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Strong coupling of collective optical resonances in dielectric metasurfaces

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Abstract

Dielectric metasurfaces can achieve strong light-matter interaction based on several types of collective (nonlocal) resonances, such as surface lattice resonances (SLRs) and quasi-bound states in the continuum (quasi-BICs). Spectral selectivity, field enhancement, and high and controllable Q-factors make these resonances appealing for technological applications in lasing, sensing, nonlinear optics, and quantum photon sources. An emerging challenge focuses on tailoring light-matter interaction via mode coupling and hybridisation between the fundamental resonances of a metasurface. While strong coupling phenomena have been demonstrated between various resonant modes, the interplay between collective resonances of different natures has not been observed to date. Here, we theoretically, numerically, and experimentally demonstrate the onset of coupling and hybridisation between symmetry-protected quasi-BICs and SLRs in a dielectric metasurface. We show the emergence of anticrossing (or Rabi splitting) in the strong coupling regime with suppression of reflection, observed under TE-polarised excitation, and the manifestation of an accidental BIC under TM-polarised illumination as a result of energy exchange between the participating collective resonances in the weak coupling regime. The first effect is accompanied by hybridised near fields of the modes. The observed coupling mechanisms can be controlled by modifying the angle of incidence, polarisation, and the surrounding environment. This foundational study on the coupling and hybridisation of collective resonances offers insights that can be leveraged for the design of metasurfaces with targeted quasi-aBIC and collective hybridised resonances. It could also open new possibilities to control the near fields associated with such resonances, with promising applications in tunable nanophotonics and light manipulation.

Introduction

Optical metasurfaces supporting collective resonances with high quality factor (Q), such as surface lattice resonances (SLRs)¹ and quasi-bound states in the continuum (quasi-BICs)^{2–4}, have been widely studied in recent years. With their ability to trap light for a relatively long time and enhance local field intensity, these resonances can boost nonlinear emission processes, including second and third harmonic generation^{5,6}, control spontaneous

parametric down-conversion to generate entangled photon pairs and complex quantum states⁷, increase the sensitivity of optical sensors⁸, and enable low-threshold lasing³.

While SLRs can be easily created in plasmonic metasurfaces based on dipolar interactions⁹, as well as in dielectric metasurfaces¹⁰, achieving quasi-BICs in plasmonic systems requires tedious design engineering and minimisation of intrinsic material losses^{11–15}, making dielectric metasurfaces a better-suited platform for their realization^{3,4}. In general, the existence of BICs in dielectric metasurfaces (and their associated quasi-BIC resonances) can be understood via multipolar analysis¹⁶. For example, symmetry-protected BICs (sBICs) are associated with multipoles of a meta-atom with zero radiation in the out-of-plane direction, for example electric dipoles. Their

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sensitivity to geometric and material parameters enables their excitation and tunability through symmetry-breaking of the metasurface unit-cell^{5,17}, illumination at oblique incidence^{18,19}, perturbation of the lattice^{20–22}, modification of the surrounding environment (which can include 2D materials)^{23–25}, or external stimuli such as electrical²⁶, thermal²⁷, and mechanical actuation²⁸. Alternatively, radiating multipoles of the unit cell can lead to the realisation of destructive interference conditions (for example, at a specific angle of incidence), generating quasi accidental BICs (quasi-aBICs). Due to their relatively broad spectrum, quasi-sBIC resonances have been demonstrated in several experiments^{18,29–32}. On the contrary, the extremely narrowband nature of quasi-aBIC resonances combined with the limited availability of analytical theories to predict their exact spectral and angular position^{16,33}, has resulted in very few experimental demonstrations to date^{20,34}.

Although SLRs and quasi-sBICs can be explained using similar theoretical approaches (such as the dipole lattice sum¹⁰ and the ED-MD coupling³⁵, respectively), the interplay between these two collective resonances has not yet been investigated and is the subject of this paper. We present a comprehensive theoretical, numerical, and experimental study of the coupling of such nonlocal modes in dielectric metasurfaces. We consider the dependence of collective resonances on the polarisation (TE and TM) and incidence angle of the incoming light, and the surrounding medium. Specifically, we demonstrate two effects deriving from the interaction between SLRs and quasi-sBICs: the emergence of strong coupling under TE polarisation, and the manifestation of an accidental BIC (aBIC) under TM polarisation as a result of near-field energy exchange between the two collective modes.

The investigation of strong coupling in metasurfaces is gaining increasing interest due to its potential to create hybrid photonic states, which can offer new possibilities for tailoring and enhancing light-matter interactions. Strong coupling involving quasi-BIC resonances has been observed with guided modes³⁶, epsilon-near-zero modes³⁷, excitons^{38,39}, as well as between adjacent quasi-BICs^{40–42}. Strong coupling has also been reported between lattice resonances of a hybrid metal-dielectric metasurface⁴³. However, strong coupling between collective resonances of different natures is to date unknown. Here, we theoretically and experimentally demonstrate strong coupling between quasi-sBICs and SLRs. In particular, under TE illumination, we observe the formation of hybrid nonlocal modes with suppression of reflection in the anticrossing spectral range due to strong coupling. We also demonstrate the possibility of tuning the coupling strength and bandwidth via the surrounding environment, angle of incidence, and polarisation.

Previous experimental demonstrations of aBICs describe their formation as the simple destructive

interference between in-plane and out-of-plane multipolar components of the single meta-atom at specific angles of incidence, with limited theoretical explanations of the underlying mechanisms²⁰. In this paper, we not only experimentally measure the aBIC and the associated quasi-aBIC hybrid modes, but also theoretically demonstrate the important role of the hybridisation between SLR and quasi-sBIC collective resonances in the formation of the aBIC in a weak coupling regime.

We believe our comprehensive numerical, theoretical and experimental study provides new insights into non-local effects in dielectric metasurfaces, and can support the design (and potentially the reverse engineering) of metasurfaces with spectral and angular control of hybrid collective modes, therefore expanding the possibilities for controlling and enhancing light-matter interactions.

Results and discussion

Experimental and numerical results

The metasurface studied in this work consists of polycrystalline Si nanodisks with a diameter $D = 220$ nm and a height $H = 100$ nm, arranged in a square lattice with a period $P = 440$ nm, with the global size of the array being $100 \times 100 \mu\text{m}^2$ (Fig. 1). The nanodisks are obtained by electron beam lithography from a 100 nm-thick Si film on a glass substrate ($n_{\text{sub}} = 1.45$). Under illumination at normal incidence, the optical response of such a metasurface is determined by the SLR excitation and strongly dependent on the refractive index mismatch between the substrate and superstrate¹⁰.

In a uniform environment, achieved by submerging the metasurface in glycerol ($n_{\text{sup}} = n_{\text{sub}} = 1.45$), the transmission spectra measured under TE-polarised illumination show a complex system of resonances, with the transmittance minima exhibiting a strong wavelength dependence on the angle of incidence, in excellent agreement with numerical modelling (Fig. 2). Most of the resonances in Fig. 2(a1) evolve from the features observed at normal incidence, such as sBIC and SLR (the origin of the latter is discussed in detail in ref. 10). The SLR resonance observed at normal incidence at a wavelength of $\lambda \approx 700$ nm splits into two spectrally narrow (FWHM ≈ 10 nm) and well-separated (60–80 nm) features that show a relatively small chromatic dispersion with the angle of incidence. An additional feature of low transmission arises at $\lambda \approx 800$ nm, as soon as the angle of incidence becomes nonzero, which red-shifts as θ increases, asymptotically approaching the main order Rayleigh anomaly (RA, representing the condition for which a diffraction order of a periodic array becomes an evanescent wave propagating in the plane of the array) of the homogeneous environment (Fig. 2(b1)). This feature is a quasi-sBIC, which shows an experimental quality factor of approximately 85 (theoretical $Q \approx 100$). The emergence of a spectral band $\Delta\lambda$ with suppressed reflection (Fig. 2(a1, a2)) due to the anticrossing of



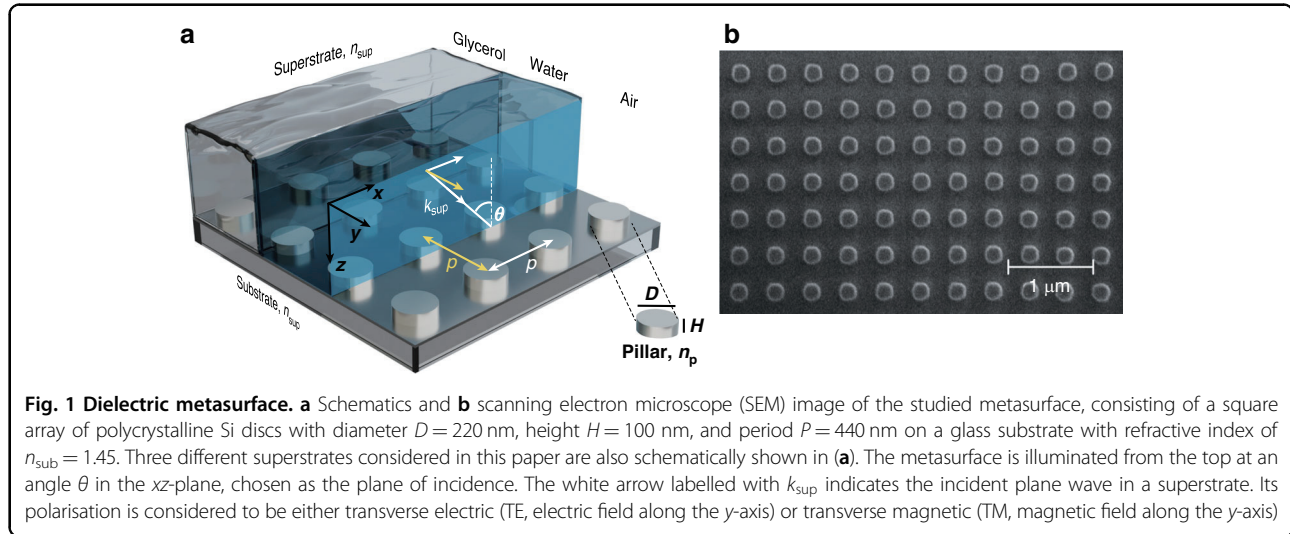


Fig. 1 Dielectric metasurface. **a** Schematics and **b** scanning electron microscope (SEM) image of the studied metasurface, consisting of a square array of polycrystalline Si discs with diameter $D = 220$ nm, height $H = 100$ nm, and period $P = 440$ nm on a glass substrate with refractive index of $n_{\text{sub}} = 1.45$. Three different superstrates considered in this paper are also schematically shown in **(a)**. The metasurface is illuminated from the top at an angle θ in the xz -plane, chosen as the plane of incidence. The white arrow labelled with k_{sur} indicates the incident plane wave in a superstrate. Its polarisation is considered to be either transverse electric (TE, electric field along the y -axis) or transverse magnetic (TM, magnetic field along the y -axis)

the SLR and quasi-sBIC features suggests the presence of strong coupling between these two collective resonances, as demonstrated in the next section. The value of the Rabi splitting energy experimentally measured is $\Delta\hbar\omega \approx 130$ meV (corresponding to $\Delta\lambda \approx 65$ nm). From the evolution of the electric field distributions in the anticrossing region, the resonances with the main contribution of (1) SLR, (3) quasi-sBIC, and (2) a hybridised mode between them can be identified (Fig. 2(e1–e3)). From the comparison of the electric field values, it is also evident that, under resonance conditions (Fig. 2(e1, e3)), the near field is amplified several times compared to the spectral region between resonances (Fig. 2(e2)). This behaviour is characteristic of the strong coupling regime and is due to the redistribution of energy between the two hybrid modes and their weak spectral overlap.

We also note the presence of additional high-order Rayleigh anomalies for wavelengths shorter than ≈ 650 nm at $\theta = 0^\circ$ (Figs. 2 and S2). However, they have a minimal influence on the effects considered here, and a detailed theoretical analysis of these diffractive contributions is beyond the scope of this paper.

In the case of TM-polarised illumination, the transmission shows a similar response as a function of wavelength and angle of incidence, and also excellent agreement between experiments and simulations (Fig. 2(c1, d1)). However, in this case, no anticrossing is observed as the spectral gap between the SLR and sBIC modes is much smaller than the width of the resonances, and the modes are in a weak coupling regime. A narrow feature, observed along the main order RA for this polarisation, evolves differently with the incidence angle. It disappears at around $\theta = 20^\circ$ and $\lambda \approx 850$ nm and later on reappears for $\theta > 25^\circ$ (inset in Fig. 2(c1) and (c2, d2)). As will be demonstrated later, this feature, known as aBIC, is the result of a weak coupling between SLR and sBIC modes.

Coupled-dipole model and demonstration of strong coupling

An isolated disk of the studied array (Fig. 1a) mainly exhibits ED and MD responses in the visible spectral range (Fig. S1 of the Supporting Information), so that the spectral features observed experimentally can be interpreted by applying the coupled-dipole model (CDM)⁴⁴. Although the model derived in ref. ⁴⁴ covers the most general case of meta-atoms with anisotropic polarizability, here, we apply it to the subclass of nanoparticles with in-plane isotropy. We note that approaches from refs. ^{33,35,45}, using a different representation, can also be adopted.

Within the CDM, the transmission t (transmittance $T = |t|^2$) and the reflection r (reflectance $R = |r|^2$) coefficients corresponding to the specular reflectance (the zero diffraction order) of an infinite metasurface composed of identical particles and embedded in a homogeneous environment (with relative permittivity ϵ_{sur}) can be written for the two TE and TM irradiation configurations as⁴⁴

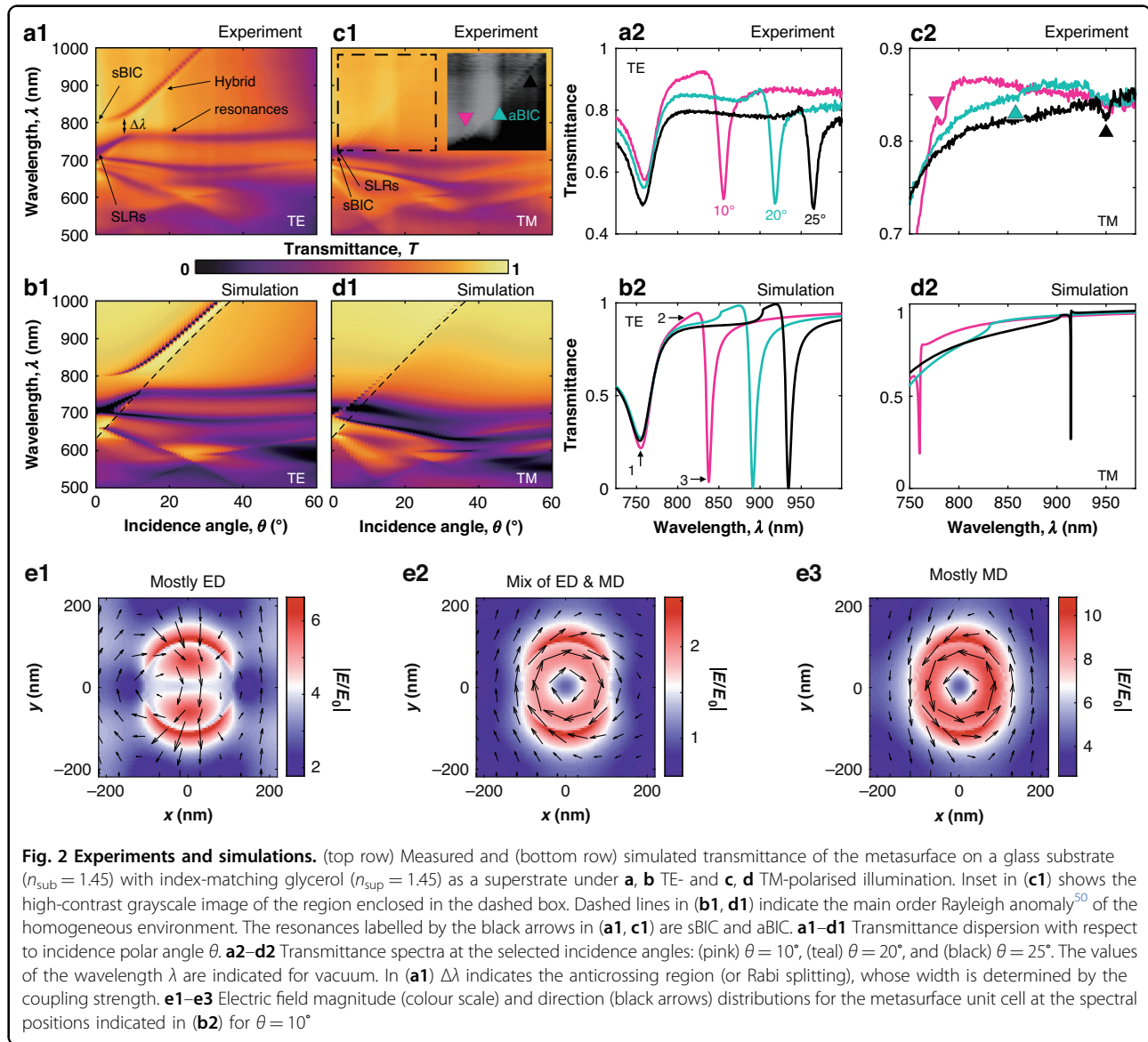
$$r^{\text{TE}} = \frac{ik_{\text{sur}}}{2S_L\epsilon_0\epsilon_{\text{sur}}E_0\cos\theta} \left(\left[p_y + \frac{\sin\theta}{v}m_z \right] + \frac{\cos\theta}{v}m_x \right) \quad (1)$$

$$t^{\text{TE}} = 1 + \frac{ik_{\text{sur}}}{2S_L\epsilon_0\epsilon_{\text{sur}}E_0\cos\theta} \left(\left[p_y + \frac{\sin\theta}{v}m_z \right] - \frac{\cos\theta}{v}m_x \right) \quad (2)$$

$$r^{\text{TM}} = \frac{ik_{\text{sur}}}{2S_LH_0\cos\theta} ([m_y - v\sin\theta p_z] - v\cos\theta p_x) \quad (3)$$

$$t^{\text{TM}} = 1 + \frac{ik_{\text{sur}}}{2S_LH_0\cos\theta} ([m_y - v\sin\theta p_z] + v\cos\theta p_x) \quad (4)$$

where ϵ_0 is the vacuum permittivity, S_L is the lattice unit cell area, k_{sur} and v are the wave number and speed of light in a surrounding homogeneous environment, respectively, E_0 and H_0 ($\epsilon_0\epsilon_{\text{sur}}E_0 = H_0/v$) are the electric and magnetic fields of the incident plane wave,



respectively, at the position of the electric $\mathbf{p} = (p_x, p_y, p_z)$ and magnetic $\mathbf{m} = (m_x, m_y, m_z)$ dipole moments of the particle in the metasurface located at the origin of the selected Cartesian coordinate system. The incident electric (magnetic) field is along the y -axis in the case of TE (TM) polarisation. The nonzero dipole moments for TE polarisation are

$$m_x = -\frac{H_0 \cos \theta}{1/\alpha_{\parallel}^m - S_x} \quad (5)$$

$$p_y = \frac{[1/\alpha_{\perp}^m - S_z] - ig_x \sin \theta}{[1/\alpha_{\parallel}^p - S_y][1/\alpha_{\perp}^m - S_z] + g_x^2} \varepsilon_0 \varepsilon_s E_0 \quad (6)$$

$$m_z = \frac{[1/\alpha_{\parallel}^p - S_y] \sin \theta - ig_x}{[1/\alpha_{\parallel}^p - S_y][1/\alpha_{\perp}^m - S_z] + g_x^2} H_0 \quad (7)$$

In the case of TM-polarised excitation, the nonzero dipole moments are

$$p_x = \frac{\varepsilon_0 \varepsilon_s E_0 \cos \theta}{1/\alpha_{\parallel}^p - S_x} \quad (8)$$

$$m_y = \frac{[1/\alpha_{\perp}^p - S_z] - ig_x \sin \theta}{[1/\alpha_{\parallel}^m - S_y][1/\alpha_{\perp}^p - S_z] + g_x^2} H_0 \quad (9)$$

$$p_z = \frac{-\left[1/\alpha_{\parallel}^m - S_y\right] \sin \theta + ig_x}{\left[1/\alpha_{\parallel}^m - S_y\right] \left[1/\alpha_{\perp}^p - S_z\right] + g_x^2} \varepsilon_0 \varepsilon_s E_0 \quad (10)$$

In the above equations, the in-plane and out-of-plane ED polarizability components of the isolated single particle are indicated as $\alpha_{\parallel}^p$ and $\alpha_{\perp}^p$, respectively, and the corresponding MD polarizabilities are indicated as $\alpha_{\parallel}^m$ and $\alpha_{\perp}^m$, while $S_x = S_x(\theta)$, $S_y = S_y(\theta)$, $S_z = S_z(\theta)$ are the lattice sums corresponding to ED-ED and MD-MD interactions in the metasurface, and $g_x = g_x(\theta)$ is the ED-MD coupling parameter which vanishes at normal ($\theta = 0^\circ$) incidence of the external wave. The explicit expressions of S_x , S_y , S_z and g_x , and their dependence on wavelength and angle of incidence are presented in the Supporting Information (Eqs. (S1–S4) and Fig. S3).

As follows from Eqs. (5–7) for TE polarisation and Eqs. (8–10) for the TM polarisation, under normal illumination (when $g_x = 0$) the ED-MD interaction disappears and the dipole moments are determined independently of each other:

$$\begin{array}{cc} \text{TE} & \text{TM} \\ m_x = -\frac{H_0}{1/\alpha_{\parallel}^m - S_x}; & p_x = \frac{\varepsilon_0 \varepsilon_s E_0}{1/\alpha_{\parallel}^m - S_x} \end{array} \quad (11)$$

$$p_y = \frac{\varepsilon_0 \varepsilon_s E_0}{1/\alpha_{\perp}^p - S_y}; \quad m_y = \frac{H_0}{1/\alpha_{\perp}^m - S_y} \quad (12)$$

$$m_z = 0; \quad p_z = 0 \quad (13)$$

Note that in this case, the ED (MD) moments depend only on the ED (MD) polarizability of the isolated single particles.

Under oblique illumination ($\theta \neq 0^\circ$), an ED-MD interaction arises in the system: in the TE case of Eqs. (6 and 7), p_y and m_z , and in the TM case of Eqs. (9 and 10), m_y and p_z are determined by both the ED and MD polarizabilities of isolated single particles. This, in turn, indicates a coupling between the corresponding ED and MD moments. In Eqs. (1–4), we have combined in square brackets the dipole moments interacting with each other in the metasurface under the condition of oblique incidence of the illuminating plane wave. The main advantage of the analytical CDM formulation is that it enables a straightforward analysis of the coupling effect between ED and MD. For example, in the case of TE-polarised illumination, p_y and m_z (for the TM case, m_y and p_z) are coupled via the parameter g_x , while the m_x (for the TM case, p_x) component is independent. Within the CDM, the coupling parameter g_x can be turned on and off in the simulations, allowing detailed studies on the specific role of the coupling.

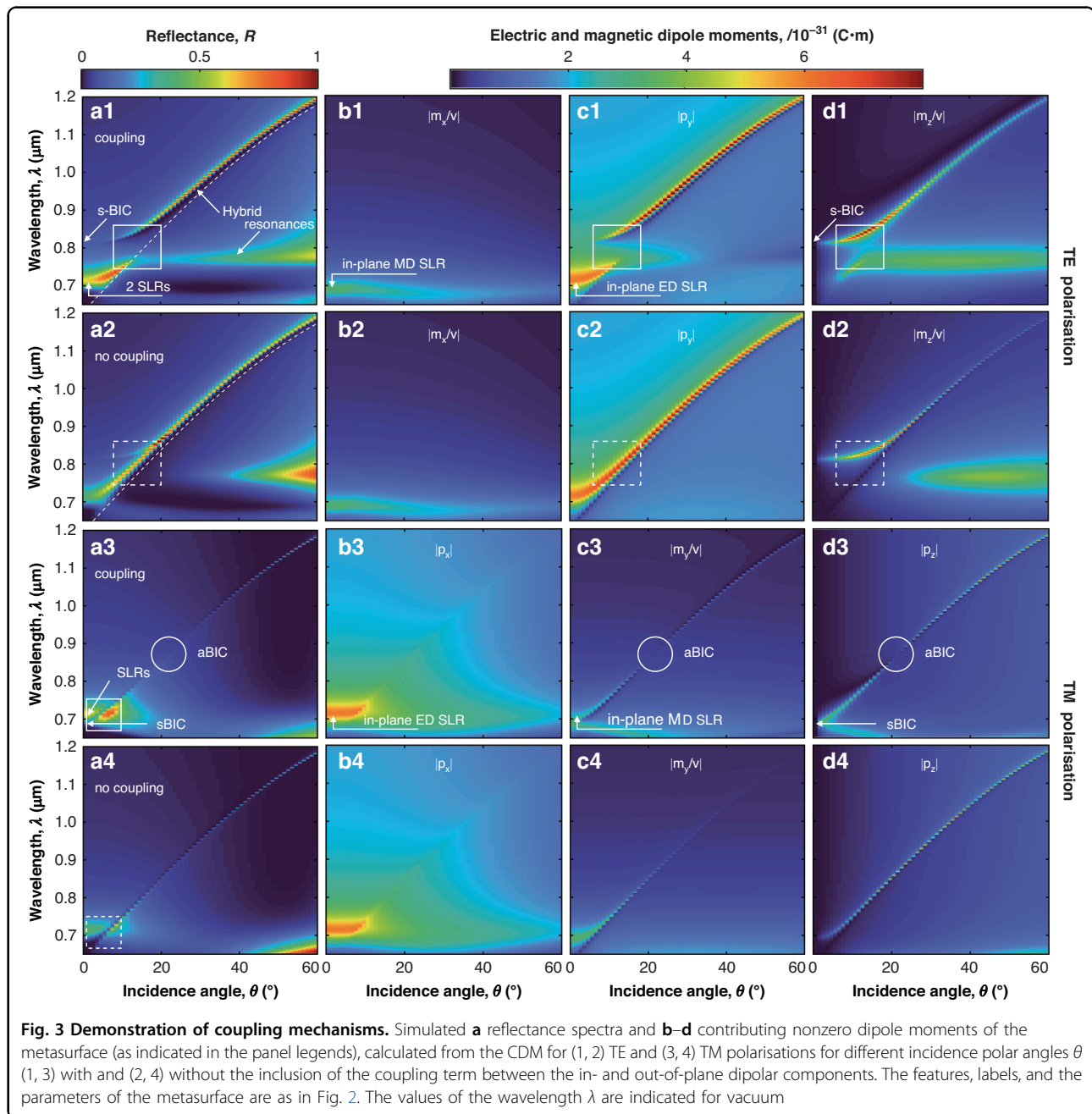
To demonstrate the applicability of the CDM, we compared the reflectance and transmittance spectra of the metasurface, with parameters as in Fig. 2, calculated using CDM and full-wave numerical simulations. These show excellent agreement with the numerical results (Fig. S4), confirming its applicability. To clearly demonstrate the dipole coupling, in the following, we focus on the reflective properties of the metasurface, which are determined only by the contribution of scattered waves. The same considerations govern the transmission.

As follows from the above equations describing the CDM, at normal incidence ($\theta = 0^\circ$), the out-of-plane components (z -components) of the dipole moments do not contribute to the transmission or reflection and cannot couple to any other component of the dipole moments due to $g_x = 0$. It is therefore impossible to excite the out-of-plane components of the dipole moments at normal incidence (Eqs. (13)), and they can only contribute to sBIC formation¹⁷. As a consequence, the resonant features, which are observed at normal incidence both in transmission and reflection, are only related to the in-plane components (x , y) of the dipole moments, determining the excitation of the SLRs¹⁰. Under oblique illumination, in-plane and out-of-plane components of the dipole moments can be excited, with the coupling being allowed between ED and MD excitations. Due to the coupling, the resonant excitation of the out-of-plane dipole moment associated with the sBIC automatically influences the excitation of the in-plane dipole moment associated with the SLR, and vice versa. At small incidence angles, the mutual influence between quasi-sBIC and SLR is small. With the increase of the angle of incidence, the interaction between the dipole moments corresponding to the sBIC and the SLR increases, and the system enters the regime of mode hybridisation, leading to several exotic phenomena depending on polarisation, as explained below. Moreover, the formation of hybrid modes is accompanied by tailored near fields (Figs. 2(e1–e3) and S4), which can be useful in applications.

Using the results of the CDM theory presented in Fig. 3, the experimental and simulated transmittance and reflectance spectra can be understood. First, we consider the spectra for TE-polarised illumination (Fig. 3(a1–d1)). At normal incidence, the metasurface reflectance spectra exhibit two overlapping SLRs around $\lambda = 700$ nm: a weak in-plane MD SLR with m_x and a strong in-plane ED one with p_y ¹⁰. Since the spectral position of the SLR with m_x is practically independent of the angle of incidence and does not contribute to ED-MD coupling (cf. Fig. 3(b1, b2)), we focus on the behaviour of m_z and p_y dipoles.

A narrow resonance at around $\lambda = 800$ nm for incidence angles $0^\circ < \theta < 5^\circ$ (Fig. 3(a1)) corresponds to the transformation of the nonradiating sBIC into the radiating quasi-sBIC,





and is caused by the out-of-plane MD moment component m_z (Fig. S5(a1–d1))^{18,33,35}. Notably, for small angles of incidence ($0^\circ < \theta < 5^\circ$), the spectral gap between the quasi-sBIC and SLRs is larger than the width of these resonances themselves (Fig. 3(a1)). Additionally, in this range of angles of incidence, the values of the dipole moments m_z and p_y , determining the quasi-sBIC and SLR, respectively, are not influenced by coupling (cf. Fig. 3(c1, d1) and (c2, d2)).

The situation changes considerably with increasing angle of incidence θ . At angles $\theta > 10^\circ$, the system enters a strong coupling regime between the quasi-sBIC with m_z

and the SLR with p_y , leading to the anticrossing effect (Fig. 3(a1, c1, d1) and Fig. S6(a1, b1)) with an anticrossing gap larger than the linewidth of the SLR and quasi-sBIC modes. According to the general strong coupling theory⁴⁶, an anticrossing effect results in two hybrid modes, each of which includes dipole moments from the two contributing modes. In this case, two non-intersecting hybrid BIC-SLR modes are formed with participation of magnetic m_z and electric p_y dipoles in each hybrid mode. These modes do not intersect with each other due to the symmetry of the related fields. With the increase of the angle of



incidence, and consequently with the increase of the coupling strength, the spectral gap between these modes increases in accordance with the general theory of strong coupling⁴⁶. Note that if the coupling parameter is excluded from the CDM, no anticrossing effect occurs in the reflection spectrum (Fig. 3(a2)).

Formally, using the contribution of the coupled dipoles to the reflection coefficient (Eq. (1)), an effective polarizability can be defined for the hybrid modes as

$$\alpha^{\text{HYB/TE}}(\theta) = \frac{p_y + (m_z \sin \theta)/\nu}{\epsilon_0 \epsilon_{\text{sur}} E_0} \quad (14)$$

In this context, since the hybrid modes are formed by two resonant dipole contributions, which generally possess different quality factors, the resonance of the coupled system will exhibit a Fano profile (see, for example, the resonant band between the hybrid resonances in Fig. 3(a1), and the corresponding experimental and simulated spectra in Fig. 2(a2, b2)). Note that the hybrid mode at longer wavelength in Fig. 3(a1) follows the Rayleigh anomaly on the diffraction-free side of the dispersion. This is due to the fact that, neglecting coupling between the modes, the quasi-sBIC (Fig. 3(d2)) and SLR (Fig. 3(c2)) are also formed in this region with increasing angle of incidence. To further prove the emergence of strong coupling, we evaluate the required conditions for the coupling coefficients^{38,47,48}:

$$c_1 = \Delta\omega / (\Delta\omega_{\text{SLR}} - \Delta\omega_{\text{q-sBIC}}) > 1 \quad (15)$$

$$c_2 = [(\Delta\omega^2 + (\Delta\omega_{\text{SLR}} - \Delta\omega_{\text{q-sBIC}})^2) / (\Delta\omega_{\text{SLR}}^2 + \Delta\omega_{\text{q-sBIC}}^2)]^{1/2} > 1 \quad (16)$$

where $\Delta\omega = \omega_{\text{SLR}} - \omega_{\text{q-sBIC}}$ is the spectral gap between SLR and quasi-sBIC modes, $\Delta\omega_{\text{SLR}}$ and $\Delta\omega_{\text{q-sBIC}}$ are their FWHMs. For TE polarisation, these coefficients determined from simulation are $c_1 = 2.46$ and $c_2 = 2.26$, and $c_1 = 2.27$ and $c_2 = 2.17$ from the experiment. This confirms that strong coupling is achieved between SLR and quasi-sBIC modes.

For TM polarisation and in the range of small angles of incidence (Fig. 3(a3–d3) and (a4–d4)), the results obtained are similar to the TE case, with the effective hybrid polarizability determined by

$$\alpha^{\text{HYB/TM}}(\theta) = \frac{m_y/\nu - p_z \sin \theta}{\epsilon_0 \epsilon_{\text{sur}} E_0} \quad (17)$$

The reflectance is determined by two SLRs related to a strong, in-plane ED excitation and a relatively weak, in-plane MD one (Fig. S5(a2–d2)). Similarly to what was

observed for the TE-polarised illumination, the reflectance shows a dip (Fig. 3(a3)) originating from the destructive interference in the backward direction between the ED and MD components p_x and m_y (the so-called Kerker effect⁴). In contrast to the TE case, a weak coupling between quasi-sBIC with p_z and the SLR with m_y is realised at small angles of incidence, as the spectral overlap between these modes is smaller than their linewidth at normal incidence. As the angle of incidence increases, a hybrid mode with the participation of p_z and m_y is formed along the Rayleigh anomaly.

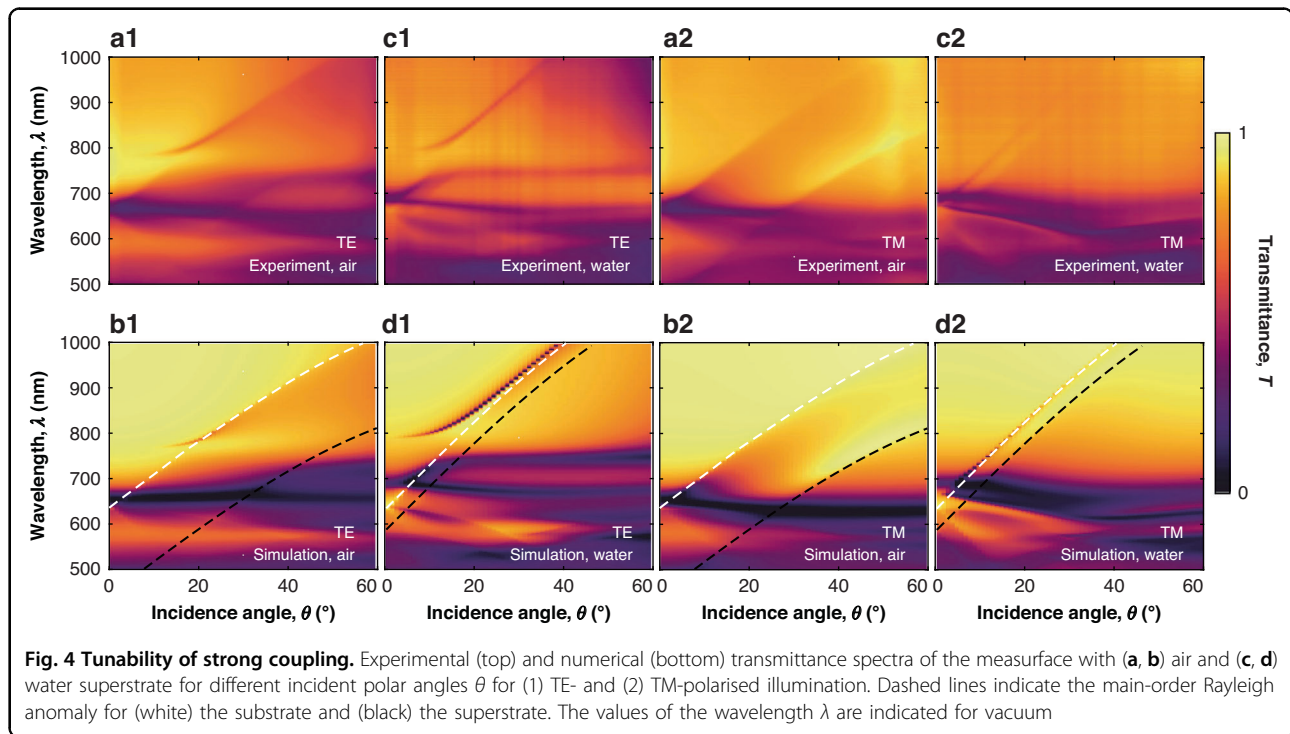
Interestingly, at higher angles of incidence ($\theta \gg 1^\circ$), the TM-polarised excitation leads to the in-plane MD component m_y and the out-of-plane ED component p_z with comparable magnitude in the hybrid mode. Their coupling, therefore, allows for the realisation of a condition of perfect annihilation between the far-field radiation of the quasi-sBIC part (induced by p_z) and that of the SLR part (induced by m_y) of the hybrid mode (Fig. S6(a2, b2, c)), perfectly cancelling each other out and resulting in an aBIC^{20,33,35}. This feature has been measured (Fig. 2) and found analytically (Fig. 3(a3)) for an angle of incidence $\theta \approx 20^\circ$. The appearance of the aBIC can be seen as a result of the self-adjustment of the contributing dipole moment components governed by the coupling strength (cf. TE and TM panels in Fig. 3). A similar feature is not observed in the TE polarisation case for the metasurface considered here, because the in-plane and out-of-plane dipolar components exhibit considerably unbalanced magnitudes. It is in principle possible to realise an aBIC with both TE and TM polarisations at the same wavelength and angle via a fine-tuning of the rectangular lattice and particle parameters³³.

As already noted, the formation of the collective modes of the metasurface is accompanied by a marked enhancement of the near field, with its spatial distributions depending strongly on the polarisation of the illumination. In the case of TM polarisation, the strong electric field is concentrated between the meta-atoms of the metasurface, whereas for TE polarisation, the electric field is enhanced in the vicinity of the meta-atoms (indicated by arrows 3 and 7, respectively, in Fig. S4). For practical purposes, this can be used for selective excitation and switching of active functions, for example, quantum dots deposited on the metasurface. It is also interesting to note that for both cases of the aBIC (TM polarisation, fields 1–3 in Fig. S4) and the anticrossing due to strong coupling (TE polarisation, fields 4–6 in Fig. S4), the electric fields are considerably reduced, leading to the suppression of reflection.

Tuning strong coupling with the metasurface environment

The response of the metasurface to light is expected to show a strong dependence on the refractive index of the surrounding medium. In particular, with the Si nanodisks





on a glass substrate, this dependence translates into a dependence on the refractive index mismatch between the substrate (glass) and the medium used as a superstrate. Submerging the metasurface in glycerol provides a practically uniform surrounding, eliminating the mismatch. This is a well-known requirement for the existence of collective resonances¹⁰. To explore the possibility of tuning the strong coupling mechanism by varying the surrounding environment, air and water superstrates were investigated (Fig. 4(a1, a2, c1, c2)) in addition to glycerol (Fig. 2). The analytical CDM introduced above cannot be directly applied in the case of an inhomogeneous environment, as it does not take into account the dipole radiation reflections at the interface between substrate and superstrate.

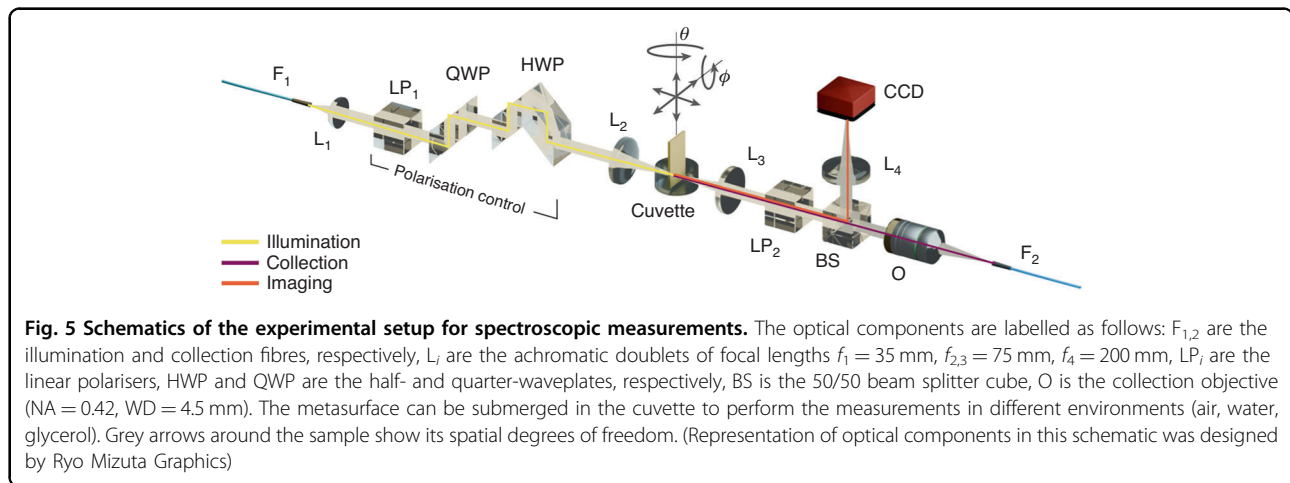
The experimental reflectance spectra and their numerical simulation for different superstrates are shown in Fig. S7 of the Supporting Information. For TE polarisation, the anticrossing character of the resonances is observed even in the presence of a dielectric contrast between the substrate and the superstrate (Fig. 4(a1, c1)). This indicates the preservation of the strong coupling regime between the corresponding collective resonances, with a reduction of the splitting for increasing mismatch. For example, the estimated splitting for air, water, and glycerol superstrates is 30 nm, 60 nm and 65 nm, respectively (more details on the physical mechanism behind it can be found in Supplementary Information and are illustrated in Fig. S8). For TM polarisation, the spectral features associated with the

superstrate undergo a blue shift, and several resonant phenomena are considerably damped. In particular, the progressive separation between the sBIC and SLR with the increasing index mismatch leads to the complete loss of the aBIC feature, which was observed with glycerol (Fig. 2(c1)). Therefore, the observed phenomena suggest strategies to tune the strength of the coupling between collective resonances via dynamic modification of the external environment.

Conclusion

We investigated the coupling between nonlocal collective resonances of a dielectric metasurface supporting excitation of SLR and BIC modes. Theoretical analysis and experimental observations reveal the emergence of either strong or weak coupling between SLRs and quasi-sBICs. This leads to the formation of hybrid resonances consisting of coupled modes, manifesting as anticrossing (or Rabi splitting) and aBIC under TE and TM excitation, respectively. Since the metasurface building block mainly exhibits dipolar response in the considered spectral range, we applied the CDM to describe optical properties under oblique illumination. This model can describe the formation of SLR and sBIC modes, which are associated with in-plane and out-of-plane electric (or magnetic) dipoles, respectively. While such modes are independent at normal incidence, the excitation of both in-plane and out-of-plane components at oblique illumination results in their coupling. Important for potential applications,





we have numerically and experimentally shown that the strong coupling can be tuned by varying the superstrate material, and its activation is possible simply via polarisation control. We believe that the obtained results provide a framework for understanding the physics behind dipole-dipole interactions leading to the hybridisation of collective modes, and are important for practical applications in sensing, nonlinear optics, enhancement and control of light-matter interaction, tunable nanophotonics, and single and entangled photon generation.

Methods

Spectroscopic measurements

The transmission and reflection spectra were measured for different angles of incidence and polarisations of the illuminating light, as well as with various superstrates (air, de-ionised water and pure glycerol). The system consists of a tabletop custom-built spectroscopy setup (Fig. 5), that can be divided into three sections built around the sample: the illumination, the imaging and the collection branches. The latter two are always kept at the same position, while the illumination branch and the sample can be independently rotated around a common axis by controlling two motors via custom-made software written in Python. After an initial careful alignment of the sample to the system rotation axis, both transmission and reflection spectra of the sample can be measured with great control over the angle of incidence. In the transmission configuration, the source is kept at the position represented in Fig. 5, and the sample is rotated about the central axis therein shown. For measuring reflection, the source and the sample are both rotated about the central axis, ensuring that light reflected by the sample is collected through the detection branch.

A broadband halogen lamp (HL-2000-HP, Ocean Optics) is fibre-coupled (F_1) and collimated by a short lens (L_1). The source is mounted on the illumination branch to allow rigid

rotation with it. After collimation, a series of three prisms is used for full and broadband control of the state of polarisation of the illuminating light. A Glan–Taylor prism initially fixes the polarisation to the horizontal direction (parallel to the optical table). A double and a single Fresnel rhomb are then used to modify the polarisation as required. These prisms work respectively as a broadband half- and quarter-waveplate, allowing to obtain linear, elliptical or circular light, with any orientation or helicity. For the measurements reported here, the illumination polarisation has been fixed to right-handed circular, and a second Glan–Taylor prism is used to select the polarisation of interest in the readout as either TE or TM. Finally, light is focused on the sample via L_2 . The location of the collimating lens L_1 is fixed so that a broad and uniform illumination of the sample is obtained.

A lens matching the focal length of L_3 is used to collect light transmitted (or reflected) by the sample, which is subsequently sent to both the imaging and collection branches, via a beam splitter cube. The surface of the sample is then imaged onto a camera via L_5 ($f = 200$ mm), and on the collection fibre (F_2) via a microscope objective O_1 (NA = 0.42, WD = 45 mm). The fibre is, in turn, coupled to a spectrometer.

To change the metasurface surroundings, the sample mount consists of two sections. Vinculated to the main rotation motor, a post mounting a round plate hosts a glass cylindrical cuvette, whose height can be adjusted to meet the light beam. A pair of post holders are mounted on the side of the same rotation motor to hold a breadboard above the glass cuvette via two long posts. The sample holder is mounted upside down on said breadboard so that it can be inserted from the top into the cuvette volume, once this has been filled with the medium of interest. For a finer adjustment of the sample position and orientation, the sample mount allows three-dimensional translation and rotation of both azimuth and tilt angles.



Numerical simulations

Numerical simulations were performed using the ANSYS Lumerical software. The properties of a single Si disk, such as scattering efficiency, dipole moments and polarizabilities, were calculated with the FDTD solver using a simulation domain of $800 \times 800 \times 800 \text{ nm}^3$, boundary conditions of 32 layers of standard PML in all directions, mesh accuracy of 8, and mesh refinement of conformal variant 1. For more details, please see the “Methods” section of ref. ¹⁰ and Appendices of ref. ⁴⁹. The reflectance and transmittance of a periodic array of discs were calculated using the RCWA solver with a circular k-vector domain, a maximum number of k-vectors equal to 225, a tangent vector field activated and mesh refinement of conformal variant 1.

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I.A. performed numerical simulations. V.A., D.J.R., B.v.C. and A.Y.B. performed experiments. I.A. and A.B.E. performed analytical studies. I.A., V.A., A.B.E., A.V.Z., and A.C.L. contributed to formulating the research direction and discussing the results. I.A., V.A., A.B.E., and A.C.L. wrote the first draft. All authors revised the paper. A.B.E., A.V.Z., and A.C.L. provided supervision.

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Data availability

All the data supporting this study are presented in the “Results” section and Supplementary Information and are available from the corresponding authors upon reasonable request.

Conflict of interest

The authors declare no competing interests.

Consent for publication

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References

- Du, X. et al. Dual-band bound states in the continuum based on hybridization of surface lattice resonances. *Nanophotonics* **11**, 4843–4853 (2022).
- Azzam, S. I. & Kildishev, A. V. Photonic bound states in the continuum: from basics to applications. *Adv. Opt. Mater.* **9**, 2001469 (2021).
- Kang, M., Liu, T., Chan, C. T. & Xiao, M. Applications of bound states in the continuum in photonics. *Nat. Rev. Phys.* **5**, 659–678 (2023).
- Babicheva, V. E. & Evlyukhin, A. B. Mie-resonant metaphotonics. *Adv. Opt. Photonics* **16**, 539–658 (2024).
- Mobini, E., Alaei, R., Boyd, R. W. & Dolgaleva, K. Giant asymmetric second-harmonic generation in bianisotropic metasurfaces based on bound states in the continuum. *ACS Photonics* **8**, 3234–3240 (2021).
- Koshelev, K. et al. Nonlinear metasurfaces governed by bound states in the continuum. *ACS Photonics* **6**, 1639–1644 (2019).
- Santiago-Cruz, T. et al. Resonant metasurfaces for generating complex quantum states. *Science* **377**, 991–995 (2022).
- Liu, Z. et al. Phase interrogation sensor based on all-dielectric BIC metasurface. *Nano Lett.* **23**, 10441–10448 (2023).
- Kravets, V. G., Kabashin, A. V., Barnes, W. L. & Grigorenko, A. N. Plasmonic surface lattice resonances: a review of properties and applications. *Chem. Rev.* **118**, 5912–5951 (2018).
- Allayarov, I. et al. Dynamic nonlocal dielectric metasurfaces: Tuning collective lattice resonances via substrate–superstrate permittivity contrast. *Adv. Photonics Res.* **5**, 2300268 (2024).
- Sun, S. et al. Tunable plasmonic bound states in the continuum in the visible range. *Phys. Rev. B* **103**, 045416 (2021).
- Azzam, S. I., Shalae, V. M., Boltasseva, A. & Kildishev, A. V. Formation of bound states in the continuum in hybrid plasmonic-photonics systems. *Phys. Rev. Lett.* **121**, 253901 (2018).
- Liang, Y. et al. Bound states in the continuum in anisotropic plasmonic metasurfaces. *Nano Lett.* **20**, 6351–6356 (2020).
- Aigner, A. et al. Plasmonic bound states in the continuum to tailor light-matter coupling. *Sci. Adv.* **8**, eadd4816 (2022).
- Liang, Y., Tsai, D. P. & Kivshar, Y. From local to nonlocal high-Q plasmonic metasurfaces. *Phys. Rev. Lett.* **133**, 053801 (2024).
- Sadrieva, Z., Frizyuk, K., Petrov, M., Kivshar, Y. & Bogdanov, A. Multipolar origin of bound states in the continuum. *Phys. Rev. B* **100**, 115303 (2019).
- Evlyukhin, A. B. et al. Polarization switching between electric and magnetic quasi-trapped modes in bianisotropic all-dielectric metasurfaces. *Laser Photonics Rev.* **15**, 2100206 (2021).
- Murai, S. et al. Bound states in the continuum in the visible emerging from out-of-plane magnetic dipoles. *ACS Photonics* **7**, 2204–2210 (2020).
- Ustimenko, N., Rockstuhl, C. & Evlyukhin, A. B. Resonances in finite-size all-dielectric metasurfaces for light trapping and propagation control. *Phys. Rev. B* **109**, 115436 (2024).
- Han, Y., Xiong, L., Shi, J. & Li, G. Observation of tunable accidental bound state in the continuum in silicon nanodisk array. *Nanophotonics* **13**, 1603–1609 (2024).
- Allayarov, I., Calà Lesina, A. & Evlyukhin, A. B. Anapole mechanism of bound states in the continuum in symmetric dielectric metasurfaces. *Phys. Rev. B* **109**, L241405 (2024).
- Wang, X., Wang, J., Zhao, X., Shi, L. & Zi, J. Realizing tunable evolution of bound states in the continuum and circularly polarized points by symmetry breaking. *ACS Photonics* **10**, 2316–2322 (2023).
- Hu, H. et al. Environmental permittivity-asymmetric BIC metasurfaces with electrical reconfigurability. *Nat. Commun.* **15**, 1–9 (2024).
- Malek, S. C., Tsai, C.-C. & Yu, N. Thermally-switchable metalenses based on quasi-bound states in the continuum. *Laser Photon. Rev.* **19**, 2300618 (2025).
- Zhao, C. et al. Electrically tunable and robust bound states in the continuum enabled by 2D transition metal dichalcogenide. *Adv. Opt. Mater.* **10**, 2201634 (2022).
- Pura, J. L. et al. Tunable bound states in the continuum in active metasurfaces of graphene disk dimers. *Nanophotonics* **12**, 4453–4460 (2023).
- Xie, Z. et al. Ultrathin BIC metasurfaces based on ultra-low-loss Sb_2Se_3 phase-change material. *Nano Lett.* **25**, 251–260 (2025).
- Huang, Y. et al. Tunable bound states in the continuum in a reconfigurable terahertz metamaterial. *Adv. Opt. Mater.* **11**, 2300559 (2023).
- Cui, C. et al. Multiple Fano resonances in symmetry-breaking silicon metasurface for manipulating light emission. *ACS Photonics* **5**, 4074–4080 (2018).



30. Vabishchevich, P. P. et al. Enhanced second-harmonic generation using broken symmetry III–V semiconductor Fano metasurfaces. *ACS Photonics* **5**, 1685–1690 (2018).
31. Liu, Z. et al. High-Q quasibound states in the continuum for nonlinear metasurfaces. *Phys. Rev. Lett.* **123**, 253901 (2019).
32. Xu, L. et al. Dynamic nonlinear image tuning through magnetic dipole quasi-BIC ultrathin resonators. *Adv. Sci.* **6**, 1802119 (2019).
33. Abujetas, D. R., Olmos-Trigo, J. & Sánchez-Gil, J. A. Tailoring accidental double bound states in the continuum in all-dielectric metasurfaces. *Adv. Opt. Mater.* **10**, 2200301 (2022).
34. Sidorenko, M. et al. Observation of an accidental bound state in the continuum in a chain of dielectric disks. *Phys. Rev. Appl.* **15**, 034041 (2021).
35. Abujetas, D. R., Olmos-Trigo, J., Sáenz, J. J. & Sánchez-Gil, J. A. Coupled electric and magnetic dipole formulation for planar arrays of particles: resonances and bound states in the continuum for all-dielectric metasurfaces. *Phys. Rev. B* **102**, 125411 (2020).
36. Chen, W. et al. All-dielectric SERS metasurface with strong coupling quasi-BIC energized by transformer-based deep learning. *Adv. Opt. Mater.* **12**, 2301697 (2024).
37. Yue, L. et al. Mid-infrared strong coupling between quasibound states in the continuum and epsilon-near-zero modes in a thin polar dielectric film. *Phys. Rev. B* **109**, 205405 (2024).
38. Weber, T. et al. Intrinsic strong light-matter coupling with self-hybridized bound states in the continuum in van der Waals metasurfaces. *Nat. Mater.* **22**, 970–976 (2023).
39. Sortino, L. et al. Atomic-layer assembly of ultrathin optical cavities in van der Waals heterostructure metasurfaces. *Nat. Photonics* **19**, 825–832 (2025).
40. Zhang, B. et al. Strong coupling and electromagnetically induced transparency in multiple-BIC-driven metasurfaces. *Nano Lett.* **25**, 4568–4575 (2025).
41. Biswas, S. K. et al. From weak to strong coupling: quasi-BIC metasurfaces for mid-infrared light-matter interactions. *Nanophotonics* **13**, 2937–2949 (2024).
42. Xie, Y. et al. Dielectric metasurface evolution from bulk to monolayer by strong coupling of quasi-BICs for second harmonic boosting. *Photonics Res.* **12**, 784–792 (2024).
43. Oleynik, P. et al. Strong optical coupling of lattice resonances in a top-down fabricated hybrid metal-dielectric Al/Si/Ge metasurface. *Nano Lett.* **24**, 3142–3149 (2024).
44. Allayarov, I., Tuz, V. R., Calà Lesina, A. & Evlyukhin, A. B. Analytical model of metasurfaces comprising meta-atoms with anisotropic polarizabilities and for arbitrary incident angles. *Phys. Rev. B* **111**, 155438 (2025).
45. Abujetas, D. R., Sanchez-Gil, J. A. & Sáenz, J. J. Generalized Brewster effect in high-refractive-index nanorod-based metasurfaces. *Opt. Express* **26**, 31523–31541 (2018).
46. Novotny, L. Strong coupling, energy splitting, and level crossings: a classical perspective. *Am. J. Phys.* **78**, 1199–1202 (2010).
47. Zhang, L., Gogna, R., Burg, W., Tutuc, E. & Deng, H. Photonic-crystal exciton-polaritons in monolayer semiconductors. *Nat. Commun.* **9**, 713 (2018).
48. Cao, S. et al. Normal-incidence-excited strong coupling between excitons and symmetry-protected quasi-bound states in the continuum in silicon nitride-ws2 heterostructures at room temperature. *J. Phys. Chem. Lett.* **11**, 4631–4638 (2020).
49. Allayarov, I., Evlyukhin, A. B. & Calà Lesina, A. Multiresonant all-dielectric metasurfaces based on high-order multipole coupling in the visible. *Opt. Express* **32**, 5641–5658 (2024).
50. Ndao, A., Salut, R., Suarez, M. & Baida, F. I. Plasmonless polarization-selective metasurfaces in the visible range. *J. Opt.* **20**, 045003 (2018).

