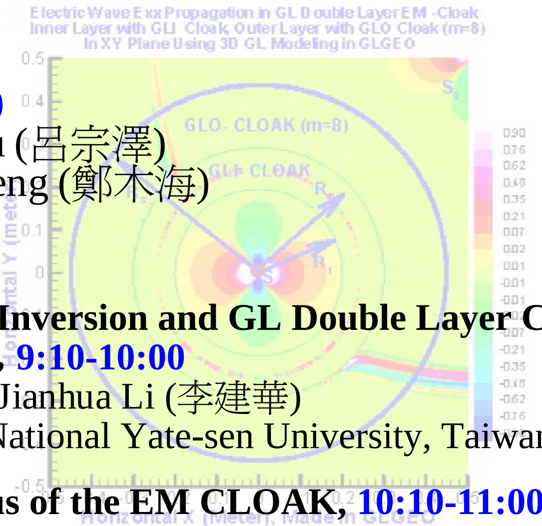
Mathematical Physical Optical EM Workshop

數物光電研討會
國立中山大學應用數學系

On

GL EM MODELING AND INVERSION AND
GL DOUBLE LAYER CLOAK AND MIRAGE

Date: June 5, 2009
Workshop Room: Science 4027 (Applied Mathematical 4th floor)

Agenda

Chairman Opening greeting **9:00-9:10**
Professor and Chairman Tzon-Tzer Lu (呂宗澤)
Professor and Chairman Wood-Hi Cheng (鄭木海)

REPORT

1. **Global and Local EM Modeling and Inversion and GL Double Layer Cloak and Mirage and PHC Metamaterials,** 9:10-10:00
   Professor Ganquan Xie (謝翰權), and Jianhua Li (李建華)
   (GL Geophysical Laboratory, USA) (National Yate-sen University, Taiwan, R.O.C.)

2. **Brag Fiber Sensor and Current Status of the EM CLOAK,** 10:10-11:00
   Professor Tzong-Jer Yang (楊宗哲)
   (National Chiao Tung University, Taiwan, R.O.C.)

3. **Photonic Crystals with LHM Metamaterials and Their Applications,** **11:10-12:00**
   Professor Chien-Jang Wu (吳謙讓)
   National Taiwan Normal University, Taiwan, R.O.C.)

Discussion 14:00 - at Science 4011-2

1. **3D GL EM modeling and Inversion and CLOAK and PHC Metamaterial Simulation, Fabrication, and Applications.**
   Physical, Mathematical and Optical Joint Research Project.
2. **Apply PIERS 2011 in Taiwan (PIERS 2009 in Moscow is attached).**

三維吉利篷罩蓬萊

隱形是個神話，現在，實現隱形神話已是一步之遙了。在數學、物理、光學、化學、生物的聯合科學工程領域，隱形就會像蒸氣機、發電機、電動機、電燈、電話一樣地實現；"隱形"就會與"有形"一樣共現於人間。與隱形相依的另一神話，就是蓬萊仙境、海市蜃樓、虛形幻影、一縷輕煙。現在蓬萊幻影也在奇特的光學材料中現形了。隱形材料的洋名叫"CLOAK"，華人叫"篷罩材料"，虛幻材料 "Mirage"叫"蓬萊材料"。令人驚嘆的是，我們的先人早就把篷蓬兩字同音相像準備好了。中華六文，深藏天機，"篷罩蓬萊"。這是非常有趣的外波場傳過目標而不發現目標，自身也不受目標干擾的正反問題，是數學、物理、光電、化學的最好接口。三維吉利建模和反算"3D Global and Local Field Modeling and Inversion" 是新建"篷罩蓬萊"的好方法。

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A Double Layer Electromagnetic Cloak And GL EM Modeling

In this paper, we propose a novel GL Double Layer Electromagnetic (EM) cloaking structure that consists of two annular layers between three spherical shells and model its performance numerically and theoretically by using a Global and Local EM field (GL) modeling and inversion method. The two annular layers contain distinct cloaking materials: the outer layer provides invisibility; the inner layer is fully absorbing. The cloaking materials are weakly degenerative. The wavefield from an EM source located outside the cloak propagates as in free space outside the outer shell, never be disturbed by the cloak and does not penetrate into the inner absorbing layer and concealment. The field of a source located inside inner layer or the cloaked concealment is completely absorbed by the inner layer and never reaches the outside of the middle shell, the EM wavefield excited in concealment is not disrupted by the cloak. The outer layer cloaks the local concealment from the Global exterior wavefield, the inner layer cloaks the global free space from the local wavefield. Therefore, we call our cloak as GL Double Layer EM cloak.

Many GL modeling and inversion simulations motivate and remind us to discover a new phenomenon that "there exists no Maxwell EM wavefield can be excited in a single layer cloaked concealment which is filled by normal material" We proved the theorem..

Moreover, we find a negative dielectric and positive susceptibility metamaterial to fill into the concealment, such that the interior EM wave propagates from the concealment to free space through the single layer cloak. Therefore, the double layer cloak is necessary for complete invisibility. Numerical simulations and theoretical analysis verifying these properties are performed using the GL EM modeling and inversion method.

The GL method is a significant physical scattering process. The finite inhomogeneous domain is divided into a set of small sub domains. The interaction between the global field and anomalous material polarization field in the sub domain causes a local scattering wave field. The local scattering wave field updates the global wave field by an integral equation. Once all sub domains are scattered, the wave field in the inhomogeneous anomalous materials will be obtained. We call the method as the Global and Local field method, i.e GL method which is fully different from the traditional numerical methods. The GL method combines the analytical and numerical method consistently together. There is no big matrix to solve in it. The GL method does not need artificial boundary and absorption boundary condition to truncate infinite domain. The GL method is suitable for any frequency band and isotropic and anisotropic materials. The GL method has double capability to discover materials and simulate the materials, also it can be useful for both of the physical mathematical theoretical proof and numerical simulations.

三維吉利篷罩蓬萊

謝幹權 李建華, 呂宗澤

國立中山大學應用數學係

隱形是個神話，現在, 實現隱形神話已是一步之遙了。在數學、物理、光學、化學、生物的聯合科學工程領域，隱形就會像蒸氣機、發電機、電動機、電燈、電話一樣地實現;“隱形”就會與“有形”一樣共現於人間。與隱形相依的另一神話，就是蓬萊仙境、海市蜃樓、虛形幻影、一縷輕煙。現在蓬萊幻影也在奇特的光學材料中現形了。隱形材料的洋名叫“CLOAK”，華人叫“篷罩材料”, 虛幻材料“Mirage”叫“蓬萊材料”。令人驚嘆的是，我們的先人早就把篷蓬兩字同音相像準備好了。中華六文，深藏天機，“篷罩蓬萊”。這是非常有趣的外波場傳過目標而不發現目標，自身也不受目標干擾的正反問題，是數學、物理、光電、化學的最好接口。三維吉利建模和反算“3D Global and Local Field Modeling and Inversion”是新建“篷罩蓬萊”的好方法。

Global and Local Electromagnetic Modeling For Simulation of The EM Cloaks

Ganquan Xie* and Jianhua Li, Feng Xie, Lee Xie†

GL Geophysical Laboratory, USA

(Dated: June 1, 2009)

Abstract

In this paper, a Global and Local field modeling is proposed to simulate the electromagnetic wave propagation in the inhomogeneous anomalous materials, in particular, in the cloak metamaterials. The method is a significant physical scattering process. The finite inhomogeneous domain is divided into a set of small sub domains. The interaction between the global field and anomalous material polarization field in the sub domain causes a local scattering wave field. The local scattering wave field updates the global wave field by an integral equation. Once all sub domains are scattered, the wave field in the inhomogeneous anomalous materials will be obtained. We call the method as the Global and Local field method, i.e GL method which is fully different from the traditional numerical methods. The GL method combines the analytical and numerical method consistently together. There is no big matrix to solve in it. The GL method does not need artificial boundary and absorption boundary condition to truncate infinite domain. The GL method is suitable for any frequency band and isotropic and anisotropic materials. Many 3D electromagnetic cloak simulations show that the GL method is effective to simulate the electromagnetic wave propagation through the anomalous materials and cloak metamaterials. The theoretical analysis of the 3D electromagnetic cloak is presented in this paper.

PACS numbers: Valid PACS appear here

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No Maxwell Electromagnetic Wave Field Excited In Cloaked Concealment

Ganquan Xie* and Jianhua Li, Lee Xie, Feng Xie†

GL Geophysical Laboratory, USA

(Dated: March 2, 2009)

Abstract

The GL electromagnetic (EM) modeling is used to simulate the 3D EM full wave field propagation through cloaks. The GL simulation of the EM wave field excited by a point source outside of the cloaks has been done and submitted to PRE. The simulation of the EM wave field from the point source excitation inside of the cloak device is presented in this paper. For a point source located inside of concealment, by using the GL modeling simulation, we discover a phenomenon that there is no Maxwell EM wave field which is excited by nonzero local sources inside of the cloaked concealment. The theoretical proof of the phenomenon by GL method is proposed in this paper. The GL method is fully different from the conventional methods. The GL method has double abilities of the theoretical analysis and numerical simulations to research the physical process and cloak metamaterial properties that is exhibited in this paper.

PACS numbers: 13.40.-f, 03.50.De, 41.20.-q, 41.20.jb,81.05.Zx, 42.70.-a, 52.25.Os,42.25.Bs

A Double Layer Electromagnetic Cloak And GL EM Modeling

Ganquan Xie* and Jianhua Li, Feng Xie, Lee Xie†

GL Geophysical Laboratory, USA

(Dated: June 1, 2009)

Abstract

In this paper, we propose a novel electromagnetic (EM) cloaking structure that consists of two annular layers between three spherical shells and model its performance numerically and theoretically by using a Global and Local EM field (GL) method. The two annular layers contain distinct cloaking materials: the outer layer provides invisibility; the inner layer is fully absorbing. The cloaking materials are weakly degenerative. The wavefield from an EM source located outside the cloak propagates as in free space outside the outer shell, never be disturbed by the cloak and does not penetrate into the inner absorbing layer and concealment. The field of a source located inside inner layer or the cloaked concealment is completely absorbed by the inner layer and never reaches the outside of the middle shell, Moreover, the EM wavefield excited in concealment is not disrupted by the cloak. There exists no Maxwell EM wavefield can be excited in a single layer cloaked concealment which is filled by normal material. Moreover, we find a negative dielectric and positive susceptibility metamaterial to fill into the concealment, such that the interior EM wave propagates from the concealment to free space through the single layer cloak. Therefore, the double layer cloak is important for complete invisibility. Numerical simulations and theoretical analysis verifying these properties are performed using the GL EM modeling method that we described in this paper.

PACS numbers: 13.40.-f, 41.20.-q, 41.20.jb,42.25.Bs

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I. INTRODUCTION

We propose a novel kind of electromagnetic (EM) double layer cloaking structure (a "Double Layer EM cloak") that consists of two annular layers between three spherical shells, $R_1 \le r \le R_2$ and $R_2 \le r \le R_3$. Distinct metamaterials are situated in the two layers: the material in the outer layer has properties that provide invisibility, while material in the inner layer is fully absorbing, which can also be useful for making a complete absorption boundary condition. We analyze the performance of the double layer cloak using a Global and Local EM field modeling "GL method" in time domain that we developed in this paper, its versions in frequency domain have been developed in our other papers [1-3]. Pendry et al. [4] proposed a single layer EM cloak material by using a coordinate transformation and ray tracing in 2006. In their cloak, 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. Later papers studied 2-D plane wave propagation through a cloaking layer are published in Physical review etc. Journals; Mie scattering analytical method for the sphere cloak is studied in [5]; Numerical methods, including finite-difference time-domain method in [6] and finite-element method in [7] are presented in which many relative research work papers are cited. Most researchers paid attention for exterior EM wave field propagation through the cloak. Two authors have studied the cloak's effect on sources located inside concealed region [8] and [9]. The authors of [8] stated that "when these conditions are over-determined, finite energy solutions typically do not exist." They wrote that the single layer cloak is insufficient and proposed a double coating to solve this problem. However, there also is disputing for this problem. In many numerical simulations using the GL method, we discovered and verified cases where a field satisfying Maxwell's equations cannot be excited by a local source inside of the single layer cloaked concealment which is filled with normal materials. For the above case of EM field excited inside the concealment, our simulations are either divergent or become chaotic when the field propagates to the inner boundary of the single cloaking layer. These simulations remind us to prove that there exists no Maxwell EM wavefield can be excited by source inside of the single layer cloaked concealment which is filled by normal material. The theoretical proof of the statement is proved in this paper by using he GL method. Moreover, we find a negative dielectric and positive susceptibility metamaterial to fill into the concealment, such that the interior

EM wave propagates from the concealment to free space through the single layer cloak. Therefore, the double layer cloak is important for complete invisibility.

The double layer cloak proposed here overcomes these difficulties described above by situating a second, absorbing layer inside the outer cloaking layer. The wavefield excited from an EM source located outside the cloak propagates as in free space outside the outer shell and never be disturbed by the cloak; it propagates around and through the outer layer cloak material and does not penetrate into the inner layer and innermost concealment. The field of a source located inside inner layer or the cloaked concealment is completely absorbed by the inner layer and never reaches the outside of the middle shell. Un Maxwaell physical behavior at the inner boundary of single cloaking layer does not appear in our simulations of the double layer cloak. The EM wavefield excited in concealment is not disrupted and has no reflection by the double layer cloak. In which the EM enviroment in the concealment is keeped to be normal and has no be changed. As a result, a double layer EM cloak appears to be more thoroughly concealing and more robust than single layer structures. Moreover, the metamaterials situated in the double layer cloak are weakly degenerative.

The analytical method and numerical method for physical simulation 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, and does not need a PML absorption condition 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 in the dispersive metamaterials. The frequency limitation is also a difficulty of FEM and FDM. The ray tracing is used for wave direction only that is not suitable to study full wave field propagation.

The GL method is a significant scattering process which reduces the numerical dispersion and is suitable to simulate physical wavefield 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 only has one iteration 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 sub-domains or sub-lattices which are as small as accurate requirement. 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]. In particular, for the radial dependent cloak materials, the GL method can be reduced to the system of the one dimensional GL processes in radial interval $[R_1, R_3]$ by using spherical harmonics expansion. We have used the GL modeling [1-2] and inversion technique in [3] to simulate many radiaul cloak metamaterials, nanometer materials, periodic photonic crystals etc. These simulations show that the GL method is fast and accurate.

The introduction is described in Section 1. The rest of this paper is organized as follows: Section 2 describes the geometry and material properties of the proposed double layer cloak. Section 3 contains a brief description of the EM integral equations and their solution by the GL method. These equations are used in Section 4 to prove certain theorems about double layer and single layer cloaks. Section 5 shows numerical simulations of the double layer cloak described in Section 2. The advantages of The GL cloak and GL modeling are presented in Section 6. Section 7 presents our conclusions.

II. DOUBLE LAYER ELECTROMAGNETIC CLOAK

In this section, by simulations using GL EM modeling and inversion in time domain which is presented in next section, we propose a novel electromagnetic (EM) cloaking structure that consists of two annular layers between three spherical shells. An inner layer EM anisotropic cloak metamaterial is situated in the inner annular layer; Outer layer EM cloak material is situated in outer layer.

It is obvious that when $r \in S_1$

$$E_{xx}(r, r_s, t)|_{r \in S_1} \neq 0. \tag{30}$$

The electric intensity field $E_{xx}(r, r_s, t)|_{r \in S_1} \neq 0$ in (30) and $E_{xx}(r, r_s, t)|_{r \in S_1} = 0.$ in (19) are an obvious contradiction. The *Statement* 2 is true.

V. SIMULATIONS OF THE EM WAVE FIELD THROUGH THE DOUBLE LAYER CLOAK

A. The Model of The Double Layer Cloak

The full 3D simulation model is a unit cube, $[0.5, 0.5]^3$, centered on the origin, discretized on a 201^3 mesh, with uniform mesh spacing of $0.005m$. The EM wavefield is excited by a point electric source:

$$s(r, r_s, t) = \delta(r - r_s)\delta(t)\vec{e}, \tag{31}$$

at location r_s where $\vec{e}$ is the (unit) polarization vector. the time step $dt = 0.3333 \times 10^{-10}$; the frequency band is from $0.05GHz$ to $15GHz$. The shortest wavelength is about $0.02m$. The GL double layer EM cloak consists of inner and outer annular regions, $\Omega_{GL} = \Omega_I \bigcup \Omega_O$, equation (3), with centers at the origin, which is situated by proposed anisotropic metamaterial D_{GL}, equation (4), the concealed central sphere $|\vec{r}| < R_1$ and the region outside the cloak $|\vec{r}| > R_3$ is filled with a normal electromagnetic material with basic permittivity and permeability, $\varepsilon{=}\varepsilon_{\mathrm{b}}, \mu = \mu_b$. The inner boundary of the cloak is $R_1 = 0.2m$; the middle shell boundary between the two layers is $R_2 = 0.3m$; and the outer boundary is $R_3 = 0.45m$. In the simulations, the sphere region $r \leq R_3$ is actually modeled in spherical coordinates, (r, θ, ϕ), where θ is polar angle. The sphere is divided 180^3 cells. The spherical coordinate grid is superimposed on the rectangular grid used to mesh the domain outside shell $r = R_3$. Because the cloaking materials are radial dependent, the EM modeling is reduced to the system of the one dimensional GL modeling by using the sphere harmonic expansion.

B. Simulation I

In this subsection, the simulation I is presented that an inner point source in the concealment and other outer source in the free space are used to excite the EM wave propagation

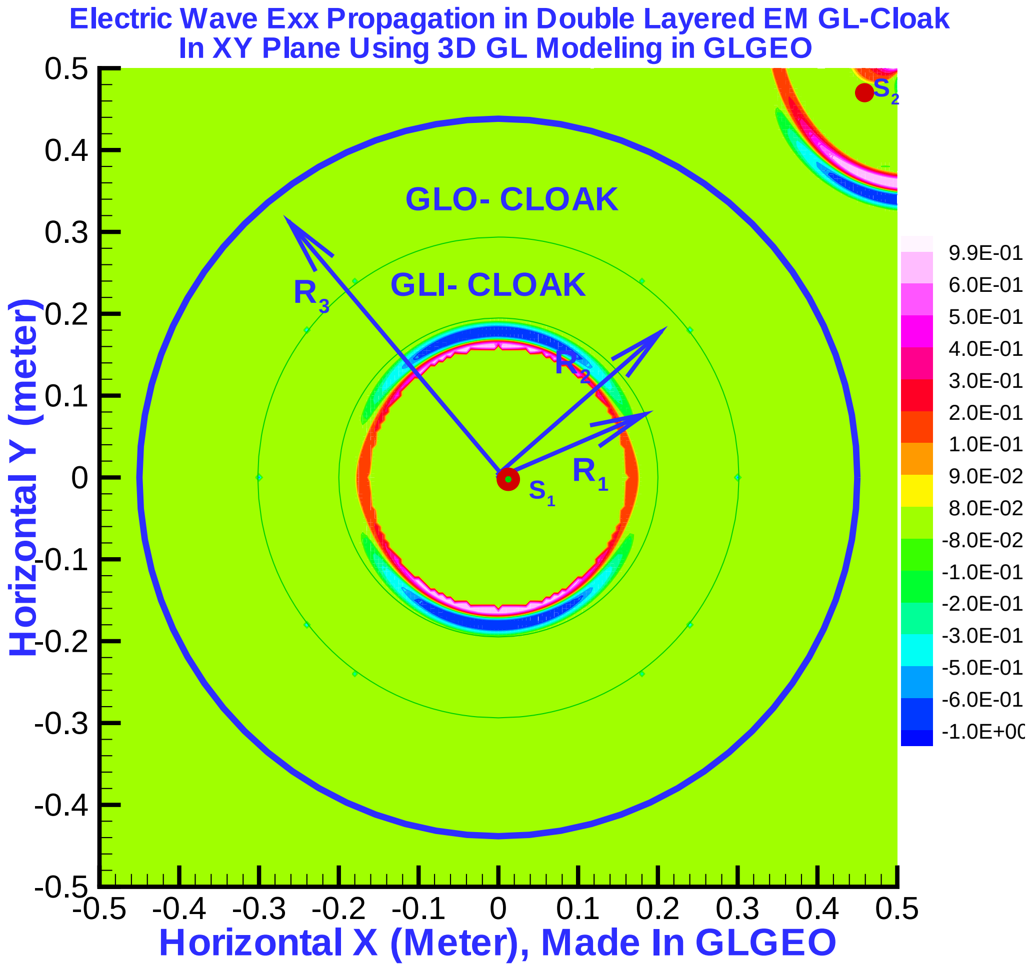

FIG. 1: (color online) At time step $18dt$, the wave front of the *First electric wave*, $E_{xx,1}$, propagates inside the concealment $r < R_1$. The front of *Second EM wave*, $E_{xx,2}$, is located in free space, the right and top corner outside of the whole GL double layer cloak.

through the double layer cloak. The point impulse current source with polarization direction $\vec{x}$, i.e.

$$S(r, r_s, t) = \delta\left(r - r_s\right)\delta(t)\vec{x}. \tag{32}$$

The first point current source is located inside the concealment at $(0.0012m, 0.0m, 0.0m)$, by which the excited EM wave is named as *First EM wave*, its component $E_{xx,1}$ is labeled *First electric wave*, The second current point source is located in free space at $(0.518m, 0.518m, 0.0)$ where is in the right and top corner outside the double layer cloak.

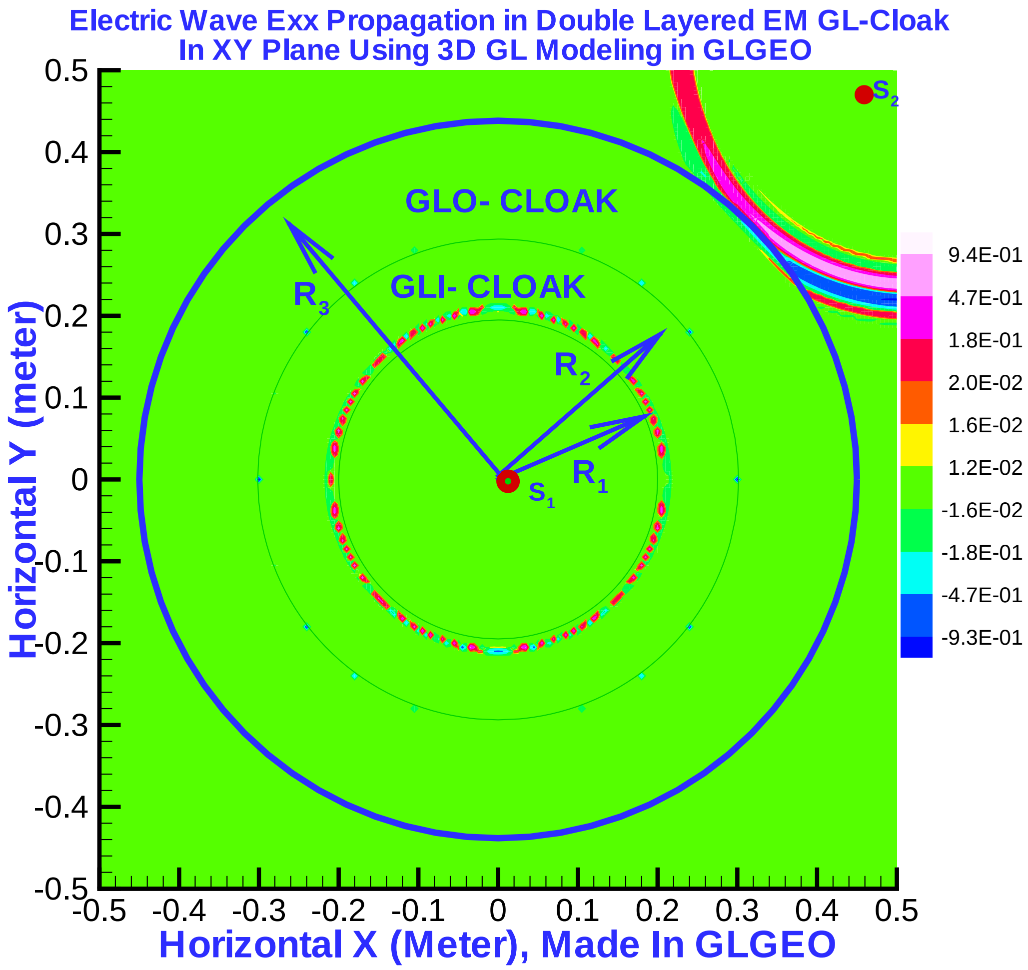

FIG. 2: (color online) At this moment of the time step 30dt, the front of the *First electric wave*, $E_{xx,1}$, propagates enter to the inner layer, $R_1 \leq r \leq R_2$; the front of *Second electric wave*, $E_{xx,2}$, reaches the outer boundary $r = R_3$ of the GL double layer cloak.

The EM wave by the second source is named as *Second EM wave*. Its component $E_{xx,2}$, is labeled *Second electric wave*. Figure 1-6 show a series of snapshots of an EM field propagating in and around the double layer cloak. The Figure 1 shows that at time step $18dt$, the wave front of the *First electric wave*, $E_{xx,1}$, propagates inside the central sphere concealment $r < R_1$ and never be disturbed by the inner layer; The front of *Second EM wave*, $E_{xx,2}$, is located in free space, the right and top corner outside the double layer cloak. At the moment $30dt$ in Figure 2, the front of the *First electric wave*, $E_{xx,1}$, propagates enter to the inner layer, $R_1 \leq r \leq R_2$; The front of *Second electric wave*, $E_{xx,2}$, reaches the outer

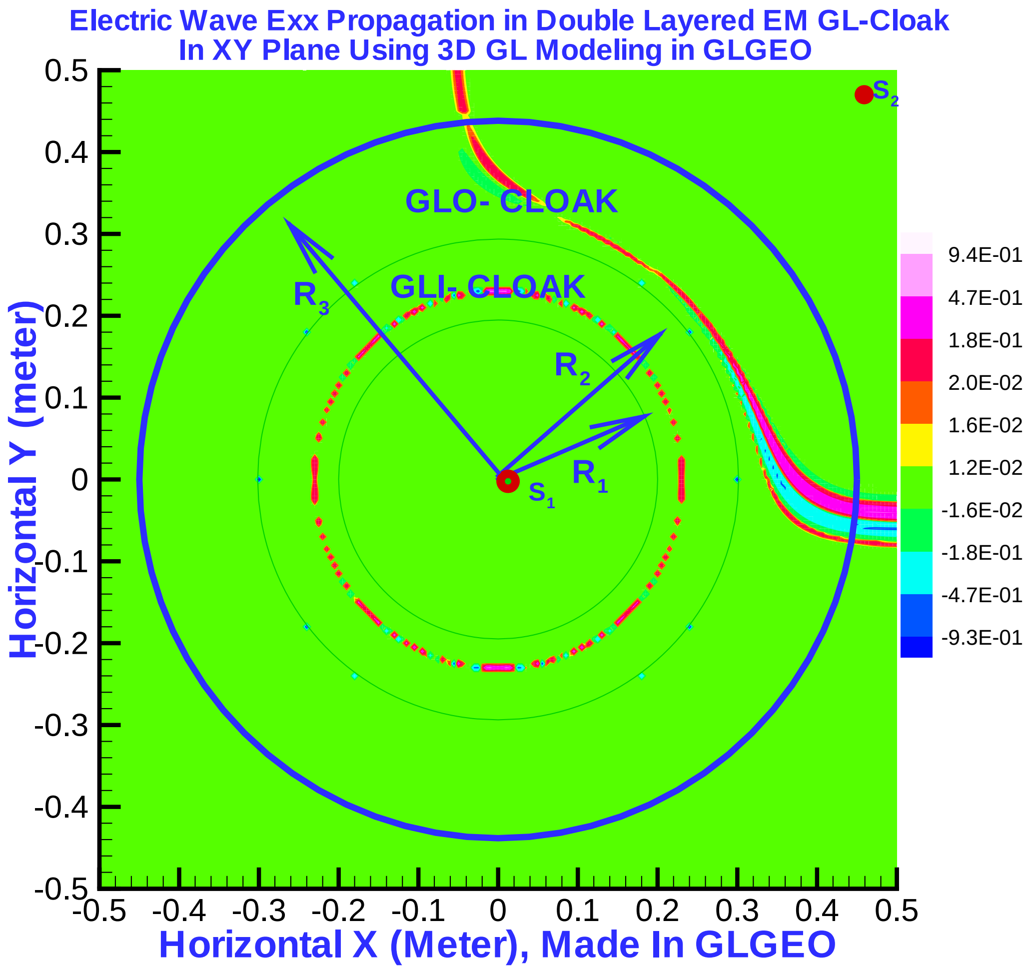

FIG. 3: (color online) At the time step $58dt$, the *First electric wave*, $E_{xx,1}$, is propagating inside the inner layer, $R_1 \leq r \leq R_2$, and becomes very slow. The part of the front of *Second electric wave*, $E_{xx,2}$, has been inside of outer layer, $R_2 \leq r \leq R_3$, and being backward bending

shell boundary $r = R_3$ of the cloak and never be disturbed. At the time step $58dt$, the *First electric wave*, $E_{xx,1}$, is propagating inside the inner layer, $R_1 \leq r \leq R_2$, and becomes very slow; The part of the front of *Second electric wave*, $E_{xx,2}$, propagates inside outer layer, $R_2 \leq r \leq R_3$, and being backward bending. The EM wave propagation image snapshot is presented in Figure 3. In the Figure 4, at time step $75dt$, the *First electric wave*, $E_{xx,1}$, is still propagating inside the inner layer, $R_1 \leq r \leq R_2$; The *Second electric wave*, $E_{xx,2}$, is propagating inside the outer layer cloak, $R_2 \leq r \leq R_3$, and around the shell $r = R_2$ and never penetrate into the inner layer and concealment, $r \leq R_2$. It does split into the two

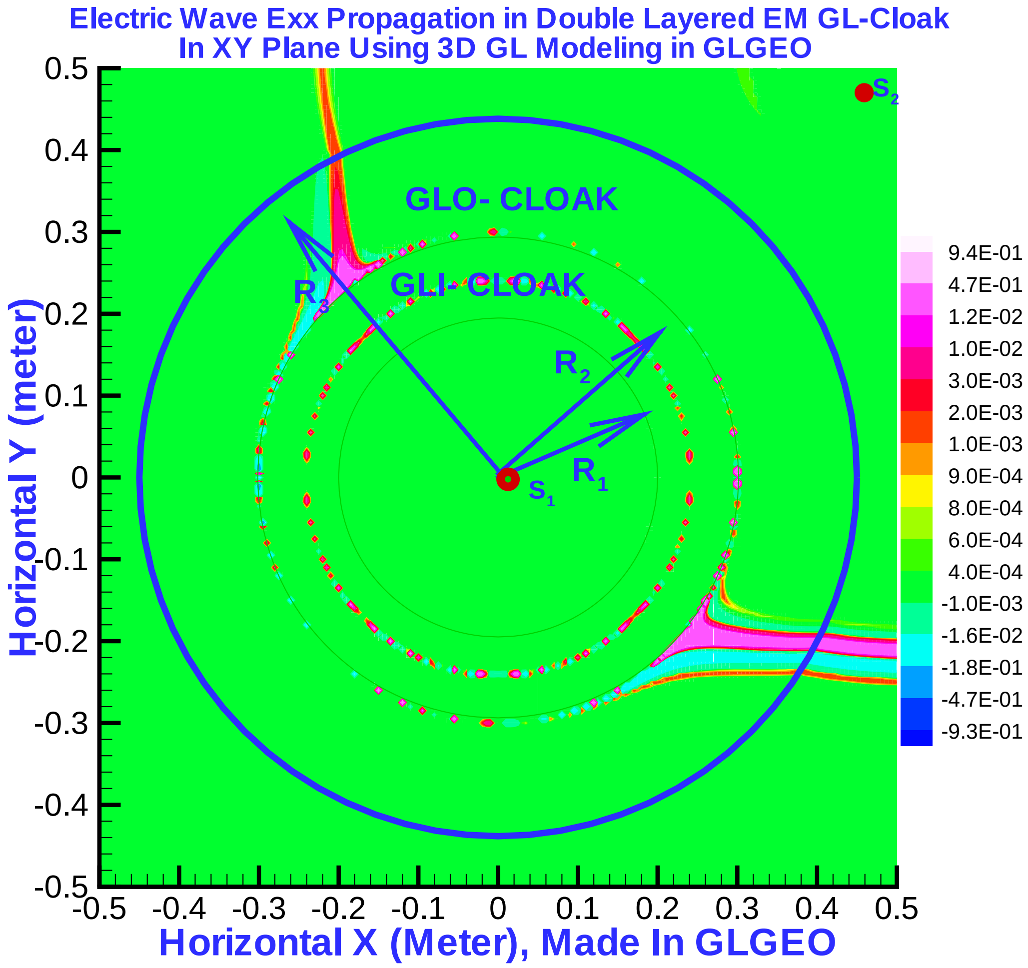

FIG. 4: (color online) At time step $75dt$, the *Second electric wave*, $E_{xx,2}$, is propagating inside of the outer layer, $R_2 \leq r \leq R_3$, and around the shell $r = R_2$ and never penetrate into inner layer and concealment, $r < R_2$. It does split into the two phases around the shell $r = R_2$. The *First electric wave*, $E_{xx,1}$, is propagating inside the inner layer, $R_1 \leq r \leq R_2$.

phases around the shell $r = R_2$, the front phase speed exceeds the light speed; the back phase is slower than the light speed. In the figure 5, at time step $98dt$, one part of front the *Second electric wave*, $E_{xx,2}$, is propagating inside the outer layer , $R_2 \leq r \leq R_3$. has a little forward bending and never penetrate into the inner layer and the concealment, i.e. $r \leq R_2$. The *First electric wave*, $E_{xx,1}$, is still propagating inside of the inner layer, $R_1 \leq r \leq R_2$. At time step $128dt$, the *Second electric wave*, $E_{xx,2}$ has propagated outside double layer cloak, a small part of its wave front is located in the left and low corner of the plot frame

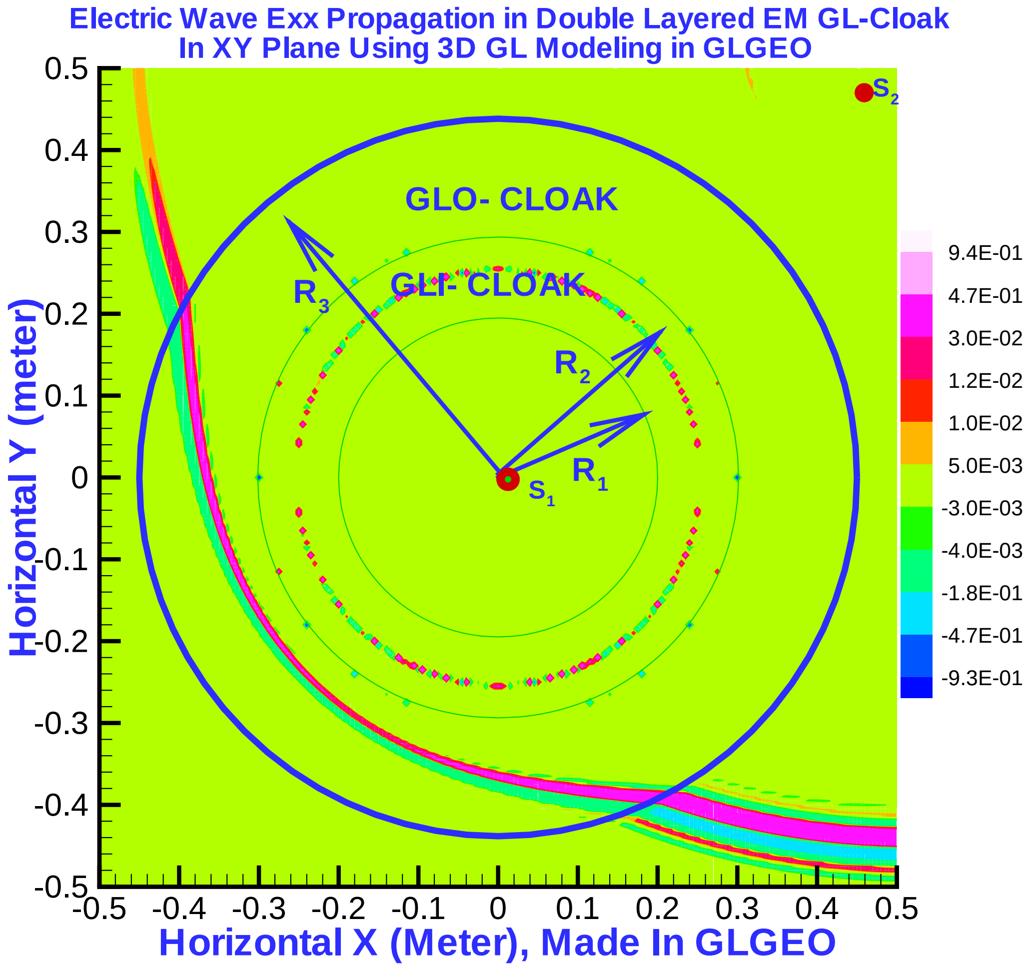

FIG. 5: (color online) At time step $98dt$, one part of front the *Second electric wave*, $E_{xx,2}$, is propagating inside of the outer layer, $R_2 \leq r \leq R_3$, and around to other side far source. It is a little forward bending. The *First electric wave*, $E_{xx,1}$, is still propagating inside the inner layer, $R_1 \leq r \leq R_2$.

which is shown in the Figure 6, most part of front of the $E_{xx,2}$ electric wave field has been out of the plot frame The exterior EM wave outside the cloak never been disturbed by the cloak and never penetrate enter its concealment and inner layer. At same time step, the *First electric wave*, $E_{xx,1}$, is still propagating inside the the inner layer, $R_1 \leq r \leq R_2$. It can be very closed to the interface boundary shell $r = R_2$, However, it can not be reached to the boundary $r = R_2$ for any long time. That means that the interior EM wavefield excited by source inside the concealment is complete absorbed by the inner layer. The inner layer

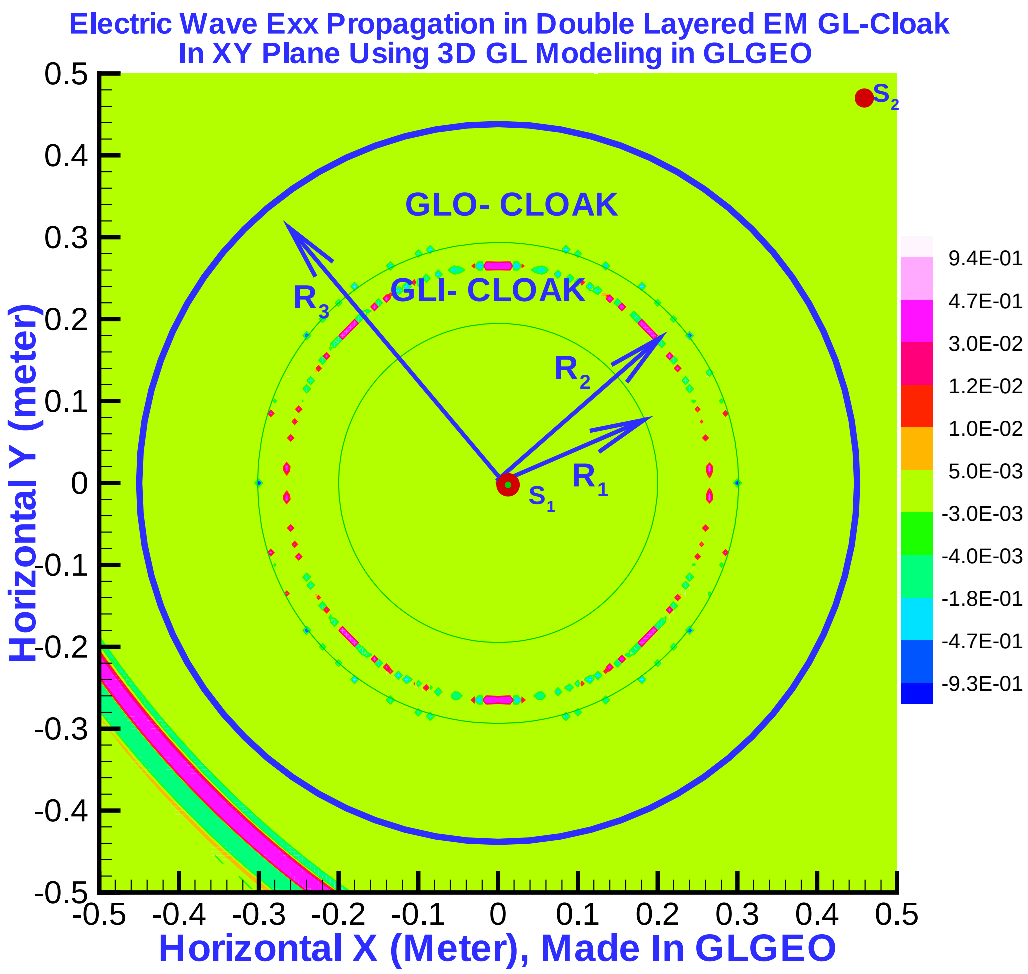

FIG. 6: (color online) At time step $128dt$, the *Second electric wave*, $E_{xx,2}$ has propagated outside the GL double layer cloak, a small part of its wave front is located in the left and low corner of the plot frame, which never be disturbed. The *First electric wave*, $E_{xx,1}$, is still propagating inside the inner layer, $R_1 \leq r \leq R_2$.

metamaterial, in equation (1), cloaks outer space from the local field excited in the inner layer and concealment, which can also be useful for making a complete absorption boundary condition to truncate infinite domain in numerical simulation.