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Tunable extraordinary optical transmission of dielectric film-coupled metallo-dielectric crystals

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ABSTRACT

In this work, we study the optical properties experimentally and theoretically of a unique structure with a dielectric film spacer intercalated between a corrugated metal film (CMF) and a monolayer colloidal crystal (CC). Multi-band enhanced optical transmission (EOT) phenomenon is achieved in this new metallo-dielectric structure, which is very different from the only one EOT band found in the conventional plasmonic crystal (CPC) composed of a metal film coated directly on the CC. Particularly, the location and intensity of the EOT spectrum can be easily tailored by varying the geometry parameters of the intercalated dielectric, which could show applications in the development of cost-effective plasmonic components for the light absorption and surface enhanced spectroscopies.

1. Introduction

Large-area sub-wavelength metallic structures have attracted much attention due to their important roles in the emerging fields of sensors, waveguides, plasmonic microcavities and circuits [1–4]. Exciting EOT phenomenon [5] has been observed and demonstrated in a variety of metallic structures [6,7]. In order to further exploit novel plasmonic and photonic properties of the metallic nanostructures, great efforts have been made by utilizing or structuring the metal materials. For instance, by introducing the hybridized plasmon modes, enhanced broadband light transmission of continuous metal film structures is achieved [8–10]. However, the high fabrication technical requirements restrict the wide applications of these metallic structures inevitably. Recently, monolayer CC with the benefit of easy-fabrication has been widely used in the plasmonics investigations [11–13], especially in the EOT phenomenon [14–16]. However, almost all the investigations in the previous reports are based on the change of metals [14–16]. Although there are new efficient ways for achieving unique optical property modifications by using the dielectrics instead of metals [17,18], up to date, there is far less attention on the exploration and development of the EOT modifications by tuning the dielectrics.

In this work, we fabricate a dielectric film-coupled metallo-dielectric crystal (FCC) and exploit the optical properties with the intercalated dielectric film under different geometry parameters. The light-matter interaction in the triple-layer structure is efficiently tuned via the intercalated dielectrics. By using a higher refractive index dielectric film, multiple enhanced EOT bands with high scalability both in the intensity and frequency range are achieved.

2. Experimental details

Large-area two-dimensional (2D) CC is fabricated on the quartz substrate with monodisperse polystyrene (PS) spheres by the self-assembly method [19,20]. A dielectric film (amorphous-silica, a-SiO_2; titanium oxide, TiO_2) with controllable thickness is then plasma sputtered on the surface of the 2D CC to form a dielectric cap on CC. Finally, a 55 nm gold film is deposited on the surface by vacuum deposition. Numerous simulations are performed using the finite-difference time-domain method [21]. Each PS sphere is assumed to be half-coated by the dielectric (metal) film. Periodic boundary conditions for the unit cell are adopted and the computational domain is terminated by perfect matching layers [23]. The dielectric constants of PS colloids, a-SiO_2 and TiO_2 are assumed to be $\varepsilon_1=2.46$, $\varepsilon_2=2.13$ and $\varepsilon_3=6.25$, respectively. The Drude model is used to describe the dielectric constant of the gold to fit the experimental data [22].

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3. Results and discussion

Fig. 1 shows the optical photo and scanning electronic microscopy (SEM) images of the fabricated crystals. Here we choose the PS sphere with a diameter (D) of 980 nm to fabricate the monolayer CC. a-SiO_2 (TiO_2) with a relative lower (higher) refractive index than that of the PS is used as the deposited dielectrics. A large-area optical microscopy photograph and a clear diffractive pattern of the sample under irradiation of a 633 nm He–Ne laser are shown in Fig. 1(a), conforming the high quality of the CC. An amplified top-view SEM image of the CC is shown in Fig. 1(b). The blue dashed rectangular marks the unit cell of the crystal for calculations and the red arrow line shows the incident irradiation light with the polarization along the x-axis. Cross-view SEM images of the CPC and the proposed a-SiO_2 FCC are shown in Fig. 1(c) and (d), respectively. The black dashed circle marks the PS sphere. The thickness (h) of the deposited a-SiO_2 film is also marked as shown in Fig. 1(d) [14,16,23].

For the proposed a-SiO_2 ($\varepsilon=2.13$) FCCs with different h, the measured transmission spectra are shown in Fig. 2(a). The transmission spectrum of the CPC is also shown in Fig. 2(a) with a main EOT peak at $\lambda=1358$ nm and several sub-peaks at the shorter wavelength range (see the black line). For the proposed structure, with h increasing, two main optical behaviors could be found. One is the obvious amplitude modification of the EOT peaks. For the original main EOT peak, a continuous decrease in transmittance is observed with h increasing. However, with h increasing, at the short wavelength range an obvious EOT peak emerges with a larger transmittance than the original main EOT peak. The other is the difference of the frequency shifts of the EOT peaks with h increasing. For the original EOT peak, with h increasing from 0 to 450 nm, almost no obvious frequency shift occurs, which is the main result of the photonic cavity mode [14,16]. While for the EOT peak at the short wavelength range, an obvious frequency shift is observed. The continuous red–shift in the wavelength range for the shorter wavelength peak is relevant to the high order photonic guided modes [14–16,23].

Fig. 2(b) shows the measured transmission spectra of TiO_2 ($\varepsilon=6.25$) FCCs. With $h=75$ nm, the original EOT peak at $\lambda=1362$ nm almost retains invariable. While strong enhancement for the other peak at $\lambda=1150$ nm is observed. When h is 150 nm, dual intensified EOT peaks are achieved at $\lambda=1387$ nm and

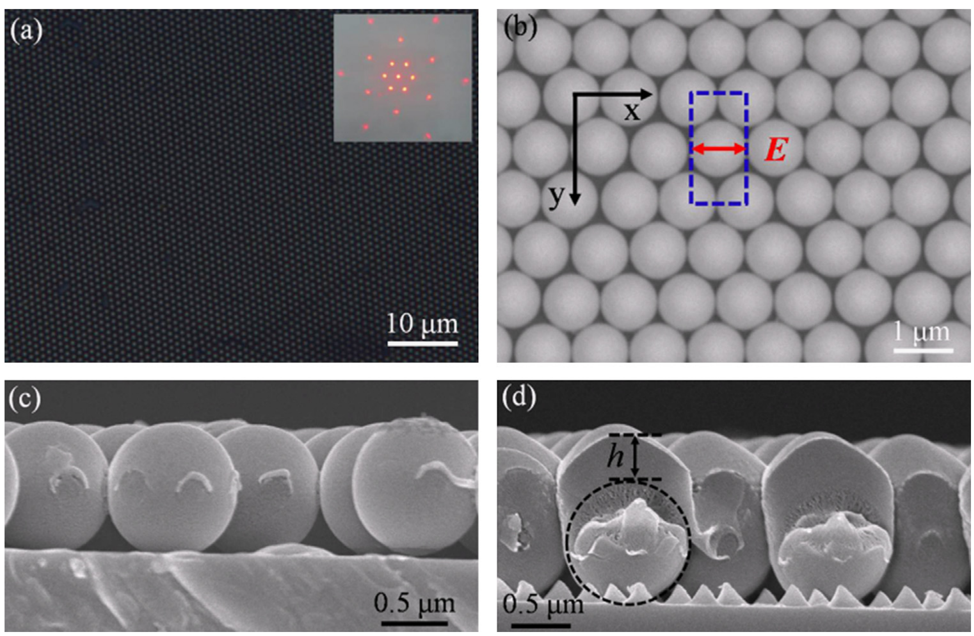

Fig. 1. (a) Optical microscopy photo of the fabricated CC, (b) top-view SEM image of the CC, (c) and (d) cross-view SEM images of the CPC and the proposed FCC, respectively.

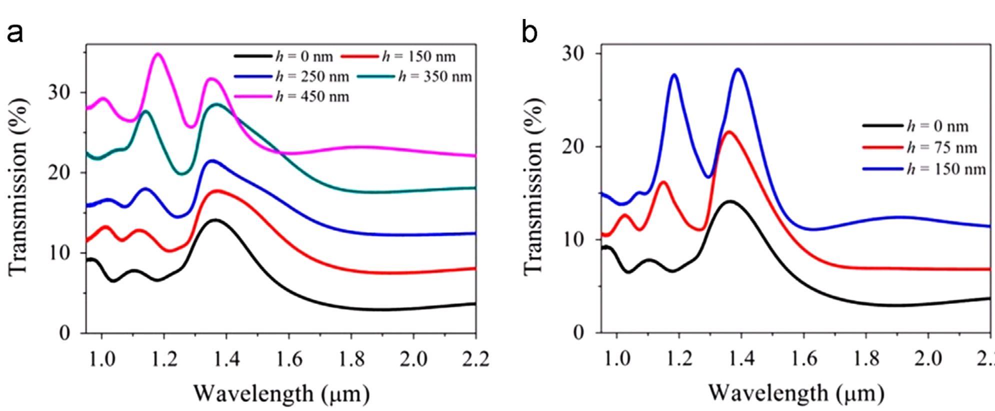

Fig. 2. Measured transmission spectra of the proposed a-SiO_2 (a) and TiO_2 (b) FCC structures under different h. For clarity, each transmission spectrum is offset by 5% from each other.

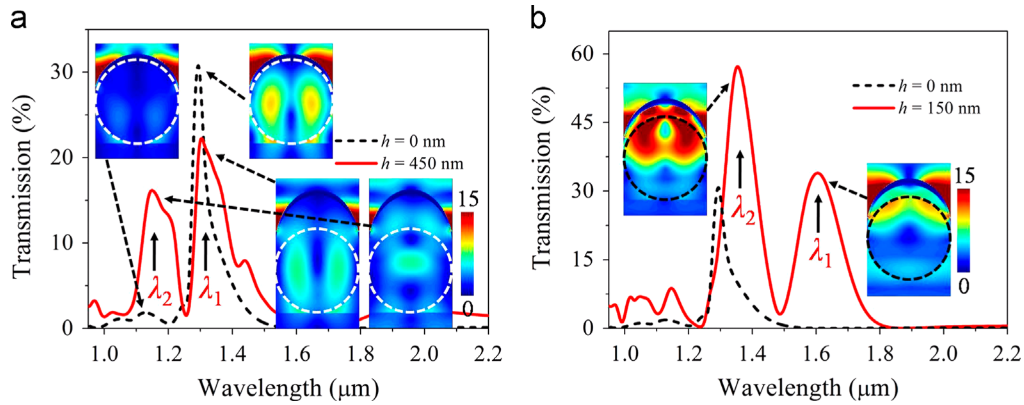

Fig. 3. (a) Calculated transmission spectra of the proposed a-SiO_2 (a) and TiO_2 (b) FCCs under different h. The inset shows the corresponding calculated electric field intensity distributions at the EOT peaks.

1185 nm, respectively. This finding suggests that the dielectric film with higher dielectric constant between CMF and CC could act as a high efficient optical field coupling and confinement cavity [5,14,23]. In addition, the high tunability in the frequency range of the EOT peaks (Fig. 2(b)) is also achieved due to the relative large refractive index difference between the intercalated dielectric film and the CC. The observed multiple enhanced EOT bands could be important in numerous applications including the surface enhanced Raman scattering [24] and enhanced light absorption [25].

Calculated transmission spectra of the proposed a-SiO_2 FCCs with $h=0$ nm (black dashed line) and $h=450$ nm (red line) films are shown in Fig. 3(a). For the CPC (black dashed line), a strong EOT peak at $\lambda=1296$ nm and some weak transmission peaks at the short wavelength range are observed. With $h=450$ nm (red line), double EOT peaks with an enhanced transmission at $\lambda_1=1298$ nm and a weakened transmission at $\lambda_2=1164$ nm are achieved. The electric field intensity distribution patterns of the CPC at $\lambda_{01}=1296$ nm and at $\lambda_{02}=1128$ nm are shown as the insets in Fig. 3(a) with the quite similar distributions to those in the previous report [16] by the excitations of lower (λ_{02}) or higher (λ_{01}) order photonic guided modes supported by the 2D CC [16,23]. For the FCC ($h=450$ nm) at λ_1, the electric field distributions in the PS sphere are much weaker than those of the CPC, confirming the reduced transmission both in the measured and calculated spectra. In addition, it should be noted that no obvious electric field is found in the silica film, which suggests that the silica film mainly works as a spatial gap for reducing the optical coupling between the CMF and the CC. At λ_2, besides the strong electric field in the PS sphere, obvious electric field distributions in the silica film are also observed, which suggests the excitation of higher order photonic guided mode or the so-called leaky guided mode [14,16].

For the TiO_2 FCC, two strongly enhanced EOT peaks with obvious red–shift are observed in the calculation spectrum with $h=150$ nm (Fig. 3(b)), in good agreement with the measured result. The electric field distributions for these two peaks at $\lambda_1=1560$ nm and $\lambda_2=1344$ nm are shown in Fig. 3(b). For λ_1, the electric field is mainly confined at the outer side of the CMF with partial electric field distributed in the sphere. This suggests that the transmission peak mainly results from the excitation of localized surface plasmon mode of the CMF and the photonic guided mode of the dielectric crystal [14,16]. For λ_2, the main electric field distributions are located at the outer side of the CMF and in the dielectric structures including the TiO_2 film and the CC [14,16], which confirms the efficient optical field coupling and confinement capability in this high dielectric constant TiO_2 layer.

4. Conclusion

In summary, we have proposed and fabricated a novel FCC structure to achieve significant modification of the EOT phenomena. By utilized a dielectric film intercalated between the top CMF and the bottom CC with lower or higher dielectric constant materials than the host colloidal substrate, significantly modified multiple EOT bands are observed. Modeled transmission spectra are in agreement with the measured ones. Further calculations confirm the efficient optical field coupling between the plasmon modes localized mostly at the outer side of the CMF and the eigen modes in the CC film. Our findings might show applications in large-area, low-cost and high tunable sub-wavelength optics, nanoplasmonics, and optoelectronic devices.

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