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High-Q and Polarization-selective Resonances in Plasmonic Metasurfaces

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Abstract: Surface lattice resonances (SLRs) in periodic plasmonic nanostructure arrays arise from the coherent coupling between localized surface plasmon resonances and lattice diffraction modes, enabling sharp spectral features and enhanced optical responses. Here, we investigate the linear polarization–dependent SLR characteristics of a rectangular lattice composed of anisotropic gold nanobars. By selectively exciting the structure with orthogonally oriented linearly polarized light, we demonstrate pronounced polarization-selective excitation of distinct SLR modes. The results reveal that the coupling strength and spectral position of SLRs are strongly governed by the interplay between particle anisotropy and lattice periodicity along different crystallographic directions. Furthermore, the polarization-dependent response leads to significantly different resonance linewidths and field distributions, indicating controllable radiative damping and mode confinement. These findings provide a comprehensive understanding of polarization-selective SLR formation in anisotropic plasmonic lattices and offer a viable route toward the design of polarization-sensitive nanophotonic devices, including sensors, spectral filters, and tunable plasmonic components.

Keywords: Surface Lattice Resonances; High Quality Factor; Polarization Selectivity.

1. Introduction

Plasmonic nanostructures enable strong confinement of electromagnetic fields beyond the diffraction limit, giving rise to pronounced local field enhancement and enhanced light–matter interactions [1],[2]. However, conventional localized surface plasmon resonances (LSPRs) supported by isolated metallic nanoparticles typically suffer from substantial radiative and non-radiative losses, resulting in broad resonance linewidths and relatively low quality factors (Q)[3]. These intrinsic limitations restrict their performance in applications requiring sharp spectral features and long photon lifetimes, such as high-resolution sensing, nonlinear optics, and strong coupling systems.

Surface lattice resonances (SLRs) have emerged as an effective strategy to overcome these constraints by exploiting the collective coupling between LSPRs and diffractive lattice modes in periodically arranged nanoparticle arrays[4],[5]. Owing to the suppression of radiative damping near Rayleigh anomalies, SLRs exhibit significantly narrowed linewidths and substantially enhanced Q factors compared with their localized counterparts[6]. Importantly, the hybrid nature of SLRs enables the coexistence of extended lattice coherence and intense near-field confinement, leading to strong electromagnetic field enhancement over large spatial regions[7]. These unique properties make SLRs particularly attractive for applications that simultaneously demand high spectral selectivity and strong field localization.

The formation and characteristics of SLRs are highly sensitive to lattice symmetry, periodicity, and nanoparticle geometry. In arrays composed of anisotropic plasmonic elements, such as nanorods or nanobars, the polarization of incident light plays a decisive role in determining the excitation efficiency of localized modes and their subsequent coupling to lattice diffraction orders. Linear polarization aligned along different principal axes selectively excites distinct plasmonic resonances, thereby modulating the strength of coupling to Rayleigh anomalies and profoundly influencing the resulting SLR spectra, quality factors, and near-field distributions.

Despite extensive studies on SLRs in plasmonic lattices, a comprehensive understanding of polarization-selective SLR behavior in anisotropic particle arrays remains incomplete. In particular, the combined impact of particle anisotropy and lattice periodicity on the achievable Q factors and electric field enhancement under different linear polarizations has not been systematically explored. Such understanding is crucial for rationally designing plasmonic systems with controllable resonance sharpness and field localization.

In this work, we investigate the linear polarization–dependent surface lattice resonances supported by a rectangular lattice of gold nanobars. By exciting the structure with orthogonally oriented linearly polarized light, we reveal pronounced polarization-selective SLR modes with markedly different quality factors and electric field enhancement characteristics. Our results elucidate the physical mechanisms governing high-Q SLR formation and near-field amplification in anisotropic plasmonic lattices, providing a robust platform for engineering polarization-sensitive nanophotonic devices with enhanced spectral and field performance.

2. Results and Discussion

The investigated structure is schematically illustrated in Fig. 1. It consists of a square lattice array of rectangular gold nanorods (Fig. 1a), where the lattice periodicities along the x- and y-directions are denoted as $\underline{P_x} = P_y = 700$ nm, respectively. The periodically arranged metallic nanoparticle array embedded in a homogeneous medium with a refractive index of $n = 1$ provides the necessary condition for the excitation of surface lattice resonances. Each gold nanorod possesses a long axis of length a oriented along the x-direction and a short axis of length b along the y-direction. For the convenience of structural parameter optimization, the height of the nanorods is set equal to the short-axis length b (Fig. 1b).

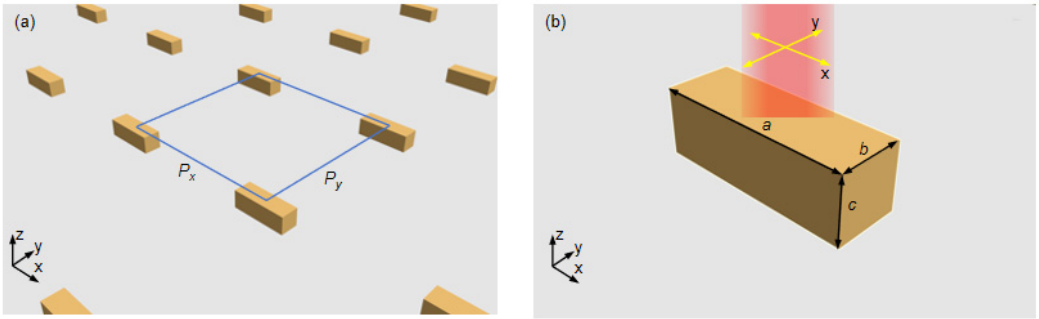


Fig 1. (a) Schematic illustration of the metallic nanoparticle array. (b) Geometry of a single nanoparticle

In addition, to investigate the polarization selectivity of the proposed structure, linearly polarized light along the x- and y-directions is employed to illuminate the nanoparticle array, and the corresponding optical responses are analyzed. The polarization directions of the incident light are indicated by the yellow arrows in Fig. 1b.

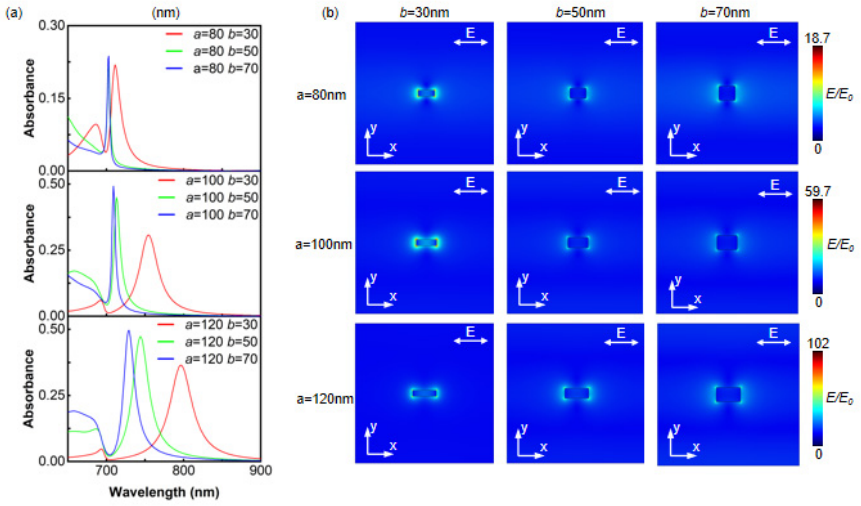


Fig 2. Under x-polarized incidence, (a) absorption spectra of the gold nanobar array for different structural parameters. (b) Electric-field distributions of the gold nanobar array for different structural parameters

To elucidate the influence of the structural parameters a and b on the excitation of surface lattice resonances under x-polarized incidence, a systematic parametric sweep was performed. The optical spectra were calculated for all combinations of a = 80, 100 and 120 nm and b = 30, 50 and 70 nm (Fig. 2a). The results show that increasing the long axis a leads to a pronounced redshift of the resonance, whereas increasing the short axis b results in a reduction of the quality factor. Based on the spectral characteristics in Fig. 2a, the geometry with a = 100 nm and b = 30 nm was selected, as it exhibits a relatively high Q factor of 146.

Subsequently, the electric-field enhancement was analyzed for different geometrical parameters. By comparing the near-field responses of the nine configurations under x-polarized excitation, the structure with a = 100 nm and b = 30 nm was found to support the strongest field enhancement, reaching $|E|/|E_0|$ = 59.7. This pronounced enhancement indicates a strong near-field confinement at the resonance, providing solid support for the superior optical performance of the optimized structure.

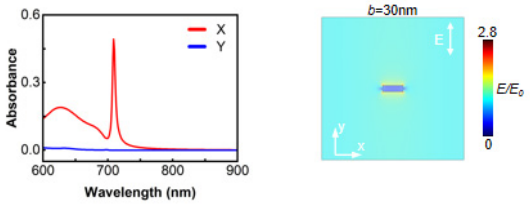


Fig 3. (a) Absorption spectra of the gold nanobar array under different incident light polarizations. (b) Simulated electric-field intensity distribution excited by y-polarized light for the gold nanobar array with structural parameters of a = 100 nm and b = 30 nm

After determining the optimized structural parameters, the optical response of the structure under y-polarized excitation was further investigated. As shown in Fig. 3a, the absorption spectra exhibit a pronounced polarization dependence. Under x-polarized incidence, the absorption reaches a maximum value of approximately 0.49, whereas it is nearly zero for y-

polarized light. This striking contrast demonstrates a strong polarization-selective response for the geometry with a = 100 nm and b = 30 nm.

Consistently, the electric-field enhancement under y-polarized excitation is only $|E|/|E_0|$ = 2.8 (Fig. 3b), indicating the absence of an efficient resonant mode. This value is in sharp contrast to the pronounced near-field enhancement observed for the same structural parameters under x-polarized excitation (Fig. 2b). Such a large disparity in both far-field absorption and near-field intensity provides a clear pathway for achieving polarization-selective surface lattice resonances.

3. Summary

Through a systematic parametric investigation, the structural geometry supporting optimal surface lattice resonance performance was identified. By tuning the nanobar dimensions, it was found that increasing the long axis induces a redshift of the resonance, whereas enlarging the short axis leads to a degradation of the quality factor. The configuration with a = 100 nm and b = 30 nm exhibits a high Q factor of 146, together with a pronounced near-field enhancement of $|E|/|E_0|$ = 59.7 under x-polarized excitation, indicating strong lattice-assisted plasmonic coupling and efficient electromagnetic confinement.

In contrast, the same structure shows a nearly vanishing absorption and a minimal field enhancement of $|E|/|E_0|$ = 2.8 under y-polarized illumination. The substantial disparity in both the far-field spectral response and near-field intensity confirms the realization of a highly polarization-selective surface lattice resonance. This pronounced anisotropic optical behavior originates from the selective excitation of the longitudinal plasmonic mode and its efficient coupling to the lattice diffraction orders.

Overall, the optimized structure simultaneously supports a high-Q resonance, strong electric-field enhancement, and a marked polarization-selective response. These results provide a robust physical framework for engineering polarization-sensitive plasmonic lattices and highlight their potential for applications in high-performance nanophotonic devices requiring spectral selectivity and enhanced light–matter interaction.

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