Electromagnetic Wave Theory and Applications

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The Electromagnetic System Initiative

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Retrieval of the bianisotropic metamaterial

The retrieval methods to compute the effective permittivity and permeability of metamaterials published so far deal with isotropic permittivity and permeability. However, it is known already that the metamaterials are intrinsically anisotropic because of the orientations of the rings and rods in space, and that they are also possibly bianisotropic because of the specific properties of their split-rings. In this work, we present a methodology to retrieve bianisotropic parameters of the original concentric split-ring resonator, known as edge-coupled SRR. Seven components of the constitutive tensors are to be solved for in this problem, thus at least seven equations are required. In order to obtain these, we resort to multiple incidences so that the problem is overdetermined.

We propose a method to retrieve the above-mentioned constitutive parameters of a homogeneous material from the measured *S* parameters. The analytical inversion equations are proposed for homogeneous lossless bianisotropic media, and a numerical retrieval approach is presented for the case of lossy bianisotropic media. Both methods are verified by numerical examples, where analytical ε, μ, and ξ, are supposed and are retrieved from the S parameters. Finally, we use the retrieval method to study the properties of various SRR-based metamaterials. The retrieval results corroborate the conclusions found in the previously published work, proving the existence of the bianisotropy in the edge-coupled SRR metamaterials, but not in the broadside-coupled SRR metamaterials.

Optimization approach to the retrieval of general bianisotropic media

Constitutive parameters are important in quantitatively characterizing the wave propagation inside metamaterials, but they are usually unknown to us. This work presents a method to retrieve the constitutive parameters of a general bianisotropic slab from the knowledge of the reflection and transmission matrix via an optimization approach. Note that each of the permittivity tensor, permeability tensor, and cross-polarization tensors is a three by three matrix with complex elements, so that there are 72 real parameters to be retrieved. The retrieval problem is challenging due the high-dimension, strong-nonlinearity, and many local-minima. In this work differential evolution (DE) and simplex optimization methods are used in order to obtain the global-minimum solution. In the optimization, we minimize the relative mismatch between the measured reflection/transmission data and the calculated ones from the forward approach, where the reflection and transmission coefficients for a plane weave obliquely or normally incident upon a slab in free space are calculated by the notion of propagators and wave-splitting technique.

The proposed method is applied for to not only general media with unknown constitutive properties, but also media with known constitutive properties. In our numerical validation, we first apply our method to the retrieval of a rotated biaxial medium, where 15 parameters need to be optimized. Then we retrieve a rotated omega medium, where 17 parameters need to be optimized. Finally, we apply the proposed method to the retrieval of two general bianisotropic media, where 72 parameters are optimized. In all the cases, we obtain a group of solutions, instead of a single one. The fact that all the obtained solutions are close to the true one shows the robustness of the proposed optimization method.

Beam shifting experiment for the characterization of left-handed properties

We report experimental results on the shift of a beam that propagates through a slab of metamaterial, known to exhibit left-handed properties. A similar experiment with a Teflon sample of similar size is also carried out for comparison The results show the existence of a frequency band over which the shift experienced by the beam exceeds the theoretical limit above which the material is left-handed. This demonstrates the effectiveness of using a beam shift experiment to characterize the left-handed properties of metamaterial.

Experimental confirmation of negative refractive index of a metamaterial composed of Ω-like metallic patterns

A one-dimensional metamaterial is realized using three connected Ω rings printed back-to back and reversed on two sides of a dielectric substrate Both transmission and prism experiments are reported, yielding concordant results of the presence of a left-handed frequency band. Experiments show reduced losses and an enlarged left-handed frequency band.

Goos-Hanchen (GH) phenomena with Left-handed materials (LHM) slabs

Simultaneous positive and negative Goos-Hanchen (GH) lateral shifts are shown to occur as a function of incident angles with a single slab of left-handed metamaterial. This phenomenon is different from previously established cases where the GH lateral shift can be either negative or positive when different LHM slab configurations are used. We also show that there exist two distinct cases with this unique phenomenon. One case has two regions of incident angles where the GH lateral shift directions are different, while another case has three regions with alternated GH shift directions. A generalized analytic formulation for the GH lateral shift direction analysis is provided, from which it is further shown that this unique phenomenon is related to the relative amplitudes of the evanescent waves inside the LHM slab. This physical interpretation is confirmed by the study of energy flux pattern inside the slab.

FDTD simulation of Goos-Hanchen (GH) phenomena with LHM slabs

This study is to rigorously validate the FDTD method in applying to LHM simulations, especially in the cases where growing evanescent waves need to be simulated inside the LHM slabs. We first show that the reflected electric field magnitude, which experiences a lateral shift from the incident electric field in the GH shift phenomenon, can be calculated from the FDTD simulation and be rigorously validated by the analytical solutions for conventional slabs (also referred to as right-handed materials (RHM) slabs). We also successfully simulate LHM slabs embedded in the air and verify the result with analytical solutions. However, we find out that when the LHM slab is matched to the medium in the transmitting region, which is the case that only growing evanescent waves occur inside the slab, the simulation results can not agree with analytical results for the slab above a certain thickness, for example, 1 wavelength thick slab in the case we simulated. Different cell sizes are tested in the simulation and yield different results for fields inside the slab, which suggest that this issue might be related to the convergence of the FDTD method.

Subwavelength imaging with finite left-handed materials (LHM) slabs

We study the subwavelength imaging capability of finite size left-handed materials (LHM) slabs using 2-D FDTD simulation methods. We realize that in this specific setup, the image resolution can be unambiguously determined by the time averaged Poynting power instead of commonly used electrical field amplitudes. Then the subwavelength resolution is demonstrated using a matched LHM slab with a length of 10 wavelengths and a width of 0.2 λ. The spatial frequency information at the image plane was obtained by doing the Fourier transform of the simulated fields in both time and space. The relation between the imaging resolution and the maximum spatial component which can be amplified by the slab is verified. Finally we study the imaging resolution affected by the length of the LHM slabs and find out that when the length is reduced from 10~λ to 1~λ, some spatial information are lost in the image and the amplitude of the image has a oscillating behavior in time.

Linear Guided Mode in LHM

A unique guided mode with a zero transverse wave number is shown to be supported by a slab of Left-Handed Material (LHM). Unlike the known guided modes with trigonometric and hyperbolic profiles, this unique guided mode has a linear profile, which was never reported before. It is a transitional mode between the sine and the sinh modes when the mode is anti-symmetric; however the transitional mode between the cosine and the cosh modes only exist in a special case as a TEM mode when it is symmetric. The properties of this unique guided mode are discussed and demonstrated by numerical examples in this study. A possible experimental configuration is given to realize the linear profile when the mode is non-physical, i.e. the field may grow outside the slab.

Cerenkov Radiation in Cylindrical Waveguide Composed of LHM

Cerenkov radiation in a multi-layered cylindrical media is systematically studied in this work. When the charged relativistic particle travels along the axis of the cylindrical core of normal media, the Cerenkov radiation can exhibit different properties when the core is covered with a material with both negative permeability and permittivity (Left-Handed material), in comparison to the outer layer being another normal media. It is shown that the radiation will bent backward if the outer layer is LHM and the Cerenkov radiation condition is satisfied. A surface plasmon could also be excited when the condition is not matched, which will result that the charged particle will always loss energy without the threshold of the velocity when the core is surrounded by LHM, although the Cerenkov radiation condition in the core is not satisfied. When the core is replaced as LHM, and covered by PEC to form a metallic waveguide filled with LHM, a high power backward radiation can be realized, which can be used as an experiment guide to detect the reversed Cerenkov radiation in LHM, as mentioned in Veselago's original paper on LHM. Due the effect of the waveguide, the radiation can be localized into frequencies for guided modes in GHz frequency, which shows the possibility for detecting the reversed Cerenkov radiation in currently realized structures. Both the dispersion and the loss of the permittivity and permeability are considered. The effect of the air channel for the particle traveling through without interacting with the core material is also investigated. The possible outcome is predicted and should be paid attention to in a future experiment design. A three layer structure is studied and proposed to utilize the LHM as a band pass filter to improve the performance of the traditional Cerenkov radiation detector.

Multifunctional Wide-Band RF Systems

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Enhancement of a Microstrip Filter using Left-Handed Metamaterials

A left-handed metamaterial consisting of split-ring resonators is constructed and used as a substrate for a microstrip line. Transmission measurements show that the substrate acts as a natural stopband filter. The effective parameters retrieved from the transmission simulation of the split-ring resonator unit cell show that the stopband in the microstrip measurement corresponds to the region of negative permeability in the substrate. The natural stopband of the substrate is used to enhance the total bandwidth of a quarter-wave stub stopband filter.

Left-handed material composed of only S-shaped resonators

We analyze an S-shaped inclusion for the realization of metamaterials exhibiting left-handed properties. Unlike most of the conventional inclusions used so far that are composed of two separate geometries – typically a split-ring and a rod -, the inclusion proposed in this project is made of only one S-shaped element which yields an overlapping negative permittivity and negative permeability response over a frequency band of about 2.6 GHz. By adopting this geometry, we manage to lower the negative permittivity frequency band down to the level of the negative permeability frequency band, thus allowing the overlapping to occur. Therefore, the structure works as a stand-alone and does not require the use of an additional rod. A theoretical analysis is carried out to study this inclusion and numerical simulations as well as a Snell refraction experiment clearly show that the material indeed exhibits a negative index of refraction at some frequencies. The simple pattern of the inclusion, the wide left-handed frequency band exhibited and the low losses measured indicate the superiority of this inclusion in the realization of left-handed metamaterials.

Design and realization of left-handed metamaterial with negative refractive index in multiple frequency bands

We present experimental measurements at microwave frequencies of a double band left-handed metamaterial. The sample of metamaterial is composed of an extended version of the S-shaped resonators that exhibit simultaneously a negative permittivity and a negative permeability response at comparable frequencies. The experimental results clearly show that there exist two frequency bands where the refraction index is negative. The double left-handed pass bands are due to the multiple capacitances and inductances induced in the structure, which can be further tuned to realize a metamaterial with multiple (more than two) left-handed frequency bands.

Design and Measurement of a Four-Port Device Utilizing Left-Handed Metamaterials

The reflected and transmitted power as well as the refraction angle from a metamaterial prism is a frequency dependent phenomenon. A four-port device utilizing a metamaterial with frequency dispersion in one component of the permeability tensor is designed and measured experimentally. In operating the device, the input signal is incident onto the metamaterial prism. Power transmitted into the prism is refracted towards the positively refracted or the negatively refracted output port depending on frequency. Reflected power is measured at a third output port. The results demonstrate the device is able to achieve mutually exclusive bandwidths at each of the output ports.

The four-port device is then investigated analytically with more rigorous design requirements. While in the measured design a very small incidence angle was needed to insure phase matching at the negative refraction port. This resulted in the input port and reflection port being at a 30^o angle relative to each other. Here we require all ports to be at right angles relative to its adjacent ports. This fixes the prism angle to 45^o. This geometry will insure the reflection port is at a 90^o angle with respect to the incident port. The prism is cut to insure positively refracted waves output port is at a 90^o angle with respect to the reflection port. The exit angle at the negatively refraction port is frequency dependent. The device must be designed to insure this refraction angle is centered at a right angle with respect to the input and positively refraction output port. With this expectation we study designs where the metamaterial prism has one, two, or three dispersive parameters. The performance is estimated analytically for a proposed design for each case. The number of dispersive parameters affects the bandwidth and power level at the negative refraction output port. Tradeoffs between metamaterial complexity, bandwidth, and power at this port are investigated.

Microwave solid-state left-handed material with a broad bandwidth and an ultralow loss

We present a solid state sample of microwave metamaterial produced by a standard hot-press technique for the manufacture of printed circuit boards. We performed three experiments to demonstrate that the sample is a left-handed material with negative refractive index. The three experiments are power transmission prism refraction, and beam shifting. We used differently shaped samples for the experiments and observed clear left-handed behaviors in a 1 GHz wide passband with an insertion loss of les than 0.5 dB per unit cell, which is no greater than the insertion loss of many microwave devices. The sample has very stable characteristics and all results are consistent with on another.

Inversion of critical angle and Brewster angle in anisotropic left-handed metamaterials

We study the inversion of critical angle when a wave propagates through an anisotropic and a bianisotropic metamaterial exhibiting negative permittivity and negative permeability along some specific directions. This inversion off critical angle is explained by the dispersion relation of the medium, which shows that waves are totally reflected for low incident angles and transmitted for high incident angles. In addition, analytical formulae for the loci of the Brewster angles are derived for both half-space and slabs of both anisotropic and bianisotropic media, where the bianisotropy is the one exhibited by some split-ring resonators. Experimental results are provided and corroborate the theoretical predictions.

Research on SAR Interferometry

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Our study investigates SAR interferometric (InSAR) height retrieval post-processing techniques. It explores the possibility of further improving results in height retrieval with the addition of a third satellite to the two already in orbit, and also some of the applications made possible. As such, two new methods for height retrieval are proposed and results are compared with the original 2-satellite method. The first method introduced would be data averaging, a deductive method that employs and uses results obtained from the 2-satellite method. The 3 sets of data attained per sampling look are grouped into pairs, and the statistical best 2 of 3 possible pairings are selected to be averaged, producing a better estimate of DEM height than would the best 2-satellite pair. The second method is the maximum likelihood estimation technique, an asymptotically efficient method which seeks to override the heavy reliance on phase unwrapping steps in the 2-satellite configuration, and within an expanded phase range seeks to predict the best value which fits the data sets provided. The method of unambiguous range magnification will serve as a precursor for the maximum likelihood method.

Results and conclusions are entirely simulation-based, using the engineering tool Matlab Version 6.1. Single- and multiple- trial simulations are compared for 1-dimensional interferograms only, since the 2-dimensional ones can be easily extended and are not part of the scope in focus. In most cases, the root-mean-square error will be the metric for comparison.

It is realized that for a single simulation, the data averaging method provides for an efficient and non-computationally intensive method for improving retrieved height results. This method can also help eliminate the need of GCPs in height retrieval, though it is shown to be limited by noisy data. The maximum likelihood method is shown to be asymptotically favorable when compared to the data averaging method, since it yields the best results when large numbers of data samples are collected.

AMTI Using a Spaceborne Satellite Constellation

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There is an interest in the use of spaceborne satellites for the detection of targets moving in the air and on the ground. Such a configuration has many benefits over traditional airborne configurations. In this study we investigate airborne moving target indication (AMTI) by means of a sparse satellite constellation. The algorithm used for the suppression of clutter is space-time adaptive processing (STAP). This method utilizes the spatial degrees of freedom and temporal degrees of freedom to suppress clutter in the azimuth-Doppler space. Spatial degrees of freedom are achieved by taking simultaneous measurements at each element on each satellite. The temporal degrees of freedom are obtained by repeating the same measurements a specified number of times.

The research investigates the performance degradation resulting from sparse antenna element positions and characterizes it using various performance parameters. Various levels of clutter presence are considered to simulate low to high clutter environments. For each element configuration, resolution bounds in azimuth and Doppler are calculated. Results are compared to the performance of an airborne AMTI mission.

Research on Geolocation and Landing Radar

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Three Satellite Geolocation Using TDOA and FDOA Measurements

Geolocation refers to the localization of an emitter from measurement by passive receivers at known locations. It is also commonly referred to as multilateration. Distance measurement has historically been done from the measurement of time difference of arrival (TDOA). When relative velocity exists between the source and receivers, frequency difference of arrival (FDOA) can also be used. We investigate the theoretical development of the 3-satellite geolocation problem and evaluate the derived solution method on realistic problems via numerical simulation.

We developed the theory from first principle of propagation delay (TDOA) and Doppler shift (FDOA). An additive noise model was applied to each measurement. The TDOA and FDOA equations were solved iteratively for the unknown source location. The source location estimates were shown to achieve the derived Cramer-Rao Lower Bound (CRLB) in low noise. Improved source location estimates were shown possible by use of an altitude constraint. However, it was also demonstrated through simulation that error in the assumed source altitude projects error bias onto the coordinates of the source location estimate. Increased satellite separation distance or the efficient use of multiple measurements can also be used to improve the location estimate.

Landing Radar

Landing radar uses an electromagnetic system for the determination of altitude and velocity of a landing craft. The altitude is determined by round-trip propagation time from a nadir pointing radar. The signal is edge triggered so that the leading edge of the return signal will render the altitude measurement. Velocity is determined in three dimensions using Doppler measurements from off-nadir radar.

We develop the equations for determining altitude and velocity from a general radar system. We show that both altitude and velocity can be determined from independent linear systems as reported in early literature for lunar landing and helicopter development. We then demonstrate the accuracy of a specific system under the influence of nuisance inputs such as timing jitter from surface roughness, measurement noise, and unintentional system rotation.

Research on Coherent Change Detection (CCD)

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One post-processing technique that takes advantage of using 3 SAR satellites is Coherent Change Detection (CCD). CCD refers to the process of using the obtained coherence values from 2 or more co-registered SAR images which have been separated by a reasonable time period to detect changes in terrain. The current configuration of CCD involves processing of SAR image values using a single 2-look satellite. Like the processing techniques of interferometry, the results of this single system is sensitive to noise, and this leads to statistical variations in results which may alter or even hide actual terrain changes which may have occurred. In view of this, the addition of a second satellite and even a third for each look of flight is explored, with the expectation that white noise can be extracted by averaging the coherence maps obtained from each satellite.

Results are entirely simulation-based, using the engineering tool Matlab Version 6.1. Single- and multiple-trial simulations are compared for 1-dimensional interferograms only. In most cases, the root-mean-square error will be used as the metric for comparison.

UXO Discrimination with Environmental Effects

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Cold Regions Research and Engineering Laboratory

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The Electromagnetic Induction (EMI) response from buried unexploded ordnances (UXO) has been studied with particular interest in the realistic problems that affect the quality of the measured response. Part of our concentration has been in the “backward problem” which is, given a measured response, we must find the correct UXO type, position, orientation, and other distinguishing factors. Thus, factors that affect the measured response are of great concern. Homogenously permeable and non-conductive soil with an idealized smooth surface has been found to produce a predictable offset to the signal. This offset can be considered to be independent of the UXO response in the range of realistic soil permeability. Using EMI responses collected from actual buried UXOs, we have had some success in finding the correct location, orientation, and UXO type, selected from a library of possible types, when the unknown buried UXO is large compared to the burial depth. This process was done with the use of a search algorithm, an empirically derived forward model, and our predictions about the affects of the soil permeability. These methods thus allow us to perform an optimization to the measured responses. However, the limitations of this approach are significant when the soil is contaminated by small pieces of metallic clutter that cannot be easily predicted using simple noise models. Furthermore, rough soil surfaces will contribute another source of noise. Distinguishing the UXO response from the noise and clutter components is part of the ongoing research.

Electromagnetic Models and Data Analysis for UXO Discrimination

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Spheroidal mode approach in detecting and classifying buried objects

We have constructed a spheroidal mode approach under time harmonic excitation in the magneto-quasistatic regime for detecting and classifying metallic buried objects. Spheroidal mode approach is chosen in this work because the spheroidal coordinate system can be made to conform to the general shape of an object of interest, whether flattened or elongated, and many of our objects of interest are bodies of revolution. Furthermore, the response of any discrete scatterer (including non-spheroidal objects) can be represented in terms of basic mode solutions in spheroidal coordinate system. It can be proved mathematically that the scattering coefficients of orthogonal spheroidal modes are characteristics of the object, thus they can be used as discriminators in the pattern matching and classification.

This work is an extension of our work in last year, where the theoretical anaylysis and basic experiment verification were presented. This work addressed some practical issues in the application of the spheroidal mode approach. The ill-conditioning is dealt with the mode truncation method and Tikhonov regularization technique. The proposed method is tested by both noisy synthetic data and experimental data. Many examples show that four fundamental primary modes and only few basic secondary modes are usually good at retrieving the characteristic scattering coefficients. Finally, we use the characteristic scattering coefficients as discriminator to train support vector machine (SVM) to sort object to some generic classes, such as elongated or not, permeable or not. Experimental results show that the spheroidal mode approach is promising in the future application in detecting and classifying buried objects.

Electrostatic Phenomena from Moving Objects

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BAE Systems

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In recent years, sensors have been developed for the detection of electrostatic disturbances from slowly moving objects. Applications for these sensors are being developed in industry, but better models for their predicted behavior is needed to facilitate the design process. We investigate the theoretical considerations for the forward electrostatic problem and inverse problems of detection and estimation.

First we investigated the solutions to forward problems involving the electrostatic potential distribution in space for a number of geometries and excitations. We considered analytic solutions for conducting and dielectric objects that disturb the incident field. We solved the problems of field disturbance for a conducting sphere in an initially uniform electric field that is either in free space, near a conducting plane, and resting on a conducting plane. We then solved the problems of a point source near a conducting/dielectric plane and sphere. Finally we solved the problems of electrostatic field disturbance due to conducting spheroids in an initially uniform field and near a point charge on the axis of rotation.

The solutions to forward problems were used to develop models for the object creating the electrostatic disturbance, as well as for the system used to detect the disturbance. A typical sensor used for detection generally consists of a band-pass amplifier with the input connected to an electrostatic electrode. To model the system, a mutual capacitance model that describes the physical interaction between source and electrode must be included in the amplifier equivalent circuit. Therefore, an analytic model for the mutual capacitance is highly desirable. We developed a potential averaging method based on the mean value theorem to give approximate analytic expression for the potential of a conducting electrode in a known incident field. Hence, due to a disturbance on known charge, an analytic approximation for the mutual capacitance can be used in the system circuit model.

Ongoing work considers the inverse problems of source localization and direction of arrival (DOA) estimation from a set of sensor measurements at known locations. We assume additive Gaussian noise for each sensor measurement and derive estimators for instantaneous source localization. We then compare with the theoretical optimal performance given by the derived Cramer-Rao Lower Bound (CRLB). It is shown that an iterative Maximum Likelihood estimator achieves the CRLB in low noise. Ongoing work also considers DOA estimation from selective measurements in low signal-to-noise ratio. The fundamental goal is the determination of optimal sensor placement for various applications and environments.

Miscellaneous

Computation of trapping and binding forces in a system of cylindrical particles

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The position of particles in space can be influenced by an external electromagnetic field. These forces are derived from the Maxwell's stress tensor, and therefore exist as soon as an electromagnetic field is present in space. If multiple electromagnetic fields coexist, their interference creates regions in space where the various forces may cancel out creating a trap for a particle. When multiple particles are present, their scattering perturbs the original field and can weaken some traps while creating others. Hence, in addition to the trapping phenomenon, a binding phenomenon also appears. In this work, we first establish the theoretical ground governing such phenomena and build simulation tools to investigate their use in applications. The main two concerns we address are (1) the stability of the mirror (i.e. how the particles perturb the electromagnetic fields and forces, how are the positions of the particles affected by external radiation, etc) and (2) the ability of the dish to focus an incoming plane wave. In order to achieve these goals, we investigate first a two-dimensional dish made of infinitely long cylinders. The forces on interacting cylinders is calculated using the Foldy-Lax multiple scattering equations, and the variation of these forces are quantified as function of external factors.

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