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(71) Applicant (for all designated States except US): **THE TRUSTEES OF THE UNIVERSITY OF PENNSYLVANIA** [US/US]; 3160 Chestnut Street, Suite 200, Philadelphia, PA 19104-6283 (US).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **ALU, Andrea** [IT/US]; 201 Lavaca Street, Apartment 315, Austin, TX 78701 (US). **ENGHETA, Nader** [US/US]; 2077 Fox Creek Road, Berwyn, PA 19312 (US).

(74) Agents: **CALDWELL, John, W.** et al.; Woodcock Washburn LLP, Cira Centre, 12th Floor, 2929 Arch Street, Philadelphia, PA 19104-2891 (US).

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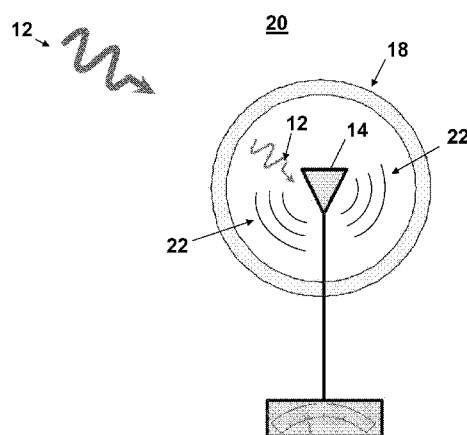


FIGURE 2

(57) Abstract: A cloaked sensing system renders a sensor essentially undetectable in a predetermined spectrum without degrading the detection capability of the sensor in the predetermined spectrum. A shield placed around the sensor allows an unattenuated, signal to reach the sensor, and cancels scattering of the signal from the sensor within the shield. Thus, the shield drastically reduces scattering from a sensor (rendering the sensor essentially invisible), without affecting the sensor's ability to receive and detect the incoming signal. In an example configuration, the shield may comprise relatively simple plasmonic materials available in nature for infrared and optical frequencies, or metamaterials for lower frequencies. The result is a cloaked sensing system that can receive a signal, while the sensor's presence is not easily perceived by its surroundings due to much lowered scattered radiation.



CLOAKED SENSOR

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] The instant application claims priority to U.S. Provisional Application No. 61/164,610, filed March 30, 2009, entitled “Cloaked Sensor” which is hereby incorporated by reference in its entirety.

TECHNICAL FIELD

[0002] The technical field generally relates to sensing devices and more specifically relates to a cloaked sensing device that essentially cancels scattered energy from the sensor while maintaining detection performance of the sensor.

BACKGROUND

[0003] Current techniques aimed at making an object unobservable (invisible) within a specific electromagnetic spectrum either attenuate electromagnetic energy prior to striking the object or bend electromagnetic energy around the object. A problem with these cloaking techniques is that the object is not exposed to the electromagnetic energy in unaltered form. This is especially significant if the object is a sensor designed to sense the electromagnetic energy.

SUMMARY

[0004] A cloaked sensing system renders a sensor essentially undetectable in a predetermined spectrum without degrading the detection capability of the sensor in the predetermined spectrum. A shield placed around the sensor allows an unattenuated signal to reach the sensor and cancels scattering of the signal from the sensor within the shield. Thus, the shield drastically reduces scattering from a sensor (rendering the sensor essentially invisible), without affecting the sensor's ability to receive and detect the incoming signal. In an example configuration, the shield comprises plasmonic materials that are available in nature for infrared

and optical frequencies, or appropriately configured metamaterials for lower frequencies. The result is a cloaked sensing system that can receive a signal, while the sensor's presence is not easily perceived by its surroundings due to much lowered scattered radiation. The cloaked sensing system can be utilized for electromagnetic sensors and acoustic sensors. Various applications in which the cloaked sensing system is applicable include biology, medicine, physics, and engineering.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] The foregoing summary, as well as the following detailed description, is better understood when read in conjunction with the appended drawings.

[0006] Figure 1 is an example diagram of energy being scattered from a sensor as a result of an impinging signal.

[0007] Figure 2 is a diagram of an example cloaked sensor system comprising a shield and a sensor.

[0008] Figure 3 is an illustration of an example three-element dipole antenna.

[0009] Figure 4 is an illustration of example graphs depicting simulated results of cloaking a three element dipole sensor with an appropriate shield.

[0010] Figure 5 is an illustration of an example three dipole antenna within an example spherical shield.

[0011] Figure 6 depicts a snapshot in time of the magnetic field in the E plane field distribution for a bare sensor with no shield.

[0012] Figure 7 depicts a snapshot in time of the electric field in the H plane of a bare sensor with no shield.

[0013] Figure 8 depicts a snapshot in time of the magnetic field in the E plane field distribution with a shield placed around a sensor.

[0014] Figure 9 depicts a snapshot in time of the electric field in the H plane with a shield placed around a sensor.

[0015] Figure 10 depicts the power flow in the E plane of a bare sensor with no shield.

[0016] Figure 11 depicts the far field scattering cross section of a bare sensor with no shield.

[0017] Figure 12 depicts the power flow in the E plane with a shield placed around a sensor.

[0018] Figure 13 depicts the far field scattering cross section with a shield placed around a sensor.

[0019] Figure 14 depicts field distributions showing a snapshot in time of the tangential electric field distribution in the E plane of a bare sensor without a shield and a snapshot in time of the tangential electric field distribution in the E plane of a sensor with a shield placed therearound.

[0020] Figure 15 depicts field distributions showing a snapshot in time of the tangential magnetic field distribution in the H plane of a bare sensor without a shield and a snapshot in time of the tangential magnetic field distribution in the H plane of a sensor with a shield placed therearound.

[0021] Figure 16 depicts power flow distributions depicting the real part of the Poynting vector distribution in the H plane of a bare sensor without a shield and the real part of the Poynting vector distribution in the H plane of a sensor with a shield placed therearound.

[0022] Figure 17 depicts a graph of scattering cross section versus frequency for an uncloaked aluminum NSOM tip compared with the same tip covered by a thin plasmonic cloaking layer.

[0023] Figure 18 depicts near-field plots of the NSOM tips of Figure 17.

[0024] Figure 19 contains three plots depicting the amplitude of a magnetic field on the E plane.

[0025] Figure 20 illustrates a comparison of the sampled images scanned in the setup of Figure 19 by an ideal mathematical probe, and the bare (uncloaked) tip and the cloaked tip of Figure 17.

[0026] Figure 21 illustrates near-field distributions and far-field distributions for a specific tip geometry.

[0027] Figure 22 depicts simulated results for the same setup as in Figure 21, but with a passive nanodipole and an emitting molecule placed at the NSOM aperture.

[0028] Figure 23 illustrates plots of calculated absorbed, scattered, and extracted power for an absorbing molecule/material/receiver, for various thicknesses of a cloaking layer that surrounds the molecule/material/receiver.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

[0029] A cloaked sensing system, comprising a plasmonic material or metamaterial shield, drastically reduces the overall scattering from an object via scattering cancellation. Plasmonic material, or plasmonic metamaterial, is used herein to refer to materials that are characterized electromagnetically by a low or negative permittivity (natural and/or effective permittivity), leading to properties analogous to those of natural plasma or plasmon-like materials, *i.e.*, noble metals, polaritonic dielectrics or ionosphere. Metamaterial is used to refer to an artificially man-made material with electromagnetic properties that are not naturally or readily available at the frequency of interest and that are not shared by any of the constituents of the composite material.

[0030] The cloaked sensing system renders an object within the shield essentially undetectable or unobservable (invisible) from the perspective of an observer outside of the shield. Thus, the observer is able to “see behind” the cloaked region without noticing its presence at a frequency of interest. The cloaked object is not isolated from its external surroundings. Rather, a non-zero field, proportional to the incoming signal, is induced inside the shield. Because the sensor is not isolated from its external surroundings, the cloaked sensor can still sense the presence of the external world, even though its scattered fields are dramatically reduced, if not eliminated, by the shield. This cloaking technique is based on cancellation and reduction of the total scattering from the object. The object to be cloaked and the cloaking shield

each are detectable when standing alone and isolated. But, when the shield and object are together their scattered fields add destructively, resulting in significant reduction of scattering, and thus inducing the cloaking effect (invisibility).

[0031] Applications of the cloaked sensor are numerous. Various sensors, such as, for example, mobile phone antennas, BLUETOOTH devices, probes, and the like, can be cloaked such that use of the sensors will not disturb the surrounding environment. For example, a passive RADAR sensor within the shield can receive and detect incoming RADAR signals, while the source of the RADAR signals will not be able to detect the cloaked sensor. Thus, the source of the RADAR signals will not know it is being detected. The cloaked sensor can be utilized in biological and medical applications to obtain less perturbed measurements. The cloaked sensor can be utilized in physics and engineering experiments. For example, a probe, such as a near-field scanning optical microscope (NSOM), or the like, can be utilized to have minimal disturbing effect on the quantity it is designed to measure.

[0032] Figure 1 is an example diagram of scattered energy 16 being scattered from sensor 14 as a result of impinging signal 12. As depicted in Figure 1, an observer will be able to “see” the sensor 14 via the scattered energy 16. That is, a detector capable of detecting the scattered energy will be able to detect the presence of the sensor 14, via detection of the scattered energy 16. The observer, as depicted, is not limited to a person, but represents any appropriate entity capable of detecting the scattered energy 16. For example, the observer could be another sensor configured to detect the scattered energy 16.

[0033] Figure 2 is a diagram of an example cloaked sensor system 20 comprising a shield 18 and the sensor 14. As shown in Figure 2, the signal 12 is able to travel through the shield 18 and be detected by the sensor 14. The signal 12 travels through the shield 18 essentially unattenuated. Thus, the signal strength and quality of the signal 12 are preserved while traveling through the shield 18. In an example embodiment, characteristics of the signal 12 (*e.g.*, signal strength, quality, etc.) after traveling through the shield 18 are essentially the same as the characteristics of the signal just prior to traveling through the shield 18. Accordingly, the sensor 14 detects the signal 12 with some of the characteristics equivalent to a signal 12 that did not travel through shield 18.

[0034] The shield 18 is configured to cancel energy 22 scattered from the sensor 14. As the scattered energy 22 reaches the shield 18, the physical configuration and plasmonic and/or metamaterial composition of the shield 18 result in destructively interacting with the scattered energy 22 to cancel the scattered energy 22. Thus, essentially no scattered energy 22 escapes from within the shield 18.

[0035] To describe how the shield 18 is capable of canceling the scattered energy 22, it is assumed, for the purpose of this explanation, that the sensor 14 is small enough that, as for any small scatterer, the scattered energy can be characterized by its own polarizability, α_s , which determines the degree at which an effective dipole moment, $\mathbf{p}_s$, is induced across the sensor 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. For example, consider a basic detector element (sensor) 24, depicted in Figure 3, which is a three-element short antenna system formed by three uncoupled dipole elements 26, 28, 30, orthogonally oriented short conducting dipoles, each properly loaded at its center with an impedance Z_L . The sensor 24 represents a model of a generic isotropic small sensor at RF (radio frequencies) or optical frequencies. Under the $e^{-i2\pi ft}$ time convention, the polarizability, α_s , of the loaded short dipole sensor 24 is related to its total length l and Z_L through equation (1) below.

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

where Z_{in} is the input impedance of the sensor 24, α_s represents the polarizability of the system, which effectively represents the scattered energy from the sensor 24, Z_L is the load impedance at the center of the sensor 24, l is the length of each dipole element (26, 28, 30), ω is equal to $2\pi f$, where f is an operating frequency of interest (resonant frequency) to the sensor 24, and i is imaginary unit (also referred to as “j” and equal to the square root of minus 1, $\sqrt{-1}$).

[0036] As is known, when $Z_L = Z_{in}^*$, (Z_L = the complex conjugate of Z_{in}), then the sensor is conjugate-matched with the load of the receiving circuit and the sensor extracts the maximum power from the measured field. From equation (1), it can be seen that this also is the condition at which $|\alpha_s|$ (the absolute value of α_s) is maximum. This also is the condition under which the sensor 24 exhibits its largest scattering cross section. In other words, a sensor that is

designed to efficiently capture the power from the signal of interest is usually expected to have a large scattering, and thus be “visible” to its surrounding. However, appropriately configuring and placing the shield 18 around the sensor 24 preserves the sensor’s ability to efficiently capture the power from the signal of interest and cancel scattering, thus rendering the sensor invisible to its surroundings.

[0037] For standard sensors, like thin dipoles or large aperture antennas, under the above conditions, the absorbed power (proportional to the ability of the sensor to measure an impinging signal) is in general equal to the scattered power (related to the possibility of the sensor to be detected). In principle, there is no upper bound for the ratio between these two quantities (absorbed power over the scattered power) when a receiver is suitably designed. Appropriately applying the shield 18 of the cloaked sensing system 20, in an example embodiment, minimizes the visibility of a given sensor without affecting its capability to detect an impinging signal.

[0038] Example configurations and material compositions for the shield 18 are described in U.S. Patent No. 7,218,190, entitled “Waveguides And Scattering Devices Incorporating Epsilon-Negative And/Or Mu-Negative Slabs,” which is hereby incorporated by reference in its entirety. Also, an example analysis of how the shield 18 can reduce total scattering cross section of cylindrical and spherical objects is described in an article entitled “Achieving Transparency With Plasmonic And Metamaterial Coating,” authored by Andrea Alù and Nader Engheta, published in The Physical Review E 72, 016623 (2005), which is hereby incorporated by reference in its entirety.

[0039] As a brief overview, the shield of the cloaked sensor system comprises a plasmonic material and/or metamaterial. In an example configuration, the shield comprises a plasmonic material for infrared and optical frequencies, or a metamaterial for lower frequencies. The shield functions as a passive shield, or cover, comprising low-loss, or in the limit, no-loss materials.

[0040] In an example configuration the shield comprises materials with negative or low electromagnetic constitutive parameters (*e.g.*, metals near their plasma frequency or metamaterials with negative parameters). Several noble metals achieve this requirement for their electrical permittivity at the infrared (IR) or visible regimes, even with reasonably low losses. At

lower frequencies, artificial materials and metamaterials can be synthesized to meet similar requirements at the desired frequency. Total scattering cross section of spherical objects having dimensions comparable with the wavelength of operation are drastically reduced via utilization of the plasmonic and/or metamaterial shield having negative or low-permittivity and/or permeability.

[0041] For a description of devices incorporating epsilon-negative and/or mu-negative slabs, see U.S. Patent number 7,218,190, which is hereby incorporated by reference in its entirety.

[0042] Figure 4 shows two graphs 32, 34, indicating the simulated results of cloaking a three element dipole sensor (*e.g.*, sensor 24) with an appropriate shield. The sensor, as modeled, comprised three uncoupled perfectly conducting wires of length $l = 3\text{ cm}$, and radius $r = 300\text{ }\mu\text{m}$, each with a load impedance having a resistance, $R = 2\text{ }\Omega$, and a series inductance, $L = 138\text{ nH}$, designed and optimized to be conjugate-matched with the receiving dipole at $f_0 = 1\text{ GHz}$ (20).

[0043] Graph 32 depicts the magnitude of the voltage at the sensor load. The curves in graph 32 show 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, and polarized parallel with the dipole. Curve 36 depicts the magnitude of the voltage at the sensor load without a shield around the sensor. Curve 38 depicts the magnitude of the voltage at the sensor load where a suitably designed plasmonic shield is placed around the sensor. Curve 40 depicts the magnitude of the voltage at the sensor load where the plasmonic shield is placed around the sensor and the inductance of the sensor was fine-tuned to bring the resonant frequency back to the original value of f_0 .

[0044] Graph 34 depicts the corresponding maximum value of the scattering cross section pattern from the sensor for the same excitation is shown in graph 32. Graph 34 depicts the scattering cross section per square wavelength (λ^2) versus frequency. Curve 42 depicts the scattering cross section without a shield around the sensor. Curve 44 depicts the scattering cross section where a suitably designed plasmonic shield is placed around the sensor. Curve 46 depicts the scattering cross section where the plasmonic shield is placed around the sensor and

the inductance of the sensor was fine-tuned to bring the resonant frequency back to the original value of f_0 . These curves confirm that, at the design frequency f_0 , with appropriately configured shield the scattering from the sensor has been substantially reduced.

[0045] In an example configuration, the plasmonic shield is placed around the sensor in such a way that the local electric field induces an effective dipole moment $\mathbf{p}_c$ on the shield, with condition $\mathbf{p}_c = -\mathbf{p}_s$. This equality ensures a zero total electric dipole moment induced on the combined system formed by the sensor and its plasmonic shield, which, due to its relatively small electrical dimensions, leads to a dramatic reduction of its total scattering and visibility. As shown in Figure 5, such a shield can be realized with a plasmonic spherical shield, with permittivity $\varepsilon_c = 0.1\varepsilon_0$ at f_0 , inner radius $a = 20\text{ mm}$ and outer radius $a_c = 23\text{ mm}$. These analytically selected design parameters are a result of imposing the condition that in the multipole expansion of the Mie scattering from the shield-covered sensor (where the sensor is modeled with its polarizability as described in Equation (1)) the total electric dipole moment becomes identically zero at the resonant frequency of the dipole antenna, f_0 . In example configurations, relatively low-loss plasmonic materials are used for these purposes at THz, infrared, and optical frequencies, and synthesized as metamaterials are utilized for lower frequencies. The results depicted in Figure 4 take into consideration the frequency dispersion of these materials using a Drude model with appropriate and reasonable Ohmic losses included. Reasonable Ohmic losses and frequency dispersion weakly affect the main features of this non-resonant cloaking mechanism.

[0046] The condition $\mathbf{p}_c = -\mathbf{p}_s$ can be achieved by making use of appropriately configured metamaterial and/or plasmonic shells. Provided that their effective permittivity is low positive or negative, the induced wave polarization in the shell is opposite to that of the sensor, and therefore a proper choice of the shell volume may provide total cancellation of the overall scattering from the combination of the shell and the sensor. Following this design principle, one may be able to achieve a design guideline for a cloaked sensor with drastic scattering reduction, compared to the bare sensor.

[0047] The plasmonic shell can be configured in accordance with numerous possible configurations. For example, if natural materials with the required low or negative permittivity are available at the frequency of interest, the shell can be designed by choosing the volume of a

cover made of such material, in such a way to cancel out the overall dominant scattering order from the object (i.e., by canceling the dominant multipoles). In the case of a spherical scatterer of radius a for instance, composed of a homogeneous material with permittivity, ϵ , and permeability μ , surrounded by free space (with constitutive parameters ϵ_0 and μ_0) the required shell with permittivity ϵ_c and permeability μ_c should be designed to have a radius $a_c > a$ satisfying the following design condition:

$$\begin{vmatrix} j_n(ka) & j_n(k_c a) & y_n(k_c a) & 0 \\ [ka j_n(ka)]' / \epsilon & [k_c a j_n(k_c a)]' / \epsilon_c & [k_c a y_n(k_c a)]' / \epsilon_c & 0 \\ 0 & j_n(k_c a_c) & y_n(k_c a_c) & j_n(k_0 a_c) \\ 0 & [k_c a_c j_n(k_c a_c)]' / \epsilon_c & [k_c a_c y_n(k_c a_c)]' / \epsilon_c & [k_0 a_c j_n(k_0 a_c)]' / \epsilon_0 \end{vmatrix} = 0,$$

where $k \equiv \omega\sqrt{\epsilon\mu}$, $k_c \equiv \omega\sqrt{\epsilon_c\mu_c}$ and $k_0 \equiv \omega\sqrt{\epsilon_0\mu_0}$ are the wave numbers in the three regions and $j_n(\cdot)$, $y_n(\cdot)$ are spherical Bessel functions. $[\cdot]'$ denotes differentiation with respect to the argument of the relevant spherical Bessel functions, in such a way to cancel the dominant scattering order n .

[0048] This means that if the sensor may be modeled as a dielectric sphere with (complex) permittivity ϵ and radius a , which is tailored to partially absorb the impinging energy, then we can design the suitable cloak geometry to be a conformal spherical shell with thickness $a_c - a$ and proper effective permittivity ϵ_c , tailored to comply with the previous equation. This condition may be seen as a design rule for the cloak in this idealized example.

[0049] When natural materials are not available with the desired electromagnetic properties, metamaterial technology can be applied in order to construct such materials. Several configurations for artificial materials that give rise to the required effective electromagnetic properties are possible, depending on the frequency of operation. (For example, for radio frequencies, embedding small metallic wires and/or metallic loops in a host medium can be considered as one possible technique.) Currently available technology at microwave or optical frequencies can be applied to synthesize the desired effective permittivity and/or permeability for the metamaterial, following the above condition for the choice of the cloak volume.

[0050] Curves 38 and 44 in Figure 4 depict the results for the case in which the sensor is cloaked with the plasmonic shield described above. As can be seen, the voltage peak has slightly shifted up in frequency due to the near-field coupling between the sensor and the plasmonic shield. This affects Z_{in} and in turn, the resonant frequency extracted from Equation (1). Yet, a peak in the scattering cross section of the shield-covered sensor is present at the new resonant frequency, although the ratio between the scattering from the antenna and the detected voltage signal is reduced due to the shield's presence. Moreover, at the original frequency for which the design was optimized, the scattering reduces smoothly to zero.

[0051] The load inductance, Z_L , was adjusted to bring back the detected voltage peak at the original frequency f_0 for which the shield had been optimized. In this case, the load inductance was adjusted from 138 nH (results depicted in curves 38 and 44 of Figure 4) to 154 nH (results depicted in curves 40 and 46 of Figure 4). 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 scattering cross section of the shield-covered sensor was significantly reduced, making the cloaked sensor effectively "invisible" to an external observer, while the sensor can still efficiently detect the impinging wave. In other words, around the design frequency the optimized shield-covered sensor can efficiently measure and observe the signal with very little scattering, and thus without disturbing its environment, and without being perceived by any external observer. The inherent frequency dispersion of the plasmonic shield is a factor limiting the bandwidth of operation of this cloaking technique. As the frequency of operation is varied, resulting in a correspondingly change in the Drude-like shell permittivity, a zero-voltage scenario was obtained for $f = 0.95f_0$ and a scattering peak at $f = 0.9f_0$. The zero-voltage arises at the frequency for which the shield has a zero permittivity (at the plasma frequency of the shield material), for which the field cannot penetrate the shield, whereas the extra scattering peak is due to a plasmonic resonance due to the negative permittivity of the shield at this lower frequency.

[0052] Full-wave analytical results for this geometry indicate that the total scattering cross section (overall visibility) of the cloaked sensor is reduced by more than 1,500 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 shield-covered sensor's load, which is responsible for the small residual

scattering cross section of the whole structure. The presence of moderate losses in the shield material does not noticeably affect these results, since the shield is inherently non-resonant.

[0053] Results of the full-wave numerical simulations of the field distributions at the operating frequency, f_0 , are shown in Figure 6 through Figure 13. Figure 6 through Figure 13 depict snapshots in time of the near-field magnetic field on the E plane, electric field on the H plane, and the real part of the Poynting vector (*i.e.*, time-averaged power flux) distributions on the E plane, together with the far-field scattering pattern, for the aforementioned geometry, both for the covered and uncovered cases, under plane wave incidence (traveling from bottom to top in Figures 6 through Figure 13) at frequency f_0 . Figure 6 depicts a snapshot in time of the magnetic field in the E plane field distribution for the bare sensor with no shield. Figure 8 depicts a snapshot in time of the magnetic field in the E plane field distribution with the shield placed around the sensor. Figure 7 depicts a snapshot in time of the electric field in the H plane of the bare sensor with no shield. Figure 9 depicts a snapshot in time of the electric field in the H plane with a shield placed around the sensor. Figure 10 depicts the power flow (real part of the Poynting vector) in the E plane of the bare sensor with no shield. Figure 12 depicts the power flow (real part of the Poynting vector) in the E plane with a shield placed around the sensor. Figure 11 depicts the far field scattering cross section of the bare sensor with no shield. And, Figure 13 depicts the far field scattering cross section with a shield placed around the sensor.

[0054] As can be seen in Figure 6 through Figure 13, for the bare sensor, the field distributions and Poynting vector are strongly perturbed by the presence of the resonant sensor. However, when an appropriately designed plasmonic shield is positioned around the sensor, the planar wave fronts and straight flow of Poynting vector are restored. Such restoration of phase front and reduction of the scattering from the shield-covered sensor does not deteriorate the capability of the inner dipole to receive the outside signal, as evident from the distributions inside the cloak and from the voltage peak still present as shown in Figure 6 through Figure 13. The comparison of the radiation patterns also confirms the drastic reduction of scattering from the object, which in the shield-covered case is drastically different both in amplitude (notice the different scales in the two panels) and in shape. In particular, the residual scattering in Figure 13 is due to the small absorption at the load and in the shield, which generates a residual small “shadow” along the positive y axis (direction of propagation of the incident plane wave). This is consistent with theoretical results for the antenna designs, which have generally shown that the

possibility of reducing the ratio between the scattered power from, and the absorbed power by, a given antenna is strictly associated with the capability of designing a very directive scattering pattern pointing towards the back direction. The plasmonic shield, as described herein, has the interesting property of automatically reshaping the scattering pattern from the sensor, suppressing the scattering in all directions, and leaving a single sharp, directed, 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 suppression is independent of the direction of the incident plane wave, thus making the cloaked sensing system completely isotropic.

[0055] Figure 14 depicts field distributions 48, 50. The field distribution 48 depicts a snapshot in time of the tangential electric field distribution in the E plane of the bare sensor without a shield. The field distribution 50 depicts a snapshot in time of the tangential electric field distribution in the E plane of the sensor with a shield placed therearound. Figure 15 depicts field distributions 52, 54. The field distribution 52 depicts a snapshot in time of the tangential magnetic field distribution in the H plane of the bare sensor without a shield. The field distribution 54 depicts a snapshot in time of the tangential magnetic field distribution in the H plane of the sensor with a shield placed therearound. Figure 16 depicts two power flow distributions 56, 58. The power flow distribution 56 depicts the real part of the Poynting vector distribution in the H plane of the bare sensor without a shield. The power flow distribution 58 depicts the real part of the Poynting vector distribution in the H plane of the sensor with a shield placed therearound. A comparison of Figures 14, 15, and 16, confirms the striking reduction of visibility for the sensor in both planes of polarization, despite its unreduced capability of detecting the impinging signal. These distributions also demonstrate the “tunneling” of electromagnetic waves through the cloaked sensing system, together with the restoration of the planar wave phase fronts immediately outside the cloak surface on both planes of polarization, despite the sensor’s absorption.

[0056] The herein described cloaking phenomenon is relatively robust to variations in the sensor geometry, in its design parameters, and in the design frequency and possible presence of losses, as it pertains to scattering reduction. Moreover, the herein described results are totally independent of the form of excitation, since for any excitation an appropriate Mie expansion may be applied. The overall robustness of the invisible sensor is evident from the results depicted in the Figures herein, for which the reduction of visibility has a smooth behavior as a function of frequency, and the effectiveness of the shield around the design frequency is not significantly

influenced by a variation in the matching features of the sensor, like a change in its load impedance. An observer seated near the cloaked sensor would simply “see behind” the cloak without perceiving the presence of a sensor, even though the sensor’s detecting abilities remain excellent.

[0057] Full-wave simulations have been conducted for the dipole sensor employed as a transmitting antenna. As expected by reciprocity, also in its transmit operation the cloaked sensor will properly operate and its radiation properties are consistent with those described above. Thus, a transmitting sensor, when appropriately cloaked, is able to receive and transmit a signal from and to its surroundings through the cloak shield, without notably perturbing the field distribution impinging on it.

[0058] In an example embodiment, the cloaked sensor system is applied to a near-field scanning optical microscope (NSOM). Far-field optical microscopes are inherently limited, by diffraction, to resolve details larger than several hundred nanometers in size. However, biology, medicine, and nanotechnology measurements, for example, often require imaging of much smaller details, up to the scale of few individual atoms. In this case, near-field imaging can be accomplished by bringing an NSOM tip close to the subject of interest to overcome the limits of far-field optics. But an NSOM can inherently perturb its own optical measurement. Accordingly, the cloaked sensor system is applied to NSOM devices in collection mode. As described herein and substantiated via full-wave numerical simulations, a properly designed plasmonic cloak placed around NSOM tips operates to capture an optical signal and can drastically improve overall tip measurement capabilities. Example improvements are shown for surface-plasmon polariton propagation and optical nanoantenna radiation.

[0059] NSOM measurements are used for resolving the sub-wavelength details, such as of complex images. As known, NSOMs can be operated in two distinct modes: aperture-less and aperture-mode. In the aperture mode, the opening of the NSOM tip is used to collect and/or illuminate the subwavelength detail of objects of interest, whereas in the aperture-less operation a sharp tip is used as a resonant scatterer to enhance and focus light on the sub-wavelength detail of interest. Aperture-less NSOMs also can be used in conjunction with collection of quantum dots localized on the tip to illuminate the detail of interest. Although the aperture-less method may ensure a smaller tip size and a larger scattering enhancement for small objects, which results in overall higher resolution, presently, the aperture mode remains more popular, due to its

flexibility and simplicity of operation. In collection mode, the aperture, a few tens of nanometers wide, is essentially used as a stethoscopic probe to capture a small amount of light scattered by the object to be imaged.

[0060] In an example embodiment of a cloaked NSOM tip in the collection mode, i.e., in the aperture mode configuration, for non-invasive near-field imaging, a wide range of metallic materials are usable in conjunction with an aperture tip, wherein the cover (shield) surrounding the opening aperture facilitates confinement of the received signal from the object and guides it towards the optical fiber connected to the tip with open aperture. Resolutions up to the order of $20 \div 50 \text{ nm}$ may be successfully achieved within this operation.

[0061] Properly designed plasmonic layers covering conducting or dielectric objects can produce a scattering cancellation effect that induces invisibility and cloaking of moderately sized objects. This cancellation effect can be utilized to counteract the inherent drawbacks of near-field measurements in which the proximity of a metallic tip induces a disturbance that can produce artifacts in an image. Plasmonic cloaking can allow field penetration and sensing inside the cloak (cover, shield), while maintaining very low scattering and independence of functionality for different polarization and angles of incidence. A suitably designed plasmonic cloak can cloak a sensor without affecting its overall capability to extract a significant level of signal and sense its surrounding. As described in more detail herein, application of a plasmonic cloak to an NSOM in the collection mode suppresses the scattering and unwanted disturbance from an NSOM aperture tip in collection mode for near-field optical measurements.

[0062] Figure 17 depicts a graph of scattering cross section (vertical axis) versus frequency (horizontal axis) for an uncloaked aluminum NSOM tip 60 with an aperture compared with the same tip with aperture covered by a thin plasmonic cloaking layer 62. Solid lines 64 and 68 refer to plane wave incidence normal to the aperture, and dashed lines 66 and 70 refer to plane wave incidence from the side of the tip. The bare (uncloaked) 60 and cloaked 62 geometries are also depicted. The tip depicted is a spherical aluminum tip of diameter $2a = 150 \text{ nm}$ with a circular aperture at its bottom of diameter $2d = 30 \text{ nm}$. The aperture represents the end of a conical aperture carved in metal, which is designed to carry the signal into an optical fiber connected at the back of the spherical tip. The aperture size is associated with the maximum resolution of the instrument. Although the tip is constructed of aluminum, various metals can be used. The choice of aluminum, here is arbitrary.

[0063] The total scattering cross-section, labeled on the vertical axis as SCS [λ_0^2], was evaluated using finite-integration commercial software, of the isolated aluminum tip. For this calculation, realistic dispersion for the aluminum permittivity reported in the literature was used, including realistic frequency dispersion and losses. It is evident that the aluminum tip, despite its sub-wavelength size, has a non-negligible scattering cross section at optical wavelengths. The shell (cloak) of the cloaked tip 62 utilizes a plasmonic cloak having permittivity $\epsilon_c \sim 0.1 \epsilon_0$ and thickness $t = 13 \text{ nm}$. The cloak was tailored to provide minimum scattering at $f = 500 \text{ THz}$, and its permittivity is assumed to have a proper frequency dispersion following a Drude model with $\epsilon_c = \epsilon_0 \left(1 - \omega_p^2 / [\omega(\omega + i\gamma)] \right)$, where ω_p is chosen to provide $\epsilon_c \sim 0.1 \epsilon_0$ at the frequency of interest and $\gamma = 10^{-3} \omega_p$ provides a reasonable level of losses for the plasmonic cloak. Effective material properties with this range of values may be realized at optical frequencies in a variety of metamaterial geometries, like arrangements of nanoparticles mixtures of plasmonic and dielectric materials or specifically tailored nanoimplants. Figure 17 illustrates the total scattering cross sections for plane wave incidence normal to the aperture (directed collection represented by solid lines 64, 68) and for incidence from the side of the aperture (reflection collection represented by dashed lines 66, 70). The designed cloak is capable of suppressing the scattering from the tip for both polarizations, in both planes and for all incidence angles and spatial wave numbers (even for evanescent waves), despite the asymmetrical shape of the tip. This property, peculiar of the plasmonic cloaking technique, is particularly relevant for the different modes of operation of aperture NSOMs. It also is noted that that moderately larger level of losses would not significantly affect the overall cloaking effect.

[0064] Figure 18 depicts near-field plots of the NSOM tips of Figure 17. Amplitude of the total electric field in the H plane in the top row of plots and of the total magnetic field in the E plane in the bottom row of plots for the bare tip (left column of plots) and cloaked tip (right column of plots) tips of Figure 12 at 500 THz for plane-wave incidence from left to right in the panels (normal incidence towards the aperture). The fields are all in scale and assume a 1 V/m electric field amplitude for the incident plane wave.

[0065] As seen in Figure 18, for the uncloaked tip, strong scattering is produced on both planes of polarization in front of the tip, causing a strong disturbance on the same measurement that the tip is performing. In contrast, when the cloak is added over the tip, the

scattering is almost completely suppressed in the near-field of the tip and the uniform plane wave distribution is restored. Note that the plasmonic cloak does not isolate the tip from the surrounding environment. The plasmonic cloak allows penetration of the fields inside the tip at a level comparable with that of the uncloaked tip scenario. In other words, although the disturbance of the tip in the near-fields is greatly reduced by the cloak, its capability to collect the external signals in its aperture is not essentially affected. This is particularly important for an NSOM tip in the collection mode that may sense the minute details and fast-varying near-fields in its surroundings without significantly perturbing its own measurement.

[0066] Described below are simulation examples showing how this simple and uniform cloaking layer can drastically improve the near-field measurements in a variety of situations of interest. As a first example, consider Figure 19, which contains three plots (panels) depicting the amplitude of a magnetic field on the E plane. Figure 19 shows the numerical simulations for an NSOM tip in the collection mode scanning of a silver surface supporting a surface plasmon polariton (SPP) wave. The surface was excited by an emitting molecule on the far left of each panel, and is carved with two narrow slits, each 30 nm wide and separated 120 nm from each other. A silver surface excited by a molecule at 500 THz (on the far-left of each panel) supports a propagating SPP impinging on two narrow slits (top panel). When a tip scans the surface (middle panel), strong disturbance to the surface-wave propagation is induced by the presence of the tip, causing standing-waves and relevant artifacts in the measurement. If a plasmonic cloak (e.g., as described with reference to Figure 17) is added around the tip (bottom panel), the disturbance is significantly suppressed, and the SPP is essentially unperturbed, as if the tip is not there. Still, the level of fields induced at the aperture is comparable to those without cloak. The tip aperture is placed at 20 nm distance from the surface.

[0067] Considering a realistic permittivity model for the silver material, including frequency dispersion and losses, in the top panel of Figure 19, the SPP distribution (amplitude of the magnetic field normal to the figure) is shown without the presence of the tip, which shows, as expected, a small perturbation of the uniform SPP mode caused by the presence of the two slits on the silver surface. In the middle panel of Figure 19, the full-wave simulation of the same setup scanned by the uncloaked NSOM tip of Figure 17, placed 20 nm above the surface, is shown. It is seen how its presence strongly perturbs the original SPP distribution, creating a strong standing-wave between the source (e.g., emitting molecule and the tip, and drastically

modifying the near-field of the aperture). The image taken by such NSOM tip will necessarily present some unwanted artifacts due to its own disturbance on the measurement. In the bottom panel of Figure 19, the tip is covered by a proper cloaking material. It is seen that in this case the SPP distribution is restored exactly as if the tip were not there, still allowing a comparable level of field penetration in the aperture. This is achieved despite the fact that the tip is kept at the same distance from the silver surface, and therefore the distance of the outer surface of the cloak from the slits is only 7 nm in these simulations. It is evident how the sensing mechanism may be greatly improved by the presence of this cloaking layer.

[0068] Figure 20 illustrates a comparison of the sampled images scanned in the setup of Figure 19 by an ideal mathematical probe (no tip), and the bare (uncloaked) tip and the cloaked tip of Figure 17. Figure 20 shows the measured images at the top end of the NSOM tip in the collection mode, proportional to the signal transmitted into the optical fiber connected to the tip in a realistic near-field measurement. The plot in Figure 20 depicts the comparison of the magnitude of the magnetic field at the end of the tip in the three cases of: (a) an “ideal” mathematical tip (No Tip) that would pick up the field across the sample, scanning the surface at 20 nm distance with a finite step of 5 nm in the transverse direction; (b) the real bare tip, as in Figure 17 (Bare Tip); (c) the cloaked tip (Cloaked Tip). The horizontal axis of the plots shows the distance from the source (*e.g.*, emitting molecule) in Figure 19. The slits are placed at $1\mu\text{m}$ and $1.12\mu\text{m}$ from the molecule. As in a realistic scanning measurement, the tip moves parallel to the surface, recording the magnetic field amplitude at the tip end. It is seen how the cloaked tip matches consistently the ideal measurement, without artifacts, whereas the realistic tip measurement creates substantial differences in the level of the measured fields and its overall distribution, associated with the mutual coupling between the tip and the two slits. Overall, the cloak ensures an essentially unperturbed measurement of the fields for imaging purposes.

[0069] As another example, consider the geometry depicted in diagram 72 in Figure 21 and the near-field distributions (plots in row 72) and the far-field distributions (plots in row 74) between cloaked and bare (uncloaked) tip measurements, sensing a resonant nanodipole antenna fed by an optical dipole source (*e.g.*, an emitting molecule) at its gap. The geometry depicted in diagram 72 is related to the same NSOM tip in the collection mode as described above, but now imaging the near-field properties of a silver nanoantenna, designed to operate at about 500 THz . The total length of the nanodipole is 65 nm , with a center-symmetrical gap of 5 nm , used for

feeding and tuning purposes, and a diameter of 14 nm . These dimensions ensure that the nanodipole can be matched to an optical source (*e.g.*, an emitting molecule, an incoming optical waveguide, *etc.*) and support its dominant resonance at the frequency of interest of 500 THz . Notice that at these frequencies, due to the plasmonic properties of the nanodipole, its overall size is extremely sub-wavelength, and even a narrow tip looks gigantic in comparison (drawing in diagram 72 is to scale).

[0070] In the left panel of row 74, is shown the amplitude of the magnetic field distribution for the emitting nanoantenna at its resonant frequency, with the bare (uncloaked) tip at a distance of 22 nm . It is evident how the dipolar near-zone fields of the nanoantenna are greatly perturbed by the presence of the tip. Indeed, the tip can collect and sense some of the radiated near-field from the antenna, but at the price of strongly perturbing its pattern, and slightly detuning its resonance (the calculated resonance frequency is shifted in this scenario by about $1\% \sim 5\text{ THz}$). In contrast, the right panel of row 74 depicts the same setup, but with the cloak of Figure 17 added to the tip geometry. It is seen that the cloak is capable of significantly restoring the dipolar fields of the nanodipole and the resonance properties of the nanoantenna, sensing and imaging the unperturbed resonant field distribution. Still, the level of fields induced at the aperture is comparable in both cases. Also in this case, the cloak proves to be an excellent mechanism for greatly improving the sensing and scanning operation of the NSOM. In row 76 is depicted the far-field radiation patterns in the two cases. In the bare (uncloaked) scenario, the pattern is mainly pointing towards the NSOM tip (positive z axis), with drastic reduction of scattering on the back and on the sides. This may strongly perturb the effective measurement of the nanodipole radiation features. In contrast, the pattern corresponding to the cloaked case is quasi-isotropic in the equatorial plane of the dipole with a clear dipolar shape, almost identical to that of the isolated nanodipole. With a proper cloak, the NSOM in the collection mode can sense and image the true radiation features of the nanodipole antenna, without perturbing them with its close presence. It is not surprising that the bulky size of the tip may strongly affect the sub-wavelength nanodipole resonance, but it is impressive to notice how a thin uniform plasmonic layer may indeed succeed in restoring the original unperturbed field distribution.

[0071] As another example of the potentials that such cloaking layers may provide for NSOM measurements, considered the case in which the tip itself is “active”, and it operates in illumination mode. Since the cloak allows field penetration inside the cloak, at levels

comparable to the uncloaked scenario, owing to the reciprocity, it is expected that a source placed inside the cloak may be able to efficiently radiate. In this sense, consider an active region at the NSOM tip, which may be obtained by coating the tip with a limited number of quantum dots or emitting molecules. Here an emitting molecule can be placed on the aperture of the same tip considered above. Note these concepts are also applicable to apertureless active NSOM tips operating in illumination mode (this technique would allow even smaller tips and consequently higher resolution, with the scattered fields being collected by a separate sensor).

[0072] Figure 22 depicts the simulation results for the same setup as in Figure 21, but with a passive nanodipole and an emitting molecule placed at the NSOM aperture. It is evident how in the case of a bare (uncloaked) tip (diagram 78), the strong coupling between the nanodipole and the tip significantly perturbs its radiation and resonance properties, and affects the dipolar shape of the near-field distribution. As shown in diagram 80, when the cloak covers the tip (and the optical source), excitation of the nanodipole at the same level is still preserved, but without any perturbation of its resonant properties. A clear dipolar pattern is observed right around the cloak, even though the excitation in this case lies inside the plasmonic layer.

[0073] The aforementioned simulation results demonstrate how a simple thin uniform plasmonic layer, properly designed to cancel the scattering from NSOM tips, can dramatically enhance the imaging and scanning properties of near-field sensors in a variety of applications and operations.

[0074] Yet another application of the cloaked system includes plasmonic cloaking for absorbing and energy harvesting devices. The possibility to extract information without necessarily producing relevant scattering opens up venues to use the plasmonic cloak to enhance and maximize the extraction of energy, and not just signals, at various frequencies. For example, plasmonic cloaking can be used to enhance the efficiency of green-energy sources and energy-harvesting devices, while concurrently minimizing the unwanted coupling effect and reflections that each absorber may produce on its neighboring elements and/or on the impinging wave. Properly designed metamaterial cloaks may suppress the unwanted reflection and scattering from energy absorbers, reducing the coupling among neighboring elements, their disturbance to the source, and maximizing the efficiency and matching to the incoming radiation for optimal extraction efficiency. These concepts may be extensively applied to THz and optical absorbing devices, *e.g.*, semiconductor materials, receiving nanoantennas, absorbing molecules and

semiconductors, and/or the absorbing units of a solar panel, or the like. Properly designed plasmonic cloaks may not only suppress most part of the scattering from an absorbing element, still achieving similar levels of energy extraction, and, it may at the same time sensibly enhance the total absorbed power by achieving the required matching with free-space.

[0075] Figure 23 illustrates two plots 82 and 84 of calculated absorbed, scattered, and extracted power for an absorbing molecule/material/receiver, for various thicknesses of a cloaking layer that surrounds the molecule/material/receiver. Inset 86 depicts a cloaked absorbing molecule/material/receiver 90 being radiated by free-space radiation 92. Considering the molecule/material/receiver as a receiving element, its absorbing mechanism can be modeled with the classic Thevenin circuit model, shown in inset 88. In the field of receiving antennas, maximum energy absorption may be achieved when the inner Thevenin resistance, a circuit element that models the capability of the element to re-radiate, or scatter, “matches” the absorption properties of the molecule, described by an equivalent resistive load. Since usually small molecules have intrinsically low resistive components, the possibility to tailor and properly reduce their scattering may provide novel tools to enhance and maximize energy extraction and absorption. Figure 23, as an example, shows some preliminary calculations for two different absorbing molecules/material/receiver, varying the thickness of a cloaking layer with low effective permittivity ($\epsilon_{\text{cloak}} = 0.1$), specifically its radius a_c normalized to the molecule/material/receiver averaged radius a . These full-wave results are obtained with an exact Mie multipole expansion technique in the dynamic case. As shown in Figure 23, the absorbed power by the molecule/material/receiver P_{abs} , the total scattered power P_{sca} , and the total extinction power $P_{\text{ext}} = P_{\text{abs}} + P_{\text{sca}}$. Their values are normalized to the value of P_{abs} with no cloak (for $a_c = a$). Plot 82 shows the case in which a specific cloak configuration, for which $a_c = 1.035a$, is capable of matching the absorbing molecule/material/receiver to the impinging radiation, without increasing its overall scattering. This is drastically different from other available techniques for enhancing the energy absorption by using plasmonic nanoparticles, which necessarily imply an associated drastic increase of the overall scattered power, with unwanted effects on the neighboring absorbing elements and on the overall efficiency of the absorption mechanism. Here instead, it is noticed that the absorbed power may be enhanced by the use of a proper cloak of about 40 times, without requiring any significant increase in the scattered power. In another configuration, as shown in plot 84, the proper choice of the cloak

geometry (in this case with $a_c = 1.06a$) may drastically suppress the scattering from the absorbing element, without severely affecting the capability of the molecule/material/receiver to extract energy from the impinging wave. In both cases, it is seen that the ratio of absorbed versus scattered power is made very high by the proper choice of the cloaking layer and geometry, which allows going beyond the general limits of current energy-harvesting devices. This is due to the unique potentials of this cloaking technique, which allows the wave to penetrate inside the cloak, therefore producing energy absorption without scattering.

[0076] It is to be understood that even though numerous characteristics and advantages of a cloaked sensor system have been set forth in the foregoing description, together with details of the structure and function of the cloaked sensor system, the disclosure is illustrative, and changes may be made in detail, especially in matters of shape, size, selection, and arrangement of parts of the shield and/or sensor to the full extent indicated by the broad general meaning of the terms in which the appended claims are expressed. Thus, while a cloaked sensor system has been described in connection with the various embodiments of the various figures, it is to be understood that other similar embodiments can be used or modifications and additions can be made to the described embodiment for performing the same function of cloaking a sensor without deviating therefrom. Therefore, the cloaked sensor system should not be limited to any single embodiment, but rather should be construed in breadth and scope in accordance with the appended claims.

What is Claimed:

1. A cloaked sensing system comprising:
 - a sensor configured to detect a signal comprising a predetermined frequency;
 - a shield placed around the sensor, the shield configured to:
 - allow the signal to penetrate the sensor and reach the sensor; and
 - reduce energy scattered from the sensor within the shield such that essentially none of the scattered energy radiates out of the shield.
2. The system of claim 1, wherein the shield comprises a plasmonic material.
3. The system of claim 1, wherein the shield comprises a metamaterial.
4. The system of claim 1, wherein the shield is configured to induce an approximately zero total electric field dipole moment within the shield.
5. The system of claim 4, wherein the shield is configured to induce the approximately zero total electric field dipole moment by inducing an effective dipole moment that is equal in magnitude and opposite in polarity to a dipole moment of the sensor.
6. The system of claim 1, wherein the sensor is configured to transmit a signal comprising the predetermined frequency.
7. The system of claim 1, wherein at least one characteristic of the signal reaching the sensor is essentially the same as the at least one characteristic of the signal just prior to traveling through the shield.

8. The system of claim 1, wherein the sensor comprises a near-field scanning optical microscope.

9. The system of claim 1, wherein the sensor comprises an energy absorber.

10. The system of claim 1, wherein:

the sensor comprises a spherical scatterer having a radius, a ;

the shield comprises a homogeneous material with permittivity, ε , and permeability, μ ;

the shield is surrounded by free space with permittivity, ε_0 , and permeability, μ_0 ;

the shield has a radius of a_c ;

a_c is greater than a ; and

the shell permittivity, ε_c , and permeability, μ_c are configured to meet the following criteria:

$$\begin{vmatrix} j_n(ka) & j_n(k_c a) & y_n(k_c a) & 0 \\ [ka j_n(ka)]' / \varepsilon & [k_c a j_n(k_c a)]' / \varepsilon_c & [k_c a y_n(k_c a)]' / \varepsilon_c & 0 \\ 0 & j_n(k_c a_c) & y_n(k_c a_c) & j_n(k_0 a_c) \\ 0 & [k_c a_c j_n(k_c a_c)]' / \varepsilon_c & [k_c a_c y_n(k_c a_c)]' / \varepsilon_c & [k_0 a_c j_n(k_0 a_c)]' / \varepsilon_0 \end{vmatrix} = 0$$

where: $k \equiv \omega \sqrt{\varepsilon \mu}$, $k_c \equiv \omega \sqrt{\varepsilon_c \mu_c}$ and $k_0 \equiv \omega \sqrt{\varepsilon_0 \mu_0}$ are wave numbers in three respective regions;

$j_n(\cdot)$, $y_n(\cdot)$ are spherical Bessel functions; and

$[\cdot]'$ denotes differentiation with respect to an argument of a relevant spherical Bessel functions, so as to cancel a dominant scattering order n .

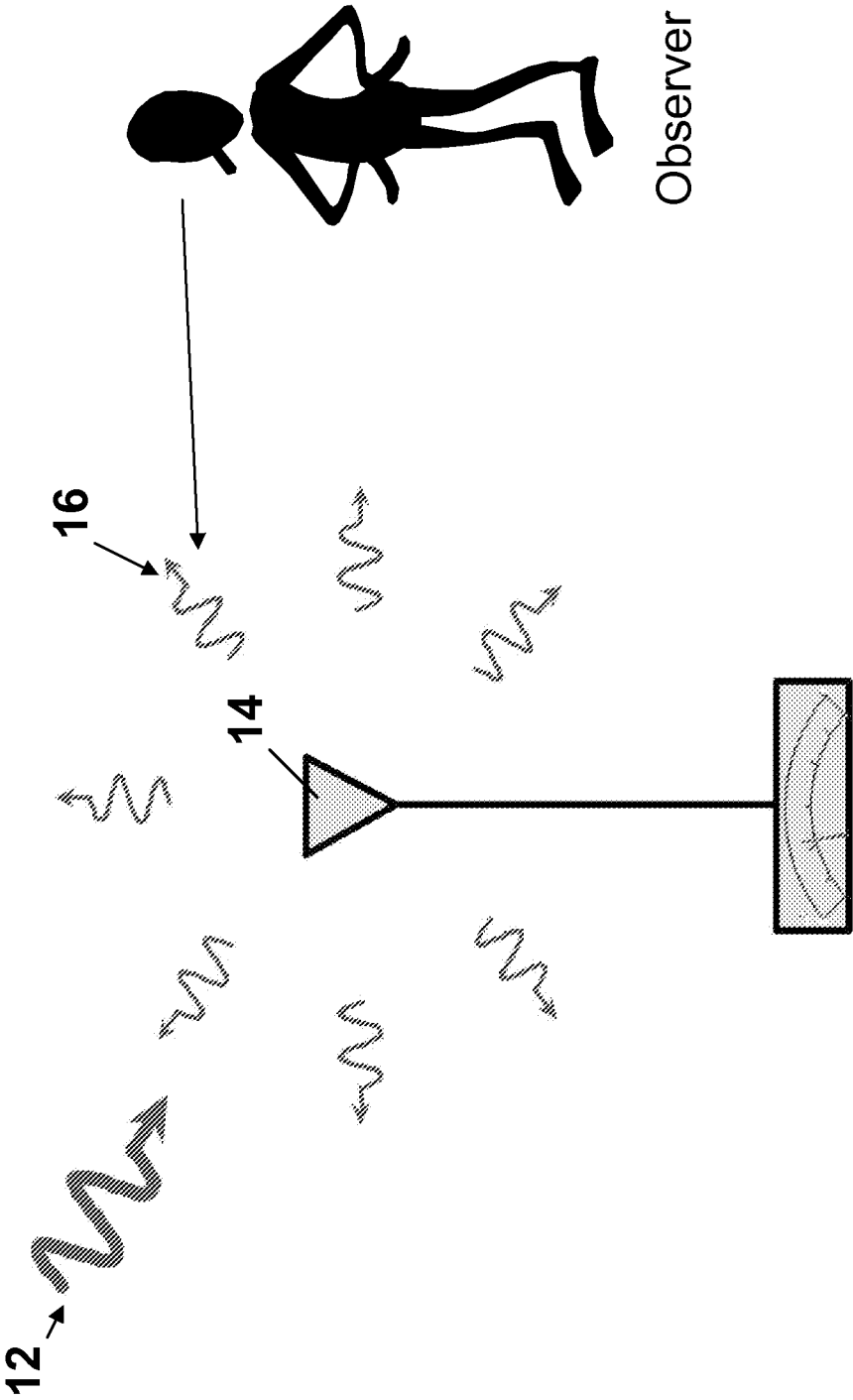


FIGURE 1

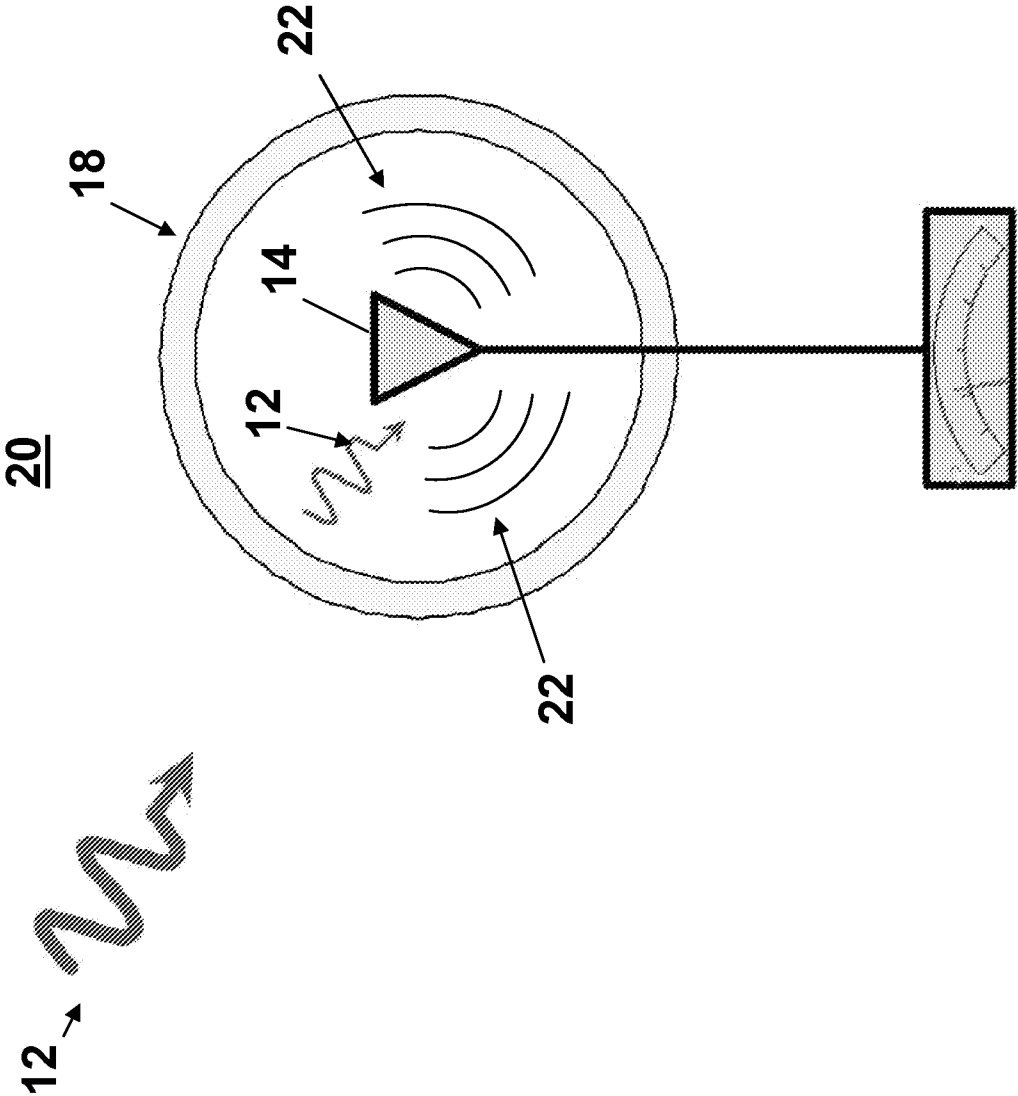


FIGURE 2

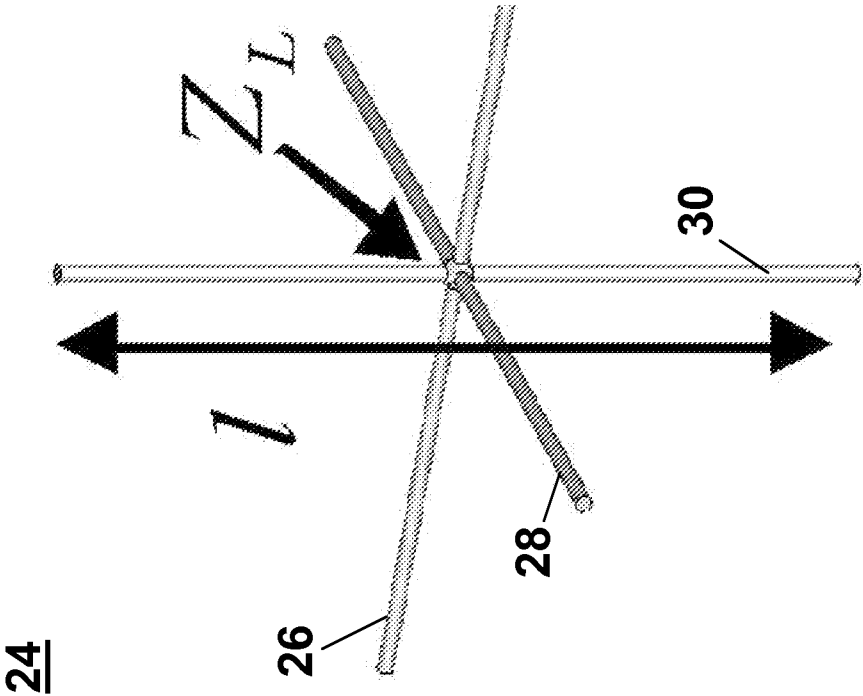


FIGURE 3

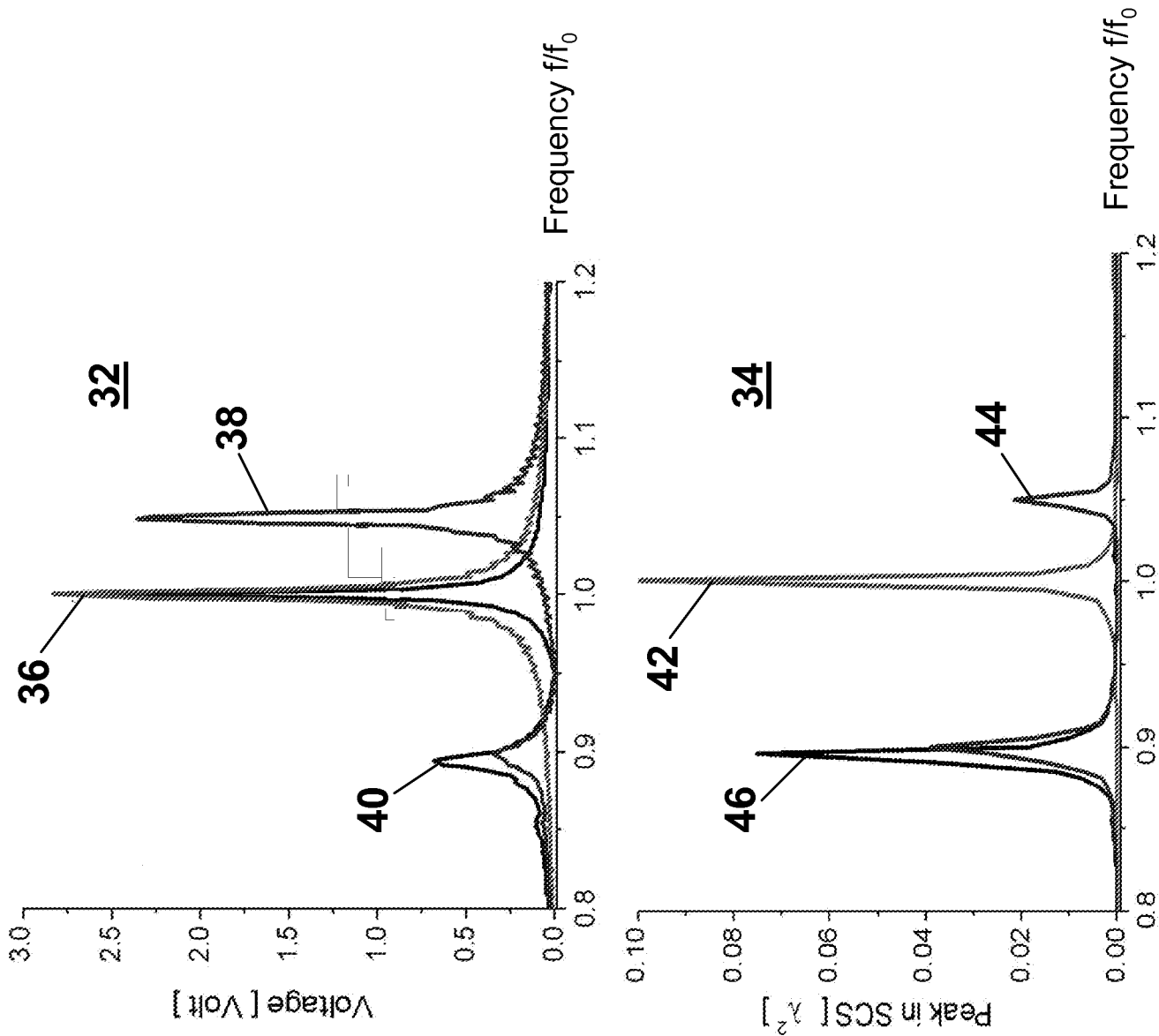


FIGURE 4

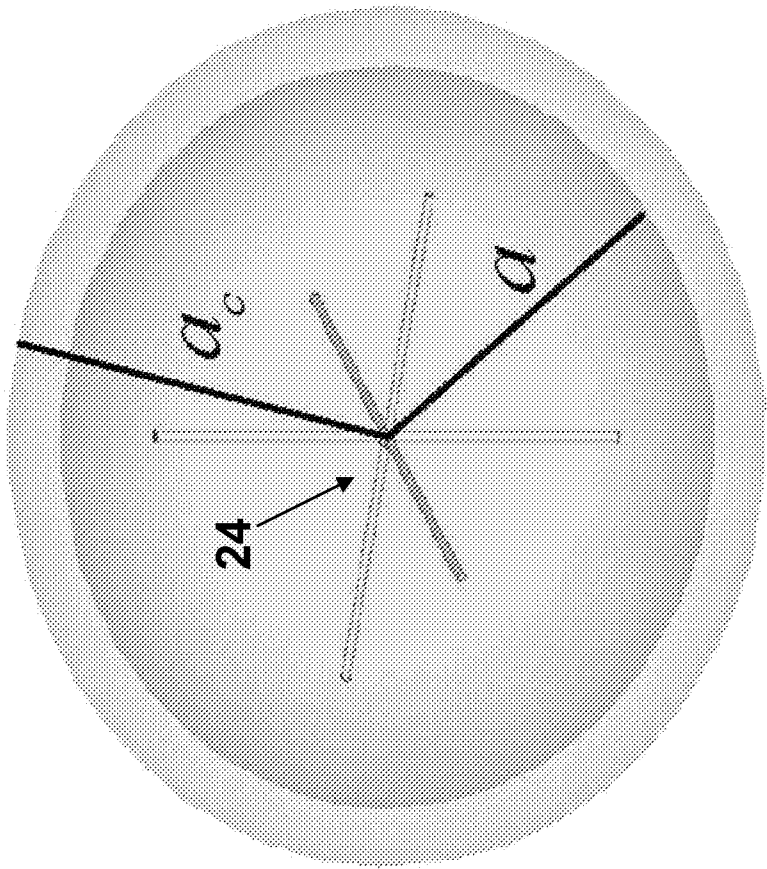


FIGURE 5

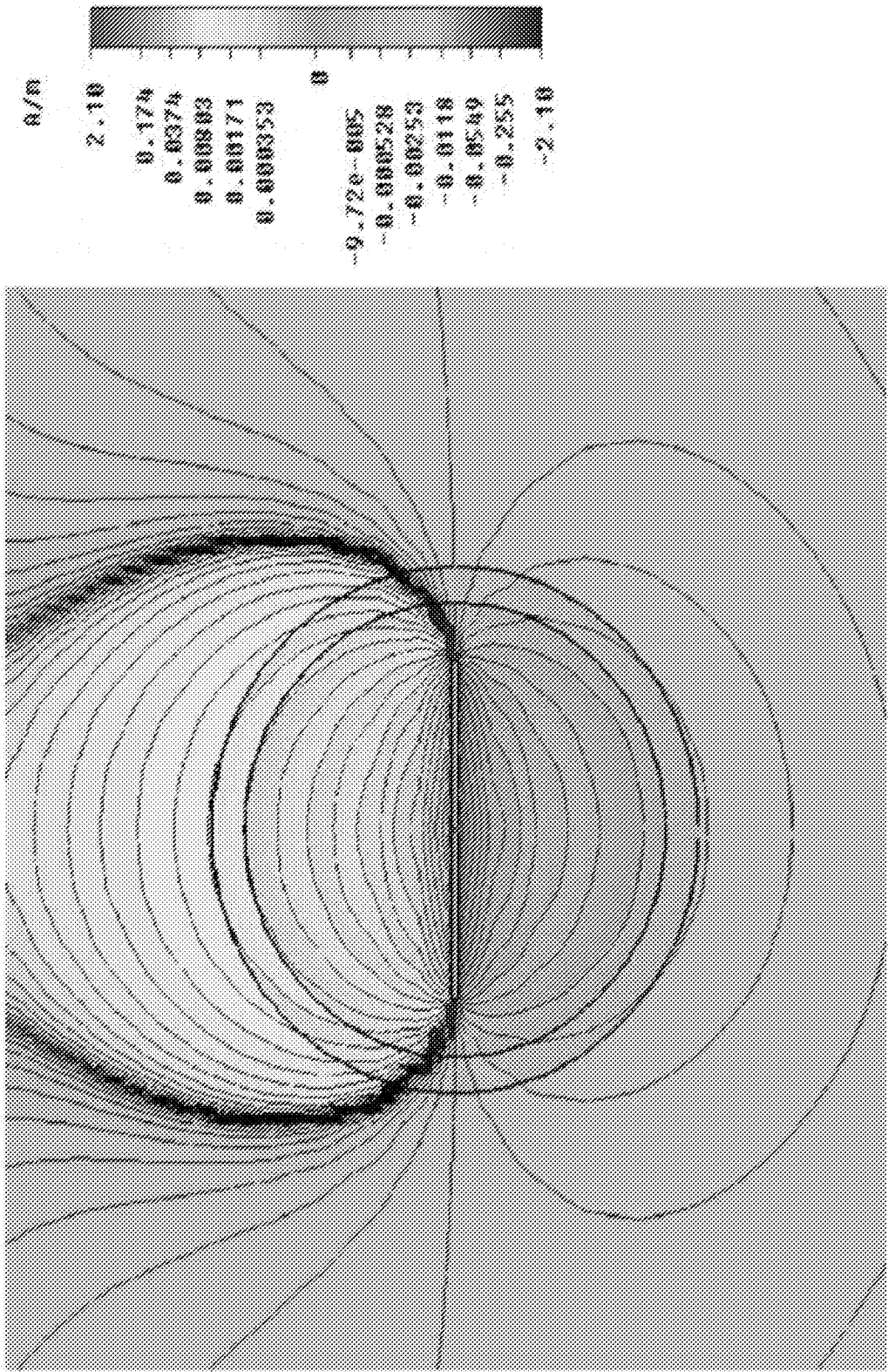


FIGURE 6

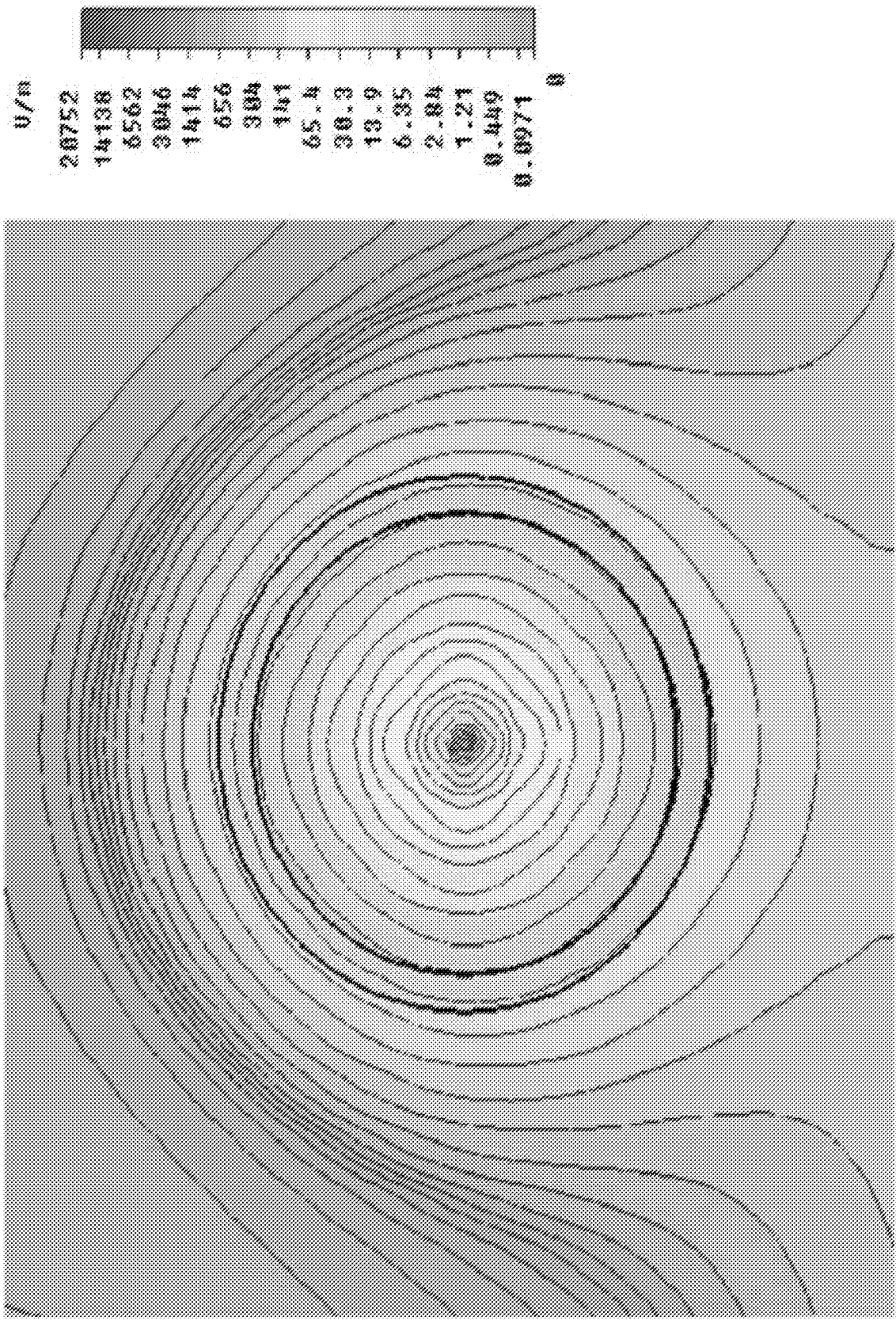


FIGURE 7

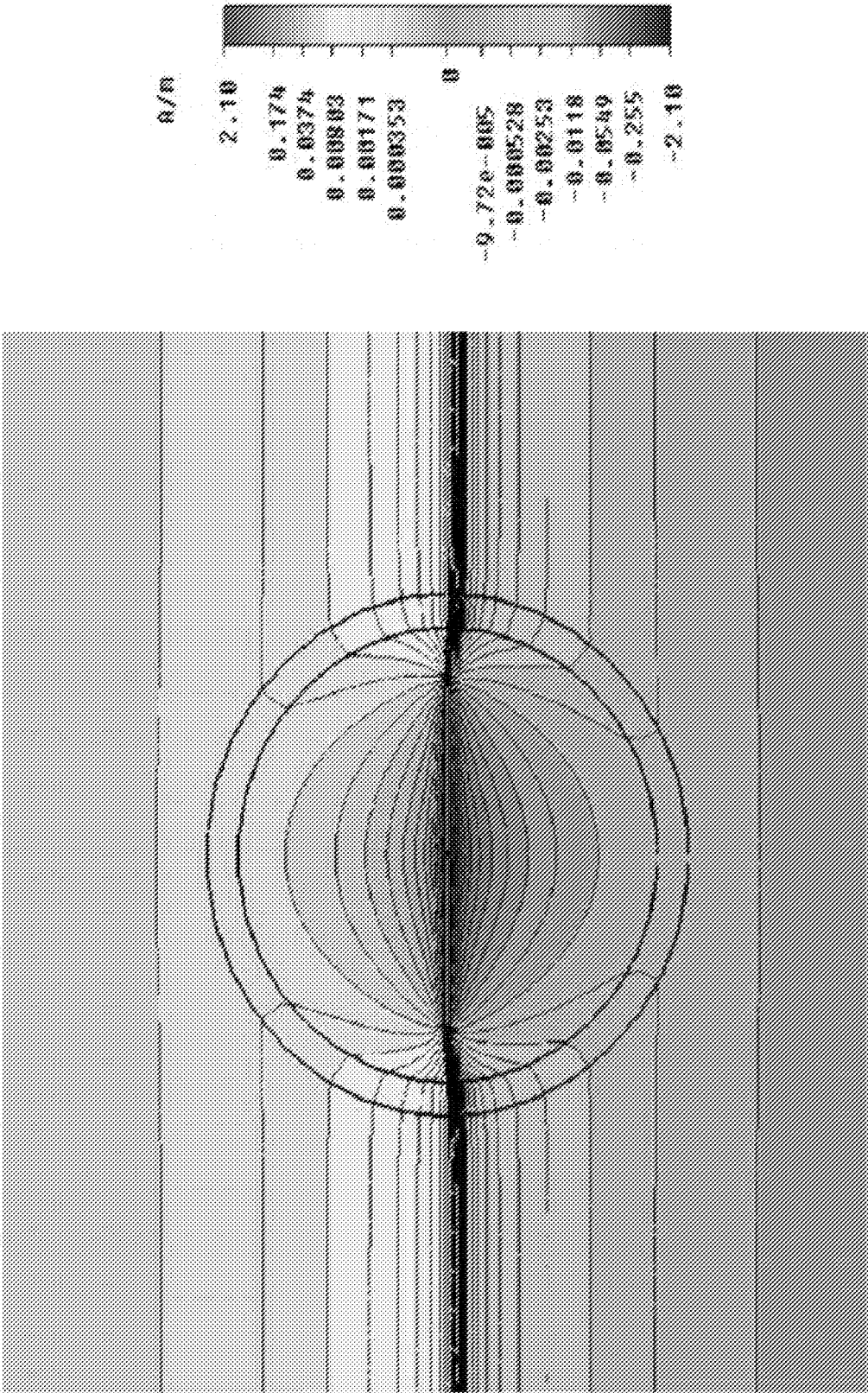


FIGURE 8

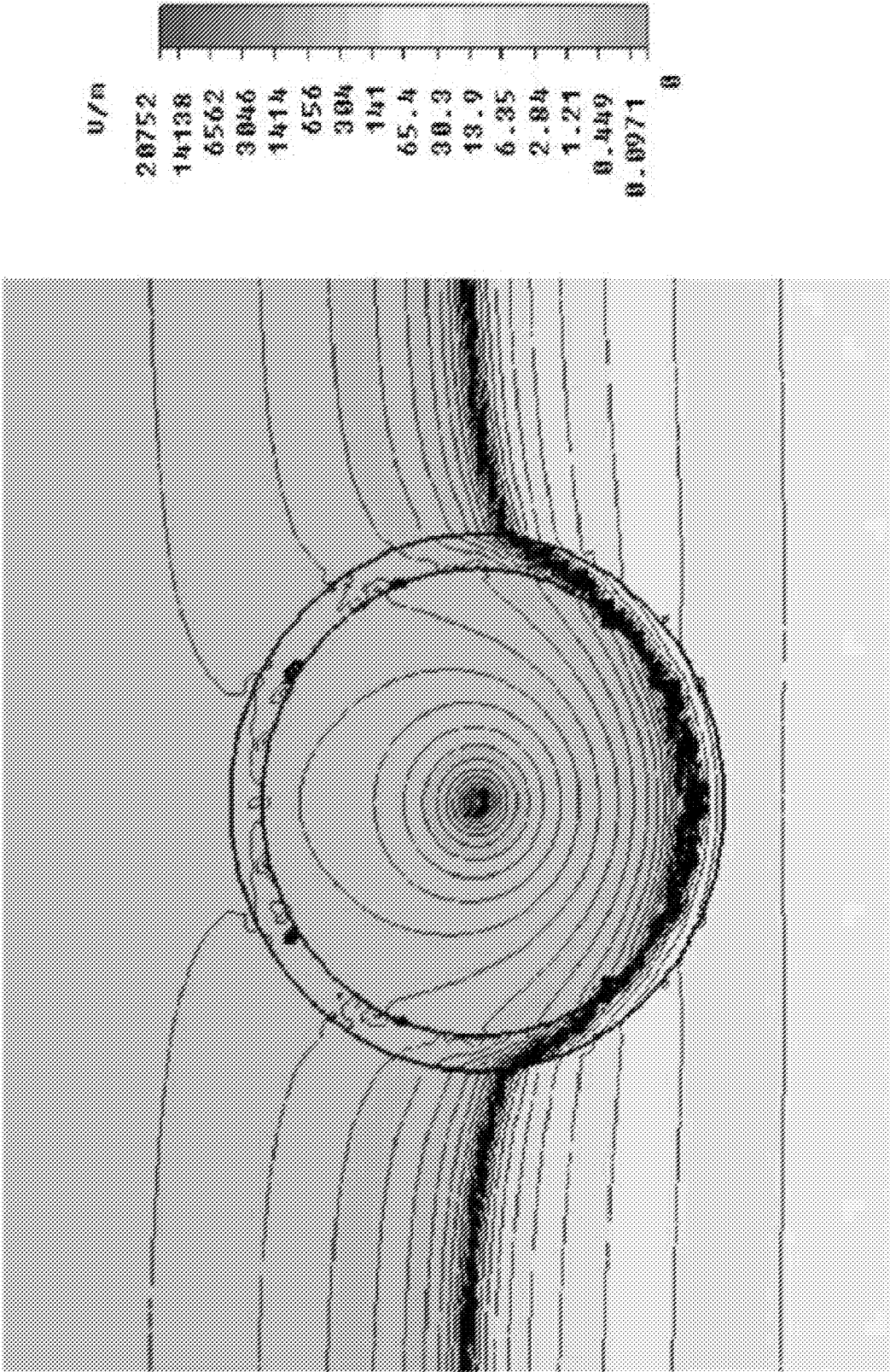


FIGURE 9

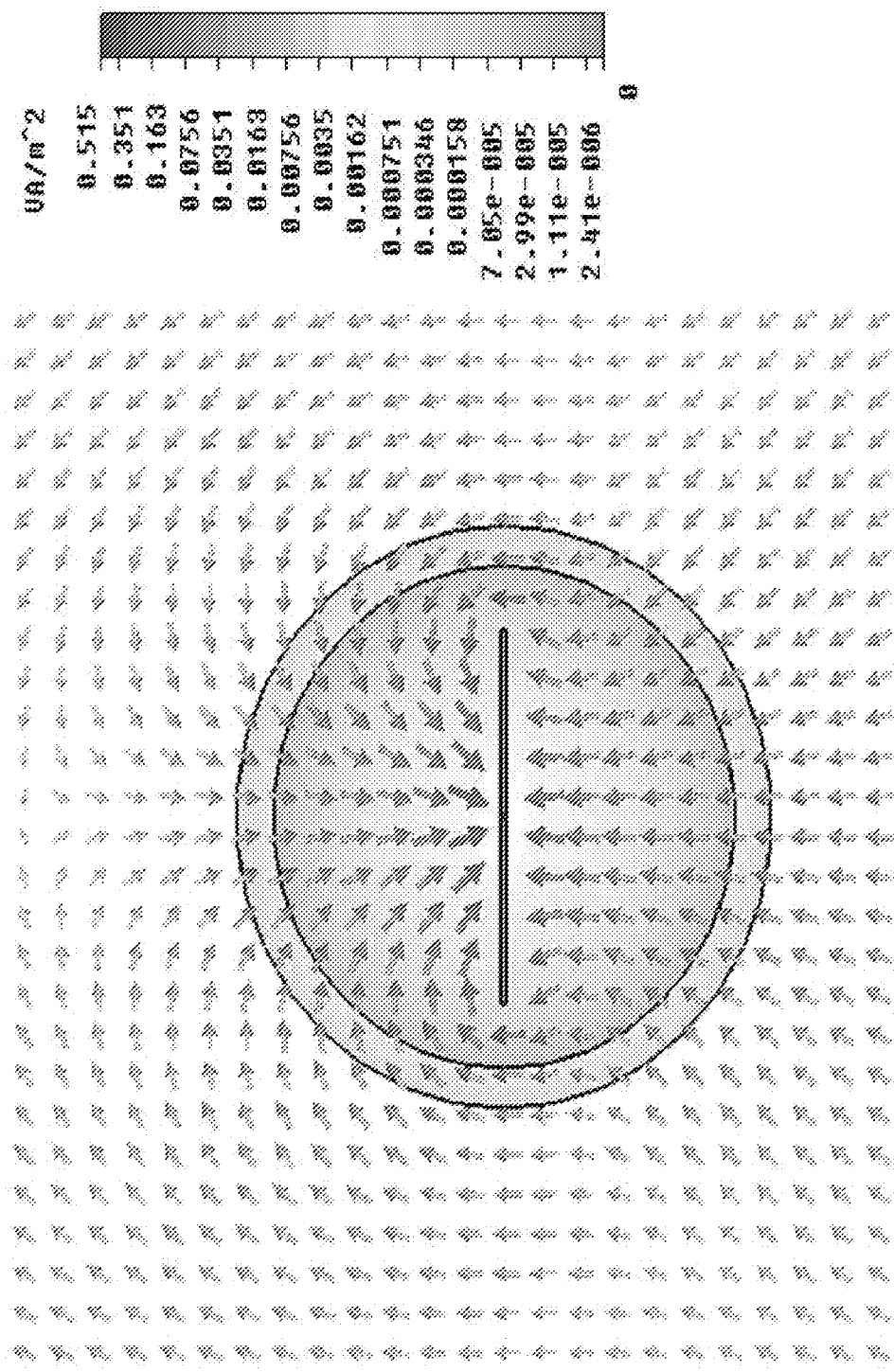


FIGURE 10

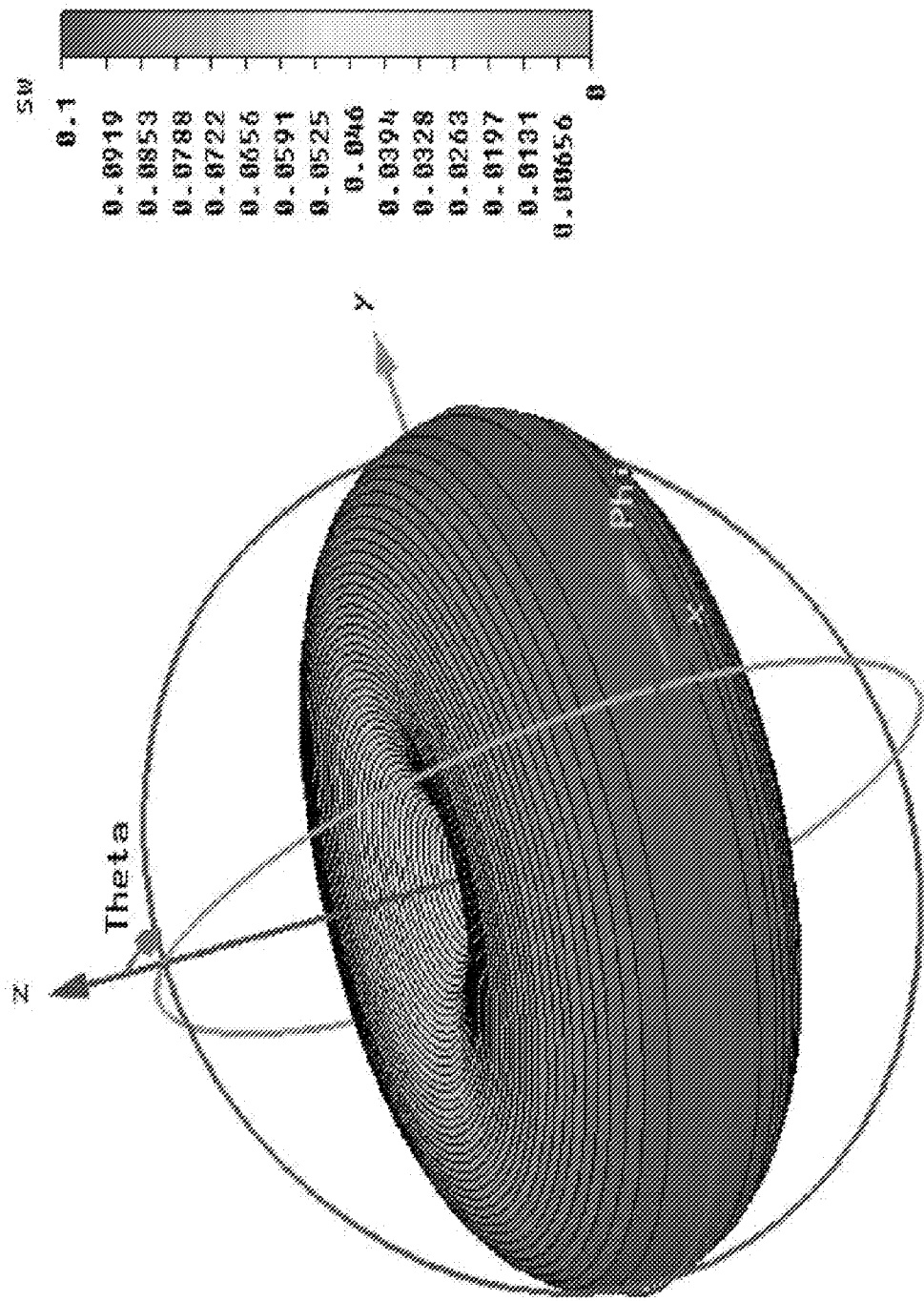


FIGURE 11

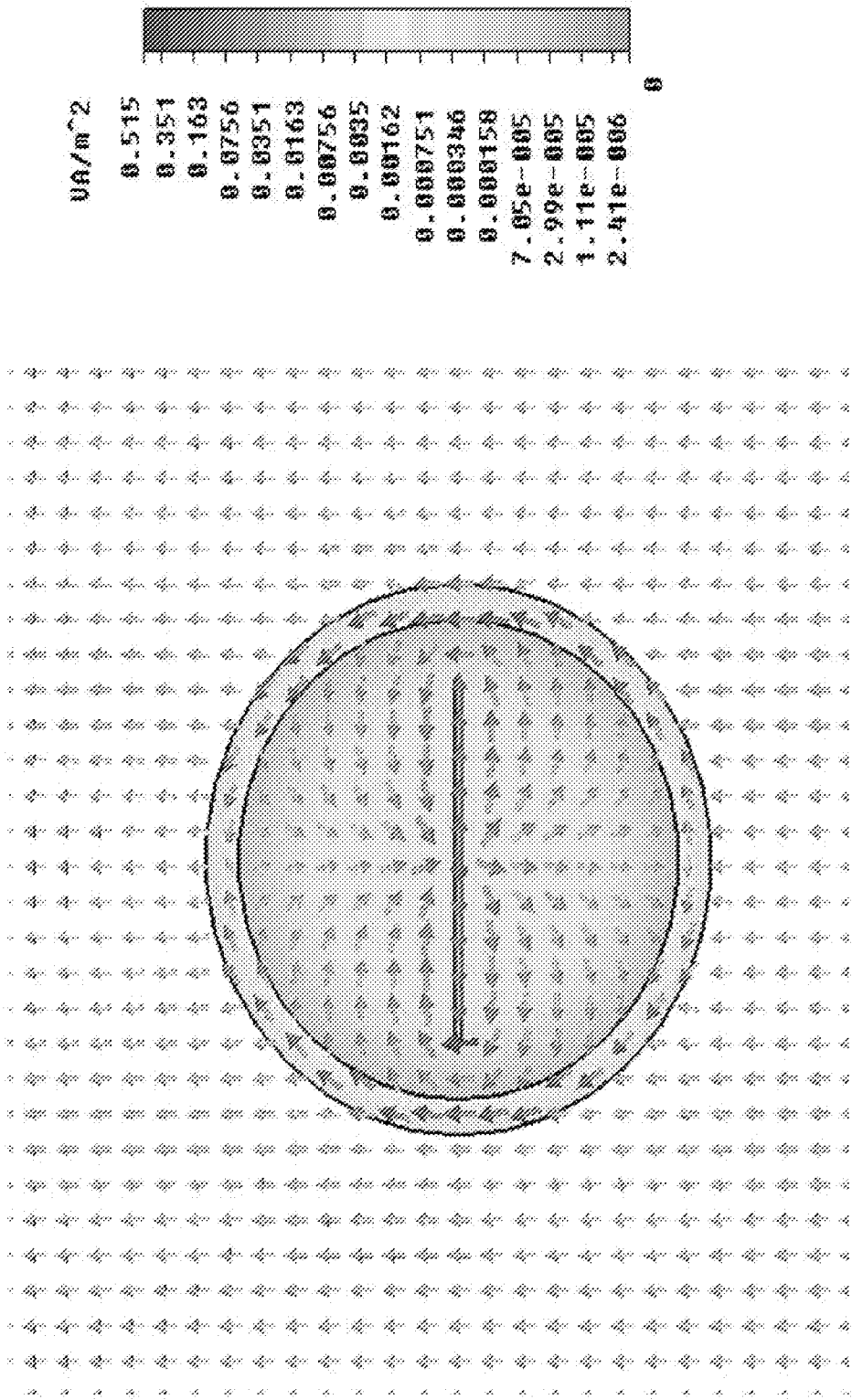


FIGURE 12

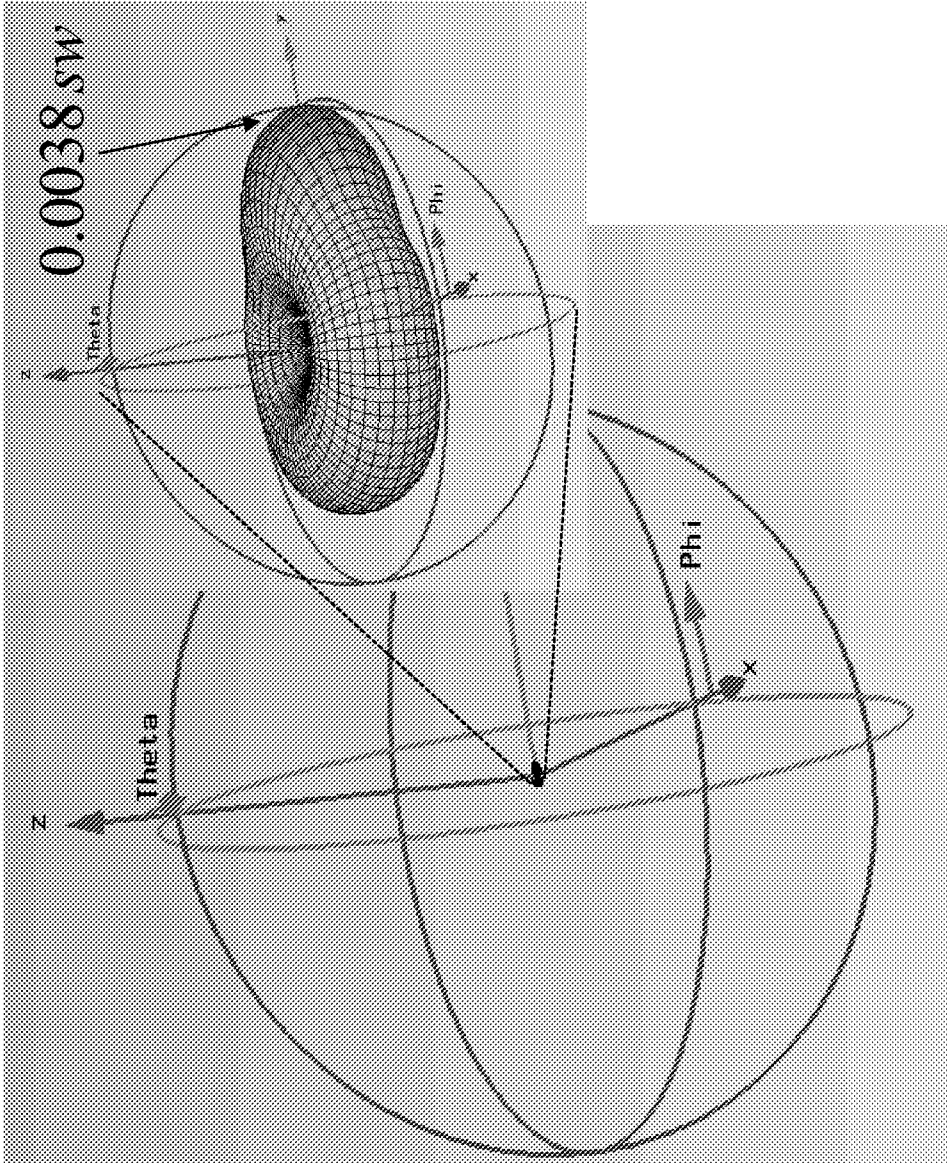
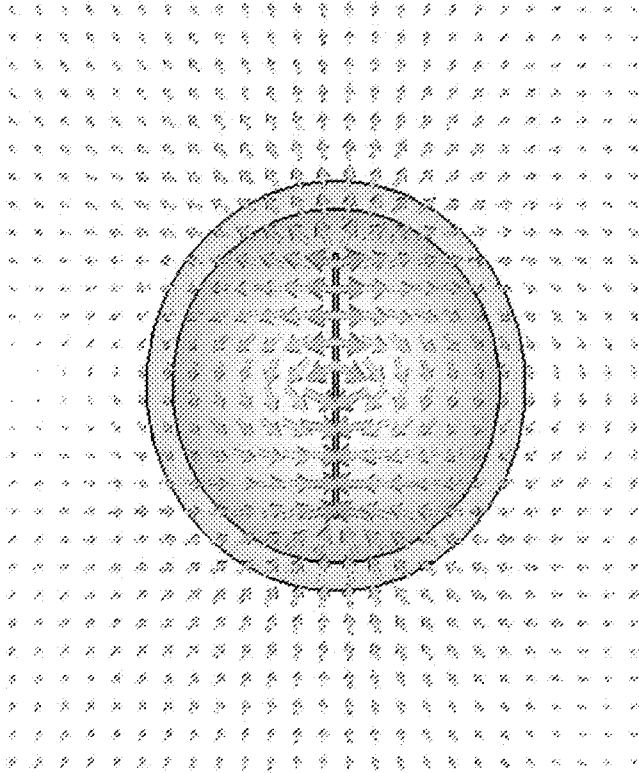
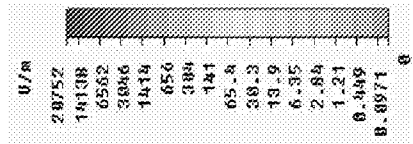
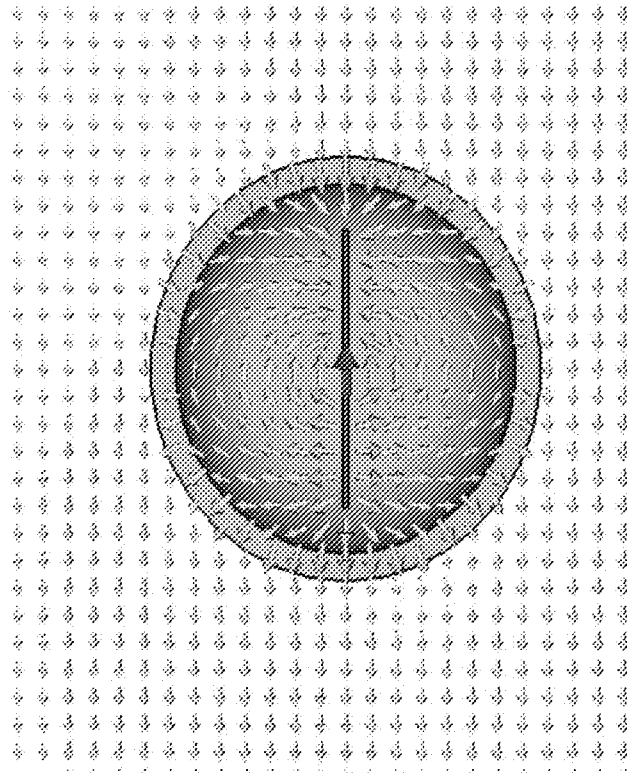


FIGURE 13

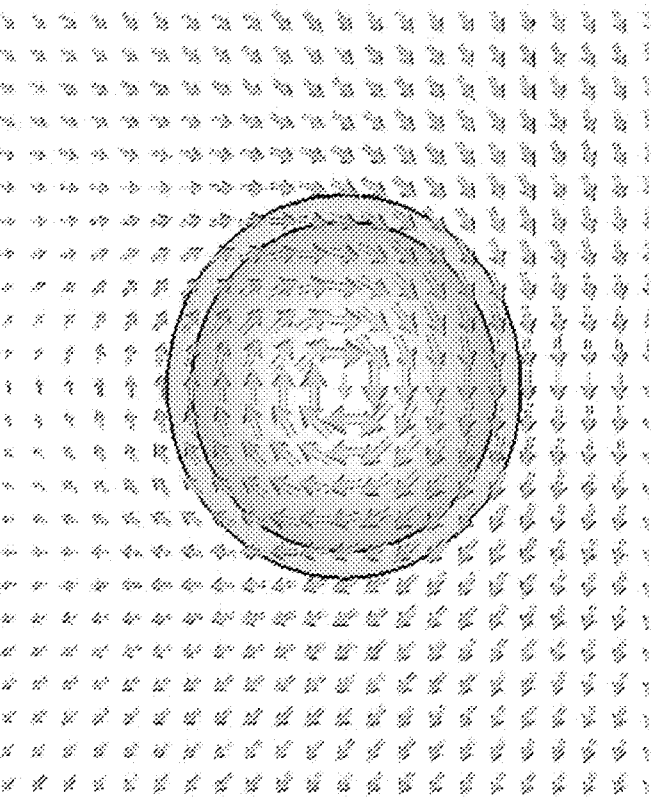
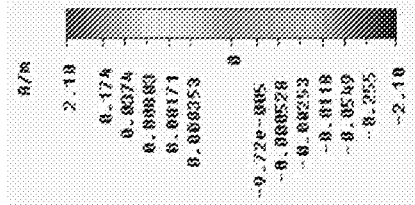
FIGURE 14



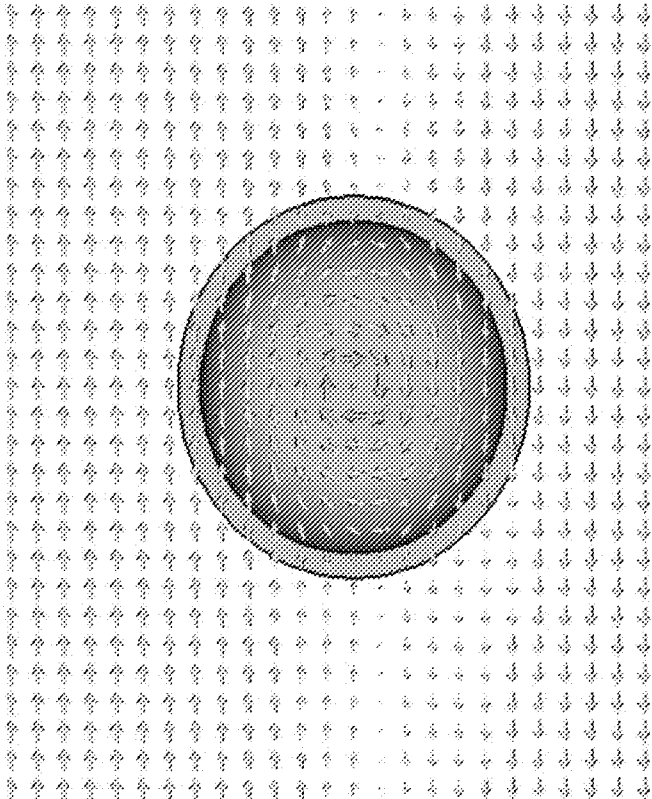
48



50



52



54

FIGURE 15

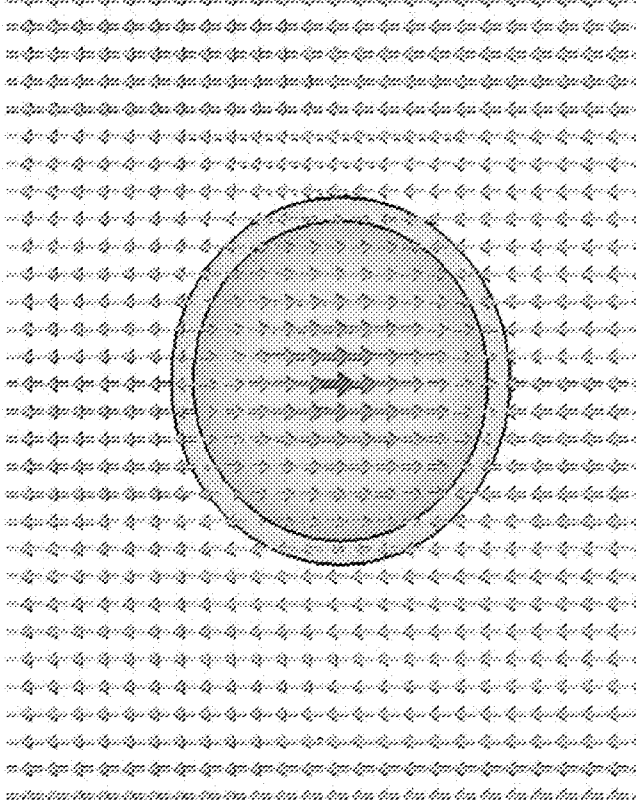
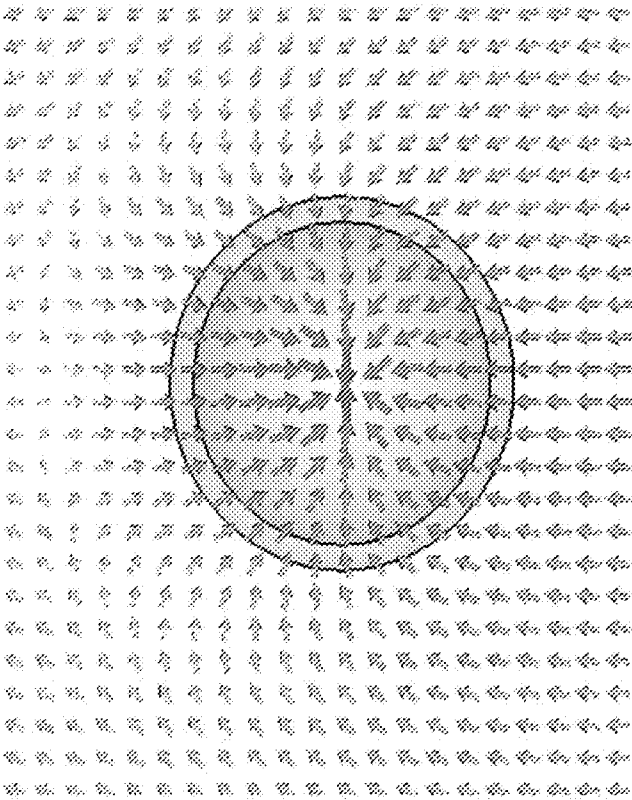
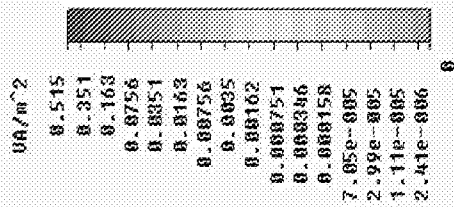


FIGURE 16

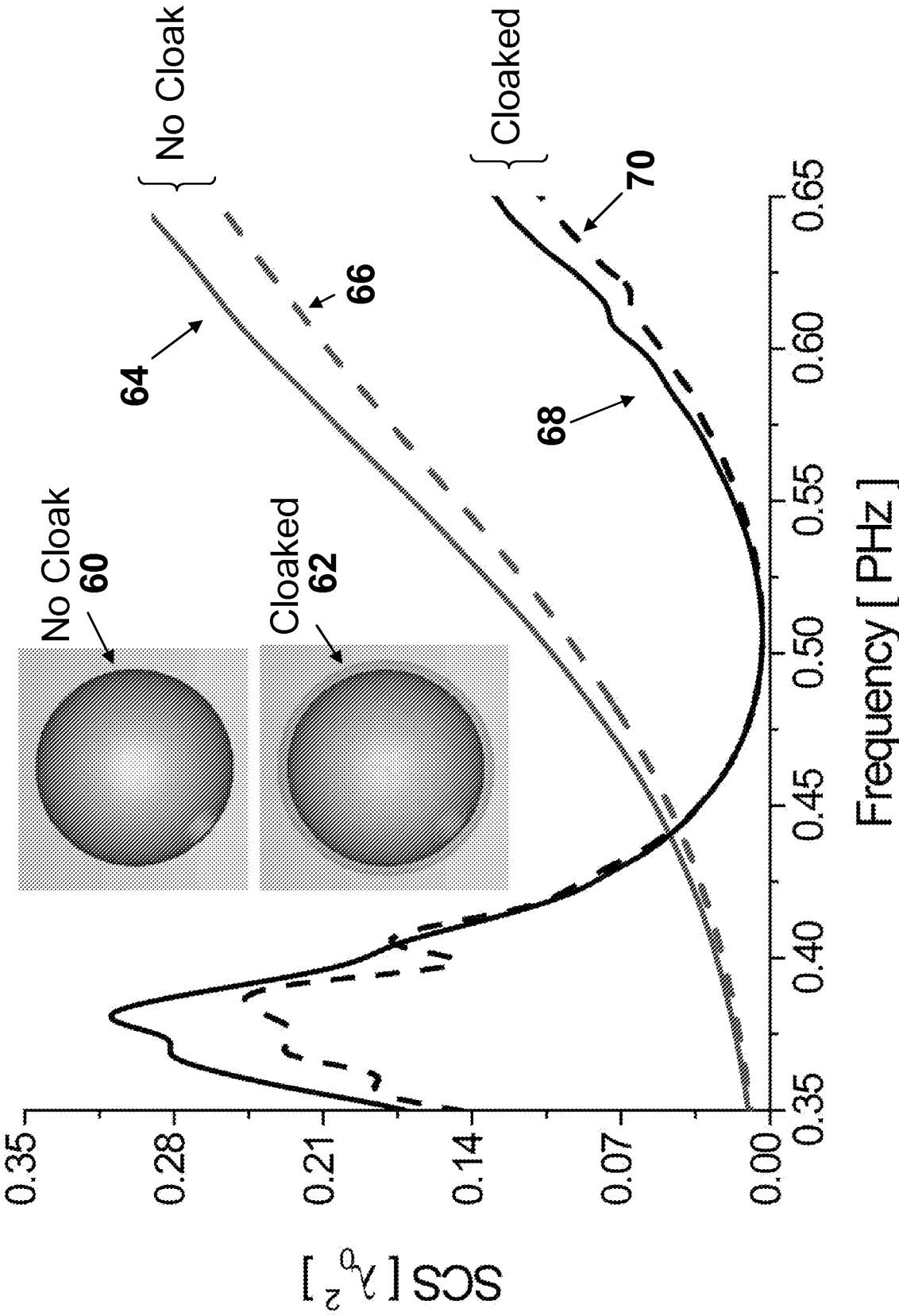


FIGURE 17

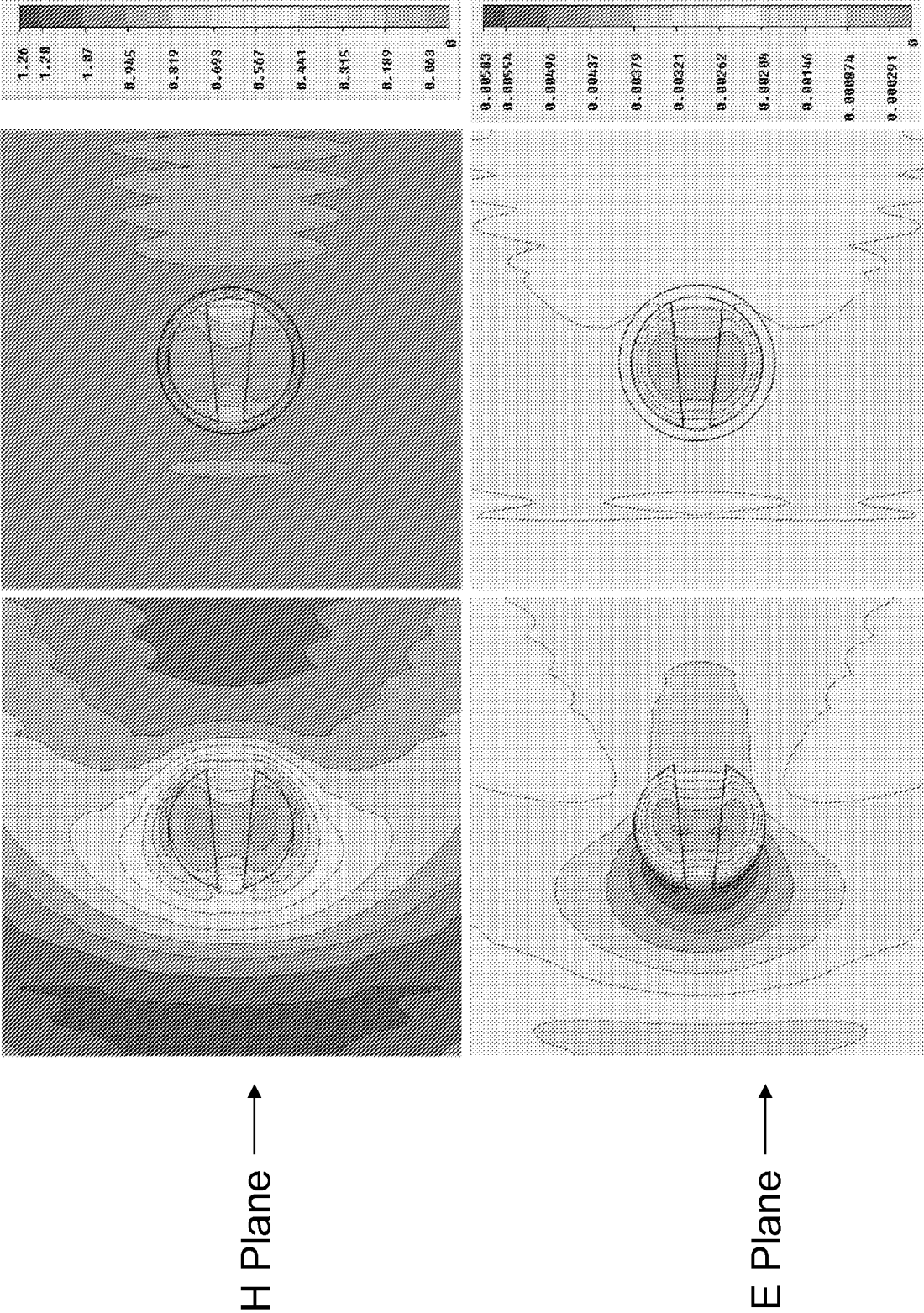


FIGURE 18

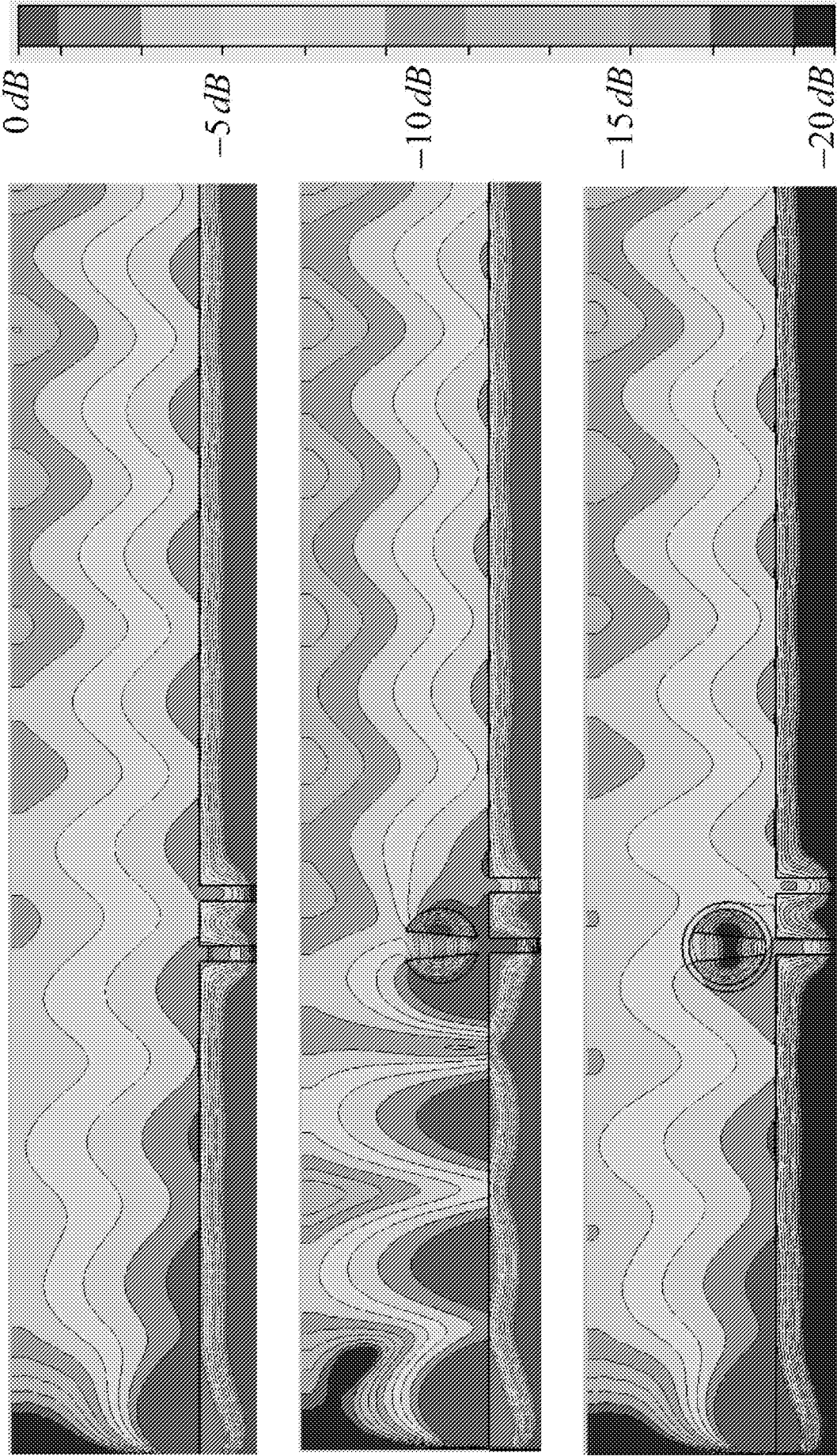


FIGURE 19

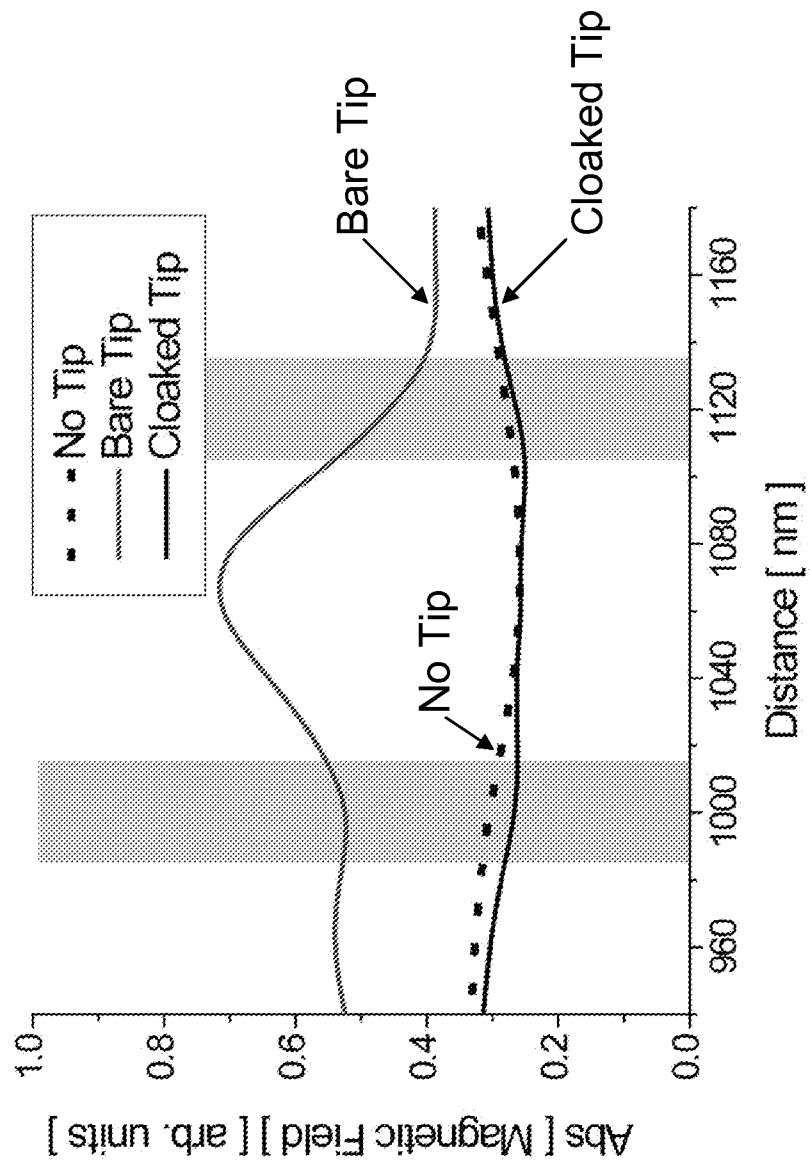


FIGURE 20

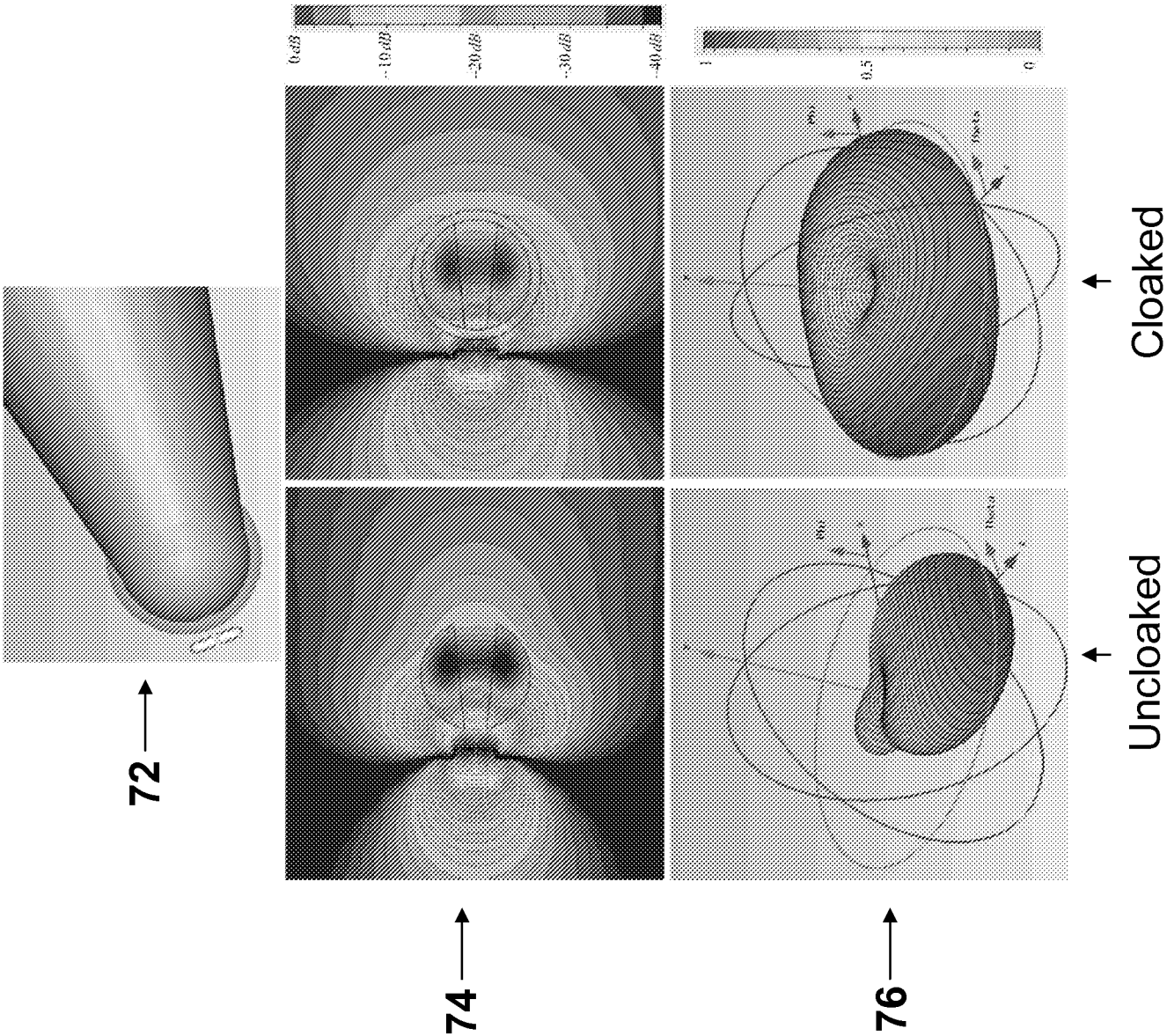


FIGURE 21

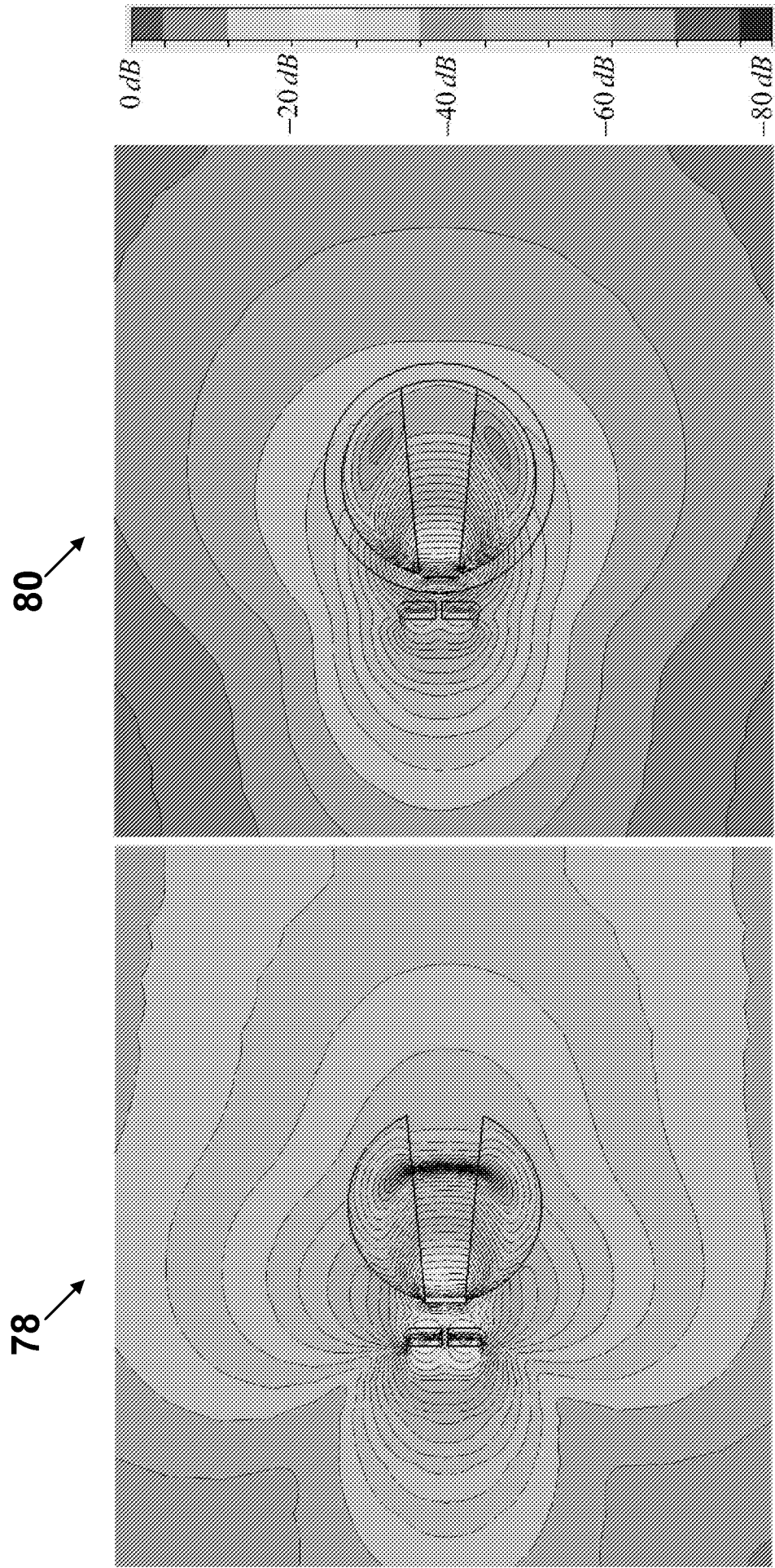


FIGURE 22

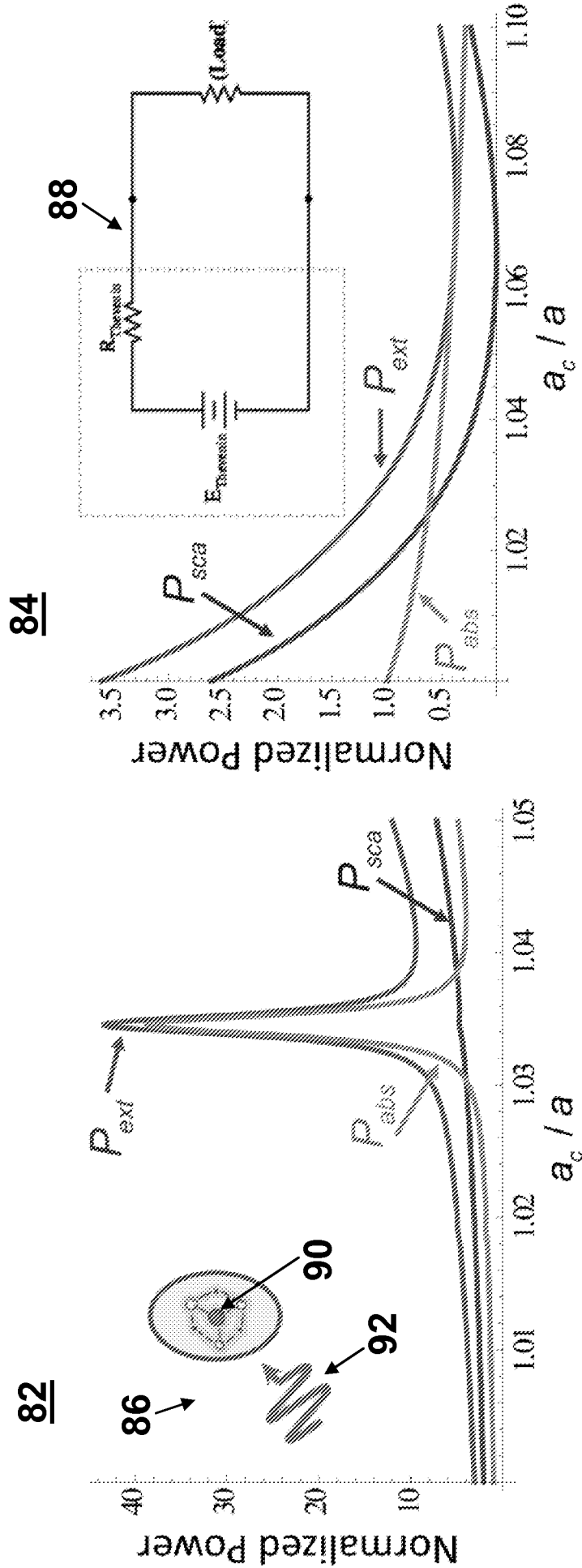


FIGURE 23

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 10/29204

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H05K 7/14 (2010.01)

USPC - 361/800

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
USPC: 361/800

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC: 361/800, 816; 438/57

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

PubWest (PGPB, USPT, EPAB, JPAB), Google,

Search terms used: cloaked, sens, cloak, unobserv, invisib, undetect, shield, energ, cancel, limit, reduc, attenuat, scatter, energ, zero, total, electric, field, dipole, penetrat, plasmonic, metamaterial, permittivit, permeabilit, spherical, bessel, function, wave, number, scatterin

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X — Y	US 7,301,493 B1 (Canales et al.) 27 November 2007 (27.11.2007), col. 2, ln. 17-66, col. 4, ln. 43 through col. 5, ln. 21	1-3, 6, 7 4, 5, 8-10
Y	US 2008/0197836 A1 (Lee et al.) 21 August 2008 (21.08.2008), para [0067]	4, 5
Y	US 7,141,804 B1 (Akselrod et al.) 28 November 2006 (28.11.2006), col. 4, ln. 53-67, col. 7, 26-48	8, 9
Y	US 5,910,268 A (Keefer) 08 June 1999 (08.06.1999), col. 12, ln. 43-67, col. 18, ln. 20-27, col. 19, ln. 60-67, col. 20, ln. 14-15, col. 35, ln. 20-25, col. 35, ln. 46-52	10
A	US 4,743,083 A (Schimpe) 10 May 1988 (10.05.1988), entire document	1-10

☐ Further documents are listed in the continuation of Box C.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

11 May 2010 (11.05.2010)

Date of mailing of the international search report

01 JUN 2010

Name and mailing address of the ISA/US

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
P.O. Box 1450, Alexandria, Virginia 22313-1450

Facsimile No. 571-273-3201

Authorized officer:

Lee W. Young

PCT Helpdesk: 571-272-4300
PCT OSP: 571-272-7774