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Letter

Achieving thermal magnification by using effective thermal conductivity

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HIGHLIGHTS

- Thermal magnification was achieved by using effective thermal conductivity.
- The magnification device only needs isotropic and homogeneous materials that are easy to obtain in nature.
- The proposed method proves more flexible for multilayered materials and simpler for non-spherical objects under non-uniform thermal fields.
- The method can also be extended to other fields and applications governed by Laplace equation.

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ABSTRACT

A thermal magnification device is proposed by using effective thermal conductivity. Different from transformation optics method, the magnification design is realized analytically by enforcing equality of effective thermal conductivity on the magnification device and the reference case in specified domains. The validity of theoretical analysis is checked by numerical simulation results, which demonstrates the magnifying effects of the proposed design. The device only needs isotropic and homogeneous materials that are easy to obtain in nature. It is also shown that the obtained magnifying conditions are the same as those derived by separation of variables. But the proposed method proves more flexible for multilayered materials and simpler for non-spherical objects under non-uniform thermal fields. It can also be extended to other fields and applications governed by Laplace equation.

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Transformation optics theory was first proposed by Pendry and Leonhardt [1, 2] in the field of achieving invisibility of electromagnetic waves. Since then transformation optics aroused extensive interests and there had been significant progress in theoretical and experimental approaches in many fields, including acoustics [3-5], magnetic field [6-8], elastic wave [9, 10], matter waves [11, 12] and thermodynamics [13-16]. Among the various applications, the most famous work was the invisible cloak which bent the light around the concealed area and made an object invisible to the observer. Later the concept of cloaking was extended. Lai et al. [17] proposed the concept of illusion optics which made an object of arbitrary shape and material properties appear exactly like another object of some other shape and material makeup. Then, the illusion device was experimentally demonstrated [18-21]. An invisible gateway was first experimentally realized by using a transmission-line medium [18]. Later on, dc illusion devices [19], radar ghost illusion devices [20], and acoustic illusion devices [21] were respectively proposed and verified experimentally by similar methods.

The illusion devices were designed to make a target image misleading due to physiological illusion or a specific visual trick, while a magnification device could change the original object into a larger one to a detector. The magnification device was indeed an application of illusion optics [22-25]. The first magnification device known as a super scatter was proposed by Yang et

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al. [22] based on the concept of complementary media. Such a device could enhance the electromagnetic wave scattering cross section of an object so that it behaved like a scatter bigger than the scale of the device. However, the device was realized by a negative refractive material shell that was difficult to implement experimentally [26, 27]. Xu et al. [28] first verified the super scatter by experiments where only anisotropic and inhomogeneous media with positive components were required. In his experiment, combination of compact electric and magnetic resonance particles was used to fulfill anisotropic and inhomogeneous materials requirements.

It has been proved that the anisotropic and inhomogeneous materials required by transformation optics method were difficult even impossible to realize exactly in practical. Many works [29-34] have been done in designing magnification devices with isotropic and homogeneous materials based on the method of separation of variables. This letter proposed a magnification designing method with the concept of effective thermal conductivity. The results of the proposed method showed good agreement with the works by Mei et al. [33, 34]. Compared with Mei's works, the method in this letter was simpler and more effective without solving Laplace equation. For non-spherical objects and non-uniform thermal fields, the proposed method showed more flexibility and convenience. In addition, separation of variables would be more complicated for multiple conducting layer materials, while more layers offered more adjustable design variables such as the thickness and conductivity of each layer. The proposed method could be applied not only to thermodynamics but also to other fields governed by Laplace equation.

An intuitive schematic diagram was illustrated in Fig. 1 to show the working principle of the magnification device. Without losing generality, the original object was supposed to be a round one with radius R_1 and thermal conductivity σ_1. When embedded in the background medium, the original object was detected. However, if the object was wrapped by a designed coating layer with thickness $R_2 - R_1$ and conductivity σ_2, it will be wrongly identified as another one with different size and conductivity to the observers. In fact, the wrapped object will not be detected as an object with radius R_2 but as an enlarged one with radius R_3 and conductivity σ_1. In this case, the original object was magnified to the observers, and a kind of illusion was thus obtained. To quantitatively demonstrate the magnifying effect, the magnifying factor was defined as $\tau = R_3/R_1$ [33, 34].

In Mei's works [33, 34], the method of separation of variables was used, and theoretical temperature distribution was obtained. By enforcing equality of temperatures on the same boundary $r = R_3$, the external temperature distribution $r \geqslant R_3$ became identical. In this letter, the method of effective thermal

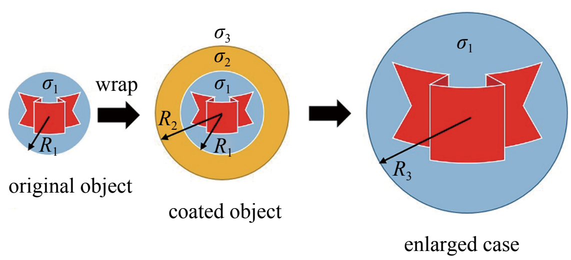

Fig. 1. The working principle of a thermal magnification device.

conductivity was employed to achieve the magnifying effect. In the following, Hashin-Shtrikman formula [35, 36] was introduced and then applied to the design of thermal magnification device. The effective thermal conductivity of the isotropic multilayered spheres could be estimated by

$$\sigma_*^l = \sigma_l + \frac{3(1-f_l)\sigma_l(\sigma_*^{l-1} - \sigma_l)}{3\sigma_l + f_l(\sigma_*^{l-1} - \sigma_l)}, l = 2, 3, \cdots, n, \tag{1}$$

where f_l was the volume fraction of the lth layer in l-layer sphere (see in Fig. 2), σ_*^l and σ^l respectively represented the effective thermal conductivity of the l-layer sphere and the thermal conductivity of the lth layer.

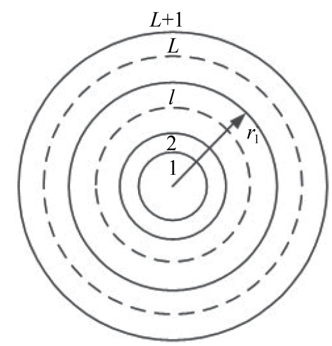

Fig. 2. The cross-section configuration of a multilayered sphere.

For multilayered spheres, f_l was obtained by

$$f_l = 1 - \frac{r^3{}_{l-1}}{r^3{}_l}. \tag{2}$$

When Eq. (1) was extended to cylindrical objects, f_l was achieved by

$$f_l = 1 - \frac{r^2{}_{l-1}}{r^2{}_l}. \tag{3}$$

It was shown in Fig. 1 that temperature distribution in the region $r \geqslant R_3$ should be identical for the coated object and the reference case. Thus, the effective thermal conductivity of the domain $r < R_3$ for the coated object should be same to the enlarged case. The magnification condition for the three-layered sphere could be obtained by

$$\sigma_*{}^3 = \sigma_1. \tag{4}$$

It should be noted that the device was a coated sphere ($l = 2$). The 3th layer, which was part of the background medium, was indeed virtual and self-defined. The three layers referred to the original object $r \leqslant R_1$, the coating layer $R_1 \leqslant r \leqslant R_2$ and the matrix layer $R_2 \leqslant r \leqslant R_3$. In Eqs. (1) and (4), the conductivity σ_2 and the radius r_2 of the coating layer were the unknown parameters to be determined. When the conductivity σ_2 was predefined, the radius r_2 will be the design variable, and vice versa. In the following, a cylindrical magnification device with predefined r_2 was considered. Substituting Eqs. (1) and (3) into Eq. (4), the thermal conductivity of the coating layer was achieved by following mathematical formulas:

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