XXI RINEM

Riunione Nazionale di Elettromagnetismo

September 12-14, 2016 Parma, Italy

Proceedings

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XXI RINEM

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Info at: http://rinem2016.unipr.it/

ISBN: 978-88-907599-1-8

SYNTHESIS OF DIELECTRIC CLOAKS VIA INVERSE SCATTERING DESIGN WITHOUT METAMATERIAL COATINGS

G. Labate(1) and L. Di Donato(2)

(1) Dipartimento di Elettronica e Telecomunicazioni, Politecnico di Torino, Corso Duca degli Abruzzi 29, Torino, Italy
giuseppe.labate@polito.it
(2) Dipartimento di Ingegneria Elettrica, Elettronica e Informatica, Università di Catania, Viale Andrea Doria 6, Catania, Italy
loreto.didonato@dieei.unict.it

Abstract

In this paper, we discuss the possibility of inducing a cloaking effect without using metamaterials. Starting from the inverse scattering problem (ISP), an ideal cloaking effect (i.e., zero scattered fields) is analytically synthetized in quasi-static regime: it is shown how object and cloak regions need positive-negative contrast values at subwavelength scale. However, reasoning on the role of contrast and source functions, both unknowns of the ISP, we intentionally pilot the ISP, solved via numerical optimizations, towards a cloak made up of only common dielectric permittivity. Interestingly, this is possible beyond quasi-static regime, where common cloaking methods (Scattering Cancellation) are no longer valid or need metamaterials (Transformation Optics).

Index Terms **– Cloaking, Contrast Source, Inverse Scattering Problem, Metamaterials.**

I. INVERSE SCATTERING: FROM PROBLEM TO DESIGN

The scattering data, naturally carried by electromagnetic fields during measurements, can be processed in order to know location, shape and even physical properties of unknown radiating systems embedded in a background scenario [1]. However, scattering data can be also postulated (and not sensed) to synthesize electromagnetic device with desired properties. In this paper, we apply this concept to the cloaking problem in order to facilitate the design of coatings able to sustain (ideally) zeros in the radar cross section (RCS) when they are put around an object to be hidden. To this aim, the scattering equation is first analyzed in the quasi-static regime, i.e. when the bare object is small with respect to the probing wavelength. In this case, it is found that a necessary and sufficient condition to achieve transparency is a positive-negative oscillating contrast values of the entire cloaking system. However, beyond quasi-static regime, the non-linearity of the ISP [2] is properly exploited to design coatings made of common dielectrics, without recurring to materials with negative constitutive parameters, i.e. metamaterials. This result implies an extraordinarily simplification in the design of the cloaking device. At the author's best knowledge, existing cloaking methods are not able to achieve such a goal, because they are not applicable beyond quasi-static regime (Scattering Cancellation [3]) or they need metamaterials in the cloak region (Transformation Optics [4]).

II. ANALYTICAL METHOD: QUASI-STATIC REGIME

We assume a cylindrical coordinate reference system and a volumetric distribution of dielectric materials, the physical cause of the scattering event is the induced currents [1]

$$\vec{J}_v(\rho',\varphi') = j\omega\varepsilon_b\chi(\rho',\varphi')\vec{E}_t(\rho',\varphi') \tag{1}$$

where volumetric (polarization) sources $\vec{J}_v(\cdot)$ show a dependence on the total field configuration $\vec{E}_t(\cdot)$ and the contrast function $\chi(\cdot)$ as well, the latter defined as

$$\chi(\rho',\varphi') = \frac{\varepsilon(\rho',\varphi') - \varepsilon_b}{\varepsilon_b}, \tag{2}$$

representing the normalized difference between constitutive parameters of the scattering system and background region. As a result, by definition, if the vacuum is assumed as background medium, positive/negative sign of the contrast indicates common dielectric objects (+) or metamaterials (-), respectively. The mathematical relation between scattered field and source is given by:

$$-j\omega\mu_b\int_\Omega \vec{J}(\rho',\varphi')G(\rho,\varphi,\rho',\varphi')\,d\Omega = \vec{E}_s(\rho,\varphi) \tag{3}$$

where a general observer, located at (ρ,φ), is looking at the scattering event $\vec{E}_s(\cdot)$ radiated by volumetric sources distributed in the scenario Ω. Moreover, the Green's function $G(\cdot)$, taking into account the mutual interactions of the scattering phenomenon, is the kernel of the radiation operator which maps sources into scattered fields. Considering the ideal scattering output of the cloaking problem (i.e., $\vec{E}_s = 0$), the ISP can be solved in a straightforward manner in quasi-static condition. In this respect, it is worthwhile mentioning that Eq. (3) can be restricted to a domain Σ where the induced sources are localized, supporting the cloaking system. For quasi-static regime, the Green's function can be assumed to be constant over Σ, as well as the total field. As a result, turning to zero the scattered fields, Eq. (3) becomes a compact relation only between contrast values of the overall cloaking system, i.e.,

$$\int_\Sigma \chi(\rho',\varphi')d\Sigma = 0. \tag{4}$$

Splitting eq. (4) in two subdomains (cloak and object areas), a positive/negative nature of the contrast function comes out as *necessary and sufficient* condition: it is interesting to note that Eq. (4) generalizes *plasmonic cloaking* [3] for scatterers of arbitrary shape. In quasi-static condition, cloaking a common material is possible only inserting metamaterials in the cloak region. In fact, the designer can turn-off the effect of the volumetric sources only by locally compensating the positive induced polarization associated to a positive contrast (i.e. the object) with the negative one associated to a negative contrast (i.e. the metamaterial cloak). An example for a non-canonical shape cloaking system at subwavelength is shown in Fig.1.

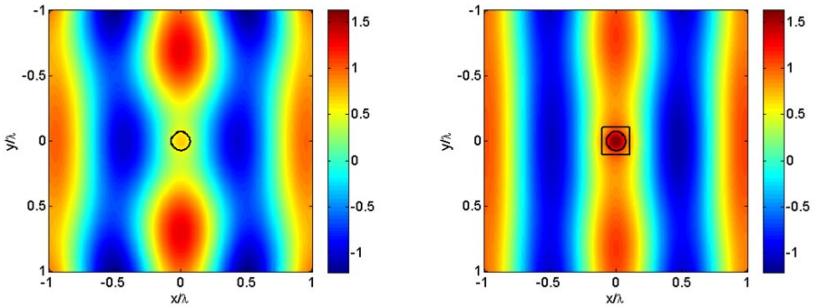

Fig.1. Real part of the total field for the bare object (left) and the cloaked object (right) synthesized by using Eq. (4). The bare object is a circle with $\varepsilon=6\varepsilon_0$ and radius r=4.2mm, while the cover is a square of $\varepsilon_c=-3.13\varepsilon_0$ and width 3r. The frequency is 5 GHz.

III. NUMERICAL METHOD: BEYOND QUASI-STATIC REGIME

Beyond quasi-static condition, the main consideration to derive condition (4) from Eq. (3) is no longer valid. However, inspired by critique and alternatives about metamaterials [5], we ask if there is still the need of making use of negative contrast within the cloak region. In fact, if we look at Eq. (3), in this case, the ISP 'reduces' to the problem of finding proper contrast distributions which account for a cancellation, or at least a considerable reduction, of the scattered field through the source function in Eq. (1). Indeed, when the size of the cloaking system become larger and larger with respect to the wavelength, non-scattering behaviour can be pursued even if the contrast shows a positive value. As a matter of fact, being the effects of total field configuration no more lumped in the cloaking domain, but distributed, the cloaking mechanism can be achieved through proper distribution of contrast taking into account the non-linear effects on the source configuration. Inspired by the reasoning above, we exploit the numerical solution of the ISP solving the following optimization problem:

$$\phi(\chi,J)=\sum_{v=1}^{N}\left\{\left.\frac{\left\|J^{v}-\chi E_i^{v}+\chi A_i[J^{v}]\right\|^{2}}{\left\|E_i^{v}\right\|^{2}}\right|_{\Omega}+\left.\frac{\left\|A_e[J^{v}]\right\|^{2}}{\left\|E_i^{v}\right\|^{2}}\right|_{\Gamma}\right\}. \qquad (5)$$

In Eq. (5), the first addendum enforces, for a given set of incident field views **N,** the solution (in the least square sense) of the scattering equation in Ω (the state equation in the common ISP [1-2]), while the second addendum is nothing but the minimization of the RCS over an observation domain Γ at a given distance from Ω. Moreover, A_i and A_e are short notations of the integral operators which relate the contrast source to the scattered field in Ω and Γ, respectively. Finally, it is worth noting that both the contrast function and the source are unknowns of the problem. In particular, in order to look for real contrast function exhibiting positive values, we enforce that the relative permittivity is everywhere greater than one and conductivity is zero (i.e., lossless).

IV. Numerical Results: Cloaking without Artificial materials

In order to demonstrate the validity of our considerations, we address the solution of Eq. (5) considering the same object discussed in the quasi-static condition (i.e., $\varepsilon=6\varepsilon_0$), but at higher frequency (e.g., 25 GHz). We choose the cloak region to be a circular annulus of radius 2λ and we require the RCS to be zero in the near-field all around the cloaking system, for two antiparallel direction of the incident (plane waves) fields (i.e. –x and x). The synthesized permittivity distribution is shown in Fig. 2. As it can be seen, this leads to a cloak with a specific arrangement of dielectric materials with $\varepsilon_c=1.6\varepsilon_0$ around the object.

The effect of the cloaking is also shown in Fig. 2.

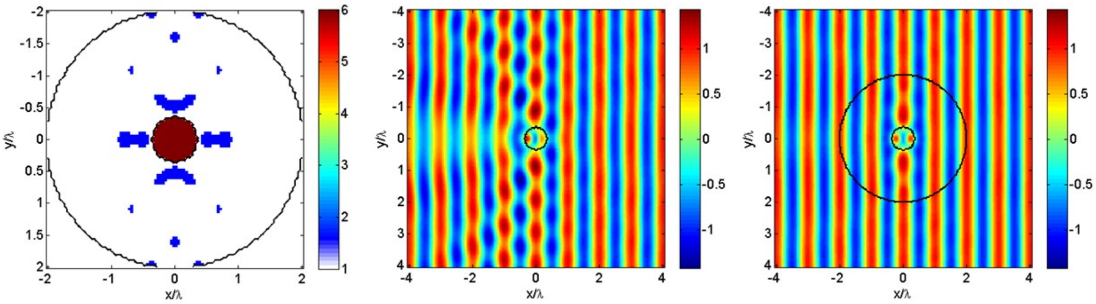

Fig.2 Results of the synthesis of natural dielectric cloak via Eq. (5). From left to right: permittivity values of the cloaking system, real part of the total field in the case of bare and cloaked object.

Conclusions

The synthesis of a cloak has been suggested with analytical and numerical approach based on the inverse scattering problem. Interestingly, the possibility to achieve transparency (with respect to the direction of the incoming wave) has been demonstrated well beyond quasi-static condition, re-evaluating standard dielectrics instead of metamaterials in the cloak region. More details and results will be shown at the conference.

Acknowledgement

The authors would like to thank Prof. L. Matekovits and Prof. T. Isernia for their valuable comments and suggestions.

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