

Excitation and Control of Multiple Surface Lattice Resonances in Gold Nanorod Dimer Arrays for Multi-Wavelength Refractive Index Sensing

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Abstract

A major challenge in plasmonic lattice research is the limited flexibility for independently controlling multiple surface lattice resonances with high quality factors within a single array, as conventional single-nanoparticle or isotropic dimer designs offer insufficient degrees of freedom for selective mode excitation and continuous Q-factor tuning. To address this, a gold nanorod dimer array is proposed where each unit cell contains two anisotropic rods, enabling precise manipulation of collective surface lattice resonances via incident polarization and inter-rod displacements. It is shown that the surface lattice resonance mode can reach a Q-factor exceeding 700 with good robustness. Symmetric displacement further enables complementary switching, where the low-order and the high-order lattice resonances are selectively activated or suppressed depending on nanorod positioning at antinodes or nodes of the lattice waves. Leveraging these dual high-Q modes, the array achieves theoretical refractive index sensitivities of 456 nm/RIU and 653 nm/RIU, with corresponding figures of merit of 98 and 409, respectively, enabling self-referenced, high-performance biochemical sensing and multi-wavelength nanophotonic applications.

1. Introduction

Periodic arrays of noble metal nanoparticles support surface lattice resonances (SLRs), which arise from the coupling between localized surface plasmon resonances (LSPRs) of individual nanoparticles and Rayleigh anomalies (diffraction orders) of the lattice [1, 2]. When the LSPR wavelength aligns with a Rayleigh anomaly, the incident light efficiently excites a coherent surface wave that propagates across the entire array. This collective mode dramatically suppresses radiative losses compared to isolated LSPRs, resulting in narrow spectral linewidths and quality factors (Q-factor) that can reach hundreds or even thousands [3–5]. Consequently, SLRs have become a key platform for enhancing light-matter interactions at the nanoscale, enabling applications including low-threshold nanolasers, high-sensitivity biochemical sensors, enhanced nonlinear optics, and plasmonic switches [6–10].

While a single SLR delivers excellent performance, many advanced applications require simultaneous operation at multiple distinct wavelengths. For instance, multi-wavelength sensing, multiplexed detection, and multi-color nanolasing demand the coexistence of several narrow resonances within the same device [11, 12]. Compared to single SLR systems, multiple SLRs provide richer spectral information, enable self-referencing, and allow parallel detection of different analytes or signals [13, 14]. To generate multiple SLRs, several strategies have been developed. The first approach uses superlattice structures with non-uniform periodicities, producing several Rayleigh anomalies at different energies [15, 16]. The second approach utilizes unit cells containing two or more nanoparticles, where each nanoparticle contributes its own LSPR that couples to distinct diffraction orders [17–20]. The third approach exploits higher-order multipolar resonances (e.g., magnetic dipoles, electric quadrupoles) by using anisotropic or high-refractive-index nanostructures [21–23]. These methods have enabled demonstrations in dual-band sensing, multimodal nanolasers, and four-wave mixing [24–27].

Despite these advances, current systems for exciting multiple SLRs suffer from several critical limitations. First, the spectral separation between different SLRs is typically small, leading to mode overlap and difficulty in addressing individual resonances independently [28–33]. Second, there is frequently a modulation depths often exhibit mutually exclusive excitation: when one SLR is strongly excited, others become weak or disappear entirely [34–37]. Third, the Q-factors of multiple SLRs are often not simultaneously high, and the ability to continuously tune Q-factors or selectively switch between modes is rarely achieved in a single, simple geometry. Most existing designs rely on fixed structural parameters, offering little post-fabrication tunability [38–40]. Therefore, a platform that provides independent, flexible control over multiple high-Q-factor SLRs with large spectral separation, non-competitive excitation, and switchable behavior remains highly desirable. In this work, we propose a gold nanorod dimer array in which each unit cell contains two anisotropic nanorods [41–44]. By tuning the incident polarization and the relative in-plane displacements between the rods, we achieve flexible control over multiple SLRs, including a tunable Q-factor from 109 to 381 under x-polarization and a Q-factor exceeding 700 under y-polarization. Moreover, symmetric displacement enables complementary switching between low-order and high-order SLRs via node-antinode engineering. Using these dual high-Q-factor resonances, the array demonstrates refractive index sensitivities of 456 and 653 nm/RIU with figures of merit of 98 and 409, respectively, enabling high-performance self-referenced sensing.

2. Results and discussions

Figure 1(a) illustrates a periodic array of single gold nanorods. Unlike the polarization-insensitive response of highly symmetric nanosphere or nanodisk arrays under normal incidence, the anisotropic shape of the nanorods renders the array's optical response strongly dependent on the incident polarization direction. This polarization sensitivity, while offering a degree of control, is inherently limited when only one nanorod is present per unit cell. As shown in the numerically simulated transmission spectra (Fig. 1(b), using the finite-difference time-domain method), for polarization along the nanorod long axis (x-polarization), a sharp resonance appears near 1161.5 nm. Given that the $(0, \pm 1)$ order Rayleigh anomaly lies at 1144.0 nm, this mode is assigned to a surface lattice resonance ($\text{SLR}_{(0, \pm 1)}$) arising from coupling between the longitudinal localized surface plasmon resonance of the nanorod and the $(0, \pm 1)$ Rayleigh anomaly. For y-polarization (along the short axis), a sharp resonance is also observed at 1144.2 nm, corresponding to the $\text{SLR}_{(\pm 1, 0)}$ mode. However, due to a significant energy mismatch between the transverse LSPR and the $(\pm 1, 0)$ Rayleigh anomaly, the modulation depth of this SLR remains very low. A third sharp resonance at 811.2 nm, close to the $(\pm 1, \pm 1)$ Rayleigh anomaly (≈ 808.9 nm), can be attributed to the high-order $\text{SLR}_{(\pm 1, \pm 1)}$ mode. Nevertheless, in this single-nanorod-per-unit-cell design, the excitation efficiency and spectral position of these SLR modes are largely fixed by the period and the nanorod's intrinsic resonances, offering limited tunability. This motivates the introduction of a richer building block (*i.e.*, a nanorod dimer within each unit cell), to achieve flexible, multi-resonant control over high-Q lattice modes, as demonstrated in the following sections.

In contrast to previously reported arrays where each unit cell contains two isotropic nanodisks, we introduce a unit cell composed of two anisotropic gold nanorods (Fig. 1(c)). This design fundamentally enriches the optical response in two crucial ways. First, the anisotropy of the nanorods makes the array's collective modes highly responsive to the incident polarization direction, offering a versatile external control parameter. Second, the relative positions (S_x and S_y) between the two nanorods provide additional degrees of freedom to tailor the near-field coupling and thus the far-field lattice resonances.

The representative transmission spectra in Fig. 1(d) demonstrate the unprecedented flexibility. By simply choosing the polarization and the dimer configuration, one can realize qualitatively different SLR excitation scenarios, including simultaneous excitation of two distinct SLR modes (red solid line, $S_x = 0$, $S_y = 120$ nm) where both the $SLR_{(0,\pm 1)}$ and the high-order $SLR_{(\pm 1,\pm 1)}$ appear with strong modulation depth; selective excitation of only the high-order $SLR_{(\pm 1,\pm 1)}$ mode (red dashed line, $S_x = S_y = 380$ nm) where the lower-order SLR is completely suppressed, a feature difficult to achieve in single-rod or nanodisk arrays; and controlled tuning of the Q-factor (blue dashed line) where the linewidth of the same lattice mode can be deliberately adjusted by changing the dimer spacing. These capabilities, that is, polarization-switchable multi-resonance, selective high-order mode activation, and Q-factor engineering, are highly desirable for functional nanophotonic devices such as multi-wavelength sensors, switches, or nonlinear metasurfaces. Motivated by this, the following sections systematically investigate how the optical response of the nanorod dimer array evolves with structural parameters and elucidate the underlying physical mechanisms.

We first investigate the tunability of the nanorod dimer array under x-polarized incidence by fixing the inter-rod displacement in the x-direction ($S_x = 0$) and varying the y-direction separation S_y (Fig. 2). As S_y increases from 0 to 240 nm, the sharp $SLR_{(0,\pm 1)}$ mode near 1150 nm exhibits a slight blue shift, approaching the $(0, \pm 1)$ Rayleigh anomaly wavelength. More importantly, its Q-factor increases substantially from 109 to 381 (right panel), demonstrating that simply adjusting the dimer spacing can significantly suppress radiative losses and enhance the coherence of the collective lattice resonance. When S_y exceeds 240 nm, the modulation depth of this lattice mode gradually decreases, and at $S_y = 320$ nm the resonance is completely suppressed. This suppression occurs because the array effectively transforms into a single-nanorod lattice with a reduced period (400 nm in the y-direction), for which the $(0, \pm 1)$ Rayleigh anomaly lies below 600 nm and can no longer couple to the nanorod's localized resonance. Further increasing S_y yields an anti-symmetric evolution of the transmission spectra, a direct consequence of the structural symmetry of the dimer array. Beyond the lattice resonance, a broad feature near 920 nm becomes most pronounced at $S_y = 320$ nm, which can be assigned to the longitudinal localized plasmon resonance of individual nanorods, and the periodic lattice coupling is minimal. These results highlight a key advantage of the dimer architecture: the ability to continuously tune the Q-factor of a collective SLR mode and even switch it on and off by controlling the relative position of the two nanorods.

To gain mechanistic insight into the tunable surface lattice resonance behavior observed in Fig. 2, we examine the near-field enhancement factor ($|\mathbf{E}|/|\mathbf{E}_0|$) distributions at the resonance modes for two representative dimer configurations (Fig. 3). When the two nanorods in a unit cell are merged ($S_y = 0$, Fig. 3(a)), the structure effectively becomes a square nanodisk. The near-field pattern clearly shows a surface wave propagating along the y -axis, confirming that the resonance is a surface lattice resonance arising from coupling between the localized plasmon resonance of the merged disk and the $(0, \pm 1)$ Rayleigh anomaly. However, due to the large radiative losses of this merged geometry, the Q-factor is modest ($Q \approx 109$). Strikingly, when the nanorods are separated to $S_y = 240$ nm (Fig. 3(b)), the surface wave propagation characteristics remain similar, yet the Q-factor jumps to 381. This marked improvement directly demonstrates a key advantage of the dimer architecture, that is, separating the two nanorods reduces radiative damping of the localized resonance, thereby enhancing the coherence of the collective lattice mode while preserving the underlying coupling mechanism. When S_y reaches 320 nm, the array transforms into a single-nanorod lattice with a y -period of 400 nm. At this point, the $(0, \pm 1)$ Rayleigh anomaly shifts below 600 nm, too far from the nanorod's localized resonance to permit coupling, and the sharp lattice mode disappears. These near-field results not only validate the origin of the observed resonances but also highlight the dimer's ability to continuously tune the resonance Q-factor and even switch the mode on and off, which are capabilities that are inherently absent in conventional single-nanoparticle arrays.

We now turn to the case where the incident polarization is along the y -axis (Fig. 4). As with x -polarization, the symmetry of the dimer array results in an anti-symmetric evolution of the transmission spectra with respect to $S_y = 320$ nm (left panel). When the nanorods merge ($S_y = 0$ or 640 nm), the structure becomes a square nanodisk, and a sharp resonance appears near 1150 nm, which is analogous to the x -polarization case but now arising from coupling between the disk's localized resonance and the $(\pm 1, 0)$ Rayleigh anomaly. Strikingly, as S_y approaches the midpoint of the range (e.g., $S_y = 120$ – 240 nm), the Q-factor of this $SLR_{(\pm 1, 0)}$ mode rapidly increases to over 700, significantly higher than the maximum Q (~ 381) achieved under x -polarization. Moreover, this ultra-high Q factor remains nearly constant over a wide range of S_y (right panel), demonstrating that the dimer array not only enables extreme Q-factor enhancement but also provides exceptional robustness against fabrication variations. This combination of high sensitivity (via high Q-factor) and tolerance to positional errors is highly advantageous for practical nanophotonic devices, particularly in sensing applications where both resolution and reproducibility are critical.

Beyond the low-order surface lattice resonance, the dimer array also enables precise control over the high-order $SLR_{(\pm 1, \pm 1)}$ mode near the $(\pm 1, \pm 1)$ Rayleigh anomaly at approximately 810 nm (Fig. 4). Critically, the relative position between the nanorods has a significant impact on their modulation depth. When the nanorods are merged ($S_y = 0$), only a broad, featureless localized resonance appears in this spectral region, which means that this is no distinct lattice mode is formed. However, as S_y increases, this broad feature rapidly transforms into a sharp resonance. For instance, at $S_y = 120$ nm, the Q-factor already reaches 174, representing an enhancement in modulation depth compared to a conventional

single-nanorod array (Fig. 1(b)). Strikingly, when S_y further increases to 240 nm, the Q-factor is about 679, rivaling the ultra-high Q (> 700) achieved for the low-order lattice mode under y-polarization. This demonstrates that the dimer array not only supports high-order lattice resonances but also allows their Q-factors to be tuned over an exceptionally wide range. Such control over multiple high-Q resonances across distinct spectral bands (the low-order resonance near 1150 nm and the high-order resonance near 810 nm) positions the dimer array as an excellent platform for multi-wavelength nanophotonic devices.

The near-field distributions in Fig. 5 provide direct evidence for the distinct coupling mechanisms underlying the two types of lattice modes observed under y-polarization. When the nanorods are merged ($S_y = 0$, Fig. 5(a)), the surface wave propagates along the y-direction, identical to the x-polarization case (Fig. 3(a)) except for the orthogonal propagation direction. This confirms that the resonance arises from coupling between the $(\pm 1, 0)$ Rayleigh anomaly and the localized mode of the merged square disk. Crucially, as the nanorods are separated ($S_y = 120$ nm, bottom panel of Fig. 5(b) and $S_y = 320$ nm, Fig. 5(c)), the overall surface wave characteristics remain intact, yet the Q-factor dramatically improves (Fig. 4, right). This improvement directly demonstrates a key design principle, that is, separating the two nanorods suppresses radiative losses of the localized resonance, thereby enhancing the coherence of the collective lattice mode without altering its fundamental coupling mechanism.

For the high-order $SLR_{(\pm 1, \pm 1)}$ mode near 810 nm, the top panel of Fig. 5(b) ($S_y = 120$ nm) reveals surface waves propagating along the diagonal direction of the unit cell, unambiguously verifying coupling between the nanorod localized resonance and the $(\pm 1, \pm 1)$ Rayleigh anomaly. More importantly, the near-field pattern shows that the two nanorods are positioned exactly at the antinodes of the standing surface wave. This spatial matching explains why the high-order mode is efficiently excited at this S_y . Conversely, when S_y is adjusted such that the nanorods move toward the node positions of the same lattice resonance, the coupling becomes inefficient, and the mode vanishes (Fig. 4). These results reveal that by simply tuning the relative position of the two nanorods within the unit cell, one can selectively activate or suppress specific high-order lattice resonances. Such precise, symmetry-guided control over multiple collective modes is an advantage of the anisotropic dimer architecture over conventional single-particle or isotropic arrays.

Beyond independently tuning S_y , simultaneous adjustment of both inter-rod displacements ($S_x = S_y$, denoted as $S_{x/y}$) provides an additional degree of freedom to engineer the array's optical response. Under x-polarized incidence (Fig. 6, left panel), the overall evolution of the sharp surface lattice resonance near 1150 nm resembles that in Fig. 2, where the resonance slightly red-shifts and its Q-factor gradually

improves as $S_{x/y}$ increases from 0 to 240 nm; further increase to 320 nm suppresses the mode entirely; beyond this point, the spectra exhibit an opposite trend. However, a key distinction arises at $S_{x/y} = 640$ nm, where the two nanorods are offset by one full nanorod length in the x-direction, breaking strict

spectral symmetry (right panel). More importantly, a new broader mode appears near 950 nm that was not prominently observed in the previous S_y -only scan. This mode becomes most pronounced precisely at $S_{x/y} = 320$ nm, and its Q-factor is noticeably improved compared to the broad localized plasmon resonance feature near 920 nm in Fig. 2.

The near-field analysis in Fig. 7(a) reveals the origin of the new resonance mode near 950 nm that emerged under symmetric displacement. The enhancement is strongly localized at the two ends of each nanorod, yet a clear surface wave propagating along the diagonal direction of the periodic lattice is also visible. This dual characteristic unambiguously identifies the mode as a high-order $SLR_{(\pm 1, \pm 1)}$ arising from coupling between the nanorod's longitudinal localized resonance and the $(\pm 1, \pm 1)$ Rayleigh anomaly. Critically, compared to the broad localized resonance feature observed in Fig. 2 (where $S_x = 0$, $S_y = 320$ nm), the present configuration achieves spatial matching, where the positions of maximum near-field enhancement (the nanorod ends) coincide with the antinodes of the diagonal surface wave. This matching enables efficient excitation of the lattice resonance and, importantly, leads to a noticeable compression of the spectral linewidth, *i.e.*, an improved Q-factor.

Figure 7(b) examines the near-field distribution of the low-order $SLR(0, \pm 1)$ mode under symmetric displacement. At $S_{x/y} = 420$ nm, a sharp resonance at 1145.7 nm is clearly observed, and the near-field pattern confirms its origin as $SLR(0, \pm 1)$. However, at $S_{x/y} = 320$ nm, this mode is completely absent (see Fig. 6). The underlying reason is symmetry, where the coupling is forbidden when the two nanorods are positioned exactly at the nodes of the $(0, \pm 1)$ lattice wave. This symmetry-controlled on-off switching represents a powerful functionality unique to the dimer-in-unit-cell design.

A dramatically different scenario emerges when the polarization is along the y -axis and both inter-rod displacements are varied simultaneously (Fig. 8). In stark contrast to the previous case where only S_y was adjusted (Fig. 4), the low-order surface lattice resonance near 1150 nm now exhibits a broad region of suppression. Specifically, for $S_{x/y}$ values between approximately 280 nm and 480 nm (centered at 380 nm), this mode has very weak modulation depth (left panel). Only when $S_{x/y}$ falls outside this range can the low-order surface lattice resonance be effectively excited, reaching a high Q-factor of about 700 (right panel). Conversely, the high-order $SLR_{(\pm 1, \pm 1)}$ mode near 810 nm displays the opposite behavior, where its modulation depth is greatly enhanced precisely within the same range (centered at $S_{x/y} = 380$ nm), achieving a Q-factor around 200. This complementary switching (where one lattice mode is suppressed exactly when the other is activated), represents a new level of control not achievable by varying S_y alone (Fig. 4).

From the left panel of Fig. 9(a), it can be seen that when $S_{x/y} = 100$ nm, the resonance mode at 814.5 nm exhibits surface waves propagating along the diagonal direction of the unit cell, belonging to the surface lattice resonance $SLR_{(\pm 1, \pm 1)}$. The right panel of Fig. 9(b) shows that in this case, the difference in the x -axis positions between the nanorods is small, and effective excitation of $SLR_{(\pm 1, 0)}$ is still possible. However, as $S_{x/y}$ further increases, the two nanorods respectively approach the two node positions of the

surface wave. This causes the inability to effectively excite this surface lattice resonance when $S_{x/y}$ varies in the range of 280–480 nm in Fig. 8. When the nanorods move out of the above node range, this mode can be effectively excited and observed again (Fig. 9(c)). Also, from Fig. 9(b), it can be seen that when $S_{x/y} = 380$ nm, for the high-order lattice resonance at 817.8 nm, the spatial positions of the two nanorods better match the surface wave antinodes, thus achieving a stronger excitation of this high-order resonance, and the near-field enhancement at the peak position is greatly improved compared to the previous various structures.

The near-field distributions in Fig. 9 provide direct visual evidence for the complementary switching behavior observed under y -polarization and symmetric displacement (Fig. 8). At $S_{x/y} = 100$ nm (Fig. 9(a), left panel), the resonance at 814.5 nm exhibits clear surface waves propagating along the unit cell diagonal, confirming its identity as the high-order $\text{SLR}_{(\pm 1, \pm 1)}$. At this same configuration, the low-order $\text{SLR}_{(\pm 1, 0)}$ can still be effectively excited (right panel of Fig. 9(a)), because the two nanorods are close enough to the antinodes of that lattice mode. However, as $S_{x/y}$ increases toward the 280–480 nm range identified in Fig. 8, the situation changes dramatically. The two nanorods progressively approach the node positions of the low-order $\text{SLR}_{(\pm 1, 0)}$ surface wave. Consequently, coupling becomes inefficient, and this mode is suppressed, which is exactly the region where the low-order lattice mode is absent in Fig. 8. When the nanorods move beyond this node range (e.g., $S_{x/y} = 640$ nm, Fig. 9(c)), they re-enter antinode regions, and the low-order mode is restored.

Conversely, the high-order $\text{SLR}_{(\pm 1, \pm 1)}$ mode benefits from antinode positioning within the same 280–480 nm range. At $S_{x/y} = 380$ nm (Fig. 9(b)), the two nanorods are situated precisely at the antinodes of the diagonal surface wave for the high-order resonance. This perfect spatial matching results in the strongest excitation of this mode among all configurations studied, with near-field enhancement significantly greater than in any previous structure (Fig. 5(b), for instance). The above results indicate that by tuning the relative position of the two nanorods within the unit cell, one can selectively couple to either the low-order or high-order lattice resonance, turning one mode on while turning the other off.

A key practical advantage of the nanorod dimer array is its ability to simultaneously support two distinct surface lattice resonances both with high Q-factors. This dual-mode capability is particularly valuable for multi-wavelength nanophotonic devices, and we demonstrate its potential in refractive index sensing (Fig. 10). As the ambient refractive index increases from 1.43 to 1.48 (Fig. 10(a)), both resonance modes exhibit clear, monotonic red shifts. The extracted peak positions follow a good linear relationship with refractive index (Fig. 10(b)), yielding sensitivities of 456 nm/RIU for $\text{SLR}_{(\pm 1, \pm 1)}$ and 653 nm/RIU for $\text{SLR}_{(\pm 1, 0)}$. More importantly, thanks to the ultra-narrow linewidths achieved in our dimer design, where the full widths at half maximum are as low as 4.66 nm and 1.60 nm, respectively. As a result, the figures of merit reach approximately 98 and 409. Furthermore, the simultaneous availability of two high-figure of merit resonances at well-separated wavelengths (around 810 nm and 1150 nm) enables self-referenced sensing, which can mitigate environmental fluctuations and improve measurement reliability.

3. Conclusions

In conclusion, this work demonstrates that a gold nanorod dimer array, with two anisotropic nanorods per unit cell, provides an exceptionally versatile platform for exciting and controlling multiple high-Q-factor surface lattice resonances through the combined tuning of incident polarization and inter-rod displacements (S_x and S_y). Under x-polarization, the $SLR_{(0, \pm 1)}$ mode exhibits a continuously tunable Q-factor from 109 to 381, while under y-polarization the $SLR_{(\pm 1, 0)}$ mode reaches a Q-factor exceeding 700 with remarkable robustness over a wide parameter range. More importantly, symmetric displacement ($S_x = S_y$) enables a complementary switching behavior where the low-order $SLR_{(\pm 1, 0)}$ and the high-order $SLR_{(\pm 1, \pm 1)}$ are selectively activated or suppressed depending on whether the nanorods reside at the nodes or antinodes of the respective lattice waves. Leveraging these dual high-Q-factor resonances, the array achieves refractive index sensitivities of 456 and 653 nm/RIU for the two surface lattice modes, respectively, with corresponding figures of merit of 98 and 409, enabling self-referenced, high-sensitivity biochemical sensing. This work establishes a paradigm for on-demand control of collective plasmonic modes via node-antinode positioning within a dimeric lattice, opening exciting avenues for multi-wavelength nanophotonic devices and advanced sensing platforms.

4. Methods

All numerical simulations were performed using the finite-difference time-domain (FDTD) method. The gold nanorods were modeled with a length $L = 160$ nm, width $W = 80$ nm, and thickness $H = 60$ nm. The array period was fixed at $P = 800$ nm in both x and y directions. The relative displacements between the two nanorods within each unit cell are denoted as S_x (x-direction offset) and S_y (y-direction offset). The ambient environment and the substrate were both assigned a refractive index of $n = 1.43$. The optical properties of gold are taken from experimental data from Johnson and Christy [45]. Perfectly matched layer (PML) absorbing boundary conditions were applied in the z-direction (normal to the array plane), while periodic boundary conditions were used in the x and y directions to model the infinite array. A plane wave source with normal incidence was employed, with polarization direction set either along the x-axis (long axis of the nanorod) or the y-axis (short axis). Transmission spectra were recorded using a frequency-domain power monitor placed behind the array.

Declarations

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Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contribution

All authors contributed to the study conception and design. Part of the work was done by all people collectively, but some parts were done individually by different people. The general division of work is as follows: Xin-Ru Ye: Methodology, Software, Formal analysis, Investigation. Yan-Jie Zhao: Data curation, Visualization, Validation. Lan-Qi Lian: Methodology, Formal analysis. Sheng-Jie Meng: Validation, Visualization. Hong-Mei Gong: Funding acquisition, Investigation. Ying Yu: Conceptualization. Shao-Ding Liu: Conceptualization, Supervision, Funding acquisition, Writing – original draft, Writing – review & editing.

Data Availability

The authors confirm that the raw data generated from the calculations fully confirm the results of the study, and if necessary, it can be presented by the corresponding author anytime.

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Figures

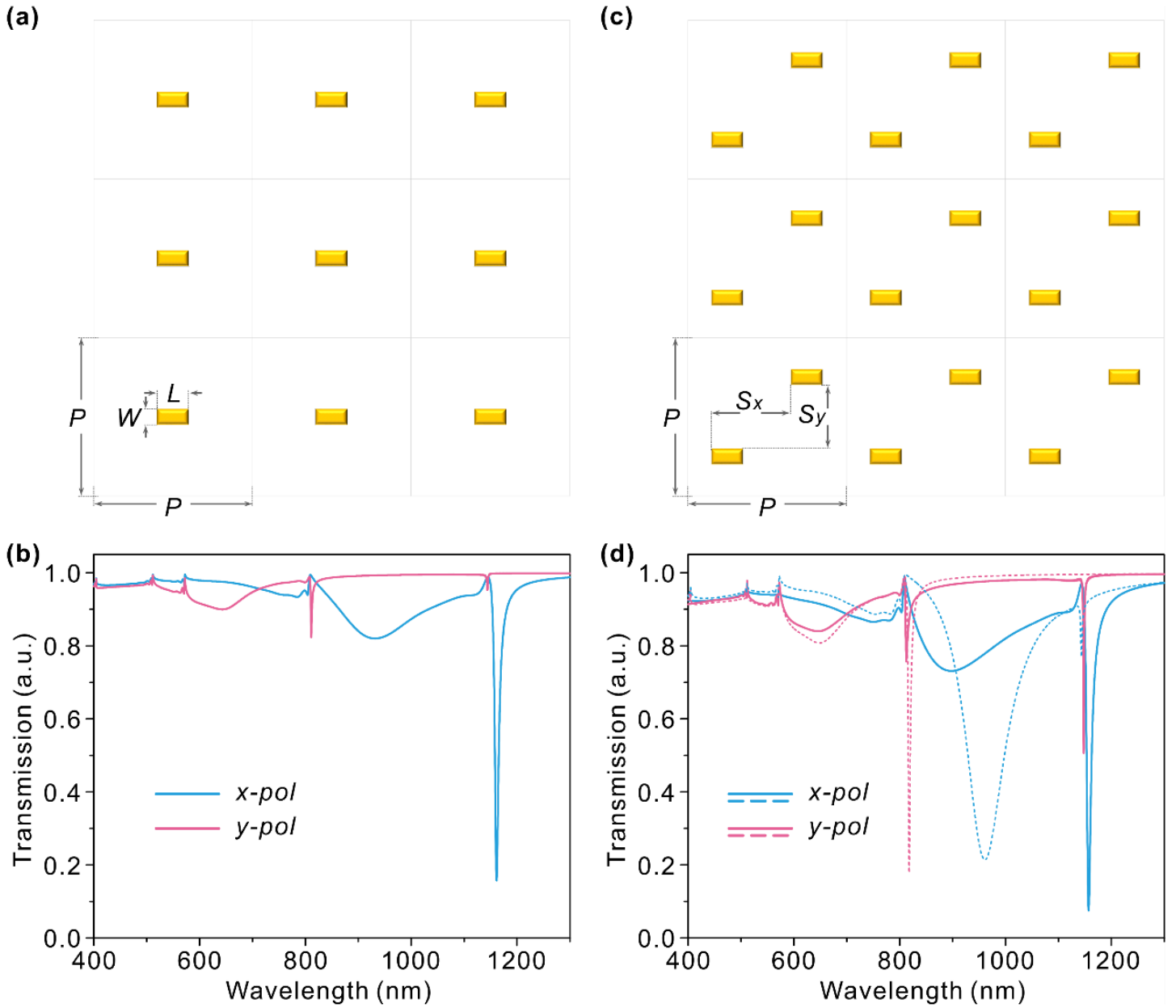


Figure 1

Comparison of an array composed of single gold nanorods and a nanorod dimer array. (a) Schematic view of the array composed of single nanorods. (b) Transmission spectra of the single nanorod array under normal incidence for different incident field polarization directions. Nanorod length $L = 160$ nm, width $W = 80$ nm, height $H = 60$ nm, array period $P = 800$ nm, the refractive index of surrounding medium $n = 1.43$. (c) Schematic view of the array composed of nanorod dimers. (d) Transmission spectra of the nanorod dimer array under normal incidence for different incident field polarization directions. The nanorod structural parameters are the same as in (b). The solid line spectra correspond to relative displacements $S_x = 0, S_y = 120$ nm; the dashed line spectra correspond to relative displacements $S_x = S_y = 380$ nm

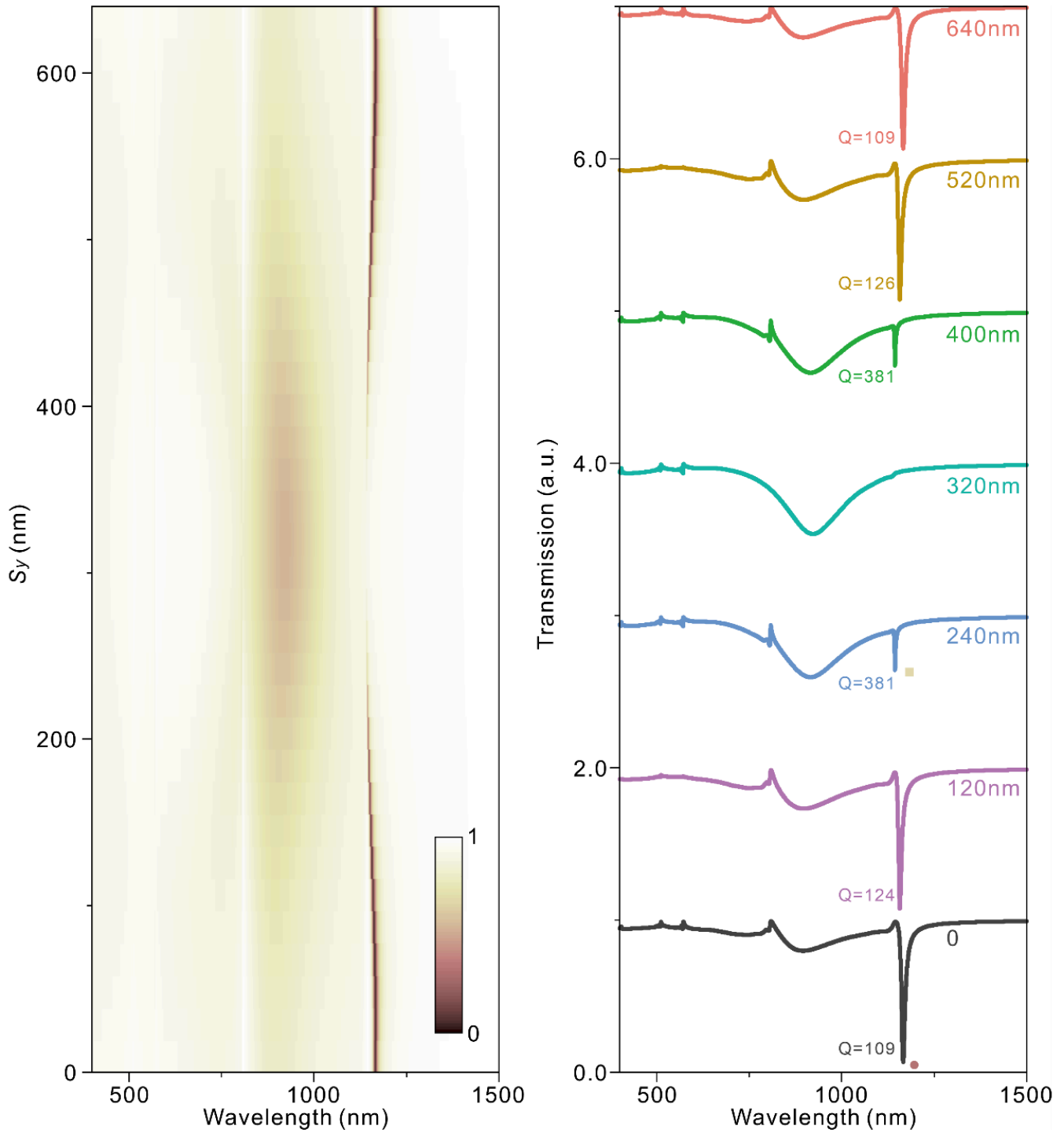


Figure 2

Dependence of the transmission spectra of the nanorod dimer array on the relative displacement S_y for x-polarization. Left panel: transmission spectra as S_y gradually increases from 0 to 640 nm (step 20 nm). Right panel: spectra for several representative relative displacements. The calculations set $S_x = 0$, and the nanorod structural parameters and array period are the same as in Fig. 1

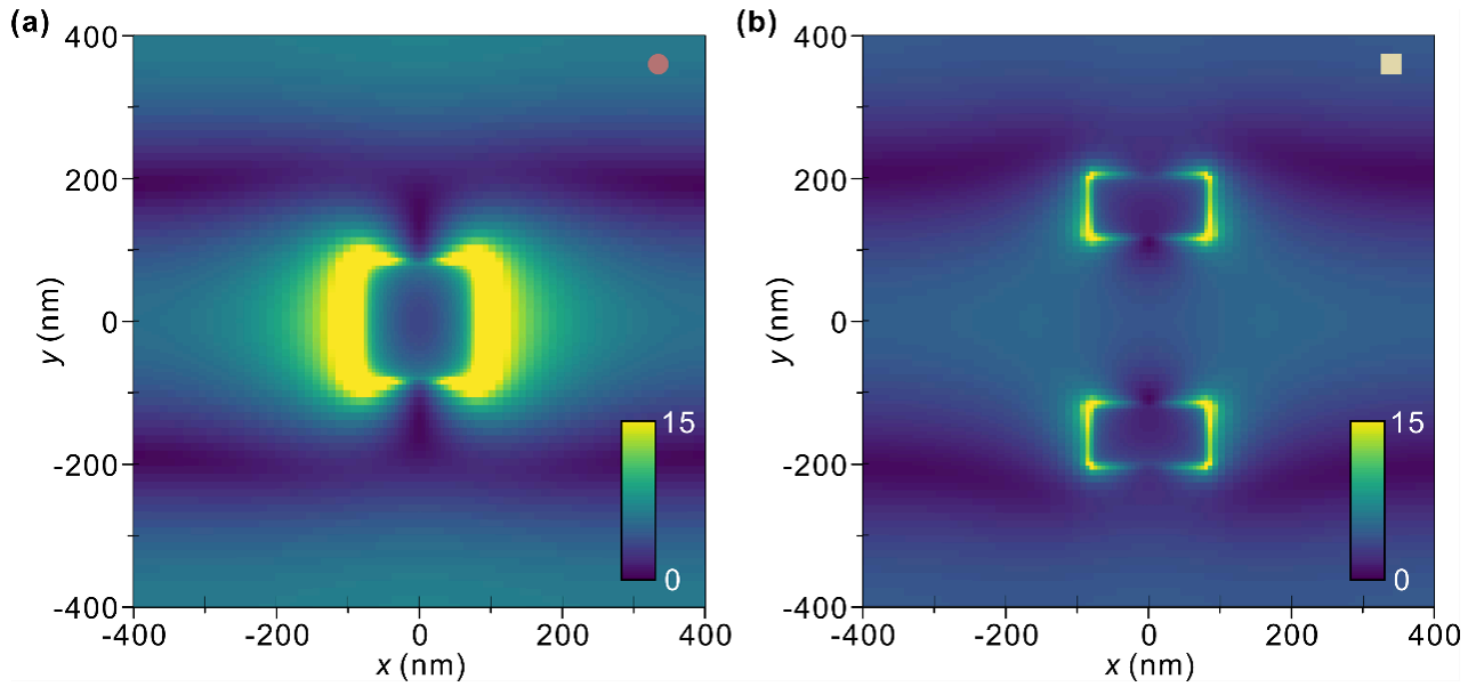


Figure 3

(a) Near-field enhancement factor distribution at the resonance peak position of 1166 nm when $S_x = 0$, $S_y = 0$. (b) Near-field enhancement factor distribution at the resonance peak position of 1144 nm when $S_x = 0$, $S_y = 240$ nm

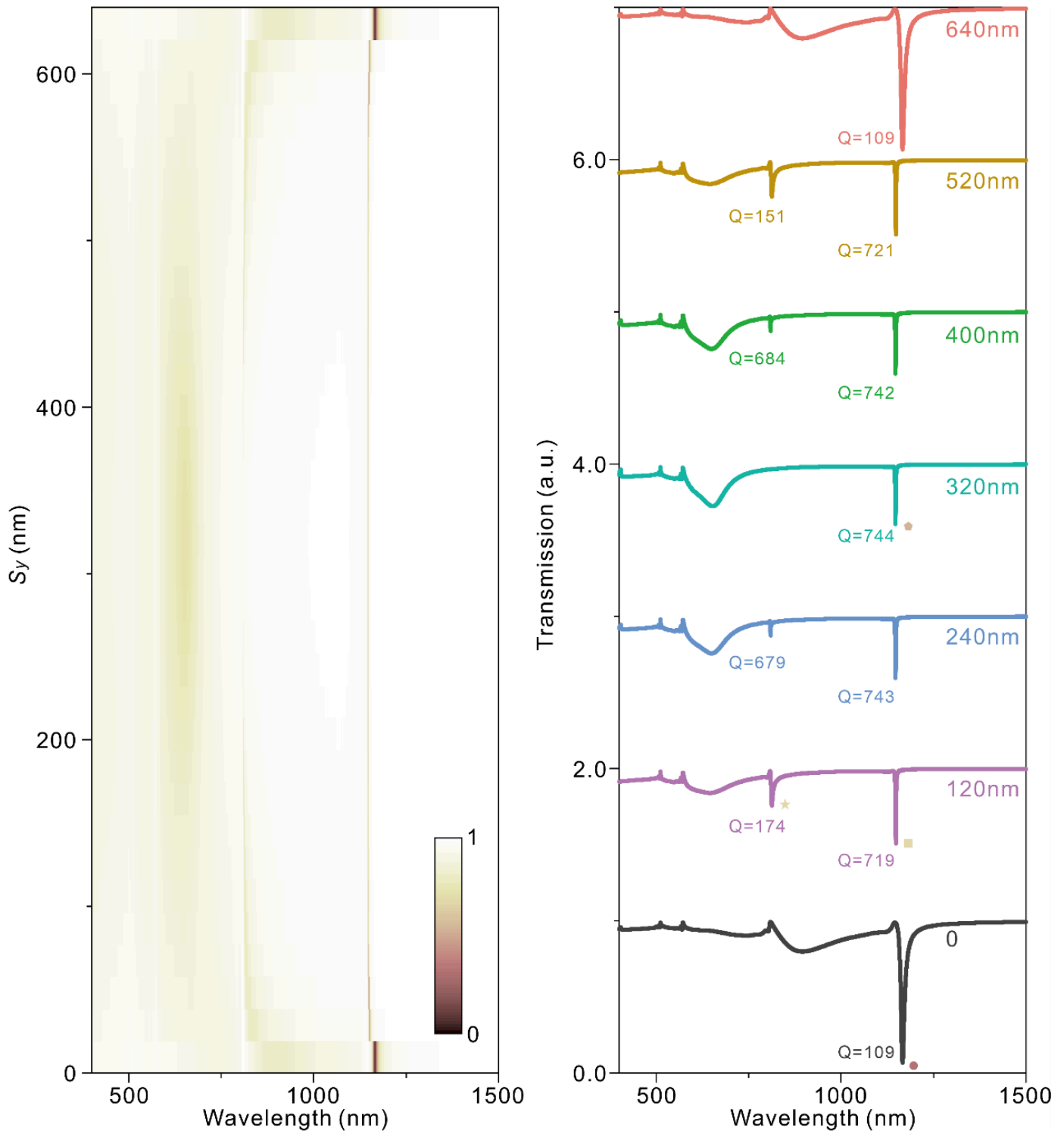


Figure 4

Dependence of the transmission spectra of the nanorod dimer array on the relative displacement S_y for y-polarization. Left panel: transmission spectra as S_y gradually increases from 0 to 640 nm (step 20 nm). Right panel: spectra for several representative relative displacements. In the calculations, $S_x = 0$, and nanorod structural parameters and array period are the same as in Fig. 1

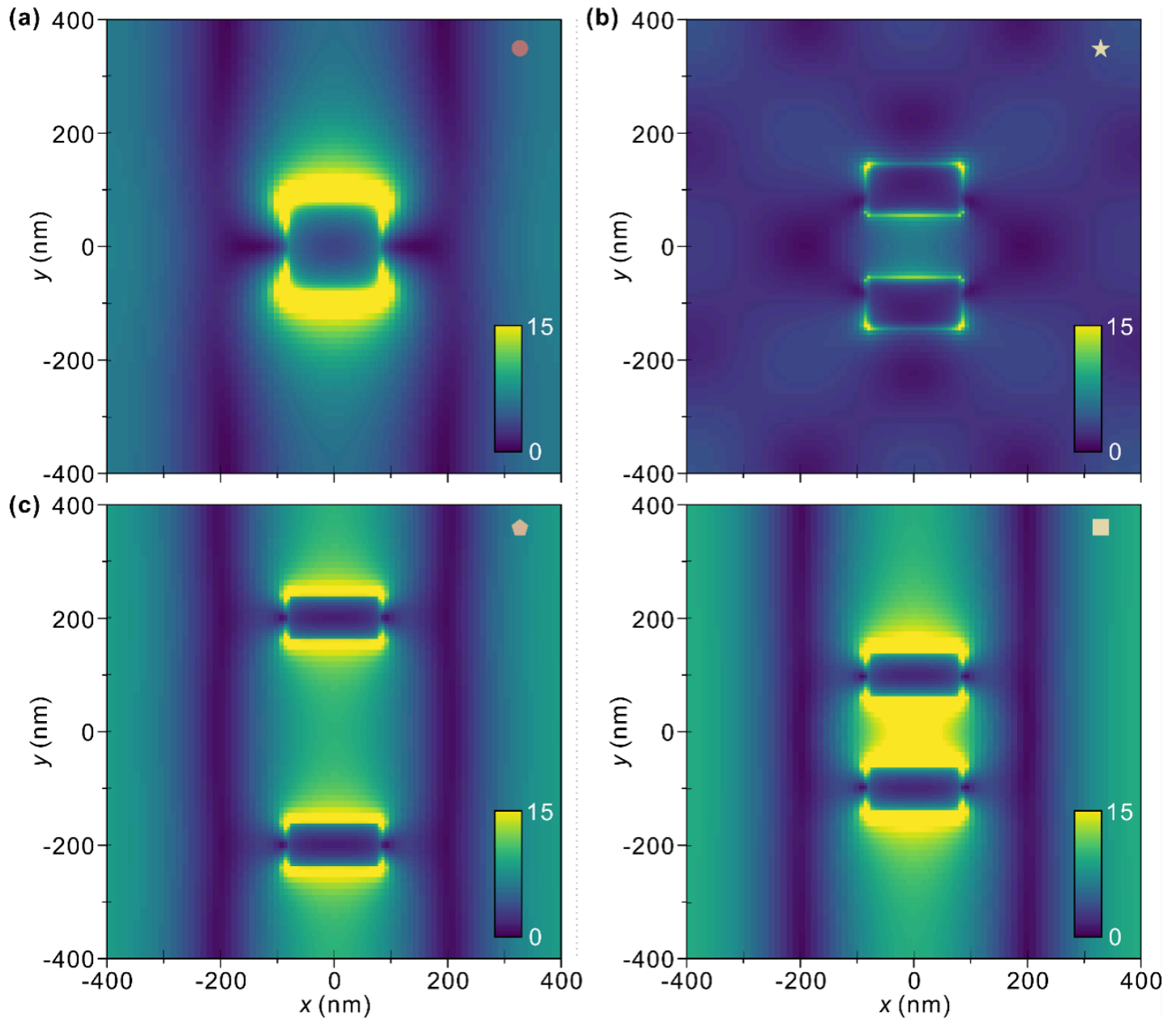


Figure 5

(a) Near-field enhancement factor distribution at the resonance peak position of 1166 nm when $S_x = 0$, $S_y = 0$. (b) Near-field enhancement factor distributions at the resonance peak positions of 812.5 nm (top) and 1147.8 nm (bottom) when $S_x = 0$, $S_y = 120$ nm. (c) Near-field enhancement factor distribution at the resonance peak position of 1147.1 nm when $S_x = 0$, $S_y = 320$ nm

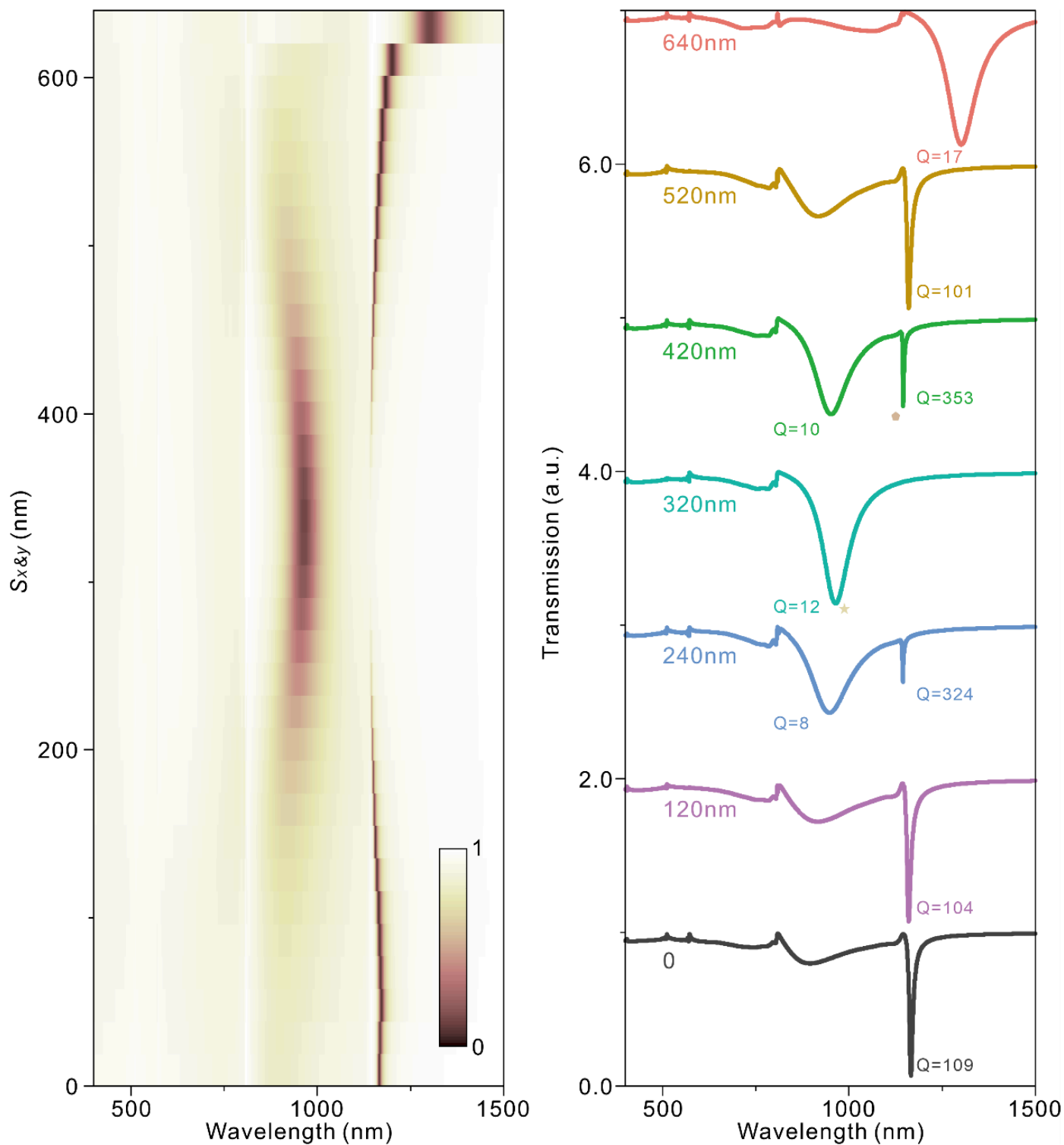


Figure 6

Dependence of the transmission spectra of the nanorod dimer array on the relative displacements S_x and S_y for x-polarization, where $S_x = S_y$ in the calculations. Left panel: transmission spectra as the relative displacement gradually increases from 0 to 640 nm (step 20 nm). Right panel: spectra for several representative relative displacements. Nanorod structural parameters and array period are the same as in Fig. 1

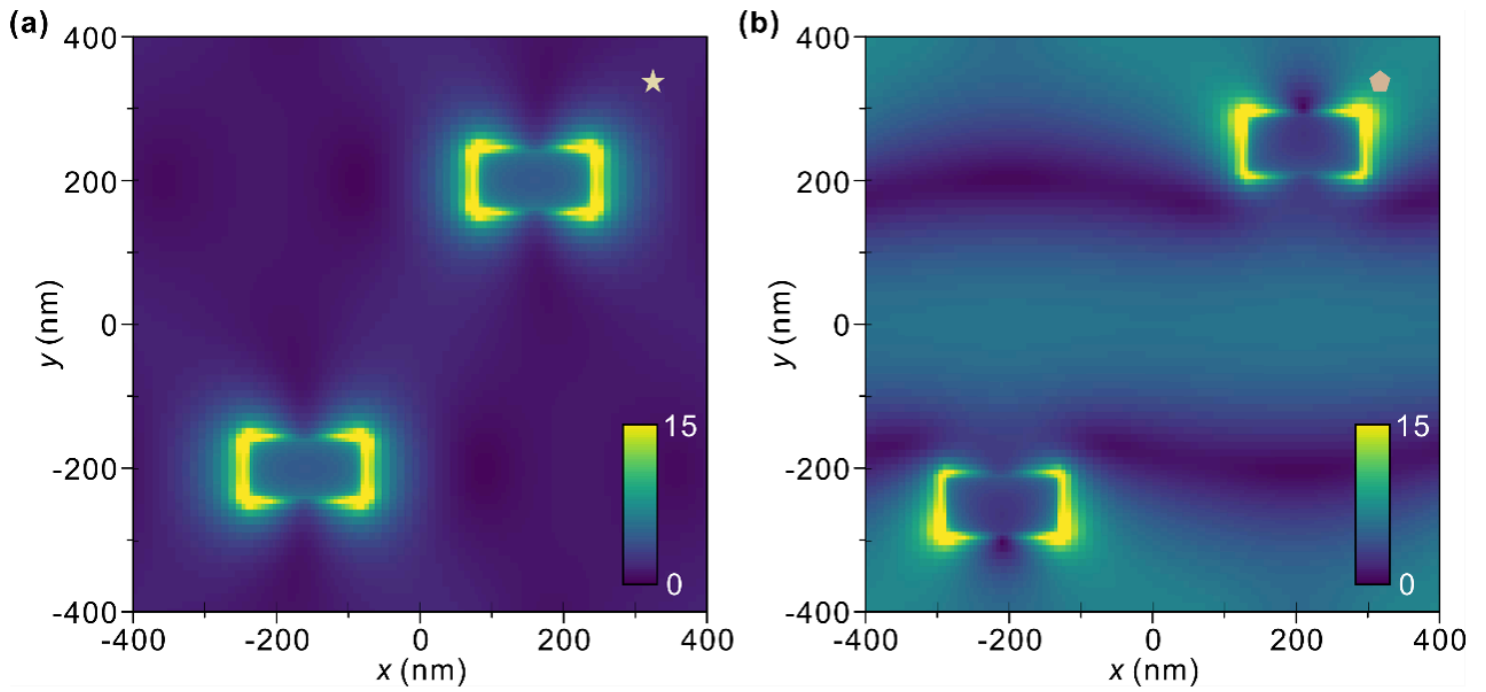


Figure 7

(a) Near-field enhancement factor distribution at the resonance peak position of 963.8 nm when $S_x = S_y = 320$ nm. (b) Near-field enhancement factor distribution at the resonance peak position of 1145.7 nm when $S_x = S_y = 420$ nm

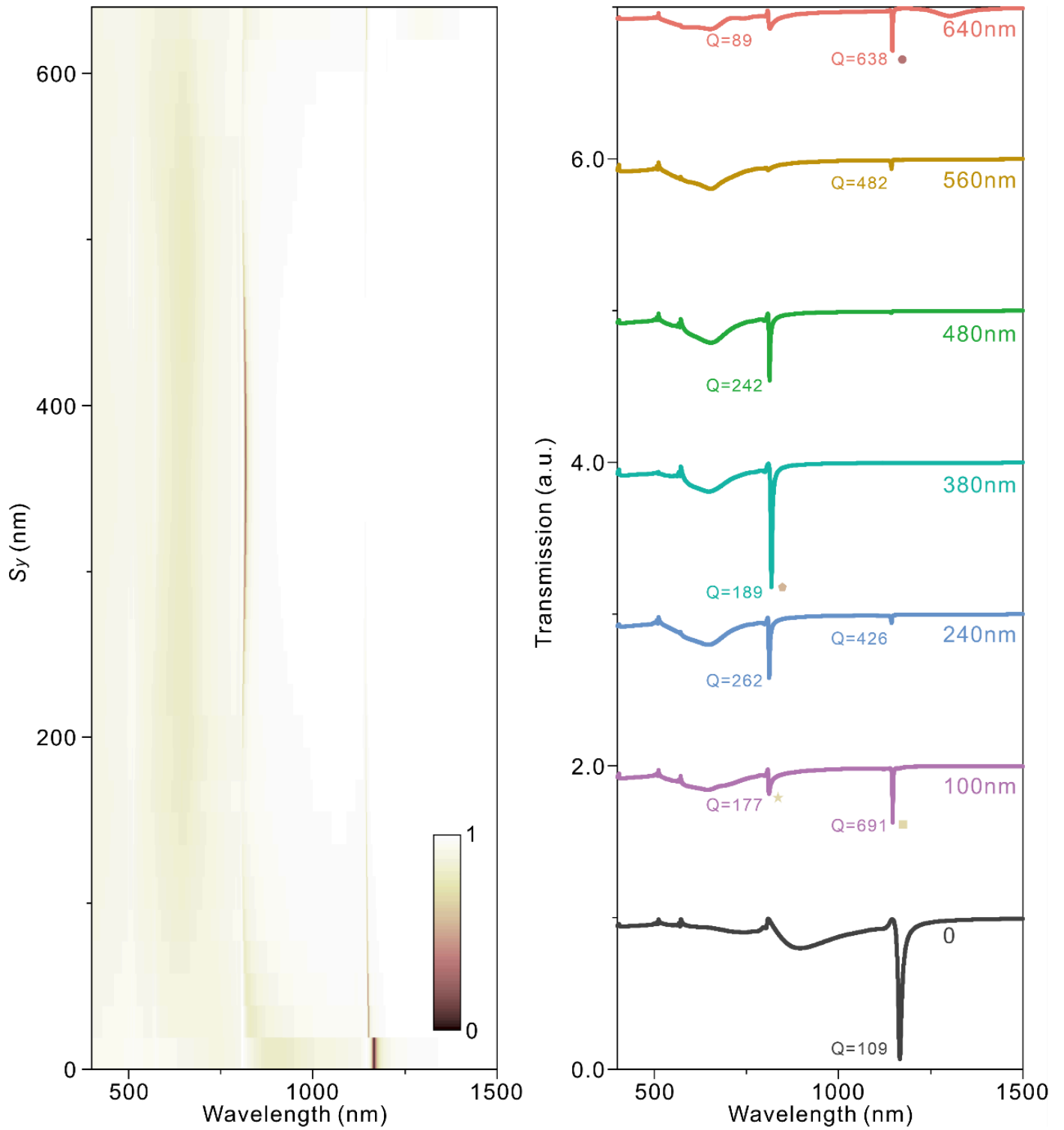


Figure 8

Dependence of the transmission spectra of the nanorod dimer array on the relative displacements S_x and S_y for y-polarization, where $S_x = S_y$ in the calculations. Left panel: transmission spectra as the relative displacement gradually increases from 0 to 640 nm (step 20 nm). Right panel: spectra for several representative relative displacements. Nanorod structural parameters and array period are the same as in Fig. 1

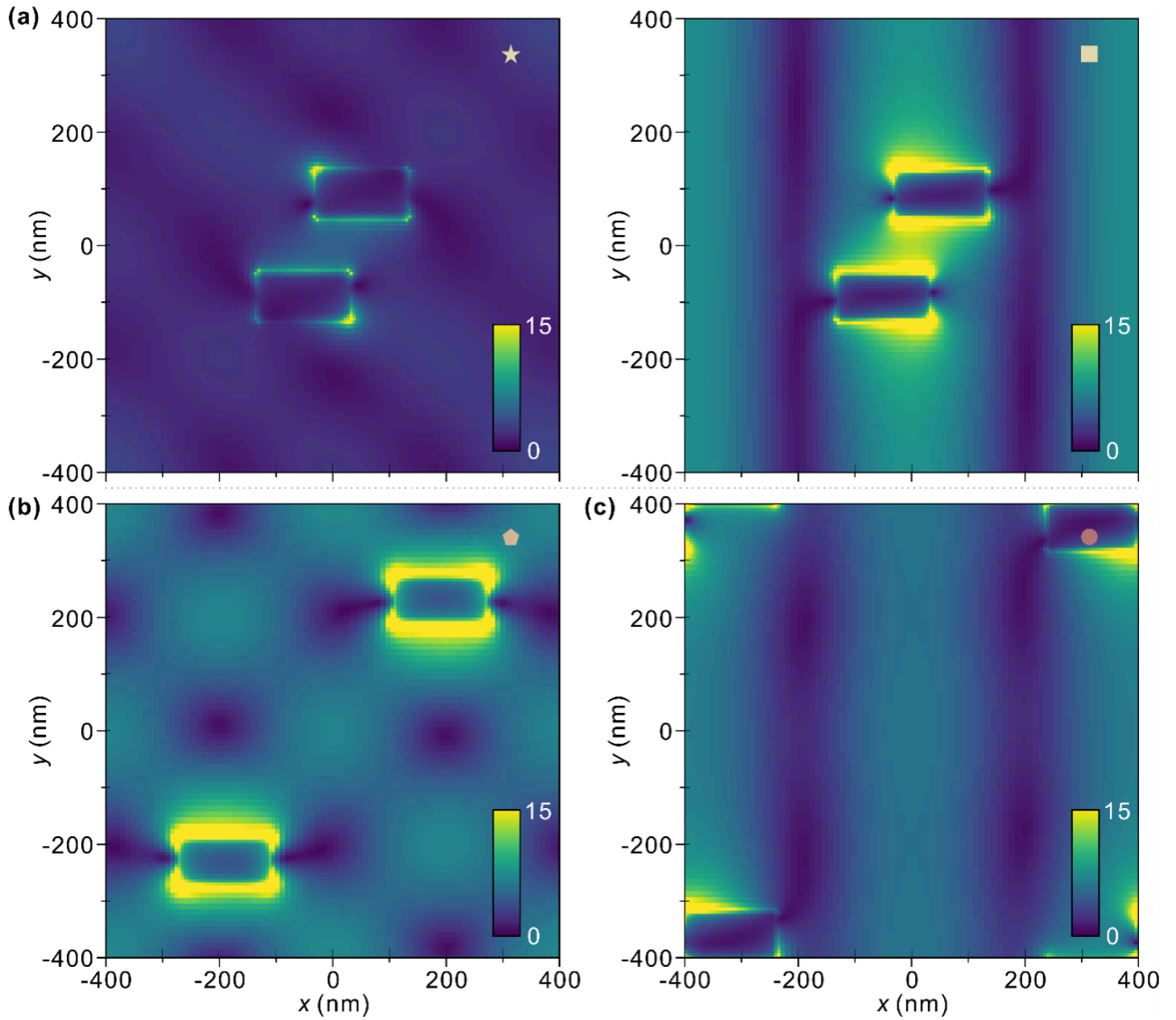


Figure 9

(a) Near-field enhancement factor distributions at the resonance peak positions of 814.5 nm (left) and 1146.8 nm (right) when $S_x = S_y = 100$ nm. (b) Near-field enhancement factor distribution at the resonance peak position of 817.8 nm when $S_x = S_y = 380$ nm. (c) Near-field enhancement factor distribution at the resonance peak position of 1146.2 nm when $S_x = S_y = 640$ nm

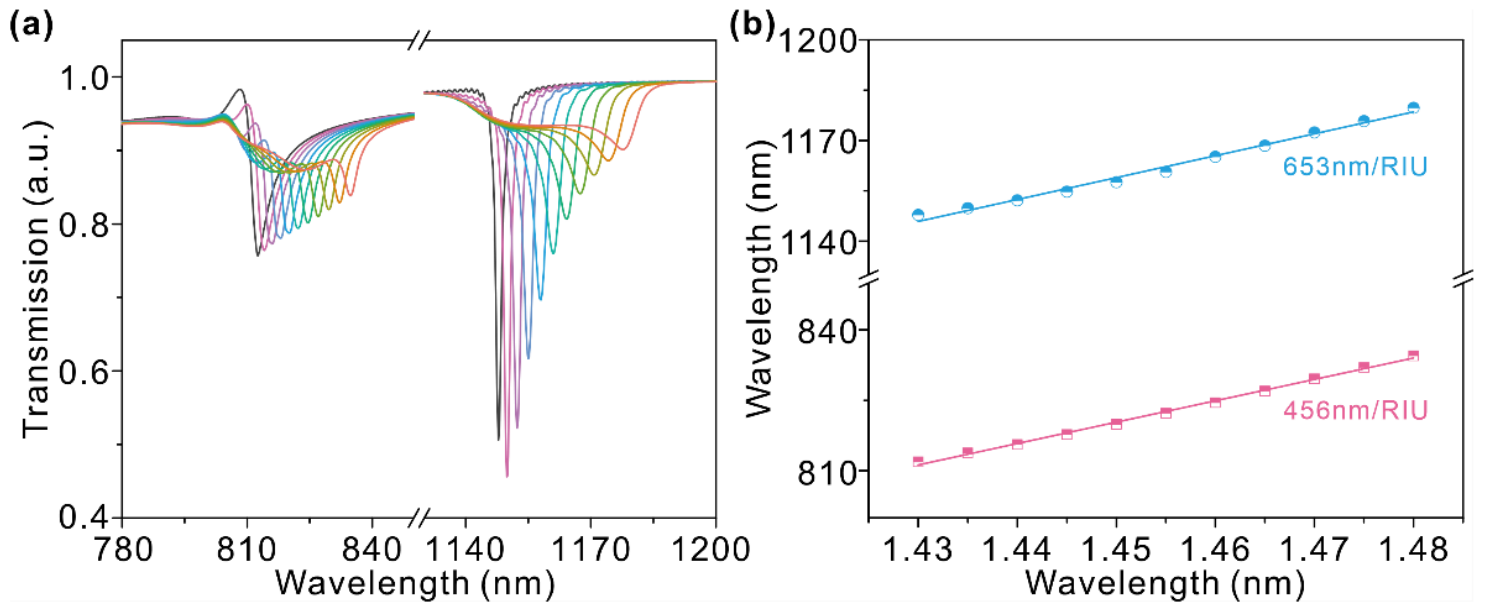


Figure 10

Refractive index sensing characteristics of the nanorod dimer array, with $S_x = 0$, $S_y = 320$ nm, and polarization along the y-axis. (a) Changes in the transmission spectra of the nanorod dimer array as the ambient refractive index increases from 1.43 to 1.48 (step 0.05). The incident field polarization is along the y-axis. The left spectra correspond to the $SLR_{(\pm 1, \pm 1)}$ mode, and the right spectra correspond to the $SLR_{(\pm 1, 0)}$ mode. The substrate refractive index is set to 1.43. (b) Relationship between the resonance peak positions of the two surface lattice resonances and the refractive index. The solid lines are linear fitting results