ELECTROMAGNETIC WAVE THEORY AND APPLICATIONS

Academic and Research Staff
Professor Jin Au Kong, Professor David H. Staelin, Dr. Bae-Ian Wu, Dr. Hongsheng Chen

Visiting Scientists and Research Affiliates
Dr. Kenneth Senne, MIT Lincoln Laboratory, Lexington, MA.
Dr. Tarek M. Habashy, Schlumberger-Doll Research, Cambridge, MA.
Dr. Fanming Kong, Shandong University, China.
Dr. Hui Huang, Beijing Jiaotong University, China.
Dr. Zhaoyun Duan, University of Electronic Science and Technology of China, China
Dr. Diren Liu, Yangtze University, China

Graduate Students
Isaac Ehrenberg, Cedric Blanchard, Shaoying Huang, Peiheng Zhou, Beijia Zhang, and Baile Zhang.

Technical and Support Staff
Sunny Lee, Zhen Wu

The Electromagnetic System Initiative

Sponsor
MIT Lincoln Laboratory

Project Staff
Dr. Bae-Ian Wu, Dr. Fanming Kong, Dr. Zhaoyun Duan, Dr. Hui Huang, Baile Zhang, Cedric Blanchard, Peiheng Zhou, Isaac Ehrenberg, and Shaoying Huang

Devices for Surface Enhanced Raman Scattering and High Harmonics Generation

Surface-enhanced Raman scattering (SERS) has recently been the subject of renewed interest, more than 30 years after the original observation of this effect. This strong interest, both in the experimental and simulation areas, is attributable to progress toward the practical realization of SERS, enabled by new nanofabrication techniques.

In the studies on surface-enhanced Raman Scattering (SERS), individual metal nanoparticle and particle assemblies introduce enhancement of electromagnetic fields. However, the contributions to enhancement due to the substrate has yet to be studied to satisfaction. We use numerical simulation method to investigate the effect of geometries with realistic layers on SERS phenomena [1-3]. The method quantifies the effect of a substrate on the electric field on nanoparticle surfaces. By applying the method, optimal constructions can be obtained to maximize the surface electric field while a poorly constructed one can be avoided. The maximization can lead to a high Raman enhancement factor.

Concurrently, the ability of nonlinear mechanisms to generate high order harmonics at frequencies beyond visible range has attracted interest as it provides a means to generate high frequency EM waves with reliable and portable sources. The mechanism requires plasmonic structures to be used in conjunction with reactive gases to facilitate the emission of high frequency waves. We are improving such concept by designing structures that are frequency selective to provide further control over the emission. These studies will hopefully provide new understanding of plasmonic devices and new methods for designing structures for high frequency applications.

Use of transformation approach for novel electromagnetic devices

The combination of the development of metamaterials and the transformation technique proposed recently has offered remarkable possibilities for control over electromagnetic fields with many potential applications, such as low-profile planar focusing antennas, electromagnetic rotators and concentrators, artificial wormholes, and so on [4-5]. This topic has attracted much attention in optics, microwave engineering, material science, and mathematical physics.

The transformation technique can be used to implement interesting functions. For example, hyperbolic antennas can be reshaped into planar antennas with low profiles, and virtual apertures offer a promising method for increasing the gains of electrically small antenna systems.

Overall, the transformation coordinate method has been used to produce material specifications that control electromagnetic fields. Given a desired device function, the transformation theory can yield electromagnetic properties that turn this function into reality. The technology, building upon developed applications using metmaterials [6-13], shows much promise in electromagnetic device design for multiple applications, but still need comprehensive investigation.

Studies on transformation-based cloaks

The combination of the development of coordinate transformation theory and modern metamaterials, which are artificial materials whose constitutive parameters can be engineered to achieve special functions, , has offered an unprecedented opportunity for realizing invisibility cloaking. Coordinate transformation theory predicts that by squeezing space to form a “hole” in it, any object inside the “hole” becomes completely invisible using electromagnetic waves [14-27]. A metamaterial shell can be designed to mimic this space squeezing and thus function as an invisibility cloak whose user cannot be seen by others within a chosen frequency band

In this research, a systematic electromagnetic study of transformation-based invisibility cloaks was provided based on the macroscopic Maxwell equations. Analytic scattering models were formulated for studying ideal and non-ideal invisibility cloaks [28-30]. The physics behind perfect invisibility that the coordinate transformation theory did not show earlier was explored by analytically calculating the spatial distribution of electromagnetic fields. Firstly, it was shown that an external electromagnetic wave illuminating a cylindrical cloak will induce electric and magnetic surface currents along the azimuthal direction at the inner boundary of this cloak [29]. These surface currents have no counterparts in the transformation theory because they do not exist before the transformation. Secondly, the reciprocity of a spherical cloak was demonstrated by showing that radiation from an active device in the concealed region is confined within the concealed region [23]. The mechanism is that the outgoing radiation induces surface voltages at the inner boundary of the cloak that reflect all waves back. These physical surface voltages provide a set of mathematical boundary conditions requiring normal D and normal B to vanish on the interface. Finally, the mechanical response of the cloak to external electromagnetic waves was analyzed by calculating the Lorentz force distribution. It was shown that an incoming plane wave tends to expand the bulk of a cloak while squeezing the outer boundary of the cloak at the same time. The recoil forces induced by these forces provide an alternative explanation for the bending of rays or photons.

Practical implementation of cloaks was also considered [28-30]. For simplified cloaks that are often preferred in experiments, the influences of nonlinear transformations and incident angle were first studied. It was shown that a square root transformation that forces the waves to be guided close to the outer boundary yields more invisibility than either linear or quadratic transformations. Simplified cylindrical cloaks may produce more scattering at some non-normal incidence angles than would objects without any cloak. In addition, we suggested using a small number of homogeneous and anisotropic metamaterial layers to construct a practical cloak with satisfying performance at both normal and oblique incidence. Genetic algorithms were used to optimize such practical multi-layer structures. It was shown that by using an optimized 4-layer cloak, the normalized scattering cross section from a cylindrical perfect electric conductor can be reduced from 2.19 to 0.0039 at normal incidence. Another optimized 4-layer cloak designed for an incidence angle of ±30 deg. reduced the scattering cross section from 1.175 to 0.013. The latter cloak exhibits reduce scattering over a large range of incidence angles.

Publications

1. Cheng, XX; Wu, BI; Chen, H; Kong, JA. 2008. Imaging of objects through lossy layer with defects. PROGRESS IN ELECTROMAGNETICS RESEARCH-PIER 84: 11-26.

2. Kong, FM; Li, K; Huang, H; Wu, BI; Kong, JA. 2008. Analysis of the surface magnetoplasmon modes in the semiconductor slit waveguide at terahertz frequencies. PROGRESS IN ELECTROMAGNETICS RESEARCH-PIER 82: 257-270.

3. Zhou, PH; Deng, LJ; Wu, BI; Kong, JA. 2008. Influence of scatterer's geometry on power-law formula in random mixing composites. PROGRESS IN ELECTROMAGNETICS RESEARCH-PIER 85: 69-82.

4. Zhang, JJ; Luo, Y; Chen, HS; Wu, BI. 2008. Manipulating the directivity of antennas with metamaterial. OPTICS EXPRESS 16 (15): 10962-10967.

5. Zhang, JJ; Luo, Y; Xi, S; Chen, HS; Ran, LX; Wu, BI; Kong, JA. 2008. Directive emission obtained by coordinate transformation. PROGRESS IN ELECTROMAGNETICS RESEARCH-PIER 81: 437-446.

6. Duan, ZY; Gong, YB; Wei, YY; Wang, WX; Wu, BI; Kong, JA. 2008. Efficiency improvement of broadband helix traveling wave tubes using hybrid phase velocity tapering model. JOURNAL OF ELECTROMAGNETIC WAVES AND APPLICATIONS 22 (7): 1013-1023.

7. Duan, ZY; Wu, BI; Kong, JA; Kong, FM; Xi, S. 2008. Enhancement of radiation properties of a compact planar antenna using transformation media as substrates. PROGRESS IN ELECTROMAGNETICS RESEARCH-PIER 83: 375-384.

8. Huang, H; Fan, Y; Kong, F; Wu, BI; Kong, JA. 2008. Influence of external magnetic field on a symmetrical gyrotropic slab in terms of Goos-Hanchen shifts. PROGRESS IN ELECTROMAGNETICS RESEARCH-PIER 82: 137-150.

9. Huang, H; Fan, Y; Wu, BI; Kong, JA. 2008. Tunable TE/TM wave splitter using a gyrotropic slab. PROGRESS IN ELECTROMAGNETICS RESEARCH-PIER 85: 367-380.

10. Huang, H; Fan, Y; Wu, BI; Kong, JA. 2009. Positively and negatively large Goos-Hanchen lateral displacements from a symmetric gyrotropic slab. APPLIED PHYSICS A-MATERIALS SCIENCE & PROCESSING 94 (4): 917-922.

11. Kong, FM; Wu, BI; Huang, H; Huangfu, JT; Xi, S; Kong, JA. 2008. Lateral displacement of an electromagnetic beam reflected from a grounded indefinite uniaxial slab. PROGRESS IN ELECTROMAGNETICS RESEARCH-PIER 82: 351-366.

12. Xi, S; Chen, H; Wu, BI; Kong, JA. 2008. Experimental confirmation of guidance properties using planar anisotropic left-handed metamaterial slabs based on s-ring resonators. PROGRESS IN ELECTROMAGNETICS RESEARCH-PIER 84: 279-287.

13. Zhang, JJ; Chen, HS; Ran, LX; Luo, Y; Wu, BI; Kong, JA. 2008. Experimental characterization and cell interactions of a two-dimensional isotropic left-handed metamaterial. APPLIED PHYSICS LETTERS 92 (8): art. no.-084108.

14. Blanchard, C; Porti, J; Morente, JA; Salinas, A; Wu, BI. 2008. Numerical determination of frequency behavior in cloaking structures based on L-C distributed networks with TLM method. OPTICS EXPRESS 16 (13): 9344-9350.

15. Blanchard, C; Porti, J; Wu, BI; Morente, JA; Salinas, A; Kong, JA. 2008. Time domain simulation of electromagnetic cloaking structures with TLM method. OPTICS EXPRESS 16 (9): 6461-6470.

16. Cheng, XX; Chen, HS; Wu, BI; Kong, JA. 2009. Cloak for bianisotropic and moving media. PROGRESS IN ELECTROMAGNETICS RESEARCH-PIER 89: 199-212.

17. Luo, Y; Zhang, JJ; Chen, HS; Wu, BI. 2008. Full-wave analysis of prolate spheroidal and hyperboloidal cloaks. JOURNAL OF PHYSICS D-APPLIED PHYSICS 41 (23): art. no.-235101.

18. Luo, Y; Zhang, JJ; Chen, HS; Xi, S; Wu, BI. 2008. Cylindrical cloak with axial permittivity/permeability spatially invariant. APPLIED PHYSICS LETTERS 93 (3): art. no.-033504.

19. Luo, Y; Zhang, JJ; Wu, BI; Chen, HS. 2008. Interaction of an electromagnetic wave with a cone-shaped invisibility cloak and polarization rotator. PHYSICAL REVIEW B 78 (12): art. no.-125108.

20. Xi, S; Chen, H; Wu, BI; Zhang, B; Huangfu, J; Wang, D; Kong, JA. 2008. Effects of different transformations on the performance of cylindrical cloaks. JOURNAL OF ELECTROMAGNETIC WAVES AND APPLICATIONS 22 (11-12): 1489-1497.

21. Xi, S; Chen, HS; Wu, BI; Kong, JA. 2009. One-Directional Perfect Cloak Created With Homogeneous Material. IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS 19 (3): 131-133.

22. Zhang, B; Wu, BI; Chen, HS. 2009. Optical delay of a signal through a dispersive invisibility cloak. OPTICS EXPRESS 17 (8): 6721-6726.

23. Zhang, BL; Chen, HS; Wu, BI; Kong, JA. 2008. Extraordinary surface voltage effect in the invisibility cloak with an active device inside. PHYSICAL REVIEW LETTERS 100 (6): art. no.-063904.

24. Zhang, BL; Wu, BI; Chen, HS; Kong, JA. 2008. Rainbow and blueshift effect of a dispersive spherical invisibility cloak impinged on by a nonmonochromatic plane wave. PHYSICAL REVIEW LETTERS 101 (6): art. no.-063902.

25. Zhang, JJ; Huangfu, JT; Luo, Y; Chen, HS; Kong, JA; Wu, BI. 2008. Cloak for multilayered and gradually changing media. PHYSICAL REVIEW B 77 (3): art. no.-035116.

26. Zhang, JJ; Luo, Y; Chen, HS; Huangfu, JT; Wu, BI; Ran, LX; Kong, JA. 2009. Guiding waves through an invisible tunnel. OPTICS EXPRESS 17 (8): 6203-6208.

27. Zhang, JJ; Luo, Y; Chen, HS; Wu, BI. 2008. Cloak of arbitrary shape. JOURNAL OF THE OPTICAL SOCIETY OF AMERICA B-OPTICAL PHYSICS 25 (11): 1776-1779.

28. Xi, S; Chen, HS; Zhang, BL; Wu, BI; Kong, JA. 2009. Route to low-scattering cylindrical cloaks with finite permittivity and permeability. PHYSICAL REVIEW B 79 (15): art. no.-155122.

29. Zhang, BL; Chen, HS; Wu, BI. 2008. Limitations of high-order transformation and incident angle on simplified invisibility cloaks. OPTICS EXPRESS 16 (19): 14655-14660.

30. Zhang, JJ; Luo, Y; Chen, HS; Wu, BI. 2008. Sensitivity of transformation cloak in engineering. PROGRESS IN ELECTROMAGNETICS RESEARCH-PIER 84: 93-104.

31. Lin, RF; Du, Y; Rong, L; Wu, BI. 2008. Size based throughput optimization of dly-ack over the ieee 802.15.3 networks. PROGRESS IN ELECTROMAGNETICS RESEARCH-PIER 85: 115-131.

32. Liu, DW; Du, Y; Sun, GQ; Yan, WZ; Wu, BI. 2008. Analysis of INSAR sensitivity to forest structure based on radar scattering model. PROGRESS IN ELECTROMAGNETICS RESEARCH-PIER 84: 149-171.

33. Wu, BI; Yeung, M; Hara, Y; Kong, JA. 2009. INSAR height inversion by using 3-d phase projection with multiple baselines. PROGRESS IN ELECTROMAGNETICS RESEARCH-PIER 91: 173-193.

34. Yan, WZ; Du, Y; Wu, H; Liu, DW; Wu, BI. 2008. EM scattering from a long dielectric circular cylinder. PROGRESS IN ELECTROMAGNETICS RESEARCH-PIER 85: 39-67.

35. Duan, ZY; Wu, BI; Lu, J; Kong, JA; Chen, M. 2008. Cherenkov radiation in anisotropic double-negative metamaterials. OPTICS EXPRESS 16 (22): 18479-18484.

36. Duan, ZY; Wu, BI; Xi, S; Chen, HS; Chen, M. 2009. Research progress in reversed cherenkov radiation in double-negative metamaterials. PROGRESS IN ELECTROMAGNETICS RESEARCH-PIER 90: 75-87.

37. Moser, HO; Kong, JA; Jian, LK; Chen, HS; Liu, G; Bahou, M; Kalaiselvi, SMP; Maniam, SM; Cheng, XX; Wu, BI; Gu, PD; Chen, A; Heussler, SP; Bin Mahmood, S; Wen, L. 2008. Free-standing THz electromagnetic metamaterials. OPTICS EXPRESS 16 (18): 13773-13780.

Theses

B. Zhang, *Study on Transformation-Based Invisibility Cloaks*, Ph.D. research, Department of Electrical Engineering and Computer Science, MIT, 2009.