Infrared thermal imaging is extensively adopted in many areas of medical science, industrial production, and military confrontation, e.g., body-temperature monitoring in clinical medicine, efficient management of heat energy, and infrared imaging guided missiles. Similar to optical or electromagnetic metamaterials, thermal metamaterials are also a kind of artificially structured material, which exhibit different thermal behaviors that cannot appear in naturally occurring materials. For example, as inspired by the concept of electromagnetic cloaks, the first thermal behavior revealed for thermal metamaterials is thermal cloaking designed by the approach of coordinate transformation and its extensions, which represents the fact that the heat flows around an object as if the object does not exist. Furthermore, thermal concentrating and rotating behaviors are also reported, which denote the concentration and rotation of heat flux across an object without disturbing external temperature profiles, respectively. As a matter of fact, all the existing thermal behaviors of cloaking, concentrating, and rotating can be essentially seen as a kind of thermal illusion, which means that an object exhibits the infrared thermogram of another object. Besides, recently, the concept of thermal illusion has been further developed to include more behaviors such as radiative camouflage and location misleading by developing different approaches of coordinate transformation. Such thermal illusion behaviors can be used for misleading infrared thermal detection.

However, almost all the existing thermal illusion behaviors were theoretically designed on the basis of unconventional thermal conductivities resulted from the analytical methods (say, coordinate transformation) in use. This problem largely limits fabrications for applications. By suggesting two discretization steps, here we put forward a numerical method instead to design thermal illusion, for which unconventional conductivities are no longer needed. In the meantime, more importantly, we reveal different thermal illusion behaviors. By tailoring the joint effects of thermal conduction and convection, we design a thermal pixel of cuboidal shape. We show that the assembly of such pixels into different two-dimensional arrays could generate infrared thermograms of different objects, which is thus called the digital thermal metasurface. Also, the metasurface is reconfigurable, and it can apparently produce all the existing thermal illusion behaviors reported in the literature. Finally, we experimentally fabricate a prototype. This work opens a door for applying conventional thermal conductivities of commercially available materials to thermal illusion, and we expect it to stimulate more exciting developments in electromagnetic disguise and confrontation. Published by AIP Publishing. https://doi.org/10.1063/1.5063619

Digital thermal metasurface with arbitrary infrared thermogram
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An object exhibits the infrared thermogram of another object, which is called thermal illusion as extensively investigated in the field of thermal metamaterials. However, almost all the existing thermal illusion behaviors were theoretically designed by using unconventional thermal conductivities, which means that the conductivities must be anisotropic, graded, or even singular due to the analytical methods in use. This problem largely limits fabrications for applications. By suggesting two discretization steps, here we put forward a numerical method instead to design thermal illusion, for which unconventional conductivities are no longer needed. In the meantime, more importantly, we reveal different thermal illusion behaviors. By tailoring the joint effects of thermal conduction and convection, we design a thermal pixel of cuboidal shape. We show that the assembly of such pixels into different two-dimensional arrays could generate infrared thermograms of different objects, which is thus called the digital thermal metasurface. Also, the metasurface is reconfigurable, and it can apparently produce all the existing thermal illusion behaviors reported in the literature. Finally, we experimentally fabricate a prototype. This work opens a door for applying conventional thermal conductivities of commercially available materials to thermal illusion, and we expect it to stimulate more exciting developments in electromagnetic disguise and confrontation. Published by AIP Publishing. https://doi.org/10.1063/1.5063619

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result, if we assemble a series of such pixels with different thermal conductivities, we start by illustrating how to manufacture a thin plate that can exhibit the human infrared thermogram as depicted in Fig. 1.

Therefore, the top surface temperature \( T \) can be expressed as

\[
T = \frac{\kappa_{\text{pixel}}/L + hT_{\text{air}}}{\kappa_{\text{pixel}}/L + h T_{\text{air}}},
\]

where \( \kappa_{\text{pixel}} \) stands for the thermal conductivity of the pixel, \( h \) is the thickness of the plate, and \( T_{\text{air}} \) is the temperature of the air. The temperature on the top surface is denoted by \( hT_{\text{air}} \).

To proceed, we know that it is particularly difficult to analytically express the temperature distribution in arbitrary infrared thermograms. For instance, the infrared thermogram shown in Fig. 1 consists of \( 240 \times 320 = 76800 \) pixels, which can be theoretically expressed by a 76799-order polynomial. However, doing so is strenuous and meaningless. In order to illustrate how to manufacture a thin plate that can exhibit the same infrared thermal imaging as a human, we start by designing a single thermal pixel as shown in Fig. 2. The pixel is placed in an environment with temperature \( T_{\text{air}} \), and its bottom surface is connected with a heat source with \( T_{\text{source}} \). Its thermal conductivity and thickness (from bottom to top) are \( \kappa_{\text{pixel}} \) and \( L \), respectively. The temperature on the top surface is denoted by \( T \), and the coefficient of heat convection between the top surface and air is \( h \). The other four side surfaces of the pixel are set to be heat insulation. Therefore, the top surface temperature \( T \) can be expressed as

\[
T = \frac{\kappa_{\text{pixel}}/L + hT_{\text{air}}}{\kappa_{\text{pixel}}/L + h T_{\text{air}}},
\]

Clearly, a series of \( \kappa_{\text{pixel}} \) will produce a series of \( T \). As a result, if we assemble a series of such pixels with different \( \kappa_{\text{pixel}} \) into a \( 240 \times 320 \) array with an appropriate pattern, the resulting array (plate) can exhibit the human infrared thermogram as depicted in Fig. 1.

However, things are not so simple and there are two additional problems: (A) the contact between neighboring pixels can affect the original temperatures; (B) manufacturing \( 240 \times 320 = 76800 \) pixels with different thermal conductivities is pretty hard.

In fact, if the contact thermal resistance between neighboring pixels is large enough or the plate is thin enough, the effect of problem (A) can be small enough to be neglected. So, only problem (B) matters, and we need to decide how to coarsen the space. For simplicity, we focus on the upper part of the human body, which contains \( 91 \times 151 = 13741 \) pixels as marked by the yellow rectangle in Fig. 1. In order to measure the information loss or information remained, we turn to the Shannon information entropy as expressed by Eqs. (1) and (2). Figure 3 shows that the Shannon information entropy decreases as the strength of coarsening increases. It can be concluded that after coarsening the thermogram to an array with \( 31 \times 51 = 1581 \) pixels, the quality of the imaging is still acceptable. After a trade-off between quality and feasibility, we choose this array (with 1581 pixels) to move on.

It should be noted that the Shannon information entropy is related to the space and temperature resolutions of infrared thermal detectors. So, the information entropies shown in Fig. 3 are calculated under different temperature resolutions from 1 to 0.01 K. Furthermore, we read \( 91 \times 151 = 13741 \) temperatures for each panel of Fig. 3 to calculate the Shannon information entropy, even though these panels are coarsened. This is because the space and temperature resolutions of infrared thermal detectors are determined by manufacturers rather than objects for detection.

For the array with \( 31 \times 51 = 1581 \) pixels, there would be \( 31 \times 51 = 1581 \) different thermal conductivities. It is still a huge workload to find 1581 materials with different thermal conductivities for experiment. It is also difficult to perform the corresponding finite element simulations. So, we coarsely discretize the 1581 quasi-continuous temperatures to 10, 20, 50, 100, or 200 ones with an equal interval and then calculate the corresponding thermal conductivities according to Eq. (3). The simulation results shown in Fig. 4 indicate that 50 conductivities are adequate to exhibit high quality imaging. More conductivities (such as 100 and 200) do not improve the imaging quality significantly.

In order to show the feasibility of a human infrared thermogram generated by a digital thermal metasurface, we fabricate a prototype. We choose 10 colloidal materials (namely, ten kinds of pixels) to conduct the experiment, each
having one thermal conductivity. All the colloidal materials or pixels are obtained by mixing silica gel [thermal conductivity, \(\kappa_{\text{gel}} = 0.15 \text{ W/(m \cdot K)}\) and mass density, \(1.14 \times 10^3 \text{ Kg/m}^3\)] and white copper powder [\(\kappa_{\text{copper}} = 33 \text{ W/(m \cdot K)}\) and \(8.65 \times 10^3 \text{ Kg/m}^3\)]. Each pixel has an overall thermal conductivity \(\kappa_{\text{pixel}}\), which is determined by the famous Bruggeman formula, namely,

\[
\frac{p_{\text{gel}}}{\kappa_{\text{gel}}} + \frac{1 - p_{\text{gel}}}{\kappa_{\text{pixel}}} = 0,
\]

where \(p_{\text{gel}}\) is the volume fraction of silica gel in the pixel. Once the \(\kappa_{\text{pixel}}\) of each pixel in the prototype is determined by Eq. (3), Eq. (4) will help to determine the composition ratio of silica gel and white copper powder for fabricating the experimental sample.

However, piecing 1581 cuboidal pixels together is not an easy job. Without loss of generality and for the sake of convenience, an acrylic plate with \(31 \times 51 = 1581\) cuboidal holes (each having a size of \(0.6 \times 0.6 \times 0.3 \text{ cm}\)) is manufactured; see Fig. 5(a). Every hole stands for the location of a pixel. The edges of each pixel naturally prevent the thermal interaction between neighboring pixels, which can be regarded as contact thermal resistance between pixels. The thermal conductivities of all the 1581 pixels can be

<table>
<thead>
<tr>
<th>Information Entropy</th>
<th>Resolution=1 K</th>
<th>0.1 K</th>
<th>0.01 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>2.9062</td>
<td>6.0189</td>
<td>9.2349</td>
</tr>
<tr>
<td>H2</td>
<td>1.8841</td>
<td>4.4703</td>
<td>6.4404</td>
</tr>
</tbody>
</table>

FIG. 3. Discretization of the infrared thermogram indicated by the yellow rectangle in Fig. 1. From left to right, the decreasing number of pixels denotes the increasing strength of coarsening. For each panel, the corresponding Shannon information entropy (H1 and H2) is also calculated for different temperature resolutions (1, 0.1, and 0.01 K) according to Eqs. (1) and (2), which is depicted under each panel accordingly.

FIG. 4. Finite element simulations of the middle panel (with \(31 \times 51 = 1581\) pixels) of Fig. 3 but for different numbers of materials (10, 20, 50, 100, and 200 from left to right). For each panel, the corresponding Shannon information entropy (H1 and H2) is also calculated for different temperature resolutions (1, 0.1, and 0.01 K) according to Eqs. (1) and (2), which is depicted under each panel accordingly. Other parameters: the simulation box consists of \(31 \times 51 = 1581\) cuboidal pixels, each having a size of \(0.6 \times 0.6 \times 0.3 \text{ cm}\); the backward heat source is set at 310 K, and the side boundaries are set to be thermal insulation; the upward surface convects thermal energy with air (273 K) with \(h = 50 \text{ W/(m \cdot K)}\).
to perform forced convection. To compromise with the high temperature in the summer of 2018, we keep the experimental environment at approximately 293 K (by using air conditioner) and the heat source at 323 ± 1 K with reference to Eq. (3).

Based on the experimental setup shown in Fig. 5(c), we obtain the experimental result in Fig. 5(d). Despite the roughness of the experiment, the outline of a human has clearly appeared in the infrared thermogram as depicted in Fig. 5(d). Meanwhile, we notice that the overall temperature in Fig. 5(d) is higher than that in Fig. 1 or Fig. 4 due to the high temperature of our experimental environment. Nevertheless, the present comparison between Fig. 5(d) and Fig. 1 (or Fig. 4) makes it reasonable to conclude that the experimental result could show a better comparison with Fig. 1 or Fig. 4, when the experimental environment (and the heat source) is changed to be 273 K (and 310 K) by considering Eq. (3). Besides, we take a video to exhibit the experiment results more intuitively, which can be found in the multimedia view.

By designing a thermal pixel involving the joint effects of thermal conduction and convection, we have proposed a numerical method to design thermal illusion. Our method does not require unconventional conductivities, which, however, have been extensively adopted in the literature based on the analytical methods. As a result, we propose a different kind of thermal illusion, namely, generating arbitrary objects’ infrared thermograms within a single digital thermal metasurface that is reconfigurable by assembling thermal pixels into suitable patterns. Also, according to the two discretization steps proposed in this work, our metasurface can apparently produce all the existing thermal illusion behaviors such as cloaking, concentrating, and rotating but without the need to use unconventional conductivities any more. Finally, we experimentally fabricate a prototype to show the feasibility of the numerical method proposed in this work.

Our work paves a way for utilizing conventional thermal conductivities of commercially available materials to exactly design and realize general thermal illusion behaviors beyond and including the existing ones such as cloaking, concentrating, and rotating. In particular, it further makes it possible to achieve a different kind of thermal illusion, namely, realizing arbitrary objects’ infrared thermograms within a single reconfigurable digital thermal metasurface. This work is practically useful for anti-detection, say, for misleading infrared thermal detection with high efficiency; it might also inspire more developments in electromagnetic disguise and confrontation.

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![Fig. 5. Experimental verification of a human infrared thermogram within a digital thermal metasurface.](image)

(a) An acrylic plate drilled with $31 \times 31 = 1581$ holes in a square lattice, each hole indicating the location of a thermal pixel. For the pixels’ locations shown in (a), (b) shows the corresponding thermal conductivities required by Eq. (3), as indicated by the numbers from 1 to 10 which represent 0.2089, 0.2480, 0.2966, 0.3588, 0.4411, 0.5552, 0.7239, 0.9987, 1.5256, and 2.9453 W/(m·K), respectively. (c) Experiment setup: the back of the sample is connected with a copper heat sink, whose temperature is maintained between 322 and 324 K; the front of the sample is exposed to air (293 K); the heat convection between the sample and air is enhanced by an electric fan with a power of 100 W. (d) The infrared thermogram of the sample shown in (c), which is taken by using the FLIR E60 infrared camera. Multimedia view: https://doi.org/10.1063/1.5063619.