Large scale cylindrical cloak in free space without superluminal propagation

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***Abstract*-Despite its remarkably fast development in the past few years, the technology of invisibility cloaking is still facing many serious bottlenecks, e.g. the bandwidth, the superluminal limitation, dispersion, loss, etc. In this paper, we experimentally demonstrated an alternative approach of invisibility cloaking that can combine technical advantages of all current major cloaking strategies in a unified manner and thus can solve bottlenecks of individual strategies. A broadband cylindrical invisibility cloak in free space is designed based on scattering cancellation (the approach of previous plasmonic cloaking), and implemented with anisotropic metamaterials (a unique property of previous transformation-optics cloaking). Particularly, non-superluminal speed of light in the cloak, a superior advantage of non-Euclidian conformal mapping cloaks, is inherited in this design, and thus is the reason of its relatively broad bandwidth. This demonstration provides a possibility for future practical implementation of cloaking devices at large scales.**

I. INTRODUCTION

The technology of invisibility cloaking, which has undergone tremendous development in the past few years, is still facing serious bottlenecks. There are three major cloaking strategies, each of which has been developed almost independently without overlapping with others. The first strategy is the plasmonic cloaking based on scattering cancellation [1-3], where a plasmonic shell with negative permittivity can cancel the scattering of a dielectric dipole object. However, the effectiveness of this approach only applies to a specific dielectric object, and is fundamentally limited to subwavelength scales. The second strategy is based on a singular coordinate transformation [4-7] where a “hole” that can hide arbitrary objects is created in the electromagnetic space. The reason why this strategy does not violate the uniqueness theorem of inverse problems is because of the anisotropy of the designed cloak [5]. Although being able to cloak an arbitrary object, the cloak designed by this method is fundamentally narrowband because the speed of electromagnetic waves inside the cloak will exceed the speed of light in vacuum [8-10], when the background environment is free space. Although the recent carpet cloaking [11-18] can mitigate the bandwidth limitation by virtue of the support of a ground plane, cloaking a free-standing isolated object using this transformation method still suffers from the superluminal limitation. The third strategy, utilizing transformation on a complex plane with properly designed branch cuts and Riemann sheets [19-20], can potentially get rid of superluminal velocity of electromagnetic waves by virtue of non-Euclidian transformation, but the required permittivity needs to continuously vary in an extremely large range [21], which is very difficult to achieve in practice.

In this paper, we experimentally demonstrated an alternative approach of invisibility cloaking that can solve the above bottlenecks and integrate the technical advantages of all previous cloaking strategies. First of all, the low scattering performance is guaranteed by using the scattering cancellation method derived from plasmonic cloaking [1]. Instead of just cancelling the dipole moments as in plamonic cloaking, our design method adopts a Mie scattering analytical model combined with an optimization algorithm [22] to minimize the total scattering from the cloak. Second, we use anisotropic metamaterials to implement a physical cloak. Anisotropy is the key reason why uniqueness theorem of inverse problems doesn’t hold for transformation-optics cloaks, and is also one of the efficient ways to manipulate electromagnetic waves. Third, our cloak intendedly imposes the condition of non-superluminal propagation inside the cloak. Both permeability and permittivity are almost non-dispersive, and the effective refractive index has no component smaller than unit. This is the mechanism underlying its broad bandwidth, which has the potential to be extended to a larger scale to implement a large-scale cloak.

II. ANALYTICAL MODEL

We explain our model in detail as shown in Fig. 1. For the sake of simplicity, we first consider a transverse electric (TE) polarized electromagnetic wave incident onto this multilayered cylindrical cloak. The layered media are rotationally anisotropic. The constitutive parameters needed to be considered here are the relative permittivity in the z direction, ε_z, the relative permeability in the tangent direction, μ_ϕ, and the relative permeability in the radial direction, μ_ρ. We express the EM field in terms of Bessel functions using the method of separation of variables and find the coefficients of

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the scattering field. Based on the cylindrical scattering model, the far-field total scattering efficiency Q_{sca} for the multilayered cylindrical cloak can be obtained. We use an optimization program, which is based on Genetic Algorithm (GA), to minimize the radar cross section (RCS) and optimize the constitutive parameters of our invisibility cloak. Given the size of an arbitrary object to be hidden, the inner radius of the cloak is fixed. The chromosome in GA is a set of constitutive parameters of each layer (i.e. $\varepsilon_z, \mu_\rho, \mu_\phi$) and the outer radius. The value of each parameter is determined by a linear mapping from the integer denoted by the binary number to the search space. The thickness of each layer is set to be identical for simplicity. The fitness of an individual is chosen to be $1/Q_{sca}$. We make use of the roulette-wheel selection and ensure the fittest individual to propagate to the next generation. Thus, evolution is carried out and optimization is obtained finally. To simplify the realization, we set the following limitations of the constitutive parameters: 10< ε_z <48, 0.15< μ_ρ <1, and $0.95 \le \mu_\phi \le 1$ in the optimization. These limitations have already imposed the condition of non-superluminal propagation inside the cloak in the optimization procedures because the refractive index in the cloak is larger than unity (i.e. $\mu_\rho \varepsilon_z \ge 1.5$). Here, a group of optimized parameters of a one-layer cloak was selected as a simple example.

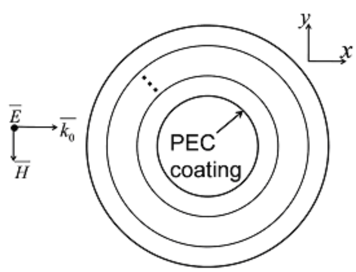

Figure 1: Configuration of a multilayer cylindrical cloak

III. EXPERIMENT

For the sake of easier demonstration and faster computation, we adopted a six-layer invisibility cloak to cloak a PEC cylinder with the diameter of λ. The optimized relative constitutive parameters in the order from the outermost layer to the innermost layer are μ_ρ = {0.18, 0.36, 0.15, 0.15, 0.15, 0.15}, μ_ϕ = {1.0, 0.95, 1.0, 0.95, 1.0, 0.99} and ε_z = {11.9, 38.85, 10.0, 36.30, 10.0, 19.15}. The thickness of each layer is 0.065λ. All the parameters in the six layers are anisotropic, positive and finite. The refractive index components, i.e. $\sqrt{\mu_\phi \varepsilon_z}$ and $\sqrt{\mu_\rho \varepsilon_z}$, are greater than one. Therefore, the speed of electromagnetic waves traveling in the cloak is always slower than the speed of light in free space. This makes possible a large-size broadband invisibility cloak in free space. Note that the original cloak design with non-superluminal propagation was first proposed based on non-Euclidean transformation on a complex plane with proper branch cuts [21]. Although designed differently, our cloak is an alternative approach with similar effects of non-superluminal propagation. To build the large-size cylindrical invisibility cloak, we use various closed rings to realize the effective constitutive parameters obtained from optimization program. We design the CR unit cells at 2.01 GHz. Here we name them Layer 1 to Layer 6 from outer layer to inner layer. The geometrical parameters in millimeter of the closed rings of six-layer cylindrical cloak are listed in Tab. 1. The variables have the same meaning as those in Fig. 2, i.e., a is the length of the closed ring in the *z* direction, b is the length of the closed ring in the ϕ direction, *w* is the width of the copper strip, t is the thickness of the copper strip. L_z, L_ϕ, and L_ρ are the dimensions of the substrate, respectively and p_z, p_ϕ, and p_ρ are the periodicities of the unit cells. We use three kinds of substrate to fabricate CR unit cells: Polimide (PI) with the relative permittivity of 2.33 for Layer 1, Layer 3, and Layer 5; FR4 with the relative permittivity of 4 for Layer 2 and Layer 4; and high frequency laminates F4B with the relative permittivity of 2.55 for Layer 6. The closed rings for Layer 4 are sandwiched in the middle of two pieces of 0.5 mm-thick FR4 substrate, while the closed rings for the other five layers are printed on one side of the substrate. The fabricated unit cells for Layer 1 to Layer 6 are shown in Fig. 3(a-f), respectively. The thickness of each layer at 2.01 GHz is $T_t = 9.74\,mm$, so the unit cells placed by N_k in ρ direction in layer *k*, where $N_k = Tt/P_{\rho k}$ and $P_{\rho k}$ is the periodicity P_ρ in layer *k*. The space of air between two contiguous CRs is supported by ROHACELL 71 HF foam with the permittivity of 1.075 at 2.5 GHz.

Tab. 1 The geometrical parameters (mm) of the closed rings of six-layer cylindrical cloak.

Layer	1	2	3	4	5	6
a	9.6	9.4	9.6	9.85	9.5	9.7
b	12.3	7.9	10.4	9.4	16.9	14.7
L_z	10	10	10	10	10	10
L_ϕ	12.5	11.5	10.5	9.5	17.1	15
L_ρ	0.025	1	0.025	0.5	0.025	0.25
w	0.15	0.15	0.1	0.15	0.1	0.15
t	0.0175	0.035	0.0175	0.035	0.0175	0.035
p_z	10	10	10	10	10	10
p_ϕ	12.5	11.5	10.5	9.5	17.1	15
p_ρ	1.62	1.62	1.62	1.39	1.39	1.39
Substrate	PI	FR4	PI	FR4	PI	P4B

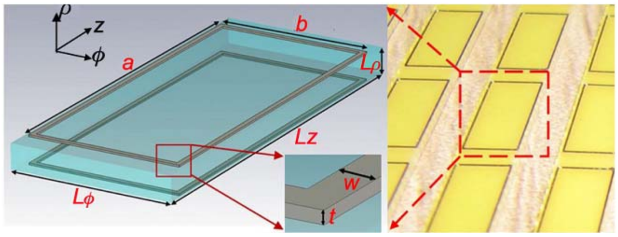

Figure 2: Periodic unit cell of the closed ring printed on two sides of the substrate (left) and the sample of closed rings without being assembled (right).

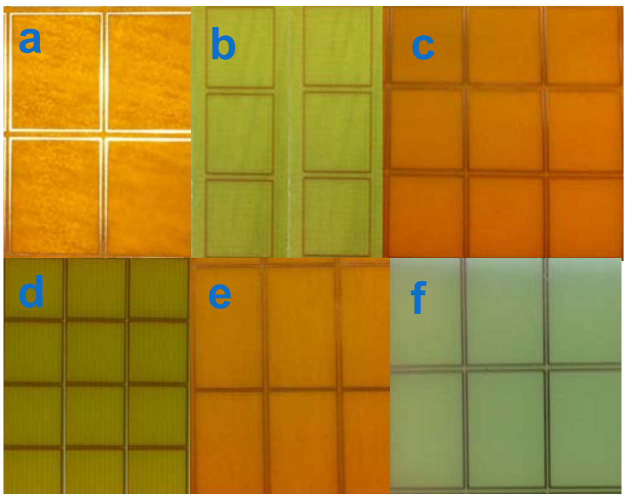

Figure 3: The fabricated unit cells for Layer 1 to Layer 6 are shown here from (a) to (f), respectively

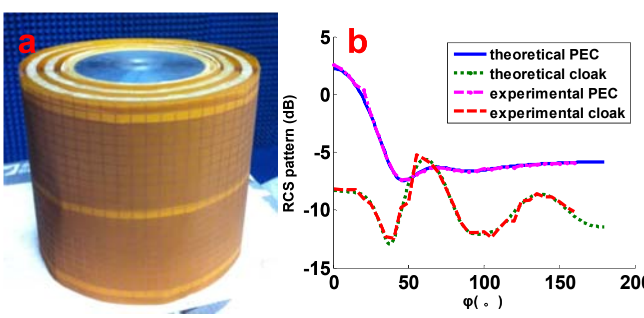

Figure 4: A photo of the multilayer cylindrical cloak. (b) The experimental RCS pattern via different azimuth angles ϕ at 2.02 GHz. The experimental setup is as same as that in the inset of Fig. 4.

The photo of the implemented invisibility cloak is presented in Fig. 4(a). The height of the cylindrical cloak is $h = 230\,mm$. The inner diameter of the cloak is $d_i = 149.25\,mm$ (1λ at 2.01 GHz). The outer diameter of the cloak is $d_i = 266.15\,mm$ (1.7832λ at 2.01 GHz). The far-field scattering from the bare PEC cylinder and from the cloaked PEC cylinder in all directions are measured in Fig. 4(b). The frequency for measurement is at 2.02 GHz. The measured RCS patterns are in good agreement with theoretical results. Therefore, the performance of the invisibility cloak designed from our approach is successfully demonstrated. Due to the unique superior advantage of non-superluminal propagation, it is possible to extend this design to eventually cloak a large-scale object in free space with broad bandwidth.

IV. Discussion and Conclusions

It is interesting to discuss the reason why our alternative approach of cloaking based on an optimization procedure can work. Previous cloaking strategies can be categorized as "forward problems," where the properties of the cloak (such as the dispersion and the range of refractive index) can be worked out only after the design is done. That is why different strategies will lead to different cloaks that possess different properties. Our proposed approach, on the other hand, is one of the "inverse problems," where the properties of the cloak are predetermined with a proper range of optimization domain. The specific means and categories of design strategies (e.g. plasmonic cloaking, singular-transformation cloaking, and non-Euclidian cloaking) are secondary from an integrated perspective. Apparently, the problem of this kind of inverse problems is that the existence of a proper solution is not always guaranteed. However, thanks to extensive studies on previous cloaking strategies that have accumulated plentiful knowledge, we know that some desired properties are achievable, such as broad bandwidth, non-superluminal propagation, and large-scale cloaking. These significant properties, although hard to achieve from individual previous strategies, may be possible for a target-oriented approach that can combine technical advantages of different strategies. After all, all current cloaking designs can be achieved in principle by a sufficiently powerful optimization program that can optimize all constitutive tensors independently. The inverse exploration from the desired properties by integrating previous strategies may provide a new prospect for the current cloaking technology.

In conclusion, we experimentally demonstrated an alternative approach of invisibility cloaking that can combine technical advantages of all current major cloaking strategies in a unified manner. A subwavelength cylindrical cloak and then a one-wavelength-large cylindrical cloak in free space are designed and measured. The design is based on scattering cancellation originated from previous plasmonic cloaking. Anisotropic metamaterials, a fundamental property of previous singular-transformation cloaking, are used to construct the cloaks. The superior advantages include non-superluminal propagation of electromagnetic waves in the cloak, previously only achievable with non-Euclidian transformation. These advantages may provide the possibility for future practical implementation of free-standing cloaking devices at large scales in free space.

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