Tunable Thermal Pattern for Thermal Illusion and Encrypted Messaging

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Abstract. Recently, metamaterials which can actively tuning heat flux has attracted a lot of researchers and these thermal functional materials can be used in many thermal application scenarios such as encrypted messaging and thermal illusion. In this paper, the bilayer structure array with a chessboard-like structure has been proposed and we have numerically acquired a tunable thermal pattern based on effective medium theory. Through this strategy, a thermal pattern which is almost the same with the patterns of ‘ECE’ can be obtained. After quickly tuning this 3*12 array of the 4*4 chessboard-like bilayer structure, another thermal pattern which looks like the patterns of ‘SOS’ is observed in the infrared camera instead, demonstrating the feasibility of thermal illusion. Furthermore, the functionality of encrypted thermal messaging is also numerically demonstrated by resorting to storing the analog patterns of the binary numbers. Besides, this kind of tunable bilayer array is quite simple and flexible, and it can also serve as thermal metamaterial when the corresponding matching function is satisfied. In all, this present bilayer structure array with a chessboard-like structure can obtain tunable thermal patterns without disassembly of any components and it might open more strategies for creating novel thermal functionalities.

1. Introduction

With the development of science and technology, the emergence of metamaterial has brought a lot of possibilities to real life, such as invisibility cloak [1], which is almost impossible for traditional materials. Thus, metamaterial has attracted enormous researchers and various corresponding research works have been reported in these related physical fields, e.g., optics [2], electromagnetic [3], acoustics [4], thermodynamics [5], direct current [6], etc. Among them, various thermal metamaterials have been proposed and achieved according to the scattering cancellation method or transformation theory, leading to the realization of different counterintuitive thermal functions such as thermal cloak [7]. Recently, a chessboard-like structure had been designed, in which doublet thermal metadevice with tunable thermal functions can be realized [8]. However, more practical applications of thermal functional material remain to be investigated.

Recently, as one of the most promising applications for manipulating heat flux, thermal pattern has attracted quite a lot of researchers and scientists [9]. Meanwhile, many application scenarios of thermal pattern have been discovered, especially in which thermal illusion [10], [11], [9], [12] and encrypted messaging [9] are both one of the hottest application scenarios. Thermal pattern has a good function of storing and transmitting information. For example, it may have a promising application prospect in military equipment [10]. But if thermal patterns can be actively tunable, it might bring more various functions such as thermal illusion in transmitting these encrypted messages in these thermal patterns. To some extent, tunable thermal patterns can also greatly improve efficiency. Perhaps tunable thermal patterns can be accomplished by tunable thermal metamaterial. Nevertheless, the specific design principle of tunable thermal metamaterial needs to be further studied.

For further research, an understanding of the development of thermal metamaterials is quite necessary. In 2008, the physical theory of manipulation of heat flux was inspired by Transformation Optics (TO) theory, which was studied by Fan et al [13]and Chen et al [14]. Then, in 2013, transient thermal cloaks were obtained by Schittny et al [15]. In 2014, bilayer thermal cloaks had been experimentally demonstrated [16], [7]. Then in 2019, for improving the limit of thermal conductivity of natural materials in a bilayer thermal cloak, a thermal conductive system with introducing a...
convective element had been designed and it had perfectly solved this problem [17]. In addition to cloaks, other thermal metamaterials have also been theoretically investigated and experimentally demonstrated, such as thermal concentration [18], [19], thermal rotation [20], thermal convergency [21], thermal camouflage [22], [9], [23] and thermal illusion [10], [11], [9], [12]. Meanwhile, tunable thermal pattern is quite a promising application. However, there is rare paper that has reported about the realization of tunable thermal pattern using the structure of tunable thermal metamaterial. Therefore, it might be a wise strategy to achieve tunable thermal patterns with the emergence of tunable thermal metamaterial. Nevertheless, the specific design of the corresponding structure remains to be explored.

Recently, since the twisted bilayers generated some interesting phenomena such as the photonic magic angles in metamaterial and the precise control of the polariton dispersion through tailored interlayer coupling in twisted bilayer flake has been experimentally demonstrated in 2020 [24]. Inspired by the above idea, the bilayer structure array with each layer possessing a chessboard-like structure has been proposed and perhaps the tunable thermal pattern can be achieved with this bilayer structure.

In summary, the bilayer structure array with a chessboard-like structure has been proposed and it can obtain the on-demand thermal patterns based on effective medium theory and steady-state thermal conduction equation. Firstly, it can actively tune the thermal patterns via the twisted angles between each layer, which can be used for thermal illusion and encrypted messages. Besides, when the matching function is satisfied, it can serve as thermal metamaterial if placing it in a constant thermal gradient background. Hence, in contrast to previous related works, this chessboard-like bilayer structure array can rapidly achieve the on-demand tunable thermal patterns without disassembly of any components, and it can also serve as thermal metamaterial under a constant thermal gradient background when the matching function is satisfied.

2. Theoretical analysis

According to the related reference [17], [25], the steady-state heat conduction equation is shown as follows:

$$\nabla \cdot (-k\nabla T) = 0$$

(1)

where $\kappa$ is the thermal conductivity tensor.

Firstly, for physicists, by expressing the above equation in a curvilinear coordinate system ($x^i$ and $x^j$, $i = 1, \ldots, n$ or $j = 1, \ldots, n$) corresponding to a transformation, we have

$$\frac{\partial}{\partial x^i} \kappa^{ij} \frac{\partial}{\partial x^j} T + \Gamma^i_{ak} \kappa^{kj} \frac{\partial}{\partial x^j} T = 0$$

(2)

where $\Gamma^i_{ak}$ is the Christoffel symbol satisfying the following equation:

$$\Gamma^i_{ak} = \frac{1}{2} g^{il} \frac{\partial}{\partial x^k} g_{kl} = \det(\mathbf{J}) \frac{\partial}{\partial x^k} \frac{1}{\det(\mathbf{J})}$$

(3)

where $g$ is the metric tensor, and $\mathbf{J}$ is the Jacobian matrix corresponding to the transformation.

Then, for symmetric materials, the exchange of two phases has no effect on the properties of the material. According to Keller Theorem [26], [27], [28] and effective medium theory [16], we can write the relation between the effective thermal conductivity tensor $\kappa^{eff}$ and the thermal conductivities of the system's constituent materials $\kappa_1$ and $\kappa_2$:

$$\det \kappa^{eff} = \kappa_1 \kappa_2$$

(4)

Therefore, the effective thermal conductivity of such a symmetric two phases material is isotropic if a special structure, which is chessboard-like, is used in Cartesian coordination. Assume that a bilayer chessboard-like structure consisting of two materials of unequal conductivities $\kappa_1$ and $\kappa_2$ is adapted. Thus, we can still obtain an isotropic effective thermal conductivity $\kappa_0^{eff}$ in this bilayer
chessboard-like structure. Then we can achieve a bilayer thermal metamaterial if the thermal conductivity of background can meet the following matching function:

$$\kappa_b = \kappa_0^{eff}$$  (5)

Therefore, when this bilayer chessboard-like structure only retains the high thermal conductivity component placed in the background, temperature gradient is diffuse as shown in Figure 1(a), while only keeping the low thermal conductivity part, temperature gradient is concentrating on as shown in Figure 1(b). Furthermore, leaving both components in this bilayer chessboard-like structure, a neutral temperature gradient can be obtained as shown in Figure 1(c).

Figure 1. Temperature gradient of the bilayer structure of two-phase or one-phase material. (a) the high thermal conductivity phase material (b) the low thermal conductivity phase material (c) two-phase chessboard-like material

For the realization of tunable thermal pattern, if a specific thermal pattern is needed, we can make these chessboard-like bilayers to be an array and it can achieve the on-demand thermal pattern via just twisting some upper layers in this array.

3. Simulation results and discussions

Firstly, the 4*4 bilayer structure of two-phase thermal material is designed into a chessboard-like structure, as illustrated in Figure 2(a). Fixed temperatures of 373K and 273K are set on the left and right sides respectively. At this time, the steady-state temperature curve presented after the original temperature is set up is illustrated in Figure 2(b), and the temperature distribution is almost uniform. The structure with the upper layer twisted by 90 degrees is illustrated in Figure 2(c). At this time, the steady-state temperature distributions are quite different from that in Figure 2(b), as shown in Figure 3(d). After the angle conversion, this 4*4 bilayer chessboard-like thermal functional material can obtain different thermal pattern. According to the rationality of the above simulation, the realization of tunable thermal pattern can be based on this bilayer structure.

Then, in order to demonstrate the illusion function of tunable thermal pattern, the 4*4 bilayer chessboard-like thermal functional material is expanded in an array of 3*12, and thermal pattern of letters ‘ECE’ is obtained, as shown in Figure 3(a). After quickly tuning this 3*12 array of the 4*4 chessboard-like bilayer structure, the new thermal pattern of letters ‘SOS’ is achieved as shown in Figure 3(b). The transition from the thermal pattern of ECE to SOS uses a simple method of twisting angles to change information, fully demonstrating the ability of tunable thermal pattern to puzzle the observer, which is quite deceptive. Thus, the feasibility of thermal illusion via tunable thermal pattern can be verified.

In addition to the function of illusion, tunable thermal pattern also features encrypted messaging. No matter what kind of information is transmitted, it can be actually stored and transmitted in binary form. Tunable thermal pattern can encrypt, store and transmit messages in binary form. In this 3*12 array, the thermal patterns of binary numbers ‘000’ and ‘111’ can be acquired by twisting angles as shown in Figure 3(c) and Figure 3(d), respectively. Besides, this kind of tunable bilayer array is quite simple and flexible, and it can also serve as thermal metamaterial when the corresponding matching function is satisfied. In all, this present bilayer structure array with a chessboard-like structure can quickly obtain tunable thermal patterns without disassembly of any components, which can be used for thermal illusion and encrypted messaging.
Figure 2. Schematics (a), (b) and steady-state temperature profiles (c), (d) of the 4*4 bilayer chessboard-like thermal functional material under specific twisted angle.

Figure 3. Tunable patterns of the 3*12 array of 4*4 bilayer chessboard-like thermal material under specific twisted angles. (a) thermal pattern of ECE (b) thermal pattern of SOS (c) thermal pattern of binary number 000 (d) thermal pattern of binary number 111.

4. Conclusion
In summary, based on effective medium theory, Keller theory and steady-state thermal conduction equation, a novel scheme using a chessboard-like bilayer structure is proposed to realize tunable thermal pattern, which can be used for thermal illusion and encrypted messaging. Firstly, we theoretically derive the corresponding relation between the thermal conductivity of background and that of two-phase materials with a chessboard-like bilayer structure if thermal metamaterial is on-demand. Then, actively tuning thermal distributions is numerically demonstrated by just 4*4 chessboard-like bilayer structure. Furthermore, the related realization of the two thermal functions which are thermal illusion and encrypted thermal messaging have been verified numerically via a 3*12
array of 4*4 chessboard-like bilayer structure. Any on-demand thermal patterns can be acquired by this chessboard-like bilayer array, in which it just needs some specific twisted thermal manipulations to control heat flux at will. Besides, this kind of tunable bilayer array is quite simple and flexible, and it can also serve as thermal metamaterial when the corresponding matching function is satisfied. In all, this present bilayer structure array with a chessboard-like structure can obtain tunable thermal patterns without disassembly of any components and it might open more strategies for creating novel thermal functionalities.

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