ELECTROMAGNETIC WAVE THEORY AND APPLICATIONS

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The Electromagnetic System Initiative

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Imaging of objects through lossy layer with defects

The imaging method when a lossy layer is present between the target and the sensor is proposed with the aid of the concept of active left-handed material (LHM). The lossy layer with different kinds of small defects can be modeled as an isotropic layer with different effective constitutive parameters. Its effect on the reflection coefficients measured by the receiver can be canceled by imaginatively adding an active LHM layer, which has the same thickness as the lossy layer but opposite constitutive parameters. Therefore the updated reflection coefficients after such a signal processing significantly improve the effect of target imaging. Our simulation results demonstrate the effectiveness of this method.

1-D Single Side Left-handed Material based paired S-shaped Resonator

A one-dimensional metamaterial structure is realized by printing sub-wavelength paired S-shaped metallic strips only on one side of a dielectric substrate. The simultaneously negative effective permittivity and permeability of such metamaterial are retrieved from the scattering parameters yielded in the numerical simulation. Experiments aimed to verify the transmission and refraction properties of the metamaterial are conducted, and the results show the existence of the negative refraction within the same frequency band as indicated in the simulation. Compared to the conventional double-sided structures, the proposed structure design makes it easy to fabricate and provides feasibilities for making controllable metamaterial by incorporating itself with lumped active elements.

Controllable Left-handed Material Based on Single Side Paired S-ring Resonators

A design for controllable left-handed material based on single side paired S-ring resonator is proposed and experimentally realized. Both the results of simulation and experiments verify the tunable Left-handed properties of the structure in microwave band. By utilizing the controllable metamaterial, a tunable prism is built and beam steering of the prism is tested in the experiment. The simplicity of the active design makes it easy to be fabricated and give feasibilities for controlling.

Multi-band Simplified Metamaterial Composed of Paired Strips Resonator

Simplified metamaterial composed of paired strips resonator is proposed and experimentally realized. Such structure can support several different current modes which corresponds to multi-frequency bands where exhibits left-handed properties. From the simulation result, the effective permittivity and permeability of the metamaterial are retrieved and found to be negative simultaneously within two frequency bands whose the negative refractive indices are verified in experiment. This metallic pattern of this design is simplified and printed on one side of the substrate that make the fabrication process easy, especially for the case where the working frequency is high.

Multi-frequency resonator realized with dual-band S-shaped left-handed material

We experimentally realize a one-dimensional RHM (Right-handed Material)-LHM (Left-handed Material) multi-frequency resonator that consists of a dual-negative-band LHM and air arranged in an X-band waveguide. Multi-resonant frequencies are observed within two left-handed bands of the LHM. The effects of the loss and the hyperbolic dispersion relation of LHM layer are discussed. The incorporation of such a LHM into the resonator design allows more flexibility to realize multi-resonance.

Measurement of negative permittivity and permeability from experimental transmission and reflection

The measurement of the negative effective permittivity and permeability of a material is a direct way to verify its left-handed properties. A transmission experiment for a left-handed material sample is performed in a parallel plate waveguide. The effective frequency dispersive permittivity and permeability are retrieved from the experimental scattering data and found to be simultaneously negative in a specific frequency range. The simulation results also show that the misalignments of the metallic inclusions of the LHM introduce some dips to the retrieved curves, which prevent us from obtaining ideal curves following the Lorentz or Drude model.

Experimental retrieval of the effective parameters of metamaterials based on a waveguide method

A waveguide-based retrieval method for measuring complex permittivity and permeability tensors of metamaterials is presented. In the proposed scheme, multiple independent sets of scattering data for the material under test with different orientations are measured in the frequency range corresponding to the dominant TE10 mode. The method is applied to various metamaterials and shows its effectiveness in the effective parameters extraction.

Experimental Observation of Left-Handed Behavior in an Array of Standard Dielectric Resonators

We demonstrate that by utilizing displacement currents in simple dielectric resonators instead of conduction currents in metallic split-ring resonators and by additionally exciting the proper modes, lefthanded properties can be observed in an array of high dielectric resonators. Theoretical analysis and experimental measurements show that the modes, as well as the subwavelength resonance, play an important role in the origin of the left-handed properties. The proposed implementation of a left-handed metamaterial, based on a purely dielectric configuration, opens the possibility of realizing media at terahertz frequencies since scaling issues and losses, two major drawbacks of metal-based structures, are avoided.

Wideband backward coupling based on anisotropic left-handed metamaterial

Waveguides using a slab of left-handed metamaterial (LHM) adjacent to a slab of right-handed material (RHM) have shown backward coupling properties over the frequency range in the LHM passband where both permittivity and permeability are negative. We further show that when both slabs are LHMs with different passbands, the resultant backward coupling frequency band is a union of both passbands. The curious fact that the stop band of a metamaterial where permittivity is negative and permeability is positive can support propagating wave is shown theoretically. Backward couplers are demonstrated experimentally to have wideband and dual-band properties by judiciously choosing LHM-LHM and LHM-RHM slabs. This proposed method offers flexibility in producing wideband/multiband coupling and can be used to design and fabricate microwave devices.

Negative refraction and cross polarization effects in metamaterial realized with bianisotropic S-ring resonator

The refraction and propagation properties of left-handed materials with bianisotropic effects are investigated in this paper. We show that the dispersion relation of the material is strongly influenced by the inclusion of chirality, therefore, different refraction behaviors are observed corresponds to different values of the chirality. A realization of the bianisotropic left-handed material based on the structure of S-ring resonator is further proposed. By subtly shorting some horizontal metallic strips inside of the ring, magnetoelectric coupling is raised, leading to a bianisotropic effect in this artificial medium. The structure is theoretically analyzed from a microscopic viewpoint and then the macroscopic constitutive parameters are presented, where a nonzero chirality component is clearly shown. Numerically simulation shows that there exists strong cross polarization effects when wave incidents onto a slab of this material, further confirms the results predicted by our theoretical analysis.

Multifunctional Wide-Band RF Systems

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Surface wave

A detailed study of surface TM modes at the interface between an isotropic medium and a gyrotropic medium with an infinitely strong external DC magnetic field in an arbitrary direction is presented. Four cases for the isotropic medium, including normal, LHM, 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 external magnetic field. 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.

Fields evaluation in metamaterial substrates for optimized antenna isolation

The surface wave coupling between two patch antennas is investigated both analytically and through independent numerical simulations as function of the substrate properties. With the goal of achieving an optimal isolation between the two antennas, we consider all possible metamaterial substrates: right-handed, left-handed, mu-negative, and epsilon-negative. First, the guidance condition is generalized to encompass all possible cases and to provide existence conditions of the surface waves as functions of the substrate parameters. Second, the actual coupling level is predicted based on the evaluation of the Green's function of the con_guration. The evaluation is performed both numerically via the Sommerfeld integrals and asymptotically, which are two methods we generalize here in order to take into account the new poles in the complex plane generated by the possibly negative constitutive parameters. The results obtained by these two methods are compared and additionally con_rmed by numerical simulations using the commercial software CST Microwave Studio. The tools thus created are subsequently used in a Genetic Algorithm optimization to select the material parameters for an optimal isolation. Finally, a physical implementation of the solution, based on split-ring resonators, is proposed and simulations of the structure show that a good isolation performance can be achieved.

Surface wave suppression in antenna systems using magnetic metamaterial

In the presence of normal substrates, it is well known that there exists strong transverse magnetic (TM) surface wave coupling between antenna ports on a shared ground plane. Through the analysis of surface wave propagation, such coupling is proposed to be substantially decreased via the use of magnetic metamaterials. The design and the characterization of the metamaterials are presented, and it is shown that within a certain frequency band, the material behaves as an anisotropic magnetic plasma, suppressing the propagation of a TM surface wave. Experimental measurements further confirm such a suppression, and an isolation improvement of 15 dB between an aperture spaced 9.2 cm apart is observed, in agreement with numerical simulations.

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). SVM and NN, being statistical learning algorithm which are able to identify trends in training data, were able to learn the association between the spheroidal mode coefficients and various appropriate classes into which UXO can be sorted. In particular, the interest lies in identifying body-of-revolution objects from non-body-of-revolution objects, homogeneous objects from non-homogenous objects, and large objects from small objects. These classification objectives are geared toward identifying UXO from clutter objects. In this study, SVM and NN were successful in classifying various objects along these lines. The spheroidal mode coefficients of the test objects were recovered from EMI data comprised of both synthetic data and measurement data. Furthermore, the effects of additive Gaussian noise and uncertainty in the object's position and orientation were studied. SVM was shown to reliably classify objects using EMI data that was corrupted by such noise.

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. Current and future work lies in applying the recovered scaling factor to estimate soil susceptibility and permeability which will provide further gauge of its accuracy.

Linear strategy for the real-time discrimination of the UXO

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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 shows the superiority of this method.

SAR Interferometry and InSAR application of CCD

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SAR Interferometry

Introduction of a third satellite to the conventional two-satellite InSAR provides us with three interferograms instead of one. We looked into ways on making use of these additional data to improve the height retrieval process. In particular, the non-collinear three-satellite setup will be addressed. *Phase averaging* method which involve combining the three available interferograms and retrieving a single set of height instead of three, is introduced. This allows the multi-baseline data to be perceived as coming from only a pair of satellites, and facilitates the application of conventional two-satellite height inversion process without need for excessive modifications. Yet, at the same time, the approach returns more accurate results than just using data from each of the satellite pairs. *3-D projection* is a technique to reduce the impact of noise during the phase unwrapping step. It makes use of the fact that the geometry of the satellite configuration constrains the relationships among the three phases retrieved by the three satellites. We have now successfully implemented 3-D projection on an interferometric cartwheel setup, and showed that the resulting retrieved terrain profile is more accurate.

Next, we consider two effects of the orbits on SAR interferometry. The first one involves relating the three-satellite configuration to an interferometric cartwheel while the second one takes into account satellite positioning errors. In the former, a circular cartwheel is setup such that the three satellites are in constant motion even within a snapshot of the interferogram. However, only a set of the height retrieval parameters, corresponding to the satellite positions at the beginning of the shot, are assumed to be known. In that case, the interferogram may be perceived as imperfect for height inversion. Nonetheless, it was found that a self-compensating mechanism exists within such a setup itself so that we are still able to correctly retrieve the terrain heights. This is made possible upon application of a *baseline-weighted averaging* scheme on the heights. In the latter, we consider errors in the satellite positioning data due to instrumental noise effects. These errors propagate into unacceptably large misalignments in the retrieved terrain profiles. Attempts are made to account for these errors without knowledge of any ground truths, making use of some cost minimization functions.

InSAR application of CCD

In InSAR application of CCD, temporal changes of illuminated scenes are detected by observing them at different times. Retrieving a CCD map using the multilook coherence estimator ignores the true topography and is therefore, slope dependent. Ways of compensating for coherence losses due to terrain slopes and inexact satellite repeat tracks are identified. These losses introduce ambiguities in the interpretations of low or medium coherence values: if they represent a scene change or simply an undulating terrain. Solutions to this issue include accounting for the topographic phase variations via prior knowledge of the DEM or a distinctive approach in the wavelet domain. While the latter is shown to produce a map with higher spatial resolutions, the former returns the best overall performance in CCD, in terms of mean RMS coherence error, and requires a multibaseline satellite configuration for accurate retrieval of the DEM.

Modeling trapping and binding forces between particles

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Two approaches were equivalently applied to various problems. The divergence of the Maxwell stress tensor relies on the conservation of momentum to deduce the forces on a material. On the other hand, the Lorentz force density states that the forces exist everywhere inside the matter once the fields are present. For example, the pressure on a lossless slab can be viewed as resulting from momentum changes at the two boundaries, or the pressure can be viewed as originating from the standing wave patterns inside the slab. In all cases studied herein, however, the prediction of experimental observable quantities is identical. Furthermore, the conceptual problem of the radiation attraction of a lossless dielectric interface has been reconciled in favor of the results derived by Daly and Gruenberg [61]. Reconciliation has also been shown for multiple examples of particles subject to multiple electromagnetic waves.

The momentum transfer to media has been separated into an adiabatic process and a non-adiabatic process. These processes are derived from the Lorentz force density exerted upon bound currents and charges and upon free currents, respectively. This separation was shown to be very useful in modeling various experimental observations of electromagnetic momentum transfer due to absorption in polarizable media. It is concluded that the direct dependence of absorbed momentum on the refractive index holds for both dielectric and magnetic media. These conclusions remain valid for temporally dispersive media. Thus, in the case where the index of refraction is negative, free currents are pulled toward the incident wave as the wave attenuates inside the material. This result is in agreement with the reversal of radiation pressure predicted by Veselago. This viewpoint of electromagnetic wave momentum is generalized to model electromagnetic momentum transfer in lossless systems such as reflections from submerged mirrors and optical manipulation of mesoscopic particles in a background medium. In this regard, the electromagnetic wave momentum, which contains contributions from the electromagnetic fields and the response of the material, can be applied to predict observations in a wide variety of problems. We may conclude that the theory presented here attaches fundamental physical meaning to Snell's law; the reflected and transmitted wave vectors ensure conservation of the momentum component which is parallel to the boundary. Likewise, the magnitudes of the reflected and transmitted waves ensure conservation of wave energy at the interface. This assertion ensures that no sheering force exists due to the reflection and transmission of an electromagnetic wave at an interface. The theory is applied to predict a decrease in optical momentum transfer to Mie particles due to absorption, which contrasts the common intuition based on the scattering and absorption by Rayleigh particles.

Evidence of optical trapping and binding forces have been predicted in one dimension and two dimensions without approximation. Optical trapping of single particles subject to multiple waves and Gaussian beams can be modeled using Mie theory and the scattering of electromagnetic wave momentum computed from the divergence of the Maxwell stress tensor. Thus the formulation is not only exact, but computationally efficient both in computing the fields and deducing the forces. Optical binding was demonstrated in one dimension by studying the interaction of multiple plane waves incident by an electromagnetic waves. Modeling of multiple particles in an in-plane electromagnetic wave is based on an extension of Mie theory to cylindrical particles combined with the Foldy-Lax multiple scattering equations. Modeling the electrodynamics of a system of particles represents an advancement in the understanding of optical trapping and binding. Using this formulation, a new trapping regime based on optical binding forces has been demonstrated analytically. The possibility of serially guiding and sorting nanometer sized particles using optical binding forces is also demonstrated. These applications are derived without approximation or explicit separation of scattering, trapping, and binding forces. However, they do serve to demonstrate the effects of multiple particle interactions.

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