Research article

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Near-infrared dual-wavelength plasmonic switching and digital metasurface unveiled by plasmonic Fano resonance

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Abstract: Plasmonic Fano resonance (FR) that contributes to multitudinous potential applications in subwavelength nanostructures can facilitate the realization of tunable wavelength selectivity for controlling light–matter interactions in metasurfaces. However, the plasmonic FR can be generated in metasurfaces with simple or complex geometries, and few of them can support flexible amplitude modulation and multiwavelength information transfer and processing. Here, we study the near-infrared plasmonic FR in a hybrid metasurface composed of concentrically hybridized parabolic-hole and circular-ring-aperture unit cells, which can induce polarization-dependent dual-wavelength passive plasmonic switching (PPS) and digital metasurface (DM). It is shown that the designable

plasmonic FR can be realized by changing the geometric configurations of the unit cells. In particular, owing to the polarization-dependent characteristic of FR, it is possible to fulfill a compact dual-wavelength PPS with high ON/OFF ratios in the related optical communication bands. Moreover, such PPS that manipulates the amplitude response of the transmitted spectrum is an efficient way to reveal a 1-bit DM, which can also be rationally extended to a 2-bit DM or more. Our results suggest a pathway for studying polarization-dependent PPS and programmable metasurface devices, yielding possibilities for subwavelength nanostructures in optical communication and information processing.

Keywords: digital metasurface; passive plasmonic switching; plasmonic Fano resonance.

1 Introduction

The Fano resonance (FR) is an interference phenomenon widely studied in the light–matter interaction systems, which is caused by the interference between a narrow discrete resonance and a broad spectral continuum [1–3]. As a universal phenomenon in optics, FR with an asymmetric profile in optical response can be observed in the plasmonic nanostructures [3, 4], electromagnetic metamaterials [3, 5], photonic crystals [6, 7], semiconductor nanostructures [8–10], etc. Plasmonic FR that originates from the destructive interference between the superradiant and subradiant resonance modes with a spectrum overlapping in the metallic subwavelength nanostructures has characteristics similar to the traditional FR in the interacting quantum systems [11, 12]. In particular, by coherently interacting with the superradiant mode, the subradiant mode that is only weakly coupled with the free space results in the presence of plasmonic FR along with a narrow spectral feature, which can be termed as wavelength selectivity [13]. In fact, owing to its strong sensitivity to the local environment and changes in geometry, the plasmonic FR in periodic metal nanostructures can be

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applied for sensing [14, 15], switching [16–19], slow light devices [20], etc.

Metasurfaces that are considered the artificial ultra-thin planar metamaterials, composed of periodic sub-wavelength unit cells arranged in specific sequences [21–23], have attracted much attention as a result of their exotic properties [24, 25]. The unit cells of the metasurfaces have been engineered to flexibly manipulate the electromagnetic wave propagations [22], leading to a plethora of applications that range from polarization control [26, 27], perfect absorption/transmission [28], and spectral responses [29, 30]. Recently, it has already been demonstrated that the operation frequency of the metasurfaces can be extended from microwaves to optical frequencies owing to their unique abilities to provide efficient control over the amplitude, phase, and polarization of the local fields [22, 31]. Therein, the dynamic metasurfaces with tunable characteristics including the optical phase and amplitude can be used to construct electromagnetic devices with reconfigurable or programmable functions, such as information processing [32] and digital metasurface [33, 34], and achieve advanced multifunctional systems [35–37]. A typical approach that elicits dynamic metasurfaces at optical frequencies is to use electrically or optically tunable diodes [32, 34, 37, 38]. However, the prevailing way usually requires auxiliary power supply and complex control circuits. These external units, which need to be physically connected to the metasurface, could not only increase the size of the system but bring in adverse cross talk. In addition, the inevitably dissipative metal losses at optical frequencies and inhomogeneous broadening could give rise to a broadband response, which indeed compromises the performance of the devices and impedes further applications [13, 39]. To unveil the sufficient versatility of the metasurfaces, it is necessary to study the plasmonic FR with tunable narrow spectral features, which has the ability to achieve the same function but at different wavelengths or to switch the functionalities at a specific working wavelength. Also, it should be stressed that the optimal way to realize single-wavelength or multiwavelength information transfer and processing through plasmonic FR that can induce the characteristic of flexible amplitude modulation is still a veil to be lifted and has not been fully explored.

Here, we numerically study the near-infrared plasmonic FR in a hybrid metasurface that consists of parabolic-hole (PH) and circular-ring-aperture (CRA) unit cells for the realization of the polarization-dependent dual-wavelength passive plasmonic switching and digital metasurface. We show that the plasmonic FR originates from the destructive interference between the superradiant and

subradiant plasmonic modes with the spectral overlapping in the hybrid metasurface, which also agrees well with the temporal coupled-mode theory (TCMT). The designable near-infrared plasmonic FR can be realized by changing the geometric configurations of the unit cells. In particular, by varying the polarization direction, a compact polarization-dependent dual-wavelength passive plasmonic switching can be implemented at the telecom *O*- and *L*-bands, respectively, with the ON/OFF ratio being 21.98 and 15.96 dB. Besides, such passive plasmonic switchings can be put forward for accomplishing a 1-bit digital metasurface, which can be extended to a 2-bit digital metasurface or more. Our results provide an alternative way for the multifunctional digital metasurface devices and can be extended to all-optical regions.

2 Structure and model

Here, we consider a hybrid metasurface, as shown in Figure 1a, that consists of periodic hole arrays with the concentric PH and CRA unit cells. The silver (Ag) film is chosen as the metal material (50 nm) [40], with low absorption loss in the visible and near-infrared regions, on a quartz substrate (225 nm). The incident pulsed light field of linear polarization propagating in the positive *Y*-direction acts vertically on the Ag film from the quartz substrate side. The polarization of incident light is initially along the *Z*-direction. Figure 1b is a cross-sectional view of the unit cell of the hybrid metasurface in the *X*–*Z* plane. P_x and P_z represent the array periods in the *X*- and *Z*-directions, respectively. The gray part is the Ag film, while the white part denotes the air. R_1 and D are the outer radius and width of the CRA unit cell, while L and W represent the length and width of the PH unit cell, respectively. The edges of the parabolic metal (see the red curves in Figure 1b) follow the quadratic function expressed as $Z_{\pm} = \pm a_p x^2 \pm b_p$, where a_p and b_p are the coefficients of the function. The numerical simulations of the hybrid metasurface are calculated by the three-dimensional finite-difference time-domain method [41]. According to the numerical stability condition, the time step and grid size are set as 8.3 (as) and 5 (nm), respectively. The permittivity of Ag film can be described by the modified Drude-model, while the dielectric constant of quartz is set as 2.25 [42]. The incident light is a modulated ultrashort Gaussian pulse, with the center wavelength, center time, and pulse width being 1550 nm, 16 fs, and 5 fs, respectively. The *X*- and *Z*-directions of the unit cell are set as the periodic boundary conditions, where the perfectly matched layer is used as the absorbing boundary condition in the *Y*-direction.

Figure 1: (a) Schematic diagram of the hybrid metasurface, which is a metallic silver (Ag) film deposited on a quartz substrate, with a periodic hole array of concentric parabolic-hole (PH) and circular-ring-aperture (CRA) unit cells. The incident pulsed light field of linear polarization propagating in the positive Y-direction acts vertically on the Ag film from the quartz substrate side. (b) The cross-sectional view of the unit cell in the X–Z plane. P_x and P_z represent the array periods in the X- and Z-directions, respectively. R_1 and D are the outer radius and width of the CRA structure, while L and W represent the length and width of the PH structure, respectively. The edges of the parabolic metal (red curves) follow the quadratic function expressed as $Z_{\pm} = \pm a_p x^2 \pm b_p$, where a_p and b_p are the coefficients of the function.

3 Results and discussions

3.1 Plasmonic FR in the near-infrared region

Here, we study the hybridized modes, under the condition of the polarization of the incident light being along the Z-direction, in the periodic arrays with individual PH and CRA unit cells, as well as the hybrid metasurface, respectively. As shown in Figure 2a, the electric dipolar (D_{PH}) mode interacts with the electric quadrupolar (Q_{PH}) mode in the PH structure. This process gives rise to the presence of hybridized bonding mode ($D_{PH} + Q_{PH}$) [43], owing to the selective excitation that the incident light with specific polarization gives access to the pure bonding mode [44]. Meanwhile, as shown in the inset of Figure 2a, the charge distribution of the PH structure at the related wavelength is presented, where the *top panel* shows the charge distribution at the *Ag/air interface*, while the *bottom panel* shows the charge distribution at the *Ag/quartz interface* [12]. This interaction of the hybridized modes, as mentioned above, can be confirmed from the charge distribution (marked by the red dot) in the inset of Figure 2a. For simplicity, the bonding mode can be considered as the effective electric dipolar mode D_1 , although the hybridized plasmonic wave functions contain an admixture of D_{PH} and Q_{PH} modes [45]. However, as depicted in Figure 2b, there are electric quadrupolar (Q_{CRA}) and hybridized bonding ($D_{CRA} + Q_{CRA}$) modes [43] occurring in the CRA structure, which can also

be confirmed by the charge distribution (marked by blue and purple dots) in the right and left insets of Figure 2b, respectively. Likewise, the hybridized bonding mode ($D_{CRA} + Q_{CRA}$) is weak excitation (see the left inset in Figure 2b), but it can also be viewed as the effective electric dipolar mode D_2 . One can notice that the electric dipolar D_1 and D_2 modes possessing different quality factors; thus, they can be regarded as the superradiant and the sub-radiant modes [46, 47], respectively. When there exist spectral overlapping between the two electric dipolar modes in the transmitted spectrum, the realization of the plasmonic FR originates from the interaction between the electric dipolar D_1 and D_2 modes in the near-infrared region, leading to the two new hybridized bonding ($D_1 + D_2$) and antibonding ($D_1 - D_2$) modes in the hybrid metasurface. This behavior can also be confirmed from the charge distributions (marked by orange and green dots, respectively) in the left inset of Figure 2c.

To further understand the plasmonic FR in our scheme, the TCMT is used [48, 49]. It is known that TCMT is a simple and effective tool to model the interaction between resonator and incident light, which is capable of being used to study the Fano-type transmission phenomena in the hybrid metasurface. By doing so, the dynamic equations of the related resonance amplitude in this system can be written as,

$$\frac{d}{dt} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = (j\Omega - \Gamma_e - \Gamma_i) \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} + C_2^T \begin{pmatrix} S_{1+} \\ S_{2+} \end{pmatrix}, \quad (1)$$

Figure 2: The origin of the near-infrared plasmonic FR in a hybrid metasurface.

Transmitted spectra correspond to periodic arrays with individual (a) PH and (b) CRA unit cells, as well as (c) the hybrid metasurface. The insets of (a) and (b) show the charge distribution of the individual PH and CRA structures at the marked wavelength, respectively. The left inset of (c) shows the charge distribution of the hybrid metasurface. While the right inset of (c) shows the related transmitted spectra (black dashed box) of the hybrid metasurface, with the blue dots and red solid curve being the simulation and fitting, respectively. The geometrical parameters are set as follows: $P_x = P_y = 600$ nm, $R_1 = 242.5$ nm, $D = 10$ nm, $L = 300$ nm, $W = 200$ nm, $a_p = 0.25$, and $b_p = 20$. FR, Fano resonance; PH, parabolic-hole; CRA, circular-ring-aperture.

$$\begin{pmatrix} S_{1-} \\ S_{2-} \end{pmatrix} = C_1 \begin{pmatrix} S_{1+} \\ S_{2+} \end{pmatrix} + C_2 \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}, \quad (2)$$

where $\Omega = \begin{pmatrix} \omega_1 & -k \\ -k & \omega_2 \end{pmatrix}$, $\Gamma_e = \begin{pmatrix} \Gamma_{e1} & 0 \\ 0 & 0 \end{pmatrix}$, $\Gamma_i = \begin{pmatrix} \Gamma_{i1} & 0 \\ 0 & \Gamma_{i2} \end{pmatrix}$, $C_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$, and $C_2 = \begin{pmatrix} j\sqrt{\Gamma_{e1}} & 0 \\ j\sqrt{\Gamma_{e1}} & 0 \end{pmatrix}$. a_1 and a_2 are the normalized resonance amplitudes of bonding ($D_1 + D_2$) and antibonding ($D_1 - D_2$) modes; S_{1+} and S_{2+} (or S_{1-} and S_{2-}) are normalized amplitudes of incoming (or outgoing) light at the input and output ports; $|S_{1+}|^2$ and $|S_{2+}|^2$ (or $|S_{1-}|^2$ and $|S_{2-}|^2$) correspond to the power of the incident (or transmitted) light; ω_1 , Γ_{e1} , Γ_{i1} (or ω_2 , Γ_{e2} , Γ_{i2}) represent the resonant frequency, radiative decay rate, and non-radiative decay rate of the bonding (antibonding) mode, respectively. k describes the direct coupling coefficient between the bonding and antibonding modes. C_1 denotes the direct scattering matrix without resonance modes. C_2 is the coupling between the resonance modes and the incident/transmitted light. In our scheme, we assume that

the radiative loss in the case of plasmonic FR is mainly dominated by the bonding mode ($D_1 + D_2$). For the anti-bonding mode, there is no direct energy exchange with the related environments, so the radiative loss is negligible (i.e., $\Gamma_{e2} \approx 0$). When the C_1 , C_2 , and Γ_e satisfy the relationships, namely, $C_1 C_2^* = -C_2$, and $C_2^* C_2 = 2\Gamma_e$, the transmittance of the hybrid metasurface can be given by [50],

$$T = 1 - \frac{(j\omega - j\omega_1 + \Gamma_{i1})(j\omega - j\omega_2 + \Gamma_{i2}) + k^2}{(j\omega - j\omega_1 + \Gamma_{i1} + \Gamma_{e1})(j\omega - j\omega_2 + \Gamma_{i2}) + k^2}. \quad (3)$$

Hence, by using the TCMT to fit the transmittance of the hybrid metasurface, the fitting (red solid line) agrees well with the numerical simulation (see the blue dot), as shown in the right inset of Figure 2c. Herein, the fitting parameters of the hybrid metasurface are obtained as $\omega_1 = 2\pi \times 1.974 \times 10^{14}$ rad/s, $\omega_2 = 2\pi \times 2.144 \times 10^{14}$ rad/s, $\Gamma_{e1} = 2\pi \times 0.099 \times 10^{14}$ rad/s, $\Gamma_{i1} = 2\pi \times 0.047 \times 10^{14}$ rad/s, $\Gamma_{i2} = 2\pi \times 0.027 \times 10^{14}$ rad/s, and

Figure 3: The designability and polarization dependence of the near-infrared plasmonic FR in a hybrid metasurface.

(a) Transmitted spectra of the hybrid metasurface with different geometric parameters (a) b_p , (b) W , and (c) D in the near-infrared region, respectively. (d–f) Polar plots of the transmittance at the related three wavelengths (corresponding to the blue square, black dot, and red triangle in (a), (b), and (c), respectively) in the hybrid metasurface with (d) $b_p = 40$, (e) $W = 150$ nm, and (f) $D = 10$ nm. The other parameters are the same as Figure 2. FR, Fano resonance.

$k = 2\pi \times 0.154 \times 10^{14}$ rad/s. In brief, the plasmonic FR that results in the hybridized modes of the hybrid metasurface can be implemented in the near-infrared region.

In the following, we explore the tunable plasmonic FR by considering different geometric configurations of the unit cells in the hybrid metasurface. For a more quantitative analysis, the W_{Fd} and D_{Fd} are defined as the width and depth of the Fano dip, respectively (see Figure 3a–c). In Figure 3a, by changing the coefficient b_p from 20 to 80 divided into four groups, there exists a fixed wavelength of the Fano dip, whereas the W_{Fd} and D_{Fd} are varied. This behavior is concomitant with the opposite shifts of the two adjacent peaks, which can also be regarded as the radiation-sensing monitoring of the depth of the Fano dip [51]. As shown in Figure 3b, when the widths of PH (W) are set as 100, 150, 200, and 250 nm, the wavelengths of the Fano dip and one of the peaks of the doublet are fixed, while the other peak of the doublet can be evidently broadened with the variation of D_{Fd} and W_{Fd} . As depicted in Figure 3c, by varying the width of the CRA unit cells (D),

which is set as 6, 10, 14, and 18 nm, it is found that the wavelength, W_{Fd} , and D_{Fd} of the Fano dip can be significantly all changed. It is worth mentioning that the fixed wavelengths of the Fano dip in Figure 3a and b can be ascribed to the parameters of the CRA unit cells remaining unchanged [47]. These results imply that the wavelength, width (W_{Fd}), and depth (D_{Fd}) of the Fano dip can be controlled by modulating the related geometric configurations of the unit cells in the hybrid metasurface, in which the wavelength mainly depends on the relevant geometric parameters of the CRA unit cells.

Next, when the geometric parameters of the unit cells are fixed, the modulated polarization direction of the incident light could potentially induce the change of the coupling strength of the electric field with the hybrid metasurface [11]. As shown in Figure 3d–f, the polar plots of the transmittance at the related three wavelengths (corresponding to the blue square, black dot, and red triangle in Figure 3a–c, respectively) in the hybrid metasurface with $b_p = 40$, $W = 150$ nm, and $D = 10$ nm are considered. The polarization angle θ is

defined as the angle between the polarization and the positive Z -direction, which can be changed from 0 to 360° in a 15° step. In Figure 3d, the transmittance at 1262 nm (marked with blue squares) reaches a maximum of 0.7607 at $\theta = 0^\circ$ and $\theta = 180^\circ$ and a minimum of 0.302 at $\theta = 90^\circ$ and $\theta = 270^\circ$. Likewise, the transmittance at 1487 nm (marked with red triangles) reaches a maximum of 0.4433 at $\theta = 0^\circ$ and $\theta = 180^\circ$ and a minimum of 0.1461 at $\theta = 90^\circ$ and $\theta = 270^\circ$. But the transmittance at 1394 nm (marked with black dots) reaches a maximum of 0.1595 at $\theta = 90^\circ$ and $\theta = 270^\circ$ and a minimum of 0.06755 at $\theta = 0^\circ$ and $\theta = 180^\circ$. As shown in Figure 3e and f, a similar conclusion can be made on the related wavelengths (see the blue square, black dot, and red triangle) in Figure 3b and c, respectively. The results elucidate that, when the geometric parameters of the unit cells are fixed, the transmittance at the related three wavelengths can be regulated by changing the polarization direction of the incident light. In other words, the polarization-dependent transmittance at the related three different wavelengths that result from different degrees of anisotropy [52] holds great promise for plasmonic sensing and switching [3], as well as polarization-dependent digital metasurface in the metasurfaces [53].

3.2 Polarization-dependent passive plasmonic switching and digital metasurface

In view of the fact that the line shape and position of the plasmonic FR can be effectually designed by changing the geometric parameters of the hybrid metasurface. Moreover, the properties of the transmitted spectrum can be controlled by adjusting the polarization angle of the incident light (θ). In this scenario, as shown in Figure 4a, by varying the θ between 0° (along the Z -direction) and 90° (along the X -direction), the passive plasmonic switching can easily change the “ON” and “OFF” states at the telecom O -band ($1260 \sim 1360$ nm) and L -band ($1565 \sim 1625$ nm). Here, the ON/OFF ratio η can be defined as [54].

$$\eta = 10 \log_{10} \left(\frac{T_{\text{ON}}}{T_{\text{OFF}}} \right), \quad (4)$$

where T_{ON} and T_{OFF} are the transmittance of the “ON” and “OFF” states at the marked wavelengths, respectively. The marked wavelength in Figure 4a presents at the telecom L -band with the center wavelength being 1571 nm, where $T_{\text{ON}} = 0.3908$ and $T_{\text{OFF}} = 0.0099$. The ON/OFF ratio η based on Equation (4) can be obtained as 15.96 dB, where the modulation depth at the marked wavelength can be obtained around 97% [19]. In particular, there exists the

marked wavelength appearing at the telecom O -band with the center wavelength of 1276 nm. In this case, $T_{\text{ON}} = 0.5045$, while T_{OFF} is only 0.0032 , leading to the ON/OFF ratio η being as high as 21.98 dB with the modulation depth being nearly 99% . It should be noted that the passive plasmonic switching can work simultaneously at the marked dual-wavelength, but the “ON” states are not realized simultaneously. Once the “ON” state of one of the dual-wavelength occurs, the “OFF” state is achieved at another wavelength under the same conditions and vice versa. Besides, by adjusting the geometric parameters of the unit cells, the “ON” and “OFF” states at a working wavelength of 1267 nm in a single-wavelength passive plasmonic switching can obtain $T_{\text{ON}} = 0.8144$ and $T_{\text{OFF}} = 0.007464$ with the ON/OFF ratio being 20.38 dB (the modulation depth is around 99%). This means that a novel compact dual-wavelength passive plasmonic switching can be realized in the near-infrared region, which is a passive device without adding another active pump light field in the hybrid metasurface. Such a high ON/OFF ratio for the polarization-dependent passive plasmonic switching allows for potential applications in optical communication with high flexibility and designability.

In addition, we further consider the hybrid metasurface to be encoded as the binary digital elements of “0” and “1.” The physical realization of digital elements requires distinct responses to obtain significant amplitude changes of the transmitted spectra, which can own dramatic freedom to control the transmission of the pulsed light field. As shown in Figure 4b, for the “ON” state at 1276 nm, the E-field distribution implies that both the CRA and the PH unit cells of the hybrid metasurface are excited, whereas the strongest resonance is activated at the center of the PH unit cells. Likewise, there is no obvious strong resonance occurring in the E-field distribution for the “OFF” state at 1276 nm. With respect to the case of the “ON” and “OFF” states at 1571 nm, the CRA unit cells are evidently excited when the plasmonic switching operates independently in the “ON” and “OFF” states, but the PH unit cells are only obviously excited when the plasmonic switching works at the “ON” state. In our scheme, the hybrid metasurface here can function as a 1-bit digital metasurface, where the “ON” and “OFF” states can be named as “1” and “0” elements, respectively. With the hybrid metasurface working at a wavelength of 1276 nm, the “1” (see the upper left of Figure 4b) and “0” (see the lower left of Figure 4b) elements refer to the case of the polarization angle of the incident light at 0° (along the Z -direction) and 90° (along the X -direction), respectively. However, with the hybrid metasurface operating at 1571 nm, the “1” (see the upper right of Figure 4b) and “0”

Figure 4: The polarization-dependent dual-wavelength passive plasmonic switching and 1-bit digital metasurface.

(a) The polarization-dependent dual-wavelength passive plasmonic switching in the near-infrared region, with the ON/OFF ratio being 21.98 and 15.96 dB at a wavelength of 1276 and 1571 nm, respectively. (b) The 1-bit digital metasurface can be obtained by encoding the elements “1” and “0” in two ways at the related wavelengths. The four subplots show the polarization of the incident light and the related E -field distributions. The parameters of the unit cells of the hybrid metasurface are set as $R_1 = 122.5$ nm, $D = 20$ nm, $L = 130$ nm, $W = 100$ nm, $a_p = 1$, and $b_p = 5$, and the other parameters are the same as Figure 2.

(see the lower right of Figure 4b) elements refer to the case of the polarization angle of the incident light at $\theta = 90^\circ$ and $\theta = 0^\circ$, respectively. In this way, the amplitude response of the “0” and “1” elements can be readily defined as $A_n = n(T_{\text{ON}} - T_{\text{OFF}})$, with $n = 0, 1$. Therefore, we can control the amplitude response of the transmitted spectra by adjusting the polarization direction of the incident light to realize the freely switching between coding elements “0” and “1.” By encoding the “0” and “1” elements with a controlled sequence (1-bit coding), it is possible to fulfill the digital metasurface in the telecom dual-wavelength with different functions in the near-infrared region.

It is obvious that the polarization-dependent digital metasurface can be extended from 1-bit to 2-bit or more. In the case of 2-bit coding, four types of polarization states with distinct amplitude responses in the transmitted spectra are required to mimic the “00,” “01,” “10,” and “11” coding elements. As for the 2-bit digital metasurface, one can obtain greater flexibility in controlling the coding sequences with extensive applications. Similar to the case of 1-bit digital metasurface, the amplitude responses are defined as $A_n = n(T_{\text{ON}} - T_{\text{OFF}})/3$, ($n = 0, 1, 2, 3$). As shown in Figure 5a, to realize 2-bit digital metasurface, the polarization angles with four different amplitude responses in the transmitted spectra are set as $\theta = 0^\circ$, $\theta = 37^\circ$, $\theta = 56^\circ$, and $\theta = 90^\circ$, respectively. When the hybrid metasurface works simultaneously (*dual-wavelength 2-bit*) at the telecom O -band with the center wavelength being 1276 nm and L -band with the center wavelength being 1571 nm, the

amplitude responses in the transmitted spectra of $\theta = 0^\circ$, $\theta = 37^\circ$, $\theta = 56^\circ$, and $\theta = 90^\circ$ are defined as “10” (see the *red* curve in Figure 5a), “11” (see the *black* curve in Figure 5a), “00” (see the *orange* curve in Figure 5a), and “01” (see the *blue* curve in Figure 5a) coding elements, respectively. With the hybrid metasurface working at wavelength 1276 nm (*single-wavelength 2-bit*), the “11,” “10,” “01,” and “00” coding elements refer to the case of the polarization angle of the incident light at $\theta = 0^\circ$ (see the *red* pentagram in Figure 5b), $\theta = 37^\circ$ (see the *black* pentagram in Figure 5b), $\theta = 56^\circ$ (see the *orange* pentagram in Figure 5b), and $\theta = 90^\circ$ (see the *blue* pentagram in Figure 5b), respectively. However, with the hybrid metasurface working at wavelength 1571 nm (*single-wavelength 2-bit*), the “11,” “10,” “01,” and “00” coding elements refer to the case of the polarization angle of the incident light at $\theta = 90^\circ$ (see the *red* triangle in Figure 5b), $\theta = 56^\circ$ (see the *black* triangle in Figure 5b), $\theta = 37^\circ$ (see the *orange* triangle in Figure 5b), and $\theta = 0^\circ$ (see the *blue* triangle in Figure 5b), respectively. As shown in Figure 5b, for the CRA unit cells of the hybrid metasurface, the E -field distributions at 1276 or 1571 nm illustrate that the orientations of the distributions are consistent with the polarization direction of the corresponding incident light. For the PH unit cells of the hybrid metasurface at 1276 and 1571 nm, the E -field is mainly distributed on the center (on both sides) of the H -shaped hole unit cells in the case of $\theta = 0^\circ$ ($\theta = 90^\circ$). Meanwhile, the E -field distributions are asymmetric in the case of $\theta = 37^\circ$ and $\theta = 56^\circ$, which is due to the geometric configuration

Figure 5: The amplitude responses in the transmitted spectra of the dual-wavelength 2-bit digital metasurface, as well as their coding elements.

(a) The amplitude responses in the transmitted spectra of the dual-wavelength 2-bit digital metasurface by encoding the polarization state of the incident light with the polarization angle θ being 0, 37, 56, and 90° , respectively. (b) The "11," "10," "01," and "00" coding elements realized at the related wavelengths. The eight subplots show the polarization of the incident light and the related E -field distributions, as well as the projection of the E -field intensity (along the polarization direction) on the X - or Z -direction.

of the PH unit cells being asymmetric along the polarization direction of the incident light (see the projection of the E -field intensity in Figure 5b). When the 2-bit digital metasurface works at the single-wavelength or dual-wavelength, not only are their coding methods different but can achieve different functions. These plasmonic optical behaviors indicate that the proposed hybrid metasurface device can possess multifunctionalities and provide for the possibility of applications in optical sensors, optics digital processing, optical communication, and optical switching in the near-infrared region.

Moreover, it is known that magnetron sputtering has been proven to be an extremely versatile tool for coating deposition in the application field of coatings with specific optical or electrical properties [55–57]. The magnetron sputtering films are superior to the films deposited by other physical vapor deposition processes in many cases, which provide the feasibility for the fabrication of high-quality metallic Ag films. In order to tailor the unit cells with the required geometric configurations in the Ag film, a focused-ion beam system can be used to generate highly symmetrical nanohole with a diameter of sub-5 nm, thus forming arrays with the multiple nanohole [58]. By doing so, a 50-nm-thick Ag film can be sputtered on the polished quartz substrate, and then, the hybrid metasurface with CRA and PH unit cells can be fabricated by using a focused-ion beam method. The

transmission spectra can be measured by using a homebuilt optical system [59]. Therein, a pair of the near-infrared objective lens can be used to focus the incident ultrashort Gaussian pulse and collect the transmitted signal. Thus, the transmitted signal can be delivered to a spectrometer equipped with a charge-coupled device detector. In brief, the proposed hybrid metasurface can be fabricated, and the dual-wavelength passive plasmonic switching and digital metasurface can possibly be observed in the experiment.

4 Conclusion

In summary, we have studied the polarization-dependent passive plasmonic switching and digital metasurface assisted by the near-infrared plasmonic FR in a hybrid metasurface, which consists of periodic silver film arrays with concentric PH and CRA unit cells. It is shown that the presence of the plasmonic FR originates from the hybridization between the effective electric dipolar mode (D_1) of the CRA structure and the effective electric dipolar mode (D_2) of the PH structure. This process gives rise to the appearance of the hybridized bonding ($D_1 + D_2$) and anti-bonding ($D_1 - D_2$) modes in the hybrid metasurface. It is further verified that the TCMT agrees well with the numerical simulation. By modulating the related geometric

configurations of the unit cells in the hybrid metasurface, the wavelength, width (W_{Fd}), and depth (D_{Fd}) of the plasmonic Fano dip can be efficaciously controlled. Moreover, when the geometric parameters of the unit cells are fixed, the transmittance with different degrees of anisotropy at the related three wavelengths can be regulated by changing the polarization direction of the incident light. In this context, a novel compact dual-wavelength passive plasmonic switching can be accomplished at the telecom O - and L -bands with ON/OFF ratios being 21.98 and 15.96 dB, respectively. In particular, such polarization-dependent passive plasmonic switching can be served as a 1-bit digital metasurface, by adjusting the polarization direction of the incident light to manipulate the amplitude response of the transmitted spectra. Therein, the amplitude responses can be referred to as the “0” and “1” coding elements, where $A_n = n(T_{\text{ON}} - T_{\text{OFF}})$, with $n = 0, 1$. Furthermore, the digital metasurface can be extended from 1-bit to 2-bit, when the four required amplitude responses are defined as $A_n = n(T_{\text{ON}} - T_{\text{OFF}})/3$, ($n = 0, 1, 2, 3$). The 2-bit digital metasurface can be encoded not only in two kinds of single-wavelength switchings but also in dual-wavelength switching simultaneously. Moreover, the proposed hybrid metasurface can provide a flexible and easy-to-implement optical control approach with the aid of the polarization-dependent optical properties. Our scheme neither needs a pump light nor a complex control circuit and power supply, which could significantly reduce the volume of the system and easy integration. Besides, our results open the avenue toward sensors [14, 15], optical digital processing [32], modulators [17], and miniaturized wireless communication systems [60] in the optical communication band. More importantly, this optically controlled hybrid metasurface can be more easily extended to the all-optical regions than their electronically controlled counterparts, which also holds great promise for wider applications.

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