Remote temperature control can be obtained by a long-focus thermal lens that can focus heat fluxes into a spot far from the back surface of the lens and create a virtual thermal source/sink in the background material, around which the temperature field distribution can be remotely controlled by varying the parameters of the thermal lens. However, because of the lack of negative thermal conductivity, existing thermal lenses have extremely short focal lengths and cannot be used to remotely control the temperature field around the virtual thermal source/sink. In this study, a general approach is proposed to equivalently realize materials with negative thermal conductivity using elaborately distributed active thermal metasurfaces (ATMSs). Subsequently, the proposed ATMS is used to implement a novel thermal lens with a long focal length designed using transformation thermodynamics, and finally realize the ATMS with realistic materials and experimentally verify the performance of the designed long-focus thermal lens (measured focal length of 19.8 mm) for remote heating/cooling. The proposed method expands the scope of the thermal conductivity and provides new pathways to realize unprecedented thermal effects with effective negative thermal conductivity, such as “thermal surface plasmon polaritons,” the thermal superlens, the thermal tunneling effect, and the thermal invisible gateway.

1. Introduction

Natural materials have a limited range of thermal conductivity, making it difficult to achieve unprecedented thermal effects. To expand the range of thermal conductivities, a few novel thermal materials with artificial structures have been proposed, often referred to as thermal metamaterials and metasurfaces.[1–3] As thermal metamaterials and metasurfaces can achieve a more diverse and wider range of thermal conductivity, such as, inhomogeneous anisotropic values, tunable thermal conductivity, and even a thermal conductivity tending to infinity,[4] the control of temperature fields has been drastically improved by achieving thermal cloaking,[5–9] thermal camouflage,[10–16] thermal concentrator,[17] thermal rectification and thermal diodes,[18–21] thermal Hall effect,[22–24] thermal encoding,[25] thermal buffering,[26] and thermal lensing.[27–30] These findings broaden the scope of thermodynamic research and pave the way for the realization of unusual thermal conductivity values. However, compared to the capability of controlling electromagnetic fields, the current control capability for temperature fields can be further improved. For example, it is simple to realize a long-focus lens that can focus an electromagnetic wave into a spot that appears to be created by a virtual electromagnetic source in free space. Nevertheless, the theoretical design and experimental demonstration of a long-focus thermal lens, which can focus temperature fields into a spot by thermal conduction and make it look like a temperature field generated by a virtual temperature source/sink in the background material, are still challenging. This can be attributed to the second law of thermodynamics, according to which heat can only be transferred from a high-temperature region to a low-temperature region spontaneously, implying that long-focus thermal lenses can only be achieved with active materials (e.g., materials with negative thermal conductivity).

From the perspective of transformation optics[31,32] and transformation thermodynamics,[33] there is no intrinsic difference between the focusing of electromagnetic fields and that of temperature fields, and both can be treated as creating a virtual electromagnetic or thermal source/sink by translation or folding coordinate transformation.[34,35] Several interesting designs on thermal focusing such as producing thermal focal spots with pre-designed shapes[36] and positions,[37–39,41] and even creating multiple focal spots from a single thermal source[37,48] have been reported using transformation thermodynamics. However, the focal length of these thermal lenses is often extremely short, that is, the distance between the virtual source (focal spot) and the back surface of the lens is close to zero, (Figure 1a) which cannot be used for the remote control of temperature fields. Although a long-focus thermal lens can be designed by a folding transformation in transformation thermodynamics, in which the virtual thermal source/sink is far from the back surface of the lens, as shown in Figure 1b, it inevitably introduces a material with a negative thermal conductivity that does not exist in nature.
Figure 1. Direct and remote control of temperature fields. a) Direct control of temperature fields by a short-focus thermal lens with anisotropic thermal conductivity (cyan and green blocks), in which the real thermal sources (yellow dots) and the virtual sources (red dots, that is, the focal spot) are directly linked by the lens. In this case, the distance between the focal spot and the back surface of the lens is zero (i.e., the focal length is zero). Left subplot: Planar plate thermal lens;[27] Middle subplot: Fan-shaped thermal lens;[30] Right subplot: Thermal lens with curved principal axes of the anisotropic thermal conductivity.[28] b) Remote control of temperature fields by a long-focus thermal lens with negative thermal conductivity (colored blue): If a real thermal source (yellow dot) is set inside the lens, a thermal focal spot (red dot) that looks like a virtual thermal source will be created outside the lens. c) Remote control of temperature fields by a circle enclosed by ATMS (colored rainbows) without any material with negative thermal conductivity. In this case, a thermal focal spot can be generated without a real thermal source by using well-designed boundary heat sources of the ATMS. Unlike the short-focus thermal lens in (a) in which the thermal focal spot occurs at the back surface of the lens, the structures in (b) and (c) are equivalent to long-focus thermal lenses, which can produce a thermal focal spot (virtual source) at a certain distance from the back surface of the lens (indicated by the distance between two red dashed lines).

The concept of apparent negative thermal conductivity has been first proposed in a theoretical study during the introduction of the thermal cloak, in which the phenomenon of heat flux inversion in negative thermal conductivity materials and potential applications of negative thermal conductivity has been predicted.[39] Subsequently, negative thermal conductivity develops rapidly in the field of thermal metamaterials and transformation thermotics,[46] which induces a series of theoretical studies on materials with negative thermal conductivity and novel thermal phenomena such as unconventional thermal cloaking,[41,42] golden touch phenomenon,[43] remote heating/cooling,[45] negative thermal transport,[46] and thermal nonlinearity enhancement.[45] In addition to current proposed applications, materials with negative thermal conductivity may also have potential applications in thermal protection/isolation, thermal sensor/detection, thermal rectification, thermal illusion/camouflage, and smart temperature control systems with high accuracy. However, there is still a lack of research on the realization of materials with negative thermal conductivity using thermal metamaterials/metasurfaces. Unlike electromagnetic metamaterials, in which negative permittivity or permeability can be obtained by resonant artificial units, thermal conduction does not have a corresponding resonance effect; therefore, materials with negative thermal conductivity cannot be designed by analogy with electromagnetic resonant metamaterials of negative permittivity/permeability.

2. Results and Discussion

2.1. Design Concept

To equivalently realize materials with negative thermal conductivity, which can then be used to construct long-focus thermal lenses for remote heating/cooling, we propose a general method of placing heat sources with pre-designed continuous power distribution along the boundary of a hypothetical material with negative thermal conductivity, which can achieve the same temperature field modulation effect in materials with a positive thermal conductivity as that in materials with negative thermal conductivity. Subsequently, we study the realization of the boundary heat source using finite active thermal metasurfaces (ATMSs), which can create special temperature distributions that previously had to be achieved by materials with negative thermal conductivity, such as long-focus thermal focusing shown in Figure 1b,c. As an example, we design a long-focus thermal lens with negative thermal conductivity using transformation thermodynamics to remotely control thermal fields (see Figure 1b) and use the proposed method to equivalently realize the designed long-focus...
Figure 2. Schematic of the equivalent realization of a material with negative thermal conductivity using the continuous boundary heat sources in Equation (2) or the discrete ATMSs in Equation (3). a) Arbitrarily shaped material with negative thermal conductivity embedded in a background material with positive thermal conductivity. b,c) Material with negative thermal conductivity replaced by the background material with positive thermal conductivity surrounded by continuous boundary heat sources (b) and discrete ATMSs (c). d,e) Simulated temperature distributions of a three-layer structure for material with negative thermal conductivity sandwiched between two background materials with positive thermal conductivity (d), and material with positive thermal conductivity sandwiched between two background materials with positive thermal conductivity and with two sets of designed ATMSs using Equation (3) (inside two dashed boxes) on the boundaries when constant high/low-temperature sources are applied at the left/right boundaries (e). The cyan arrows indicate the direction of heat flux.

2.2. Equivalence between Material with Negative Thermal Conductivity and ATMS

For the 2D case, a piece of material with negative thermal conductivity \(-\kappa_a\) (\(\kappa_a > 0\), blue region 1 in Figure 2a) is assumed to be embedded in a background material with positive thermal conductivity \(\kappa_b\) (\(\kappa_b > 0\), white region 0 in Figure 2a). The heat flux density in the normal direction should be continuous at each point of the boundary without considering the interface thermal resistance\(^{[50,51]}\) and is given as follows:

\[
q_u = -\kappa_b u \cdot (\nabla T)_{\text{region 0}} = \kappa_a u \cdot (\nabla T)_{\text{region 1}} \quad (1)
\]

where \(u\) is the unit vector normal to the interface (indicated by the red arrow in Figure 2a–c). Due to the continuity of the heat flux according to Equation (1), the temperature gradients along the boundary between materials with positive and negative thermal conductivity have opposite directions as shown in Figure 2a. To maintain the same temperature field distribution in each region (including the boundary) upon replacing the material with negative thermal conductivity (Figure 2a) by a material with positive thermal conductivity (Figure 2b), the heat fluxes around the boundary close to the region 1 become \(-\kappa_a u (\nabla T)_{\text{region 1}}\), which have opposite directions of the heat fluxes at the same position as in Figure 2a. In this case, it is necessary to introduce a boundary heat source (i.e., described by the boundary heat power density \(q_s\)) to maintain the continuity of the heat flux at each point on the boundary in the normal direction without having an additional effect on the temperature field in the two regions (i.e., to keep the temperature field inside the region (0) and the region (1) the same in Figure 2a,b), which can be given as follows:

\[
q_s = -2q_u = -2\kappa_a u \cdot (\nabla T)_{\text{region 1}}. \quad (2)
\]
The boundary heat power generated per unit area (or per unit length in the 2D case) has the same dimension as the heat flux and is related to the normal component of the heat flux at the interface. The minus sign in Equation (2) indicates that the boundary heat source is used to eliminate the effect of the heat flux from both sides of the boundary, whereas factor 2 in Equation (2) corresponds to heat fluxes from two normal directions aside from the boundary all contribute to the boundary heat source. Note that the heat flux in the tangential direction is continuous and does not contribute to the boundary heat sources.

To discretize the boundary heat source \( q_{\text{m}} \) in Equation (2) into a finite number of ATMSs with designed heat power distribution, the boundary is discretized into \( M \) curve segments with an equal interval \( \Delta \). A total of \( M \) ATMSs are placed at the center of each curve segment as shown in Figure 2c. The heat power of the \( m \)th ATMS \( (m = 1,2,3,..., M) \) can be designed as the line integration of the boundary heat source \( q_{\text{m}} \) over the \( m \)th curve segment, and is given as follows:

\[
Q_m = \int_{\theta_{m-\Delta\theta}}^{\theta_{m+\Delta\theta}} q_r d\theta, \quad \Delta = \int_{\theta_{m-\Delta\theta}}^{\theta_{m+\Delta\theta}} r d\theta
\]

(3)

Note that the intervals of ATMS are not necessarily chosen to be equal. For a given boundary shape, the intervals can be flexibly selected to reduce the number of ATMS. For example, larger intervals (i.e., sparser ATMS) can be used at the boundary with smaller curvature (e.g., at smooth boundaries), and smaller intervals (i.e., denser ATMS) must be used at the boundary with smaller curvature (e.g., at geometrical singularities). More explanations and numerical verifications are given in Note S1.1 (Supporting Information). All the above formulas deduced in the 2D case can be extended to the 3D case and are provided in Note S1.2 (Supporting Information).

To initially verify the validity of the discretized ATMSs with designed heat power distribution in Equation (3) that can equivalently perform as materials with negative thermal conductivity, numerical simulations of a three-layer structure were conducted. As shown in Figure 2d,e, the temperature distributions in all regions are the same when the material with negative thermal conductivity in the middle layer (Figure 2d) is replaced by the background material with positive thermal conductivity and the designed ATMSs on both sides of the middle layer (Figure 2e), which verifies the equivalence between material with negative thermal conductivity and the designed ATMSs.

To verify the generality of the proposed method, additional simulations are given in Note S1.1 (Supporting Information) when the materials with negative thermal conductivity have arbitrary irregular shapes, which show arbitrary-shaped materials with negative thermal conductivity can be equivalently realized by the designed ATMSs in Equation (3).

2.3. Long-Focus Thermal Lens for Remote Heating/Cooling Using Transformation Thermodynamics

First, we designed a long-focus thermal lens with negative thermal conductivity using transformation thermodynamics to achieve remote heating/cooling effects, as shown in Figure 1b. The reference space and physical space are shown in Figure 3a,b, respectively, in which the quantities are distinguished with respect to primes. In the reference space, a line heat source with constant power \( Q'_{\Omega} \) is set at \( \rho' = h_{\Omega}, (\theta' = 0) \) between the circle \( C_2 \) with radius \( R_2 \) and the circle \( C_3 \) with radius \( R_3 \) in Figure 3a. Next, we transform the location of the heat source \( (\rho = h_{\Omega}, \theta = 0) \) in the reference space to another location \( (\rho = h_{\Omega}, \theta = 0) \) in the physical space using transformation thermodynamics. We fix the boundary of the circle \( C_2 \) and fold the circle \( C_3 \) inward to another circle \( C_1 \) with radius \( R_1 \) \( (R_1 = R_2^2/R_3) \), that is, the transformations \( \rho = R_2^2/\rho' \) and \( \theta = \theta' \) are used to fold the region \( R_2 < \rho < R_3 \) in Figure 3a to the region \( R_1 < \rho < R_2 \) in Figure 3b. To maintain the continuity of the space, the region inside circle \( C_1 \) should be squeezed into the interior of circle \( C_1 \) using the transformations \( \rho = \rho' R_1/R_2 \) and \( \theta = \theta' \). Consequently, the source is squeezed to the new position at \( \rho = h_{\Omega} = h_{\Omega} R_1/R_2 \) in the physical space (see Movie S1, Supporting Information for the variations of the coordinate grids and heat source during this process). Assuming that a uniform background medium with positive thermal conductivity \( \kappa_b \) fills the whole reference space, the 2D in-plane thermal conductivity in each region of the physical space can be calculated by transformation thermodynamics[33] as follows (refer to Note S2, Supporting Information for details):

\[
\begin{align*}
\kappa_1 &= \kappa_b \quad \text{for region } \rho < R_1 \\
\kappa_2 &= -\kappa_b \quad \text{for region } R_1 \leq \rho < R_2 \\
\kappa_3 &= \kappa_b \quad \text{for region } \rho \geq R_2
\end{align*}
\]

(4)

In the physical space, the thermal material in region \( R_1 < \rho < R_2 \) has negative thermal conductivity, \(-\kappa_b\), which corresponds to the designed long-focus thermal lens, whereas the thermal conductivity of the remaining parts is kept as the uniform background medium with positive thermal conductivity, \( \kappa_b \). Moreover, the power of the transformed heat source located at \( (\rho = h_{\Omega}, \theta = 0) \) in the physical space can also be calculated by the transformation thermodynamics (refer to Note S2, Supporting Information), which is the same as the power of the heat source located at \( (\rho' = h_{\Omega}, \theta' = 0) \) in the reference space, that is, \( Q_{\Omega} = Q'_{\Omega} \).

From the perspective of transformation thermodynamics, the function of the materials with the thermal conductivities in Equation (4) is to “fold” the heat source of power \( Q_{\Omega} \) at \( (\rho = h_{\Omega}, \theta = 0) \) in the physical space to create a virtual heat source (i.e., thermal image) at \( (\rho = h_{\Omega}, \theta = 0) \), which performs as a long-focus thermal lens with a focal length \( f = h_{\Omega} - R_1 \) (see Figure 3d). The temperature field distribution produced by this virtual heat source is almost the same as that produced by a heat source of power \( Q_{\Omega} \) placed at \( (\rho' = h_{\Omega}, \theta' = 0) \) in a uniform material with positive thermal conductivity \( \kappa_b \) in the reference space (see Figure 3c) for the region \( \rho > R_2 \), except the regions near the boundaries between materials with positive and negative thermal conductivity, where the temperature is extremely high. This interesting phenomenon is similar to the surface plasmon polaritons generated on the boundary between a dielectric and a metal (negative permittivity) in optics, which can be treated as “thermal surface plasmon polaritons”.

Considering the geometric and coordinate transformation relations, the focal length of the designed long-focus thermal lens
Figure 3. Folding transformation between a) the reference space and b) the physical space is used to design a long-focus thermal lens with negative conductivity (blue region) to create a virtual heat source (thermal image) at \( f = h_i - R_2 \) from the back surface of the thermal lens when the real heat source is at \((\rho = h_o, \theta = 0)\) inside the lens. c,d) Simulated temperature distributions for the reference space (c) and the physical space (d), corresponding to (a) and (b), respectively. The temperature distributions in (c) and (d) are almost the same (especially the region \( \rho > R_3 \)), implying that a line heat source at \((h_o, 0)\) surrounded by the designed thermal lens with negative thermal conductivity can create almost the same temperature distribution as the case when a line heat source at \((h_i, 0)\) with the same amplitude is in a uniform medium with positive thermal conductivity. The white regions denote that the temperatures are beyond the range of the color bar. The white dashed circles in (c,d) represent virtual boundaries, and green solid circles in (d) represent boundaries between different thermal materials.

with negative thermal conductivity in Figure 3b can be further expressed as follows:

\[
f = h_i - R_2 = R_1 \left( \frac{h_o R_2}{R_1^2} - 1 \right) \tag{5}
\]

The focal length is independent of the thermal conductivities and is determined by the geometric parameters of the lens \((R_1\) and \(R_2\)) and the location of the actual heat source \(h_o\). According to Equation (5), a longer focal length can be obtained by increasing \(R_2\) or reducing \(R_1\). If the source position \(h_o\) and the inner boundary of the lens \(R_1\) are fixed, a longer focal length can be achieved by a longer outer boundary of the lens \(R_2\), (see Note S3, Supporting Information for additional calculated results). By adjusting the power of the heat source \(Q_0\) in the physical space, the temperature field distribution around the virtual source (at \(f = h_i - R_2\) from the back surface of the thermal lens) can be varied correspondingly. For example, remote heating and cooling can be achieved by setting the heat source to release and absorb heat power, respectively. This remote temperature control capacity is further described in Section 2.7.

2.4. Long-Focus Thermal Lens by ATMS

In this section, we describe the realization of the designed long-focus thermal lens with negative thermal conductivity (Equation (4)) by the proposed ATMS (Equation (3)) to achieve the same remote thermal focus effect as that in Figure 3d. As the thermal conductivity is uniform for each region in the physical space, we can calculate the temperature distribution in each region directly by solving the 2D thermal conduction equation with a line heat source given as follows: \(\nabla (\kappa \nabla T) = A_0 \delta (\rho - h_o) \delta (\theta) / \rho\). The temperature inside the designed long-focus thermal lens with negative thermal conductivity can be written as follows (detailed calculations are given in Note S3, Supporting Information):

\[
T = \frac{A_o}{2\pi \kappa_b} \ln \rho + \frac{A_o}{2\pi \kappa_b} \sum_{n=1}^{N} \frac{1}{n} \left( \frac{\rho h_o}{R_1^n} \right)^n \cos n\theta + T_b + \frac{A_o}{2\pi \kappa_b} \ln R_0 - \frac{A_o}{\pi \kappa_b} \ln R_2, \quad R_1 \leq \rho \leq R_2 \tag{6}
\]

where the constant \(T_b\) is the constant temperature of the far-field background (i.e., the room/environment temperature), and
positive integer \( N \) is the highest order in the Fourier series. Equation (6) gives the temperature field distribution in the region with negative thermal conductivity; therefore, the heat flux distribution on the boundaries \( C_1 \) and \( C_2 \) can be calculated from the temperature field gradient using Equation (1), and then the equivalent two-boundary heat sources with continuous thermal flux distribution along circles \( C_1 \) and \( C_2 \) can be calculated using Equation (2), and given as follows:

\[
\begin{align*}
q_{\theta,i} &= -\frac{A_0}{2\pi R_1^2} - \frac{A_0}{2\pi R_2^2} \sum_{n=1}^{N} \left( \frac{h_1}{R_1} \right)^n \cos(n\theta) \\
q_{\theta,j} &= \frac{A_0}{2\pi R_1^2} + \frac{A_0}{2\pi R_2^2} \sum_{n=1}^{N} \left( \frac{h_2}{R_2} \right)^n \cos(n\theta) \tag{7}
\end{align*}
\]

The analytical calculations show that the temperature created by two boundary heat sources along circles \( C_1 \) and \( C_2 \) in Equation (7) together with a line heat source \( A_0\delta(\theta)(\rho - h_3)/\rho \) is the same as the temperature created by one boundary heat source along the circle \( C_1 \) without any line heat source for region \( \rho > R_2 \); this temperature is given as (refer to Note S4, Supporting Information for details) follows:

\[
\tilde{q}_{\theta,i,j} = -\frac{A_0}{2\pi R_1^2} + \frac{A_0}{2\pi R_2^2} \sum_{n=1}^{N} \left( \frac{h_1 R_2}{R_1^2} \right)^n \cos(n\theta). \tag{8}
\]

Simulated results in Figure 4a,b verify that two-boundary heat sources with a line heat source \( \text{line source at } \rho = h_3, \theta = \theta_m \) and a one-boundary heat source without any line heat source \( \text{line source at } \rho = h_3, \theta = \theta_m \) in Equation (7) can create the same expected remote thermal focus effect, which is similar to the effect produced by materials with negative thermal conductivity shown in Figure 3d. Therefore, an expected remote virtual heat source outside the outer boundary \( C_2 \) can be produced by any set of equivalent boundary heat sources using Equations (7) and (8). Similar “thermal surface plasmon polaritons”, that is, the oscillatory distribution of high- and low-temperature fields occurs near equivalent boundary heat sources, where the magnitude of the temperature field is extremely high.

Next, we discretize the one-boundary heat source with continuous thermal flux distribution \( \tilde{q}_{\theta,i,j} \) in Equation (8) into \( M \) equal-spaced ATMSs using Equation (3), and the heat power of the \( m^{th} \) ATMS can be written as:

\[
\tilde{Q}_{\theta,i,m} = -\frac{A_0}{2\pi} \Delta \theta + \frac{A_0}{2\pi} \sum_{n=1}^{N} \left( \frac{h_1 R_2}{R_1^2} \right)^n \sin \left( \frac{n}{2} \Delta \theta \right) \cos \left( n\theta_m \right) \tag{9}
\]

where \( \Delta \theta = 2\pi / M \), \( \theta_m \) is the polar angle of the \( m^{th} \) ATMS (see Figure 2c), and the total number of the ATMS, \( M \), is designed such that it is twice the highest order of the Fourier series, \( N \), that is, \( M = 2N \). Figure 4c–f shows the simulated temperature distributions, in which the numbers of ATMS are \( M = 6 \) (c), \( M = 12 \) (d), \( M = 18 \) (e), and \( M = 24 \) (f). The temperature distribution in the region concerned tends to be more similar to the temperature distribution created by a virtual source in Figure 3c as \( M \) increases, whereas the focal length of the lens remains approximately the same as the theoretically expected value calculated using Equation (5) when \( M \) increases to 12. To achieve a satisfactory remote heating effect, a larger \( M \) is required. However, as \( M \) increases, more ATMS are required to realize the thermal lens and more power is consumed. Therefore, the thermal lens with \( M = 12 \) is chosen to be fabricated in the subsequent experiments. Note
Figure 5. Experimental setup and measured results. a) Schematic of the designed thermal lens with 12 ATMSs to realize remote heating/cooling effects. The blue blocks are ATMSs with serial numbers marked in the illustration below it. The brown circular region represents the copper plate, and the gray paper represents the graphite sheet. b) Schematic diagram of ATMS operation and heat dissipation (side view), and the yellow arrows represent the heat flow. c,d) Simulated and measured temperature distributions with the designed thermal lens to demonstrate the remote heating effect, respectively. e,f) As a reference to demonstrate the remote cooling effect, simulated and measured temperature distributions without the designed thermal lens, respectively, in which only a line high-temperature source is present in the background material. g,h) Simulated and measured temperature distributions with the designed thermal lens for a remote cooling effect, respectively, in which a line high-temperature source is located at the focal point of the designed thermal lens.

that \( M = 2N \) represents the minimum required number of ATMS based on Nyquist’s theorem. \( M \) can be designed larger than \( 2N \) but is not necessary because \( 2N \) ATMSs can already sufficiently mimic the fluctuation of the boundary heat source between positive and negative values. Figure 4g,h show the cases with \( M = 3N \) and \( M = 4N \), respectively, which show approximately the same temperature distribution as that in Figure 4c (\( M = 2N \)) with the same \( N \).

2.5. Experimental Measurements

A schematic of the experimental setup is shown in Figure 5a. A thermal lens with 12 ATMSs was fabricated to experimentally demonstrate the remote heating and cooling effect. The ATMSs with predesigned power can be realized using thermoelectric (TE) components, which are based on the Peltier effect and can release or absorb heat by applying forward or reverse electric currents, respectively.\(^{52}\) Detailed implementation/realization of ATMS is provided in Note S6.1 (Supporting Information). The released and absorbed heat powers, \( Q_H \) and \( Q_L \), for each ATMS can be calculated as\(^ {53,54}\) follows:

\[
Q_H = \alpha IT_H + \frac{1}{2} P^2 R - \kappa T \Delta T \\
Q_L = \alpha IT_L - \frac{1}{2} P^2 R - \kappa T \Delta T
\]

where \( I \) is the amplitude of the input current, and \( \Delta T = T_H - T_L \) is the temperature difference between the high-temperature surface, \( T_H \), and the low-temperature surface, \( T_L \), of the TE component. \( \alpha \), \( R \), and \( \kappa T \) represent the Seebeck coefficient, electrical resistance, and thermal conductance, respectively, of the TE component.

Twelve ATMSs (with a size of 6.0 mm \( \times \) 6.0 mm \( \times \) 0.05 mm) were arranged in a circle of radius \( R_2 = 33 \) mm. Graphite sheets
with sizes of 500 mm × 500 mm × 0.1 mm and lateral thermal conductivity of ≥1500 W m⁻¹ K⁻¹ [53] were covered on the top surface of each ATMS, which served as the background material. To handle the heat generated from powering the ATMSs, the ATMSs were not embedded inside the background material but attached to the surface of the background material. Therefore, only one side of each ATMS works to provide a heat/cold source to the background material, see Figure 5b. The other side of each ATMS was stuck to a common circular copper plate with a radius of 125 mm and thickness of 3 mm by thermally conductive silicone grease (thermal conductivity of 6 W m⁻¹ K⁻¹). The common copper plate serves as a thermal sink to absorb or release heat at the bottom surface of the TE components to offset/balance the heat generated from powering the ATMS and best perform equivalent to the theoretically required ATMS. A foam board with a thickness of 3 mm and thermal conductivity of ≈0.035 W m⁻¹ K⁻¹ [54] was placed on the bottom side of the graphite sheets to reduce thermal convection. More details on sample preparation are given in Note S6 (Supporting Information).

To demonstrate the remote heating effect, the virtual thermal image created by the designed thermal lens should be a high-temperature image (i.e., \( A_r > 0 \) in Equation (9)). In this case, the required thermal powers of the 12 ATMSs were calculated using Equation (9) with \( A_r = 0.187 \) W m⁻¹, which were normalized as the power ratio using the power of the first ATMS in the experiment. Once the required source power ratio of each ATMS was obtained, the required electric currents applied to each ATMS was initially estimated using Equation (10) under the linear approximation, which was slightly corrected during the experimental testing. The 12 ATMSs were connected to four adjustable DC power supplies (each power supply had three independent outputs), which provided energy for the 12 ATMSs and powered the whole system. The precise driving currents for remote heating are listed in Table S1 (Supporting Information). Subsequently, a real-time temperature distribution of the detection region with the fabricated thermal lens was observed using an infrared camera (FOTRIC 288). The general procedure of the experimental measurement is provided in Movie S2 (Supporting Information).

More details on the measurement process are given in Note S7 (Supporting Information). Figure 5c,d shows the simulated temperature distributions and measured temperature distributions captured by the infrared camera, respectively. The measured result corresponds well with the simulated result, which demonstrates that the remote heating effect is realized by a long-focus thermal lens with outer radius \( r_o = 33 \) mm and focal length \( f = 19.8 \) mm. See Movie S3 (Supporting Information) for the real-time measured temperature distribution.

For a remote heating/cooling effect, the virtual thermal image created by the designed thermal lens performs as a low-temperature image (i.e., \( A_r < 0 \) in Equation (9)). In this case, the required power ratio of each ATMS and the corresponding applied electric currents on each ATMS were obtained using the same steps (see Note S7, Supporting Information for more details). Similarly, 12 independent power supply outputs were used to drive all 12 ATMSs; the driving currents for remote cooling are given in Table S2 (Supporting Information). To observe the cooling effect clearly, the temperature created by a line high-temperature heat source (constant normalized power of 0.187 W m⁻¹ and located at \( (h, 0) \)) to be cooled later was simulated (Figure 5e) and measured (Figure 5f) as a reference. When the reference high-temperature heat source was set at the focal point of the designed thermal lens, both simulated and measured results showed that the temperature around the high-temperature heat source was considerably decreased (see Figure 5g,h). The corresponding temperature distributions along the line \( x = h \) for each case were plotted on the right side (Figure 5e–h). Compared with the reference in Figure 5e,f, the expected heat flux suppressing effect and remote cooling effect were observed with the designed thermal lens in Figure 5g,h. The temperature drop of the fabricated thermal lens was ≥1 °C in the experiment, which was further improved by increasing the power of each ATMS unit or the number of ATMSs. Note that increasing the power of each ATMS unit would result in a temperature drop in the surrounding area other than the target point, whereas increasing the number of ATMSs can provide a higher temperature drop at the target point almost without affecting the temperature of the surrounding area.

Note that ATMSs require additional energy, implying that our device is not energy-saving. However, similar to the further improvement of the resolution of a superlens by an active negative refractive index media and the bandwidth of invisibility by active cloaks, several novel features and performance improvements can only be achieved at the expense of energy consumption. Therefore, achieving novel functions (e.g., remote heating/cooling with a non-zero focal length) that cannot be achieved using passive materials with the help of additional energy consumption is a challenging research topic, and it is specifically the issue addressed in this paper. Compared to passive thermal lenses without energy drive (the focal length can only be zero), the long-focal thermal lens fabricated in this study can achieve remote thermal focusing with the measured focal length \( f = 19.8 \) mm using ATMSs driven by precisely designed electric currents from DC power supplies.

2.6. Potential Applications

The proposed approach to equivalently realize a material with negative thermal conductivity using ATMS may have several novel applications in temperature control and thermal engineering. Analogous to a superlens in optics that can achieve subwavelength resolution owing to its negative refractive index, a thermal superlens, which is a slab with a negative thermal conductivity that can significantly improve the resolution of thermal imaging systems, can be realized using the proposed ATMS. Similar to the surface plasmon polaritons that occur on the interface between positive and negative refractive index media for optical superlens, “thermal surface plasmon polaritons” appear in thermal superlens (Note S8.1, Supporting Information). The temperature distribution of two heated objects located close to each other can be resolved when the observation plane is far away from the object plane with the help of thermal superlens by the proposed ATMS (see more in Note S8.2, Supporting Information).

Similar to an electromagnetic complementary media pair in optics, a thermal complementary media pair is two thermal media whose thermal conductivities have the same magnitude but opposite signs. The region occupied by the thermal complementary media pair is equivalent to the void region for heat flow,
which can be used to thermally eliminate the space. The proposed ATMS can be utilized to realize the thermal complementary medium of the thermal insulation wall, which can be placed along the thermal insulation wall to enable heat flow to continue propagating through the thermal insulation wall and achieve a thermal tunneling effect (more details are provided in Note S8.3, Supporting Information). In this case, the heat flux can pass through the thermal insulation wall, which performs as a thermally conductive but electrically non-conductive medium.

In thermal protection applications, it is often desired to prevent external heat flow from entering the region containing some thermally sensitive components, yet allow an electric current to enter the same region to power these components. This is difficult to realize by natural materials due to the Wiedemann–Franz law. A thermally invisible gateway, which can be realized by the designed ATMS, can block the heat flow and allow electric current through the gateway (refer to Note S8.4, Supporting Information for more details). The physical mechanism of this novel phenomenon is that charge and heat are transported differently in an invisible gateway, that is, the charge is transported in the same way as in a normal metal, whereas the heat transport is influenced by the additional heat flows introduced by ATMS, which is unlike normal metals for which the same quasiparticles that transport charge also carry heat. From the heat transfer perspective, the proposed invisible gateway uses ATMS to interfere with the heat transport in metals by dissipating and injecting heat fluxes into the background copper. At the same time, the charge transfer in the background copper is not influenced by ATMS, implying that the background copper is still an electric-conducting metal from a charge transfer perspective. This is the reason for the realization of the same high electrical conductivity as metal and the same low thermal conductivity as air by the thermal invisible gateway.

In our experiment on remote heating/cooling, a common copper plate is utilized to connect the opposite sides of all ATMSs together, which has been experimentally verified to be an effective way to deal with the heat generated from powering the ATMS. Therefore, to experimentally realize the above applications (e.g., thermal protection and thermal insulating wall), the heat generated from powering the ATMS can also be dissipated by introducing a common copper plate on the other side of the ATMS, which performs as a heat sink to offset/balance the heat generated from powering the ATMS.

From various examples attributed to the proposed method of implementing materials with negative thermal conductivity by ATMS in this study, previous novel optical phenomena and electromagnetic devices with various functions based on negative refractive index media, complementary materials, and surface plasmon polaritons can be extended to the thermal field correspondingly, thus providing an unprecedented new approach to control the temperature field and heat flux.

### 2.7. Remote Temperature Control by ATMS

The proposed long-focus thermal lens by ATMS can provide three ways for remote temperature control, including a switching function between cooling and heating at the thermal focal point, tuning the temperature at the focal point, and varying the position of the thermal focal spot. These three functions of remote temperature control can all be achieved in real-time by varying the electric currents loaded on ATMS.

By adjusting the sign and value of the current applied to each ATMS, the amplitude $A_0$ of the virtual heat source in the reference space in Equation (9) can change its sign or value correspondingly, which in turn can generate a heating/cooling function switch (see Figure 5d,h for measurement results) or a temperature value adjustment at the thermal focal spot (see more in Note S9.1, Movie S4, Supporting Information). Note that this real-time remote temperature control effect only varies the temperature in the region near the thermal focal spot (i.e., blue dots in Figures 4.5c,d), whereas the temperature in the region outside the thermal focal spot remains unchanged and is equal to the room/environment temperature. This method of remote temperature field control can be used in biochemistry experiments to provide real-time heating/cooling of a specific region (e.g., the region where biochemical reactions occur) while the temperature field in the surrounding area remains the room/environment temperature.

The focal length of the thermal lens ($f$) in Equation (5) can be tuned by changing the parameters of the thermal lens ($R_c$ and $R_e$) or the position of the line thermal source ($h_e$), which can be equivalently achieved by tuning the heat power of individual ATMSs in Equation (9) (see Note S9.2, Movie S5, Supporting Information). The angular position of the focal point can also be tuned by introducing a rotation angle parameter in Equation (9), which can also be realized by tuning the power of individual ATMSs (see Note S9.2, Movies S6, S7, Supporting Information). Therefore, the position of the thermal focal spot, that is, both the focal length and angular position, can be changed in real time by adjusting the current applied to individual ATMSs. This adjustment of the focal position can be spatial continuous or discrete, which may have applications in spatial alternating heating/cooling, the channel assignment of thermal signals, and time division heating.

### 3. Conclusion

A method to equivalently realize negative thermal conductivity by ATMSs was proposed and experimentally verified, which was used to design a series of novel thermal devices (e.g., thermal “surface plasmon polaritons”, thermal superlens, thermal tunneling effect, and thermal invisible gateway) that were previously only available for electromagnetic waves. As an example of experimental verification, a long-focus thermal lens, which focuses heat fluxes onto a spot far away from the lens for a remote temperature field control, was designed based on the proposed method and fabricated using 12 thermoelectric components driven by precisely designed electric currents from DC power supplies. Both simulated and measured results verified the proposed method and the ability of the long-focus lens for remote temperature control including heating/cooling switching and thermal target shifting (e.g., focal length and orientation). A fabricated thermal lens with a focal length $f = 19.8$ mm for both remote heating and cooling was verified experimentally, in which an expected temperature jump/drop at the precise target point was observed.

In addition to the experimentally verified long-focus thermal lens, other novel thermal devices based on negative thermal...
conductivity mentioned in the supporting information Notes or not mentioned in this study can also be implemented experimentally in the same way, which is summarized as follows: Replace the negative thermal conductivity medium by ATMSs with required absorbed/released heats in Equation (3); Obtain the required driving current for each ATMS (i.e., thermoelectric component) from Equation (10) using linear approximation; and Power each thermoelectric component by a DC power supply with the required driving current after fine-tuning the experiment. The proposed method extends the scope of thermal conductivity and has potential applications in remote temperature control and thermal engineering (e.g., dynamic thermocool control systems, thermal imaging, thermal illusions, and thermal coupling/communication).

4. Experimental Section

**Numerical Simulations:** All numerical simulations were conducted using the commercial software COMSOL Multiphysics 5.6 (license number: 9 406 999; https://www.comsol.com), which is based on the finite element method. The 2D solid heat transfer module with a steady-state solver was selected to simulate the temperature field distributions in various examples. Free tetrahedral meshing with an automatically generated mesh grid was used. The upper and bottom boundaries were set as thermal insulation, the left boundary was set as a constant high temperature of 100 °C, and the right boundary was set as a constant low temperature of 0 °C (Figure 2d,e). The thermal conductivity of the background was set at 1 W m⁻¹ K⁻¹ (Figure 2d,e), and the thermal conductivity of the material with negative thermal conductivity was set at −1 W m⁻¹ K⁻¹ (Figure 2d). Two sets of ATMSs (each with M = 10 units) were introduced on two boundaries (Figure 2e), whose heat powers were calculated using Equations (2) and (3). In Figures 3c,d, 4a, and 5e,g, the line heat sources (Figure 2d). TwosetsofATMSs(eachwith

**Supporting Information**

**Conflict of Interest**

The authors declare no conflict of interest.

**Data Availability Statement**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Keywords**

metasurfaces, negative thermal conductivity, remote temperature control, thermal lenses
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