

Chiral molecular sensing based on spatially selective coupling between achiral metasurface and chiral molecules

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Abstract

Detection and identification of chiral molecules are important for pharmaceutical industry, clinical analysis, and food analysis. Here, chiral molecular sensing based on spatially selective coupling between achiral metasurface and chiral molecules is demonstrated. The designed achiral metasurface exhibits strong optical chirality and electric field with dissymmetric distribution, and chiral molecules are selectively placed over the area with large optical chirality to form the coupled metasurface-molecule system with circular dichroism (CD) response for chiral molecular sensing. The CD spectra of the metasurface coupled with pure D-alanine enantiomer, L-alanine enantiomer and their mixtures are examined. The linear relationship between the peak CD value and the enantiomeric excess is demonstrated for the detection and identification of pure enantiomers and their mixtures. Furthermore, the CD response of the coupled system shows potential for the sensing of molar concentration of chiral molecules. Moreover, the effect of spatial location of molecules on the CD response is analyzed to show potential for position sensing of chiral molecules. These results of chiral molecular sensing with achiral metasurface offer new opportunities for advancing biomolecular sensing applications.

Keywords: optical chirality, metasurface, chiral molecules

1. Introduction

Chirality plays a vital role in the functionality of chiral biomolecules such as proteins, amino acids, and carbohydrates [1]. Chiral molecules possess chemical structures which cannot be superimposed on their mirror images, and they usually exist in two enantiomer forms. Although enantiomers of the same compound share similar physical and chemical properties, they may differ in biological properties, and sometimes

that leads to different toxicities. Therefore, identifying the handedness of pure enantiomers, enantiomer composition of mixtures and molar concentration of diluted enantiomers are all of importance in food industry [2], medical diagnostics [3], and drug development [4]. Meanwhile, the spatial location sensing of molecules is also important, as it provides valuable information on the dynamics of molecules, which is essential for elucidating biological processes [5].

The conventional circular dichroism (CD) spectroscopy is usually utilized for chiral molecule sensing. The sensitivity of molecule detection through CD spectroscopy is limited because of the scale mismatch between light wavelength

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and molecular size. Chiral metasurfaces with superchiral near-fields have been extensively exploited to enhance chiral light-matter interaction, and thus, enhance the detection sensitivity of chiral enantiomers [6–8]. On the other hand, achiral metasurfaces with mirror symmetry can also provide dissymmetric near-field optical chirality distribution under circular polarizations. Particularly, the spatial location of the chiral radiative local density of states hot-spots varies with different circular polarizations, which renders the manipulation of chiral photon emission in achiral metasurface [9]. Furthermore, achiral metasurfaces with dissymmetric near-field distributions can also be utilized for identification of chiral enantiomers and the sensing of chiral molecule locations.

In this work, chiral molecular sensing based on spatially selective coupling between achiral metasurface and chiral molecules is demonstrated. The V-shaped achiral metasurface is designed to exhibit strong optical chirality and electric field with dissymmetric distribution under circular polarizations. Chiral molecules are selectively placed over the area with large optical chirality in the metasurface, and CD response of the coupled metasurface-molecule system is analyzed and exploited for the detection of chiral molecules. It is shown that the CD spectrum is closely correlated with the spectrum of dissymmetric factor of optical chirality g_c . The contributions of energy dissipation terms associated with electric field and optical chirality to the CD spectrum are also revealed. The CD spectra of the metasurface coupled with pure D-alanine enantiomer, L-alanine enantiomer and their mixtures are examined to identify the enantiomer handedness, where the peak CD value follows a linear relation with the enantiomeric excess. Furthermore, it is also shown that the CD value is linearly correlated with the molar concentration of chiral molecules. Moreover, the effect of spatial location of molecules on the CD response is analyzed to show potential for position sensing of chiral molecules. These results demonstrate the capability of chiral molecule sensing with achiral metasurfaces, which provides new opportunities for advancing biomolecular sensing applications in pharmacology, medical diagnostics, and food industry.

2. Results and discussion

Figure 1(a) shows the schematic of the three-layer metal-dielectric-metal structure with the V-shaped resonator in the top gold layer with thickness of 65 nm. The middle alumina (Al_2O_3) spacer has the thickness of 250 nm, and the bottom gold mirror is 200 nm thick. The metasurface unit cell has the periods of $p_x = 5943$ nm and $p_y = 2932$ nm. The V-shaped resonator is composed of one horizontal slot with the length of $l_1 = 2509$ nm and the width of $w_1 = 1102$ nm, and two tilted slots with $l_2 = 2378$ nm, $w_2 = 551$ nm, and the tilted angle $\theta = 50^\circ$. COMSOL Multiphysics software is used to simulate the optical response of the designed V-shaped resonator under LCP and RCP excitation, where the permittivity of alumina is taken from the experimental data

[10] and the permittivity of gold is taken from the Drude model [11]. The circularly polarized light is normally incident on the metasurface from the top. The periodic boundary conditions are imposed along both x and y directions of the metasurface unit cell, while the open boundary conditions are applied along the z direction. The simulated reflection spectra for the metasurface under circular polarization excitation are depicted in figure 1(b). The two reflection dips correspond to the plasmonic resonances at 6106 nm under x -polarized light and 6426 nm under y -polarized light, respectively. Under circular polarization excitation, the LCP or RCP resonance mode is formed as a result of the simultaneous excitation and interference of the x -polarized and y -polarized resonance modes with the relative phase delay of $\pi/2$. It shows that the overlapped region of the x -polarized and y -polarized resonances is centered around 6262 nm in the reflection spectra. The reflection spectra under LCP and RCP incident light are identical, and there is no CD response because of the mirror symmetry of V-shaped resonator. The chiral property of electromagnetic field is described by optical chirality $C = -\frac{\varepsilon_0\omega}{2}\text{Im}(\mathbf{E}^* \cdot \mathbf{B})$ [12, 13], where ε_0 is the permittivity of the free space, ω is angular frequency, and \mathbf{E} and \mathbf{B} are the complex electric and magnetic fields, respectively. The optical chirality and electric field distributions of the bare metasurface under RCP excitation are shown in figure 1(c) at the wavelength of 6262 nm for the plasmonic mode in the middle of the overlapped region of the x -polarized and y -polarized resonances. The optical chirality C is normalized by C_0 , which is the optical chirality of incident circularly polarized light in free space. The dissymmetric distributions of both optical chirality and electric field are observed with strong confinement on the right side of the V-shaped structure for the plasmonic mode induced by the superposition of x -polarized and y -polarized resonance modes with a phase difference of $\pi/2$. To study the chiral molecular sensing based on the V-shaped metasurface, an 80 nm-thick D-alanine enantiomer layer is coated on the right side of the metasurface unit cell as shown in figure 1(a), covering the areas with strong optical chirality and electric field. To model the electromagnetic behavior of chiral media, the constitutive equations in COMSOL Multiphysics software are modified as $\mathbf{D} = \varepsilon_0\varepsilon\mathbf{E} - i\frac{\kappa}{c}\mathbf{H}$, $\mathbf{B} = \mu_0\mu\mathbf{H} + i\frac{\kappa}{c}\mathbf{E}$, where ε is permittivity, μ is permeability with $\mu = 1$ for nonmagnetic materials and κ is Pasteur parameter representing the strength of chirality [14, 15]. The optical properties of the alanine enantiomers are modeled as Lorentz oscillators for the permittivity $\varepsilon = \varepsilon_0 - \gamma\left(\frac{1}{\hbar\omega - \hbar\omega_0 + i\Gamma}\right)$ and the Pasteur parameter $\kappa = \beta\left(\frac{1}{\hbar\omega - \hbar\omega_0 + i\Gamma}\right)$, where the background permittivity $\varepsilon_0 = 1$, coefficients $\gamma = 1.2483 \times 10^{-3}$ eV, $\beta = 4.6812 \times 10^{-4}$ eV, damping constant $\Gamma = 1.56 \times 10^{-3}$ eV, and resonance frequency multiplied by the reduced Planck's constant $\hbar\omega_0 = 1.98 \times 10^{-1}$ eV [16]. The plasmonic mode of the metasurface is designed to match with the vibrational mode of alanine molecule at 6262 nm. Figure 1(d) shows the simulated reflection spectra of V-shaped metasurface with selectively coated alanine layer under LCP and RCP incidence. Compared to the bare metasurface in figure 1(b), a reflection

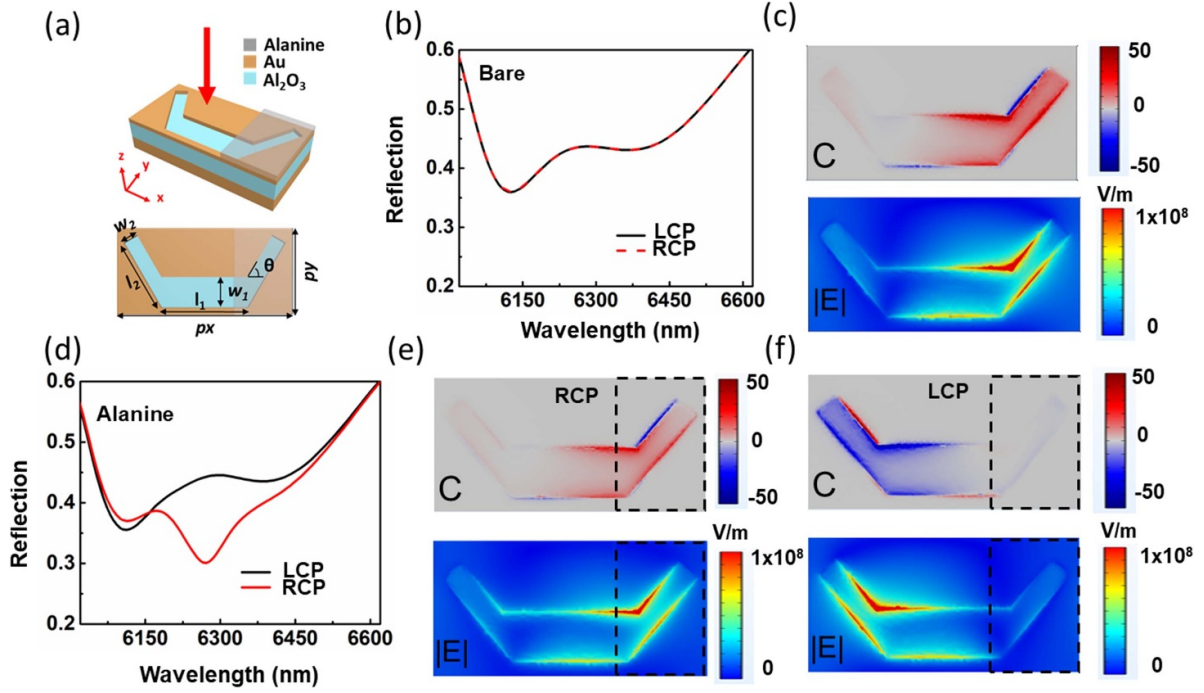


Figure 1. (a) Schematic of the unit cell of the designed V-shaped metasurface coated with alanine molecule layer with the size of $1/3 px$ by py . (b) Reflection spectra of bare metasurface under LCP and RCP incidence. (c) The distributions of optical chirality C and electric field $|E|$ of bare metasurface under RCP incidence at the plane 5 nm above top Au layer. (d) Reflection spectra of the metasurface coated with alanine molecule layer under LCP and RCP incidence. (e) and (f) The distributions of optical chirality C and electric field $|E|$ of the metasurface coated with alanine molecule layer under RCP and LCP incidence, respectively. The black dashed boxes indicate the location of alanine molecule layer.

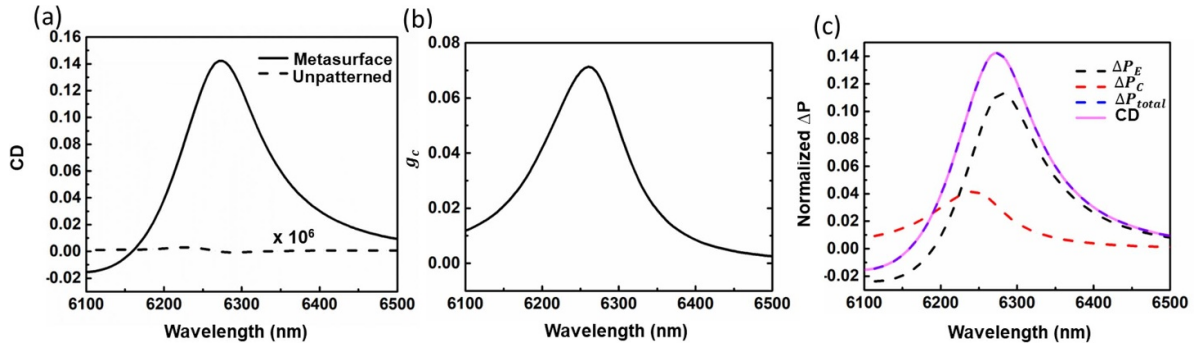


Figure 2. (a) The CD spectrum of the metasurface coupled with the alanine molecule layer (solid curve), along with a reference CD spectrum for the same molecule layer on the unpatterned three-layer structure (dashed curve). (b) The g_c spectrum of the coupled metasurface-molecule system. (c) The spectra of ΔP_E , ΔP_C and ΔP_{total} for the coupled system.

dip is observed around 6262 nm under RCP incidence while the reflection spectrum under LCP incidence is almost the same. The distinct chiroptical response is due to spatially selective coupling between the plasmonic mode and the vibrational mode of alanine molecules. It is noted that the chiroptical response of the coupled metasurface-molecule system can be induced for both chiral molecules and achiral molecules with strong infrared vibrational modes. Figures 1(e) and (f) show the distributions of optical chirality C and electric field $|E|$ of the metasurface coupled with the alanine molecule layer under RCP and LCP excitation, respectively. It is observed that the optical chirality and electric field in the selectively coated molecule layer are strong under RCP incidence, whereas

they are very weak in the molecule layer under LCP incidence. The strong light-matter interaction between the alanine molecules and the dissymmetric optical near-fields leads to the large chiroptical response in metasurface under circular polarizations.

Figure 2(a) plots the spectrum of CD in reflection, defined as $CD = R_{LCP} - R_{RCP}$, for the V-shaped metasurface coupled with the alanine molecule layer, with the maximum value of 0.14 at the wavelength of 6262 nm. For comparison, the CD spectrum for the same alanine molecule layer on unpatterned Au- Al_2O_3 -Au three-layer structure without V-shaped resonator is also plotted as the dashed curve in figure 2(a), showing extremely small CD values. It is observed that giant

CD enhancement on the order of 10^7 is achieved for the molecules coupled with V-shaped metasurface due to the enhanced chiral light-matter interaction between the metasurface resonance mode with dissymmetric near-field distribution and chiral molecules. It is noted that for the chiral molecule induced CD, which is defined by subtracting the CD of the structure coupled with the racemate mixture of $\kappa = 0$ from the overall CD of the chiral molecule-structure coupled system, an enhancement on the order of 10^6 is still obtained for the metasurface case compared to the unpatterned three-layer structure case. The dissymmetric factor of the optical chirality $g_c = \frac{|C_{\text{int,LCP}}| - |C_{\text{int,RCP}}|}{|C_{\text{int,LCP}}| + |C_{\text{int,RCP}}|}$ is used to describe the difference of optical chirality under LCP and RCP incidence, where $C_{\text{int,LCP}}$ ($C_{\text{int,RCP}}$) is the integrated optical chirality over the whole simulation domain under LCP (RCP) incidence. Figure 2(b) shows the g_c spectrum of metasurface coupled with alanine molecule layer with a peak around 6262 nm, exhibiting a similar spectral shape to the CD spectrum in figure 2(a).

To further understand the origin of the chiroptical response of metasurface coupled with chiral molecules, the electromagnetic energy dissipation in the coupled system can be decomposed into the two terms of P_E related to electric fields and P_C related to optical chirality [17, 18]:

$$P_E = \omega/2 \iiint \text{Im}(\varepsilon) |\mathbf{E}|^2 dV \quad (1)$$

$$P_C = \omega \iiint \text{Im}(\kappa) \text{Im}(\mathbf{E} \cdot \mathbf{H}^*) dV \quad (2)$$

where ε and κ are permittivity and Pasteur parameter of materials within the integration volume. Figure 2(c) displays the spectra of ΔP_E and ΔP_C , with $\Delta P_{E(C)} = P_{E(C),\text{RCP}} - P_{E(C),\text{LCP}}$ which is normalized to the input power of circularly polarized light. The chiroptical responses of energy dissipation terms P_E and P_C reveal the underlying mechanisms of the spatially selective light-matter interaction with the dissymmetric electric field distribution, and the coupling between chiral molecules and the optical chirality of the near-fields, respectively. The chiroptical response of total energy dissipation $\Delta P_{\text{total}} = \Delta P_E + \Delta P_C$ is further shown in figure 2(c). As the transmission in the Au-Al₂O₃-Au three-layer structure is negligible due to the bottom gold mirror layer, the reflection is equal to unity minus the absorption of the coupled system, so that the chiroptical response of total energy dissipation is consistent with the far-field spectrum of the CD in reflection.

To demonstrate the capability of chiral molecule sensing with the designed metasurface, figure 3(a) depicts the CD spectra for pure D-alanine enantiomer with positive κ , L-alanine enantiomers with negative κ , and a racemate of both enantiomers with $\kappa = 0$, where different CD peak values around 6262 nm are observed. It is shown that the overall CD value of the coupled metasurface-molecule system is 0.143 for chiral molecules with $+\kappa$, 0.107 for chiral molecules with $-\kappa$, and 0.126 for the racemate mixture with $\kappa = 0$, respectively. Figure 3(b) further plots the chiral molecule induced CD

spectra which are obtained by subtracting the CD spectra of the racemate mixture from the overall CD spectra. It shows that a positive peak value of 0.017 is obtained for pure D-alanine enantiomer with $+\kappa$, whereas a negative peak value of -0.021 is obtained for pure L-alanine enantiomers with $-\kappa$. Therefore, the sign of the chiral molecule induced CD value can be utilized for identifying the handedness of enantiomer. For mixtures of chiral molecules with different handedness, enantiomeric excess is defined as $\xi = (n_D - n_L) / (n_D + n_L)$ [19, 20], where n_D and n_L are the moles of right- and left-handed enantiomers, respectively. κ is correlated with ξ via $\kappa = A\xi$ [21], where $\xi = 1$ for D-alanine enantiomer, and $\xi = -1$ for L-alanine enantiomer, and A is a coefficient specific to the molecular species corresponding to the Pasteur parameter of pure D-alanine enantiomer. Figure 3(c) shows the peak CD value as a function of enantiomeric excess ξ , where a linear relationship between CD value and ξ is observed. The sensitivity for the detection of chiral molecule mixtures with enantiomeric excess ξ is evaluated by the linear slope $S_\xi = \Delta CD / \Delta \xi$, and the sensitivity value is 0.018 for the coupled metasurface-molecule system. Figure 3(d) plots the peak value of chiral molecule induced CD as a function of enantiomeric excess ξ . It shows that the peak value linearly changes from -0.021 to 0.017 as ξ varies from -1 to 1 , which can be used to characterize the mixtures of chiral molecules with different handedness. For chiral molecules with different molar concentration ζ , κ and ε are correlated with ζ via $\kappa = B\zeta$ and $\varepsilon = \varepsilon_0 + C\zeta$ [21], where ζ varies from 0 to 1, B and C are coefficients specific to the molecular species. The values of B and C are determined by the Pasteur parameter and the permittivity of pure and undiluted D-alanine enantiomer. Figure 3(e) shows the CD spectra for the diluted D-alanine enantiomer with different molar concentration ζ , where the peak CD value gets larger with the increasing molar concentration. In figure 3(f), a linear relationship is presented between the peak CD value and ζ . The detection sensitivity for chiral molecule molar concentration is represented by the linear slope $S_\zeta = \Delta CD / \Delta \zeta$, which has the value of 0.142 for the coupled system. The detection sensitivity for molar concentration is contributed by the change of ΔP_E related to the permittivity ε and ΔP_C associated with the Pasteur parameter κ as the molar concentration ζ varies.

To further study the effect of spatial location of molecules on the CD response in the coupled system, a small patch of D-alanine molecules with the size of $0.1px$ by py is moved from left to right across the metasurface unit cell along x direction, as illustrated in the inset of figure 4(a). As molecular location changes from $-0.31px$ to $0.31px$ in the step of $0.125px$, the coupling between the metasurface mode and the chiral molecules varies due to the dissymmetric near-field distributions, which leads to different CD responses in figure 4(a). The CD values change from negative to positive as the D-alanine molecule patch moves from left to right of the unit cell. Figure 4(b) shows that there is a linear relationship between the peak CD value and the molecular location, which can be used for the sensing of chiral molecule locations.

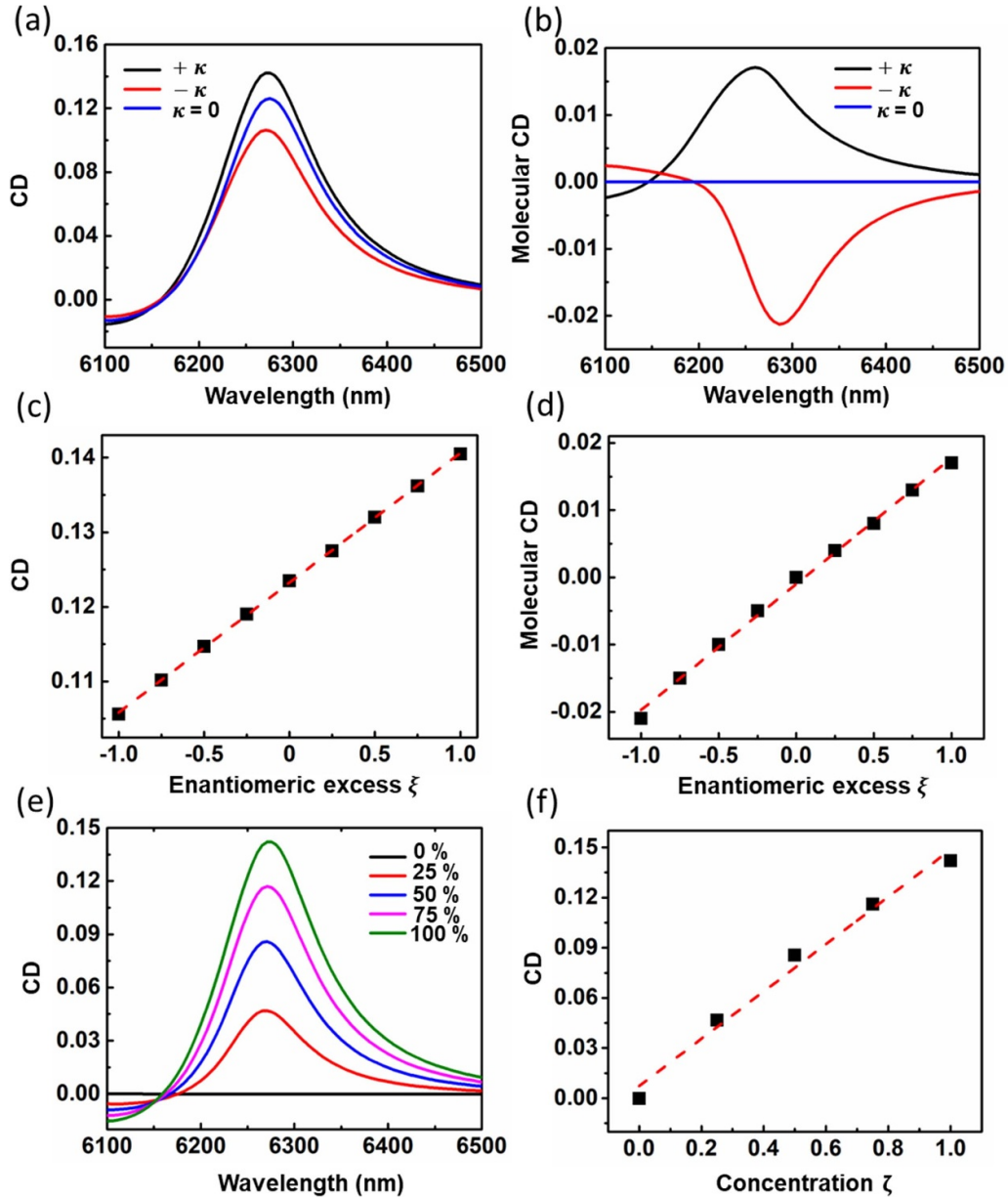


Figure 3. (a) CD spectra for pure D-alanine enantiomer with $+\kappa$, L-alanine enantiomer with $-\kappa$, and a racemate with $\kappa = 0$. (b) Chiral molecule induced CD spectra for molecules with $+\kappa$, $-\kappa$, and $\kappa = 0$. (c) Peak CD value as a function of enantiomeric excess ξ . The linear fitting is shown as the red dashed line. (d) Chiral molecule induced CD peak value as a function of ξ . (e) CD spectra for the diluted D-alanine enantiomer with different molar concentrations. (f) Peak CD value as a function of molar concentration ζ . The linear fitting is shown as the red dashed line.

3. Conclusion

We have demonstrated chiral molecular sensing based on spatially selective light-matter interaction between achiral metasurface and chiral molecules. Chiral molecules are selectively placed over the area with large optical chirality in the designed achiral metasurface, and CD response of the coupled metasurface-molecule system is studied for chiral molecular sensing. It is found that the CD spectrum is closely correlated with the spectrum of dissymmetric factor of optical chirality. The contributions of energy dissipation terms associated

with electric field and optical chirality to the CD spectrum are also revealed. The demonstrated linear relationship between the peak CD value and the enantiomeric excess can be utilized for the detection and identification of pure enantiomers and their mixtures. Furthermore, the CD response of the coupled metasurface-molecule system shows potential for the sensing of molar concentration and spatial location of chiral molecules. These results of chiral molecular sensing with achiral metasurfaces offer new opportunities for advancing biomolecular sensing applications in pharmacology, medical diagnostics, and food industry.

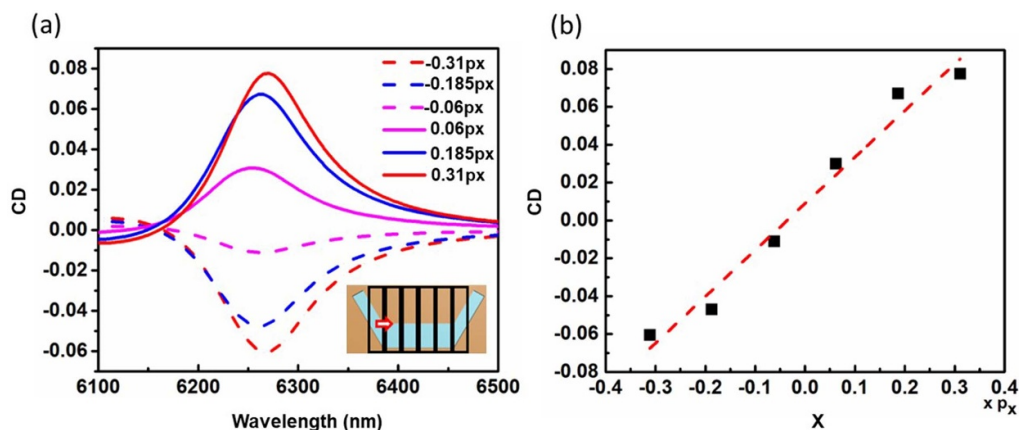


Figure 4. (a) CD spectra for a D-alanine molecule patch at different locations. The inset illustrates the molecule patch moves from left to right across the metasurface unit cell along x direction. (b) Peak CD value as a function of molecular location with a linear fitting in red dashed line.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors have no conflicts of interest to disclose.

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