Optik 126 (2015) 1245–1248

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Waveguide-metal–dielectric bi-layer gratings for reflective filtering and color security

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ARTICLE INFO

Article history:
Received 25 February 2014
Accepted 1 April 2015

Keywords:
Structural color
Subwavelength grating
Reflective filtering
Color security
Material

ABSTRACT

A multi-material structure composed of a linear polarizer and a dielectric sandwiched between two metal–dielectric gratings of with π phase shifts and embedded in dielectric is proposed. Its properties of reflection resonance together with filtering ability of visible light are discussed thoroughly and main factors of impacting its functions are identified. Both such properties and line-shapes of its spectra can be effectively trimmed by thickness, symmetry, period and metal material of two gratings. The behaviors of its single-peaks and peak-splits in spectra in combination with peak-shifts can generate uncommon color variation of interchanges in reflection based on structured coloration. Various color filters of reflection operating in visible light can be realized by it as well as intricate color effects arising from structures. This structure is valuable for applications of filtering, decoration and security.

1. Introduction

Structural color that arises due to interaction of light with structures is ubiquitous in nature and can be found in various species [1,2]. Its success in nature together with special functions such as conspicuousness, camouflage, non-fading and environmental friendliness has inspired incorporation of it into technologies including textiles, decorations, displays, sensors and securities [3–5]. For these and other applications, the design of a suitable structure capable of producing desired colors using its resonance is very crucial. A variety of such devices using one-dimensional (1D) as well as two-dimensional (2D) subwavelength gratings (SWGs) have been proposed thus far, most of which are exploited for color filtering in transmission for image sensors and displays [6,7]. Some SWG structures as colorimetric sensors and reflective displays have also been investigated. Davoine et al. [8] developed a visual sensor composed of a dye layer and a waveguide grating for providing visual indications of chemical contamination. Uddin and Magnusson [9] fabricated a highly efficient dielectric guided-mode resonant (GMR) array of filters for reflective display. Moreover, the properties of filtering and coloration for metal SWGs [10,11] as well as 2D arrays of both nanoholes and nanodisks on surface of silicon [12,13] are studied. Recently, Wang et al. [14] presented a concept of reproducing colored images by GMR SWGs and Lochbihler demonstrated a SWG structure for coloring by reflectance capable of reproducing colored images [15].

In this paper, an alternative structure for filtering and coloring in reflection by its resonant excitations has been proposed. It will be demonstrated that through it all kinds of color filters with center wavelengths in visible light can be realized for both normal and oblique incident lights, together with intricate color effects perceived by naked eyes and based on structural colorations. Special attention is drawn to controls and trims of spectral lineshapes of the structure as well as understanding of its related properties so that main factors of impacting its filtering and colorations are identified. Distinctive characteristics of the structure such as structural colors, color variations from blue to red due to increase of viewing angles and color interchanges owing to rotation, are uncommon and valuable for color related applications, especially for color filtering and optical security.

2. Device design and theoretical analysis

Fig. 1 illustrates cross sectional views of the waveguide-metal–dielectric bi-layer grating (WMDBG) structure under consideration embedded in dielectric including a middle dielectric with refractive index n_f sandwiched between two metal–dielectric subwavelength gratings (MDSGs) with a π phase shift in x direction and a linear polarizer with polarization perpendicular to grating lines of the gratings. As shown in Fig. 1, refractive indices of cover and substrate are denoted separately by n_c and n_s, metal and dielectric with refractive index n and n' constitute the MDSGs, other

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http://dx.doi.org/10.1016/j.ijleo.2015.04.001
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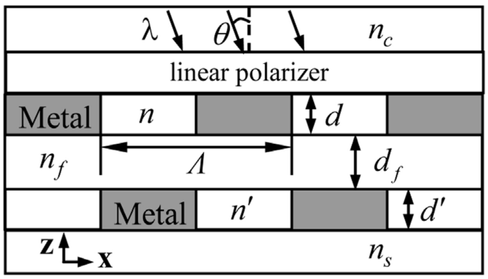

Fig. 1. Schematic of embedded WMDBGs.

parameters of the structure are denoted as Λ for grating period, $f = 0.5$ for duty cycle (ratio of metal width to Λ), and d_f, d and d' separately for thicknesses of middle dielectric, top and bottom gratings. When a natural light impinges the structure at an angle θ of incidence, special resonant behavior in reflection can be excited and a spectrum of with specific profile will be achieved along with desired color aspect, e.g. the spectrum of solid lines in Fig. 2 at $\theta = 0°$ with resonant wavelength $\lambda_{res} = 0.516$ μm for the structure with parameters: $\Lambda = 0.3435$ μm, $d = d' = 0.05$ μm and $d_f = 0.023$ μm.

To clarify performances of the structure in filtering and resonance, rigorous coupled wave analysis [5,16] calculation of reflectance from it has been carried out. In this study, ridge regions of both MDSGs are fabricated of aluminum (Al) with dispersion data of material from Ref. [17] while its grooves are filled with a polymethyl methacrylate (PMMA) with constant $n = n' = 1.48$, the middle dielectric is a PMMA layer, and 1.48 is also assumed for n_c and n_s. Effects of the bottom grating d' on spectrum profiles over range of 0.38–0.8 μm at $\theta = 0°$ are evaluated first and provided in Fig. 2. Noted that the structure at $d' = 0.0$ μm exactly corresponds to the grating of Ref. [18], and here two peaks in spectra together with a dip at ∼0.535 μm exist respectively at ∼0.52 and ∼0.56 μm of which the former is designed while the latter is unwanted. Reflections at ∼0.55–0.8 μm decrease greatly when d' increases from 0 up to ∼0.05 μm, yet as d' is further enhanced some unwanted reflections with efficiency of higher than ∼15% appears at ∼0.6–0.8 μm. In contrast, reflections at wavelengths shorter than ∼0.52 μm are quite insensitive to d'. Based on the structure, thus color filters in reflection with specific spectral profile along with seen color aspect can be realized, for which the existence of both MDSGs with identical grating strengths is very vital, and the thickness of the bottom grating is a crucial factor to suppress redundant spectral peaks and high sidebands at locations beyond λ_{res} (here 0.516 μm).

Fig. 3 illustrates the dependences of resonant spectra of the structure with designed $\lambda_{res} = 0.516$ μm on symmetrical strengths of both MDSGs at $d = d'$. Obviously, the peak reflection for λ_{res} is almost independent of thicknesses of both gratings similar to the case of Fig. 2 and most sideband reflections at unwanted wavelengths are well suppressed owing to increases of $d = d'$ from 0.03 μm up to 0.05 μm. When it increases further from 0.05 μm higher reflections appear for shorter wavelengths (near 0.4 μm) while better suppressions for reflections of near-infrared region are obtained. So for the structure this symmetry strength of $d = d'$ should be used mainly for trimming spectral lineshapes at wavelengths shorter than λ_{res}.

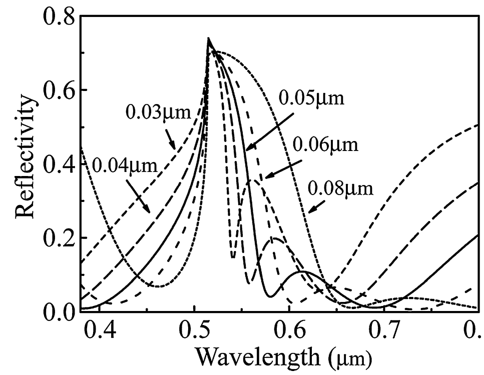

Fig. 3. Trims for reflection lights shorter than λ_{res} by symmetry strength of both MDSGs with $d = d'$.

3. Results and discussion

For the success in design of the filter with desired resonance and color aspect, the incorporation of both MDSGs with specific grating strengths into the structure is significant, but besides d and d' other parameters such as d_f, n_f, n_c, n_s and Λ also are very important for resonance and should be prudently considered. To get further understandings for filtering and color properties, effects of their fluctuations on resonant spectra are studied. Figs. 4 and 5 provide spectra in reflection as functions of changes of d_f and n_f. The designed behaviors of resonance at near λ_{res} from Fig. 4 are nearly not affected by variation of n_f, yet fluctuations of sideband reflections are more obvious especially for wavelengths at ∼0.6–0.8 μm. Noted that the geometry of the structure at $n_f = 0.0$ μm is similar with that of Ref. [19], but their behaviors of reflections and resonances in spectra are different due to diversities of grating materials, of which the former is metal and the latter is dielectric. With increase of d_f from 0 up to 0.04 μm, high sideband reflections at ∼0.7–0.8 μm are well suppressed, but an unneeded peak appears at ∼0.6–0.7 μm arising from film interference [5,14]. So a compromise between sideband reflection and redundant peak must be made so as to obtain better filtering and color aspect, and an optimized value of $d_f = 0.023$ μm is ultimately found. From Fig. 5,

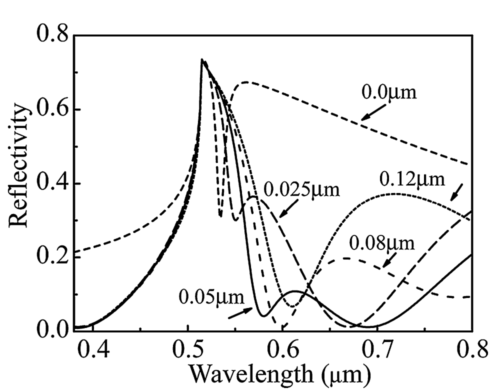

Fig. 2. Reflection suppressions for lights beyond λ_{res} by grating strength of the bottom grating.

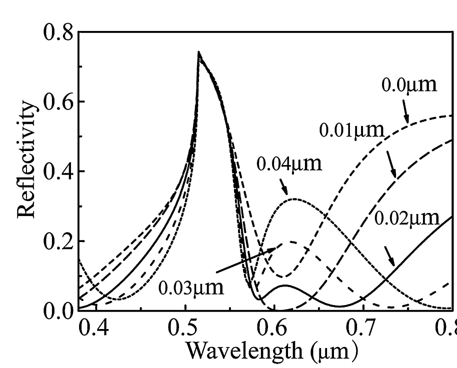

Fig. 4. Effects of d_f on reflection spectra.