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Membrane guided-mode resonant color filters exhibiting adjustable spectral response

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ABSTRACT

We demonstrate membrane guided-mode resonant color filters exhibiting adjustable spectral response using freestanding subwavelength HfO_2 gratings. Color filters capable of reflecting arbitrary colors can be achieved by varying the grating periods. Three primary colors with efficiencies of 55.3%, 73.2% and 62.5% are observed for filters with periods of 320, 400, and 500 nm, respectively. Resonance wavelength tuning capability of 120 nm is attained through adjustment of incident angle of input light using a filter with period of 320 nm. Blue, green, and red color responses are observed at 0°, 13°, and 31°, respectively. These membrane devices provide an approach for color filtering and spectral imaging with extremely compact structure.

1. Introduction

Color filters have been widely investigated due to their vital role in a variety of applications such as liquid crystal display devices, image sensors, light emitting diodes, etc. [1–3]. The conventional organic dye-based color filters, which transmit a certain color while absorbing the undesired spectral components under white light illumination, have disadvantages such as low efficiency, imperfect color selectivity, and performance degradation under long-time light illumination [4,5]. In an attempt to overcome these limitations, many approaches have been developed, including plasmonic nano-structures [6], metal–dielectric Fabry–Perot cavities [7], photonic crystal color filters based on a multilayer stack [8], and guided mode resonant (GMR) structures [4,9–15]. Among these technologies, GMR color filters are particularly attractive due to high efficiency, good color purity, simple structure and compact size. GMR color filters based on various materials, including semiconductor [9,10], metal [11,12], dielectric [4,13,14], and polymer [15], have been extensively investigated. However, metal and Si color filters exhibit relatively low efficiency owing to strong absorption in the visible wavelength range. Color filters based on lossless dielectric materials can provide high efficiency to make good use of available illumination. Using Si_3N_4 GMR gratings, Uddin et al. reported highly efficient reflection color filters with efficiencies of 94%, 96%, and 99% for blue, green, and red filters, respectively [4]. The red, green, and blue color components were generated by distinct filters with different grating periods. Besides, the resonant wavelength of GMR grating can also be tuned by incident angle and/or polarization of the input light. Angle-tuned [13] and polarization controlled tunable color filters [14] were demonstrated experimentally. Color filters have been mostly developed to improve the performance, in terms of high efficiency, narrow bandwidth, broad spectral tuning range, etc. To data, the efficiency and purity of three primary colors are mostly taken into account and have been intensively studied. However, performance of color filters in term of broad spectral tuning range should also be attentively considered. Recently, color filters capable of transmitting arbitrary colors using plasmonic nanoresonators were demonstrated [6]. The counterpart of reflective color filters still needs to be explored.

On the other hand, freestanding structures have been greatly developed as promising candidates for high efficient and compact devices [16–20]. With air as surrounding low refractive index materials, freestanding structures feature good optical confinement in the vertical direction, enabling superior optical performance. Such simple single layer characteristic offers more compact device design comparing with traditional multilayer dielectric film structures [16–20]. In Ref. [17], we have presented suspended HfO_2 resonant nanostructures combined with active material for

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developing integrated surface emitting devices. As an excellent optical material, HfO_2 is transparent from visible to infrared range, which also have thermal and chemical stability [21,22]. Currently, freestanding HfO_2 membrane structures have attracted special interest [20,23,24]. We developed a double-side process to achieve HfO_2 membrane structures by a combination of ion beam etching (IBE) of HfO_2 and deep reactive ion etching (DRIE) of silicon [20]. Unfortunately, cracks in the HfO_2 membrane were observed due to the strong residual stress. In this paper, cross arms are employed to fully release the stress and support the suspended membrane. We present the design and fabrication of membrane GMR color filters using subwavelength HfO_2 gratings in freestanding HfO_2 membrane. The devices are designed using a rigorous coupled-wave analysis (RCWA) method [25] and fabricated through the double-side process. Adjustable spectral response is attained through variations of incident angle of the input light or the grating period, which allows the proposed devices produce arbitrary color.

2. Device design and fabrication

The proposed color filters, consisting of an HfO_2 linear grating along with an HfO_2 homogeneous waveguide layer, are implemented on an HfO_2-on-silicon platform. Fig. 1 shows the cross-sectional schematic diagram of the proposed devices. Silicon substrate beneath the grating region is removed from backside, making the devices suspend in space. D_g denotes grating depth, P grating period, W grating width, and D thickness of homogenous waveguide layer. Fill factor F is defined as the ratio of grating width to grating period, i.e. $F=W/P$. I represents incident light, R_0 zero-order reflectance, T_0 zero-order transmittance, θ_i incident angle, and θ_0 angle of zero-order reflected light. When such a structure is illuminated with an incident light beam, GMR behavior occurs if coupling of diffracted light from the grating structure with a leaky waveguide mode satisfies phase-matching condition [26]. Sharp resonant peak can be observed, where 100% switching of light energy between reflected and transmitted waves occurs. The position and bandwidth of the resonance can be adjusted by geometric parameters, such as grating depth, grating period, fill factor and thickness of the waveguide layer, as well as optical parameters of the incident light, i.e. incident angle and polarization [26]. The grating periods of the proposed devices are chosen to be smaller than the wavelengths, allowing the devices to work in the zero-order diffraction regime.

GMR color filters with different grating periods while keeping other device parameters constant are used to produce various colors. To achieve optimal reflectance with reasonably narrow linewidth and low sidebands, the structural parameters including grating depth, grating period, fill factor and waveguide thickness are adjusted. To facilitate fabrication, we keep all structural parameters the same except the grating period. The optimized design parameters for all color filters are $D=150$ nm, $D_g=50$ nm, and $F=0.5$. The refractive index of HfO_2 film is considered constant $n_{HfO_2}=1.95$, since it changes slightly with wavelength in the considered range. The periods of the filters for three primary colors are 320, 400 and 500 nm, respectively. Calculated reflectance spectra of the designed blue, green and red color filters for transverse-magnetic (TM; with electric field normal to the grating bars) polarization at normal incidence is given in Fig. 2(a). The center wavelengths for blue, green, and red filters are 493, 576 and 669 nm, respectively, where strong coupling between the GMR structures and the incident light is observed.

The position of the resonance proportionally shifts to larger wavelength when the grating period increases, as shown in Fig. 3

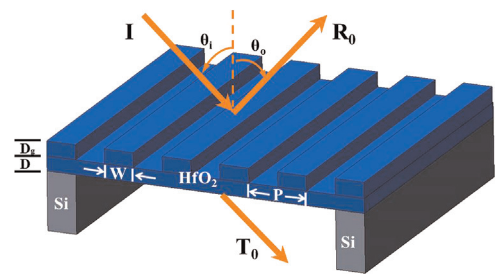

Fig. 1. Schematic of the GMR color filter structure.

(a), which illustrates the reflectance contour as a function of wavelength and grating period. Broad spectral tuning range is observed, indicating that color filters capable of reflecting arbitrary colors can be achieved through adjustment of the grating period. This characteristic may provide a way to realize a tunable filter in combination with microelectromechanical system [27]. Fig. 3 (b) shows the calculated reflectance spectra as a function of wavelength and fill factor of the filter with $P=500$ nm at $\theta_i=0$ for TM polarization. As the fill factor increases, the position of the resonance wavelength shifts slightly to larger wavelength. The inset of Fig. 3(b) treat example color filters with $F=0.45$, 0.5 and 0.55. It is evident that even though the fill factor varies from 0.45 to 0.55, the resonances remain in red-color region and spectrally close, indicating that the color filters can be rather tolerant to fabrication imperfections.

The resonance wavelength of the GMR color filters also depends on incident angle of the input light. Different from the above mentioned period-tuned color filters, where filters with different grating periods produce individual colors, angle-tuned color filter can obtain a multitude of colors using a single physical filter by changing the incident angle. At normal incidence, the GMR filter possesses a symmetric profile exhibiting a single resonance. As the incident angle deviates from zero, the resonance splits and results in resonances at different wavelengths, which is caused by coupling of the positive and negative first-order evanescent waves with the leaky mode of the waveguide [20,28]. Angle-tuned color filter is designed such that one resonance falls in the visible range while the other resonance falls outside, so that it does not have any effect on the perceived color. Fig. 2(b) shows the calculated reflectance of the tunable color filter for TM polarization. The designed period is 320 nm. Blue, green, and red responses are observed for $\theta_i=0°$, 16° and 31°, respectively. The center wavelengths are 497, 557 and 613 nm for blue, green, and red colors, respectively. The reflectance contour as a function of incident angle and wavelength is illustrated in Fig. 3(c). It is evident that the resonance of the color filter is sensitive to the incident angle. When the incident angle increases, red shift of the resonance position is observed. The resonance wavelength could shift spectrally across 140 nm with an angular tuning range of 40°. For transverse-electric (TE; with electric field parallel to the grating bars) polarization, the calculated angular-resolved reflectance spectrum of this tunable color filter is plotted in Fig. 3(d). For oblique incidence, there are more than one resonance in the visible range, which is not suitable for angle-tuned color filter application.

To confirm the GMR origin of the filtering characteristic of the proposed color filter, the magnetic field distribution is investigated. Fig. 4(a) and (b) show the magnetic field intensity profile of the red filter with grating period of 500 nm at wavelength of 669 nm, where there is a reflection peak, and 600 nm, where the reflectance is low. The difference in the magnetic field distribution between the two figures is apparent. In Fig. 4(a), the