6-8-2009

Cloaking a Sensor

Andrea Alù
University of Texas at Austin; University of Pennsylvania

Nader Engheta
University of Pennsylvania, engheta@ee.upenn.edu

Recommended Citation

Andrea Alù and Nader Engheta, "Cloaking a Sensor", . June 2009.

Suggested Citation:
Alù, A. and Engheta, N. (2009). "Cloaking a Sensor." *Physical Review Letters.* **102**, 233901.

http://dx.doi.org/10.1103/PhysRevLett.102.233901

Cloaking a Sensor

Abstract

We propose the general concept of cloaking a sensor without affecting its capability to receive, measure, and observe an incoming signal. This may be obtained by using a plasmonic sensor, based on cloaking, made of materials available in nature at infrared and optical frequencies, or realizable as a metamaterial at lower frequencies. The result is a sensing system that may receive and transmit information, while its presence is not perceived by the surrounding, which may be of fundamental importance in a wide range of biological, optics, physics, and engineering applications.

Disciplines

Electrical and Computer Engineering | Engineering

Comments

Suggested Citation:

Alù, A. and Engheta, N. (2009). "Cloaking a Sensor." *Physical Review Letters.* **102**, 233901.

http://dx.doi.org/10.1103/PhysRevLett.102.233901

Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

week ending
12 JUNE 2009

Cloaking a Sensor

Andrea Alù[1,2,†] and Nader Engheta[2,*]

[1] *Department of Electrical and Computer Engineering, University of Texas at Austin,*
1 University Station C0803, Austin, Texas 78712, USA
[2] *Department of Electrical and Systems Engineering, University of Pennsylvania*
200 South 33rd Street, ESE 203 Moore, Philadelphia, Pennsylvania 19103, USA

(Received 6 February 2009; revised manuscript received 8 April 2009; published 8 June 2009)

We propose the general concept of cloaking a sensor without affecting its capability to receive, measure, and observe an incoming signal. This may be obtained by using a plasmonic sensor, based on cloaking, made of materials available in nature at infrared and optical frequencies, or realizable as a metamaterial at lower frequencies. The result is a sensing system that may receive and transmit information, while its presence is not perceived by the surrounding, which may be of fundamental importance in a wide range of biological, optics, physics, and engineering applications.

DOI: 10.1103/PhysRevLett.102.233901 PACS numbers: 42.70.−a, 33.20.Fb, 42.50.Gy, 42.79.−e

Many different arguments may motivate the need for effectively "cloaking" sensors and detectors so that their presence may be less "disturbing" to the surrounding environment: in physics and engineering experiments, this may mean that a probe, e.g., near-field scanning optical microscope (NSOM), or an antenna may have a minimal disturbing effect on the quantity it is designed to measure. Biological and medical research and optical sciences, moreover, often require imaging the nanoscopic details of molecules and nanoparticles for a wide range of applications. Such subdiffractive measurements are necessarily performed in the very near field of the particle, and therefore they are intrinsically limited by the level of noise introduced in the measurement by the close proximity of the sensing instrument. Intuitively, one may note that a sensor with a larger "visibility" may indeed more easily capture, sense, and measure the data of interest, but it would also imply that its presence may disturb the measurement and may be perceived more strongly in the surroundings. Would it be possible to overcome or reduce these inherent limitations and design a sensor essentially "invisible" to the surrounding space, but still capable of "observing" efficiently?

To address this question, novel technological advances in material science may come to our help. Electromagnetic metamaterials and plasmonic structures, in particular, have been successfully considered for cloaking passive objects at different frequencies. Our idea [1–3] of employing a plasmonic or metamaterial cover to drastically reduce the overall scattering from moderately sized objects by means of a "scattering cancellation" effect, and other ideas for cloaking and transformation optics [4–8] that tailor complex metamaterial response to reroute the electromagnetic signals around a given region of space (thus, isolating that region from its surrounding) have been recently proposed. All these cloaking techniques would in principle ensure the "invisibility" of a passive cloaked system for any observer sitting around (and outside) the object, which implies that they would also allow "seeing through and behind" the cloaked region without noticing its presence at the frequency of interest.

However, one of the interesting features specific to our cloaking technique when applied to a dielectric object [1] is the fact that the interior of the cloaked region is *not isolated* from its external surrounding, but instead a nonzero field, proportional to the incoming signal, is induced inside the cloak. This implies that, if the cloaked object is a sensor (e.g., an optical nanoprobe, a receiving antenna…), it may still sense the presence of the external world even though its scattered fields may be dramatically reduced by a properly designed cover, as envisioned in Fig. 1. This is drastically different from the solutions proposed in [4–6,8], for which the region of space surrounded by the cloak is effectively isolated electromagnetically from its surrounding.

To approach the problem formally, we assume, as it is often the case to ensure a good spatial resolution, that our detector is small enough to be characterized by its own polarizability α_s, which determines the degree at which an

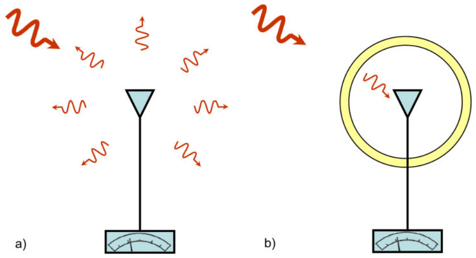

FIG. 1 (color online). (a) A bare sensor may receive signals, but its presence may as well perturb its surrounding, and thus being detectable from the outside; (b) a properly designed plasmonic cloak over the sensor may allow the detector to receive the signal coming from outside, but it may drastically reduce the system's overall scattered radiation, making its presence essentially undetectable.

effective dipole moment $\mathbf{p}_s$ is induced across the element for a given level of local electric field $\mathbf{E}_0$ impinging on it. A higher α_s ensures better receiving and transmitting properties for the sensor. As an example, consider a basic sensor element, depicted in the left inset of Fig. 2, which is a three-element short antenna system formed by three uncoupled, orthogonally oriented short conducting dipoles, each of them properly loaded at its center with an impedance Z_L. This may model a generic isotropic small sensor at rf or optical frequencies. Under the $e^{-i2\pi ft}$ time convention, the polarizability of a loaded short dipole may be related to its total length l and Z_L through the approximate formula [9],

$$\alpha_s = i\frac{4Z_{\rm in} + Z_L}{Z_{\rm in} + Z_L}\frac{l^2}{12\omega Z_{\rm in}}, \tag{1}$$

where $Z_{\rm in}$ is the input impedance of the dipole, available in the literature [10].

When the receiving load at the sensor gap is optimally chosen such that $Z_L = Z_{\rm in}^*$, i.e., when the sensor is *conjugate matched* with the load of the receiving circuit, the sensor may extract maximum power from the measured field. From (1), one can see that this is also the condition at which $|\alpha_s|$ is maximum, where the sensor shows large scattering cross section. In other words, a sensor that is designed to efficiently capture the power from the signal of interest is generally expected to have a large scattering, i.e., to be "visible" to its surrounding. For standard sensors, like thin dipoles or large aperture antennas, under the above condition the absorbed power (proportional to the ability of the detector to measure an impinging signal) is in general comparable with the scattered power (related to the possibility of the sensor to be detected). However, in principle, there is no upper bound for the ratio between these two quantities when a receiver is suitably designed, as it has been theoretically proven for idealized scenarios in [11,12]. We have simulated the problem of a three-element isotropic short dipole sensor with full-wave computational software. We assume, without loss of generality, that the sensor is formed by three uncoupled perfectly conducting wires of length $l = 3$ cm, radius $r = 300\ \mu$m, each with a load impedance consisting of a resistor $R = 2\ \Omega$ and a series inductor $L = 138$ nH, designed to be ideally conjugate matched with the receiving dipole at $f_0 = 1$ GHz [13]. The red dashed line in the upper panel of Fig. 2 shows the variation of the voltage induced at the sensor load (i.e., at the terminal port) versus frequency for an incident plane wave with 1 [V/m] electric field amplitude. In the lower panel, we report the corresponding maximum value of the scattering cross section (SCS) pattern from the sensor for the same excitation. These curves confirm that at the design frequency f_0, the maximum of the received voltage coincides with the peak of the maximum scattering from the sensor.

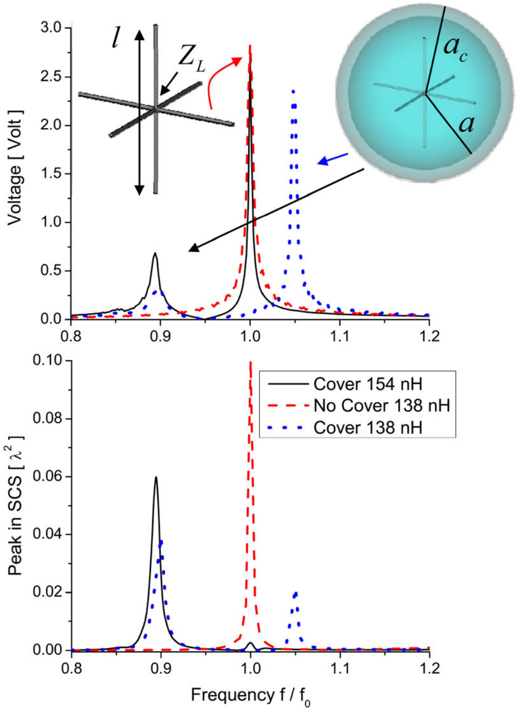

FIG. 2 (color online). Magnitude of the voltage at the sensor load (top) and maximum peak in the SCS (bottom) versus frequency, as obtained from full-wave simulations, for: a sensor made of three orthogonally crossed, electrically short, loaded dipoles (red dashed lines); the same setup, but with a suitably designed plasmonic shell around it (blue dotted lines); the same shell-covered setup, but after the load inductance has been fine tuned in order to bring the resonant frequency back to the original value f_o (black solid lines). (Only one dipole needed to be simulated for the specific polarization and angle of incidence.)

Applying the plasmonic cloaking concepts [1], imagine now to place a suitably designed plasmonic shell around the sensor, in such a way that the local electric field would induce an effective dipole moment $\mathbf{p}_c$ on the cover, with condition $\mathbf{p}_c = -\mathbf{p}_s$. This equality would ensure a zero total electric dipole moment induced on the combined system formed by the sensor and its plasmonic shell, which, due to its relatively small electrical dimensions, leads to a dramatic reduction of its total scattering and visibility. For the case at hand in the example of Fig. 2, such a cover may be realized with a plasmonic spherical shell, as depicted in the second inset of Fig. 2, with permittivity $\varepsilon_c = 0.1\varepsilon_0$ at f_0, free-space permeability μ_0, inner radius $a = 20$ mm, and outer radius $a_c = 23$ mm. These design parameters have been analytically selected by imposing the condition that in the multipole expansion of the Mie scattering from the shell-covered sensor [where the sensor is modeled with its polarizability (1)], the total electric dipole moment becomes identically zero at the resonant frequency of the dipole antenna f_0. Relatively low-loss plasmonic materials might be naturally available for these purposes at THz, infrared, and optical frequencies, and they may be synthesized as metamaterials at lower frequencies. In all our numerical simulations, we have considered a Drude model for their frequency dispersion $\varepsilon = \varepsilon_0\{1 - f_p^2/[f(f + i\gamma)]\}$, where f_p is selected in such a way to provide the required $\text{Re}[\varepsilon]$ at the design frequency f_0, and $\gamma = 5 \times 10^{-3} f_p$ takes into account of a reasonable level of absorption in the plasmonic shell.

The blue dotted lines in Fig. 2 show the numerical results for the case in which the sensor is cloaked with the plasmonic shell described above. We clearly see that the voltage peak has slightly shifted up in frequency, due to the near-field coupling between the sensor and the plasmonic shell. This certainly affects Z_{in}, and, in turn, the resonant frequency extracted from (1). Still a peak in the scattering cross section of the shell-covered sensor is present at the new resonant frequency, although the ratio between the scattering from the antenna and the detected voltage signal has been reduced due to the cover's presence. Moreover, at the original frequency for which the design was optimized, the scattering smoothly reduces to a very small value near zero. Now it is possible to fine tune the load inductance Z_L in order to bring back the detected voltage peak at the original frequency f_0 for which the cover had been optimized. This case is shown by the black solid lines in Fig. 2, for which the load inductor has been changed to $L = 154$ nH. In this scenario, despite the fact that the peak in the terminal voltage is still present and comparable in value with the induced voltage in the uncovered geometry, the SCS of the shell-covered sensor has been significantly reduced, making the cloaked sensor effectively "invisible" to an external observer, while the sensor can still efficiently detect the impinging wave. The inherent frequency dispersion of the plasmonic shell is the main factor limiting the bandwidth of operation of this cloaking technique. Indeed, we note that, as we vary the frequency of operation and correspondingly change the Drude shell permittivity, we obtain a zero-voltage scenario for $f = 0.95 f_0$ and a scattering peak at $f = 0.9 f_0$. The zero-voltage arises at the frequency for which the shell has a zero permittivity, for which the field cannot penetrate the shell, whereas the extra scattering peak is due to a plasmonic resonance due to the negative permittivity of the shell.

We have obtained full-wave analytical results for this geometry, and from our calculations, we note that the total scattering cross section (overall visibility) of the cloaked sensor can in principle be reduced by more than 1500 folds (~32 dB reduction) with respect to the case of a bare sensor, effectively making the sensor "invisible" to its surrounding even at its resonant frequency. These results fully take into account the power absorbed by the shell-covered sensor's load, which is indeed responsible for the small residual scattering cross section of the whole structure. Moreover, we have verified analytically that the total scattered power can ideally become less than 1% of the power received at the load. The presence of moderate losses in the shell material does not noticeably affect these results since the cloak is inherently nonresonant [2]. Indeed, the small residual absorption in the shell may even help further in reducing the visibility and disturbance of the sensor.

To gain further insights into this phenomenon, Fig. 3 reports the real part of the Poynting vector distribution on the E plane for this geometry, both for the covered and uncovered cases, under plane wave incidence (traveling from bottom to top in the figures) at f_0. Figure 4 reports the corresponding far-field scattering patterns. From Fig. 3, it is clearly observed that for the bare sensor, the Poynting vector is strongly perturbed by the presence of the resonant sensor. However, when our properly designed plasmonic shell is positioned around the sensor, the planar wave fronts and straight flow of Poynting vector are restored. This results in much reduced scattering from the cloaked sensor, which however does not deteriorate the capability of the inner dipole to receive the outside signal, as evident from the power flow inside the cloak and from the voltage peak in Fig. 2, making this solution quite different from the minimum-scattering antennas presented in the literature [9–12]. The residual scattering in Fig. 4(b) is only due to the absorption at the load and minor absorption in the shell, which generates a residual small "shadow" along the positive y axis (direction of propagation of the incident plane wave). This is totally consistent with the theoretical results for the antenna designs, presented in [11], which have generally shown that the possibility of reducing the ratio between scattered power from and power received by

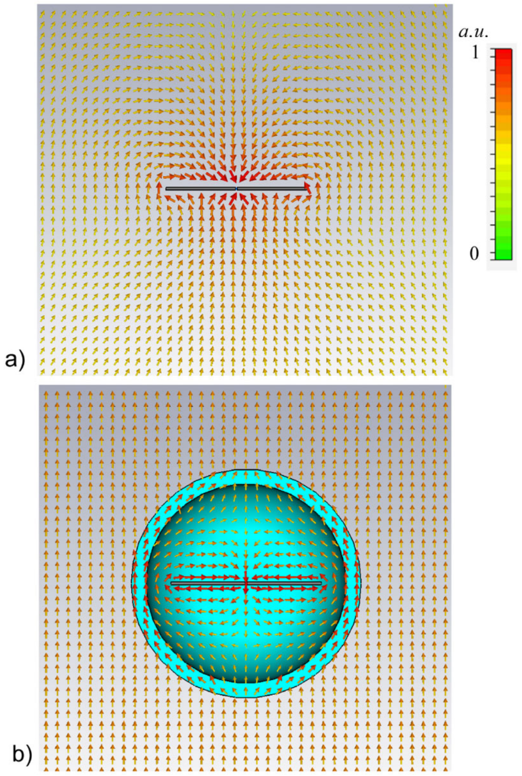

FIG. 3 (color online). Power flow distribution in the E plane for (a) bare sensor (red dashed lines in Fig. 2) and (b) the shell-covered sensor (black solid line) at the resonant frequency f_0.

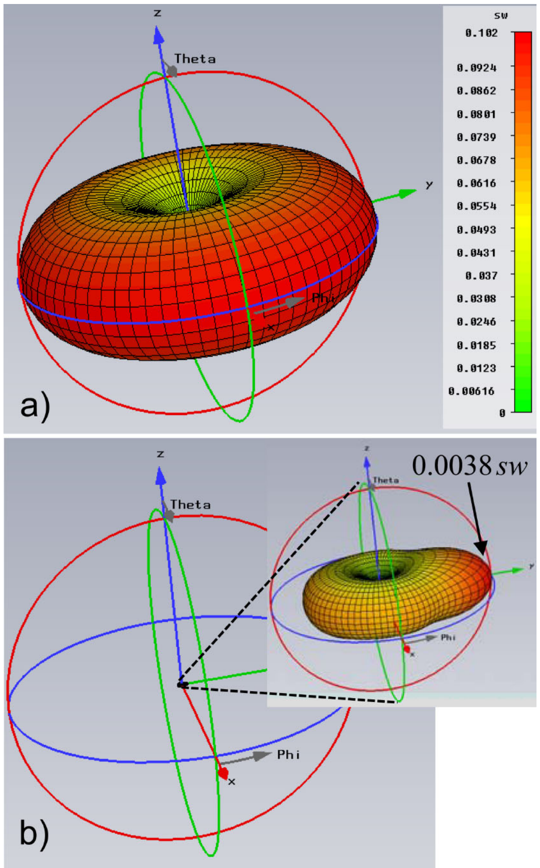

FIG. 4 (color online). Far-field SCS patterns with no cover (a) and with the shell cover, using the same scale (b). In the inset, we show the pattern (b) normalized to its peak value.

a given sensor is strictly associated with the capability of designing a directive scattering pattern pointing towards the back direction. The plasmonic cloak proposed here has the interesting property of automatically reshaping the scattering pattern from the sensor, significantly reducing the scattering in all directions and leaving a single, more directive, and very low-scattering beam that points towards the back of the sensor, representing the very small "shadow" associated with the cloaked sensor's absorption. This drastic reduction is independent of the direction of the incident plane wave, thus making the cloaked sensing system isotropic and independent of the wave polarization, shape of the phase fronts, and direction of the incoming signal. Compared to other examples of minimum-scattering antennas, this setup has two clear advantages: (1) the simplicity of the design, which does not require complicated circuit networks or loads, and whose conceptual idea may be scaled to infrared and optical frequencies; (2) while the minimum-scattering antennas previously proposed in the literature may indeed achieve a large ratio between absorbed and scattered power, this is often done at the expense of a low absolute level of absorbed power. These low-scattering antennas are usually mismatched, making them less useful as sensors. However, as Fig. 2 shows, the plasmonic shell proposed here may drastically reduce the unwanted scattering without requiring mismatch, which may be tailored to receive similar levels of power with much reduced scattering.

We have also performed full-wave simulations for the sensor employed as a transmitting antenna. As expected by reciprocity, also in its transmit operation, the cloaked sensor would properly operate and its radiation properties are consistent with those reported above; i.e., such a device, when suitably cloaked, is able to receive and transmit signal from and to its surrounding through the cloak shell, without notably perturbing the field distribution impinging on it.

It should be emphasized that the design geometry presented here should be considered just as an example of the broadly appealing potentials of this measurement technique. For instance, in biomedical applications, an NSOM tip may be covered by a suitably designed thin plasmonic layer, which may substantially reduce the disturbance of the tip to its near-field measurement. We envision various innovative potential applications of these "invisible sensors" in numerous fields, such as medicine, biology, physics, and engineering.

---

*To whom correspondence should be addressed: engheta@ee.upenn.edu
†alu@mail.utexas.edu

[1] A. Alù and N. Engheta, Phys. Rev. E **72**, 016623 (2005).
[2] A. Alù and N. Engheta, Opt. Express **15**, 3318 (2007).
[3] A. Alù and N. Engheta, Phys. Rev. Lett. **100**, 113901 (2008).
[4] J. B. Pendry, D. Schurig, and D. R. Smith, Science **312**, 1780 (2006).
[5] D. Schurig *et al.*, Science **314**, 977 (2006).
[6] W. Cai, U. K. Chettiar, A. V. Kildishev, and V. M. Shalaev, Nat. Photon. **1**, 224 (2007).
[7] G. W. Milton and N. A. Nicorovici, Proc. R. Soc. A **462**, 3027 (2006).
[8] U. Leonhardt, Science **312**, 1777 (2006).
[9] S. A. Tretyakov, S. Maslovski, and P. A. Belov, IEEE Trans. Antennas Propag. **51**, 2652 (2003).
[10] R. W. P. King and C. W. Harrison, *Antennas and Waves: A Modern Approach* (MIT Press, Cambridge, MA, 1969).
[11] J. Bach Andersen and A. Frandsen, IEEE Trans. Antennas Propagat. **53**, 2843 (2005).
[12] W. K. Kahn and H. Kurss, IEEE Trans. Antennas Propagat. **13**, 671 (1965).
[13] This choice of f_0 is completely arbitrary. Moreover, the chosen geometry simply models a basic sensor, which should not limit the generality of this idea. The concepts described here may be applied to different classes of sensors, at microwave and optical frequencies. The specific features of such cloaking of a sensor or detector at the optical frequencies will be reported in a future publication.