Asymmetric excitation of surface plasmons by dark mode coupling

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Control over surface plasmons (SPs) is essential in a variety of cutting-edge applications, such as highly integrated photonic signal processing systems, deep-subwavelength lasing, high-resolution imaging, and ultrasensitive biomedical detection. Recently, asymmetric excitation of SPs has attracted enormous interest. In free space, the analog of electromagnetically induced transparency (EIT) in metamaterials has been widely investigated to uniquely manipulate the electromagnetic waves. In the near field, we show that the dark mode coupling mechanism of the classical EIT effect enables an exotic and straightforward excitation of SPs in a metasurface system. This leads to not only resonant excitation of asymmetric SPs but also controllable exotic SP focusing by the use of the Huygens-Fresnel principle. Our experimental findings manifest the potential of developing plasmonic metadevices with unique functionalities.

INTRODUCTION

The common motivation in realizing the electromagnetically induced transparency (EIT) effect in metamaterial systems is to deliver a sharp transmission resonance that can slow down light (1). To achieve this, the design generally consists of two artificial resonant elements, a radiative bright resonator that strongly couples with the light in free space and a dark resonator that weakly couples to the incident light (2–12). These artificial structures thus have EIT-like resonances due to near-field Fano-type destructive interference (13–16). Therein, the dispersion property of the coupled system is markedly modified, leading to an enhanced group refractive index around the transparency window. Such a behavior renders the metamaterial-based EIT effect very promising in optical switching, sensing, slow light, light storage, and enhanced nonlinear effects (9–12, 17–20).

Although a series of micro- and nanostructures have been developed to demonstrate the EIT effect, the strategies investigated thus far mostly involve manipulating the electromagnetic waves in free space (2–20) or plasmonic waveguides using cavity structures and antennas (21–23). However, it is expected that the unique mode coupling mechanism of the EIT effect could be used to control not only the electromagnetic waves propagating in free space and waveguides but also surface plasmons (SPs) existing at the near-field metal-dielectric interface (24). The ever-increasing demands for functional plasmonic devices have driven great efforts to exploit new methods for excitation and manipulation of SPs, especially for asymmetric or unidirectional excitation of SPs. Among these, one approach is to use metasurfaces with controllable phase profiles (25–32), where the designed phase gradient serves as an additional in-plane wave vector that is critical to satisfy the momentum-matching condition between the free-space wave and SPs in a selective excitation direction (33–35). Another route is to control the SP interference by two or more isolated couplers with different SP excitation phases or scattering parameters, including previously reported compact asymmetric gratings and plasmonic antenna couplers (36–42). However, to achieve the desired functionality with high performance, simplifications were usually made where freedoms in controlling the SPs were also missed at the same time. For example, the coupling effects among the excitation units have been purposely excluded or minimized in previous studies. Instead, coupling can also be an essential factor in designing the SP excitation and cannot be neglected in many applications. New designs for much improved control over the SPs may be achieved by investigating the sophisticated coupling mechanism, such as EIT, within the building block.

Here, we apply the EIT mode coupling mechanism to the near-field SPs, enabling a new degree of freedom in controlling the excitation and propagation of the SP resonance. We show that the resonance strength of the bright resonator, which determines the strength of the excited SP along a specific direction, can be suppressed strongly at one side when coupled with the dark resonator. Once stimulated, the dark resonator excites a new orthogonally propagating SP resonance. Both the intensities of these two SP beams can be effectively manipulated by varying the coupling between the two sets of resonators. Different from previous studies on the asymmetric excitation where the far-field interference of the scattered SP fields played an essential role, here, the near-field coupling–induced destructive mode interference is responsible for the asymmetric response. In addition, we demonstrate that the proposed method can be further used to achieve an exotic SP focusing by simply applying the Huygens-Fresnel principle (43, 44). The unique property of our strategy delivers a versatile platform for various applications in asymmetric SP excitations, plasmonic circuitry, and energy harvesting.

RESULTS

Sample design and terahertz near-field characterization

The proposed design of the subwavelength unit cell is schematically illustrated in Fig. 1A. The structure contains a bar-shape slit resonator (BSSR) and a split-ring slit resonator (SRSR) at the lower right side of
The inset schematically shows the excitation pattern, where 8 × 8 unit cells were contained and arranged in a square lattice. Amplitude at 0.75 THz under normal incidence of an \( k = 45\) quartz substrate using conventional photolithography. In the terahertz metasurface with 8 × 8 such unit cells made from aluminum on a BSSR. The resonance frequency of the structure is designed at 0.75 THz, where the SPs can be excited most efficiently. To increase the overall SP coupling strength at the resonance, we fabricated a 2D translation stage, the microprobe raster scans the SP field (see Fig. 1C and Materials and Methods). \( \varepsilon_q = 3.76\) was used as the substrate to avoid Fabry-Perot reflections within 26 ps after the main terahertz pulse.

The measured SP field distribution is illustrated in Fig. 1D, in which the inset schematically shows the excitation structure and its actual area. An asymmetric SP excitation pattern is clearly observed along the \( x \) direction. That is, the SPs mainly propagate toward the left side (\(-x\) direction) of the structure, whereas there are almost no SPs on the right side (\(+x\) direction). Another intriguing effect is that an \( x \)-polarized wave is also coupled to the \( y \) direction propagating SPs with nearly the same strength on both the top side (\(+y\) direction) and the bottom side (\(-y\) direction). It is known that the SP propagating at a metal-dielectric interface is actually an electron density wave, which only exists as a transverse magnetic mode. This oscillation of electrons is driven by the electric field of the incident wave; thus, the propagating direction of the SPs is usually locked to be along the polarization at normal incidence. However, now, we can obtain SPs propagating along the \( y \) axis, although the incident light is \( x \)-polarized. Through analyses presented in the following, we find that the effect can be well explained by the EIT coupling theory.

**Theoretical analysis**

To explore the underlying physical mechanism of the phenomena, we first individually analyzed the SP responses of the two resonators...
structive interference effect leads to the disappearance of the right-side strongly suppressed. The scattered field of the SPs arisen from the de-
the right side of BSSR, the SP intensity at the right side of the BSSR is
with the same strength (see fig. S1). Because SRSR is only located at
(D and E) Simulated SP amplitude spectra excited to the right and top sides of the structures, with s
in the ±x and ±y directions. This can be described by applying the coupled Lorentzian oscillator model, through which the resonance amplitude of the resonators with respect to k can be solved (see note S1). It can be deduced that the resonance amplitude of the bright resonator gradually increases to approach that of a single bright resonator as k decreases, whereas the resonance amplitude of the dark resonator does not change monotonically with k and a maximum of the resonance amplitude of the dark resonator can be found when k changes. Such a behavior will directly transfer to that of the excited SP intensity, which is strongly dependent on the resonance amplitude of the resonators.

Numerical simulations and experimental verification
There are two approaches to change the coupling coefficient: varying the relative vertical distance d or horizontal distance s between the two resonators. Figure 3 (A and B) illustrates the change of the SP amplitude spectra with respect to d at the right and top sides of the structure, respectively. As d varies from −40 to 40 μm (s is kept at 5 μm), the SP excitation dip on the right side is gradually converted to one peak, whereas the SP excitation peak on the top side rises first and then decreases. Such variations are more clearly shown in Fig. 3C at 0.75 THz. Similar modulation of the SP excitation amplitudes is also observed as s varies from 5 to 45 μm (d is kept at −40 μm; see Fig. 3, D to F). The variation of the SP amplitude spectra at the left and bottom sides of the structure can be seen in fig. S3.

To identify how the coupling coefficient changes with these two parameters, we look into the electric and magnetic coupling regimes between BSSR and SRSR. For the well-known split-ring resonator (SRR), it can be excited by either an electric field perpendicular to
the gap $E_x$ or a magnetic field passing through the ring $H_x$. On the contrary, SRSR can be excited by a magnetic field perpendicular to the gap $H_x$ or an electric field passing through the ring $E_z$ according to the Babinet principle (51–53). From simulations, we found that the localized electric field $E_z$ of an excited BSSR is strongest at the center whereas the localized magnetic field $H_x$ is strongest around the ends of BSSR but in opposite phase (see fig. S2). At $s = 5 \mu m$, the electric and magnetic couplings from BSSR to SRSR are in phase when $d = -40 \mu m$, resulting in maximum excitation of the SRSR. As SRSR is gradually moved to $d = 40 \mu m$, the electric and magnetic couplings to the SRSR become out of phase, and so, SRSR is hardly excited. Therefore, the overall coupling coefficient decreases with $d$ increasing. As for the case of increasing the coupling distance $s$, both the electric and magnetic couplings decrease, and hence, the overall coupling coefficient also decreases.

Notice that such a coupling mechanism is strongly related to the direction of SRSR. If the SRSR is flipped up and down with respect to its own center, the overall coupling coefficient increases with increasing $d$, as the structure becomes its mirror structure along the $y$ direction (see fig. S4A). To explore the specific effects of the electric and magnetic couplings in this process, we could achieve further in-depth understanding by analyzing the complementary structure of the design, which consists of a bar-shape resonator (BSR) and SRR (8). As an example, we consider a case of flipping the SRR at $d = 40 \mu m$ where the overall coupling is quite weak (see fig. S4B). First, the magnetic coupling effect from the $H_x$ resonant field of BSR to SRR persists, because it penetrates the SRR and causes an inductive surface current, which circulates along the SRR in a certain direction regardless of the direction of SRR. However, the electric coupling effect from the $E_x$ resonant field of BSR to SRR is different. Because the coupling field $E_x$ from BSR will strongly attract or repel the free electrons at the nearest edge of SRR, whereas it has a less effect on the other edge of SRR due to asymmetric $E_x$ environment caused by the distance (7); such behavior will also cause a circulating surface current along the SRR. The difference is the fact that the circulating direction will reverse.

**Fig. 4. Measured and simulated SP amplitude distributions.** (A to D) Measured SP amplitude distributions, with $d$ varying from $-20$ to $40 \mu m$ and $s = 5 \mu m$ at 0.75 THz. The insets schematically show the measured structures. (E to H) Simulated SP amplitude distributions corresponding to (A) to (D), respectively. (I to L) Measured SP amplitude distributions, with $s$ varying from 5 to 45 $\mu m$ and $d = -40 \mu m$ at 0.75 THz. The insets schematically show the measured structures. (M to P) Simulated SP amplitude distributions corresponding to (I) to (L), respectively.
DISCUSSION

The preceding analysis shows that the excitation of SRSR resonance arises from the near-field coupling with BSSR. Therefore, it can be understood that the SPs to the SRSR (right) side are gradually converted to the SPs propagating to the top and bottom sides. Such a behavior is further applied to control the focusing direction of the SPs, which is fascinating in many applications. The schematic diagram is illustrated in Fig. 5A. Two series of concentric circles centered respectively at the blue and red elliptical points intersect with each other. The radial difference between the neighboring concentric circles is 400 μm. The structural unit cells are placed right at the intersection points, as indicated by the brown points. When there are only the BSSRs (Fig. 5B), a strong focusing behavior is observed at the red central point, and a diverging behavior is observed at the opposite (left) side. However, the SPs at the top and bottom sides are much weaker because of the fact that the SP excitation along the long-axial direction of BSSR is weak. Figure 5 (C and D) illustrates the results when SRSR is placed at the right and left sides of BSSR, respectively. For the first case, part of the focused SP toward the right side in the original configuration (Fig. 5B) is now redirected to the focused SP propagating downward toward the blue point and the diverged SP propagating upward (Fig. 5C). Whereas for the second case, most of the energy in the diverging SP toward the left side in the original configuration (Fig. 5B) is redirected into those two directions (focusing downward and diverging upward) (Fig. 5D). The energy redirection in both cases is indicated by the corresponding white arrows and the amplitude changes. This method also provides a route for fully using the energy of the excited SPs where the part of the concomitantly diverging SPs is usually useless in many cases. Here, the focusing area is a line segment rather than a point-like spot due to the fact that only parts of the circles are applied to excite the SPs. The focusing resolutions of all the focus points are around 0.65λSP, with λSP (=400 μm) denoting the SP wavelength at 0.75 THz.

It should be noted that the intensity of the SPs along the y direction cannot be enhanced but will decrease to zero if another SRSR is placed symmetrically at the outside of BSSR. Owing to the resonant feature of BSSR, it will excite SRSRs at its two sides with an exact π phase difference. Although the SPs along both the +x and −x directions will be suppressed simultaneously, the excited SPs by these two SRSRs will cancel each other out (see fig. S5). Furthermore, because the coupling mechanism of the EIT in metamaterials is universal, the proposed method of asymmetric excitation of SPs is also applicable to other spectral regimes. As an example, we theoretically investigate a metasurface that is made up of similar BSSRs and SRSRs at infrared frequencies and achieve results comparable to those in Figs. 2 and 3 (see fig. S6).

In summary, SP excitation via the EIT coupling mechanism is proposed in a metasurface containing two coupled hole-type resonators. Through manipulating the near-field coupling, the intensity of the excited SPs can be effectively controlled. The proposed approach is further applied to control the SP focusing by properly engineering the arrangement of the unit cells. Our experimental findings provide the possibility of developing a wide range of SP-based applications.

MATERIALS AND METHODS

Experimental design

All the metasurfaces were characterized by using a terahertz time-domain near-field scanning system that we recently developed. Different from a traditional terahertz time-domain system, here, the terahertz detector was a near-field photoconductive antenna-based probe (Protemics GmbH). To allow the movements of the probe, the detection beam of the system was coupled to a 2-m-long optical fiber. Before that, a pre-dispersion-compensation grating pair was used to suppress
pulse stretching in the fiber. Then, the probe was fixed onto a 2D electrically controlled translation stage. In the measurements, the terahertz probe was placed approximately 50 μm above the sample surface. The entire 2D scanning range was 8 × 8 mm² for the metasurface with 8 × 8 unit cells and 7.8 × 7.8 mm² for the SP focusing metasurfaces.

Numerical simulations

The numerical simulations were carried out using the finite-element time-domain solver of the CST Microwave Studio. The entire simulation area was 8 × 8 mm². The structure contained 8 × 8 unit cells located at the center of the simulation area. Open-boundary conditions were applied in both the x and y directions. The incident wave was x-polarized and normally illuminating on the metasurface from the substrate side. The SP spectra were extracted by setting field probes at the corresponding positions, whereas the field distributions of the SP were mapped by defining electric field monitors at 0.75 THz. The simulated results were also obtained at 50 μm above the metasurface on the air side.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/2/2/e1501142/DC1

Fig. S1. Simulated SP spectrum and field distribution of the BSSR array.

Fig. S2. Simulated Ez and Hx field distributions of the BSSR and BSSR + SRSR.

Fig. S3. Simulated spectrum variations with different values of d and s.

Fig. S4. Schematics to describe the coupling mechanism using complementary structures.

Fig. S5. Simulated SP spectrum and field distribution of the BSSR + 2 × SRSR array.

Fig. S6. Simulated SP field distributions and spectra of similar metasurfaces in the infrared regime.

Note S1. Coupled Lorentzian oscillator model.

REFERENCES AND NOTES


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