The general two-dimensional open-closed cloak with tunable inherent discontinuity and directional communication

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We propose general two-dimensional open-closed cloaks with controllable and inherent discontinuity, which is manipulated to create fully open, partially open, and fully closed cloaks rigorously. Multiple objects can be concealed separately in multiple controllable touching domains, with or without openings. The openings in proposed open-closed cloaks are introduced by inherent discontinuity without any approximation, and can be much larger compared to the approximate method [H. Ma, S. B. Qu, Z. Xu, and J. F. Wang, Appl. Phys. Lett. **94**, 103501 (2009)]. More importantly, quasiperfect cloaking performance is kept while allowing the cloaked objects to communicate with the outer region directionally. © *2010 American Institute of Physics*. [doi:10.1063/1.3493182]

The electromagnetic cloak was first proposed by Pendry *et al.*[1] In the past few years, different kinds of cloaks have been studied, including arbitrarily shaped cloaks,[2,3] slab cloak,[4] toroid cloak,[5] cloaks of twisted domains,[6] cloaks designed by "inverse mechanism,"[7,8] and nonmagnetic isotropic flat cloaks.[9] The dissipation and loss limitations upon cloaking effects are also considered.[10,11] Usually the object to be concealed is placed within a closed cloaking shell, while the concept of complementary media allows the design of external cloaks that can cloak objects at a distance outside the cloaking shell.[12,13] On the other hand, the open cloaks have been investigated,[14] which are based on numerical approximation. This cloak itself has an open window based on the approximation that the cloak is infinitesimally thin in certain areas, and such discontinuity is thus ignored, resulting in an "effective" open window. In fact, such approximation is not rigorous, and, in turn, restricts the size of the window to be very small in order to maintain the scattering reduction. The small opening[14] artificially introduced makes wave fronts greatly distorted over a wide range of observation angles just due to the small breach. To date, the open cloak with inherent large openings/discontinuities, which can reduce the scattering significantly in most angles and communicate directionally with the outer space simultaneously, is a problem yet to solve.

In this paper, we propose a general two-dimensional (2D) open-closed cloak with controllable discontinuous boundaries inherently from the coordinate transformation rather than the man-made approximation. Compared to the approximate open cloak,[14] the window size of the inherent open-close cloaks proposed in this paper can be systematically controlled and much larger openings can be realized. In the mean time, the quasiperfect cloaking performance is achieved while enabling directional communication with outer space. More interestingly, from our model, one can choose to create touching cloaks (openings eliminated), open-closed cloaks (openings and closures coexisting), and solely open cloaks (openings only). It may pave a promising path to practical and interesting applications of the recent cloaking technique, especially when directional communication and scattering reduction are both indispensable.

Assume that the outer boundary of the cloak can be expressed as $r_{\text{out}}(\theta)=R|\sin(\theta/N)|$ where $N\in(0,\infty)$ and R is the maximal length along the radial direction. If $0<N\leq 1$, we can construct a class of touching cloaks with multiple cloaking regions, in which multiple objects can be concealed independently, as shown in Fig. 1(a). If $1<N<2$, we can construct a class of open-closed cloaks with two independent cloaking regions including one closed region and one open region, as shown in Fig. 1(b). If $2\leq N<\infty$, we can construct a snail-shaped open cloak, and thus the cloaked object is not blinded and can exchange information with the outer region, as shown in Fig. 1(c). The case corresponding to $N=2$ in Fig. 1(c) stands for the transition situation from closed cloaks to solely open cloaks. It should be also noted that the shape of the case of $N=2$ is quite similar to that in Ref. 14, in which a small breach was approximated in a limited area near the center (the cloak is very thin there).

Supposing that the cloak has conformal inner and outer boundaries, the inner boundary then becomes $r_{\text{in}}(\theta)=(1-m)R|\sin(\theta/N)|$ where $m(0<m<1)$ denotes the scaling factor. We obtain the following transformation function $r'=mr+r_{\text{in}}(\theta)$, $\theta'=\theta$, and $z'=z$, where (r,θ,z) and (r',θ',z') represent the original coordinate systems and the transformed systems, respectively. The relative parameters of the transformed medium becomes

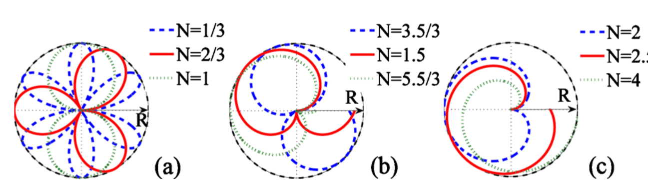

FIG. 1. (Color online) Three types of proposed open-closed cloaks with different values of N. (a) Touching closed cloak $(0<N\leq 1)$. (b) Open-closed cloak $(1<N<2)$. (c) Fully open cloak $(2\leq N<\infty)$.

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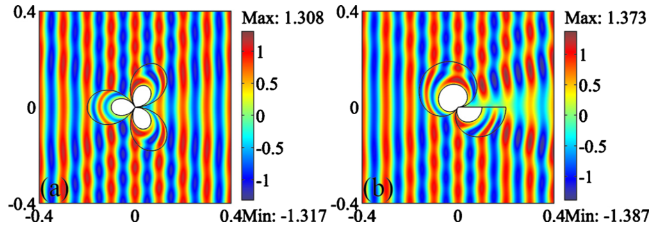

FIG. 2. (Color online) (a) The snapshots of total electric fields for a touching cloak with $N=2/3$. (b) The snapshots of total electric fields for the open-closed cloak with $N=4/3$.

$\bar{\bar{\varepsilon}}'=\bar{\bar{\mu}}'=\mathbf{\Lambda}\mathbf{\Lambda}^{\mathrm{T}}/\det(\mathbf{\Lambda})$, where the Jacobian matrix $\mathbf{\Lambda}$ is expressed $\mathbf{\Lambda}=[m,r_{\mathrm{in}}'(\theta)/r,0;0,r'/r,0;0,0,1]$, where $r_{\mathrm{in}}'(\theta)=[\mathrm{d}r_{\mathrm{in}}(\theta)/\mathrm{d}\theta]=[(1-m)R\sin(2\theta/N)/2N|\sin(\theta/N)|]$. Each component of the transformed material can thus be obtained $\varepsilon_{rr}'=[r-r_{\mathrm{in}}(\theta)/r]+[[r_{\mathrm{in}}'(\theta)]^2/r[r-r_{\mathrm{in}}(\theta)]]$, $\varepsilon_{r\theta}'=\varepsilon_{\theta r}'=[r_{\mathrm{in}}'(\theta)/r-r_{\mathrm{in}}(\theta)]$, $\varepsilon_{\theta\theta}'=[r/r-r_{\mathrm{in}}(\theta)]$, $\varepsilon_{zz}'=[r-r_{\mathrm{in}}(\theta)/m^2r]$, and $\varepsilon_{rz}'=\varepsilon_{\theta z}'=\varepsilon_{zr}'=\varepsilon_{z\theta}'=0$. Those parameters reduce to those of a classic closed cylindrical cloak when $r_{\mathrm{in}}(\theta)$ is a nonzero constant. If $r_{\mathrm{in}}(\theta)=0$, then the transformed parameters becomes diagonal, i.e., $\varepsilon'=[1,1,1/m^2]$. On the other hand, $r_{\mathrm{in}}(\theta)=0$ implies $m=1$, which in turn degenerates to the free space (no scattering). Throughout the paper, the frequency is set to be 3 GHz under TE polarization. The inner boundary is assumed to be perfect electric conductor (PEC) for simplicity. We set $R=0.2$ m and the scaling factor $m=0.5$.

First we consider the case of touching cloaks $(0<N\leq 1)$, in which the cloak includes multiple isolated cloaking regions. As an example, we set $N=2/3$ and there are three independent cloaking regions touching each other. The electric-field distribution of such a touching cloak is shown in Fig. 2(a). It can be seen that the wave fronts are bent around the touching cloak and return to their original trajectories outside the cloak. The perfect cloaking effect can be observed.

If $1<N<2$, the open-closed cloak is composed of two independent regions including a closed region and an open region. Figure 2(b) shows the field distribution of the cloak when $N=4/3$. It can be seen that the scattering is reduced drastically over a wide range of angles except for the forward direction due to the opening. Such feature can be particularly exploited in practical applications because the cloaked object is able to exchange information with the outer space at a well confined direction while being blind at other angles. The upper-left portion of the Fig. 2(b) will have very thin coatings in the vicinity of the center, however modern nanolayer deposition techniques of conformal thin films (U.S. patents No. 6689220 and No. 6756318) can be used.

Then we consider the case $2\leq N<\infty$, in which the approximate open cloak[14] is found to be in a similar shape of our $N=2$ case. Figure 4 shows the electric-field distribution of the $N=2$ open-closed cloak with and without an artificial opening. Obviously, if $N=2$ apple-shaped cloak is closed as in Fig. 3(a), it has ideal cloaking performance. Since the apple-shaped cloak shell is very thin at the dip in the center, we can artificially open a small window as,[14] and an approximate open cloak can be achieved in Fig. 3(b). As we have mentioned, such an opening is manually enforced and hence the opening cannot be too large. Otherwise, the cloaking performance will be greatly deteriorated over a wide range of angles.[14]

In order to observe the scattering reduction quantitatively, we define the normalized scattering electric field (NSEF) as $\mathrm{NSEF}=20\log|\vec{E}^{\mathrm{s}}/\vec{E}^{\mathrm{i}}|$, where $\vec{E}^{\mathrm{i}}$ and $\vec{E}^{\mathrm{s}}$ denote the incident and scattering electric fields, respectively. In Fig. 3(c), NSEF is computed on the observation circle at $\rho=0.25$ m, for the bare PEC without the cloak, PEC core with closed cloak, and PEC core with the approximate open cloak, respectively. Clearly, the approximate open cloak in Fig. 3(b) still maintains cloaking performance over almost all angles, while the forward scattering is larger than that of the perfectly closed cloak in Fig. 3(a).

To overcome the disadvantages of the approximate open cloak,[14] a class of open cloaks with inherent discontinuous boundaries can be designed when $N>2$, resulting in wide openings only. Figure 4 shows the electric-field distribution of the solely open cloak designed with $N=8/3$ [(a) and (b)] and $N=4$ [(d) and (e)]. Such open cloaks are generally of snail shape with varying sizes of the openings. It can be seen that the cloaking performance of the open cloak with $N=4$ is similar to the cloak with $N=8/3$, i.e., the invisibility holds over a wide coverage of angles leaving only the forward direction for communication purposes.

In Fig. 4, NSEF is still calculated on the observation circle at $\rho=0.25$ m for $N=8/3$ [Fig. 4(c)] and $N=4$ [Fig. 4(f)], respectively. It reveals that the overall scattering in the presence of the proposed open cloak can be significantly reduced, compared to that of the uncovered PEC. It is also interesting to note that the inherent open cloak with $N=4$ has the maximum opening size and the forward scattering is stronger than that of $N=8/3$ open cloak. Thus the inherent open cloak $N=4$ is particularly useful when strong directional communication is required and the quasiperfect invisibility is still desired in the application.

In this paper, a 2D open-closed cloak is proposed based on the inherent boundary discontinuities induced by the coordinate transformation. This general cloak can be degenerated to touching closed cloaks, open-closed cloaks, and solely open cloaks. Each case has potential applications, e.g., the touching closed cloaks can possess as many separated cloaking regions as possible to cloak isolated objects; the open-closed cloaks enable us to have open and enclosed cloaking regions in the mean time; and the solely open cloaks outperform the previous approximate open cloaks

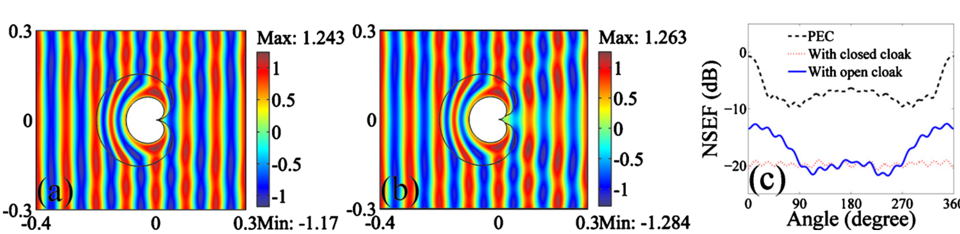

FIG. 3. (Color online) (a) The electric-field distributions of the closed apple-shaped cloak designed with $N=2$. (b) An artificial opening is introduced in the center region of (a) where the cloaking shell is sufficiently thin. (c) The comparison of NSEFs.

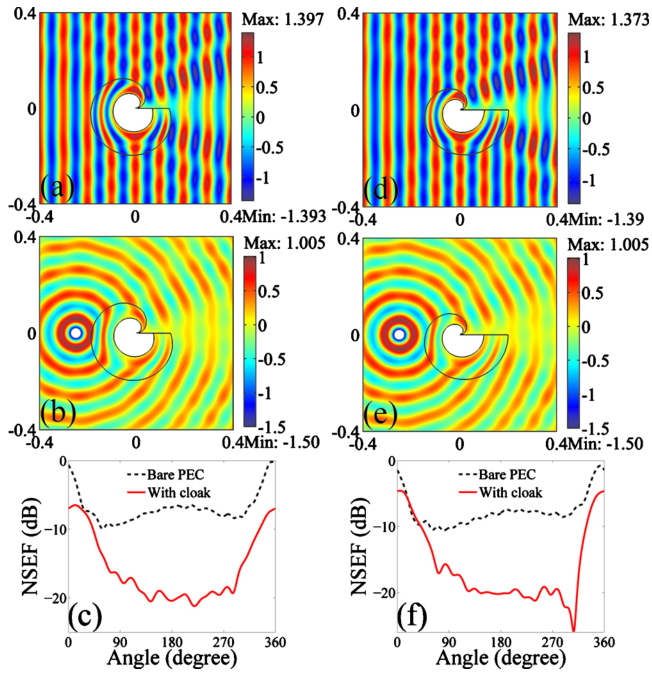

FIG. 4. (Color online) The numerical simulation results for the solely open cloak with $N=8/3$ [(a), (b), and (c)] and $N=4$ [(d), (e), and (f)]. [(a) and (d)] The snapshots of total electric fields with plane-wave illumination. [(b) and (e)] The snapshots of total electric fields with line-source illumination. [(c) and (f)] The comparison of NSEFs.

with small artificial breach and confine the communication tightly along a fixed direction. Moreover, the mechanism to create the openings is based on a rigorously inherent way without approximations. Therefore the cloaked object is not blinded, and the opening aperture can be tuned to be very large while keeping quasiperfect invisibility.

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