A Unidirectional TM-Wave Cloak With Full Parameters

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ABSTRACT Unidirectional cloaks or carpet cloaks have become an essential branch of invisibility cloaks due to non-extreme parameters that are relatively easy for realization and potential applications. So far, a unidirectional cloak for transverse electric (TE) polarized wave has been successfully realized to hide an object in the air along a single direction with almost ideal performance. However, a practical method to achieve a unidirectional cloak for transverse magnetic (TM) polarization is still missing. In this paper, we successfully have designed, fabricated, and measured a full-parameter unidirectional TM-wave cloak in free space. In comparison to the previously-realized TE-wave counterpart, our cloak uses a perfect electric conductor boundary to obey the free-space symmetry condition of the TM incident wave and is therefore much more convenient to fabricate. The cloaking performance of the fabricated sample has been demonstrated via both full-wave numerical simulation and near-field measurement.

INDEX TERMS Unidirectional cloak, TM wave, transformation optics, metamaterial.

I. INTRODUCTION

In 2006, Pendry et al. proposed the transformation optics method to control the electromagnetic field [1]. After that, researchers have tried to further control the electromagnetic field by using transformation optics method to realize some novel electromagnetic devices [2]–[29]. Among them, one of the most exciting devices is the invisibility cloak [3]–[28]. The first experimental demonstration of the proposed cloak is an omnidirectional cylindrical cloak [3]. Initially, as a result of transformation optics, two major challenges occur when a point in virtual space transforms into a circle [3], [4] (2D case), or a surface [1] (3D case) in physical space. First, the values of the cloak parameters are spatially dependent in the radial direction, i.e., inhomogeneous parameters. Due to this inhomogeneity, achieving this cloak in practice is very challenging. In order to simplify the design, reduced-parameter omnidirectional cloaks are proposed and implemented by using approximations [3], [5]. Nevertheless, these approximations introduced inherent scattering. Second, the constitutive parameters near the inner boundary are extreme. To overcome the limitation of the extreme constitutive parameters, researchers have proposed the carpet cloaks and unidirectional cloaks, wherein the transformation is from a line in virtual space to another line in physical space. However, this line-line transformation is achieved at the cost of reducing the viewing angles, and therefore, the cloak works at very narrow observation angles, or the cloak should sit on a conducting ground plane. On the other hand, in order to make the cloak much simpler to design, quasi-conformal mapping method was also proposed to get further rid of the anisotropy of the materials [6]–[12]. Finally, a linear homogeneous coordinate transformation (LHCT) method was proposed to design a carpet cloak or one-dimensional cloak [13], [14]. In this method, both the singularity and inhomogeneity of the parameters are eliminated, which will vastly facilitate the experimental realization. However, the realization of an impedance-matched one-dimensional cloak is still challenging. Most of the experimentally realized homogenous carpet cloaks are based on the simplified LHCT model, where the permeability and permittivity are altered while the index of the refraction stays the same to provide more freedom for cloak design [15]–[19].
This reduction procedure introduces a reflection at the interface between the free space and the cloak, which inevitably decreases the invisibility performance.

In order to recover the impedance-matching property, a full-parameter unidirectional cloak for transverse electric (TE) wave has been realized very recently [20]. The biggest challenge to implement such a cloak is to design a metamaterial unit cell to provide three material response with little spatial dispersion. In this cloak, a double-side split-ring resonator (SRR) is used to provide a paraelectric response along the \( x \)-direction and a diamagnetic response along the \( x \)-direction, and subtly adopted a corrugation under the SRR to provide a paramagnetic response along the \( y \)-direction. It is commonly known that electromagnetic waves are usually categorized as two independent polarizations: the transverse electric wave and the transverse magnetic waves. However, to achieve a unidirectional cloak for another polarization (i.e., the transverse magnetic (TM) polarization) that is an important step towards a perfect full-polarization unidirectional cloak, still lacks a practical solution.

In this paper, we propose and demonstrate a unidirectional full parameter cloak for TM wave for the first time. Physically, when a TM wave impinges a curved surface, it will cause a scattering field, while if it impinges an infinitesimal plane with electric field perpendicular to the surface, no scattering will occur. Therefore, in comparison to the TE-wave cloak, there are two advantages for TM-wave cloak. The inner boundary of the TE-wave cloak is a perfect magnetic conductor (PMC), which should be implemented with artificial materials, while the inner boundary of TM-wave cloak is a perfect electric conductor (PEC), which can be easily replaced by conducting metals at microwave frequency. Besides, a PEC sheet can be treated as a symmetry plane for TM-wave cloak; thus a half of the cloak with a symmetry plane can work as a one-dimensional cloak, which facilitates the experimental realization. With the above consideration, the cloak is designed with a two-layer metamaterial unit cell to provide three material responses for TM wave. We perform the simulation of the unidirectional cloak using the commercial, full-wave, finite-element simulation software (Microwave Studio Computer Simulation Technology). We also fabricated and measured the field of the wave incident onto this full-parameter unidirectional TM cloak. Both simulation and experiment results show good invisibility performance, which is a substantial improvement over the simplified methods. The ease of fabrication with good invisibility performance makes our designed cloak to have a potential application at microwave frequency.

II. METHODS
The design method is based on the linear transformation method [14]. To better comprehending the methodology, we first consider the following transformation from the virtual space \((x, y)\) to the physical space \((x', y')\) for TM wave [14]:

\[
\begin{align*}
x' &= x, \\
y' &= -\tau x + \kappa y, \\
\kappa &= (\tan \alpha - \tan \beta)/\tan \alpha.
\end{align*}
\]

Following the transformation optics procedure, we can obtain the constitutive parameters:

\[
e' = \begin{pmatrix}
1/\kappa & -\tau/\kappa \\
-\tau/\kappa & \kappa + \tau^2/\kappa
\end{pmatrix},
\]

\[
\mu' = 1/\kappa.
\]

For the first quadrant, \(e'\) can be expressed as a diagonal constant tensor \((\epsilon_\alpha' \ 0 \ 0 \ \epsilon_\nu')\) via rotating the coordinate system by \(\theta = 1/2\arctan(2\tau/(\kappa^2 + \tau^2 - 1))\). In our case, we set \(\alpha = 49.49^\circ\) and \(\beta = 20.16^\circ\), thus, the following parameters can be obtained: \(\epsilon_\alpha' = 1.77, \epsilon_\nu' = 0.57, \mu_\alpha' = 1.46, \mu_\nu' = -3.89^\circ\).

The next step is to design a metamaterial unit cell that can provide these three electric and magnetic material responses. Figure 1(a) shows a periodic unit cell of the metamaterial. It is composed of two-layered structures. The bottom layer is a double-I-shape structure, which is used to provide a paraelectric response along \(u\) direction, while the top layer is designed with fourfold rotational symmetry, as shown in Fig. 1(c). In order to obtain a para-electric response along \(u\) direction, we add a top layer composed of cut wires, as shown in Fig. 1(b). With a judicious design and optimization, the proposed cut wires will affect mainly the electric field along the cut wires but have little effect on the magnetic field vertical to the cut wires in the operating frequency. By changing the length of the cut wires, the permittivity along \(u\) direction can be tuned, while the permittivity along \(v\) direction and permeability are nearly unchanged. In the implementation, both the double-I-shape structure and the cut wires are printed on a substrate, which is a 0.25 mm Teflon woven glass fabric copper-clad laminates with a permittivity of 2.25 and \(\tan \delta < 0.001\) at 10 GHz. These two layers (including the metallic geometries and the substrate) are separated with a distance of \(h_z = 3\ mm\), as shown in Fig. 1(a). In order to make a solid cloak sample, the gap \((h_z = 3\ mm)\) between these two layers is filled with foam with the permittivity and permeability both close to air. The dimensions of the unit cell in millimeters are listed in the table of Fig. 1. The sample composed of these periodic unit cells is fabricated using a conventional printed circuit board (PCB) technology. A retrieval procedure was employed to get the effective constitutive parameters of the unit cell from the S parameters [30], [31]. The retrieved permeability and permittivity are shown in Fig. 1(d). One can see that in the vicinity of 9.3 GHz, the parameters well meet the theoretical requirements, i.e., \(\epsilon_\alpha' = 1.77, \epsilon_\nu' = 0.57, \mu_\alpha' = 1.46, \mu_\nu' = -3.89^\circ\), and the spatial dispersion is very little. Moreover, both the imaginary parts of permittivity and permeability are near zero, indicating the loss is very low.

III. SIMULATION RESULTS
In order to demonstrate the effectiveness of our method, we performed the simulation results of the cloak with actual metamaterials in the CST. The practical structure of the cloak is shown in Fig. 2(a), which includes more than 700 unit cells. The size of the cloak are: \(h_1 = 53\ mm, h_2 = 117\ mm, w_1 = 291\ mm\). The length of the cloak is about ten operational wavelengths. \(u\) and \(v\) vectors are the local coordinate system, which is rotated anticlockwise by \(\theta = 30.89^\circ\) according to
FIGURE 1. (a) A two-layer structure of the metamaterial unit cell. (b) Top layer: an array of cut wires provide a para-electric response along \( u \) direction. (c) Bottom layer: a double-I shape structure with four rotational symmetry provides a dia-electric response along \( u \) and \( v \) direction, and a para-magnetic response along the \( z \)-direction. The table shows the dimensions of the unit cell in millimeters. (d) Retrieved parameters as a function of frequency near 9.3 GHz. Note that \( \mu_{zu} \) and \( \mu_{zv} \) represent the permeabilities when the EM waves propagate from \( v \) and \( u \) direction, respectively.

In the simulation, a TM-polarization plane wave is incident from the left onto the cloak. The magnetic field distributions without cloak and with cloak at 9.43 GHz are shown in Fig. 2(c) and (d), respectively. One can see that without the cloak, the plane wave will be split into two parts when impinging the PEC bump, which cannot rejoin again after passing through the bump. While with the cloak, the amplitude and phase of the incident plane wave are restored at the other side of the cloak. As the shape of the metamaterial unit cell is a rectangle, it will introduce some voids at the intersection of each quadrant in the cloak. This imperfection of the invisibility will slightly shift the optimal frequency from 9.3 GHz to 9.43 GHz. From the simulation results, one can still see that both the amplitude and phase of the transmitted wave are still preserved by the proposed cloak. Because we use a low-loss substrate with a loss tangent \(< 0.001 \) at 10 GHz, the absorptive loss in the TM cloak-wave is relatively small. This is also manifested by the negligible imaginary parts of the permittivity and permeability from 8.8 GHz to 9.8 GHz (see Fig. 1). Besides, one can see the transmission level of the electromagnetic wave at other side of the cloak is very high (Fig. 4). Further simulations show that the cloaking metamaterial with a loss tangent less than 0.02 is acceptable. In such a case, the transmitted wave can still be reconstructed at the other side of the cloak.

FIGURE 2. (a) Actual metamaterial cloak model in the CST. \( u \) and \( v \) indicate the local coordinate system, where \( \theta = 30.89^\circ \), \( k_0 \) and \( E_0 \) represents the direction of the incident electric field and wave vector, respectively. (b) \( H_z \) field distribution in free space at 9.43 GHz. (c) \( H_z \) field distribution without the cloak at 9.43 GHz. (d) \( H_z \) field distribution with the cloak at 9.43 GHz.

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IV. EXPERIMENT

In order to further verify the performance of the proposed full-parameter unidirectional TM wave cloak, we set up an experimental system to measure the field distribution in and near the cloak in a fully anechoic chamber. Since the cloak is highly symmetric, we fabricated only a half of the unidirectional cloak and a half of the PEC bump for demonstration, as shown in Fig. 3. For the TM wave case, the PEC sheet can be treated as a symmetry plane, with which the half of the cloak and the half of the bump can be treat as full ones. Therefore, considering the PEC symmetric boundary and TM polarization incidence, this setup is physically equivalent to the unidirectional cloak shown in Fig. 2(a), and will not alter the behavior of the cloak.
FIGURE 3. (a) Scheme of the measurement setup. Half of the cloak and a half of bump with the symmetry plane (PEC sheet) can be treated as full ones. The cloak is divided into two parts. Each part is 145 mm thick. The gap between them is 5 mm. A loop antenna is inserted into the gap to probe the magnetic field along the z-direction and a horn antenna with a magnetic field polarized along the z-direction is located 1.5 m away from the cloak to transmit a quasi-plane wave. (b) Three-dimensional perspective of the metamaterial cloak sample in the microwave anechoic chamber. (c) A zoom-in view of the actual metamaterial cloak sample.

Fig. 3(b) shows the case when the cloak is placed onto a PEC sheet. The size of each layer of the cloak is the same as that of the simulated model in the CST. The thickness of the cloak along the z-direction is 189 mm, which is about six wavelengths large at the operation frequency. In order to measure the magnetic field distribution in the cloak, we divided the cloak into two parts, and the gap between them is about 5 mm. The probing antenna is composed of a coaxial cable and a loop with a radius of 5 mm, which is inserted into the gap to map the magnetic field vertical to the loop. A horn antenna is located at a distance of 1.5 m away from the cloak with a magnetic field polarized along the z-direction, which can be treated as a quasi-plane wave source. Both of the transmitted horn antenna and probing antenna are connected with the vector network analyzer to obtain the amplitude and phase of the magnetic field. The probing antenna is fixed on a mechanical arm of a three-dimensional measurement platform and is controlled to move in the vertical xy plane to get the magnetic field point by point. The scanning range covers a square of 501 x 270 mm² with a spatial resolution of 3 mm. With the aid of MATLAB, we can plot the magnetic field distribution in the scanning range.

Figure 4 shows the measured field distribution of Hz component at 9.5 GHz. Three cases: (a) free space, 6 bump in free space, and (c) an aluminum bump covered by the cloak, are measured respectively. In Fig. 4(a), one can see that a quasi-plane wave with slightly curve wavefront propagates from left. Fig. 4(b) shows that the quasi-plane wave impinges onto the aluminum triangle bump, which will cause a strong scattering, especially the forward scattering.

While Fig. 4(c) shows that with the cloak, the scattering wave is strongly suppressed, and the plane wave is successfully guided around the aluminum triangle bump. Note that there are slightly some degradations in the cloaking case compared with the free space case. This imperfection may be introduced by the imperfection of the fabrication and the void in the cloak. Nevertheless, both simulation results and experiment results show the functionality of the proposed full-parameter unidirectional TM-wave cloak in free space.

As the designed metamaterial structure is a dispersive medium, the bandwidth of the cloak is relatively small. The cloak is supposed to work at a chosen frequency, namely, 9.5 GHz. Figure 5 shows the measured near field in a frequency range from 9.3 GHz to 9.7 GHz. One can see that in comparison to the results at 9.5 GHz, the cloaking performance at other frequencies is worse, although the scattering of the bump can still be suppressed to a certain extent. This indicates that the acceptable cloaking performance is limited in a small frequency range, roughly 0.1 GHz.
our cloak only needs to include the PEC inner boundary or the PEC symmetry plane, which can be easily replaced with the metallic conductor, and therefore, is much easier to fabricate.

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