Tunable anisotropic plasmon response of monolayer GeSe nanoribbon arrays

Supporting Information

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S1. Intrinsic anisotropy of infinite monolayer GeSe

We calculate the absorption of infinite monolayer GeSe (without patterning), and the intrinsic anisotropy is descripted as below. The low absorption shows weak light-matter interaction due to its nanometer thickness.

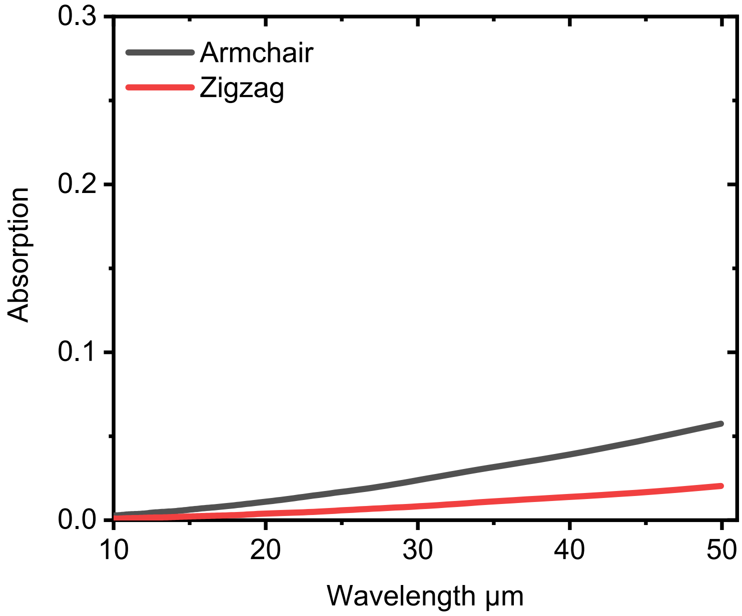

Figure S1. The intrinsic anisotropy of infinite monolayer GeSe

S2. Absorption spectra for nanoribbons along *y* direction

In Figure S2, we show the absorption spectra with different nanoribbon widths and refractive index of substrate for the case of nanoribbons along *y* direction. The period of nanoribbons is p=200nm and the substrate of thickness is set to be infinite. Compared with Figure 1(e, f) in the main text, the plasmonic behaves are similar to the case of nanoribbons along x direction but with lower resonant peaks.

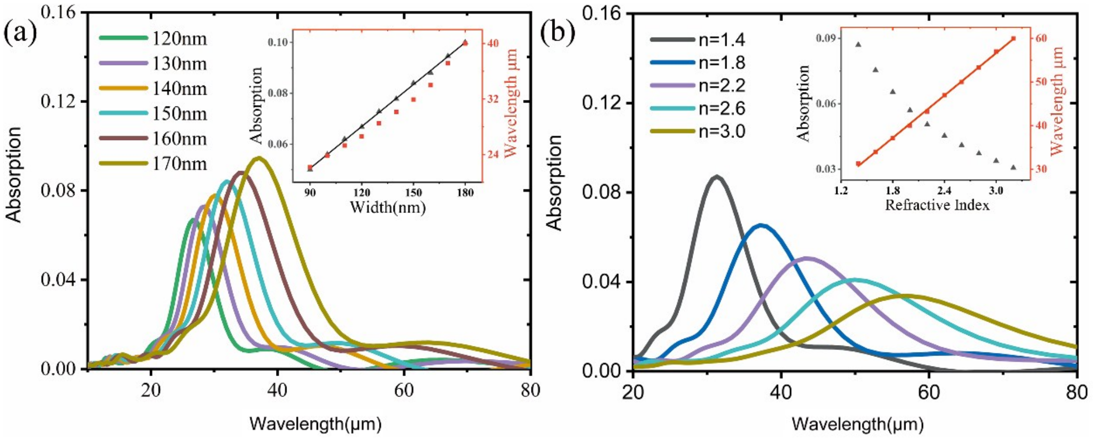

Figure S2. (a) Absorption spectra with various nanoribbon widths for nanoribbons patterned along y direction. The period of nanoribbon arrays is set as p=200nm and the substrate is given as PMMA with infinite thickness, whose refractive index is 1.45. The inset shows relation between the nanoribbon width and resonant peak and amplitude. (b) Absorption spectra with various refractive index of substrate for nanoribbons patterned along y direction, where period and width of nanoribbons are p=200nm and w=150nm. The thickness of substrate is infinite too. The inset shows relation between the refractive index of substrate and resonant peak and amplitude.

S3. FWHM and quality factor as a function of the substrate refractive index

In the case of infinite thickness of substrate, we extract the central wavelength λ_0 and the full width at half maxima (FWHM) by fitting the curves with Lorentzian function. The FWHM gets boarder and the quality factor decreases with the refractive index, indicating the plasmon is more lossy at longer wavelength. Besides, at the same condition, the quality factor along armchair direction is larger than the case of nanoribbons along zigzag direction. It is noted that the response is a mix of localized plasmon and FP cavity modes for the case where a metal reflector is set at the bottom of substrate, so it is hard to analyze the quality factor of plasmon modes alone.

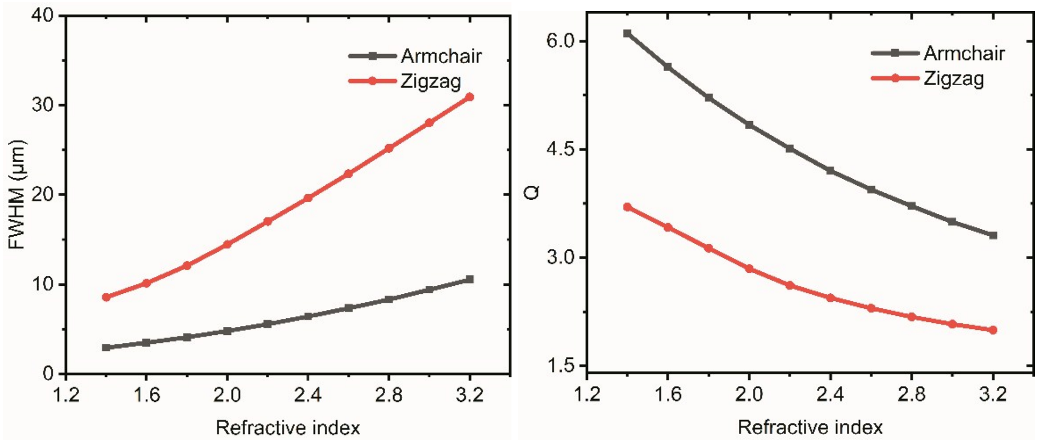

Figure S3. FWHM and quality factor with the refractive index of substrate in the case of infinite thickness of substrate.

S4. Electric field amplitude for various thicknesses of substrate

Total electric field amplitude ($|E|$) with substrate of various thicknesses for nanoribbons along both x and y direction are depicted in Figure S4. All results show plasmonic behaves in this period nanostructure, as electric field is highly localized at the two sides of nanoribbon. Combining Figure S4 with Figure 3 in the main text, we can see that the larger absorption peak corresponds to stronger local field amplitude, confirming the plasmon nature of the spectra.

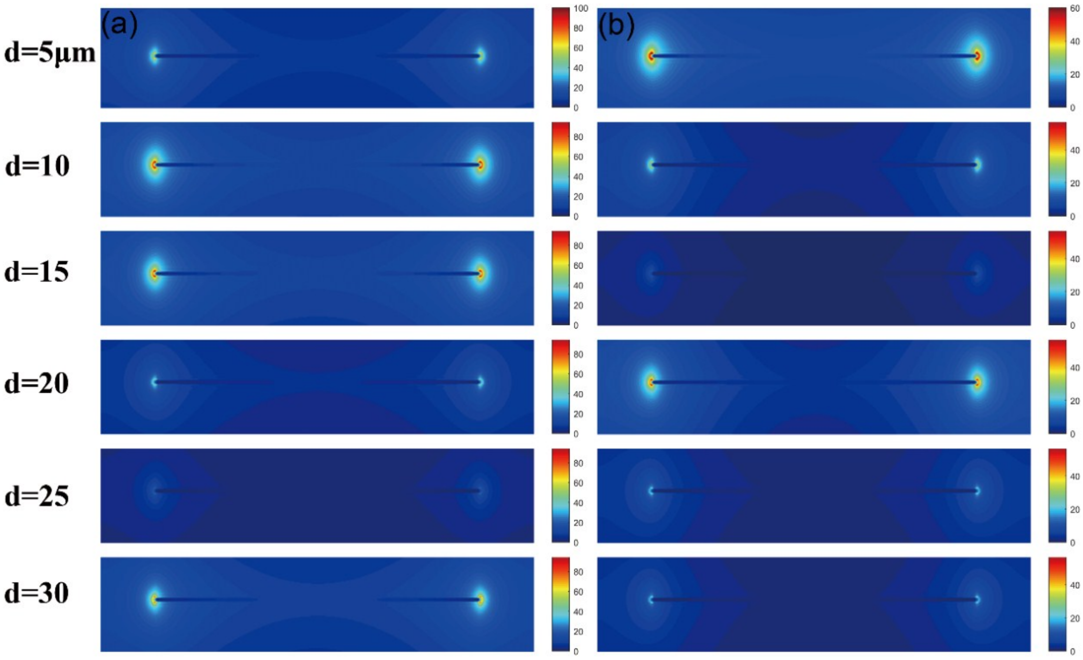

Figure S4. (a) Electric field amplitude at resonant wavelength (around 18.3μm) with various thicknesses of substrate for nanoribbons along x direction. The period and width of nanoribbons are p=200nm and w=150nm. The substrate is given as PMMA with a silver metal reflector at the bottom. (b) Electric field amplitude at resonant wavelength (around 32μm) with various thicknesses of substrate for nanoribbons along y direction. The parameters are set as the same as the case of nanoribbons along x direction.

S5. A Fabry-Perot-like model

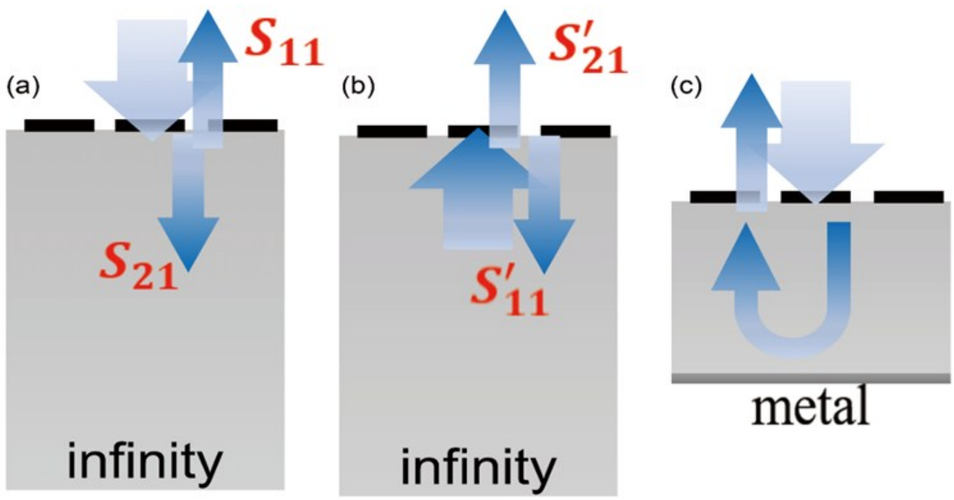

Figure S5. (a) Incident plane wave propagates from air to substrate with infinite thickness along negative z axis and interacts with the monolayer GeSe nanoribbons, where S_{11} is complex reflectance and S_{21} is complex transmittance. (b) Plane wave propagates from substrate to air along z axis with the same nanostructure, where $S_{11}^{'}$ is complex reflectance and $S_{21}^{'}$ is complex transmittance. (c) Illustration of the Fabry–Perot cavity with absorption formed between the GeSe nanoribbons and the metal reflector at the bottom side of substrate.

When the plane wave propagates perpendicularly from the air to the nanoribbon arrays supported on a transparent substrate, some are reflected and some are transmitted, and the other part is absorbed. Metal below the limited thickness substrate can reflect the transmitted from nanoribbons totally. Then the reflected light continues to interact with nanoribbons, some light will be reflected from nanoribbons and interact with the bottom metal reflector again, this process continues until the energy exhausts. The dielectric layer between the GeSe nanoribbons and metal reflector forms a Fabry–Perot cavity. To analyze the relation between absorption and thickness of substrate, we consider these three cases. Firstly, incident plane wave propagates from air to substrate with infinite thickness along negative z axis, S parameters can be gained via simulation, shown in Figure S5(a). The absorption satisfies $A = 1 - |S_{11}|^2 - |S_{21}|^2$, where S_{11} and S_{21} is complex numbers contained amplitude and phase information. Secondly, keeping the structure the same, incident plane wave propagates from substrate to air along z axis and gain S parameters in the same way, shown in Figure S5(b). Finally, combining first two steps, the light trapped in the dielectric goes back and forth until decays to zero. A Fabry–Perot cavity has formed and the reflection coefficient is expressed by

$$\begin{aligned} r &= S_{11} + \frac{S_{21}S'_{21}\exp(\mathrm{i}\,\delta)}{1 - S'_{11}\exp(\mathrm{i}\,\delta)} \\ \delta &= \frac{2\pi}{\lambda_0}2nd + \pi \end{aligned} \tag{1}$$

thus, the total absorption ($A = 1 - |r|^2$) is only related to phase difference which is from thickness of substrate. With this nanostructure whose parameters are set as *p*=200nm, *w*=150nm and n=1.45, the model calculation is quite consistent with the numerical simulation, shown as Figure S6.

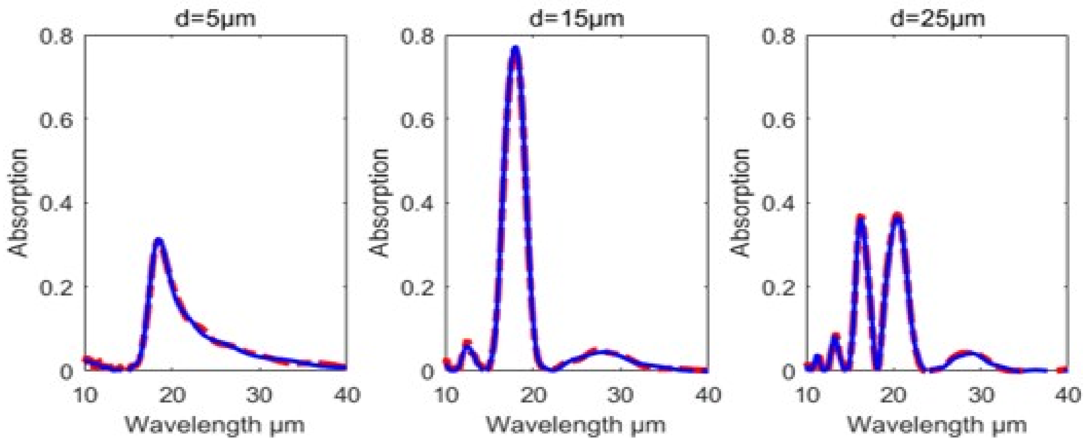

Figure S6. Comparing the model calculation (red dashed lines) with the numerical simulation (blue solid lines) at three different thicknesses (d=5μm, 15μm, 25μm) of substrate, they are obviously consistent with each other.

S6. The absorption and plasmon response with the thickness less than 5μm

Considering that the plasmon resonance occurs in the mid-infrared range, we take 5μm as the minimum thickness of the substrate as a reference value. For the case of nanoribbons patterned along armchair direction, we calculate the absorption curve and electric field with the thickness less than 5μm. (e.g. d=1μm, 500nm, 50nm, 10nm) The absorption curve and local field are shown in Figure S7 and Figure S8, respectively. As can be seen, the absorption trends to vanish with substrate thickness less than 500 nm and the local field profiles changes too. Thus, it is reasonable for our work to take 5μm as the minimum reference thickness of substrate in this work.

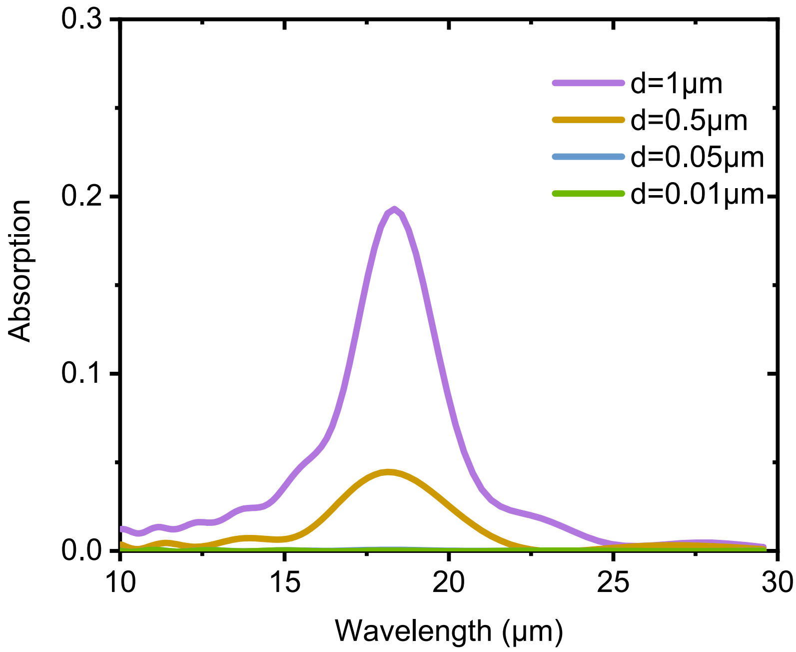

Figure S7. Absorption spectra with various thicknesses of substrate at the case of nanoribbons patterned along armchair direction. The blue and green curves, which are overlapped, perform zero absorption.

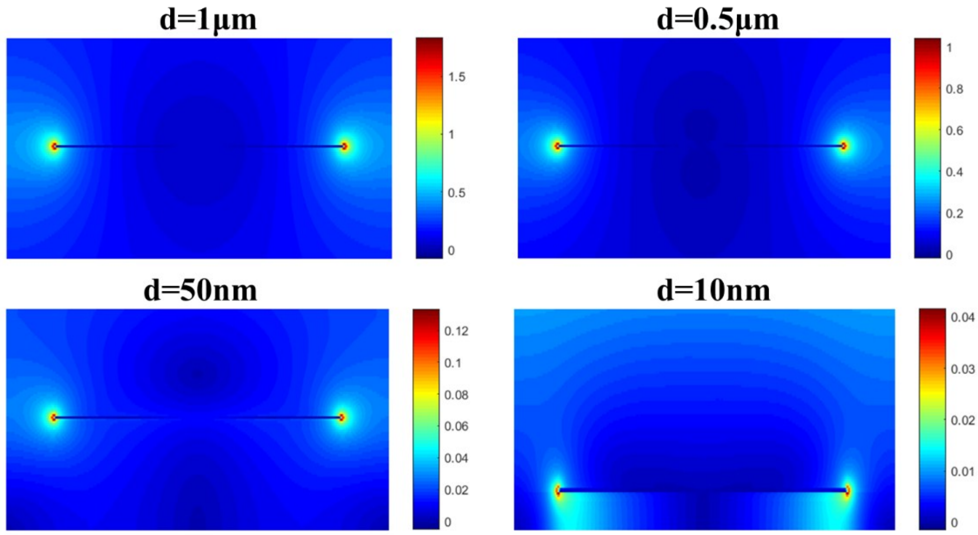

Figure S8. The profile of electric field of nanoribbon with the various thicknesses of substrate. (d=1μm, 500μm, 50nm and 10nm)