Near-field radiative heat transfer of nanoparticles mediated by moving metasurfaces

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The bidirectional symmetry of electromagnetic wave propagation in optomechanical systems can be effectively disrupted, leading to the achievement of novel devices for unconventional photon transport. This article investigates the near-field radiative heat transfer (NFRHT) between nanoparticles based on moving metasurfaces. The modeling is based on isotropic silicon carbide (SiC) particles and a graphene metasurface and the NFRHT is analyzed using the Green's function and conductivity approximation. This study reveals that when the velocity of the metasurface is sufficiently high, the radiative heat flux in the near field becomes highly nonreciprocal. By selecting appropriate chemical potentials and particle arrangement positions, the thermal conductivity coefficient can be enhanced or suppressed by up to five orders of magnitude. The required threshold velocity for the thermal diode we constructed is also significantly reduced under specific chemical potentials. These findings provide theoretical support for scenarios involving high-speed relative motion in the near field.

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I. INTRODUCTION

When the distance between two objects is reduced to the micro/nanometer scale, their radiative heat transfer (RHT) is significantly enhanced due to the tunneling effect of the evanescent wave and the excitation of surface plasmon polaritons (SPPs) or phonon polaritons (SPhPs), resulting in near-field radiative heat transfer (NFRHT) [1-9]. NFRHT has found wide applications in the fields of nanooptics, nanomaterials, and thermology since the experimental confirmation of SPPs by Ebbesen *et al.* [10,11]. Modulating the amplitude and phase of the electromagnetic waves in the near field to achieve optical nonreciprocity has garnered significant interest [12-14]. Additionally, with the development of moving medium electrodynamics, it has been shown theoretically and experimentally that the bidirectional symmetry of electromagnetic wave propagation in optomechanical systems can be effectively broken, leading to novel devices for unconventional photon transport [15-22]. Under strong excitation of moving structures, various exciting phenomena such as optical isolation [23,24], enhanced wave instability [25,26], and quantum friction [27-33] can occur.

Metasurfaces, as synthetic approximate two-dimensional (2D) structures of ultrathin materials, possess remarkable properties such as negative refraction, hyperbolic dispersion, and the ability to modulate evanescent waves [34–39]. They are widely used for nonreciprocal optical control in the near field. Previous research on nonreciprocal transmission controlled by metasurfaces has mainly focused on modifying the metasurface structure and the distribution of localized electromagnetic fields [40–45]. While periodic metasurfaces exhibit stronger nonreciprocity compared to perfect metasurfaces, the enforced modulation of conductivity leads to energy

losses, thereby limiting the maximum energy transmission [46]. Although the use of a magnetic bias can achieve the near-field nonreciprocal optical properties of metasurfaces, this method requires magnetic-optical materials that are difficult to integrate and miniaturize in industry. Moreover, in scenarios involving near field controlled by moving structures, the periodic complex structures or special electromagnetic field distributions required under static conditions may be challenging to maintain due to mechanical motion.

Recently, the analysis of impedance surfaces demonstrates that these surfaces exhibit unidirectional hyperbolic propagation characteristics when in motion [47]. The concept of utilizing mechanical motion to induce SPPs for unidirectional hyperbolic transmission without modulating the metasurface is highly attractive. In this work, we investigate the influence of moving metasurfaces on NFRHT in greater detail. We utilize a universally isotropic metasurface and introduce the boundary conditions provided by the moving metasurface through the approximation of conductivity and the reflected vector Green's function. Specifically, we select graphene as the metasurface in this study due to its high mechanical strength and exceptional electron mobility. It is worth emphasizing that the motion considered in this paper is constant in order to exclude the influence of quantum friction.

We observe that when the speed exceeds a certain threshold, NFRHT significantly responds to the motion of the surface, resulting in several orders of magnitude of enhancement or inhibition. Furthermore, this change exhibits a strong dependence on chemical potential. By analyzing the wave vector space distribution and SPPs' transmission characteristics based on the Green's function, we investigate the underlying mechanisms behind this effect. In addition to the conversion of mechanical energy input into optical energy, the coupling between SPPs and propagating waves plays a crucial role in NFRHT. These findings provide theoretical

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FIG. 1. Moving metasurface controlling nonreciprocal transmission of near-field radiation of nanoparticles.

support for the integration of moving media with complex surfaces, enabling further advances in this field.

This paper is organized as follows. Section II describes the geometric structure, provides the effective conductivity tensor of the moving metasurface, and presents the expression for the heat flux between two nanoparticles based on the Green's function. Section III discusses the significant differences in the NFRHT speed response under different chemical potentials, elucidating the physical mechanism behind this phenomenon. The Green's function in wave vector space and the energy density distribution in space are also explored. Section IV investigates the effects of particle orientation, particle-particle distance, and particle-surface distance. Finally, in Sec. V, we summarize our findings.

II. THEORETICAL ASPECTS

Figure 1 illustrates our system model, which is situated in a vacuum environment. A graphene metasurface is employed to modify the interaction between nanoparticles. The infinitely large metasurface moves along the x axis at a constant speed v, while two nanoparticles are positioned above the surface at a distance of d from each other and a height of h. We have selected isotropic silicon carbide (SiC) nanoparticles with a particle radius of R = 5 nm due to their excellent optical and thermal conductivity properties. Particle 1 serves as the heat source of the system with a temperature T_1 , while particle 2 acts as the cold source with a temperature T_2 (where $T_1 =$ $T_2 + \Delta T$). In this model, the electromagnetic waves emitted by particle 1 excite SPPs on the metasurface, which can propagate over long distances. When the SPPs reach the position below particle 2, evanescent waves generated by photon tunneling are captured by particle 2, resulting in energy transfer. Consequently, the RHT between particles can be divided into two parts: direct radiative heat transfer occurring in vacuum and indirect thermal energy transfer relying on the metasurface. Additionally, the mechanical energy input by the moving metasurface is converted into thermal energy and participates in the heat exchange between the particles. The temperature of the metasurface, denoted as T_M (where $T_M = T_2$), is assumed to exclude the influence of the metasurface temperature itself.

First, it is worth noting that our calculations are based on a rest frame *S* in which the particles remain stationary, while

the metasurface continues to move in the *x*-axis direction. Within the framework of fluctuation-dissipation electrodynamics, the moving metasurface distorts the electromagnetic field in frame *S*. Directly introducing velocity terms would complicate the analysis of the entire field. Therefore, we consider using equivalent boundary conditions combined with Green's functions to describe the electromagnetic field under velocity changes. In the initial calculation, we discuss the case where the particles are arranged along the *x* axis, with the thermal source particle upstream of the velocity. By utilizing the ultrathin thickness characteristic of the metasurface, which is smaller than the incident wavelength, combined with Lorentz transformations, we can obtain the boundary conditions as [47,48]

$$\hat{\mathbf{z}} \times (\mathbf{H}_2 - \mathbf{H}_1) = \underline{\tilde{\boldsymbol{\varphi}}} \mathbf{E}_{\parallel} + \gamma \sigma \mu_0 (\mathbf{v} \times \mathbf{H}_z) -\varepsilon_0 \gamma \mathbf{v} \sum_i E_{iz}, \qquad (1)$$

where $\beta = v/c$, $\gamma = (1 - \beta^2)^{-1/2}$, $\mathbf{v} = v\hat{\mathbf{x}}$, and i = 1, 2 refer to below and above the surface, respectively. The symbol \parallel denotes the field components parallel to the metasurface. $\underline{\tilde{\boldsymbol{\sigma}}} = \sigma(\gamma \ 0; \ 0 \ \gamma^{-1})$ represents the velocity-induced conductivity tensor.

The right-hand side of Eq. (1) can be expressed in terms of the following concepts: the first term represents the anisotropic conduction current induced by motion, the second term represents magnetoelectric coupling, and the third term represents the current generated by surface charge motion induced by mechanical motion. By deriving the impedance surface waveguide theory, simplified boundary conditions such as $\hat{\mathbf{z}} \times (\mathbf{H}_2 - \mathbf{H}_1) = \underline{\boldsymbol{\sigma}}^{\text{eff}} \mathbf{E}_{\parallel}$ are obtained. The effective conductivity tensor is given as

$$\underline{\underline{\sigma}}_{\underline{\underline{\sigma}}}^{\text{eff}} = \begin{bmatrix} \sigma \gamma^{-1} - 2\varepsilon_0 k_x v/k_z & -2\varepsilon_0 k_y v/k_z \\ \sigma \gamma \beta k_y/k_0 & \sigma \gamma (1 - \beta k_x/k_0) \end{bmatrix}.$$
(2)

The effective conductivity tensor is evidently anisotropic. Through the transformation, the problem of stationary particles and a moving surface is transformed into a problem of stationary particles and an isotropic surface. Moreover, since the nanoparticles are linear, nonmagnetic, and isotropic, with dimensions much smaller than the thermal wavelength $\lambda_T = c\hbar/(k_BT)$, they can be modeled as individual electric dipoles [49]. Below, we provide the formula for calculating the interparticle radiative heat transfer coefficient [50,51]

$$H = 2\hbar \int_0^{+\infty} \frac{d\omega}{\pi} \omega k_0^4 n'(\omega, T) \chi(\omega)^2 \text{Tr}(\mathcal{GG}^{\dagger}), \qquad (3)$$

where k_0 is the wave vector in vacuum, $n'(\omega, T)$ is the derivative of the Bose-Einstein $n(\omega, T) = (e^{\hbar\omega/k_BT} - 1)^{-1}$ with respect to temperature *T*, and $\chi(\omega) = \text{Im}[\alpha(\omega)] - k_0^3 |\alpha(\omega)|^2 / 6\pi$ represents the modified electric frequency-dependent polarizability. Since the skin depth δ of the metasurface is much larger than the radius of the nanoparticles, $\alpha(\omega)$ can be expressed in the Clausius-Mossoti form [52] as $\alpha(\omega) = 4\pi R^3 [\varepsilon(\omega) - 1] / [\varepsilon(\omega) - 2]$, where $\varepsilon(\omega)$ represents the dielectric function of the nanoparticles.

In Eq. (3), the dyadic Green's tensor \mathcal{G} incorporates the metasurface velocity into the entire system and its expression is given by

$$\mathcal{G} = \mathbb{M}^{-1}\mathbb{G},\tag{4}$$

where $\mathbb{M} = \mathbb{I} - k_0^4 \alpha^2 \mathbb{G} \mathbb{G}^T$ takes into account multiple absorption and reflection between particles, as well as between particles and the metasurface. Here, \mathbb{I} represents the identity matrix and \mathbb{G} represents the Green's function of the particle-surface system, which can be divided into two parts

$$\mathbb{G} = \mathbb{G}^0 + \mathbb{G}^{sc}.$$
 (5)

 \mathbb{G}^0 represents the direct reception component between two nanoparticles, which is unaffected by the moving metasurface and can be written as

$$\mathbb{G}_0 = \frac{e^{ik_0d}}{4\pi k_0^2 d^3} \begin{pmatrix} a & 0 & 0\\ 0 & b & 0\\ 0 & 0 & b \end{pmatrix},$$
(6)

where $a = 2 - 2ik_0d$ and $b = k_0^2d^2 + ik_0d - 1$.

 \mathbb{G}^{sc} represents the portion of interaction between two nanoparticles through the metasurface. This term should be zero when the particles are far away from the surface and can be written as [40,53–55]

$$\mathbb{G}^{sc} = \iint \frac{dk_{\parallel}}{8\pi^2} e^{i\mathbf{k}_{\parallel}(\mathbf{r}_2 - \mathbf{r}_1)} i e^{2ik_z h} \sum_{\alpha,\beta} \frac{r_{\alpha\beta}}{k_z} \boldsymbol{\xi}_{\alpha}^+ \otimes \boldsymbol{\xi}_{\beta}^-, \qquad (7)$$

where $\mathbf{R}_i = \mathbf{r}_i + h_i \hat{z}$ (i = 1, 2) denotes the coordinates of the nanoparticles and k_{\parallel} satisfies the free-space dispersion $k_0^2 = k_{\parallel}^2 + k_z^2$. Equation (7) takes into account the contributions related to *s* and *p* polarized waves ($\alpha, \beta = s, p$), with $\boldsymbol{\xi}_s^{\pm} = (k_y, -k_x, 0)/k_{\parallel}, \boldsymbol{\xi}_p^{\pm} = k_z(\mp k_x, \mp k_y, k_{\parallel}^2/k_z)/k_{\parallel}k_0$, and $r_{\alpha,\beta}$ represents the individual components of the reflection matrix

$$\mathbb{R} = \begin{pmatrix} r_{ss} & r_{sp} \\ r_{ps} & r_{pp} \end{pmatrix}$$
$$= \frac{1}{\zeta} \begin{pmatrix} 4 + 2Z^s \eta_0 \sigma'_{xx} - \zeta & -2\eta_0 \sigma'_{xy} \\ -2\eta_0 \sigma'_{yx} & 4 + 2Z^p \eta_0 \sigma'_{yy} - \zeta \end{pmatrix}, \quad (8)$$

with η_0 representing the free-space impedance, $Z^s = k_z/k_0$, $Z^p = k_0/k_z$, $\zeta = (2Z^s + \eta_0 \sigma'_{yy})(2Z^p + \eta_0 \sigma'_{xx}) - \eta_0^2 \sigma'_{xy} \sigma'_{yx}, \underline{\sigma}'$ is the conductivity tensor in wave vector space given by

$$\underline{\underline{\sigma}}' = \underline{\underline{a}}^T \underline{\underline{\sigma}}^{\text{eff}} \underline{\underline{a}},\tag{9}$$

where $\underline{\underline{a}} = (k_x - k_y; k_y k_x)/k_{\parallel}$, and $\underline{\underline{\sigma}}^{\text{eff}}$ represents the effective conductivity matrix in Eq. (2).

At this point, the mathematical model has been constructed and it is necessary to provide the material properties of the materials used. The electrical conductivity of isotropic graphene is given in [56] and the dielectric function of SiC particles is described using the Drude-Lorentz model as follows:

$$\varepsilon(\omega) = \varepsilon_{\infty} \frac{\omega_L^2 - \omega^2 - i\Gamma\omega}{\omega_T^2 - \omega^2 - i\Gamma\omega},$$
(10)

where $\omega_L = 1.83 \times 10^{14}$ rad/s and $\omega_T = 1.49 \times 10^{14}$ rad/s are the longitudinal and transverse optical frequencies, respectively. $\varepsilon_{\infty} = 6.7$ represents the high-frequency dielectric constant and $\Gamma = 8.97 \times 10^{11}$ rad/s is the electron damping. Based on the expression of the polarizability, the resonance frequency of the particle to $\varepsilon(\omega) + 2 = 0$ can be predicted as $\omega_r = 1.756 \times 10^{14}$ rad/s.

III. INFLUENCE OF METASURFACE VELOCITY AND CHEMICAL POTENTIAL ON NFRHT

By utilizing the long-range transmission characteristics of near-field radiation mediated by metasurfaces, we investigate the influence of metasurface velocity and chemical potential on NFRHT between nanoparticles. In this study, we consider a distance of $d = 1 \ \mu m$ between the two particles and the distance between the particle and the surface, h, is set to 60 nm to ensure accurate calculations [57]. The temperature of the particles and the metasurface is maintained at $T_1 = T_M =$ 300 K and $T_2 = 0$ K. In low-temperature doped graphene, the imaginary part of the dynamic conductivity exhibits a logarithmic divergence at the interband transition threshold. This behavior indicates that changes in the chemical potential can alter the carrier density and band structure of graphene, thereby significantly influencing its optical properties. Therefore, we approach the problem of moving metasurfaces from the perspective of chemical potential.

The frequency and propagation length of SPPs excited on the graphene surface can be adjusted by tuning its chemical potential. In Fig. 2(a), we present the response of the wave vector in the x direction and propagation length above the graphene surface to velocity at different chemical potentials. The wave vector is obtained using

$$K = \sqrt{k_0^2 - \left(2\varepsilon_0 \omega / \sigma_{xx}^{\text{eff}}\right)^2}.$$
 (11)

The propagation length is obtained through L = 1/Im(K)[2]. It can be observed that when graphene is at rest, the SPPs excited by particles on the surface have extremely high wave vector magnitudes at a chemical potential of 0.1 eV, but their propagation length is much shorter than the particle spacing *d*, indicating that, although these waves carry significant energy, they cannot propagate effectively. With an increase in chemical potential, a trend is observed where the frequencies decrease and the propagation length extends. When the condition $L \ge d$ is satisfied, it indicates that the SPPs excited by particle 1 can propagate to the region below particle 2 and be captured by it, which is consistent with the results calculated in [42]. Interestingly, when the velocity is



FIG. 2. (a) Response of the *x*-direction wave vector magnitude and propagation length on the graphene surface to velocity under different chemical potentials, where the rad and blue lines represent the wave vector magnitude and propagation length, respectively. (b) Spectral thermal flux coefficient under different velocities and chemical potentials, where $\omega_r = 1.756 \times 10^{14}$ rad/s represents the resonant frequency of SiC particles. (c) The response of the spectral thermal flux coefficient at ω_r to velocity under different chemical potentials. Here, $d = 1 \mu m$ and $\beta = v/c$.

sufficiently large, these trends are significantly altered. When β increases to 0.1, the corresponding curve of propagation length exhibits a significant increase and a distinct peak, while the curve corresponding to the wave vector magnitude shows a noticeable decrease. This implies that the SPPs on the high-velocity surface, although experiencing some energy loss, can propagate over extremely long distances.

Now let us discuss the thermal flux coefficient H defined by Eq. (3). Figure 2(b) illustrates the impact of velocity and chemical potential on H at unit frequency. It can be observed that H_{ω} exhibits a peak at the resonant frequency ω_r and neither changes in velocity nor changes in chemical potential cause a shift in this peak. The overall H in the system can be effectively represented as a linear superposition of H_{ω} . Therefore, in the following calculations, we focus on analyzing H_{ω} at ω_r . Figure 2(c) presents the response of H_{ω_r} to velocity for different chemical potentials. It can be observed that when the velocity exceeds a certain threshold, particularly for systems with low chemical potential, H_{ω_r} can undergo significant changes. We select two representative curves corresponding to μ values of 0.1 eV and 0.5 eV for analysis. Combining with Fig. 2(a), we can see that for the case of $\mu = 0.1$ eV, when $\beta = 0$ (i.e., at rest), SPPs can hardly propagate. When $\beta = 0.05$, the propagation length of SPPs already exceeds the interparticle spacing d and their carried energy is captured by particle 2, resulting in a significant upward trend. When $\beta = 0.1$, the decrease in SPPs' wave vector leads to a reduction in the energy captured by particles, hence exhibiting a downward trend. For the case of $\mu = 0.5$ eV, when $\beta = 0$, the propagation length of SPPs already exceeds d; therefore, its overall H_{ω_r} level at low velocities is higher compared to the $\mu = 0.1$ eV case. As β increases, the decrease in wave vector leads to a downward trend in H_{ω_r} at $\beta = 0.05$ and $\beta = 0.1$. Thus this also explains why H_{ω} exhibits distinctly different trends under different chemical potentials and velocities in Fig. 2(b). Finally, it is worth emphasizing that the slight increase in H_{ω_r} when β approaches 1 is attributed to the spectral thermal effects generated by the mechanical motion of surface charges.

The influence of mechanical motion on electromagnetic field in the *S* system is essentially the Doppler frequency shift effect between moving objects. For the purpose of comparison, we analyze the graphene surface with chemical potentials of 0.1 eV and 0.5 eV. Figures 3(a) and 3(b) show the wave vector spatial dispersion plots of the graphene surface at the corresponding chemical potentials and different velocities. The dispersion curves can be obtained using [48,58],

$$2k_0^2 \eta_0 (\sigma'_{xx} + \sigma'_{yy}) + k_0 k_z [4 + \eta_0^2 (\sigma'_{xx} \sigma'_{yy} - \sigma'_{xy} \sigma'_{yx})] = 2\eta_0 (k_x^2 + k_y^2) \sigma'_{xx}.$$
(12)

It is evident from the dispersion plots that the breaking of time-reversal symmetry due to linear motion leads to nonreciprocal dispersion. As the velocity increases, the dispersion curve transitions from circular dispersion at rest to elliptical dispersion and eventually becomes unidirectional hyperbolic dispersion, which is consistent with the results presented in [47]. The critical velocity at which the transition from elliptical dispersion to hyperbolic dispersion occurs can be calculated using

$$\beta_c = \operatorname{Re}[(1 - 4/\eta_0^2 \sigma^2)^{-1/2}].$$
(13)

For a chemical potential of $\mu = 0.1$ eV, the critical point is denoted as $\beta_c = 0.0074$, while for $\mu = 0.5$ eV, it is denoted as $\beta_c = 0.062$. It can be observed that under low chemical potential, the surface dispersion exhibits a significant response to velocity. The excited SPPs have a large wave vector and carry high energy. Conversely, under high chemical potential, the response is completely opposite. Figures 3(c), 3(d), and 3(e) depict the contour lines of the wave vector for the first part Re[$\mathbb{G}^{sc}(1, 1)$] of the Green's function reflection matrix at chemical potential of 0.5 eV for β values of 0, 0.05, and 0.1. These contour lines align with the dispersion curves of the three different propagation modes of SPPs, providing a visual representation of the transition of the Green's function. To provide



FIG. 3. When the chemical potential is (a) 0.1 eV and (b) 0.5 eV, the spatial dispersion of the surface wave vector varies at different velocities. When the chemical potential is 0.5 eV, and β is (c) 0, (d) 0.05, and (e) 0.1, the contour of the wave vector for the first part Re[$\mathbb{G}^{sc}(1,1)$] of the Green's function reflection matrix.

a more intuitive description of the impact of surface motion on the energy in the *S* system, Fig. 4 illustrates contour maps of energy density distribution in the cross-sectional plane at position h = 60 nm and in the longitudinal plane at position y = 0 nm for different velocities, with chemical potentials of 0.1 eV and 0.5 eV, respectively. The energy density calculation formula is represented by [59]

$$\mathbf{U}(\mathbf{R},\omega) = \left(2\hbar k_0^4/\pi\right) \sum_i \chi_i n(\omega, T_i) \mathrm{Tr}[\mathbb{N}_{\mathbf{R}i} \mathbb{N}_{\mathbf{R}i}^*], \quad (14)$$

with $\mathbb{N}_{\mathbf{R}i} = (\mathbb{G}^0_{\mathbf{R}i} + \mathbb{G}^{sc}_{\mathbf{R}i})\mathcal{G}.$

$$\underline{\underline{\sigma}}^{\text{eff}} = \gamma \mathbb{Z} \left(\sigma \mathbb{Z} + v \begin{bmatrix} \cos \theta & \sin \theta \\ \sin \theta & -\cos \theta \end{bmatrix} \times \begin{bmatrix} -2\varepsilon_0 k_x/k_z & -2\varepsilon_0 k_y/k_z \\ -\sigma k_y/\omega & \sigma k_x/\omega \end{bmatrix} \right)$$
(15)



(c)

FIG. 4. Energy density distribution contour maps in the cross-sectional plane at h = 60 nm and in the longitudinal plane at y = 0 nm, considering (a) the absence of the metasurface and the presence of the metasurface with chemical potentials of (b) 0.1 eV for the velocities take on the values of 0, 0.02, and 0.1 and (c) 0.5 eV for the velocities take on the values of 0, 0.04, 0.06, and 0.1.



FIG. 5. (a) Illustration of particles' deflection. (b) Distribution contour maps of dispersion curves and real part of the first part of the reflection Green's function in the S' system for $\mu = 0.5$ eV, $\beta = 0.1$, and $\theta = 60^{\circ}$. Variation curves of the spectral thermal flux coefficient in the S' system with respect to deflection angle and velocity for (c) $\mu = 0.1$ eV or (d) $\mu = 0.5$ eV. Panels (e) and (f) represent contour maps of the spectral thermal flux coefficient as a function of surface velocity and particle deflection angle with chemical potentials of 0.1 eV and 0.5 eV. The calculations were performed using $\log_{10}(H_{\omega_r}/H_{\omega_r0})$, where H_{ω_r0} represents the spectral thermal flux coefficient at angle θ when β is equal to 0.

We can observe that, in the absence of a graphene surface, the energy emitted by particle 1 rapidly decays in vacuum and is barely received by particle 2. When a graphene surface is present, consistent with the predicted results in Fig. 2(a), under low chemical potential (e.g., 0.1 eV), the propagation length of SPPs excited on the stationary surface is nearly zero. However, as the velocity increases, the propagation of SPPs exhibits significant directionality and a noticeable increase in propagation length. Under high chemical potential (e.g., 0.5 eV), the propagation length of SPPs excited on the stationary surface is already greater than the interparticle spacing d. With increasing velocity, SPPs display noticeable directionality only at relatively large β values. Due to the decrease in the wave vector in the x-axis direction, the extension of the propagation length, and the distinct response of velocity to different chemical potentials, the energy density above the surface along the x-axis direction at $\beta = 0.1$ exhibits enhanced behavior compared to the stationary surface under low chemical potential and reduced behavior under high chemical potential.

IV. INFLUENCE OF RELATIVE POSITION OF PARTICLES ON NFRHT

We now focus on the influence of the relative positions of particles on the spectral thermal flux coefficient H_{ω_r} . In the previous calculations, the particles were arranged along the positive *x*-axis direction in the *S* system. In Fig. 5(a), we introduce a deflection angle θ , which represents the angle between the vector pointing from the heat source particle 1 to the cold source particle 2 and the *x* axis. We define a coordinate system S' that rotates with the deflection angle. The calculation formula for the effective conductivity tensor in the S' system is represented by Eq. (15), with $\mathbb{Z} = \mathbb{I} + (1/\gamma - 1)$ (cos² θ sin θ cos θ ; sin θ cos θ sin² θ).

Figure 5(b) shows the distribution contour map of the surface wave vector space dispersion and the real part of the reflection Green's function's first part in the S' system at a deflection angle of 60° , which undergoes deflection with the change of θ . In Fig. 5(c), we plot the variation curve of H_{ω_r} in the S' system with respect to θ and β . It can be observed that, at low speeds (e.g., $\beta < 0.01$), the magnitude of H_{ω_r} is nearly identical to that when there is no surface present. When the velocity exceeds a certain threshold, at small angles and relatively low speeds (e.g., $\theta < 40^\circ$, 0.01 $< \beta < 0.1$), H_{ω_e} exhibits a significant increasing trend, reaching up to five orders of magnitude higher than at $\beta = 0$. This is mainly attributed to the extension of the SPPs' propagation length in the positive x-axis direction. As shown in Fig. 4(b), energy transfer in space exhibits significant directionality, with the strongest intensity along the positive x axis. However, at relatively high speeds (e.g., $\theta < 40^{\circ}$, $\beta > 0.1$), H_{ω_r} shows a noticeable decreasing trend, primarily due to the Doppler effect causing a reduction in the SPPs' wave vector in the positive x-axis direction. In the case of large angles and relatively low speeds (e.g., $\theta > 40^{\circ}$, $0.01 < \beta < 0.1$), H_{ω_r} exhibits an oscillatory trend. This is because the changes in the SPPs' wave vector magnitude and propagation length compete with each other, resulting in a combined suppression of H_{ω_r} for $\theta < 90^\circ$ and even phenomena where H_{ω_r} is lower than particle radiation in vacuum. Nonetheless, under relatively high speeds (e.g., $\theta > 40^{\circ}, \beta > 0.1), H_{\omega_r}$ shows a gradual upward trend due to



FIG. 6. Distribution contour maps of the spectral thermal flux coefficient in the S' system for particles at (a) $\theta = 0^{\circ}$ and (b) $\theta = 180^{\circ}$ as a function of chemical potential and surface velocity. (c) Distribution contour map of the spectral thermal rectification coefficient $\eta = (H_{\omega_r}^{0^{\circ}} - H_{\omega_r}^{180^{\circ}}) / \max[(H_{\omega_r}^{0^{\circ}}, H_{\omega_r}^{180^{\circ}})]$.

the contribution of mechanical motion thermal effects caused by surface charges. Figure 5(e) presents the variation contour map of H_{ω_r} for $\mu = 0.1$ eV, calculated using $\log_{10}(H_{\omega_r}/H_{\omega_r0})$. Here, $H_{\omega_r 0}$ represents the spectral thermal flux coefficient when there is a stationary surface and it can be seen that the overall enhancement is evident, particularly at small angles and moderate velocities. The highest suppression, up to 4.76 orders of magnitude, occurs near $\theta = 0^{\circ}$ and $\beta = 0.065$. Figure 5(d) shows the variation curve of H_{ω_r} for $\mu = 0.5$ eV. It can be observed that, at low speeds, H_{ω_r} is significantly higher than particle radiation in vacuum. With increasing velocity, the combined effect of SPPs' wave vector magnitude, propagation length, and current generated by surface charges leads to a wide range of suppression observed in Fig. 5(f). Contrasting the case at 0.1 eV, the highest suppression, up to 4.16 orders of magnitude, occurs near $\theta = 70^{\circ}$ and $\beta = 0.1$.

The spectral thermal rectification effect, achieved by varying the deflection angle, can be utilized to design highperformance "thermal diodes." Figures 6(a) and 6(b) present the distribution contour maps of H_{ω_r} with respect to the chemical potential and surface velocity for particle orientations of $\theta = 0^{\circ}$ and $\theta = 180^{\circ}$, respectively. It can be observed that the forward heat transfer coefficient $H_{\omega_r}^{0\circ}$ is significantly higher than the reverse heat transfer coefficient $H_{\omega_r}^{0\circ}$. The thermal rectification coefficient is defined as $\eta = (H_{\omega_r}^{0\circ} - H_{\omega_r}^{180^{\circ}})/\max[(H_{\omega_r}^{0^{\circ}}, H_{\omega_r}^{180^{\circ}})]$. From Fig. 6(c), it can be seen that near a chemical potential of 0.139 eV, a surface velocity corresponding to a thermal rectification coefficient close to 0.8 only requires a β value of 0.00047. This provides potential for practical applications of this theory.

Next, we conduct a study on the distance between particles and particle-to-surface interactions. Figures 7(a) and 7(b) illustrate the variations of H_{ω_r} with respect to the particles' spacing *d* and velocity at $\mu = 0.1$ eV and 0.5 eV, respectively. Increasing the particle spacing inevitably leads to a decrease in H_{ω_r} , but at different chemical potentials, there are significant differences in the variation of H_{ω_r} with respect to *d*, particularly at lower chemical potentials where the response to velocity is evident. Overall, at small distances, an increase in velocity reduces the heat transfer coefficient between particles due to the dominant contribution of the reduced wave vector of SPPs, as analyzed in Fig. 2(a). At larger distances, an increase in velocity enhances the heat transfer coefficient

between particles due to the main contribution of the extended propagation length of SPPs. For detailed explanations, refer to Fig. 2(a). Figures 7(c) and 7(d) show the variations of H_{ω_r} with respect to the particle-to-surface distance *h* and velocity at $\mu = 0.1$ eV and 0.5 eV, respectively. The trends are similar to the changes caused by particle spacing and we predict that this is due to the decreased wave vector of evanescent waves and the resulting extension of propagation length.

V. CONCLUSIONS

This article investigates the control of radiative heat transfer (RHT) between two isotropic dielectric (SiC) nanoparticles at the near-field scale using a moving (graphene) metasurface. We have demonstrated that nonreciprocal propagation guided by the moving metasurface can significantly modify the radiative heat transfer between the particles. The wave vector space dispersion changes from circular dispersion to unidirectional hyperbolic dispersion. Different chemical potentials exhibit distinct responses to velocity and the spatial distribution of energy density further confirms that the moving surface imparts clear directionality to the radiative heat flow in the upper space, concentrating the heat transfer. The underlying cause of these effects lies in the Doppler shift effect between the moving media. The wave vector and propagation length of the excited surface plasmon polaritons (SPPs) on the surface change significantly with velocity, resulting in a complex interplay between the two.

Subsequently, we investigated the influence of particle deflection angles on near-field radiative heat transfer (NFRHT). We found that the deflection angles of the metasurface coupled with particles, with different chemical potentials, can enhance or suppress the thermal flux coefficient H and this effect can be controlled over five orders of magnitude. Finally, we demonstrated that increasing velocity enhances heat transfer at large distances between particles and between particles and the surface, while exhibiting the opposite phenomenon at small distances.

The unique mechanism of the moving metasurface in the near field is undoubtedly fascinating. In near-field scenarios involving relative motion, the influence of moving surfaces on spatial radiative heat exchange cannot be ignored [60]. This



FIG. 7. Variation of the spectral thermal flux coefficient with the particles' spacing and velocity at chemical potentials of (a) 0.1 eV and (b) 0.5 eV. Variation of the spectral thermal flux coefficient with particle-to-surface distance and velocity at chemical potentials of (c) 0.1 eV and (d) 0.5 eV.

theory provides theoretical support for future scenarios involving moving surfaces. The assumption of constant velocity translation in this study is idealized and there have been numerous studies on quantum friction and applications between moving objects [27–33]. We predict that the Casimir effect between high-speed moving objects may introduce more complex phenomena for theoretical analysis. Although the surface velocity investigated in this article is significant, recent developments in rotating surfaces [23,24], rotating particles [61,62], and other areas offer possibilities for the practical application of this theory. Furthermore, the model used in the article is topologically expandable and further exploration is needed to discover additional methods to reduce the required speed.

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