Watching outside while under a carpet cloak of invisibility

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We demonstrate in this work a unique approach for watching outside while hiding in a carpet cloaking based on transformation optics. Unlike conventional carpet cloaking, which screens all the incident electromagnetic waves, we break the cloak and allow incident light get into the carpet. Hence outside information is detected inside the cloak. To recover the invisible cloaking, complementary techniques are applied in the broken space. Consequently, a hiding-inside and watching-outside (HIWO) carpet cloak is sewed, which works as an invisible cloaking and allows surveillance of the outside at the same time. Our work provides a strategy for an ideal cloak with "hiding" and "watching" functions simultaneously.

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I. INTRODUCTION

The idea of an invisible cloak has been conceived by mankind for a long time. Very recently this dream has turned into a possibility. Pendry *et al.* [1] proposed a scheme to design a cloaking of objects from electromagnetic fields by using transformation optics [2], while Leonhardt [3] developed optical conformal mapping for an invisibility device. Inspired by the theoretical strategies, metamaterial microwave cloaking has been experimentally realized for the first time [4]. However, some problems remain challenging, such as the singular parameter and narrow-band limit of the cloak [1]. In order to solve parameter singularity of the cloak, carpet cloaking has been proposed to give all cloaked objects the appearance of a flat conducting sheet [5], which has been experimentally demonstrated at microwave [6] and optical frequencies [7], respectively. As we know, the early approaches tended to hide an object inside the cloaked domain. Recently Lai *et al.* proposed a different approach which allows to cloak the object at a distance outside the cloaking shell based on complementary media [8]. Until now the concept of cloaking has been extended from electromagnetic wave to both acoustic wave [9] and matter wave [10] on the analogy of wave equations.

However, current invisibility cloaks are still far from satisfactory. People always expect that a man in an invisibility cloak can not only hide but also be able to watch the outside [11]. In principle, it is difficult to watch outside within a conventional perfect cloaking simply by electromagnetic (EM) response because it is equivalent to a curved but empty EM space created by coordinate transformation. Within the concept of illusion optics, people can indeed carry out detection, where people see through a wall by opening a virtual hole in it [12]. Actually, by doing so, people in front of the wall and behind the wall can "see" each other, *i.e.*, the device does not function as an invisible cloak. However, in the complementary media cloak proposed in Ref. [8], the cloak is invisible while the object is exposed to the external field; thereafter the people inside the object can "watch" outside. Very recently, Alù and Engheta have proposed a concept of cloaking a sensor [13], which has opened a way of sensing with light through a nearly invisible detector [14], and Zhu *et al.* have proposed a specific transformation in cloaking to make an acoustic sensor undetectable, in which the cloaking shell is proved to be a magnifying superlens with single-negative materials [15]. Furthermore, non-double-blinded cloakings have been achieved for the electromagnetic waves and also acoustic waves [11,16]. Now the concepts of cloaked sensing and cloak detection are being extensively studied [17–19].

In this work we propose a scheme for watching the outside while hiding under a carpet cloak based on transformation optics. Unlike conventional carpet cloaking, which screens all the incident electromagnetic waves, we break the cloak and allow incident light get into the carpet; hence outside information is detected inside the cloak. To recover the invisible cloaking, a complementary medium is embedded in the broken space. Meanwhile, in order to detect incident light, an ordinary sensor (OS) and an "anti-sensor" (AS) are designed in the broken space. The OS detects the incoming signal yet breaks the cloaking again, whereas the AS compensates the breaking induced by the OS and recovers the invisible carpet. In this way our hiding-inside and watching-outside (HIWO) carpet cloak functions not only as an invisible cloak but as the surveillance under the cloaking as well.

II. THEORETICAL MODEL AND ANALYSIS

The concept of complementary media is regarded as a special type of transformation media [20–23] which achieves potential applications in the perfect lens [20], novel imaging devices [8], superscatterers [24], the cylindrical superlens [25], and the anticloak [26]. Very recently, complementary media have been successfully applied to create a cloak outside the cloaking shell [8] and to design an illusion device [12]. Here we apply complementary media to achieve a HIWO carpet cloak. According to transformation optics [27], when a space is transformed into a different shape the permittivity and permeability in two spaces are connected by

$$\varepsilon^{i'j'} = \frac{1}{\det\left(\Lambda_i^{i'}\right)}\Lambda_i^{i'}\Lambda_j^{j'}\varepsilon^{ij}, \qquad (1)$$

$$\mu^{i'j'} = \frac{1}{\det\left(\Lambda_i^{i'}\right)}\Lambda_i^{i'}\Lambda_j^{j'}\mu^{ij}, \qquad (2)$$

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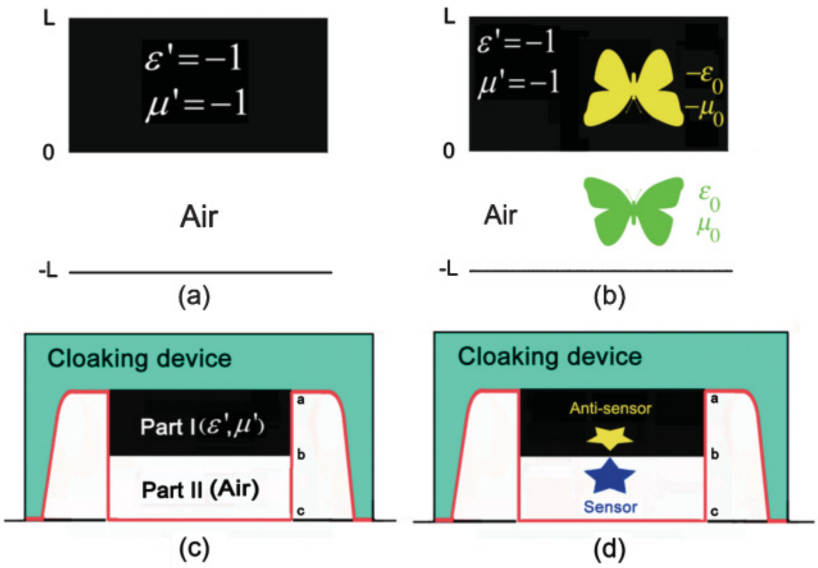

FIG. 1. (Color online) (a) The schematics to show the complementary media (black region), $0 < y' < L$, which is used to cancel the volume of air, $-L < y < 0$. (b) The schematics to show a complementary media with an embedded complementary image of $-\varepsilon_0$ and $-\mu_0$, which cancels an object in the air with ε_0 and μ_0. (c) The schematics to show an amended broken carpet cloaking device. The broken space is separated into two parts: Part I ($b < y < a$, black region) is composed of complementary medium with $\boldsymbol{\varepsilon}'$ and $\boldsymbol{\mu}'$, and Part II ($c < y < b$, white region) is filled with air. The red line is the boundary with a perfectly reflective conductor. (d) The schematics of the HIWO carpet cloaking device. On the device shown in Fig. 1(c), a sensor (blue region) with permittivity ε_0 and permeability μ_0 is embedded inside Part II (air), and an anti-sensor (yellow region) with $\boldsymbol{\varepsilon'_0}$ and $\boldsymbol{\mu'_0}$ is embedded inside Part I.

respectively. Here $\varepsilon^{ij}$and μ^{ij} are the permittivity and the permeability tensors in original space ($i,j = 1,2,3$), $\varepsilon^{i'j'}$ and $\mu^{i'j'}$ are the permittivity and the permeability tensors in the new space, and $\Lambda_i^{i'} = \frac{\partial x^{i'}}{\partial x^i}$ is the Jacobian tensor of the transformation. Then it is possible to design the complementary media by operating a specific coordinate transformation to fold a piece of space into another. A typical example of complementary media is the perfect lens. As shown in Fig. 1(a), a perfect lens [20] can be a slab designed by the coordinate transformation of $y' = -y$ for $-L < y < 0$, which means folding an air slab of $-L < y < 0$ into the slab of $0 < y' < L$ with $\varepsilon' = -1$ and $\mu' = -1$. (Here L is the width of the slab.) Due to the cancellation of the optical path, the region (-L, L) does not exist optically. Now we consider an object with permittivity ε_0 and permeability μ_0 located in the air [Fig. 1(b)]. We can design a slab of complementary media by the coordinate transformation of $y' = -y$ for $-L < y < 0$, which results in a slab of $\varepsilon' = -1$and $\mu' = -1$. A complementary medium with permittivity $-\varepsilon_0$ and permeability $-\mu_0$ is embedded inside the slab. Similar to the perfect lens, the object and the complementary media optically cancel each other.

In order to watch outside under the original carpet cloaking [5], we have to break the carpet cloaking and let some of the incident electromagnetic fields get into the cloaking, which eventually makes the object under the carpet visible. However, if we separate the broken space into two parts—Part I filled by a complementary medium with permittivity $\boldsymbol{\varepsilon}'$ and permeability $\boldsymbol{\mu}'$ and Part II filled with air [Fig. 1(c)]—the complementary medium (Part I) and air in Part II optically cancel each other. In this way the invisible carpet is recovered. As illustrated in Fig. 1(c), the complementary medium can be obtained by the coordinate transformation of folding and compressing the volume of air ($c < y < b$) into the layer of complementary medium ($b < y' < a$). Here a, b, and c denote the coordinates of the interfaces of different media as shown in Fig. 1(c). We consider a coordinate transformation $y' = f(y)$, where $f(y)$ is a continuous function satisfying $f(c) = a$ and $f(b) = b$. Parameters $\boldsymbol{\varepsilon}'$ and $\boldsymbol{\mu}'$ in the complementary layer can be obtained based on Eqs. (1) and (2). For simplification we take linear relation $y' = f(y) = \frac{b-a}{b-c}y + \frac{b(a-c)}{b-c}$. It follows that $\boldsymbol{\varepsilon}'$ and $\boldsymbol{\mu}'$ are expressed as

$$\boldsymbol{\varepsilon}' = \boldsymbol{\mu}' = \begin{pmatrix} \frac{b-c}{b-a} & 0 & 0 \\ 0 & \frac{b-a}{b-c} & 0 \\ 0 & 0 & \frac{b-c}{b-a} \end{pmatrix}. \tag{3}$$

Consequently, Part I and Part II are optically cancelled, and the reflection from the breaking on the carpet is the same as that from the original invisible carpet.

Now that incident electromagnetic fields come into the broken space in our device, we can put an OS with permittivity ε_0 and permeability μ_0 inside Part II to detect the incident wave, as schematically shown in Fig. 1(d). However, introducing OS makes the cloak visible. To avoid this penalty, based on transformation optics we introduce an AS embedded in the complementary layer [Part I, as shown in Fig. 1(d)] with parameters

$$\begin{cases} \boldsymbol{\varepsilon'_0} = \varepsilon_0 \boldsymbol{\varepsilon}' \\ \boldsymbol{\mu'_0} = \mu_0 \boldsymbol{\mu}' \end{cases}. \tag{4}$$

In this way, OS and AS are optically cancelled. The object under the carpet becomes invisible, yet the OS can still detect the incident wave from the invisible carpet. This unique design allows visibility outside by hiding a sensor under the carpet cloak without being detected from the outside, *i.e.*, "seeing without being seen" [14].

III. NUMERICAL CALCULATIONS AND DISCUSSIONS

A. Numerical demonstration of the HIWO

We carry out full-wave simulation with commercial software (COMSOL MULTIPHYSICS 3.5 solver) to verify the above idea. The incident wave is taken as a Gaussian beam at a wavelength of 0.3 m, which is transverse magnetic (TM) polarization (**H** along the z direction). (Here the intensity distribution of the beam follows a Gaussian function in space.) The incident light approaches the cloak at 45° with

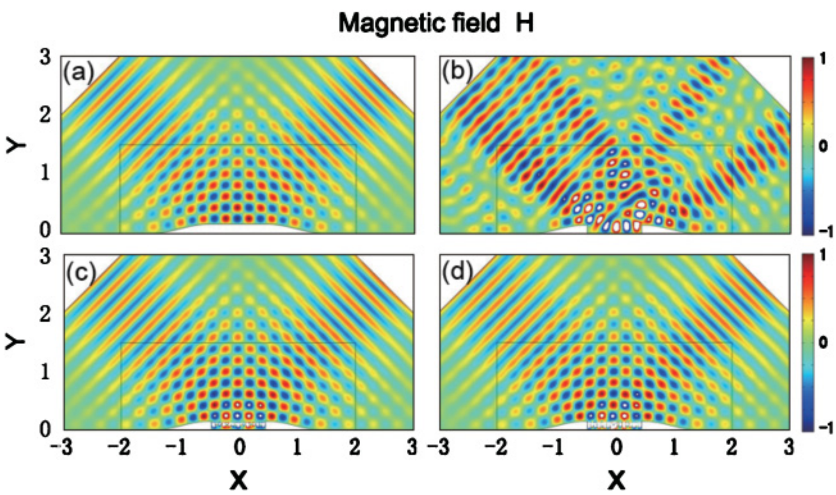

FIG. 2. (Color online) The plots to show the magnetic field distribution when the incident transverse-magnetic wave launches towards the ground plane at 45° from the left. The spatial width of the beam is 1.3 m at a wavelength of 0.3 m, the unit for the positions (X and Y) is meters, and the cloak is within the rectangle in the black line in each case. (a) The field distribution around an original carpet cloak as reported in Ref. [5]. (b) The field distribution around a broken carpet cloak without complementary media. (c) The field distribution around a broken carpet cloak with complementary medium as shown in Fig. 1(c). Here $a = 0.16$ m, $b = 0.128$ m, and $c = 0$. Both $\boldsymbol{\varepsilon}'$ and $\boldsymbol{\mu}'$ are given by Eq. (3). (d) The field distribution around the HIWO carpet cloaking as shown in Fig. 1(d). In this device a sensor with $\varepsilon_0 = 2$ and $\mu_0 = 2$ is inside Part II, and an anti-sensor with $\boldsymbol{\varepsilon}'_0$ and $\boldsymbol{\mu}'_0$ is inside Part I, where $\boldsymbol{\varepsilon}'_0$ and $\boldsymbol{\mu}'_0$ are given by Eqs. (3) and (4).

respect to the ground plane. First, we start from the original carpet cloak covering the bump region as shown in Fig. 2(a). Reflection at 45° is clearly observed, and the distribution of magnetic fields outside the cloak is the same as that from a flat plate. In this case the incident wave is totally reflected by the highly reflective boundary, and the electromagnetic wave cannot get into the bump. Consequently the incident wave cannot be detected from the inside of the bump. Second, we break part of the highly reflective boundary. As shown in Fig. 2(b), the electromagnetic wave propagates into the bump region, and the reflected beam is scattered into two beams. The magnetic field outside the cloak becomes quite different compared with the magnetic-field distribution from a flat plate. Obviously, the cloak is broken and the bump becomes visible. Third, we recover the invisible cloak with complementary media. The broken space is amended in the following way: Part I ($b < y < a$) is filled by a complementary medium with permittivity $\boldsymbol{\varepsilon}'$ and permeability $\boldsymbol{\mu}'$, and Part II ($c < y < b$) is filled with the air [as schematically shown in Fig. 1(c)]. By taking $a = 0.16$ m, $b = 0.128$ m, and $c = 0$, we apply linear transformation $y' = -\frac{1}{4}y + \frac{4}{25}$. Thereafter, the parameters $\boldsymbol{\varepsilon}'$ and $\boldsymbol{\mu}'$ for the complementary medium are given by Eq. (3). As shown in Fig. 2(c), the magnetic field outside the carpet cloak becomes the same as that in Fig. 2(a), indicating that the invisibility cloaking is recovered. Moreover, some incident waves get into the bump region, which makes it possible to detect the external information inside the cloak. We can push one step further to detect the incident wave inside the cloak and finally obtain a HIWO carpet cloak. For example, we put an ordinary sensor with the parameters $\varepsilon_0 = 2$ and $\mu_0 = 2$ in Part II and an anti-sensor with the parameters of $\boldsymbol{\varepsilon}'_0$ and $\boldsymbol{\mu}'_0$ in Part I [Fig. 1(d)]. Here $\boldsymbol{\varepsilon}'_0$ and $\boldsymbol{\mu}'_0$ are given by Eqs. (3) and (4). As shown in Fig. 2(d), the magnetic field distribution outside the carpet cloak stays the same as that in Fig. 2(a), indicating that the invisibility cloaking resumes. Inside the cloak, as shown in Fig. 2(d), the field distribution indicates that the incident light enters the cloak already, which is different from that of Fig. 2(a).

In order to confirm that the incident wave can indeed be detected in the HIWO carpet cloak, we show the distribution

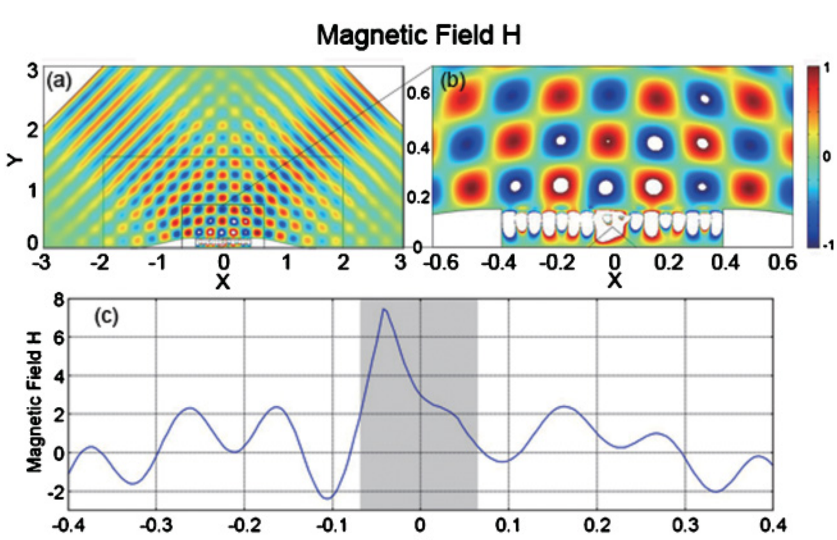

FIG. 3. (Color online) (a) The distributions of magnetic field around the HIWO carpet cloak as shown in Fig. 2(d), launching at 45° towards the ground plane from the left. The spatial width of the beam is 1.3 m at a wavelength of $\lambda = 0.3$ m. In order to show how the sensor inside of the cloak works, the detailed distributions of the magnetic fields close to the sensor (located at the triangle site) are given in (b). (c) The intensity of magnetic field along $y = 0.05$ m. Here the shadowed region corresponds to the place where the sensor is located.

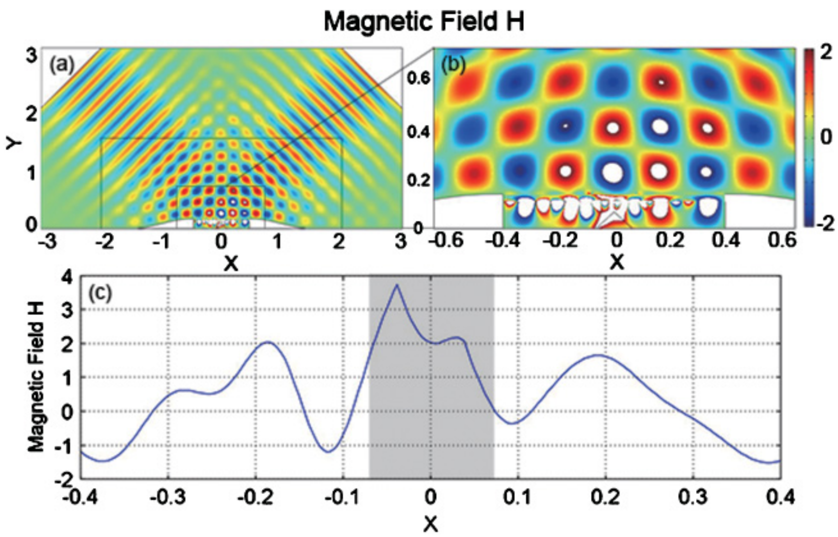

FIG. 4. (Color online) (a) The distributions of magnetic field around the HIWO carpet cloak, which consists of a weakly absorbing sensor with $\varepsilon_0 = -2 + 0.1i$ and $\mu_0 = 1$, and an ordinary anti-sensor with $\varepsilon'_{0x} = 8$, $\varepsilon'_{0y} = 0.5$, and $\mu'_{0z} = -4$. The incident beam is TM polarized, launching at 45° towards the ground plane from the left. The spatial width is 1 m at a wavelength of $\lambda = 0.3$ m. (b) The detailed distributions of the magnetic fields are close to the sensor (located at the triangle site). (c) The intensity of the magnetic field along $y = 0.05$ m in this HIWO. Here the shadow region indicates the sensor's location.

of magnetic field in the sensor when the incident beam shines on the identical HIWO carpet cloak, as shown in Figs. 3(a) and 3(b). The magnetic field distributions outside the cloak [as shown in Fig. 3(a)] are the same as those of a flat plate, indicating that the cloak functions and the invisibility persists. Meanwhile, the electromagnetic signal can be detected by the sensor under the cloak [as shown in Fig. 3(b)]. Figure 3(c) shows the magnetic field along the line of $y = 0.05$ m, where the gray region corresponds to the position of the sensor. The intensity of the signal can be received clearly by the sensor. These data indicate that the information carried by incident wave can be detected and watching outside from the HIWO carpet cloak is indeed possible.

B. The HIWO with absorption media

It is worthwhile to discuss how the HIWO works when it contains the absorption media. First we consider the weak-absorption case. For example, the HIWO consists of a weakly absorbing sensor with $\varepsilon_0 = -2 + 0.1i$ and $\mu_0 = 1$ and an ordinary anti-sensor with $\varepsilon'_{0x} = 8$, $\varepsilon'_{0y} = 0.5$, and $\mu'_{0z} = -4$. (The loss of the dielectric carpet is neglected.) When the incident beam shines on this HIWO cloak, the distributions of magnetic fields are shown in Figs. 4(a) and 4(b). It is shown that the field pattern in Figs. 4(a) and 4(b) have no evident difference from that in Figs. 3(a) and 3(b), which means the cloak function of the HIWO is kept in the weak-absorption case. Moreover, to verify the functionality of the sensor, the magnetic field along the line of $y = 0.05$ m is observed and shown in Fig. 4(c), where the gray region indicates the position of the sensor. Obviously, the signal of the electromagnetic field can be received by the sensor. In some senses the HIWO can work well in the weak-absorption case.

In cases where the absorption is strong enough, the "hiding" function of the HIWO is destroyed and the HIWO cloak cannot work well [as shown in Fig. 5(a)]. Fortunately, it is found that strong absorption of the sensor can be compensated for by applying an active medium as the AS in the HIWO. For example, in a HIWO which consists of a strongly absorbing sensor with $\varepsilon_0 = -2 + 0.6i$ and $\mu_0 = 1$ and an active AS with $\varepsilon'_{0x} = 8 - 2.4i$, $\varepsilon'_{0y} = 0.5 - 0.15i$, and $\mu'_{0z} = -4$, strongly absorbed power has been compensated by the active medium;

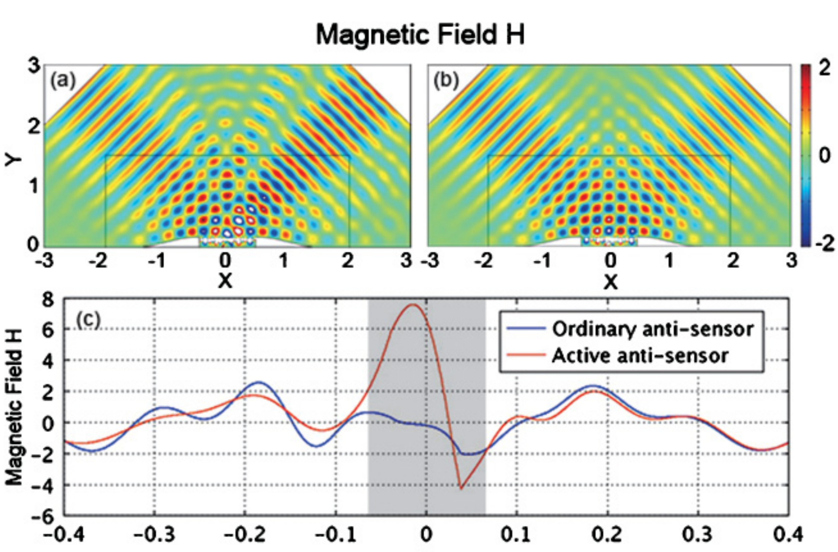

FIG. 5. (Color online) (a) The distributions of magnetic fields in the HIWO, which consists of a strongly absorbing sensor with $\varepsilon_0 = -2 + 0.6i$ and $\mu_0 = 1$ and an ordinary anti-sensor with $\varepsilon'_{0x} = 8$, $\varepsilon'_{0y} = 0.5$, and $\mu'_{0z} = -4$. The incident beam is launching at 45° towards the ground plane from the left and the spatial width of the beam is 1 m at a wavelength of $\lambda = 0.3$ m. (b) The distributions of magnetic fields in the HIWO, which consists of a strongly absorbing sensor with $\varepsilon_0 = -2 + 0.6i$ and an active anti-sensor with $\varepsilon'_{0x} = 8 - 2.4i$, $\varepsilon'_{0y} = 0.5 - 0.15i$, and $\mu'_{0z} = -4$. (c) The intensity of magnetic field along $y = 0.05$ m in the HIWO. The shadow region indicates the sensor's location.

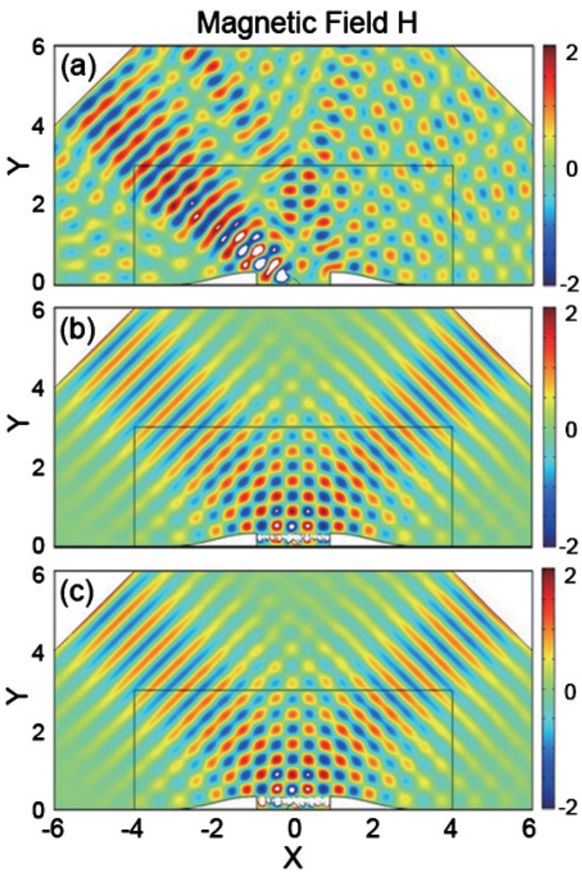

FIG. 6. (Color online) The plots to show the distribution of magnetic field at optical frequency. The incident transverse-magnetic wave launches at 45° towards the ground plane from the left. The parameters are set as $a = 0.32$ μm, $b = 0.256$ μm, and $c = 0$. The spatial width of the beam is 2 μm at a wavelength of $\lambda = 600$ nm, the unit for the positions (X and Y) is microns, and the cloak is within the rectangle in black line. (a) The field distribution around a broken carpet cloak. In the broken space, a sensor with $\varepsilon_0 = -2$ and $\mu_0 = 1$ is embedded, but no complementary layer and anti-sensor are introduced. (b) The field distribution around the HIWO carpet cloaking. Here, the broken space is separated into two parts: Part I is composed of a complementary medium with parameters $\boldsymbol{\varepsilon}'$ and $\boldsymbol{\mu}'$, and Part II is filled with air, where $\boldsymbol{\varepsilon}'$ and $\boldsymbol{\mu}'$ are given by Eq. (3). Then a sensor with $\varepsilon_0 = -2$ and $\mu_0 = 1$ is put inside Part II and an anti-sensor with $\boldsymbol{\varepsilon}'_0$ and $\boldsymbol{\mu}'_0$ inside Part I, respectively, where $\boldsymbol{\varepsilon}'_0$ and $\boldsymbol{\mu}'_0$ are given by Eqs. (3) and (4). (c) The distributions of magnetic field around the HIWO carpet cloak. In this case Part II is filled with a single-negative material with parameters $\varepsilon = -1$ and $\mu = 1$, and Part I is composed of a single-negative complementary medium with $\varepsilon'_x = 4$, $\varepsilon'_y = 0.25$, and $\mu'_z = -4$. The sensor and the anti-sensor are the same as in Fig. 6(b).

thereafter, the hiding function of the HIWO is recovered and the HIWO cloak can work well again [as shown in Fig. 5(b)]. We also observe the magnetic field along the line of $y = 0.05$ m, as shown in Fig. 5(c). It is illustrated that the signals received by the sensor become much stronger when the active medium is used. Therefore we demonstrate that it is possible to compensate for the strong absorption of the sensor by applying an active medium as an AS and make the HIWO work well, even if there is strong absorption in the system.

C. Possible experimental realization of the HIWO

The above-discussed HIWO cloaking consists of the original carpet cloak, the complementary medium, a sensor, and an anti-sensor. It is known that original carpet cloaks have been experimentally realized at microwave frequencies [6] and at optical frequencies [7], respectively. The complementary medium, the sensor, and the anti-sensor in the HIWO cloaking can be readily realized by a metamaterial with both negative permittivity and negative permeability at microwave frequency [28]. As for optical frequency, for example, by setting $a = 0.32$ μm, $b = 0.256$ μm, and $c = 0$ in a HIWO invisible cloaking and applying a metallic sensor with $\varepsilon_0 = -2$ and $\mu_0 = 1$, and the anti-sensor with $\boldsymbol{\varepsilon}'_0$ and $\boldsymbol{\mu}'_0$ following Eqs. (3) and (4), a HIWO invisible cloaking can work at an optical wavelength of $\lambda = 600$ nm. As illustrated in Fig. 6(a), the cloak is broken without a complementary layer and an anti-sensor. However, once we introduce a complementary layer and an anti-sensor in the device, invisibility resumes while the sensor under the cloak detects the incidence beam [as illustrated in Fig. 6(b)]. However, at the optical frequency, three-dimensional negative refractive index materials usually depend on the incident angle, and it is more difficult to fabricate them than to make single-negative materials. Thereafter, we try to use single-negative materials to achieve the HIWO [as shown in Fig. 6(c)], where Part I is composed of a single-negative complementary medium with $\varepsilon'_x = 4$, $\varepsilon'_y = 0.25$, and $\mu'_z = -4$, and Part II is filled with a single-negative material with $\varepsilon = -1$ and $\mu = 1$. The sensor and the anti-sensor are the same as those in Fig. 6(b). As shown in Fig. 6(c), the HIWO still can work well. Based on all these evidences, it may be possible to realize experimentally the HIWO carpet cloak at microwave and optical frequencies.

Note that the HIWO cloak should perform in a steady state in order to cancel out completely the wave scattering between the sensor and the anti-sensor. Due to the high-intensity local fields as well as the rapid oscillations in the interface between the complementary medium and the "cancelled" object [12], the phase inside the cloaked region could be distorted. Once this scenario occurs, the cloaked sensor may detect the outside world with a certain degree of distortion.

IV. CONCLUSION

In summary, we have proposed a HIWO carpet cloak based on transformation optics and demonstrated that the HIWO carpet cloak works not only as a perfectly invisible cloaking, but as surveillance under the cloaking as well. With such a unique HIWO carpet cloak, we can watch outside while hiding under a carpet cloaking of invisibility, which contributes a method which allows an ideal cloaked observation strategy.

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