Macroscopic broadband optical escalator with force-loaded transformation optics

Dongliang Gao,[1,2] Cheng-Wei Qiu,[1*] Lei Gao,[2] Tiejun Cui,[3] and Shuang Zhang[4]

[1]*Department of Electrical and Computer Engineering, National University of Singapore, Kent Ridge 119620, Republic of Singapore*
[2]*Department of Physics, Suzhou University, Suzhou 215006, People's Republic of China*
[3]*Department of Radio Engineering, State Key Laboratory of Millimeter Waves, Southeast University, Nanjing 210096, People's Republic of China*
[4]*School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, UK*
[*]*eleqc@nus.edu.sg*

Abstract: Transformation optics enables one to guide and control light at will using metamaterials. However the designed device is deterministic and not flexible for different objects. Based on force-loaded transformation optics we propose a force-induced transformational device, which can realize dynamic escalator metamorphosing continuously between optical elevator and invisibility cloak. This escalator can visually lift up and down the perceived height of a plane fixed in space by controlling the forces loaded in different directions. Or conversely, the escalator can physically lift up and down a plane while visually maintaining the same height to an outside observer. One can quickly adjust this device to the required demand without changing the background index, while the usual transformation cloak will be detectable due to the lateral shift from mismatched background. The schematic is self-adaptive, multi-functional, and free of metamaterial or nanofabrication. Our work opens a new perspective in controlling light dynamically and continuously, empowering unprecedented applications in military cloak, optic communication, holographic imaging, and phase-involved microtechnique.

OCIS codes: (160.1190) Anisotropic optical materials; (120.4820) Optical systems.

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1. Introduction

Transformation optics has offered an important approach to control electromagnetic fields [1, 2], which can be used to design various amazing optical devices, including invisibility cloaks [3–14], beam shifters and splitters [15], wave adapters [16], deep-subwavelength transformers [17] and light concentrators [18, 19]. Despite the extreme values and complicated spatial distribution of electric permittivity and magnetic permeability, those devices can be realized with the help of metamaterials [20–22], which guide and control the electromagnetic waves by its structure rather than chemical composition. Metamaterials’ permittivity and permeability can be constructed as desired, from positive to negative values. However, using metamaterials to design optical illusion devices also brings some shortcomings such as very narrow-band operation [1, 10], microscopic size, and requirement of complicated as well as time-consuming nanofabrication [8, 12, 23].

New approaches or materials are required to overcome these limitations. Based on angular spectrum theory, an isotropic dielectric device is proposed to create optical illusions at visible frequencies [24]. Simple isotropic material can also be designed as transformation media [25]

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to manipulate light. Meanwhile, homogeneous birefringent natural crystals, instead of metamaterials, are used to achieve carpet cloak [26, 27], and subsequent experiments successfully demonstrated macroscopic cloaks at visible frequencies via a naturally available calcite [3, 28] whose fabrication is very easy and simple. What's more, the limitations of metamaterials, such as energy loss, narrow bandwidth, and size, are eliminated in those devices. These works offer a practical way to realize macroscopic invisibility-cloak.

Nevertheless, once the optical device is designed and fabricated, it is only working for an object of a specific size or shape and not easy to dynamically tune physical parameters. The height of the illusion region is dependent on the thickness of the birefringent layer, which is changeless once fabricated. One has to cut down the layer or stack up more crystal layers to change the perceived height of the elevator. To dynamically control the perceived height (from negative to positive), we introduce force-loaded transformational materials in the escalator, whose index of refraction can be adjusted by loaded stress in different directions [29]. One can easily obtain desired birefringence by varying the strength and direction of external forces without changing the device's configuration (see Fig. 1). This is not attainable even in the use of natural calcite crystals, since the thickness of calcite will require not only new fabrications but also corresponding alteration of the refractive index of the background medium [30].

Based on transformation optics and photoelasticity, the force-loaded transformational device is phase-preserved, broadband at all angles and easy to control. More importantly, during the operation of dynamic elevating or cloaking, it is not necessary to adjust the index of the background. Our schematic eliminates the use of artificially structured metamaterials, hence it is of broadband operation and the metamorphosis from elevator to cloak is only completed via the control of external mechanical force. This demonstration of force-loaded transformation offers new perspective in optical manipulation.

2. Design and Method

To lift a plane without being noticed by the observer, one must manage to restore both the angle and the position of reflected light [28]. Simply putting a mirror above the plane or using an isotropic lower index medium will cause the reflected light to suffer a lateral shift [28, 30]. This lateral shift is alleviated by using the strategy of quasiconformal mapping [31], which minimizes the anisotropy and replaces it with inhomogeneous isotropic dielectrics. However, the energy propagation fails to be preserved due to omitting the anisotropy and makes the cloak detectable [30]. The proposed optical escalators made by birefringent material cannot only restore the angle and the position of the reflected light, but also preserve the phase since the optical path length is preserved by transformation optics.

As shown in Fig. 1, we can expand or compress the physical space so that the light propagates just as in the virtual space. First we show how to expand the physical space. According to the principle of transformation optics [1, 2], the transformation equations between physical space (x,y,z) and virtual space are,

$$\begin{aligned} x &= x' \\ y &= \frac{H}{H-h}y' + \frac{H}{h-H}h \\ z &= z' \end{aligned} \tag{1}$$

Then the physical parameters of the material can be obtained

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$$\varepsilon = \mu = \frac{J \cdot J^T}{\det(J)} = \begin{pmatrix} \frac{\text{H-h}}{\text{H}} & 0 & 0 \\ 0 & \frac{\text{H}}{\text{H-h}} & 0 \\ 0 & 0 & \frac{\text{H-h}}{\text{H}} \end{pmatrix} \quad (2)$$

where $J = \partial(x, y, z) / \partial(x', y', z')$ is the Jacobian transformation matrix between the physical space and virtual space, ε and μ are relative permittivity and relative permeability respectively.

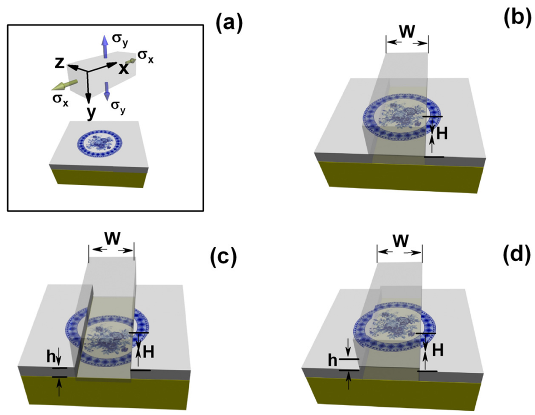

Fig. 1. Illustration of tunable force-induced escalator by changing loaded forces. (a) An image of a flat plate, and force-loaded material loaded with forces along different directions. (b) The middle part keeps the same position after being covered by the escalator loaded with appropriate stresses along x and y directions. The observer will still see a image of a flat plate. (c) After adjusting the loaded stresses, the middle part is "pushed" below the original plane of the plate. (d) The middle part is "floating" above the plane. The ***movie*** shows the phase-preserved floating process, which is provided in supplementary information [32].

In this Letter, we only consider transverse magnetic (TM) field polarization incident in the x-y plane. Equation (2) is reduced to

$$\varepsilon_{x-y} = \begin{pmatrix} \frac{H-h}{H} & 0 \\ 0 & \frac{H}{H-h} \end{pmatrix}, \quad \mu_z = \frac{H-h}{H} \quad (3)$$

To deal with nonmagnetic material, $\mu_z = 1$ is enforced. Therefore, the permittivity tensor of the material are scaled accordingly

$$\varepsilon_{x-y} = \begin{pmatrix} \left(\frac{H-h}{H}\right)^2 & 0 \\ 0 & 1 \end{pmatrix} \quad (4)$$

For photoelastic materials with $\sigma_z = 0$, the index of refraction is given [30]:

$$
\begin{aligned}
n_x &= n_0 + C_x \sigma_x + C_y \sigma_y \\
n_y &= n_0 + C_x \sigma_y + C_y \sigma_x
\end{aligned} \tag{5}
$$

where n_0 is the refraction index at unloaded state, C_x and C_y are the stress coefficients along x and y axis directions. σ_x, σ_y and σ_z are the principal stress tensor components along the x, y and z axis. Here, we assume the material refractive index and stress coefficients are independent of wavelength. The photoelastic materials acts as a birefringent material when $C_x \neq C_y$. Given the background refractive index n', to fulfill the requirement by transformation optics, we can adjust the principal stress tensor σ_x and σ_y such that $n_x = n'$. Then the elevated height is give as

$$
h = -\frac{C\sigma H}{n'} \tag{6}
$$

where $C = C_y - C_x$ is the relative stress coefficient, $\sigma = \sigma_x - \sigma_y$ is the difference of the principal stress tensor components in x and y axis directions. Similarly, for the compress case the descend amount is $h = \dfrac{C\sigma H}{n'}$ ($\Delta n = n_y - n_x = C\sigma$).

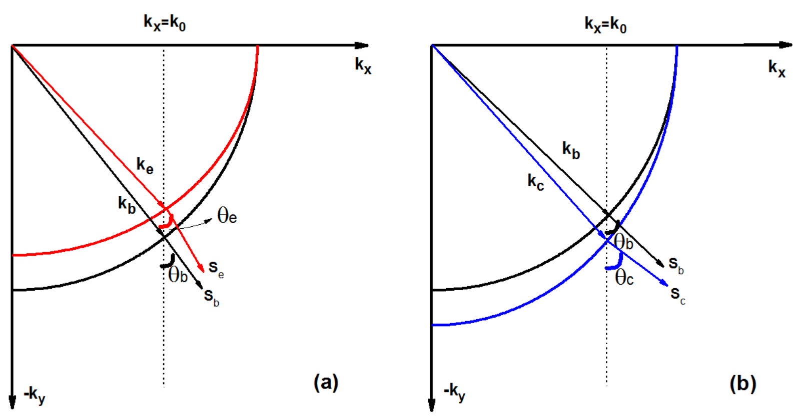

Fig. 2. k-surface diagram of the escalator at lift-up states (a) and lift-down states (b). The black circles represent the background medium with equivalent position of mirror. The red and the blue ellipses represent the escalator at lift-up state (expanded space) and lift-down state (compressed space), respectively. k_b, k_e and k_c are the wave vectors in background medium, expanded space and compressed space. The transmitted Poynting vector **S** is along the normal of k surface.

Firstly, we discuss how the escalator preserves position and phase. With the help of transformation optics, one can compress or expand a "physical space" into a desired "virtual space" by changing the constitutive parameters, while maintaining the form of homogeneous Maxwell equations [30]. For a transverse magnetic (TM) polarization plane wave (vectors in the x-y plane), the dispersion relation of wave vectors is determined by

$$
\frac{k_x^{\,2}}{\varepsilon_y} + \frac{k_y^{\,2}}{\varepsilon_x} = \omega^2 \mu \tag{7}
$$

The transmitted Poynting vector **S** can be expressed as

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$$\mathbf{S}=\frac{H_0^{\,2}k_x}{2\omega\varepsilon_y}\vec{e}_x+\frac{H_0^{\,2}k_y}{2\omega\varepsilon_x}\vec{e}_y \tag{8}$$

where H_0 is the amplitude of incident magnetic field. When light propagates in an expanded space, it appears that light goes through a shorter distance, as if the image were floated by the escalator. As is shown in Fig. 2(a), the line at $k_x = k_0$ represents the phase-preserved condition between the equivalent space and the expanded space, i.e. the escalator. This condition determines the transmitted wave vectors k_b and k_e in the equivalent space and the expanded space. Note that the Poynting vector is the direction of power propagation, which is different from the direction of the wave vector in anisotropic materials. The light undergoes a smaller refracted angle θ_e in the expanded space than it does at θ_b in the equivalent background space. This ensures the reflected light are at the same position, while the phase is preserved in the x direction. The light in compressed space undergoes the similar way, as in shown in Fig. 2(b).

3. Simulation Results

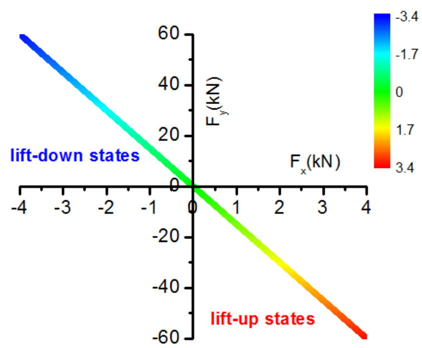

Fig. 3. The relations between lifted height and loaded forces. The color bar represents the amount of height that the image is lifted up (h>0) or lifted down (h<0). The positive (or negative) values of the forces mean the forces pulling (or pressing) the device.

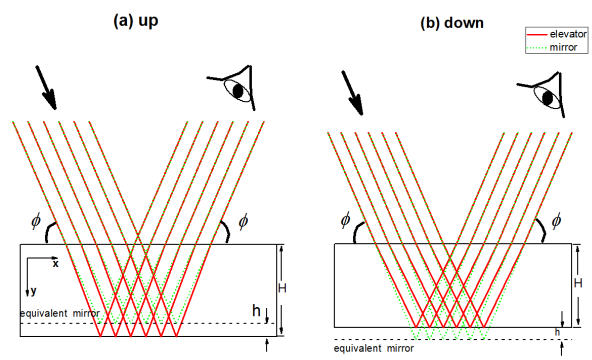

Fig. 4. Ray tracing of light passing through the force-loaded escalator and the equivalent mirror. a): $\phi = 45°$, $n_x = 1.4$, $n_y = 1.2$, $n' = 1.4$, H = 21mm, h = 3mm, the image is above the plane. b): $\phi = 45°$, $n_x = 1.4$, $n_y = 1.6$, $n' = 1.4$, H = 21mm, h = 3mm, the image is below the plane. The light from the force-loaded escalator and the one from the reference mirror are identical in the view point of the observer.

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According to the relation between elevated height h and the difference of the principal stress tensor components, we can lift the plane up and down at any level by adjusting the forces in x and y directions. Note that the loaded forces F_x and F_y should satisfy the condition $n_x = n'$, which preserves the phase and maintains the index of the background. So for a given lifted height, there is only one pair of forces that can make this device a phase-preserved escalator. As an example, we study the relation between lifted height and the loaded forces for an escalator made of a single piece of photoelastic slab with a size of H = 21mm, W = 21mm, and L = 42mm. The other physical parameters are $n_0 = 1.4$, $n' = 1.4$ the stress coefficients along x and y axis directions are $C_x = 5\times10^{-8} Pa^{-1}$ and $C_y = 1\times10^{-8} Pa^{-1}$. As shown in Fig. 3, with appropriate combinations of Fx and Fy, the escalator can shift up or down the plane as much as 3.2mm.

Ray tracing is preformed to verify the above results, as is shown in Fig. 4(a) and 4(b). Transverse magnetic (TM) light rays through a stress escalator lifted up or down by h coincide perfectly with that reflected by a mirror fixed at the original height in the background liquid. The dynamic procedure of tuning forces is presented in supplementary information (Fig. S1, [32]).

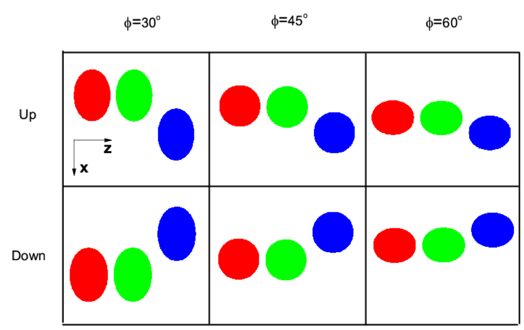

Fig. 5. Lights with 2.5 mm diameter are incident on three configurations. A: force-loaded escalator (green), B: equivalent mirror in background material with corresponding highness (red), C: reference mirror in background material at the high of escalator's bottom (blue). The three configurations are 3 mm apart along the z axis. The other physical parameters are same as in the Fig. 4.

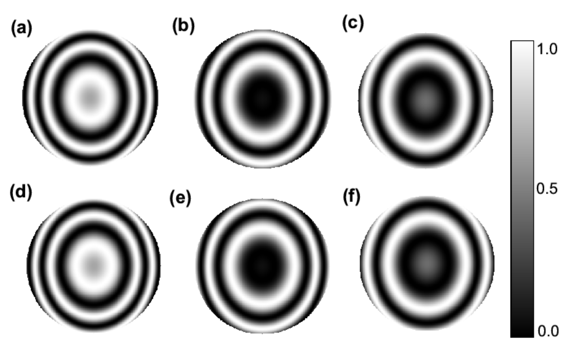

Fig. 6. The interference patterns of the proposed escalator (a, b, c) and equivalent mirror (e, f, g) with respect to the reference mirror, respectively. The wavelengths of the light are 488nm, 561nm, and 650 nm, respectively. The other parameters are the same as those in Fig. 4a. The grey contour scale means the intensity of the interference.

The proposed escalator is independent on different incident angles and wavelengths. As shown in Fig. 5, screen is placed at the position of the observer to show the light spots at three

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configurations for different incident angles. The light from the escalator and the equivalent mirror experience the same lateral shifts with the reference mirror in the x axis direction, proving that the escalator is valid for all incident angles. Dynamic ray tracing of different incident angles is demonstrated in supplementary information (Fig. S2, [32]). It is worth noticing that the force-loaded escalator preserves the phase within broadband frequencies. To verify this feature, we compared the interference patterns with different light wavelength at various incident angles. A collimated light beam is split into three parts: an object beam passing through the escalator, a parallel beam passing through the equivalent mirror, and the reference beam. The first two beams interfere with reference beam separately. The identical interference pattern indicates the unchanged phase when it passes through the escalator. For simplicity, we only show the patterns at the incident angle 45°. The interference patterns of such escalator with a reference mirror (Fig. 6a, Fig. 6b, Fig. 6c) is in agreement with that between the equivalent mirror to a reference mirror (Fig. 6e, Fig. 6f, Fig. 6g) at the same wavelengths, confirming that the dynamic escalator is phase-preserved in broadband frequencies.

4. Conclusions

In conclusion, a macroscopic and broadband escalator has been proposed which achieves smooth and dynamic metamorphosis between optical elevator and invisibility cloak. Hence the natural crystal based macroscopic cloak [3, 28] becomes a very limited subset of the current optical escalator. Only appropriate external forces are needed to be controlled for cloaking different size of macroscopic objects. The functionality of the escalator can be dynamically controlled by varying the strength and direction of external forces without changing the device's configuration. The range of controllable height is from −3 mm (down) to 3 mm (up) for a device of 21 mm thickness within the visible spectrum, which is far beyond the current capability of metamaterials in terms of that the metamorphosis distance is at the order of 10^4 wavelength. Throughout the metamorphosis, it restores the angle and the position of the reflected light and preserves the phase within broadband frequencies at all angles. But the conventional method based on natural calcite crystals requires not only new fabrications of the calcite piece but also corresponding change of background refractive index, when there is any change of cloaking size. More importantly, this schematic can even go beyond dynamic fabless cloak. These features ensure the escalator suffer from no detectable lateral shift during and after the metamorphosis. Furthermore, the escalator can be easily expanded to three dimensional optical illusion devices by controlling the principle stress tensor components along z axis. Then the virtual image can be placed everywhere in three-dimensional space by tuning three pairs of force on individual directions. Since the escalator is easy to operate and flexible for various size objects, we anticipate our work will pave an unprecedented way toward the optic manipulator with higher controllability. The macroscopic and flexible operability of the escalator may find applications in military camouflage, holographic imaging, and phase-involved microtechnique.

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