Physics Letters A ••• (••••) •••–•••

Contents lists available at ScienceDirect

Physics Letters A

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Quasi-invisible thermal cloak based on homogenous materials

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ARTICLE INFO

Article history:
Received 8 November 2017
Received in revised form 17 May 2018
Accepted 29 May 2018
Available online xxxx
Communicated by V.A. Markel

Keywords:
Metamaterials
Thermal cloak
Transformation thermodynamics
Thermal conduction

ABSTRACT

Invisible thermal cloak, which cancels distortions of temperature distribution caused by objects, has many potential applications in thermal engineering. In this letter, we theoretically proposed and simulatively verified a new design method for quasi-invisible thermal cloak. Different from conventional transformation thermodynamics that focus on complete invisibility, our method only decreases the effective scale of objects to small enough and realizes a quasi-invisible cloaking effect in thermal conduction regime. However, this quasi-invisible cloak has the same effect as that of invisible thermal cloak in practical engineering. More important, our cloak is easy to construct by natural materials due to its homogenous thermal properties and can cloak objects with different shapes and properties. These characters make the clock more comfortable for engineering applications.

1. Introduction

Recently, electromagnetic metamaterials combined with transformation electromagnetics have attracted much attention, because of their capability of manipulating electromagnetic energy [1–3]. The corresponding methods and concepts are also extended to heat transfer regime [4,5], and promote the inventions of novel thermal devices, such as heat flux concentrator [6–8], heat flux reversers and guiders [9–11], transient thermal shield [12], uniform plate heater [13], macroscopic thermal diodes [14], remote cooling thermal lens [15], thermal illusion device [16–19], and thermal radiative camouflage [20].

Analog to optical cloak, researchers proposed thermal cloak in thermal conduction regime. The objects covered by the thermal cloak will not influence the temperature profiles outside the cloak. Consequently, they will not be detected by observers or probes outside the cloak. In this sense, the objects are invisible for thermal conduction. The cloak may have many potential applications in thermal engineering, such as heat flux manipulation, thermal shielding, improving performance of thermal sensors, etc., and therefore has been investigated by many researchers.

Guenneau et al. [21] proposed the transformation thermodynamics method and theoretically designed a thermal cloak to make a circular object invisible in 2-dimensional (2D) thermal conduction regime. Yang et al. [22] extended the cloak for arbitrarily shaped objects. Schittny et al. [23] and Narayana et al. [24] realized 2D thermal cloak experimentally by micro-structured materials and layer engineering materials, respectively. Besides the transformation thermodynamics, neutral inclusions concept has also been used for thermal cloak design [25]. Han et al. [26] proposed a thermal cloak for 2D thermal conduction based on the neutral inclusions concept. Chen et al. [27] extended the design to 3-dimensional (3D) situation and provided more critical analysis. Han et al. [28] and Xu et al. [29] constructed the cloak by simple materials for 2D and 3D situations in practice, respectively. Besides these, the transient thermal cloak [30], the thermal ground cloak [31] and the cloak in microscale [32] are also proposed recently.

In conventional transformation thermodynamics, linear coordinate transformations are mostly applied, which normally result in cloaks with **both inhomogeneous and anisotropic** thermal conductivities. Then many kinds of materials and structures are required to construct the cloaks, which largely increases the fabrication complexity. Furthermore, the perfect cloaks predicted by the method should possess very low (close to 0) or very high (close to infinity) thermal conductivities (along different directions) in some regions, far beyond the scope of real materials, but can only be realized approximately in engineering. The effects of the approximations, however, have never been analyzed exactly. These challenges make the prefect cloaks difficult to construct. Ooi et al. [33] applied nonlinear coordinate transformations to design the perfect cloaks. Their method can locally decrease the inhomogeneity of properties, but faces to the same challenges those appear in linear transformations.

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https://doi.org/10.1016/j.physleta.2018.05.052
0375-9601/

To make thermal cloaks homogenous, the neutral inclusions concept has been employed [20,21]. In this method, the cloaks will have homogeneous and isotropic thermal conductivity and can be realized very easily. These cloaks, however, have only low flexibility, because their parameters strongly depend on the properties and shapes of objects. Objects with different thermal conductivities will need different cloak. In addition, since the complexity in mathematics, this method has only been applied to cloak circular or spherical objects, while other shaped objects are rarely discussed. Therefore, it is still a large challenge to develop new approaches to design high flexible and easy-fabricated thermal cloaks in various applications.

In this letter, by combining power function coordinate transformation and linear coordinate transformation, we theoretically proposed and simulatively verified a new design method for thermal cloak with high flexibility. Different from conventional transformation thermodynamics that focus on complete invisibility, our method suggests a quasi-invisible cloak by decreasing the effective scale of objects to small enough in thermal conduction regime. However, this quasi-invisible cloak was demonstrated to have the same effect as that of perfect invisible thermal cloak in practical engineering. Especially, this quasi-invisible cloak can be constructed by anisotropic but homogenous materials, which is much easier in fabrication than conventional thermal cloaks which need both anisotropic and inhomogeneous materials. In addition, the cloak designed by this method can be used to cloak objects with different shapes and properties when designed under extreme conditions. These characters make quasi-invisible cloak have high flexibility and pave the way for potential applications in thermal engineering.

2. Theory and design

Objects will disturb the temperature field of matrix medium when inserted to them. The magnitude of the disturbance depends on two factors: (1) the differences in properties between the objects and the medium, and (2) the scales of the objects. The large differences in properties and the large scales of the objects will lead to large disturbance. However, if the scales of the objects are very small, the disturbance will become weak, no matter how large the difference in properties is. In engineering, thermal probes or sensors have finite resolutions δT. If a cloak can reduce the effective scales of objects small enough, and make the disturbance lower than the resolutions of probes, the objects will not be detected in practice. In this sense, the objects will be quasi-invisible. Based on this idea, we can design the quasi-invisible thermal cloak through transformation thermodynamics, in which the effective scales of objects reduce not to zero but only to a finite small value.

For steady heat conduction without heat source, the governing equation can be written as $\nabla \cdot (\kappa \nabla T) = 0$, where κ is the thermal conductivity, and T is the temperature. Based on the transformation thermodynamics, the thermal conductivity at a point in physical space (after transformation) can be calculated as

$$\boldsymbol{\kappa}' = \frac{\mathbf{J}\kappa\mathbf{J}^T}{\det(\mathbf{J})}, \qquad (1)$$

where $\mathbf{J}^T$ and $\det(\mathbf{J})$ are transform and determination of $\mathbf{J}$, respectively, and $\mathbf{J}$ is the Jacobi matrix of the coordinate transformation from illusional space $\boldsymbol{r}$ (before transformation) to physical space $\boldsymbol{r}'$ $\mathbf{J} = \partial(x', y', z')/\partial(x, y, z)$.

Considering two dimensional case, where a circular shaped object with radius r_o is inserted into a medium and disturbs the surrounding field. To make the object quasi-invisible, a ring cloak with outer radius r_c is applied. In previous studies, the ring cloak region can be regarded as compressed by a circular region with

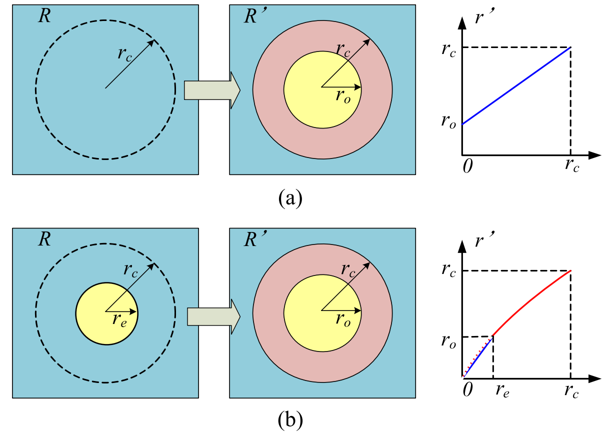

Fig. 1. The schematics of (a) the linear transformation and (b) the transformation proposed in this paper.

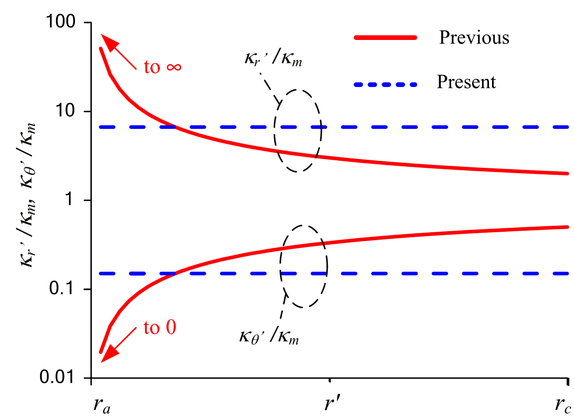

Fig. 2. Thermal conductivity of the thermal cloak varying with radius.

radius r_c, which means the effective radius of the object r_e is zero. For quasi-invisible thermal cloak, the cloak region can be regarded as compressed by a thick annular ring with inner radius r_e ($0 < r_e < r_o$). The schematic of the transformation is shown in Fig. 1. In previous studies, linear coordinate transformations are always considered due to their simplicity as

$$\begin{cases} r' = \frac{r_c - r_o}{r_c} r + r_o, \quad (r < r_c), \\ \theta' = \theta. \end{cases} \qquad (2)$$

Then the thermal conductivity of the cloak can be calculated by Eq. (1) as

$$\begin{cases} \kappa_r' = \kappa_m \frac{r' - r_o}{r'}, \\ \kappa_\theta' = \kappa_m \frac{r'}{r' - r_o}, \end{cases} \qquad (3)$$

where κ_m is the thermal conductivity of medium. Clearly, both components vary with r', which implies that the thermal cloak has inhomogeneous and anisotropic properties. In addition, at the inner bound of the cloak ($r' = r_o$), abnormal thermal conductivities can be observed, i.e. $\kappa_r' \to 0$ and $\kappa_\theta' \to \infty$, as shown in Fig. 2.

For our quasi-invisible thermal cloak, a power function transformation is proposed for the cloak region as

$$\begin{cases} (\frac{r'}{r_c}) = (\frac{r}{r_c})^C, \quad (r_e < r < r_c), \\ \theta' = \theta, \end{cases} \qquad (4)$$

where the power exponent C can be determined as

$$C = \frac{\ln(r_o/r_c)}{\ln(r_e/r_c)}. \qquad (5)$$