ELECTROMAGNETIC WAVE THEORY AND APPLICATIONS

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The Electromagnetic System Initiative

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Research in applied transformation based electromagnetics

The interactions of electromagnetic wave with a general class of spherical cloaks based on a full wave Mie scattering model is establish analytically. We show that for an ideal cloak the total scattering cross section is absolutely zero, but for a cloak with a specific type of loss, only the backscattering is exactly zero, which indicates the cloak can still be rendered invisible with a monostatic (transmitter and receiver in the same location) detection. Furthermore, we show that for a cloak with imperfect parameters the bistatic (transmitter and receiver in different locations) scattering performance is less sensitive to the impedance than the refractive index.

We consider the case where the background is no longer a homogeneous medium and determine the relative constitutive parameters of the cloak according to the multilayered and gradually changing background. We propose the parameters of cylindrical cloak structures working in multilayered and gradually changing media and the scheme of specifying these parameters could also be applied to the design of cloak in arbitrary isotropic background. The theoretical analysis based on coordinate transformation is given and numerical simulations are performed to illustrate these properties. The simulation results show that the cloaking with the proposed parameters performs well in these inhomogeneous background media. Potential applications are also discussed.

Effects of different transformations on the performance of cylindrical cloaks

Based on the scattering theory, the cylindrical cloak created with nonlinear transformation is studied. The cylindrical cloaks created with nonlinear transformations are confirmed to be perfect. The equivalent surface displacement current at the inner boundary of an ideal cloak is shown to be independent of the transformation function. For the nonideal cloak with perturbations on the inner boundary, we show that the performance of the cloak with low loss can be greatly improved by using certain nonlinear transformations.

Directive Emission Obtained by Coordinate Transformation

We use coordinate transformation theory to realize substrates that can modify the emission of an embedded source. Simulation results show that with proper transformation functions the energy radiated by a source embedded in these space variant media will be concentrated in a narrow beam. The thickness of the slab achieved with our transformations will no longer be restricted by the evanescent modes and the source can be placed at any position along the boundary of the substrate without affecting the radiation pattern. We also discuss the case where reduced parameters are used, which still performs well and is physically realizable.

Transmission of electromagnetic waves through circular defects in a metallic screen

The extraordinary optical transmission (EOT) phenomenon is one of the key problems in imaging of objects through lossy layer with defects. We utilized modal matching method to model the electromagnetic transmission through circular defects in metallic screen, especially at the THz band which is below the cut off frequency of a single defect. For randomly distributed defects, the total transmission can be obtained by simply summing transmission through individual defects while neglecting the coupling among different defects. For periodically distributed defects, the total transmission will be enhanced with increasing the size of the screen. Thus modeling a defected lossy layer with effect constitutive parameters must take into account the periodicity of defects.

Cherenkov radiation in an unbounded anisotropic double-negative metamaterial

Cherenkov radiation for a charged particle traveling in an unbounded anisotropic double-negative metamaterial is theoretically investigated to obtain the analytical expressions for the Cherenkov radiation condition, Cherenkov radiation angle and inversed Cherenkov radiation. The total radiated energy (spectral density) per unit length of path is derived using rigorous field theory. As a specific example, the effects of loss of the anisotropic double-negative metamaterial and the effective plasma frequency on the total radiated energy per unit length of path are also discussed. It turns out that the wave vector and time-averaged Poynting vector in an anisotropic double-negative metamaterial are nearly though not exactly anti-parallel, and the Cherenkov radiation angles and the total radiated energy in this case are different from those in the isotropic double-negative metamaterial.

Propagation properties of the SPPs modes in nanoscale narrow metallic waveguides

The propagation properties of surface plasmon polaritons (SPP) modes in nanoscale narrow metallic structures: gap, channel, and rectangular-hole waveguides, are analyzed by the complex effective dielectric constant approximation. The results show that all the SPP modes exist below the critical frequency where the real part of metal permittivity is negative unity. It is found that both cutoff frequency and cutoff height exist in channel waveguide and rectangular-hole waveguide. The channel and rectangular-hole waveguides have different propagation properties at cutoffs due to their different cutoff conditions. Compared with the gap waveguide, the channel waveguide has shorter propagation length and better confinement when the operation frequency is near the critical frequency, but has longer propagation length and worse confinement when the operation frequency is far from the critical frequency. Among the three waveguides, the rectangular-hole waveguide has the best confinement factor and the shortest propagation length. The comprehensive analysis for the gap, channel, and rectangular-hole waveguides can provide some guidelines in the design of subwavelength optical devices.

Research in Scattering from randomly rough surface

In analyzing electromagnetic scattering from randomly rough surfaces, we have extended the advanced integral equation model (AIEM) by a more rigorous treatment of the complementary scattering coefficient, and an inclusion of the error function terms that represent corrections to the models where they are neglected. Besides this model, we have also developed another analytical model which extends the IEM model by incorporating both statistical treatment of the surface slopes and field shadowing.

On the numerical technique side, fast numerical techniques have been proposed in the literature. One popular method is the sparse matrix /canonical grid (SMCG) iterative method, where the impedance matrix is divided into three parts, namely, i) a strong part to recognize the coherent mutual interaction for two points in the neighborhood of each other; ii) a canonical grid weak part which is obtained for the weak part by assuming a flat surface; and iii) a Taylor expanded flat surface matrix. This approach is computationally efficient for matrix-vector product, either involving sparse matrix or through the fast Fourier transform (FFT).

Recently we proposed another efficient method which was based on the stochastic second degree (SSD) method to solve the optimal structural parameter s which minimizes the expected spectral radius, in combination with the efficient approach for computing the matrix-vector product as embedded in the SMCG method. A new matrix-splitting scheme was also used for the impedance matrix generated from the magnetic field integral equation (MFIE). Appealing features of this new method include desirable stability in terms of time increase due to increase of the number of surface unknowns.

Multifunctional Wide-Band RF Systems

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Surface wave analysis of gyrotropic medium

A detailed study of surface TM modes at the interface between an isotropic medium and a uniaxial plasma is presented. Four cases for the isotropic medium, including normal, Left-handed, magnetic, and metallic media, are considered. The conditions for the existence of surface modes in each case are analyzed, showing that the existence is determined by the parameters of media, working frequency, and the direction of the principle axis. The Poynting vector along the propagating direction is also calculated. Depending on the media parameters and the frequency, the surface mode can have time-average Poynting vector in the opposite direction of the mode phase velocity.

A detailed study on the influence of an external magnetic field on a symmetrical gyrotropic slab in terms of Goos-Hänchen (GH) phase shifts is presented. The GH phase shifts at both boundaries of the slab are calculated, and the guidance condition is explained by means of them. It is found that the external magnetic field destroys the spatial symmetry of the field distribution, and we use the concepts of ‘penetration’ distance as well as effective thickness to illustrate the phenomenon. In term of the GH phase shifts, the spatial distribution of the time-average Poynting power is also derived. We find that influenced by the external magnetic field, the positive and negative time-average Poynting power along the waveguide direction can exist simultaneously in the gyrotropic medium, depending on the transverse position.

Research in metamaterials

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Research in metamaterials

A new design methodology for a low profile planar focusing antenna which can be achieved by constructing an anisotropic and inhomogeneous metamaterial structure has been proposed based on the transformation of a parabolic antenna. The electromagnetic behavior of the planar antenna is simulated by a two-dimensional finite element method and the results show that the planar antenna has the same performances as the parabolic antenna. This new technology provides an alternative design method to the conventional antennas.

A metamaterial-filled waveguide is designed to be able to bend at a right angle without reflection at the incident port. It is found that in the case of metallic waveguide, by applying transformation to the medium inside the waveguide at the right angle bend, a low reflection can be obtained. For a dielectric waveguide, we have applied transformation to both the dielectric core and the thin layer of cladding surrounding it at the bend to obtain a low reflection. Our proposed technique provides an alternative to designing bent waveguide with low insertion loss.

Effective EM parameter calculation

Effective EM parameter calculation- a widely used class of mixing models, formed by the ‘power-law’ approximation is studied for the design of random dispersing absorbers. It is found that scatterer’s geometry has an influence on the decision of formula’s power parameter in spite of random orientation. Our simulation shows that the formula fits to the effective permittivity of randomly orientated and located spherical and flake like scatterers with power factor equals to 1/3 and 1/2 respectively. Our analysis further introduced a geometric influence on the solution of the special beta distribution function which determines the value of β relating to the shape dependence of depolarization factors. It is found that the geometric feature of scatterers contributes to the mean depolarization through the integral of the whole composite. By this approach, a mixing law is figured out for the design of random dispersed composite in absorbing application.

Classification of UXO Via Machine Learning

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The Electromagnetic Induction (EMI) response from buried unexploded ordnance (UXO) has been studied with interest in identifying the buried object’s physical attributes. EMI signals can be decomposed into modes within a spheroidal coordinate system. The coefficients of those modes have been shown to be unique for unique objects. Therefore, these modes readily lend themselves for use in identifying and classifying the buried objects. With synthetic data generated by forward models, the appropriate coefficients were recovered and were processed using support vector machine (SVM) and neural networks (NN). Furthermore, the effects of small diffuse clutter fragments and uncertainty about the target position are investigated. This discrimination procedure is applied on both synthetic data from models and measurements of UXO and clutter. It is found that good discrimination is possible for up to 20 dB SNR. But the discrimination is sensitive to inaccurate estimations of a target's depth. It is found that the accuracy must be within a 10 cm deviation of an object's true depth. The general conclusion forwarded by this work is that while increasingly accurate discrimination capabilities can be produced through more detailed forward modeling and application of robust optimization and learning algorithms, the presence of noise and clutter is still of great concern. Minimization or filtering of such noise is necessary before field deployable discrimination techniques can be realized.

EMI Sensor Calibration

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This project seeks to characterize the output of a widely used EMI instrument, GEM-3, into known units of the magnetic field (A/m). This characterization will enable correct identification of physical properties of measured objects and of half-space soil such as the ground. To do the calibration, measurements were taken of several solid metal spheres. These measurements were then matched to modeled responses predicted by a reliable forward model. Thus an appropriate scaling factor to convert from the instrument output to the known units of the model was obtained. Furthermore, it was found that very simple modeling of the instrument's receiver is insufficient to characterize the response; the finite size of the receiver must be taken into account. In applying the recovered scaling factor to estimate soil susceptibility and permeability, this study concludes that the discontinuity created by the air to permeable soil interface produces minimal effect in the response of a buried object. The change is limited to a magnitude shift of the real portion of the EMI response and can be reproduced by superposition of a permeable halfspace response on the response of the same object in freespace.

Linear strategy for the real-time discrimination of the UXO

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Cold Regions Research and Engineering Laboratory

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This project seeks to find a linear strategy for the real-time discrimination or classification of UXOs under EMI measurement. The linear inversion procedure is used to find the location of the object, the orientation of the target, as well as it polarizabilities in the three spatial directions. We use a high frequency limit to obtain the volume and the shape of the object, from which we can get a real-time determinant whether the buried object is a UXO or not. Our analytical model is based on the spheroidal model and ellipsoidal model in the skin penetration approximation limit. The experimental measured results show the superiority of this method.

THz S-ring resonators

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The Defense Advanced Research Projects Agency

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This project seeks to characterize the output of arrays of THz S-ring resonators with different dimensions. Featuring dense spatial distributions of engineered metallic particles, electromagnetic metamaterials exhibit simultaneously negative values of both, dielectric permittivity and magnetic permeability, within a resonance frequency band called left-handed passband. The common embedding of the metal particles in plastic matrices or deposition on dielectric substrates within a small area severely limits the usefulness of the materials. We use UV or X-ray lithography to build comparably large areas and quantities of the freely-suspended matrix-free metamaterials in which the metallic structures are S-string-like with their ends held by a window-frame. *In vacuo* spectral characterization combined with simulation reveals left-handed passbands from 1.6 to 2.2 THz. Owing to their size, the devices can be easily handled. They offer a straightforward way of making them tunable and two-dimensionally isotropic.

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