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Design and realization of thermal camouflage with many-particle systems

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ABSTRACT

An object can be found and identified by detecting its scattering signature of various physical fields, e.g., electromagnetics, acoustics, thermotics, etc. Similar to optical illusion, a thermal camouflage device can replace an expected object without altering the heat scattering pattern. Here, we propose and realize a two-dimensional metasurface, which is capable of controlling the heat flow and can be used as a device for misleading thermal sensors. The thermal metasurface is composed of conventional particles with many-body local-field effects. Our experiments and finite-element simulations have confirmed the thermal camouflage effect for both line and point heat sources, demonstrating the performance of thermal illusion. Also, we show that this many-particle structure can be extended to three-dimensional systems, which opens a door for designing applicable camouflage devices in the future.

1. Introduction

Controlling various physical fields, including optics [1–3], electromagnetics [4–6], magnetics [7,8], acoustics [6,9,10], etc., is highly desired for the design of field manipulation devices. Among all these fields control devices, thermal metamaterial [11,12,14–19,21–27] has recently stimulated great interest due to the important role it played in thermotics devices design. Along with rapid development of artificial technology, many thermal metamaterials with novel thermal properties have been experimentally demonstrated, such as invisibility cloaks [11–17] (which are used to let heat flow around an object as if the object does not exist), thermal concentrators [18–20] (which are used to concentrate heat into a specific region) and rotators [19,21] (which are used to rotate the flow of heat as if it comes from a different angle).

Instead of invisibility cloaks that can change an expected object into nothing, a thermal camouflage device [23–27] can replace an object A by using special designed structures of an object B without changing heat flux pattern. Recently, there has been a surge of attention focused on the designs of thermal camouflage devices, including Laplace-equation-based devices [23,24] which can exhibit thermal illusions not only in a steady state but also in a transient state, transformation-optics-based devices [25,26], and camouflaging devices in multiphysical fields [27]. However, for the former design of camouflage devices, unconventional material parameters are required to experimentally realize thermal camouflage. Namely, the parameters of the materials have to satisfy either the singularity in the bilayer-cloak designs or inhomogeneity in the coordinate-transformation designs.

In this paper, we report a thermal camouflage device based on many-body local-fields effect, which can simulate the thermal scattering signature of an expected object in the environment. In contrast to the previous designs which require unconventional material properties, our many-particle metasurface is composed of conventional particles based on naturally occurring materials. In an actual experimental setup, the proposed device is carefully examined for both line and point heat/cold sources by inserting thermal sensors, demonstrating an excellent sensor misleading performance. Furthermore, three-dimensional simulated results show that this structure can be extended to practical camouflage device.

The function of many-particle structure and its realization of sensors misleading are schematically illustrated in Fig. 1. A speaker exposed in a thermal conduction field can be detected by three thermal sensors because of the thermal conductivity difference between the speaker and the background environment. However, when the speaker is replaced by a many-particle structure with well-designed effective thermal conductivity, the thermal properties of the speaker can be simulated by the many-particle structure, and able to provide three thermal sensors the same thermal signature of the speaker. Therefore, the thermal sensors which are given a thermal signature of an expected object can be 'deceived' by precisely designed many-particle camouflage structure.

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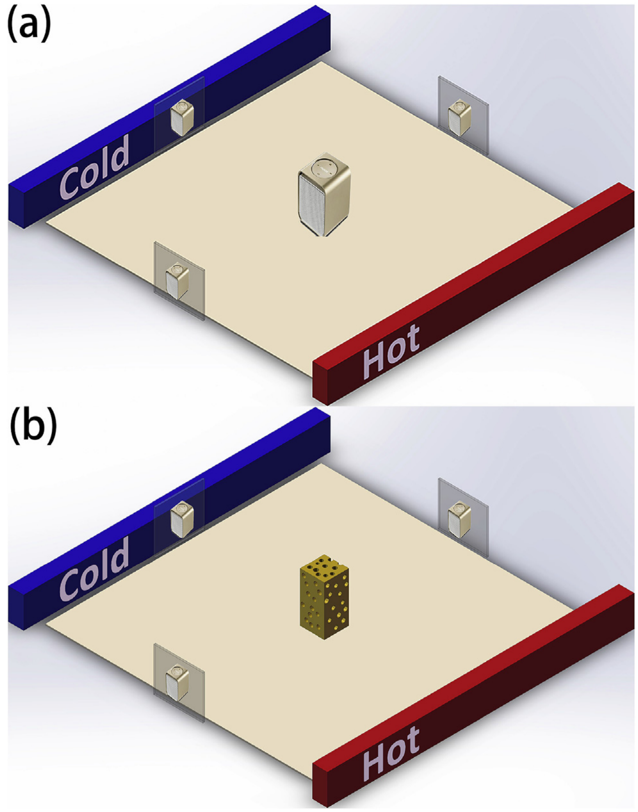

Fig. 1. Schematic illustration of the thermal sensor misleading device: (a) Three thermal sensors can detect a speaker in the heat conduction field; (b) Well designed many-particle device can "deceive" thermal sensors by providing them the same thermal signature of the speaker.

2. Theory

We consider two simple two-dimensional square systems. In the first system [Sample I in Fig. 2], n kinds of circular particles, each with thermal conductivity κ_i and area fraction p_i $(i = 1, ..., n)$, occupy the whole central square region with a random distribution (the many-particle structure). Four small square areas, which are placed around the central square region with thermal conductivity κ_d, play the role of thermal detectors, and the environment background is occupied by a material with thermal conductivity κ_b. For comparison, in the second system [Sample II in Fig. 2], the central square region is replaced by a uniform material serving as an expected object with thermal conductivity κ_o , and the same thermal detectors and environment background with that of first system are used. In the presence of an external temperature gradient, if the temperature distribution or heat flows at the detectors for two systems are the same, the many-particle structure is considered to be a sensor-misleading device. For this purpose, it is necessary to set the many-particle structure to possess an effective thermal conductivity κ_e that must be equal to κ_o .

For a single circular particle with thermal conductivity κ_i , area fraction p_i and radius R embedded in a uniform two-dimensional host with effective thermal conductivity κ_e, the solution of the Laplace's equation in polar coordinates (r,θ) is

$$T_{\text{inner}}(r, \theta) = a_0 + b_0\ln(r) + \sum_{m=1}^{\infty}[a_m\cos(m\theta) + b_m\sin(m\theta)]r^m + \sum_{m=1}^{\infty}[c_m\cos(m\theta) + d_m\sin(m\theta)]r^{-m},$$

$$T_{\text{outer}}(r, \theta) = a'_0 + b'_0\ln(r) + \sum_{m=1}^{\infty}[a'_m\cos(m\theta) + b'_m\sin(m\theta)]r^m + \sum_{m=1}^{\infty}[c'_m\cos(m\theta) + d'_m\sin(m\theta)]r^{-m},$$

where $T_{\text{inner}}(r, \theta)$ and $T_{\text{outer}}(r, \theta)$ denote the distribution of temperature in the particle and the host, respectively. Here a_0, b_0, a_m, b_m, c_m, d_m, a'_0, b'_0, a'_m, b'_m, c'_m, and d'_m are undetermined coefficients. The accompanying boundary conditions are

$$T_{\text{inner}}(r = 0) < \infty,$$

$$T_{\text{outer}}(r \to \infty, \theta) \to T_0 + C\, r\cos(\theta),$$

$$T_{\text{inner}}(r = R) = T_{\text{outer}}(r = R),$$

$$\kappa_e \left.\frac{\partial T_{\text{outer}}}{\partial r}\right|_{r=R} = \kappa_i \left.\frac{\partial T_{\text{inner}}}{\partial r}\right|_{r=R},$$

Here T_0 denotes the temperature at $r = 0$, C is a constant depending on applied temperature gradient. Thus, we can obtain the temperature

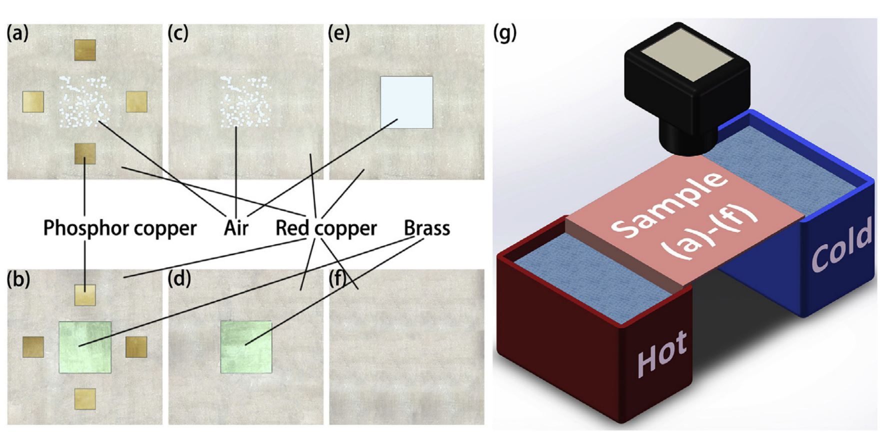

Fig. 2. (a–f) Experimental samples I-VI and (g,h) experimental setup. (a–f) show a 20 cm×20 cm system, which owns a central square area (6.7 cm×6.7 cm). Brass (b,d) with thermal conductivity 148 W/(m·K) is serving as an expected object. For (a,c) the many-particle structure, the central square area contains air particles of thermal conductivity 0.026 W/(m·K) and area fraction 31.03% randomly embedded in red copper of 390 W/(m·K) and 68.97%; the red copper can be seen as an assembly of circular particles with different sizes; outside the central square area is the background environment also occupied by red copper. Four small phosphor copper square areas in (a,b) with 54 W/(m·K) play the role of thermal detectors. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)