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For Dr. John Pazik and Dr. V. Browning on

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DOD/ONR MURI

Scalable and Reconfigurable Metamaterials

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Summary

The first quarter of our MURI project was highlighted during the kick-off meeting of the project. In accordance with the program roadmap, several thrust areas have started, including the meta-materials synthesis, new physics study, and electromagnetic characterizations.

Work in Progress:

Meta-material synthesis

*Micro stereo Lithography System:* Zhang’s group work on the construction of the proposed advanced projection micro-stereo lithography (µSL) system, which is consisted of computer-programmable array of digital and a reduction lens. Black-white images of the patterns sliced from the 3D structures (following CAD design) are projected onto the surface of the UV curable monomer resin, so that one layer of structures can be polymerized simultaneously at one single exposure, leading to a much faster process than previous direct writing systems. Zhang’s group has added various absorbers to the monomer resin and focused on testing their effects on polymerization depths, trying to obtain an optimized solidification depth (the vertical resolution). The UV light source is homogenized by using a diffuser, and the setup alignment is optimized, so that field of view (the area which can be solidified homogeneously) has been increased. They also have completed a new design of high resolution reduction system that promises single pixel resolution. The micro-molding technique is also under development. They have identified a few candidates for chemical based molding. They recently developed a Cr layer based method that enable the structure adhere the substrate well during electro-deposition for metallic meta-materials.

*Bubble and Droplet based reconfigurable Meta-materials:* Chen’s group is working on the reconfigurable and switchable bubbles and droplets based meta-materials. Creating bubbles for infrared or smaller wavelength EM waves is possible and a device to test the idea is currently being fabricated. With this device, they expect to test the concept of reconfigurability completely. To create steady bubbles of the size required for the microwave range, i.e., of the order of a few millimeters, is not easily feasible. Hence, for the microwave range, Chen’s group is currently in the process of investigating a switchable microstrip with a periodic structure machined into it. The microstrip is fabricated with varying hole diameter (1/8” and 3/16”) and depth (0.05” and 0.07”) in order to study the effects of hole diameter and depth on their frequency response. The switchability comes from the fact that we can fabricate a device to fill this array of holes with another material with a high dielectric constant in the microwave range, which changes the contrast in dielectric constant and thus brings about a change in the frequency response.
**Metamaterials Physics Study**

*Negative Metamaterials:* A planar of materials having both $\varepsilon$ and $\mu$ equal to $-1$ act as a perfect lens, in that electromagnetic fields emanating from a source of radiation will be focused perfectly to an image point. In order to align the perfect lens concept with experimental reality, UCSD’s group and J.B. Pendry’s group has been focused on qualitatively understanding the details of the “Perfect Lens”. Parametric studies of the imaging characteristics of various left-handed slab configurations of UCSD’s and Pendry’s groups have led to a definition of the resolution that encompasses the subwavelength imaging properties and to establish the dependence of this resolution on deviations from perfect lens condition of $\varepsilon=1$ and $\mu=1$: for S-polarization, $\text{Resolution}=-\lambda \ln(\delta\mu)/2\pi d$, where $\lambda$ is the free space wavelength, $d$ is the slab thickness and $\delta\mu$ is the deviation from $-1$ of $\mu$. Also the effect of periodicity of the meta-materials is considered on the resolution, which can be expressed as: $\text{Resolution}=-\lambda \ln(\lambda^2/\Delta^4)/4\pi d$, with $\lambda$ being the lattice spacing and $\Delta$ the strength of the periodic modulation. These results provide the more concrete requirements on the material properties and configurations for experimental realization of the predicted exotic effects.

*Thin silver films:* As a first step to the imaging by using ultra-thin silver film predicted by JB Pendry, Zhang’s group is setting up an experiment to verify the amplification of evanescent waves in the thin metal films. Silver films of thickness of 40-80 nm have been deposited on glass, and the optical system is being set up. Two designs of the experiment are currently under investigation. Meanwhile, they have numerically studied the evanescent waves’ behavior in the medium that will be compared with the experiments.

*Defect Engineering:* Joannopoulos’s group has begun investigating the possibility of exploiting the ability of photonic crystals to control the flow of light in truly unique ways, in order to design point-defects in photonic crystals as basic building blocks for engineering meta-materials with novel dielectric and magnetic responses. Very recently, the MIT group has succeeded in designing a new 3D photonic crystal that possesses a large omnidirectional photonic band gap (up to 27% using Si at 1.5 microns) and consists of alternating stacks of the two basic 2D slab configurations. The key advantage of this structure is that point-defects can now be introduced systematically in the layers consisting of dielectric-rods-in-air (to create electric moments) or in the layers consisting of air-holes-in-dielectric (to create magnetic moments), without incurring intrinsic radiation losses due to the lack of a complete photonic band gap. Calculations of prototype point-defects have been performed for both types of slab layers.

*Chiral Structures:* Zhang’s group has also started investigation of the chiral structures via experiments. Various periodic spiral structures have been designed and being fabricated with the current $\mu$SL system. However, the nature of the thin spirals makes it to crash after fabrication, and need to be solved. The team is also developing a new method to release the structure from liquid with reduced or without surface tension.
**Electromagnetic Characterization of Metamaterials:**

A novel surface wave photonic band gap (PBG) structure with two stop bands instead of one has been developed and tested in Yablonovitch’s group. These structures consist of arrays of metal patches, connected to an underlying ground-plane with conducting bias. The problem was approached from two directions, yielding two different designs, which were adopted for the specific case of the Global Positioning System (GPS) operating frequencies. GPS uses two separate frequency bands centered at $L_1 = 1.557 \text{ GHz}$, and $L_2 = 1.225 \text{ GHz}$ respectively, corresponding to a total band width of $\Delta f/f = 2(L_1-L_2)/(L_1+L_2) = 24\%$.

Itoh’s group has started to investigate a novel **uniplanar** left-handed (ULH) structure - in fact a monolayer reduction of the LH of UCSD - that might be easily integrated into conventional microwave devices. The circuit, is constituted by a coplanar waveguide (CPW) line on one side of the substrate and a ULH structure on the other side of the substrate. It should then be possible to obtain a LH effect using the configuration of Fig. 1, since this effect results from excitation electric and magnetic fields parallel to the wires and perpendicular to the plane of the rings, respectively. A smart way to demonstrate a LH behavior in a line is to examine the $S_{21}$ parameter in the Smith Chart: if the equivalent transmission line has a positive effective wavenumber, $\beta_{\text{eff}}$, then the curve in the Smith Chart (assuming the dependency $\exp(-j\beta_{\text{eff}} z)$) rotates clockwise for increasing frequencies (increasing electrical line length); if a LH effect is present, the wave travels in the opposite direction, $\beta_{\text{eff}}$ is negative, and therefore the curve should rotate **counter-clockwise** in the corresponding frequency range. Unfortunately, this phenomenon has not been observed for the CPW-ULH structure of Fig. 1, and we must therefore deduce that left-handedness has not been obtained in that circuit.

**Work Planned for Next Quarter (Sept. –Dec. 2001)**

**Metamaterial Synthesis**

$\mu$SL: Zhang’s group will continue to develop the high resolution micro stereo lithography by optimize the chemical components and optical systems. Owing the requirements of FTIR measurements on the samples size, the stepping process will be explored to increase the lateral sample size. Zhang’s group is working on the designing and purchasing optical components for a 2$\text{nd}$ generation micro-stereolithography system, intending to share some of the working load on the current low resolution system. The team will start to develop system CAD simulator.

Chen’s group, in collaboration with Itoh’s lab, will perform more tests on the microstrips with different parameters. From these tests, important information regarding the fabrication of the final device is expected. Finite Element Modeling for Electromagnetics is also used to simulate the devices to fabricate and the results are compared with experimental data. The experiments on bubbles or droplets for higher frequencies will also be continued.
Metamaterials Physics Study

Negative Materials: UCSD and Pendry’s group on detailed parametric studies on perfect lens concept. UCSD will consider the experiment using their LFH structures. Zhang’s group will continue on the silver film experiments concerning the evanescent field amplifications.

Defect Engineering, Joannopoulos’s group is going to proceed to incorporate 1D, 2D, or 3D arrays of defects in their photonic crystal design with potentially novel permittivities or permeabilities. They will collaborate with Zhang’s group in utilize the unique uSL technique to design and fabricate arbitrary defects in meta-materials in IR ranges. Also they will investigate the incorporation of metallic components to a photonic crystal system which would enable the design of electromagnetic moments operating at wavelengths much longer than the scale of the periodicity.

Itoh’s group is developing a spectral domain approach (SDA) code with the purpose to determine the exact dispersion relations of planar circuits on LH substrates.

Electromagnetic Measurements

Chen’s group is in the process of devising an experimental technique for measurement of reflection, transmission and radiative properties of electromagnetic waves for the devices designed. They are also going to simulate the devices and compare the results with experimental data.

Itoh’s group is investigating several factors that might explain the absence of left-handedness. The most important one, according to a discussion with David Smith and recent simulations, is the non-centered position of the wires with respect to the rings. They plan to study two-layer configurations in which the wires would be centered in another plane (to avoid short-circuits between them and the rings) and other uniplanar configurations with a modified geometry of the rings.

Zhang’s group is going to fabricate periodic spiral structures and measure their electromagnetic properties. They will also collaborate with UCSD group on miniaturization of split ring structures for possible high frequency LFH metamaterials.

As part of the experimental program on left-handed meta-materials, UCSD’s group are arranged to design several types of structures that will be fabricated at UCLA and measured at UCSD. UCSD will also work on explore direct measurement method to extract the ε and µ from experiments on LFH metamaterials.
Administrative Issues

Kick-Off Meeting: The kick-off meeting was held at UCLA on June 5-6, 2001. The meeting has provided a good forum for the planning of research and exchange of ideas. The kick-off meeting was well attended by about 40 participants from both MURI program and other US industry and institutions. We have formed an MURI Advisory Board including: Rockwell, Boeing, Lockee-Martin, Raythoen, GE-Honeywell, and NRL, and Dr. John Pazik of ONR and Dr. Valerie Browning of DARPA.

MURI Website: currently is under construction. A specialist is hired to work on putting various MURI documents on this site. We expect that all MURI quarterly reports, as well as annual reports and other communications and working news will be posted.

Prof. Gang Chen moved from UCLA to MIT in Aug. 2001. We expect that he will closely collaborate with UCLA groups and Joannopoulos’ group at MIT.

Synergy and Interactions:

There are many informal and formal interactions among the members of the MURI team, for instance, (1) Prof. Chen and Prof Itoh have been working together on reconfigurable lattice. Their students work closely in this collaboration. (2) On Aug. 22, UCSD group visited UCLA, and had a meeting UCLA Zhang and Itoh groups. They exchanged their recent progress on the research projects, and discussed some experimental designs and made good suggestions. After the meeting, UCSD group visited the Zhang and Itoh laboratories and Center for High Frequency Electronics. They discussed details of using the UCLA facilities for some of their metamaterials fabrications and measurements. (3) Prof Pendry has been in close contact with rest of the MURI groups through emails. He plans to visit UCSD and UCLA in later this year for collaborative research.