Low-temperature linear thermal rectifiers based on Coriolis forces

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We demonstrate that a three-terminal harmonic symmetric chain in the presence of a Coriolis force, produced by a rotating platform that is used to place the chain, can produce thermal rectification. The direction of heat flow is reconfigurable and controlled by the angular velocity $\Omega$ of the rotating platform. A simple three-terminal triangular lattice is used to demonstrate the proposed principle.

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I. INTRODUCTION

In the past few years considerable research effort has been invested in developing appropriately engineered structures that display novel transport properties not found in nature. In the thermal transport framework, this activity has recently started to gain a lot of attention. Apart from the purely academic reasons, there is a growing consensus on its practical implications in the efforts of society to manage its energy resources efficiently. Thus, research programs that aim to propose new methods, designs, or materials that allow us to harness and mold the heat flow at the nanoscale level in ways that can affect society’s energy consumption needs are at the forefront of the research agenda. Some of the targets that are within our current nanotechnology capabilities include the generation of nanoscale heat-voltage converters, thermal transistors and rectifiers, nanoscale radiation detectors, heat pumps, and even thermal logic gates [1–6].

In spite of these efforts the understanding of thermal transport and more importantly the manipulation of heat current is still in its infancy. This becomes more obvious if one compares with the tremendous achievements of the past 50 years in understanding and managing electron transport. In contrast, for example, the important problem of thermal rectification is addressed only by a handful of researchers. For example, the investigation of radiative thermal rectification, both in the nearfield and farfield regimes, has recently attracted significant attention [7–9]. In the case of phononic heat transport, the majority of the existing proposals rely on the interplay of system nonlinearities with structural asymmetries [10–12]. At the nanoscale limit where the phonon mean-free path is comparable to the size of the devices the inherent nonlinearities are irrelevant and transport is fully dominated by ballistic phonon transport (ballistic limit). However, recently it was shown in Refs. [13–15] that in the ballistic regime one can achieve thermal rectification under very specific conditions: low temperature limit associated with quantum harmonic systems in the nonlinear response domain, and the presence of a third reservoir, which acts as a probe and is coupled asymmetrically with the rest of the system in order to break any spatial symmetry. The importance of asymmetry of the system was further highlighted in Ref. [15].

In this paper, we focus on the development of a concept for the creation of unidirectional thermal valves that control and direct heat currents on the nanoscale level. Specifically, we propose to create a ballistic symmetric thermal rectifier that relies on Coriolis forces. In contrast to previous studies our proposal does not rely on any structural asymmetry. Rather, an asymmetry is induced in a very controllable way by the Coriolis force allowing a high flexibility in the rectification properties without a change of the structural setup. The system consists of a symmetric harmonic lattice placed on a rotating platform with angular velocity $\Omega$. The direction of heat current is controlled on the sign of $\Omega$, thus allowing for a reconfigurable heat-current management. A schematic of such a setup, consisting of three harmonic masses coupled to a rotating platform, is shown in Fig. 1. Using the nonequilibrium Green’s function formalism we derive the conditions of optimal operation of the structure. Subsequently, we have verified these predictions via detailed numerical calculations using a simple variant of the proposed structure.

The paper is organized as follows. In Sec. II we present the theoretical model. The mathematical formalism for the evaluation of heat current and the conditions for nonreciprocity are discussed in Sec. III. Finally, a numerical confirmation of our predictions is given in Sec. IV. Our conclusions are given in Sec. V.

II. THEORETICAL MODEL

We consider a harmonic lattice of $N$ particles coupled together with spring constants $k_C$. All particles are assumed to have the same mass $m$. Below, without any loss of generality, we assume that all masses are $m = 1$. The lattice is placed on a platform in the $X$-$Y$ plane. Thus, each particle can move on this platform and has $D = 2$ degrees of freedom. The connectivity of the lattice is uniquely defined by the $N = N \times D$-dimensional symmetric force matrix $K^C$. We will assume the most general case where the coupling is not necessarily confined to be only between nearest (in space) masses. Moreover we will assume that all masses are coupled harmonically to a central post that is parallel to the $Z$ axis and placed in the middle of the platform.

The lattice rotates around the post with a constant angular velocity $\Omega$. It is useful to describe the motion of the system in the rotating frame. In this frame the particles are characterized by their equilibrium position vector $R^0 = (R^0_1, \ldots, R^0_N)^T$, by their displacements vector $S = (S_1, S_2, \ldots, S_N)^T$ and the associated conjugate canonical momenta vector $p_C = (p_{C1}, p_{C1}, \ldots, p_{CN}, p_{CN})^T$ (the superscript $T$ indicates transposition). The Hamiltonian that describes the...
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A high-temperature bath with temperature $T_R$ where reservoirs are not affected by the Coriolis force and respect that the statistical properties of the phonons in these thermal systems in the rotating frame takes the form $T_R = T_p$ is again connected to the probe bath with a different temperature $T_R$, while the mass $R_3$ is coupled to the high-temperature bath with temperature $T_R = T_p$. The mass $R_2$ is again connected to the probe bath with a different temperature $T_R = T_p$. The mass $R_1$ is coupled to a low-temperature bath with temperature $T_R = T_p$, while the mass $R_2$ is coupled to the low-temperature bath with temperature $T_R = T_p$, while the mass $R_3$ is connected to the probe bath with temperature $T_R = T_p$. (b) The mass $R_1$ is coupled to a low-temperature bath with temperature $T_R = T_p$, while the mass $R_2$ is coupled to the high-temperature bath with temperature $T_R = T_p$. The mass $R_3$ is again connected to the probe bath with a different temperature $T_R = T_p$. The mass $R_2$ is coupled to the low-temperature bath with temperature $T_R = T_p$, while the mass $R_3$ is connected to the probe bath with temperature $T_R = T_p$. (b) The mass $R_1$ is coupled to a low-temperature bath with temperature $T_R = T_p$, while the mass $R_2$ is coupled to the high-temperature bath with temperature $T_R = T_p$. The mass $R_3$ is again connected to the probe bath with a different temperature $T_R = T_p$.

The system in the rotating frame takes the form

$$H_C = \frac{1}{2} p_C^T p_C + \frac{1}{2} \kappa S \omega^2 + (R^0 + S)^T A p_C,$$

where $A$ is the $N \times N$ block-diagonal matrix,

$$A = \text{diag}(\tilde{A}_D); \quad \tilde{A}_{D=3} = \begin{bmatrix} \tilde{A}_{D=2} & 0 \\ 0 & 0 \end{bmatrix}; \quad \tilde{A}_{D=2} = \begin{bmatrix} 0 & \Omega \\ -\Omega & 0 \end{bmatrix},$$

with the property $A^T = -A$. The last term in Eq. (1) describes the Coriolis force in the rotating frame.

The rotating lattice described by Eq. (1) is coupled with three equivalent corotating heat baths. The latter are always attached to the same three particles of the lattice $\alpha = R_1, R_2, R_3$. We will assume that two of these baths are at high $T_\text{hot}$ and low $T_\text{cold}$ constant temperatures, respectively. The third bath acts as a probe and its temperature $T_{R_3} = T_p$ is adjusted self-consistently such that the heat flux from it is zero. In general, this can lead to different $T_p$ values in the forward ($T_{R_1} = T_\text{hot}$ and $T_{R_2} = T_\text{cold}$) and backward ($T_{R_1} = T_\text{cold}$ and $T_{R_2} = T_\text{hot}$) process.

For simplicity, the heat baths are described quasiclassically, i.e., we promote the relative momenta $p_\alpha$ of the $\alpha$-bath particles and their displacements $u_\alpha$, with respect to the rotating frame, to conjugate canonical pairs [16]. Nevertheless, we assume that the statistical properties of the phonons in these thermal reservoirs are not affected by the Coriolis force and respect quantum statistics [17]. The three baths, each consisting of an infinite number of harmonically coupled bath particles, are described by Hamiltonians,

$$H_\alpha = \frac{1}{2} p_\alpha^T p_\alpha + \frac{1}{2} \kappa u_\alpha^2, \quad \alpha = R_1, R_2, R_3,$$

with a (semi-infinite) harmonic force matrix $K_\alpha = (K_\alpha^T)^T$ containing additional $-\Omega^2$ terms due to the centrifugal force ($I$ denotes the semi-infinite identity matrix).

Finally, we have assumed that each particle is pinned to the substrate (i.e., the rotating platform; see Fig. 1 for a special case of three masses) via a quadratic potential with a coupling constant $k_0$. This pinning potential guarantees that the lattice particles have an equilibrium position and it can be incorporated easily in all force matrices $K_\alpha, K_\alpha^T$; see Eqs. (1) and (3).

We are now ready to write down the total Hamiltonian of the bath-lattice system, which takes the form

$$H_\text{tot} = H_C + \sum_\alpha H_\alpha + \sum_\alpha H_\alpha C,$$

where $H_\alpha C = u_\alpha^T V^C u_\alpha$ describes the coupling between the lattice particles and the heat baths.

Below we will be assuming that the initial condition of the total system is a direct product state

$$\hat{\rho}_\text{ini}(t_0) = \prod_\alpha \text{Tr}(e^{-H_\text{ini} / (k_B T_\alpha)}) \otimes \text{Tr}(e^{-H_\text{ini} / (k_B T_\alpha)}),$$

which after sufficient long time will be relaxing to a steady state $\hat{\rho}^{ss}$. Note that the temperature of the two baths $T_a$ are kept constant and the steady-state thermal current will not depend on the initial temperature of the lattice model $T_C$. The value of the temperature of the probe in the nonequilibrium steady state (NESS) will be determined by the temperature of the other baths.

### III. FORMALISM

#### A. Heat current

We want to calculate the steady-state thermal current flowing from the hot reservoir $T_\text{hot}$ toward the cold reservoir $T_\text{cold}$. To this end we will employ the standard nonequilibrium Green’s function technique [18–20]. The steady-state current out of the heat bath $\alpha$ is

$$I_\alpha = -\text{Tr} \left[ \hat{\rho}^{ss} \frac{d \hat{H}_\alpha(t)}{dt} \right]$$

$$= \sum_{\gamma \neq \alpha} \int_0^\infty \frac{d\omega}{2\pi} \text{Re} \omega \text{Tr}_\gamma \{ \omega (f_\alpha - f_\gamma) \},$$

where $f_\alpha = f(\omega, T_\alpha) = \{ \text{exp}(\hbar \omega / k_B T_\alpha) - 1 \}^{-1}$ is the Bose distribution associated with the particles at the bath $\alpha$, which have fixed temperature $T_\alpha$ and $T_\gamma$ is the transmission coefficient from the orth bath to the $\gamma$th bath. The hot and cold reservoirs, with temperatures $T_\text{hot}$ and $T_\text{cold}$, will be attached to the particles $R_1, R_2$ while the third—probe—reservoir with varying temperature $T_p$, will be always attached to the $R_3$ particle.
During the forward process we attach the hot reservoir to the particle $R_1$ so that $T_{R_1} = T_{\text{hot}}$, and we attach the cold reservoir to the particle $R_2$ so that $T_{R_2} = T_{\text{cold}}$. The associated heat current $I_f$ out of bath $R_2$ is then given from Eq. (6):

$$I_f = \sum_{\gamma=R_1,R_2} \int_0^\infty \frac{da}{2\pi} \hbar \omega \Gamma_T f(T_{\gamma,R_1,R_2}[\omega]) f(T_{\gamma} - f(T_{\gamma})), \quad (7)$$

where a negative value in $I_f$ will indicate current flowing from the hot reservoir to the cold reservoir. The bath temperature $T_R = T_0^f$ associated with the probe reservoir has to be evaluated from the requirement that the net current $I_p$ flowing in the probe reservoir is zero; i.e.,

$$I_p = \sum_{\gamma=R_1,R_2} \int_0^\infty \frac{da}{2\pi} \hbar \omega \Gamma_T f(T_{\gamma,R_1,R_2}[\omega]) f(T_{\gamma} - f(T_{\gamma})) = 0. \quad (8)$$

The backward process is associated with the reverse configuration, i.e., $T_{R_1} = T_{\text{hot}}$ and $T_{R_2} = T_{\text{cold}}$. The associated heat flux $I_b$ out of bath $R_2$ and the corresponding temperature of the probe $T_0^b$ are derived using similar relations as the ones shown in Eqs. (7) and (8).

For the probe temperatures in the forward and backwards process, respectively, we find

$$T_0^f = T_0 + a \Delta T + g \Delta T^2 + O(\Delta T^3),$$

$$T_0^b = T_0 - a \Delta T + g \Delta T^2 + O(\Delta T^3), \quad (9)$$

where $T_{\text{hot/cold}} = T_0 \pm \Delta T$. The constants $a, g$ are

$$a = -\frac{1}{\int_0^\infty \frac{da}{2\pi} \hbar \omega \Gamma_T f(T_{\gamma,R_1,R_2}[\omega]) f(T_{\gamma} - f(T_{\gamma}))} \int_0^\infty \frac{da}{2\pi} \hbar \omega \Gamma_T f(T_{\gamma,R_1,R_2}[\omega]) f(T_{\gamma} - f(T_{\gamma})) |_{T_0}, \quad (10)$$

where $G^{\text{cc}}(\omega)$ is the retarded (advanced) Green’s functions of the lattice.

Finally, the retarded Green’s function $G^{\text{cc}}(\omega)$ for the central junction in the frequency domain takes the form

$$G^{\text{cc}}(\omega) = [(\omega + i0^+)^2 - K^2 - \Sigma'(\omega) - A^2 - 2i\omega A]^{-1}, \quad (12)$$

where $\Sigma' = \sum_\alpha \Sigma'_\alpha$ denotes the total retarded self-energy due to the interaction with all the heat baths. The advanced Green’s function can be expressed in terms of $G^{\text{cc}}$ as

$$G^{\text{cc}}(\omega) = (G^{\text{cc}}(\omega))^\dagger. \quad (13)$$

Using expression Eq. (12) we can deduce that

$$G^{\text{cc}}(\omega, -\Omega) = G^{\text{cc}}(\omega, \Omega)^\dagger. \quad (14)$$

Using the cyclic property of the trace, the symmetric nature of further $\Gamma'_\alpha = \Gamma_\alpha$ and Eq. (14), we can easily show that

$$\Gamma_{\alpha}[\omega, -\Omega] = \Gamma_{\alpha}[\omega, \Omega] \neq \Gamma_{\alpha}[\omega, \Omega], \quad (15)$$

which leads us to the conclusion that for $\Omega \neq 0$ the time-reversal symmetry of the system is broken due to the rotation.

In order to highlight the importance of the Coriolis force in thermal rectification we will be considering setups that involve structural rotational symmetry. In this case, any asymmetric heat transport phenomena that we will find are due to Coriolis force only (contrast this with the studies of Refs. [10–12], where thermal rectification is due to structural asymmetries).

As an outcome of this rotational symmetry assumption we have that the transmission coefficients $\Gamma_{\alpha,\gamma}$ satisfy the following relations:

$$\Gamma_{\alpha,\gamma} = \Gamma_{\alpha,\gamma} = \Gamma_{\alpha,\gamma} = \Gamma_{\alpha,\gamma}, \quad (16)$$

The above expressions can allow us to calculate the transmission coefficient $\Gamma_{\alpha,\gamma}[\omega]$, and thus to proceed with the evaluation of the forward and backward currents $I_f, I_b$.}

### C. The rectification parameter

Below we will quantify the rectification effect by the rectification parameter $R$ defined as

$$R = \frac{-\Delta I}{\max[|I_f|, |I_b|]}; \quad \Delta I = I_f + I_b. \quad (17)$$

When $\Delta I > 0 (R < 0)$ the system acts as a thermal rectifier favoring the direction from the bath placed at $R_2$ to the bath attached at $R_1$, while the reverse is true in the case that $\Delta I < 0 (R > 0)$. We will assume $T_{\text{hot/cold}} = T_0 \pm \Delta T$ and analyze the dependence of $R$ on the temperature difference $\Delta T$.

Using Eqs. (6), (8), and (16) we can evaluate the rectification parameter $R$ up to the second order in the temperature difference $\Delta T$. The current difference $\Delta I$ is given by [14]

$$\Delta I = (1 - a^2)^{\frac{K}{F(T_{R,R}) + F(T_{R,R})}} \Delta T^2, \quad (18)$$

where the parameter $a$ has been already defined in Eq. (10) and its absolute value is always smaller than unity; i.e., $|a| \leq 1$. Therefore, the coefficient $(1 - a^2)^{\frac{K}{F(T_{R,R}) + F(T_{R,R})}}$ is always greater than zero; i.e., $(1 - a^2) > 0$. The positive definite functions $F(T_{R,R}) > 0$ are defined as $F(T_{R,R}) = + \infty \frac{da}{2\pi} \hbar \omega \Gamma_T f(T_{\alpha,R,R}[\omega, -\Omega]) f(T_{\alpha,R,R}[\omega, -\Omega]) |_{T_0}, \quad (19)$

with the weight function $W$ and $T(\omega_1, \omega_2)$ as

$$W = h^\theta \omega_1 \omega_2 \kappa B T_0^2 \left( \frac{\partial f(T_{\omega_1,T})}{\partial T} \frac{\partial f(T_{\omega_2,T})}{\partial T} \right) |_{T_0} (\omega_2 + 2 f(\omega_2, T_0)), \quad (19)$$

with the weight function $W$ and $T(\omega_1, \omega_2)$ as

$$T(\omega_1, \omega_2) = \sum_{\omega_1, \omega_2} \left( f(T_{\omega_1, \omega_2}) \right) \left( f(T_{\omega_1, \omega_2}) \right),$$

and

$$f(T_{\omega_1, \omega_2}) = f(T_{\omega_1, \omega_2}).$$

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From Eq. (18) and the subsequent discussion we can draw a number of conclusions: Since the linear term in the \( \Delta T \) expansion is zero we immediately conclude that in the linear-response regime or in the classical limit our system has zero expansion is zero we immediately conclude that in the linear-

Second, we evaluate the contribution to the matrix \( \mathbf{K} C \) due to the spring coupling between the mass \( R_j \) and the center \( O \). We have that \( [\mathbf{K} C]_{R_j,R_j} = [\mathbf{K} C]_{R_j,R_j} = k_C \). Similarly, the coupling between the mass \( R_j \) and the platform provides the contribution \( [\mathbf{K} C]_{R_j,R_j} = [\mathbf{K} C]_{R_j,R_j} = k_p \). Third, due to the coupling with the bath \( \alpha \) additional terms are added to the matrix \( \mathbf{K} C \). For example, for \( \alpha = R_1 \) they are \( [\mathbf{K} C]_{R_1,R_j} = [\mathbf{K} C]_{R_1,R_j} = k_R \).

Finally, the nonzero elements of the coupling matrices [see below Eq. (4) for a definition] are, respectively, \( [\mathbf{V} R,C]_{1,1_1} = [\mathbf{V} R,C]_{2,2} = -k_R \) and \( [\mathbf{V} R,C]_{1,3_1} = -k_R \). In the following, \( k_{R} = k_{R} = k_R = k \) is assumed for simplicity.

The thermal rectification effect is present when the (structurally) symmetric system is rotating with an angular velocity \( \Omega \) around the post situated at the center \( O \). To be specific, first the bath coupled to the mass \( R_1 \) is set to the higher temperature \( T_{\text{R}_1} = T_{\text{hot}} = T_0 + \Delta T \) and the bath coupled to the mass \( R_3 \) is set to the lower temperature \( T_{\text{R}_3} = T_{\text{cold}} = T_0 - \Delta T \) (forward process). The temperature \( T_p \) of the probe bath coupled to the mass \( R_3 \) is determined by the zero flux condition as discussed above. We then calculate the forward thermal current \( I_f \) using Eq. (7). Second, by reversing the temperature bias, i.e., \( T_{\text{R}_3} = T_{\text{hot}} \) and \( T_{\text{R}_1} = T_{\text{cold}} \) and adjusting the temperature of the probe bath \( R_1 \) to be \( T_{p}^F \), the thermal current \( I_p \) for the backward process is evaluated. In the following natural units are assumed; i.e., \( \hbar = m = 1, k = 1, K_B = 1 \).

**IV. AN EXAMPLE OF THERMAL RECTIFICATION DUE TO CORIOLIS FORCE**

We will demonstrate the rectification effect, induced by the Coriolis force (\( \Omega \neq 0 \)), using a simple version of the general model, Eq. (4). The underlying symmetric harmonic system has an equilibrium configuration associated with an equilateral triangle. Each of the three corners of the triangle \( R_1, R_2, R_3 \) are occupied by equal masses \( R_1, R_2, R_3 \), coupled with the same harmonic coupling \( k_c \) to a post that is placed at the center \( O \) of the triangle. On every edge of the triangle, say, for example, edge \( R_1^2 R_2^2 \) (by excluding the masses at the vertexes), there are additional \( N_b \) equal masses, which are connected with the center \( O \) of the triangle by springs dividing the angle \( \angle R_1^2 O R_2^2 \) equally. An equal harmonic coupling up to the next-nearest neighbor is considered between the masses on each edge of the triangle. Furthermore, the masses \( R_1, R_2, R_3 \) are attached to three equivalent 1D Rubin baths [21]. The 1D Rubin baths \( \alpha = R_1, R_2, R_3 \) are made up of a semi-infinite spring chain with \( K_{nm} = \delta_{nm}(2k^2 - \Omega^2 + k_0) - k^2 \delta_{m:1,n} \). Here an additional coupling \( k_0 \) with the substrate is assumed.

An illustration of our model with \( N_b = 1 \) is shown in Fig. 1.

The symmetric force matrix \( \mathbf{K} C \) in Eq. (1) can be obtained systematically as follows. Each spring (harmonic coupling) will contribute to the matrix \( \mathbf{K} C \) with an additive harmonic term.

**FIG. 2.** (a) Plots of rectification \( R \) versus angular velocity \( \Omega \) for different average temperatures \( T_p \). (b) A plot of the transmission coefficient ratio \( \frac{T_{\text{R}_1}/T_{\text{R}_3}}{T_{\text{R}_1}/T_{\text{R}_3}} \) versus frequency \( \omega \), with the fixed angular velocity \( \Omega = 0.03 \). The inset shows this ratio from \( \omega = 0.45 \) to 0.75. Other parameters are \( N_b = 4, k_c = k = 1 \), and \( \Delta T = 2.5\% T_p \).
Our numerical results for the rectification parameter $R$ versus the angular velocity $\Omega$ and different average temperatures $T_0$ are shown in Fig. 2(a). These data clearly demonstrate that the rectification effect is present once $\Omega \neq 0$. Figure 2(a) confirms that for high average temperatures $T_0$, corresponding to the classical limit, the rectification effect is suppressed (compare, e.g., the curves for $T_0 = 0.1$ and $T_0 = 3$) as we have predicted in Sec. III C.

From Fig. 2(a) we further see that the rectification parameter $R$ for a fixed angular velocity may change sign when the average temperature $T_0$ changes from 0.1 to 0.4. This can be understood from the perturbation result in Eq. (18). Figure 3 demonstrates that when the average temperature $T_0$ changes from 0.1 to 0.4, the frequency region for which the absolute value of the weight function $|W(\omega_1, \omega_2, T_0)|$ is large will shift toward high frequencies. Bearing this fact in mind, we are now able to explain the change of sign in the rectification. For example, for $\Omega = 0.03$, we find that the transmission ratio $T_{R_1,k_C}/T_{R_2,k_C}$ initially decreases as a function of frequency while for larger frequencies it increases; see Fig. 2(b). As a result $K$ [see Eq. (19)] changes sign from negative to positive so that the rectification parameter $R$ [Eq. (18)] also changes sign from positive to negative. As $T_0$ increases further, quantum effects are destroyed and the classical limit will be reached so that $R \to 0$. As a result, for some intermediate value of $T_0$ the nonreciprocity will reach a maximum (negative) value. This is clearly seen in Fig. 2(a) where for $T_0 \approx 0.4$ the maximum rectification performance is achieved.

Furthermore, we see that, the rectification direction is controlled by the sign of the angular velocity $\Omega$, thus allowing a greater flexibility to reconfigure “on the fly” the direction of the heat current. This can be understood from the equality $T_{R_0,k_C}(\omega, \Omega) = 1/(T_{R_2,k_C}(\omega, -\Omega))$, which is directly derived from Eqs. (15) and (16). Specifically, due to this equality, in the frequency region where $|W(\omega_1, \omega_2, T_0)|$ is large (for a fixed average temperature $T_0$), the behavior of $T_{R_1,k_C}/T_{R_2,k_C}$ as a function of $\omega$ will turn from decreasing (increasing) function to increasing (decreasing) function when $\Omega \to -\Omega$. Thus, the function $K$ [defined in Eq. (19)] and correspondingly the rectification parameter $R$ will change sign when we reverse the angular velocity $\Omega$.

Finally, a 3D plot for the rectification $R$ versus $k_C$ and the angular velocity $\Omega$ is shown in Fig. 4. In these calculations the spring constant that couples the particles $R_1$, $R_2$, $R_3$ with the heat baths is taken to be $k = 1$. We see that the maximum rectification of $R_{\max} = 1.6 \times 10^{-3}$ is observed for $k_C \approx 0.65$ and $\Omega \approx \pm 0.02$ near the origin. The nonmonotonic behavior of $R$ versus $k_C$ is associated with an impedance mismatch between the two chains associated with the central junction lattice (with coupling constant $k_C$) and the one-dimensional chain of the bath (which involves coupling constants $k = 1$).

V. CONCLUSIONS

We have proposed the use of the Coriolis force in order to break time-reversal symmetry and induce thermal rectification in a ballistic three-terminal nanojunction. Two of these terminals are attached to a hot and a cold reservoir, respectively, while the third one is attached to a probe reservoir whose temperature is self-consistently adjusted such that the net current toward this reservoir is zero. The nanojunction consists of a symmetric lattice that is placed on a rotating...
platform. Using nonequilibrium Green’s function formalism we have calculated the rectification effect up to second-order in the temperature difference between the two reservoirs. We conclude that the Coriolis-induced rectification effect is of quantum mechanical nature and its direction and magnitude depend on $\Omega$. It will be interesting to extend this study beyond the ballistic limit and investigate the effects of nonlinearity and disorder. The latter phenomena can be important to any realistic structure where phonon-phonon interactions and structural imperfections are generally also present.

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