Global and Local Field EM Modeling and Novel GL Double Layered Electromagnetic Cloaks

Ganquan Xie, **Jianhua Li**, **Feng Xie**, **and Lee Xie**
GL Geophysical Laboratory, USA

Abstract— In this paper, we propose global and local electromagnetic (EM) field modeling in time domain and a novel GL double layered EM cloak. The GL double layered cloak (GL cloak) consists of two sphere annular layers, $R_1 \leq r \leq R_2$ and $R_2 \leq r \leq R_3$. Two type cloak materials are proposed and installed in its each layer, respectively. The outer layer of the GL cloak has the invisible function, while its inner layer has the fully absorption function. The outer layer cloaks the Local concealment from the Global exterior EM field; The inner layer cloaks the Global free space region from the Local field excited inside the concealment. The GL cloak metamaterials are weak degenerative When the source is located outside of the GL cloak, the excited EM wave field propagation is similar as that in free space, hence cannot be disturbed or disrupted by the cloak. Furthermore, the exterior EM wave does not penetrate into the inner layer, or the concealment. When local sources are located inside of the GL double cloaked concealment with normal EM materials, the excited EM wave propagates subject to Maxwells equations. It is completely absorbed by the inner layer of GL cloak and never propagate outside of the inner layer. Moreover, the EM wave-field in concealment is not disrupted by the cloak. The GL cloak is a robust, since it has complete and sufficient invisibility functions. Its concealment is the normal electromagnetic environment. Our EM GL double layered cloak is different from conventional common cloaks. The GL double layered EM cloak is proposed and developed based on a 3D GL EM modeling. Our GL modeling combines analytical and numerical approaches. There are no large matrices to solve in the GL method. Moreover, the GL method does no need artificial boundary and absorption boundary condition on it to truncate infinite domain. The 3D GL EM modeling simulations for the double layered cloak are presented. The GL method is different from the conventional methods. It has dual capabilities of the theoretical analysis and numerical simulations to study the cloak meta-materials, and field scattering problem in physical sciences.

1. INTRODUCTION

Finding and exploration is inverse problem; Hiding and cloaking is other inverse problem. They have close relationship. Based on the 3D GL EM modeling simulations [1, 2] and GL inversion [3], we propose global and local electromagnetic (EM) field modeling in time domain and a double layered EM cloak in this paper which is called, GL double layered cloak, simply labeled as the GL cloak. The single layer cloak proposed by Pendry et al. [4] is labeled, PS cloak. The GL double layered cloak consists of two sphere annular layers, $R_1 \leq r \leq R_2$ and $R_2 \leq r \leq R_3$. Two different type cloak materials are proposed and installed in its each layer, respectively. The outer layer of the GL cloak has the invisibility function, while its inner layer cloak has a fully absorption function to absorb the EM wave excited from local sources inside of the concealment. The outer layer cloaks the Local concealment from the Global exterior EM field; The inner layer cloaks the Global free space region from the Local field excited inside the concealment. That is the significance of the GL double layer cloak. When the source is located outside of the GL cloak, the excited EM wave field propagation outside of the cloak is similar to that in free space and never be disrupted by the cloak. Moreover, the exterior EM wave does not penetrate into the inner layer and concealment. When local sources are located inside the GL double cloaked concealment with the normal EM materials, the excited EM wave propagates according to Maxwells equations, and is completely absorbed by the inner layer cloak of the GL cloak, and does not propagate outside of the inner layer of the GL cloak. Finally, the EM wave-field in the concealment is not disrupted by the cloak. The GL doubled layered cloak is robust, and has complete and sufficient invisibility functions. Its concealment is the normal electromagnetic environment. Our EM GL double layered cloak is different from conventional common cloak. The GL double layered meta-materials are weakly degenerative, and dispersive.

A double layer cloth phenomenon to prevent the GILD inversion [5–7] detection has been observed in [8] in 2001 which is published in SEG online: The double cloth anti detection is obvious

around the fly in Figure 12 and around the bar in Figure 13. After that year, we developed a novel and effective Global and Local field (GL) modeling and inversion to study and simulate the meta-materials, periodic photonic crystals and condense nanometer materials etc. wide physical sciences. 3D GL EM modeling and inversion [9] and computational mirage [10] have been presented in PIERS 2005 and published in the proceeding of PIERS 2005 in Hangzhou in PIERS web. Metamaterial of the novel GL double layer cloak is proposed and simulated in this paper and eprint paper [11].

The analytical method and numerical method for physical sciences have been developed separately in history. The GL method consistently combines both analytical and numerical approaches. The GL method does not need to solve large matrix equations, it only needs to solve 3×3 and 6×6 matrix equations. Moreover, the GL method does not prescribe any artificial boundary, or a PML absorption condition necessary to truncate the infinite domain. The Finite Element Method (FEM) and Finite Difference Method (FDM) have numerical dispersions which confuse and contaminate the physical dispersion resulting from field and materials interactions. The frequency limitation is a difficulty of FEM and FDM.

The GL method is a significant scattering process which reduces the numerical dispersion and is suitable to simulate physical wave-field scattering in the materials, in particular, for dispersive materials. Born approximation is a conventional method in the quantum mechanics and solid state physics. However, it consists of one iteration only in the whole domain which may not be accurate in the high frequency and high contrast materials. The GL method divides the domain as a set of small sub-domains or sub-lattices. The Global field is updated by the local field from the interaction between the global field and local sub-domain materials successively. Once all sub-domain materials are scattered, the GL field solution obtained turn out to be more accurate than the Born approximation.

Moreover, the GL method can be mesh-less, including arbitrary geometry sub-domains, such as rectangle, cylindrical and spherical coordinate mixed coupled together. It is full parallel algorithm. The GL method advantages help overcome many historical obstacles described in detail in [1]. The theoretical foundation of the GL method is described in the paper [2]. We have used the 3D GL modeling [1, 2] and inversion technique in [3] to simulate many cloak meta-materials, nanometer materials, periodic photonic crystals etc. When the point source is located outside or inside of the various geometry cloaks, the 3D GL EM modeling simulations for the EM wave-field propagation through the cloaks have been done. These simulations show that the GL method is fast and accurate. In this paper, the 3D GL EM modeling simulations of the EM wave field propagation through the new GL double layered cloak is presented. When the local sources are located outside or inside of the outer layer cloak, EM wave propagation through outer layer cloak, do not penetrate into the inner layer and the concealment, i.e., $r \leq R_2$. The exterior EM wave-field propagation outside of GL double layered cloak is not disrupted by the cloak. The outer layer cloak has the invisibility function. When the local sources inside of the GL double layer cloaked concealment with normal materials, the excited EM wave normally propagating subject to Maxwells equations, the EM field is then completely absorbed by the inner layer cloak and can not propagate outside of the inner cloak. The EM environment in the GL double cloaked concealment is normal, in which there exist a Maxwell EM wave field excited by nonzero local sources, have no reflection from the boundary $r = R_1$, and does not propagate outside of of the boundary $r = R_2$.

By using the 3D GL EM modeling [1, 2] simulation and its theoretical analysis, we found and verified a phenomenon, that there exists no Maxwell EM wave field that can be excited by nonzero local sources inside of the single layer cloaked concealment with normal materials. Our GL double layered cloak overcomes the drawback and difficulty in the single cloak. Pendry et al. in paper [4] used a coordinate transformation and ray tracing to propose the annular cloak in which the ray being bending and re-direction around central sphere object and cannot penetrate into it. The cloak device like the vacuum and does not disturb exterior wave field. There are several other works that simulated the exterior plane wave propagation through the cloak [13–15]. Chen et al. presented the Mie analytical TEM model to simulate the plane wave through the spherical cloak [13]. Cummer et al. in paper [14] presented numerical simulations by using the COMSOL Multi-Physics finite element-based electro-magnetics solver for the 2D plane wave propagation through cylindrical cloak. Argyropoulos et al. described a dispersive finite difference method in time domain (FTFD) in [15] to simulate 2D TEM plane wave field through cylindrical cloak, in which the authors considered the difficulty of conventional FDTD scheme for dispersive materials. In papers [14] and [15], authors introduced many papers for cloak research works. Because the plane wave is excited by plane

sources, it cannot be located inside of the cloak or concealment. To study the EM wave excited from local sources inside of the cloaked concealment is absent from these papers. Authors of [16] and [17], studied the effect on invisibility of active devices inside the cloaked region. Author in [17] stated that "when these conditions are over-determined, finite energy solutions typically do not exist."

We use 3D GL method to do many simulations for studying the behavior of EM field excited inside of the single layer cloaked concealment. These simulations are divergent or become chaos when the EM wave propagates to the inner boundary of the single layer cloak. Our statement is that: There exists no Maxwell EM wave field that can be excited by nonzero local sources inside of the single layer cloaked concealment with normal materials [12]. For overcoming the weakness and difficulty of the single layer cloak, we propose the GL double layer EM cloak, which is on Eprint [11]. The detailed proof and 3D GL simulations are presented in this paper. Before the practice production of the single layered cloak, the electromagnetic field environment inside of the concealment cannot be studied in physical experiment. Our GL double layered cloak proposed in this paper overcomes the drawback and difficulty of the single layer cloak, and avoid disrupting the EM phenomenon inside of the single layered cloaked concealment with normal materials. The GL double layered EM cloak meta-materials inventive and fabrication technology right and 3D GL EM modeling software are patented by GL Geophysical Laboratory. The GL double layer cloak figures and movies are protected by GLGEO's color mapping and all right is reserved by GLGEO. We present grateful thanks to GL Geophysical Laboratory for approving the publication of the GL modeling method, GL double layered cloak material, theory, and simulations [11, 12]. If our GL double layer cloak material, method, properties, simulation results, figures and similar contents are appear in any publication by other author will be detection and identified and request the author to cite our papers as reference.

We describe this paper in the following order: The introduction is described in Section 1. In Section 2, we propose a GL double layered cloak materials. The EM integral equations are presented in Section 3. The 3D GL EM modeling are described in Section 4. The theoretical analysis of properties and functions of the GL double layered cloak are proposed in Section 5. The simulations of the EM wave propagation through the GL double layered Cloak by using the GL EM modeling are presented in Section 6. The advantages of the GL double layered cloak is presented in Section 7. In Section 8, we conclude this paper.

2. GL DOUBLE LAYERED CLOAK MATERIALS

2.1. GL Inner Layered Cloak Anisotropic Material

On the inner sphere annular domain, $\Omega_{\mathrm{GLI}} = \{r : R_1 \le r \le R_2\}$, by the GL EM modeling and inversion [1–3], we propose an anisotropic material as follows,

$$
\begin{aligned}
&[D]_{\mathrm{GLI}} = \mathrm{diag}\left[\bar{\varepsilon}_i, \bar{\mu}_i\right], \quad \bar{\varepsilon}_i = \mathrm{diag}\left[\varepsilon_{r,i}, \varepsilon_{\theta,i}, \varepsilon_{\phi,i}\right]\varepsilon_0, \quad \bar{\mu}_i = \mathrm{diag}\left[\mu_{r,i}, \mu_{\theta,i}, \mu_{\phi,i}\right]\mu_0, \\
&\varepsilon_{r,i} = \mu_{r,i} = \left(\frac{R_2^2 - R_1^2}{R_2^2}\right)\sqrt{\frac{R_2^2 - r^2}{R_2^2 - R_1^2}}, \quad \varepsilon_{\theta,i} = \varepsilon_{\phi,i} = \mu_{\theta,i} = \mu_{\phi,i} = \sqrt{\frac{R_2^2 - R_1^2}{R_2^2 - r^2}}\frac{R_2^2}{R_2^2 - r^2}.
\end{aligned} \tag{1}
$$

The Ω_{GLI} is called as GL inner layered cloak, the materials, $[D]_{\mathrm{GLI}} = \mathrm{diag}[\bar{\varepsilon}_i, \bar{\mu}_i]$ in (1), are the anisotropic GL inner layered cloak materials.

2.2. GL Outer Layered Cloak Anisotropic Material

Let the outer sphere annular domain $\Omega_{\mathrm{GLO}} = \{r : R_2 \le r \le R_3\}$ be the GL outer layered cloak with the following anisotropic GL outer layered cloak materials,

$$
\begin{aligned}
&[D]_{\mathrm{GLO}} = \mathrm{diag}\left[\bar{\varepsilon}_o, \bar{\mu}_o\right], \quad \bar{\varepsilon}_o = \mathrm{diag}\left[\varepsilon_{r,o}, \varepsilon_{\theta,o}, \varepsilon_{\phi,o}\right]\varepsilon_0, \quad \bar{\mu}_o = \mathrm{diag}\left[\mu_{r,o}, \mu_{\theta,o}, \mu_{\phi,o}\right]\mu_0, \\
&\varepsilon_{r,o} = \mu_{r,o} = \frac{R_3}{r}\frac{r^2 - R_2^2}{r^2}\frac{\sqrt{r^2 - R_2^2}}{\sqrt{R_3^2 - R_2^2}}, \quad \varepsilon_{\theta,o} = \mu_{\theta,o} = \varepsilon_{\phi,o} = \mu_{\phi,o} = \frac{R_3}{\sqrt{R_3^2 - R_2^2}}\frac{r}{\sqrt{r^2 - R_2^2}}.
\end{aligned} \tag{2}
$$

The GL inner cloak Ω_{GLI} domain and GL outer cloak Ω_{GLO} domain are bordering on the sphere annular surface $r = R_2$. We assemble the Ω_{GLI} as the inner sphere annular domain and Ω_{GLO} as the outer sphere annular domain and make them coupling on their interface boundary annular surface $r = R_2$ as follows,

$$
\Omega_{\mathrm{GL}} = \Omega_{\mathrm{GLI}} \bigcup \Omega_{\mathrm{GLO}} = \{r : R_1 \le r \le R_2\} \bigcup \{r : R_2 \le r \le R_3\} = \{r : R_1 \le r \le R_3\}, \tag{3}
$$