission and controllable trimming ability in coloration and spectrum are systematically studied as well as origins of the resonances. Several specific grating structures are designed and optimized for color security and transparent display, and their characteristics of peak-splitting, resonance, filtering and polarization for coloration also discussed. By virtue of the structure, respectively manipulation and control for resonant spectra including locations of peak-valley, line-shapes and band-widths for TE- and TM-lights can be realized as well as simultaneously combined modulation for both polarizations. Better prospect of application exists in various fields for the structure including color decoration, optical and color security, transparent display and color imaging, etc.

1. Introduction

Structure coloration as a special color in nature is produced mainly by physical interactions of incident light with structures of materials including interference, diffraction and scattering etc. rather than absorption [1], widely existing in nature and used by plants and animals [2]. However, in our society, by utilization of the structures with feature size smaller than wavelength of incident light, the manipulation for light at deep subwavelength scale is feasible so that some colors with the effect similar or superior to that of the nature's color can be created [3–8]. Chen et al. proposed a one-dimensional metal-dielectric structure embedding a 0.1μm-thick Ag grating with the abilities of reflection resonance [3]. Lochbihler et al. presented a concept of two-dimensional periodic gratings incorporating two metal gratings for color filtering of un-polarized lights and exemplified its optical and color properties [4,5]. Ye et al. reported a polarizing color filter combining the functions of a polarizer and a color filter [6]. Hguyen-Huu et al. designed a transmission color filter based on a waveguide-metallic grating with advantages of single peak and broader bandwidth [7]. Qin et al. fabricated three primary color filters consisting of triangular-lattice hole-arrays in an aluminum film on glass [8]. Such colors above are primarily originated from the mechanisms of waveguide resonance (WGR) and extraordinary optical transmission (EOT) [9,10] and the imbedding of an optically-thick dielectric-metal grating into the filters is usually indispensable to color applications of filtering. Much less

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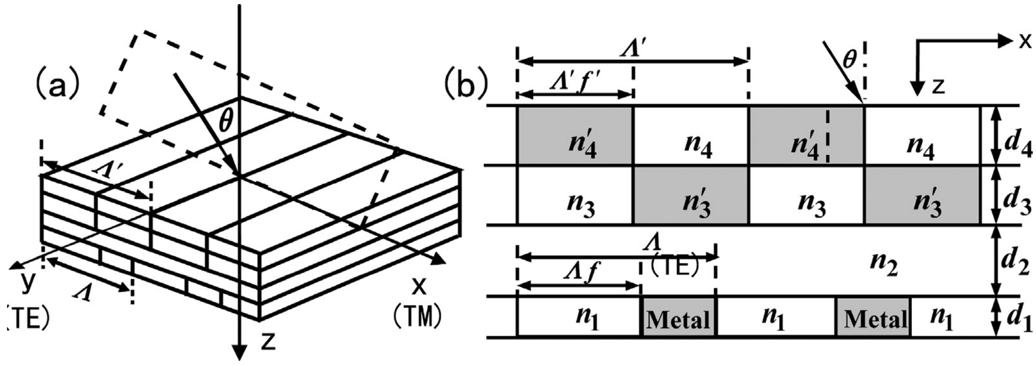

Fig. 1. Schematics of the MDHGS for (a) the geometry structure and (b) the transverse view.

work to my knowledge has been focused on the study on the structure of incorporating ultrathin dielectric-metal gratings as well as its optical and filtering behaviors so far.

In this paper, a novel metal/dielectric hybrid grating structure (MDHGS) incorporating ultrathin plasma metals and intercross-cascaded dielectric gratings, with the potentials of freely design of resonance and flexibly controls for filtering and polarization for TE- and TM-polarizations, has been proposed for the first time. Its distinctive resonant behaviors in reflection and transmission and controllable trimming ability in coloration and polarization have been systematically studied as well as origins of the resonances. Several specific grating structures have been designed and optimized for color security and transparent display and their characteristics of peak-splitting, resonance and filtering in spectra and polarization for coloration also discussed. By virtue of the structure, separately manipulation and control for resonant spectra including locations of peak-valley, line-shapes and band-widths for TE- and TM-lights can be realized as well as simultaneously combined modulation for both polarizations. Due to its fine performances, better prospect of application exists in various fields including color decoration, optical and color security, transparent display and color imaging, etc.

2. Device design and theoretical analysis

Fig. 1 depicts the schematics of the MDHGS for (a) the geometry structure and (b) the cross-sectional view consisting of four functional layers, i.e., from bottom up a d_1-grating incorporating ultra-thin plasma metals of “Metal” with thickness d_1 and a dielectric with refractive index n_1 interval arrangement in x-direction, a d_2-dielectric layer with refractive index n_2 and thickness d_2, and two dielectric gratings (d_3-grating and d_4-grating) with interval materials of respectively refractive indices n_3, $n_3{}'$ and $n_4{}'$, n_4 in x direction ($n_3{}'$-$n_3 \geq 0.35$, $n_4{}'$-$n_4 \geq 0.35$). Owing to the special design for d_3-grating and d_4-grating, the peculiar behavior of WGR [11] is supposed to arise in reflection for TE-lights providing a flexible way of controlling its spectra and colors. The d_1-grating is designed to offer resonance behavior in transmission for TM-lights, with the mechanism of different from WGR and EOT [12], used for freely trimming its spectra and coloration. For the TE and TM lights, the electric fields are assumed to be of the directions shown in Fig. 1(a). Other parameters of the structure shown in Fig. 1 are denoted as $\Lambda \in [0.05\ \mu\text{m}, 0.35\ \mu\text{m}]$ and $\Lambda' \in [0.1\ \mu\text{m}, 0.4\ \mu\text{m}]$ for grating periods, $f \in [0.35, 0.85]$, $f' \in [0.3, 0.7]$and $d_1 \in [0.002\ \mu\text{m}, 0.045\ \mu\text{m}]$, d_3, d_4 for duty cycles and thicknesses of the gratings ($0.15\ \mu\text{m} \leq d_3 + d_4 \leq 0.3\ \mu\text{m}$). For the structure, the ″Metal″ must be a special material of plasmonic metal, here Ag is chosen, so as to achieve highly controlled performances of filtering in spectra, colors and polarizations for TM-lights. Through the structure, singly control for the resonances of TE- and TM-lights in spectrum and coloration can be realized at any location of visible region as well as simultaneously combined control for both resonances, and ultimately structural colors with some unique properties such as high quality, rich variety and color variability, etc. may be controllably generated.

To predict its real performance more efficiently, the model of MDHGS has been established by means of DiffractMod 3.1 and FDTD Solutions and the rigorous analysis calculation [13,14] of reflectance and transmission carried out. In calculation, dispersion characteristic of the ″Metal″ is considered, dispersion data on Ag are derived from Ref. [15], $n_1 = n_2 = n_3 = n_4 = 1.5$, $n_3{}' = n_4{}' = 2.0$, $f' = 0.5$, $f = 0.65$, and TE- and TM-polarized white lights are incident normally at the structure. Fig. 2 gives characteristic spectra of the structure in reflection and transmission with the optimized parameters of $d_1 = 0.02\ \mu\text{m}$, $d_2 = 0.01\ \mu\text{m}$, $d_3 = d_4 = 0.1\ \mu\text{m}$, $\Lambda = \Lambda' = 0.25\ \mu\text{m}$ under TE- and TM-lights. Surprisingly, for TM-lights a transmission minimum of close to zero here at 0.618μm has been found, opposite to EOT phenomenon [9,10,16], and the incentives of surface plasmons at top and bottom interfaces of d_1-gratings as well as their couplings [17–19] are responsible for the resonance of extraordinary low transmission (ELT). Owing to the presence of Ag which causes losses, for TM-lights, the total efficiency of reflection and transmission is less than 100% for any wavelength of 0.3–1.0 μm, especially 74% total efficiency for the resonant location. In contrast, for TE-lights, its reflection exhibits a unique behavior of narrow-band resonance in spectrum, with single peak of not less than 80% efficiency, low sideband of not higher than 30% efficiency and narrow FWHM of 0.02 μm. And the WGR is response for the unique behavior of TE lights for the structure [2–4]. So the MDHGS is a structure with the capacity of combining TE-reflection peak-resonance and TM-transmission trough-resonance.