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An Optically Controllable Transformation-dc Illusion Device

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Metamaterials refer to a class of materials with some special properties that are not possessed by natural materials. Many unusual and interesting properties of metamaterials have been predicted and verified, such as negative refractions,[1–4] perfect lenses,[5] super-lenses [6] and hyper-lenses.[7] In 2006, Pendry et al. proposed the concept of transformation optics (TO), which provides a distinct methodology to control and redirect the electromagnetic fields,[8,9] which is employed in the design of invisibility cloaks. Soon afterwards, the experimental demonstration of a 2D invisibility cloak was accomplished using simplified material parameters.[10] A great deal of other preeminent work has been demonstrated to achieve invisibility cloaks in time-varying electromagnetic fields.[11–16] On the other hand, Greenleaf et al. have presented the rudiment of invisibility cloak in electrostatics[17] in 2003. Subsequently, invisibility cloaks in static magnetic fields were also proposed in theory[18] and verified in experiments.[19] Recently, Yang et al. proposed a method to realize the invisibility cloak in electrostatic fields with the help of steady circuit theory.[20] Later, an ultrathin dc invisibility cloak with nearly perfect invisibility effect was proposed and demonstrated experimentally.[21] Apart from invisibility cloaks, other transformation devices in static fields were also studied, such as electric concentrator,[22] dc illusion device,[23] etc. More recently, the manipulation of dc currents based on natural undecorated materials was also verified by experiments.[24]

In this paper, we propose and fabricate a light-controlled transformation-dc device in steady electric fields, which is made of resistor network with light-sensitive semiconductor resistors embedded. By tuning the intensity of illumination light, the functionalities of the transformation electrostatics device will metamorphose from a dc invisibility cloak to varying dc illusion devices. The real-time metamorphose is controllable by the external illumination light with varying light intensity, which is confirmed by measurements of voltage profiles.

Our goal is to construct an electrostatic meta-device allowing an externally applied light to mediate dc currents on the device to achieve multiple functionalities, which is illustrated in **Figure 1**a. For example, at the OFF state (when the light is switched off), the device is actually a dc invisibility cloak, which makes the core invisible in terms of the restoration of equal-potential lines. At the ON state (when the light turns on), the same device becomes a tunable electrostatic illusion device without using any varactors or active components. The measuring apparatus/probe will perceive various virtual objects in equivalence. When tuning the intensity of the illuminating light, the sizes and effective material properties of virtually perceived (equivalent) objects can be changed accordingly. The illustration of light-controlled dc device is shown in Figure 1b, in which the green region is the illusion region that will generate the illusion objects, as shown in Figure 1c.

We start with general current redirection and control in electrostatics. In a source-free conductive region, the currents are governed by $\nabla\cdot\vec{J}=0$. Since $\vec{J}=\sigma\vec{E}$ and $\vec{E}=-\nabla V$, the Laplace equation can be obtained:

$$\nabla\cdot(\sigma\nabla V)=0 \tag{1}$$

We know that if V is obtained from the above equation and boundary conditions, then the current $\vec{J}=-\sigma(\nabla V)$ will be given. That is to say, the current and potential distributions are determined by the conductivity of the material and the boundary conditions. Here, we present a strategy to redirect the currents at will by designing the conductivity of the media without changing the boundary conditions. We assume that the original current is uniform $\vec{J}$ and now make it flow like a fluid in an arbitrary way, denoted as $\overline{J'}$. Here, $\overline{J'}$ can be regarded as a distortion of $\vec{J}$ by some pulling and stretching process. Such a distortion will be expressed as a coordinate transformation from a Cartesian mesh to another distorted mesh:

$$x'(x,y,z),\ y'(x,y,z),\ z'(x,y,z)$$

where (x',y',z') is the corresponding point in the new coordinate system. The Laplace equation will keep form invariance under the coordinate transformation. In the distorted space, the material properties can be expressed as:

$$\overline{\overline{\sigma'}}=\frac{\Lambda\cdot\overline{\overline{\sigma}}\cdot\Lambda^T}{|\Lambda|} \tag{2}$$

in which Λ is the Jacobian transformation matrix.

The typical example of redirecting the currents is dc invisibility cloak.[20,21] A perfect dc invisibility cloak can guide the currents around the centered enclosed object and return back to their original propagation direction as if there is nothing in the conducting material. To design the dc invisibility cloak, the coordinate transformation, constructing the equivalence between the virtual space and the physical one, is expressed as:

$$r'=f(r)=(b-a)r/b+a,\qquad \varphi'=\varphi \tag{3}$$

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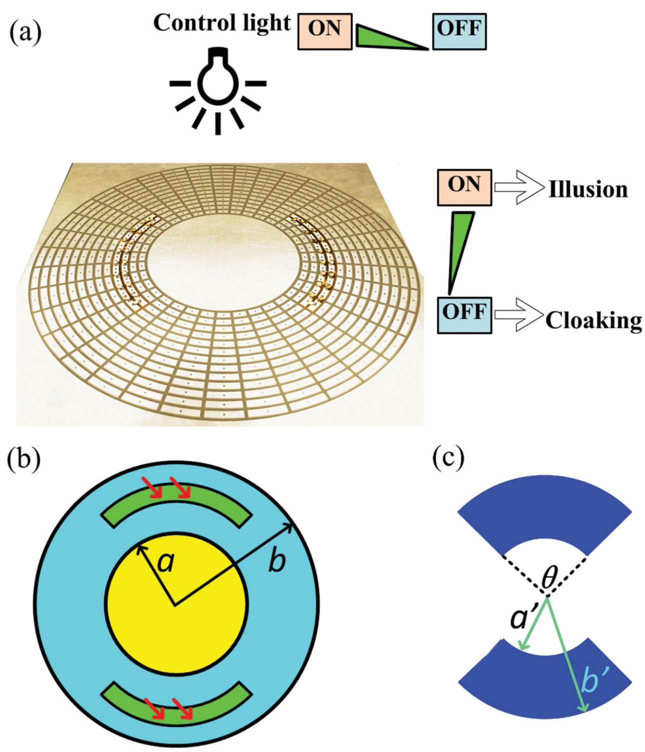

Figure 1. a) The principle of light-controlled transformation-dc device. When light source turns off, the transformation-dc device acts as a dc invisibility cloak, when light source turns on, the transformation-dc device acts as a dc illusion device. When tuning the intensity of illuminating light, the sizes and material properties of perceived objects will be changed according to strength of the light. b) Illustration of light-controlled transformation-dc device, the yellow region denotes the cloaked object, the light-blue region together with the green region denote the dc devices, the green region is the illusion region, which will generate the illusion objects. c) The illusion objects in virtual space. The geometry parameters are chosen as $a' = 5$ cm, $b' = 10$ cm, and $\theta = \pi/2$ in our simulation and experiment.

The currents will be conducted smoothly around the object without any perturbation as if they travel in free space. The anisotropic conductivity of cloaking shell can be obtained from Equation (2) as:

$$\sigma_\rho = \frac{\rho - a}{\rho} \cdot \sigma_0, \qquad \sigma_\varphi = \frac{\rho}{\rho - a} \cdot \sigma_0 \tag{4}$$

where a is the radius of the real object and σ_0 is the conductivity of background material in the virtual space. Apparently, the conductivities in the ρ direction and ϕ direction are different, yielding an anisotropic and inhomogeneous conducting material.

Now we will extend dc invisibility cloak to dc illusion device. In time-harmonic fields, the creation of illusion functionality is of great interest because it can potentially transform an actual perception into the precontrolled perception.[25] A simplified-parameter illusion device has been proposed and realized by using the space transformation theory and engineering capability of metamaterials.[26] The experimental demonstration of the illusion opens a novel avenue to the wave-dynamic illusion and cognitive deception. For electrostatic fields, the material properties of the illusion regions in dc device are described as:

$$\sigma_\rho = \frac{\rho - a}{\rho} \cdot \sigma_\mathrm{v}, \qquad \sigma_\varphi = \frac{\rho}{\rho - a} \cdot \sigma_\mathrm{v} \tag{5}$$

in which σ_v denotes the conductivity of the illusion objects in virtual space. Obviously, the dc illusion device has an inhomogeneous and anisotropic conductivity profile, which is very difficult to realize by natural materials. However, from the analogy between conducting materials and resistor networks, we emulate the illusion device by the circuit theory. First, we discretize the continuous material using the polar grids, to make a resistor network equivalent to the material. According to Ohm's law, each elementary cell in the grid can be implemented by two resistors. The expressions of resistances can be written as:

$$R_\rho = \Delta\rho / (\rho\Delta\varphi\sigma_\rho h), \qquad R_\varphi = \rho\Delta\varphi / (\Delta\rho\sigma_\varphi h) \tag{6}$$

where $\Delta\rho$ and $\Delta\phi$ are step lengths in the radial and tangential directions, respectively. The conductivities in radial and tangential directions are controlled by resistances along the corresponding directions. Thus, the anisotropic conductivity tensor can be easily realized using the resistor network.

Next, we go further to illusion device. To design an illusion device, we first choose some illusion objects in virtual space, then such objects will map to the corresponding region in physical space. Generally, the resistors in illusion region can be calculated and manipulated. However, here, we propose a new idea different from the illusion device. In illusion region, we would like to create some convertible and tunable illusion objects in virtual space. To generate a tunable dc metamaterial unit cell, we add a light-dependent resistor in parallel to the original resistors, as shown in **Figure 2**. Then, the resulted resistors will be:

$$R_{\rho 1} = \frac{R_\rho R_1}{R_\rho + R_1}, \qquad R_{\varphi 1} = \frac{R_\varphi R_1}{R_\varphi + R_1} \tag{7}$$

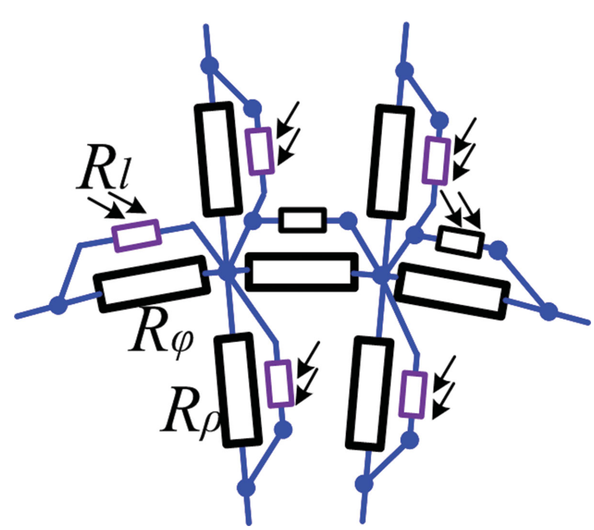

Figure 2. The unit cells of tunable dc metamaterials. The purple small bounding boxes denote the photoconductive resistances.

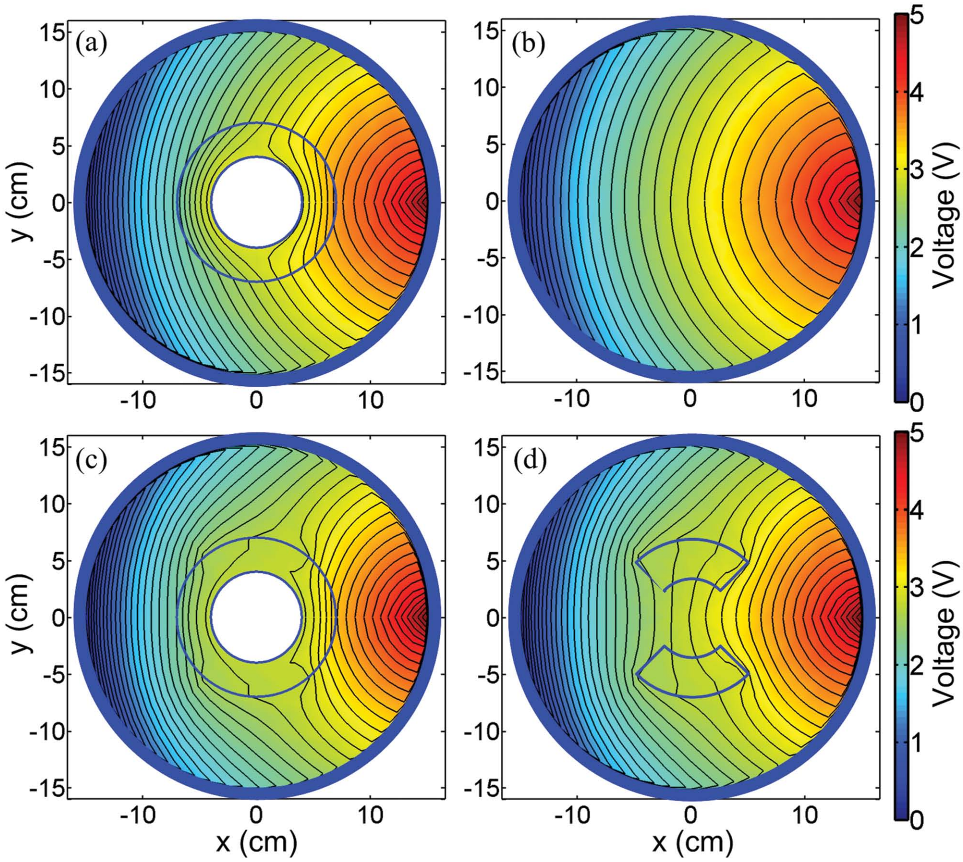

Figure 3. The simulation results of the light-controlled dc illusion device. a) The equipotential-line distributions when the light-dependent resistor is selected as infinite. b) The equipotential-line distributions when there is nothing in virtually homogeneous space. c) The equipotential-line distributions when the light-dependent resistor is selected as a small value. d) The equipotential-line distributions when there are two virtual wing-shaped objects in virtually homogeneous space. The geometries of the illusion objects are equivalent to two sectors with $a' = 5$ cm, $b' = 10$ cm, and $\theta = \pi/2$.

in which, R_l is the value of the light-dependent resistor, which is controlled by the intensity of the illuminating light in a non-touching manner.

When the light is impinged on the device, the power-dependent resistor R_l is determined and the $R\rho_1$ and $R_{\phi 1}$ are also fixed. When the resistors are known, the effective conductivities can be determined as:

$$\sigma_{\rho g} = \frac{\Delta\rho}{\rho\Delta\varphi R_\rho h}, \qquad \sigma_{\varphi g} = \frac{\rho\Delta\varphi}{\Delta\rho R_\varphi h} \tag{8}$$

According to the transformation electrostatics theory, we can derive the material parameters of the illusion objects in virtual space as:

$$\sigma_{0_g} = \frac{\rho}{\rho - a}\cdot\sigma_{\rho g}, \qquad \sigma_{0_g} = \frac{\rho - a}{\rho}\cdot\sigma_{\varphi g} \tag{9}$$

Hence, when the intensity of illuminating light changes, the illusion object in virtual space can be controlled and changed. In other words, the illusion object in virtual space can be remotely controlled by a beam of light. It is noted that the geometrical dimensions of the illusion objects are limited by the linear transformation in Equation (3). As a result, the largest dimensions of the illusion objects will not exceed the outermost boundary of the original device (i.e., $r = b$ in our case), while the size and position of illusion objects can be manipulated.

Similar to the perfect matching layer in time-harmonic fields, we set up an impedance-matching layer between the simulation materials and the ground. We used Bloch impedances to realize resistor matching and to mimic the infinitely extended background. The matching resistors have been given in ref., [20] which relates to the distance between the source point and ground. The resistance network for illusion was constructed based on the aforementioned method.

To verify the light-controlled transformation device based on the resistor network numerically, we carried out the simulation using the commercial software package, Agilent Advanced Design System (ADS). The voltage of the excited source was 5 V and the point source was 19 cm far from center of the object with 6 cm radius, which was enclosed by the transformation device with inner radius 6 cm and outer radius 10 cm. To observe the light-controlled effect, we simulated two representative cases. In the first case, we assumed that the photoresistor value R_l was infinite, which mimicked the light-off case. In such a case, the device acted as a dc invisibility cloak. The equipotential lines and potential distributions were plotted by program based on the data retrieved from ADS. The simulation result is shown in **Figure 3**a. Outside the dc invisibility cloak, the equipotential lines are the same as those in homogeneous space, as

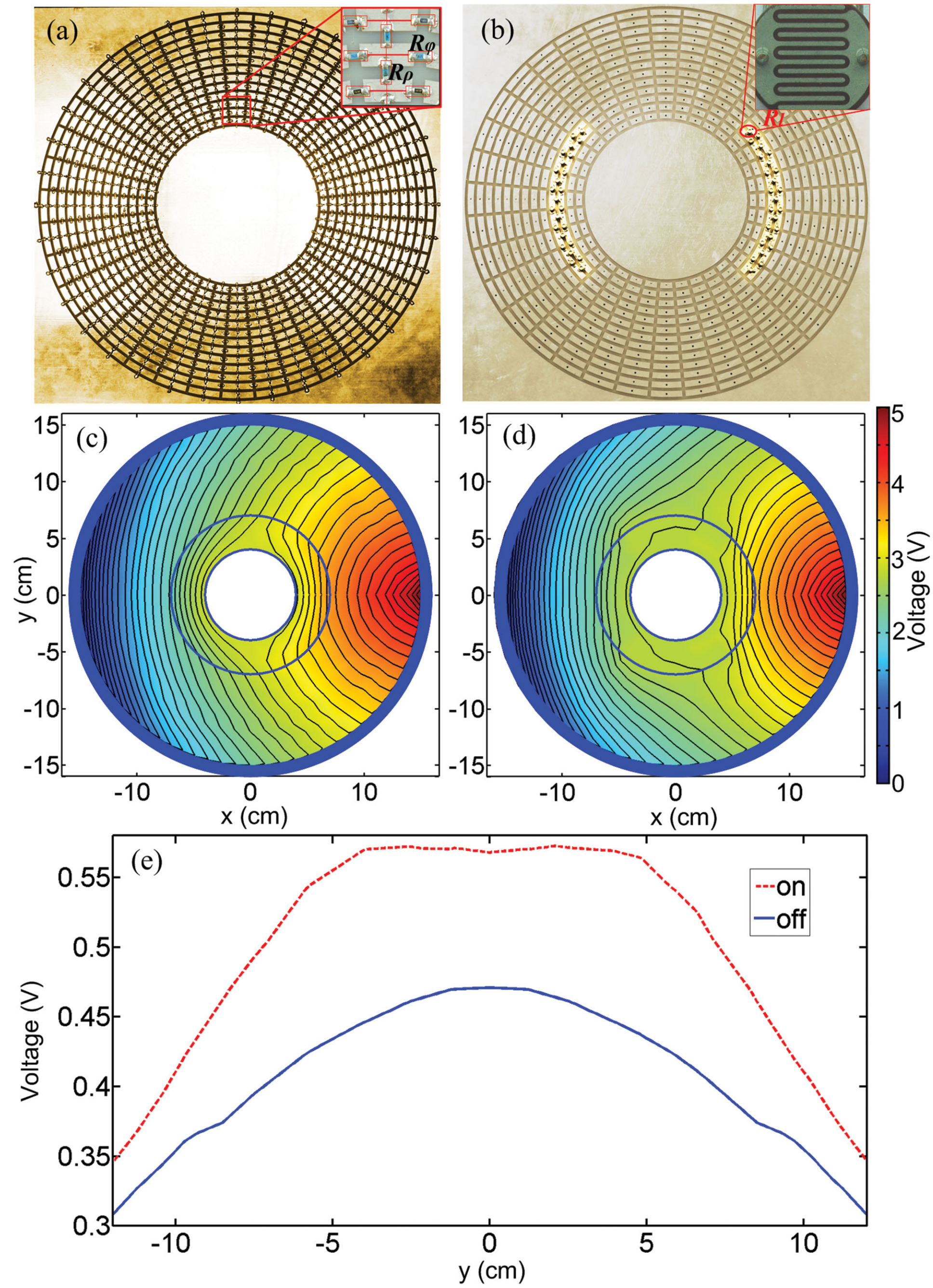

Figure 4. The photograph and experiment results of the light-controlled transformation-dc device based on resistor network. a) The front view of the fabricated light-controlled transformation-dc device. The inset is the detail of chip resistors. b) The back view of the fabricated light-controlled dc transformation device. The inset is the internal structures of light-dependent resistors. c) The tested equipotential-line distributions when the illuminating light turns off. d) The tested equipotential-line distributions when illuminating light turns to the brightest and intensity is 74 000 lm. e) The tested potential-distribution comparison along the observation line $x = -9$ cm when the illuminating light turns from "off" state to the brightest state.

shown in Figure 3b; inside the dc invisibility cloak, the equipotential lines are bent smoothly as expected. In the second case, we assumed that the photoresistor value R_l was zero, which mimicked the light-on case. In such a case, the device acted as a kind of illusion device. Figure 3c shows the equipotential-line distribution when the object is enclosed by the illusion device. To verify the illusion effect of the device, we plotted the equipotential line distribution of the two virtual wing-shaped objects with geometry parameters $a' = 5$ cm, $b' = 10$ cm, and $\theta = \pi/2$. It is obvious that the equipotential-line distributions outside the illusion device are the same in Figure 3c,d.

To demonstrate the effect of remotely controlled illusion device in experiments, we fabricated a sample of the light-controlled functional transformation-dc device using resistor network on printed circuit board (PCB). The photo of the sample is shown in **Figure 4**. The front view of the fabricated device

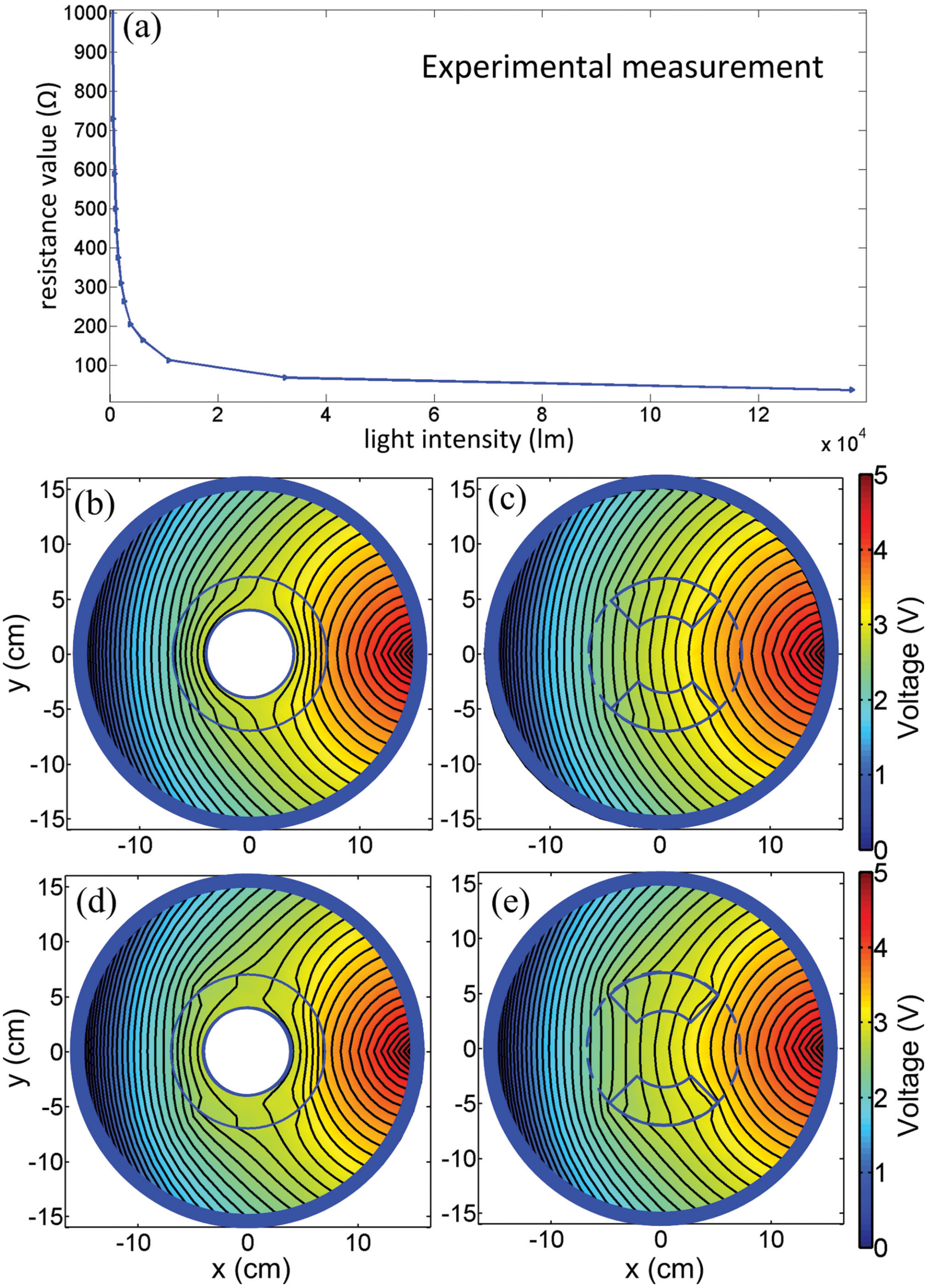

Figure 5. a) The measured relationship between the resistor value of the light-dependent resistor and the light intensity. b–e) The simulated potential and equipotential line distributions of the light-controlled illusion device based on real-measured resistor value and the corresponding illusion objects in virtual space. b) The real-measured resistor value is 590 Ω with light intensity 926 lm. c) The illusion objects corresponding to (b). d) The real-measured resistor value is 114 Ω with light intensity 11000 lm. e) The illusion objects corresponding to (d). The geometries of the illusion objects in (c) and (e) are equivalent to two sectors with $a' = 5$ cm, $b' = 10$ cm, and $\theta = \pi/2$.

is illustrated in Figure 4a, in which the inset is the detail of the chip resistors. There were 36 nodes in the angular direction and 20 layers in the radial direction. The back view of the fabricated device is illustrated in Figure 4b, in which the inset is the internal structures of the light-dependent resistors.

The experimental results are presented in the lower row of Figure 4. Due to the limitation of measurement conditions, homogeneous light intensity was operated in experiments, hence, the value of the working light-dependent resistors was the same. Figure 4c shows the potential distribution and the equipotential lines of the dc device when the light turns off in experiments. In such a case, the light-controlled illusion device acted as a dc invisibility cloak. The equipotential lines outside the device are the same as those in Figure 3c. When the illuminating light turns on, the transformation device acts as an illusion device, the potential distribution and the equipotential lines are plotted in Figure 4d. Outside the illusion device, the potential distribution and equipotential lines are exactly the same as those of two virtual wing-shaped objects, as shown in Figure 3d. Comparing Figures 3d with 4c, the experimental result agrees well with simulation, which demonstrates the possibility to control the sophisticated transformation-dc devices by illuminating light. We observe a distortion of equipotential-line distributions outside the device in Figure 4c, which shows the tested equipotential-line distributions of a cloak when the illuminating light turns off, namely, the intensity of illuminating light should be 0 lm. The possible reason could be that in the weak-light condition (necessary to read and record the dataset), the light-dependent resistors are very sensitive to the intensity of the light (as shown in **Figure 5**a) leading to the altered potential distribution of the whole resistor network, which causes such unexpected distortion. While in Figure 4d, the tested equipotential-line distributions are shown when illuminating light turns to the brightest. In such a case, the values of light-dependent resistors were not sensitive to the change of light intensity. Hence, the equipotential lines are bent smoothly outside the original device, as shown in Figure 4d. A detailed study is presented in Figure 4e to quantify the distinction between two cases of Figure 4c,d, in the exterior area outside the illusion device. The tested potential-distribution comparison is recorded along the observation line $x = -9$ cm when the illuminating light turns from "off" state (Figure 4c) and to the brightest state (Figure 4d), which markedly demonstrates the difference.

So far, we studied two particular states. Actually, the resistance value of the light-dependent resistor could be changed continually according to the intensity of light. To measure the resistance of the light-dependent resistor (VT20n1) when it was illuminated by the light, we used an illuminometer (victor 1010a) to characterize the intensity of the light. The relationship between the resistor and the light intensity is shown in Figure 5a. We tested it at the room temperature 25 °C. To verify more functions of the light-dependent transformation-dc device, we made other numerical simulations on the device based on the measured resistance values of the employed resistors. The simulation results are shown in Figure 5b,d, the results of corresponding equivalent illusion objects are shown in Figure 5c,e, respectively. In such cases, the transformation dc device shows multi-functional illusion effects. Hence, the tunable transformation-dc device had been verified in both numerical simulations and experiments. It should be noted that although the shapes of the illusion objects, two wings with geometry parameters $a' = 5$ cm, $b' = 10$ cm, and $\theta = \pi/2$ in Figure 5c,e are exactly the same, the material profiles of these virtual objects in two figures, determined by Equation (8), are totally different due to the various light-dependent resistors R_l.

The fabricated transformation-dc device demonstrated that the complicated functionalities are possible to be controlled by remotely illuminating lights. TO, proposed in 2006 by Pendry and co-workers, have always been used to design many unusual single-functional devices. We designed, fabricated, and measured a light-controlled multifunctional illusion device using the transformation electrostatics and resistor-network current circuits. The experimental and numerical results agreed very well with the theoretical predictions, which demonstrated that transformation devices are possible to extend to multi-functional remotely controlled devices.

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