

Amplified Cooling of Light via Emergent Onsager Irreversible Thermodynamics

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Abstract: While conventional cooling schemes solely depend on temperature differences, here we demonstrate that in photonics configurations, amplified cooling can be achieved by judiciously manipulating Onsager coefficients through engineering the density of states of the structure. © 2024 The Author(s)

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Recent studies have revealed that photon-photon interactions can drive weakly nonlinear photonic systems into equilibrium states, exhibiting distinct thermodynamic behaviors [1–3]. As such, the modal occupancies follow Rayleigh-Jeans (R-J) distributions characterized by a photonic temperature and chemical potential that can be uniquely determined by the initial conditions. Such temperature and chemical potential have been demonstrated to guide the direction of energy and power flows, paving the way for an all-optical cooling scheme in photonic systems, leading to the generation of a bright, high-quality beam. As anticipated by the second law of thermodynamics, these cooling processes rely on the fundamental principle that energy tends to flow from hot to cold.

Here, we introduce an unconventional cooling scheme that not only depends on temperature differences but also exploits the gradient in chemical potentials. This is made possible by manipulating the cross terms in the Onsager reciprocity relation [4] and is achieved through the density of state management of the structure, where photonics holds intrinsic advantages over condensed matter. In this context, we reveal that, due to energy and photon number conservation, the nonequilibrium transport behavior in these photonic systems can be accurately described by effective thermoelectric transport equations. These equations cover energy and particle (photon) transport under temperature and density gradients (chemical potential), as well as the cross-correlated transport between energy and particles. Furthermore, these transport equations can be generalized to encompass both positive and negative temperature [5] regimes under the same formula. Through theoretical analysis and microscopic simulations, we demonstrate that an inverse current, such as photon diffusion against a temperature gradient, can be induced in the thermoelectric transport of photons. Importantly, this inverse current can be systematically achieved through spectrum engineering, involving the shifting and scaling of lattice spectra. Finally, leveraging the inverse photon current, we propose a repetitive amplified cooling scheme to achieve a large-area light source with high brightness and high coherence in waveguide lattices.

To setup the problem, we consider an optical waveguide array that is at a thermal equilibrium described by R-J distribution $|c_i|^2 = -T/(\varepsilon + \mu)$, where $|c_i|^2$ and ε_i are modal occupation and normalized eigen-value of the i -th supermode (ε_{\max} and ε_{\min} are eigenvalues of fundamental and highest order modes, respectively), T is optical temperature and μ represents chemical potential. The propagation behavior of such optical waves is governed by nonlinear Schrödinger equations (NLSE), where the propagation distance z plays the role of time. In investigating non-equilibrium transport in optical thermodynamics, we first examine transport between two such nonlinear photonic lattices. In this scenario, the fundamental transport phenomena are the photon flux dP/dz driven by the density gradient (i.e., chemical potential gradient) and the energy flow dU/dz driven by the temperature gradient. The former is governed by Fick's law, while the latter is governed by the generalized Fourier's law. It is worth noting that cross-correlated transport could also take place, specifically the generalized Seebeck effect and Peltier effect in standard thermoelectrics, wherein energy (heat) flow is driven by the chemical potential gradient and photon flux is driven by the temperature difference. For simplicity, we discuss these emergent transport phenomena between two optical thermal bodies labeled as left (L) and right (R). In practice, the two thermal bodies can be two photonic waveguide lattices that are brought into proximity, facilitating the exchange of power and energy at their shared boundary through tunneling effects. From the formulation of entropy production, Onsager's linear irreversible thermodynamic theory yields following transport equation: $\mathbf{J} = \hat{\mathbf{L}}\mathbf{F}$ where $\mathbf{J} = [J_w, J_\rho]^T$, $\mathbf{F} = [F_w, F_\rho]^T$, and $\hat{\mathbf{L}}$ is the Onsager matrix.

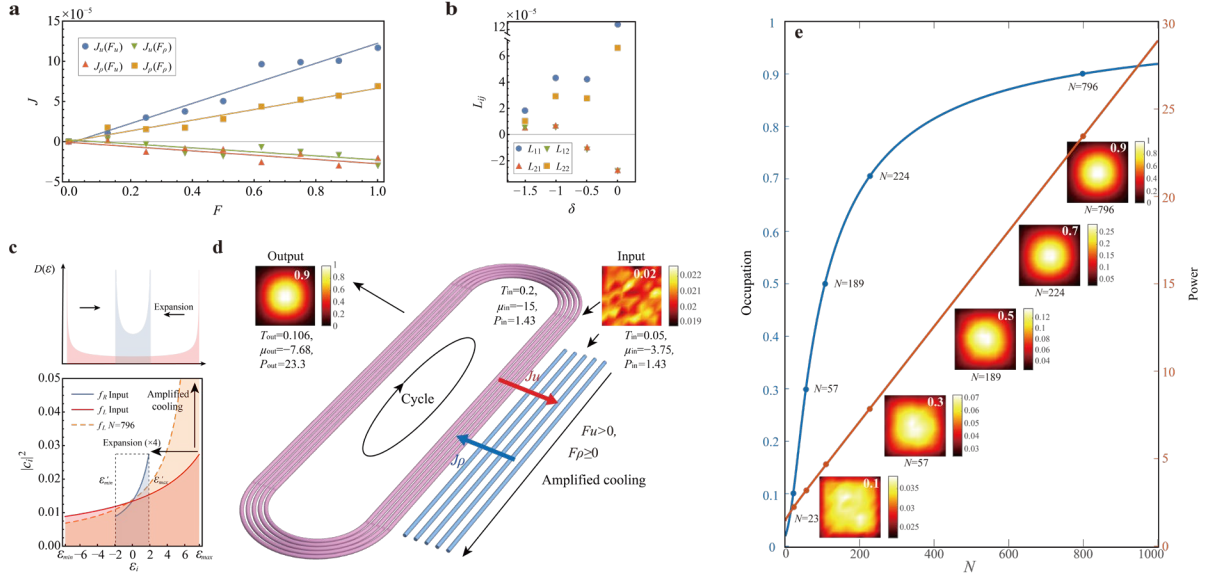


Figure 1. a. The power and energy flux between two optical lattices have linear relations with the thermodynamic forces, which is introduced by perturbing the system away from equilibrium. b. The value of Onsager coefficients L varies with an overall detuning introduced in one of the subsystems. c. Density of state management can also be introduced by isentropic expansion/compression. d. A schematic demonstration of amplified cooling. e. The modal occupancy of the fundamental mode and the corresponding near-field image after different round-trip N .

Explicitly, the energy and photon flows mediated through the interlayer are defined as $J_u = -dU_L/dz = dU_R/dz$ and $J_\rho = -dP_L/dz = dP_R/dz$ respectively, which are driven by the thermodynamic forces as given by $F_u = 1/T_L - 1/T_R$ and $F_\rho = \mu_L/T_L - \mu_R/T_R$. Under Onsager's reciprocity relation, $\hat{\mathbf{L}} = \hat{\mathbf{L}}^T$, i.e., $L_{12} = L_{21}$.

To validate these hypotheses, we conduct numerical simulations by directly integrating the corresponding nonlinear Schrödinger equations (NLSE) when two connected lattices are pushed away from their equilibrium states. Figure 1a demonstrates that, during such non-equilibrium processes, the flux and force indeed follows a linear relation, in full accord with the theoretical predictions. Moreover, the Onsager's reciprocity relation is confirmed by the same slopes between $J_\rho(F_u)$ and $J_u(F_\rho)$, i.e., $L_{12} = L_{21}$. In this particular case, L_{12}/L_{21} so happens to be negative, implying that a positive force can induce a negative flux that is in the opposite direction of the force. More importantly, the Onsager coefficient can be tuned by altering the density of state of the structure. For example, Fig. 1b illustrates how the L coefficients vary when an overall detuning in one of the subsystems is introduced. Similarly, such effects can be accomplished by isentropically expanding/compressing the optical lattice (Fig. 1c) or by changing the structure of the lattices, to mention a few.

The ability to manipulate Onsager coefficients in photonic configurations empowers us to devise an all-optical cooling scheme based on a carefully selected set of Onsager coefficients achieved by controlling the density of state of individual subsystems. As depicted in Fig. 1d, in this scenario, the signal beam in the waveguide loop (purple) undergoes a cooling process in a grand-canonical-like setting, where both the optical power and energy can be exchanged with the auxiliary lattice (blue). Throughout this process, the optical power is transferred into the signal beam, while its energy is extracted. Consequently, the signal beam becomes brighter (higher power) and cleaner (lower energy). As illustrated in Fig. 1e, our simulation results demonstrate that an approximately 16-fold power improvement can be attained, which accompanied by a substantial increase in the percentage modal occupancy in the fundamental mode – from a mere 0.2% to a remarkable 90%

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