Many-body thermal invisibility beyond cloaking and many-body thermal diode with invisibility

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I. Introduction

Invisibility has recently been achieved in optics[1], electromagnetics[2], acoustics[3], thermotics[4], fluid mechanics[5], and quantum mechanics[6]; it was realized through a properly designed cloak structure with unconventional (anisotropic, inhomogeneous, and singular) material parameters, which limit practical applications. Here we show, directly from the solution of Laplace's equation, that two or more conventional (isotropic, homogeneous, and nonsingular) materials can be made thermally invisible by tailoring the many-body local-field effects. Our many-body thermal invisibility essentially serves as a new class of invisibility with a mechanism fundamentally differing from that of the prevailing cloaking-type invisibility. We confirm it in simulation and experiment. Further, the concept of many-body thermal invisibility helps us propose a class of many-body thermal diodes: the diodes allow heat conduction from one direction with invisibility, but prohibit the heat conduction from the inverse direction with visibility. This work reveals a different mechanism for thermal camouflage and thermal rectification, and it also suggests that besides thermotics, many-body local-field effects can be a convenient and effective mechanism for achieving similar controls in other fields, e.g., optics, electromagnetics, acoustics, and fluid mechanics.

II. 2D Thermal Invisibility

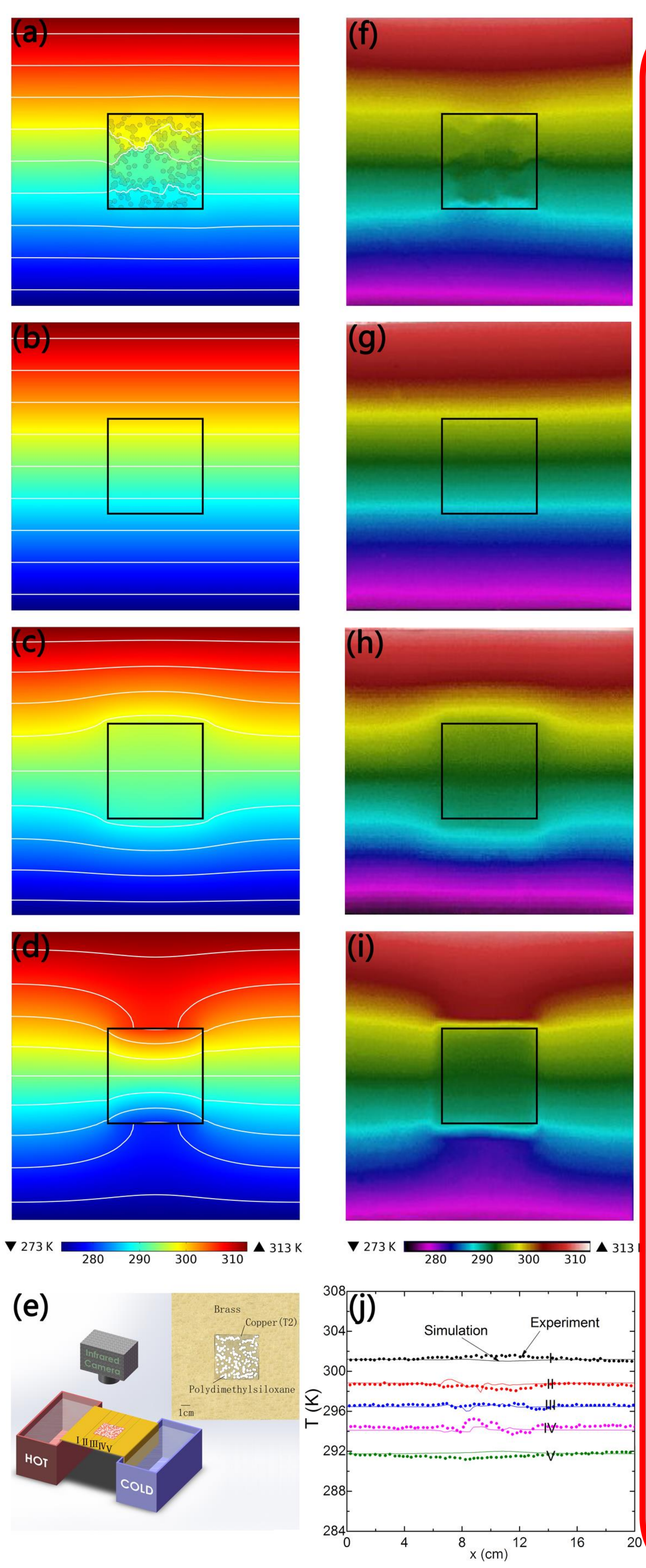

Fig. 1. Two-dimensional results of (a-d) finite-element simulations and (f-i) experiments based on (e) the experimental setup: the white lines in (a-d) represent the isothermal lines. (a,f) show a 20 cm×20 cm system, which owns a central square area (6.7 cm×6.7 cm) containing the first material [as shadowed in the central square area of (a)] of thermal conductivity 0.15 W/(m·K) and area fraction 36.4% randomly embedded in the second material of 400 W/(m·K) and 63.6%; the first (second) material can be seen as an assembly of a kind of circular particles with different sizes; outside the central square area is the environment occupied by the material of κ_m =109 W/(m·K). (b,g) show the case of the pure environmental material κ_m =109 W/(m·K). (c,h) and (d,i) are same as (a,f), respectively, but the central square area only includes the material of 400 W/(m·K) and 0.15 W/(m·K). (j) shows the quantitative comparison of temperature distribution between simulation and experiment, for the structure of (a) and (f). The "I-V" represent the five positions as depicted in (e).

III. Many-body Thermal diode

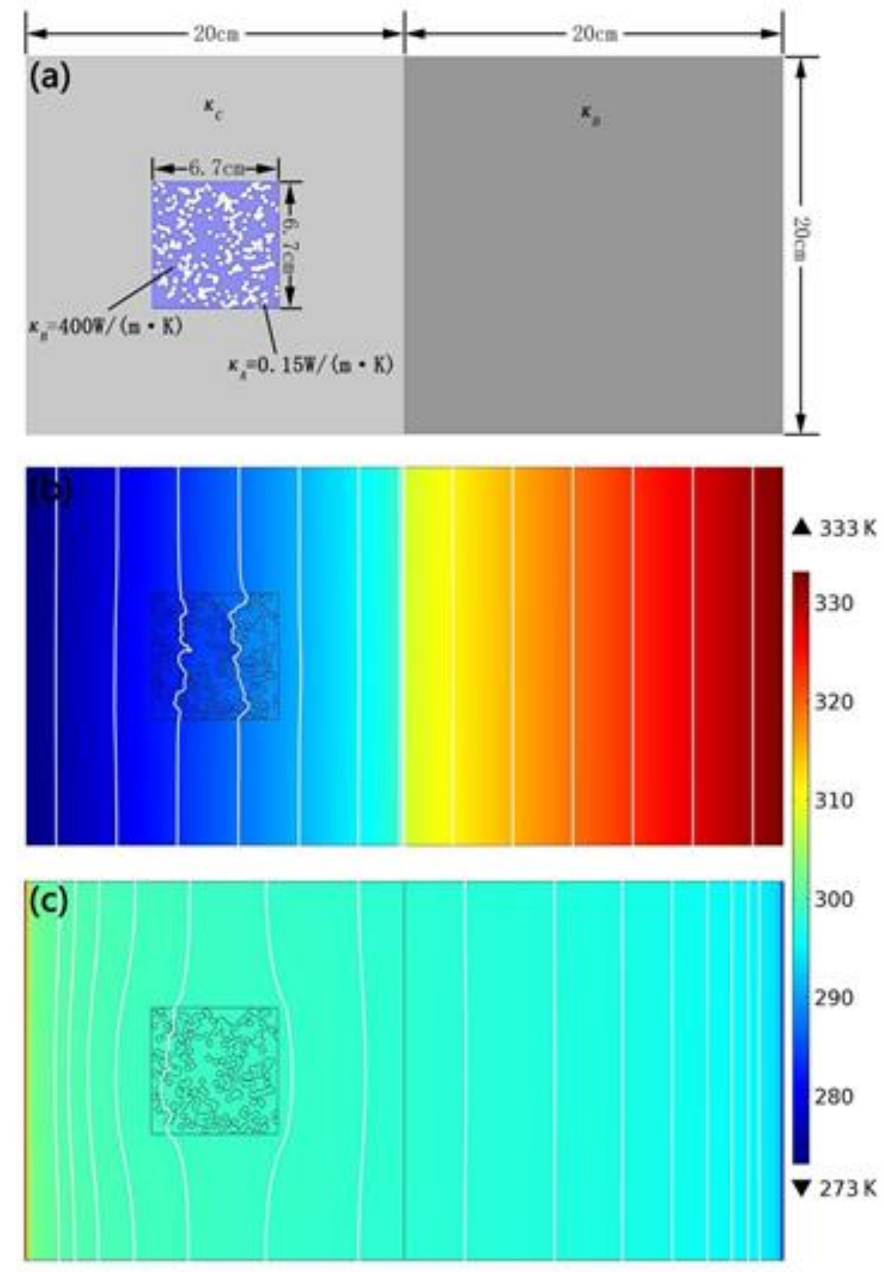

Fig. 2. Many-body thermal diode: simulation results. (a) schematic graph, where the left part has a central square area containing material A randomly embedded in material B with area fraction 36.4%. Materials C and D occupy the other areas with temperature-dependent thermal conductivities $\kappa_C = \kappa_l+(\kappa_s-\kappa_l)/\{\exp[(T-Tc)/1.0]+1\}$ and $\kappa_D=\kappa_l+(\kappa_s-\kappa_l)/\{\exp[-(T-Tc)/1.0]+1\}$ with κ_l = 0.026 W/(m·K) (e.g., air), κ_s = 109 W/(m·K) (e.g., brass) and Tc = 298 K, which may be experimentally realized with the aid of shape-memory alloy according to the design depicted in Fig. 2 of Ref. [7]. (b) the distribution of temperature and isotherms in the thermal diode for high flux $J_H = 1.31\times10^4$ W/m². (c) same as (b), but the positions of the heat source and cold source are exchanged, thus showing the case of low flux $J_L = 3.88\times10^2$ W/m². The corresponding rectification ratio $(J_H - J_L)/(J_H + J_L)$ = 94%.

IV. Theoretical context

Consider a two-dimensional square system, which contains a central square area and an environment occupied by a material with thermal conductivity κ_m surrounding the central square area. n kinds of circular particles, each with thermal conductivity κ_i and area fraction p_i ($i = 1, 2, 3, \cdots, n$), occupy the whole central square area with a random distribution, thus yielding a many-body system. In the presence of an external temperature gradient, if the existence of the central square area does not disturb the temperature distribution or heat flow in the environment, the central square area is thermally invisible. For this purpose, we need to set the central square area to possess a special effective thermal conductivity that must be equal to κ_m. In this regard, what we need is to let the thermal contrasts (described by the Clausius-Mossotti factor) of all the particles within the central square area be cancelled out. Thus, we obtain

$$(\text{Clausius}-\text{Mossotti factor})_{2D} = 0, \qquad (1)$$

where $(\cdots)_{2D}$ denotes the area average of $\cdots$ over the central square area. Equation (1) owns at least two features. On one hand, when the thermal conductivities of the particles, κ_i, satisfy Eq. (1), the effective thermal conductivity of the central square area equals κ_m. This is because the many-body local-field effects lead to the overall disappearance of the thermal contrasts between all the particles and the environment. On the other hand, if the central square area is divided into plenty of sub-areas, each including many particles distributed randomly, the equivalent thermal conductivities of the sub-areas are still equal to κ_m according to Eq. (1). That is, these sub-areas become homogeneous indeed.

V. Conclusion

we have experimentally demonstrated that tailoring many-body local-field effects can cause a many- body system to be thermally invisible in an environment. This invisibility has a mechanism essentially differing from that of the well-known cloaking-type invisibility. Our concept of many-body thermal invisibility has helped to propose a class of many-body thermal diodes with invisibility. This work provides a new design strategy for thermal camouflage and thermal rectification. And it also implies that, besides thermotics, many-body local-field effects could be a useful mechanism for achieving similar controls in other fields like optics/electromagnetics, acoustics, and fluid mechanics, where the electric permittivity and magnetic permeability, mass density and modulus, and diffusion coefficient respectively play the same role as the thermal conductivity in thermotics.

Reference

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