High performance transmissive color filter with hybrid Tamm plasmon-cavity modes

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Research Article

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Abstract

A dual distributed Bragg reflector (DBR)-based structure embedded with silver (Ag) layer is proposed to demonstrate a transmissive color filter induced by the optical Tamm states (OTSs). The hybrid formation ensures optical Tamm resonance can be excited and the energy is concentrated at the DBR/Ag interface, resulting in a sharp transmittance feature with a narrow bandwidth. To optimize the device performance with desired red-green-blue (RGB) additive colors, transfer matrix method is carried out for simulations. The resonances and corresponding color appearance can be tailored dynamically through the manipulation of the Bragg wavelength and the angle of incident light. Through adjusting the structural parameters, the wavelength of transmission peak could be fixed at 455 nm, 550 nm and 620 nm, respectively. Thus, chromaticity points with a large color gamut space in the CIE coordinate can be constructed. The structure is totally planar and the fabrication process is lithography-free, which may find great potential in the application of optical thin films.

1. Introduction

Hetero structures with photonic crystal (PhC) interface have been extensively studied for the localized behavior of optical Tamm states (OTSs) [1–4]. These modes have attracted wider attentions because of its potential applications in nanophotonic devices, such as metamaterials, plasmonic structures and metasurfaces [5–7]. OTSs can be excited at the interfaces between metal and distributed Bragg reflector (M-DBR) or between two PhCs. The energy of OTSs is localized between different interfaces and the intensity of decays with distance from the interface [8–10]. OTS has a high-intensity local mode and perfect absorption of incident electromagnetic wave with a narrower linewidth.

The OTS is usually called as Tamm plasmon polariton (TPP) that result from the confinement of the field at boundary of a DBR and a thin plasmon-active metal layer [11–14]. Due to the existence of photonic band gap (PBG) resulting from the periodicity of multilayer structure, strong light confinement can be accomplished. In comparison to surface plasmon (SP) modes, TPP modes occur for both transverse electric (TE) and transverse magnetic (TM) polarizations. Complex architectures like prisms or gratings are not needed for exciting TPP modes, which is due to the fact that TPPs in-plane $k$ vector is close to zero and therefore can be excited directly. Resonance of TPPs depends on lots of factors like metal type, metal thickness, the thickness of dielectric adjacent to metal.

Recently, activity in study associated with TPP modes has increased because of numerous applications, such as TTP lasers [15], light trapping [16], optical splitting [17], sensing [18, 19], and so on. Among these potential applications, it has been demonstrated that narrow visible resonance with one or more peaks can be realized with the association of OTSs.

Till now, various approaches and versatile designs have been proposed to construct transmissive/reflective color filter. Surface plasmon resonance [20, 21], guided-mode resonance [22], as well as thin-film interference have been introduced [23, 24]. While most of the above-mentioned designs
are polarization and angle-dependent, which restricts their practical usage. Moreover, the fabrication complexity also limits their compatibility for upscaling.

In this paper, the transmissive color filter composed of dual distributed Bragg reflector (DBR)-based structure embedded with silver (Ag) layer is demonstrated. Accompanied by the excitation of Tamm plasmons, sharp transmission with suitable bandwidth has been verified through the TMM numerical calculation. High quality can be maintained with the controlment of efficiency and color purity. With proper optimization, this structure can achieve high transmission (> 80%) over a wide range of incidence angles under both TE and TM polarizations. The proposed strategy and findings in this work can be utilized to modulate the color response, and be extended to other multilayer structures support OTS.

2. Model And Method

Figure 1 presents the schematic diagram of the filter by embedding hybrid cavity between dual DBRs. The top DBR (DBR1) consists of $M$ layers of GaN/SiO$_2$ pairs (with thicknesses $d_1 = 91$ nm and $d_2 = 67$ nm respectively, $M = 2$). The bottom DBR (DBR2) consists of $N$ layers of Si$_3$N$_4$/SiO$_2$ pairs is set (with thicknesses $d_3 = 70$ nm and $d_4 = 40$ nm respectively, $N = 3$).

The refractive index of SiO$_2$ is considered as $n_0 = 1.47$, and the optical properties of Si$_3$N$_4$ and GaN are described by the following dispersion formulas, respectively [25, 26]:

$$n_{\text{Si}_3\text{N}_4} = \sqrt{\frac{2.8939\lambda^2}{\lambda^2-0.13967^2}+1}$$

1

$$n_{\text{GaN}} = \sqrt{\frac{1.75\lambda^2}{\lambda^2-0.256^2} + \frac{4.1\lambda^2}{\lambda^2-17.86^2}} + 3.6$$

2

$\lambda$ is the considering wavelength.

Ag layer is embedded in the middle with thickness of $d_{\text{Ag}} = 30$ nm. This design can simulate the TPP mode effectively. The dielectric constant of Ag is expressed by Drude model [27]:

$$\varepsilon_r = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\omega\gamma} - \frac{\Delta\times\Omega^2}{(\omega^2-\Omega^2)^2+i\Gamma}$$

3
The related parameters are listed in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_\infty$</td>
<td>2.4064</td>
</tr>
<tr>
<td>$\omega_p$</td>
<td>$2\pi \cdot 2214.6 \cdot 10^{12}$ Hz</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$2\pi \cdot 4.8 \cdot 10^{12}$ Hz</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>1.6604</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>$2\pi \cdot 620.7 \cdot 10^{12}$ Hz</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>$2\pi \cdot 1330.1 \cdot 10^{12}$ Hz</td>
</tr>
</tbody>
</table>

Thickness of Layer A and Layer B is changeable to maintain different color through adjusting the designed central wavelengths of the dual DBRs. There is a great need on the balance between color intensity and purity influenced by the bandwidth for color filter when designing the structure. Thickness of each layer and the number of pairs in DBRs can be optimized so that high-intensity transmission with proper bandwidth can be obtained.

To calculate the optical properties of the structure, the simulation in this paper uses the transfer matrix method (TMM) due to simplicity and flexibility of the method. The transfer matrix $M$ is constructed firstly with the individual interface matrices $I_j$ and propagation $P_j$, the index $j$ is identifier of the interface in discussion [28]

$$r_j = \frac{\mu_{j+1} n_j - \mu_j n_{j+1}}{\mu_{j+1} n_j + \mu_j n_{j+1}}$$

$$\tau_j = \frac{2\mu_{j+1} n_j}{\mu_{j+1} n_j + \mu_j n_{j+1}}$$

$$I_j = \frac{1}{\tau_j} \begin{pmatrix} 1 & r_j \\ r_j & 1 \end{pmatrix}$$
\[ P_j = \begin{pmatrix} e^{-\phi_j} & 0 \\ 0 & e^{\phi_j} \end{pmatrix} \]

where \( r_j \) and \( \tau_j \) are the reflection and transmission coefficient, respectively. \( \mu_j \) and \( n_j \) are the (relative) magnetic permeability and refraction of index respectively. \( \phi_j \) is the layer phase thickness corresponding to the phase change of incident light from top of the structure when traverses layer \( j \). Fields at incidence and substrate side can be described by the transfer matrix \( M \),

\[ M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = \prod_{j=1}^{L} I_j P_j I_{L+1} \]

Along the \( z \) axis, the incident electric field is \( E_0^- \), the reflected field is \( E_0^+ \), the transmitted field is \( E_{L+1}^- \). In the demonstration, transmission is dependent on the polarization of incident light and incident angle. The initial condition for the calculation is under normal incidence with TE polarization before discussing the influence of the incident angle and polarization.

### 3. Results And Discussion

Among the candidates for plasmonic applications, Ag owns much better characteristics than others within the full-range wavelength visible light. Therefore, Ag is chosen and investigated in the hybrid structure. Figures 2(a)-2(c) shows transmittance with a 30 nm Ag film under normal incidence. As off-resonance is suppressed, sharp resonance with the transmission efficiency of 87.3%, 83.8% and 74.4% for B, G, R is obtained, respectively. The insets show the displayed color obtained from calculation. Standard red-green-blue (sRGB) color space has become a generally accepted international standardization of color standards. In Fig. 2(c), RGB filters construct a red triangle which is close to sRGB chromatic gamut (black triangle area), which shows it can provide vivid color performance while the proper bandwidth provides enough intensity. Besides, suppress of off-resonance wavelength can be observed, which is effective and crucial for improving color purity.
Figure 2(e) illustrates the simulated transmission spectrum with Ag, Au and Al as embedded metal in the hybrid structure for G color. Two different layer thicknesses (30 nm and 50 nm) are considered. Sharper resonance curve can be obtained by this comparative study.

The results manifest that the excellent filtering effect with Ag thin layer as we expected. Taking advantage of lower extinction coefficient in Ag, the hybrid design not only provides plasmonic properties, but also prevent the oxidization.

To check the feasibility of the color filter, the achievable color palette from adjusting the structural parameters is depicted in Fig. 3(a). \(d_A\) and \(d_B\) are tunable so that the transmissive spectra and color display can be controlled effectively by this way. With a fixed \(d_B\), \(d_A\) is changed by steps of 10 nm from 50 nm to 200 nm, enable additive color is mixed by two or three resonances which distribute in the visible spectral range. And this color variability can be adjusted by \(d_A\) and \(d_B\) in two dimensions. Figure 3(b) shows a series of obtainable color filters. It is clear that high saturation and brightness colors span the entire visible spectrum are obtained by coordinated \(d_A\) and \(d_B\). The details are listed in Table 2.

<table>
<thead>
<tr>
<th>(d_A) (nm)</th>
<th>(d_B) (nm)</th>
<th>Central Wavelength (nm)</th>
<th>Maximum Transmittance</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>115</td>
<td>440</td>
<td>0.77</td>
</tr>
<tr>
<td>60</td>
<td>137</td>
<td>460</td>
<td>0.87</td>
</tr>
<tr>
<td>70</td>
<td>172</td>
<td>480</td>
<td>0.82</td>
</tr>
<tr>
<td>80</td>
<td>86</td>
<td>500</td>
<td>0.77</td>
</tr>
<tr>
<td>90</td>
<td>113</td>
<td>520</td>
<td>0.80</td>
</tr>
<tr>
<td>98</td>
<td>138</td>
<td>540</td>
<td>0.86</td>
</tr>
<tr>
<td>105</td>
<td>148</td>
<td>560</td>
<td>0.87</td>
</tr>
<tr>
<td>115</td>
<td>168</td>
<td>580</td>
<td>0.86</td>
</tr>
<tr>
<td>122</td>
<td>183</td>
<td>600</td>
<td>0.84</td>
</tr>
<tr>
<td>132</td>
<td>200</td>
<td>620</td>
<td>0.79</td>
</tr>
</tbody>
</table>

Characteristics of the structure are explored through the mentioned process and the results are presented in Figs. 4(a)- (f). When \(d_B\) is fixed as shown in each figure, the influence of \(d_A\) is evaluated, and it can be seen that the optical response can be divided into two series. The red lines mark a series of resonance that redshifts as \(d_A\) increases, and the green lines mark a series of resonance which is not affected by \(d_A\) but redshifts as \(d_B\) increases from 86 nm to 183 nm. When the response influenced by \(d_A\) and \(d_B\)
resonance at the same wavelength, they superimpose here to form a transmission peak with an efficiency higher than 80%. For non-superimposed bands, the transmittance efficiency of a resonance is much lower. Pure color with narrow transmissive peak can be obtained by this method, as well as other mixed color.

To evaluate the properties of transmissive color filter more thoroughly, the situation of oblique incidence is also considered. Figures 5(a)-5(b) present contour map of the angle-resolved transmittance. With an angle of incidence up to 60° and 40° for two linear polarizations (TE and TM), respectively, sharp resonance with high intensity can be retained. From Figs. 5(a) and 5(b), it can be observed that the transmission peak blue-shifts with the increasing incident angle. The color-change with incident angle provides another freedom for the design of transmissive filters.

To reveal the physical origin of the displayed color, the intensity of electric field at the resonance wavelength (560 nm) is simulated and presented in Fig. 5(c). The result indicates the confinement of TPs on the contact of Ag and DBR. As a result of the Bragg forbidden effect, the mode decays into the DBR and characterized by periodically oscillating attenuation. The typical high-order Fabry-Perot (FP) resonance shows the cavity’s enhancement for light with specific wavelength. Thus, high transmittance for certain color can be realized.

4. Conclusions

We have proposed and demonstrated a tunable transmissive color filter through manipulate the OTSs inside a hybrid multilayer structure. The aim of this work is the generation of a wide gamut in the visible range with the manipulation of structural color. The maximum transmission exceeds 80% at the resonance wavelength, enables high brightness of the designed color. The enhanced transmission is attributed to the cavity modes supported in the hybrid structure. Meanwhile the structure can provide good angle-tolerant for maintain the resonance response under both TE- and TM-polarized incidence.

Declarations

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript. No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication. I would like to declare that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed. The simulation, data processing, analysis and the first draft of the manuscript were performed and written by Haohan Chen and Gaige Zheng and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

References


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Figures

**Figure 1**

Schematic of the Ag embedded DBR-based color filter.
Figure 2

Simulated transmission spectra of optimized designed RGB filters. (a) blue, (b) green and (c) red filter achieve with $d_A=60$ nm, $d_B=137$ nm; $d_A=102$ nm, $d_B=142$ nm; $d_A=0$ nm, $d_B=50$ nm, respectively. The calculated transmission are changed into the CIE 1931 chromaticity diagram and shown in (d) with red triangle, and the sRGB chromatic gamut is shown with black triangle. (e) Calculated transmission spectrum with different embedded metals including Ag, Au and Al.

Figure 3

(a) The displayed colors of the tunable color filter by changing $d_A$ and $d_B$. (b) A series of color filters is obtained by matching thicknesses of $d_A$ and $d_B$.

Figure 4

Contour map of the transmittance as function of wavelength and $d_A$ when $d_B=86$ nm, 113 nm, 138 nm, 148 nm, 168 nm and 183 nm.

Figure 5

Simulated angle-resolved transmission under (a) TE-polarized and (b) TM-polarized light illumination. (c) Electric field intensity distribution at the wavelength of 560 nm.