Robust Q-tunable topological induced transparency in metasurface

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Abstract

In this study, we demonstrate first, to the best of our knowledge, robust and dynamically polarization-controlled tunable-high-Q (~9nm FWHM, ~λ/100) PIT in designed nanostructures metasurface, whose sharp resonance is guaranteed by design and protected against large geometrical imperfections. By employing the explicit analysis of near-field characteristic in the reciprocal-space based on the momentum matching, and the far-field radiation features with point-scattering approach in real-space sparked from Huygens’s principles, the physics of interference resonance in the spectra for plane-wave optical transmission and reflection of the metasurface is theoretically and thoroughly investigated. The experimental results verify the theory prediction. The distinctive polarization-selective and Q-tunable PIT shows robust features to performance degradations in traditional PIT system caused by inadvertent fabrication flaws or geometry asymmetry-variations, which paves way for the development of reconfigurable and flexible metasurface and, additionally, opens new avenues in robust and multifunctional nanophotonics device design and applications.

INTRODUCTION

Plasmon-induced-transparency (PIT) is a widespread wave scattering phenomenon associated with a peculiar coupled interference effect. Since its first demonstration [1] in the plasmonic nanostructures, PIT has been widely and thoroughly studied both theoretically and experimentally [2-4] due to a large variety of pivotal and potential applications in sensing, filter, switches, slow-light, and nonlinearity. However, the study of PIT with reconfigurable dynamic tunability poses several challenges. Many works report tunable PIT resonance by employing the geometrical asymmetry/variations, which is inherently static and the control of channels for the PIT windows are rarely studied [3]. Favorably, phase-change-materials (PCM), graphene, magnetic-materials, and nonlinear dielectric nanostructures have auspiciously emerged as a promising alternative and platform for dynamic control of PIT, and are expected to complement or even replace plasmonic nanostructures for a wide range of potential applications [5].

Recently, carefully designed plasmonic nano-antennas take advantages of the polarization-selective excitation and evolution of the split-ring-resonator (SRR) like unit have been proposed to shed light on dynamic PIT construction, not only providing a notable sequential polarization-controlled switchable PIT channels, but also flexibility and configurability [3]. The selective-excitation of coupled-SRR-resonance strategy may offer an unprecedented solution to the vexing problem about dynamic PIT manipulation. Nevertheless,
these devices perform structure-parameters sensitivity, which conversely challenges the state-of-art fabrication and owns inferior tolerance to fabrication errors and mismatch, leading to deficiency of robustness of the PIT resonance for practical applications. Tunable PIT with dynamic manipulation is unresolved for PIT with immunity against fabrication imperfections/flaws and geometrical variations. Topological optics is inspiring a new perspective on design of nanophotonics metasurface and devices [6, 7]. The manipulation of photonics by employing nanoscale photonics structures with exotic properties are well demonstrated with fascinating design [6-8]. Due to their simple construction and efficient tunability, metasurface using nanoslits or slot antennas topology as building blocks has been identified as a versatile platform to study topological nature and manipulation of photonics for helicity dependent directional surface plasmon polaritons (SPP) excitation [9], flexible control of in-plane SPP shaping and focusing or far-field radiation[10, 11], chirality of asymmetric transmission [12], parity-time (PT) symmetry breaking [13], and spin optics in metasurface [14].

In this study, we introduce a class of compact slits nano-antennas array in metallic film that lift all these limitations and show their feasibility to be dynamically controlled by incidence polarization, where robust PIT with tunable quality factors is demonstrated. The physics of the generation, evolution, and annihilation of the PIT, and the immunity of the proposed system to the asymmetry geometry parameters variation are investigated and illustrated by exploring the dispersion band characteristics in the real-space and the reciprocal-space. The simulated results are verified by the point-scattering approach model theoretical predictions and the experimental measurement, where the interference of the field in the slits and the far-field radiation features are revealed. The results pave the way for reconfigurable, flexible multifunctional metasurface and robust nanophotonics device design and applications.

PROPOSED METASURFACE AND METHOD

The proposed topology consists of periodic rectangular nanoslits antenna array in gold film on substrate. Figure 1(a) illustrates the schematic of plasmonic nanostructures. A 50-nm-thick gold film was deposited on a glass substrate. The designed nanoslits apertures array can be milled into the gold film using focused ion beam (FIB). The incidence is denoted as linear polarized light with an angle of polarization (AOP) $\alpha$. Figure 1 (b) shows the scheme of the unit cell slit orientation and the corresponding coordinate system. The unit cell with perforated specifically arranged resemble slot antennas ($L = 200$ nm, $W = 40$ nm) is shown in figure 1 (c). The equal periods $P_x, P_y$ are set as 600 nm on both $x$ and $y$ directions.

The geometrical parameters shift $S$ and gap $G$ is denoted in figure 1 (c), respectively. The rotation coordinate system denotes as $u-v$ and the translational coordinate system as $x-y$ are shown in the figure 1 (b). The coordinate vector system for the proposed metasurface is shown in figure 1 (c), which will be described thereafter. For the case of a rectangular-shaped nano-slot in metal film with a high aspect ratio, the resonance and amount of SPP generation are significantly dependent on the orientation of the incident polarization [15-18]. Different from the metallic nanobars where the plasmonic resonance mode is excited with polarization along the long-arm, the SPP can only be excited when the polarization direction of the incident light is perpendicular to the counterpart metal slits.
The physics and model of optical transmission of periodic subwavelength holes array (SHA) nanostructures have been vastly and thoroughly studied, where several model such as the coupled-mode equation [19], hybrid-wave model [20], and the ab initio theory of Fano-formula [21] were proposed. Meanwhile, the resonance role of SPP modes was studied by reciprocal-space momentum-match conditions. For single-interface SPP, the dispersion relation can be described as follow:

\[ K = k_{spp} = 2\pi\sqrt{\varepsilon_m \varepsilon_d / (\varepsilon_m + \varepsilon_d) / \lambda} \]  

(1)

where \( \varepsilon_d \) and \( \varepsilon_m \) are the relative permittivity of the dielectric and the metal. The dispersion relation of the SPP Bloch mode generated under the Bragg coupling condition can be obtained by the momentum match:

\[ \vec{k}_{spp} = \vec{k}_{in} + i \frac{2\pi}{P_x} \vec{u}_x + j \frac{2\pi}{P_y} \vec{u}_y \]  

(2)

where \( \vec{k}_{in} \) is the component of wave vector \( \vec{k} \) parallel to the array surface, \( \vec{u}_x \) and \( \vec{u}_y \) are the unit vector in plane. Instead of straightforward description of the transmission, the reciprocal-space method relies on a priori definition of resonance as unperturbed smooth surface mode without the nanostructures. In 2005, Genet et al. presented a real-space Huygens description instead of the more conventional reciprocal-space description of interfering resonance features in the SHA [22]. However, the anisotropic designed holes arrays increasingly utilized in the metasurface for flexible control and modulation of electromagnetic wave are seldom treated. Recently, the SPP far-field radiation in an anisotropic SHA metasurface is demonstrated [11, 23]. In the point-scattering model, the unit cell of the hole openings are treated as resonance point-scatter. In the figure 1(b), the angle \( \phi \) between the \( \nu \) axis (also referred to as the normal direction of a nanoslit) and \( y \) axis is defined as the rotating angle of the nanoslit. By setting the first, lower-left nanoslit’s center as the origin \( O \) of the whole system, the contribution of all the point-scatter to the transmission spectra can be processed based on the Huygens’ Principles.

The disposition vector of the center of the first nanoslit in the \( j \)th (the \( m \)th row and the \( n \)th column) supercell is \( \vec{R}_j = mP_x \vec{x} + nP_y \vec{y} \). The unit vector for the position vector is \( \vec{u}_j = \vec{R}_j / |\vec{R}_j| \). In one unit cell, the relative coordinate of the center of the \( j \)th nanoslit’s center...
relative to the first nanoslit’s center in the same supercell is set as \( \vec{r}_s \) (figure 1(c)). The absolute coordinate of the \( j \)th nanoslit’s center can be obtained as \( \vec{r}_j = \vec{R}_j + \vec{r}_s \).

With the propagation direction of SPP expressed as \( \hat{u}_{\text{app}} = (\vec{v} \cdot \vec{E}_{\text{in}}) \cdot \vec{v} \), where the polarization of the incident plane wave is set as the direction along the \( y \)-axis (\( \vec{E}_{\text{in}} = \vec{y} \)) for TE (Transverse Electric), and \( x \)-axis (\( \vec{E}_{\text{in}} = \vec{x} \)) for TM (Transverse Magnetism), and the excited SPP propagation vector of the nanoslits \( \vec{v} = y \cos \phi - x \sin \phi \). The full polarization behavior of the SPP is contained in the tensorial nature of the elementary scattering matrix. Assuming that the scattering matrix of the far-field is spherical so that the intensity of the transmission for the metasurface can be calculated [11, 22, 23],

\[
\text{Ratio} = \frac{1}{T_0} \left| \sum_{j} \hat{u}_j \otimes \hat{u}_j \right|^2 = \frac{1}{T_0} \exp\left(\frac{-|\vec{K}|^2}{2|\vec{r}_j|^2}\right) \exp\left(\frac{\text{Re}\{\vec{K}\}^2}{4|\vec{r}_j|^2}\right) \frac{|\text{Re}\{\vec{K}\}|^{1/2}}{\sqrt{|\vec{r}_j|^2}}
\]

Where the spectrum for \( m = 1, n = 1 \) are defined as a normalized coefficient \( T_0 \). Under point-scattering limit, the shape factor \( S(|\vec{K}|) \) can be replaced with a constant. This relates the present formulation to the two-dimensional Green function of the surface-wave with no need to investigate the full three-dimensional Green function half-space problem [22]. For a given hole, the incoming field is converted into two-dimensional surface waves that propagate away from the hole as a spherical (Huygens) wave. Based on the point-scattering-approach, the plane-wave optical transmission of the designed metasurface for arbitrary angles and polarizations can be evaluated and predicted theoretically.

![Fig.2](image-url) (a) Theoretic model calculated transmission coefficient at TM (solid-lines)/TE (dashed-lines) incidence, and (b) numerical simulated transmission and reflection spectra of the metasurface. “Sub” and “Air” indicate the substrate and upper air interfaces.

The intensity of transmission spectra for both TM/TE plane-wave at normal incident for the symmetric/asymmetric structure are theoretically calculated using Eq. (3) for convergent
values at \( m=n=100 \), and the results are shown in the figure 2 (a). It is demonstrated that the PIT resonances are directly linked to the spectral position of the Au/glass interface SPP Bloch Mode, which shows robust polarization-insensitive features. As studied and shown by Pacifici et al from Prof. Atwater’s group, the positions by the point-scattering model theory prediction should be the transmission minimum [23]. To verify the theory prediction, the full-field electromagnetic calculations were performed using the finite difference time domain (FDTD) method. The permittivity of Au was taken from the experiment data [24], while the refractive index of the glass substrate was fixed at 1.45. The calculated reflectance and transmission spectra are shown in the figure 2(b). Clear transparency window with narrow peaks in the reflection spectrum is observed at 904 nm wavelength, for both the system with and without broken-symmetry. Excellent agreement between the theory and the simulation is observed.

RESULTS AND DISCUSSION

The PIT is maintained and obtained in the system without geometry symmetry-breaking, which shows extraordinary immunity to the symmetry-breaking employed and usually required in the traditional plasmonic nanostructure using the resemble resonance nanobar/nanoslit unit. The in-plane interference of the surface wave by the scattering of light from the arranged nanoslits is attributed to the variation of the reflection and transmission spectra for different gaps of the nanoslits. The results in the figure 3 (a) show clear emerging and vanishing of the PIT peak for different gap values, where the PIT peak is shrinking and fading for increased gaps below 20 nm, while the notable regeneration of the PIT with broaden and enlarged peak is observed for further increased gaps. The result shows quite unique trends featured with unusual fading and revival of the PIT resonance when increasing the gaps \( G \) of the nanoslits. Hence, once the distance for varied coupling is increased or decreased, the PIT resonances position moves. The oscillatory behavior as a function of varied gaps is also observed as theoretically predicted from the surface-wave mediated interference model, where the first-order interference between SPP and these out-of-plane component at the subwavelength scattering sites formed by the slits openings gives rise to the observed spectra [23]. The PIT-like resonance is maintained for vast range of gaps, which shows relatively robust performance to fabrication flaws or imperfection. To further verify this, the rotation angles \((\phi_1, \phi_2, \phi_3, \phi_4)\) of the slits are slightly and randomly changed, where by theory prediction, besides of the shrink ratio values, the unchanged fixed transmission ratio peak position centered at 904 nm is still observed agreeing with the simulation results.

![Fig. 3](image)

Fig. 3. Calculated reflection spectrum as a function of varied Gaps values \( G \) (a), and shift \( S \) (b) for TM-polarization. Robust PIT spectra immune to marginal geometry variations is observed.
At the same time, changing the distance (Shift) between the nanoslits vertical to the incidence polarization will not significantly affect the frequency position of the PIT resonance due to the fact that the slot-antenna’s polarization-excitation-selective property. Figure 3 (b) shows the reflectance spectrum at normal incidence as a function of varied shifts of the nanoslit 1, where the PIT resonance effect shows slight changes for shifts below 40nm, and the transparency window shows negligible and almost unchanged features for larger values of the shifts. By carefully designing utilizing the polarization-selective bound-charge-oscillator like slot antenna unit [15, 17], the singular features of the PIT resonance in the system is reported for the first time, to the best of our knowledge, that the topologically robust PIT resonance is demonstrated in plasmonic nanostructures metasurface for both symmetric or asymmetric unit. Most works indicated that asymmetry is crucial to realize PIT when the interaction of dipole resonance and the plasmon resonance modes in the nanostructure is considered. Here we propose structure that is not limited by the asymmetry condition and PIT resonance with robustness features shows immunity to the asymmetry geometry variation.

Furthermore, to verify the theory, the sample is fabricated and the system is experimentally studied. A 50-nm-thick continuous gold film was deposited on a glass substrate with electron-beam evaporation. The designed nanoslit apertures array was milled into the gold film using focused ion beam (FIB) (with the voltage and current of the ion beam as 5 kV and 24 pA), with the dimensions of period $P = 600$ nm for both $x$-$y$ directions. The substrate is cleaned and processed firstly, then covered with a 50 nm gold film using electron-beam evaporation procedure. The optical spectra are measured using a commercial micro-spectrophotometer (IdeaOptics Technologies, Shanghai, China)) and normalized with respect to the transmittance and reflectance spectra of a quartz substrate and a standard silver mirror, respectively. The scanning electron microscope (SEM) image of the final structure shows clear nanoslits periodic array.

Figure 4(a) shows the top view SEM image of the fabricated nanostructures. Figure 4(b) shows the measured reflectance spectra of the system for an selected array of $30 \times 30$ periodic unit at three different incidence AOP. The valley of reflection is clear seen with observable slight PIT-like peak, where the small area of the array, the imperfection of the sample is attributed to the discrepancy from the whole array calculation and theoretical analysis. The slight peak around 900 nm in reflection is observed as predicted by the theoretic model and simulation results (see figure 3(a)).

![Fig. 4. (a) Top view SEM image of the fabricated plasmonic metasurface nanostructures. (b) Measured reflection spectra of the sample for three different angles of polarization (AOP). Slight peak at 900 nm is seen for micro-area array, which is verified by the simulation (see Fig. 3(a)).](image-url)
For varied incidence polarization orientation, the tunability of the system with fascinating sequentially switchable PIT resonance peaks with tuned quality factor and contrast is obtained, where dynamic PIT with tunable quality can be efficiently tailored by adjusting the incidence polarization. The results shown in figure 5(a) exhibits clearly evolution of the PIT resonance, where broaden resonance with PIT effect associated with almost fixed resonance position is demonstrated for increased angles of polarization. The resonance quality factors of the system with minimum 9 nm linewidth can be gradually tuned by controlling the AOP (angle of polarization). For asymmetry structures, the PIT resonance is also observed from the results in figure 5(b). Incidence polarization tunable robust PIT in designed metasurface is obtained immune to the geometry symmetry/asymmetry.

Fig. 5. (a) Reflection spectra as a function of the polarization orientation angles for symmetric \((G = 15 \text{ nm}, S = 0 \text{ nm})\) structure. (b) Reflection spectra as a function of polarization orientation angles for asymmetric \((G = 15 \text{ nm}, S = 120 \text{ nm})\) geometry. The PIT-like spectra is robust centered at fixed resonance position.

Fig. 6. Calculated dispersion of the system for TM polarization incidence. Calculated transmission spectra of the system as a function of the frequency and in-plane wave vector \(k_y\) (Left panel). Right panel: Calculated reflection spectra of the system as a function of the frequency and in-plane wave vector \(k_x\). The superimposed white solid line denotes the calculated dispersion curves for asymmetry (air-Au-glass) three-layer (insulator-metal-insulator, IMI) waveguide-mode. The superimposed black lines are the dispersion curves of air and substrate SPP modes (solid lines) and Wood Anomaly (dashed lines). “Sub” and “Air” indicate the substrate and upper air interfaces. Robust PIT-like effect is observed.
Fig. 7. Calculated dispersion of the system for $y$ polarization incidence. Left panel: Calculated transmission spectra as a function of frequency and in-plane wave vector $k_y$. Right panel: Calculated reflection spectra as a function of frequency and in-plane wave vector $k_y$. The superimposed white solid line denotes the calculated dispersion curves for SPP Bloch-mode and the asymmetry IMI waveguide-mode. The superimposed dashed lines are the dispersion curves for Wood Anomaly. “Sub” and “Air” indicate the substrate and upper air interfaces. Robust PIT resonance is observed for large angles-variations.

Furthermore, there has been plenty of designed controllable light beams with tailored wave-front and vector vortex are realized using coded metasurface or spatial light modulator (SLM), the fruitful dynamic PIT resonance with striking features inspired by manipulating the incidence polarization shows remarkable potential for dynamic metasurface devices design and applications. To gain clear systematic properties of the system, the topological properties are investigated by exploring the dispersion of the nanostructure. The result in the figure 6 and figure 7 shows the dispersion calculated band for TM-polarization and TE-polarization for both $k_x$, and $k_y$ momentum using the reciprocal-space theory by momentum matching (Eq. (2)).

The PIT-like resonance is revealed origins from the directional excitation coupled Bloch-surface-wave, which indicates that the directional excitation SPP is obtained in the metasurface system. It is crucial to dynamically control PIT resonances while maintain robust profile features. However, typically emerged PIT system introduces geometry asymmetry and consequently static tunability, hampering their use for dynamic, robust, practical applications. The active control of plasmonic PIT resonance in the proposed metasurface can be implemented using only one optical field by adjusting the incidence polarization. The result paves way for active engineering of robust PIT and dynamic nanophotonics devices.

CONCLUSION

We demonstrate for the first time that the ultra-narrow PIT-like resonances can be guaranteed by carefully designed metasurface without stringent geometrical requirements, and with immunity to structural variations and misalignment. The PIT resonance is not disturbed by any coupling distance/asymmetry/polarizations; the PIT resonance can shift and is still sensitive to the angles of the incident light. Robust PIT with unique properties of versatile tunability can be achieved by adjusting the incident angles/polarization orientation, where
high-Q PIT at different wavelengths and PIT at fixed position with tunable Q values can be achieved in one system. The result may inspire the realization of a new generation of robust devices with unprecedented robustness to fabrication flaws without uncontrollably spectra deformations. We envision that the topologically protected robust PIT effect, can offer new perspectives for the generation of various reliable nanophotonics devices in many applicative fields, including robust sensing, filter, ultrafast switches or metasurface devices, by circumventing the performance degradations caused by fabrication flaws and maintain robust features without stringent geometrical requirements.

The compactness, the simple topology of the system, and the ease of engineering and tailoring the PIT show potential and a wide array of promising design and applications for dynamic multifunctional nanophotonics devices. The pivotal results provide a design strategy for plasmonic multifunctional nanostructures and versatile metasurface [25, 26].

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