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Thermal cloak-concentrator

Xiangying Shen,[1,2,a),b)] Ying Li,[3,a)] Chaoran Jiang,[1,2,a)] Yushan Ni,[3] and Jiping Huang[1,2,c)]
[1]*Department of Physics, State Key Laboratory of Surface Physics, and Key Laboratory of Micro and Nano Photonic Structures (MOE), Fudan University, Shanghai 200433, China*
[2]*Collaborative Innovation Center of Advanced Microstructures, Nanjing 210093, China*
[3]*Department of Mechanics and Engineering Science, Fudan University, Shanghai 200433, China*

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For macroscopically manipulating heat flow at will, thermal metamaterials have opened a practical way, which possesses a single function, such as either cloaking or concentrating the flow of heat even though environmental temperature varies. By developing a theory of transformation heat transfer for multiple functions, here we introduce the concept of intelligent thermal metamaterials with a dual function, which is in contrast to the existing thermal metamaterials with single functions. By assembling homogeneous isotropic materials and shape-memory alloys, we experimentally fabricate a kind of intelligent thermal metamaterials, which can automatically change from a cloak (or concentrator) to a concentrator (or cloak) when the environmental temperature changes. This work paves an efficient way for a controllable gradient of heat, and also provides guidance both for arbitrarily manipulating the flow of heat and for efficiently designing similar intelligent metamaterials in other fields. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4959251]

Heat flow is a common phenomenon in nature. However, how to macroscopically manipulate the heat flow at will remains poorly explored in the literature, which, however, is crucial for human life or military uses, say, efficient refrigerators, solar cells, energy-saving buildings, or infrared camouflage. It is known that our world has been changing by *intelligent* electronic components or *intelligent* materials. Here *intelligent* means that the component or material has properties that can be tuned in a controllable manner by external stimuli. For example, electronic diodes belong to intelligent electronic components, which have much lower resistance to electric current along one direction than the other; shape memory alloys are a kind of intelligent materials, which can recover their original shapes by stimuli (say, heating[1] or adding an external magnetic field[2]) after big deformations. Manipulating thermal conduction equations to achieve desired temperature distributions or heat flux patterns in thermal metamaterials is promising for thermal counterparts of *intelligent* electronic components or *intelligent* materials. As a result, this manipulation might produce a unique class of intelligent thermal metamaterials, thus yielding an intelligent way for macroscopically controlling the flow of heat at will. For this purpose, let us trace back to the birth of transformation optics theory.[3,4]

In 2006, Leonhardt and Pendry *et al.* independently established the transformation optics theory, which leads to a concept of invisibility cloaking.[3,4] Such a significant progress soon enlightened a lot of scientists in different fields since it offers a powerful method for designing metamaterials with new properties in optics,[5] acoustics,[6] and electrics.[7] In essence, this theory demands the form invariance of domain equations under linear coordinate transformations. This characteristic serves as the foundation of transformation optics theory. Inspired by it, some researchers extended the transformation mapping theory to the domain of thermal conduction, and then proposed a type of thermal metamaterials, which function as thermal cloaking for steady state heat flow (i.e., the temperature, T, is independent of time) by using inhomogeneous anisotropic materials.[8] The original intention of designing such type of thermal metamaterials is to hide an object inside the cloak from the detection through measuring the external temperature distribution, and thus these metamaterials can thermally protect the central zone containing the object. So far, the steady-state thermal cloak[8] and its theoretical extensions[9,10] have been experimentally realized or developed.[11–16] Meanwhile, researchers also designed a lot of thermal metamaterials with different thermal characteristics beyond cloaking,[9–11,17–19] such as concentrators.[10,11,20–22] The concentrator helps to focus heat flux in a particular region, and thus yields a higher temperature gradient inside the region, which benefits thermoelectric effects.[23]

Unfortunately, although multiple-field metamaterials have been demonstrated,[15,24] the existing thermal metamaterials reported still do not have the essential feature of intelligence because they only have a single function, such as either cloaking or concentrating the flow of heat even though environmental temperature changes. A so-called intelligent thermal metamaterial should have at least two functions, which can automatically change from one to the other as the environmental temperature varies. In other words, intelligent thermal metamaterials must have the ability to automatically sense and respond to the change of environmental temperature. In this work, we first develop a theory of transformation heat transfer for multiple functions, which is in contrast to the existing theories for single functions only. As a result, we shall show that thermal metamaterials can be made intelligent indeed, which automatically change from a cloak (concentrator) to a concentrator (cloak) when the environmental temperature changes. Below we shall present theory and experiment.

[a)]X. Shen, Y. Li, and C. Jiang contributed equally to this work.
[b)]Electronic mail: xiangyingshen13@fudan.edu.cn
[c)]Electronic mail: jphuang@fudan.edu.cn

The traditional thermal cloak helps to prevent heat from traveling inside the central zone without disturbing the temperature distribution outside, thus hiding an object inside it. As schematically drawn in Fig. 1 (left), a two-dimensional thermal cloak is designed according to a compression transformation which maps a circle of radius R_2 to a ring with interior radius R_1 and exterior radius R_2. On the other hand, a traditional thermal concentrator guides more heat flux into the central zone and increases the temperature gradient inside. As Fig. 1 (right) shows, the corresponding transformation of a two-dimensional concentrator maps a ring with interior radius R_3 and exterior radius R_2 to a ring with interior radius R_1 and exterior radius R_2.

Recently, it has been shown that the transformation heat transfer can be generalized by introducing the nonlinear effect of temperature-dependent thermal conductivities.[19] This theory enables us to make use of a certain temperature-dependent transformation to achieve switching functions. The foundation of this approach is the equivalence between such transformation and a normal transformation applied on nonlinear materials (whose conductivity depends on temperature). Based on the generalized transformation heat transfer, here we propose a device whose function can be switched between cloaking and concentrating as temperature T varies. The corresponding theoretical analysis can also be applied to achieve the switching effect between two other functions, such as, "rotating and cloaking" or "rotating and concentrating." In a polar coordinate system, the thermal conductivity $\kappa(T)$ of this bi-functional device can be expressed as

$$\kappa_r(T) = \kappa_0\left[1+\frac{R_2(R^*(T)-R_1)}{r'(R_2-R^*(T))}\right],$$
$$\kappa_\theta(T) = \kappa_0\left[1+\frac{R_2(R^*(T)-R_1)}{r'(R_2-R^*(T))}\right]^{-1}, \quad (1)$$

where $\kappa_r(T)$ and $\kappa_\theta(T)$ are the radial and azimuthal components of $\kappa(T)$, respectively. κ_0 is the conductivity of the background. To obtain Eq. (1), vigorous analysis can be found in the supplementary material[25] (which presents the details of transformation heat transfer for multiple functions in Part I).

The specific term $R^*(T)$ is determined according to the desired behavior of the cloak-concentrator. Symmetrically, the apparatus has two different forms of transformation. Therefore, two forms of $R^*(T)$ can be written as

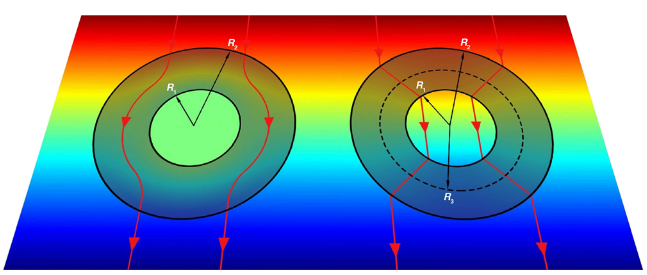

FIG. 1. Schematic graph showing a thermal cloak (left) and a thermal concentrator (right). The red lines with arrows denote the pathway of heat flow. R_1 is the radius of the central zone; R_1 and R_2 are, respectively, the interior radius and exterior radius of the cloak or concentrator; R_3 is the radius between R_1 and R_2.

$$R^*(T) = \frac{R_3}{1+e^{\beta(T-T_c)}} \text{ (Form I)},$$
$$R^*(T) = \frac{R_3 e^{\beta(T-T_c)}}{1+e^{\beta(T-T_c)}} \text{ (Form II)}, \quad (2)$$

where β is a scaling factor which determines the sensitivity of the device to T. Indicated by the above equation, for Form I, we want the device to behave as a concentrator when the environmental temperature is lower than a critical temperature, T_c, such that the central zone receives more heat flux from the heat source. And when the environmental temperature increases to be higher than T_c, we want the device to behave like a cloak in order to avoid heat flux from entering the central zone. In this case, an object located in the central zone is able to experience a relatively more stable thermal environment. On the contrary, for Form II, the device functions as a cloak at low environmental temperature, while at high temperature it turns to a concentrator.

However, it is still a challenge to realize such an intelligent heat-gradient rectifier, since the thermal conductivity should be inhomogeneous, anisotropic, and nonlinear as required by Eq. (1). Fortunately, such problems can be overcome according to the following two steps: first, cancelling the heterogeneity and anisotropy by designing the thermal cloak and concentrator with homogenous and isotropic materials in same dimensions; second, finding the connections between them according to the nonlinear effect.

To fabricate such a cloak with homogeneous isotropic conductivities, we resort to the well-developed bilayer design.[14] As shown in Fig. 2(b) (upper panel), assume a bilayer cloak, consisting of an inner layer (with radius r satisfying $a<r<b$) and an outer layer ($b<r<c$), is located in the center of a host. The conductivities of the host (region 1), outer layer (region 2), inner layer (region 3), and cloaking area (region 4) are indicated as κ_1, κ_2, κ_3, and κ_4, respectively. Here, κ_3 tends to zero for prohibiting the heat from entering the "invisible" area (region 4). According to the relationship $\kappa_2 = [(c^2+b^2)/(c^2-b^2)]\kappa_1$,[14] all the parameters needed for constructing the cloak can be figured out.

Next, we propose the design of a bilayer concentrator (see the lower panel of Fig. 2(b)), which has not been investigated in the literature. To proceed, consider a bilayer concentrator with the same configuration and dimension as the cloak, while the conductivities of regions 1–4 are κ'_1, κ'_2, κ'_3, and κ'_4, respectively. Now, we are in a position to cancel the anisotropy introduced by transformation. One solution is to build a stacked composite, which is composed with alternating layers of two different isotropic materials.[11] Since a space extension operation is applied in the concentrating case for raising the temperature gradient in the central zone, two types of sheets should be alternatively arrayed in a ring along the tangential direction. As a result, we replace region 3 with such a laminated structure to achieve the extension transformation. For multi-layered structure with the same thickness, the effective medium theory[9,26,27] helps to give $\kappa'_3 = \sqrt{\kappa_A\kappa_B}$, where κ_A and κ_B are the conductivities of the two different materials. More details can be found in Part II of the supplementary material.[25]

Nevertheless, the heat gradient increase is just one characteristic of a concentrator, and a uniform temperature

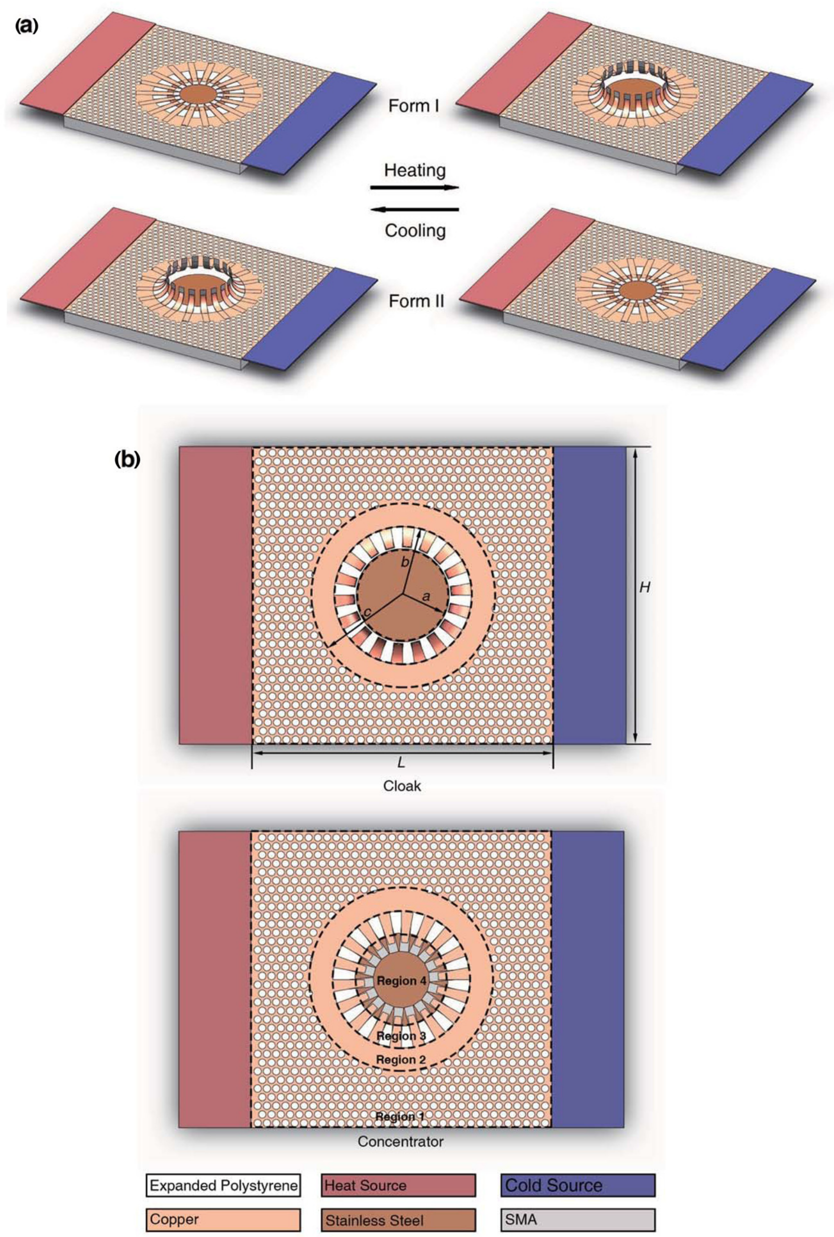

FIG. 2. Schematic of the two experimental samples: Form I and Form II. (a) The transition between two states of Form I or Form II upon heating or cooling. Form I functions as a thermal concentrator below 278.2 K but a cloak above 297.2 K; Form II behaves in the opposite way. (b) The structure of the cloak (upper panel) or concentrator (lower panel). Regions 1–4 indicate the four regions separated by dashed lines. Parameters: $L = 16$ cm, $H = 16$ cm, $a = 2.6$ cm, $b = 3.7$ cm, and $c = 4.9$ cm.

distribution in region 1 must be fulfilled in the meantime. To eliminate the distortions caused by regions 2–4, the conductivity of region 4, κ_4', should satisfy

$$\kappa_4' = \kappa_3' \frac{-b^2(b^2 l_1 + c^2 l_2) - a^2\kappa_3'(c^2 + b^2 l_1 l_2)}{ab(b^2 l_1 + c^2 l_2) - a^2(c^2 + b^2 l_1 l_2)}, \qquad (3)$$

where $l_1 = (\kappa_1' + \kappa_2')/(\kappa_1' - \kappa_2')$ and $l_2 = (\kappa_2' + \kappa_3')/(\kappa_2' - \kappa_3')$. The above formula is a solution of Laplace's equation by taking into account the continuity of diffusion; the detailed derivations are given in Part III of the supplementary material.[25] An important property of the bilayer structure is that there is no restriction on what material should be settled in region 4. Thus, the cloak and concentrator may share the same parameters except for the conductivity of region 3, i.e., $\kappa_1' = \kappa_1$, $\kappa_2' = \kappa_2$ and $\kappa_4' = \kappa_4$. This key feature provides a solution to realize intelligent bi-functional thermal metamaterials.

According to Eq. (1), the term $R^*(T)$ implicates the temperature-dependent transformation of thermal conductivities, which is actually equivalent to the temperature-controlled geometrical deformation [$R^*(T)$ changes between 0 and R_3 in the aforementioned theory]. As long as β in Eq. (2) is large enough, the exponential description of $R^*(T)$ can be seen as a step function which contains only two states. On the same footing, in our bilayer design the automatic switching between cloaking and concentrating can be achieved by simply changing the materials in region 3. In fact, which function to be activated is determined by whether the laminated structure exists or not. More specifically, for the cloaking case, the preset material in region 3 is a thermal insulator, and it is covered by another conductive material at regular intervals to assemble the structure for realizing a thermal concentrator instead. To create such temperature-controlled covering or uncovering states, a practical way is to let metal films flat or warp as temperature varies. In our experiment, these deformations are achieved by using a special kind of bimetallic strips, which are prepared by sticking two-way shape memory alloys (SMAs) to metal slices. Due to the solid–solid phase transition, these SMAs are able to change their shapes at different temperatures. For Form I, the SMA in use would tilt up to the maximum angle when the temperature T reaches 297.2 K (or higher), and make region 3 thermally insulated, yielding a thermal cloak. Once $T = 278.2$ K (or lower), the SMA is completely leveled to cover the insulator, thus constituting the desired thermal concentrator. In contrast, with the same transition temperature, the SMA adopted for Form II deform in a completely opposite way.

For the sake of reducing the thermal impedance caused by heat conduction among different materials, the whole bifunctional device is made from a 16 cm × 16 cm copper plate ($\kappa_{cu} = 394$ W/mK). The overall dimensions are as follows: $a = 2.6$ cm, $b = 3.7$ cm, and $c = 4.9$ cm. As shown in Fig. 2, more than one thousand holes on the plate are chemically etched off and filled with polydimethylsiloxane, in order to match the conductivity of host (details are presented in Part II of the supplementary material[25]). The key part is the 18 copper sawteeth in region 3. They are movable by attaching SMAs beneath. Thus, the deformation of these sawteeth leads to the covered or uncovered states as we need, which makes the device switch from concentrating (or cloaking) to

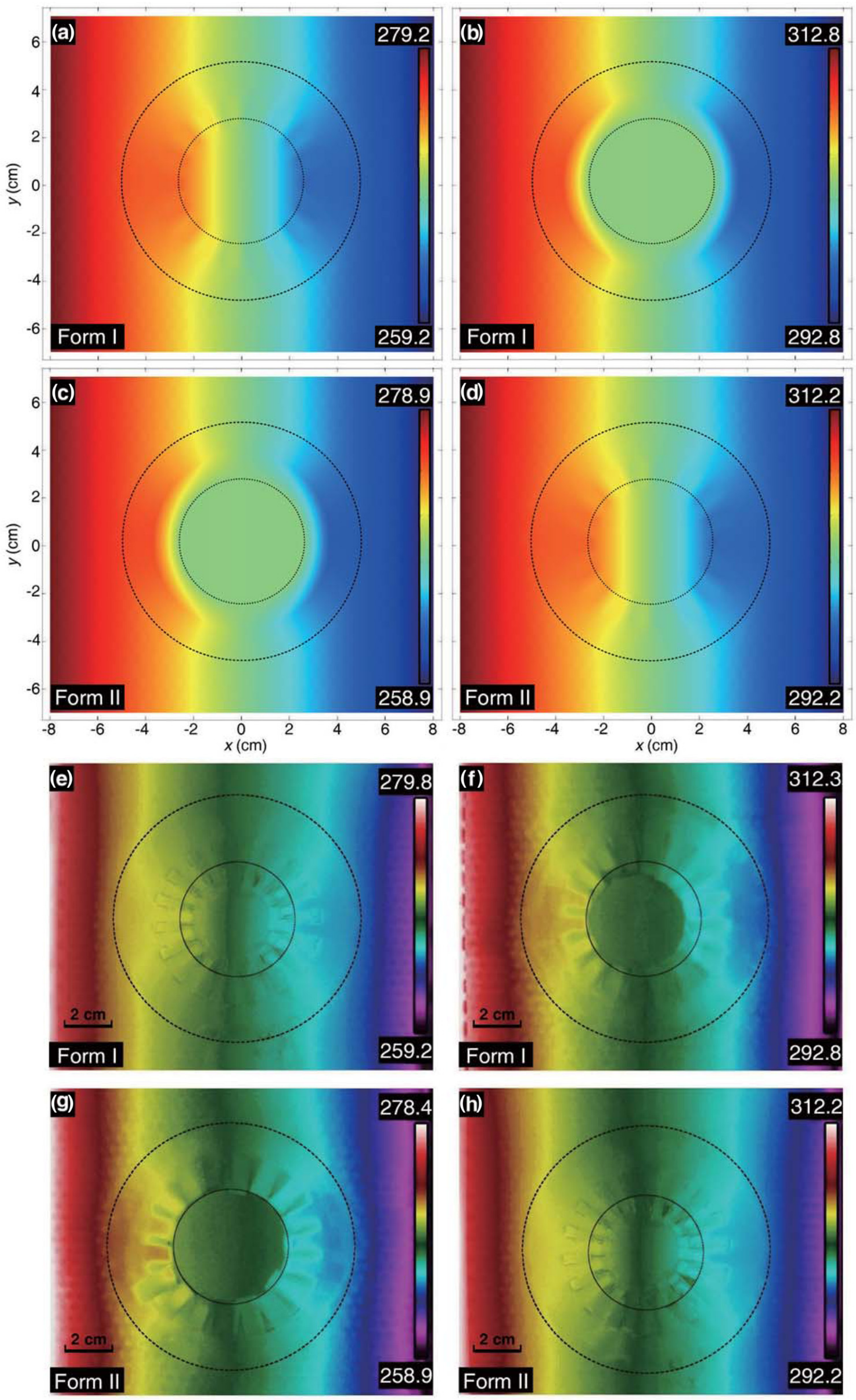

FIG. 3. Results of ((a)–(d)) simulations and ((e)–(h)) experiments in ((a), (c), (e), and (g)) low and ((b), (d), (f), and (h)) high temperature at the range of 20 K, where color surfaces represent the distribution of temperature in units of K. ((a)–(d)) Finite-element simulations according to Eq. (1) for ((a), (b)) Form I and ((c), (d)) Form II: ((a), (d)) concentrating and ((b), (c)) cloaking the flow of heat. ((e)–(h)) Experimental measurement of ((e) and (f)) Form I and ((g) and (h)) Form II: ((e) and (h)) concentrating and ((f) and (g)) cloaking the flow of heat. The temperature gradient within region 4 for ((a), (d), (e), and (h)) the concentrating cases is significantly raised, while that for ((b), (c), (f), and (g)) the cloaking cases is almost eliminated; the temperature distribution within region 1 keeps almost undisturbed.

cloaking (or concentrating). Besides, a circular stainless steel film is located in the center of region 4 to fulfill the requirement of κ_4' indicated by Eq. (3). At last, due to the high reflectivity of copper plate, the whole device is covered by a polydimethylsiloxane layer with thickness 0.1 mm, which helps cope with heat dissipation and make temperature images visible for the thermal heat camera. The deformation procedure of the whole device switching between the two states is provided in Part IV of the supplementary material[25] with the photographs of the actual device at low (or high) temperature.

The experimental measurements are presented in Figs. 3(e)–3(h), and the temperature distribution patterns obtained from simulations (Figs. 3(a)–3(d)) are also given for comparison. Clearly, the bi-functional device (Form I or Form II) works for either cloaking (Figs. 3(b), 3(c), 3(f), and 3(g)) or concentrating (Figs. 3(a), 3(d), 3(e), and 3(h)) the flow of heat flux, and it has (almost) no interference in the temperature distribution pattern of region 1. It should be noted that the temperature difference $\nabla T \approx 1.3$ K is measured within region 4 when the cloaking effect appears (Figs. 3(f) and 3(g)). For comparison, as shown in Figs. 3(e) and 3(h) the temperature varies significantly in the same area, yielding $\nabla T \approx 11$ K. As a result, changing the boundary conditions to control the temperature gradient in region 4 is not only automatic, but also noninvasive. One may notice that some sawtooth in Fig. 3(f) are comparatively droopy. It is a normal phenomena caused by the gradual deformation of SMA when the temperature is not far below T_c.

To summarize, in this work we have developed a macroscopic theory of transformation heat transfer for multiple functions and applied the theory to introduce the concept of intelligent thermal metamaterials. Unlike conventional transformation mapping theories, which usually permit a device possessing a single function, our theory of transformation heat transfer for multiple functions paves a practical way for designing a single device with multiple functions. The resulting concept makes it possible that the heat flux gradient of a certain region can be automatically adjusted as the environmental temperature changes. As a model application, this concept may help to noninvasively switch on or off thermoelectric effects[23] when the applied temperature varies, thus achieving so-called switchable thermoelectric effects. Moreover, since there is no disturbance in the external temperature distribution, the intelligent thermal metamaterial can also be employed as elements of larger facilities or buildings without interference. We also have experimentally realized the concept of intelligent thermal metamaterials by only utilizing homogenous isotropic materials and shape memory alloys. All the elements involved are commercially available, which makes the design readily applicable to technology. In addition, due to the similarity between the governing equations, our theoretical consideration can be extended to obtain the counterparts of such intelligent multi-functional thermal metamaterials in other disciplines like optics, electromagnetics, acoustics, and elastodynamics.

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[25] See supplementary material at http://dx.doi.org/10.1063/1.4959251 for more detailed theoretical deductions of transformation mapping, bilayer concentrator and effective medium theory. Photographs and a short movie of experimental samples are also provided.

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