Thermal Cloak with Switchable Manipulating Direction Based on Linear Transformation Thermotics

Tiancheng Han,* Wei Luo, Guang Yang and Longjiang Deng*

Abstract

Thermal metamaterials, especially invisibility cloaks, have been attracting more and more attention due to their powerful manipulation on heat transfer. Here, we design a diamond shaped thermal cloak based on linear transformation thermotics. In contrast to the same shaped electromagnetic cloak that functions in only x direction, the proposed thermal cloak may function in both x and y directions. More interestingly, the manipulating direction is switchable, depending on whether the inner layer of the thermal cloak is a thermal insulator or a thermal superconductor. This is not possibly achievable for the same shaped electromagnetic cloak. It changes the usual perception that transformation thermal metamaterials are just a direct and simplified derivative of the transformation-optic counterpart. We experimentally validate the proposed design, which agrees well with the simulation results. The proposed methodology may open a new avenue to manipulating the Laplacian fields.

Keywords: Thermal metamaterials; Invisibility cloak; Transformation thermotics; Switchable manipulating direction.

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1. Introduction

Since the beginning of 21st century, metamaterial technology has attracted considerable attention and shows great potential in controlling various physical fields.^[1,2] Especially with the emergency of transformation optics^[3,4] and scattering cancelling method,^[5] a plethora of unprecedented metamaterials/meta-devices have been successfully demonstrated.^[6] One of the most attractive functionalities is invisible cloaking that prevents electromagnetic waves from entering the cloaking region without perturbing the exterior fields.^[7-9] Inspired by the metamaterial progress in electromagnetic/optics realm, thermal metamaterials was first theoretically investigated by Huang's Group,^[10,11] and then experimentally demonstrated by Narayana *et al.*^[12] Subsequently, transformation thermodynamics, which is extended from transformation optics,^[1,2] is demonstrated theoretically^[13] and experimentally.^[14] Meanwhile, inspired by the scattering cancelling method,^[5] bilayer thermal cloaks are experimentally demonstrated,^[15,16] and further extended to multi-physical cloak,^[17] anisotropic cloak,^[18] and thermal

camouflage.^[19] Due to the powerful manipulation on heat transfer, thermal metamaterials have attracted more and more attention.^[20-22]

Though thermal metamaterials are extended form electromagnetic/optical metamaterials, there are some fundamental difference between them, which is attributed to their different governing equations. For example, by using only two naturally occurring materials, cylindrical thermal cloak has been theoretically^[23] and experimentally^[12] demonstrated. However, such a strategy cannot be utilized to the design of a cylindrical electromagnetic cloak.^[24] Another example is that bilayer thermal cloaks have been theoretically and experimentally validated as exact ones rather than reduced ones.^[15,16] However, bilayer electromagnetic cloaks are approximated ones and function only for dipolar fields.^[5] Therefore, a widely accepted characteristic of electromagnetic metamaterials may be subverted in thermal metamaterials.

Here, a diamond shaped thermal cloak is designed based on linear transformation thermotics. The proposed thermal cloak may function in both x and y directions, which is completely different from the same shaped electromagnetic cloak that functions in only x direction.^[25] More interestingly, the manipulating direction is switchable, depending on whether the inner layer of the thermal cloak is a thermal insulator or a thermal superconductor. The proposed methodology, which makes no approximation in any

National Engineering Research Center of Electromagnetic Radiation Control Materials, State Key Laboratory of Electronic Thin Film and Integrated Devices, University of Electronic Science and Technology of China, Chengdu 610054, China

* Email: tchan@uestc.edu.cn (T. Han), denglj@uestc.edu.cn (L. Deng)

parameters, only requires naturally available materials for practical implementation. Experimental results are in good agreement with simulation results, which validates the design. Our method is applicable not only to thermal cloak, but also to dc electric cloak^[26] and dc magnetic cloak.^[27]

2. Design and analysis

Fig. 1 Schematic demonstration of the linear transformation for the design of a diamond shaped thermal cloak. $\Omega'(x', y')$ and $\Omega(x, y)$ correspond to virtual space and real space, respectively.

Without loss of generality, the diamond shaped thermal cloak is designed and demonstrated in two-dimensional case. We start from a linear coordinate transformation as shown in Fig. 1, in which a stretching transformation along y -axis is applied between the virtual space $\Omega'(x', y')$ and the real space $\Omega(x, y)$. A cloaking shell (green region) is thus formed and the central region can be utilized to hide objects. The linear coordinate transformation can be expressed as

$$x = x', y = b \frac{a-\delta}{b-\delta} \operatorname{sgn}(y') \left(1 - \frac{x'}{a} \operatorname{sgn}(x')\right) + \frac{b-a}{b-\delta} y' \quad (1)$$

According to the transformation thermotics,^[13] we derive the thermal conductivities of the diamond shaped thermal cloak (green region)

$$\vec{\kappa} = \kappa_0 \begin{pmatrix} \frac{b-\delta}{b-a} & -\frac{b(a-\delta)}{d(b-a)} \operatorname{sgn}(xy) \\ -\frac{b(a-\delta)}{d(b-a)} \operatorname{sgn}(xy) & \frac{b^2(a-\delta)^2}{d^2(b-a)(b-\delta)} + \frac{b-a}{b-\delta} \end{pmatrix} \quad (2)$$

where κ_0 is the thermal conductivity of the background material. When we consider $\delta \rightarrow 0$, Eq. (2) becomes

$$\vec{\kappa} = \kappa_0 \begin{pmatrix} \frac{b}{b-a} & -\frac{ab}{d(b-a)} \operatorname{sgn}(xy) \\ -\frac{ab}{d(b-a)} \operatorname{sgn}(xy) & \frac{a^2b}{d^2(b-a)} + \frac{b-a}{b} \end{pmatrix} \quad (3)$$

From Eq. (3) we can see that the thermal conductivities of the diamond shaped thermal cloak are spatially invariant. To validate our design, simulations based on the finite element method are carried out. We choose $a=25$ mm and $b=d=53$ mm throughout. We first consider a thin heat-insulating sheet ($\kappa \rightarrow 0$) located in the virtual space. When heat flows from left to right, the simulated temperature distribution is demonstrated in Fig. 2(a). It is seen that the temperature distribution is not disturbed as if nothing were there. According to the transformation in Fig. 1, the inner layer of the diamond shaped thermal cloak is thermally insulated in such a situation. Fig. 2(b) shows the temperature distribution of the cloak, which demonstrates an excellent cloaking performance. For comparison, a reference structure with only a thermally insulating ring is demonstrated in Fig. 2(c). It is clear that a

ring with low thermal conductivity repels the heat flux and makes the isothermal lines near the center of the reference structure significantly curved toward the center.

Fig. 2 Temperature distributions when the heat flows from left to right. (a) A heat-insulating sheet with thermal conductivity $\kappa \rightarrow 0$. (b) The thermal cloak with a heat-insulating inner layer. (c) The reference structure with only a thermally insulating ring. Isothermal lines (white) and streamlines (pink) are also represented in the panel.

Fig. 3 Temperature distributions when the heat flows from top to bottom. (a) A super-conductive sheet with thermal conductivity $\kappa \rightarrow \infty$. (b) The thermal cloak with a super-conductive inner layer. (c) The reference structure with only a thermally super-conductive ring. Isothermal lines (white) and streamlines (pink) are also represented in the panel.

Next, we consider a thin super-conductive sheet ($\kappa \rightarrow \infty$) located in the virtual space. Interestingly, it is found that the temperature distribution is not disturbed when the heat flows from top to bottom, as shown in Fig. 3(a). This means that, with a super-conductive inner layer, a thermal cloak is also achievable when the heat flows from top to bottom, which is validated in Fig. 3(b). Therefore, the proposed thermal cloak may function in both x and y directions. Moreover, the manipulating direction is switchable, depending on whether the inner layer of the thermal cloak is an insulator or a superconductor. This is completely different from the same shaped electromagnetic cloak that functions in only x

direction.^[25] For comparison, a reference structure with only a thermally super-conductive ring is demonstrated in Fig. 3(c). It is clear that a ring with high thermal conductivity attracts the heat flux and makes isothermal lines curve outwards both on its top and bottom.

Fig. 4 (a) Photo of the fabricated diamond shaped thermal cloak. (b) Detailed geometric parameters of the fabricated cloak. (c) Scheme of the experimental setup.

3. Implementation and fabrication

From Eq. (3) we can see that the proposed thermal cloak requires homogenous and anisotropic thermal conductivities. To eliminate non-diagonal elements, we need to do a rotation transformation as

$$\vec{\kappa} = \vec{Q} \begin{pmatrix} \kappa_u & 0 \\ 0 & \kappa_v \end{pmatrix} \vec{Q}^T \quad (4)$$

where $\vec{Q} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix}$.

By making Eq. (3) equal to Eq. (4), κ_u , κ_v , and α can be determined once the geometric parameters a , b , and d are

given. On the other hand, we can first choose arbitrarily κ_u , κ_v , and α , and the geometric parameters a , b , and d are accordingly determined. The relationship between them is give as follows

$$\frac{a}{d} = \frac{(\kappa_u - \kappa_v) \sin \alpha \cos \alpha}{\kappa_u \cos^2 \alpha + \kappa_v \sin^2 \alpha} \quad (5a)$$

$$\frac{a}{b} = 1 - \sqrt{\frac{\kappa_u \sin^2 \alpha + \kappa_v \cos^2 \alpha}{\kappa_u \cos^2 \alpha + \kappa_v \sin^2 \alpha} - \left(\frac{a}{d}\right)^2} \quad (5b)$$

$$\kappa_0 = \left(1 - \frac{a}{b}\right) (\kappa_u \cos^2 \alpha + \kappa_v \sin^2 \alpha) \quad (5c)$$

Fig. 5 Measured and simulated results when the heat flows from left to right. (a) Experimental setup. (b) The measured temperature profile for the thermal cloak. (c) The simulated temperature distribution for the thermal cloak. (d) The simulated temperature distribution for the reference structure.

For practical realization, we choose $\kappa_u = 8.25 \text{ W/m} \cdot \text{K}$, $\kappa_v = 1.4 \text{ W/m} \cdot \text{K}$, and $\alpha = 30.5^\circ$. If we set $a=25 \text{ mm}$, we derive $b=d=53 \text{ mm}$ and $\kappa_0 = 3.4 \text{ W/m} \cdot \text{K}$ according to Eq. (5). Based on effective medium theory,^[28] the required thermal conductivities can be achieved by drilling periodical holes in a stainless steel 304 plate with thermal conductivity of $16 \text{ W/m} \cdot \text{K}$. The periodical holes are filled with polydimethylsiloxane (PDMS) with thermal conductivity of $0.15 \text{ W/m} \cdot \text{K}$. The isotropic background and the anisotropic cloaking shell can be realized by drilling square holes and rectangular holes, respectively. Figs. 4(a) and 4(b) demonstrate the fabricated diamond shaped thermal cloak and the detailed geometric parameters, respectively. To reduce the heat convection by air as well as the high reflection by stainless steel 304, a thin PDMS film ($\approx 0.1 \text{ mm}$) is deposited on the surface of each sample. The scheme of the experimental setup is illustrated in Fig. 4(c). The left side of the sample is connected to a tank filled with hot water fixed at 70°C , while the right side of the sample is connected to a tank filled with

ice water (0°C). We use an Optris PI400 infrared camera to capture the cross-sectional temperature.

4. Results and discussion

We first examine the cloaking performance of the designed thermal cloak when the heat flows from left to right, as shown in Fig. 5(a). In accordance with Fig. 2(b), a heat-insulating inner layer is required in this situation. For practical realization, PDMS is chosen as an approximated heat-insulating material. Fig. 5(b) shows the measured temperature profile of the thermal cloak. We can see that the external isotherms are vertical and not distorted, which has a good agreement with the simulation result in Fig. 5(c). For comparison, we simulated the temperature distribution of the reference structure with only a thermally insulating ring, as shown in Fig. 5(d). It is obvious that the reference structure repels the heat flux and makes the isothermal lines significantly curved.

Fig. 6 Measured and simulated results when the heat flows from top to bottom. (a) Experimental setup. (b) The measured temperature profile for the thermal cloak. (c) The simulated temperature distribution for the thermal cloak. (d) The simulated temperature distribution for the reference structure.

We next examine the cloaking performance of the designed thermal cloak when the heat flows from top to bottom, as shown in Fig. 6(a). In accordance with Fig. 3(b), a super-conductive inner layer is required in this situation. For practical realization, copper is chosen as an approximated super-conductive material. Compared to the background with a small thermal conductivity of $3.4\text{ W/m}\cdot\text{K}$, this is a fair good approximation. Fig. 6(b) shows the measured temperature profile of the thermal cloak, which has a good agreement with the simulation result in Fig. 6(c). For comparison, we also simulated the temperature distribution of the reference structure as shown in Fig. 6(d). Obviously, the reference structure attracts the heat flux and makes the

isothermal lines significantly curved. With the thermal cloak, the curved isothermal lines restore exactly without distortion as if nothing were there, which validates the proposed design.

5. Conclusion

Heat constitutes the largest portion of wasted energy in modern society. Therefore, the importance of effectively manipulating of heat transfer cannot be overstated.^[29,30] Based on linear transformation thermotics, we have designed, fabricated, and measured a diamond shaped thermal cloak. The proposed cloak demonstrates a switchable manipulating direction and functions in both x and y directions, which is not possibly achievable for the same shaped electromagnetic cloak.^[25] It changes the usual perception that transformation thermal metamaterials are just a direct and simplified derivative of the transformation-optic counterpart. Our approach is feasible for the design of bifunctional devices that manipulate thermal-electric fields simultaneously.^[17]

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Supporting Information

Not applicable

Conflict of interest

There are no conflicts to declare.

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Author information

Tiancheng Han is currently a professor in School of Electronic Science and Engineering of University of Electronic Science and Technology of China (UESTC). He obtained his bachelor's degree in 2005 and master's degree in 2008 from Lanzhou University, and his Ph.D. degree in 2012 from UESTC. In 2013-2014, he did postdoctoral research at National University of Singapore. His current research interests focus on manipulating heat transfer and electromagnetic wave based on metamaterials/metasurface.

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