**Contract Information**

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<tr>
<th>Contract Number</th>
<th>N00014-01-1-0803</th>
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<tr>
<td>Title of Research</td>
<td>Scalable and Reconfigurable Metamaterials</td>
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<tr>
<td>Principal Investigator</td>
<td>Xiang Zhang</td>
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<tr>
<td>Organization</td>
<td>University of California in Los Angeles</td>
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**Technical Section**

**Technical Objectives**

The goals of this project are to develop new synthesis technologies for fabrication of 3D scalable and reconfigurable meta-materials, to explore the new physics and simulation methods of meta-materials, to experimentally characterize the physical properties of meta-materials, to demonstrate prototype metamaterial-based devices for novel electromagnetic wave applications and to transfer the developed technology to defense industries and to develop an interdisciplinary educational program that trains a new generation of graduate students and post-docs in the science and technology of meta-materials.

**Technical Approach**

We are developing a set of innovative synthesis technologies for meta-materials. We have recently developed unique micro free forming techniques - micro stereo lithography (µSL) that builds complex 3D micro structures by solidifying UV curable polymer layer-by-layer (1-5 µm) either serially with a focused laser beam direct or parallel writing with a novel micro-mirror dynamic mask. These techniques are scalable and capable of fabricating the truly 3D complex meta-structure with feature size ranging from 1 µm to 1 cm and total sample size up to 12” wafer, and can be seamlessly integrated with CAD tools. To convert the polymer molds into metal or dielectrics, additional methods, such as sputtering, electroplating, and micro-molding have been developed and coupled to the µSL fabrication. Meta-materials operating at optical wavelength usually require the features fabricated at subwavelength scale (i.e. 100-1000 nm). We are also making ambitious efforts developing three promising 3D nanofabrication technologies for optical meta-materials and devices: 3D near-field nanofabrication, two photon nanofabrication and e-beam direct writing. The ceramic molding process has been developed for the fabrication of All Angel Negative Refraction structures. CNC milling process has been established in UCSD for the synthesis of microwave metamaterials.

**Theoretical modeling** is a vital component in developing new ideas in this field. Sophisticated simulation tools have been developed by several leading groups including two of our co-PIs, Profs Joannopoulos and Pendry. These simulation tools will be further advanced through this project to explore the new physics of meta-materials, to refine design criteria, and to realize novel devices.

Full-wave electromagnetic characterizations of meta-materials will be carried out to determine the dielectric permittivity and magnetic permeability, using the advanced characterization facilities at UCLA and UCSD. In addition, innovative near field experiments are designed to demonstrate the super lens’ ability of nanometer focusing.
Progress

Major Accomplishments during This Period

Considerable progresses have been made during the second year on metamaterial synthesis, novel physics study, and metamaterial devices and metamaterial characterizations.

(1) Metamaterial synthesis
- Integration of multi-chip dynamic mask for metamaterials fabrication: Zhang
- Developing metallization process for THz plasmonic filters and magnetic resonators: Zhang
- Demonstrating Two-Photon Near-field Lithography for nanofabrication of metamaterials: Zhang
- Developing Sol-Gel molding process for dielectric mold transfer: Zhang
- Developing CNC milling process for microwave metamaterials: Smith/Schultz
- Ceramic micromolding for AANR metamaterials: Chen

(2) Metamaterial physics
- Anisotropic wave propagation and near field spatial filtering in Indefinite Media: Smith/Schultz
- Theoretical prediction of 2D magnifying superlens by conformal transformation: Pendry/Smith/Schultz
- Simulation Design of Optical Magnetic Emitter by defect engineering in 3D photonic crystal: Joannopoulos/Pendry/Chen/Smith/Schultz
- Backward Cerenkov radiation in Photonic Crystals: Joannopoulos/Chen/Smith/Schultz
- Subwavelength focusing and imaging in all angle negative refraction photonic crystals: Joannopoulos/Pendry/Chen/Smith/Schultz
- Demonstration of THz Magnetic Activity using metallic resonators: Zhang/Pendry/Smith/Schultz/Basov
- Conceptual design of 3D vanishing lens by “complementary media”: Pendry

(3) Metamaterials characterization and Metamaterial devices
- Free space FTIR angular reflectivity characterization of magnetic resonators: Basov/Smith/Schultz/Zhang
- Prototyping high frequency tunable THz plasmonic filter: Zhang/Basov/Smith/Schultz
- Demonstration of high throughput Near-field lithography using plasmonic elements: Zhang/Pendry/Yablonovitch
- Prototype of Backfire to Endfire Leaky wave Antenna: Itoh
- Prototype of Arbitrary coupling Coupled Line Coupler: Itoh
- Prototype of dual band Non-harmonic Branch-Line Coupler: Itoh
- Prototype of Phase Conjugation Meta-interface: Itoh
- Prototype of anisotropic RH-LH interface and investigation of surface plasmon: Itoh
- Exploration of CRLH reflector surface: Itoh
- Design and Optimization of thermophotovoltaic conversion using lefthanded metamaterials: Chen
- Design and modeling of surface emitting metamaterial devices: Chen
- Study of anisotropic plasmonic wire waveguide: Chen

Detailed Description of Accomplishments and Results
Metamaterials synthesis:

(1) Development of nanofabrication technology for metamaterials: near-field based lithography and two photon nano-fabrication

While each of the two approaches, near-field based lithography and two photon nano-fabrication, can achieve sub-diffraction-limited spatial resolution, a combination of these two techniques can provide even higher spatial resolution. **Zhang’s group** combined apertureless near-field enhancement and nonlinear absorption techniques to achieve a spatial resolution as high as $\lambda/10$ (Fig 1), nearly a factor of two higher than the resolution achieved in far-field exposure. We expect that even greater spatial resolution should be possible using this two-photon apertureless near-field lithographic technique.

Figure 1. Left: The proof-of-concept setup of two-photon near-field lithography. Right: The cross-sectional view of line patterns demonstrates that two-photon apertureless near-field lithography can produce ~72nm±10nm features using 790 nm light.

(2) Nanowires plasmon

Based on the feedback from Dr. Pazik, **Gang Chen’s group** explored the plasmonic effects in nanowire arrays. They collaborated with the Prof. Dresslhaus group at MIT in electrodepositing silver nanowire arrays with a commercial available anodized Al$_2$O$_3$ template, i.e., Anodisc 47 from the Whatman. International Ltd. The diameter of the nanowires we got is about 200 nm, and the average length of wires is about 20 µm. The plasma wavelength was tested by measuring the reflectance of the nanowire arrays. The results show that the nanowires array has a plasma wavelength of 325 nm while the bulk silver has a plasma wavelength of 320 nm. The long-wavelength-shift is not significant because the silver nanowires fabricated with the current technique were too dense. According to Prof. Pendry’s wire-plasma theory, for example if the plasma wavelength is needed to shift to 3 µm which corresponding to 0.3 ev, the lattice constant should be at round 1 µm with wire radius of 100 nm, however the lattice constant of the current nanowires is about 300 nm.

(3) Development of synthesis technique for terahertz magnetic metamaterials

**Zhang’s group** developed a unique synthesis technique of the terahertz magnetic metamaterials, named Photo-Proliferated Lithography(PPL). With this promising synthesis approach, we expect to produce split-ring structures with gap down to 2 micron and height up to 20 micron. We further demonstrated (the first time to our knowledge) THz magnetic response using these synthesized split ring resonators on quartz. In collaboration with UCSD group, we utilized FTIR with an oblique incidence beam to characterize the spectral reflectance of a monolayer sample. Due to the presence of
a magnetic field component normal to the interface, the inductive current in the split ring arrays are excited by the incident TE wave, and a pronounced reflection peak can be observed at designed resonance frequency. Detailed analysis and simulation efforts are underway to elaborate the mechanism of enhanced reflectance.

![Image](image1.png)

**Figure 3.** Left: Ion Image of the THz magnetic metamaterials. Right: FTIR Spectral Reflection at oblique angle reveals the artificial magnetic activity of the split-ring resonators with a pronounced peak under TE excitation (0°) in contrast to TM waves (90°).

(4) All-Angle Negative Refraction

Gang Chen’s group has fabricated the structure for All Angle Negative Refraction (AANR) as proposed by the Joannapoulos group. The material used for the structure is Magnesium Calcium Titanate (MCT), obtained from Trans-tech Inc. The dielectric constant of the material was measured by Schultz and Smith groups at UCSD at 6GHz with $\varepsilon$ at 38 and the loss tangent is 0.0003. The details of the structure are shown in the figure below. The sample was sent to Prof. Schultz at UCSD for measurements.

![Image](image2.png)

**Figure 3.** Magnesium Calcium Titanate Structure fabricated for All Angel Negative Refraction (AANR) measurement.

(5) Metamaterials for Thermophotovoltaic Energy Conversion

Thermophotovoltaic (TPV) energy conversion can immensely benefit from an increase of energy density as well as energy transmission efficiency. Stimulated by Prof. Pendry’s perfect lens conception based on left-handed materials, Gang Chen’s group have developed a strategy to improve the energy density and the transmission efficiency of TPV through perfectly imaging the thermal source onto the active layer of TPVs by metamaterials. They have analyzed the radiation energy transfer between layered and closely spaced media using a method based on Green’s functions techniques and the fluctuation-dissipation theorem. Theoretical analysis shows that by for example,
using a polar material like Boron Nitride (BN) or Silicon Carbide (SiC) as emitters of a TPV converter, the energy transfer from the emitter to the receiver can be orders of magnitude greater than the energy transfer between two black body surfaces at the same temperatures because of both surface phonon polaritons effect and evanescent wave tunneling effect. We are interested in BN or SiC because their surface phonon polariton resonance frequency is about 0.2 eV, which is suitable for TPV applications operated at a temperature range of 1000 - 1300K. Their analysis has shown that polar materials like SiC or BN can be used as novel near-field emitters in TPV devices. Physics involved in this TPV application is similar to the "superlens" theory of Prof. Pendry. In addition, other ideas of increasing the resonance frequency of the emitter material to near-IR regime are under investigation.

(6) Enhancement of Evanescent Waves in Waveguides by Left Handed Materials

Electromagnetic waves in waveguides containing metamaterials with negative permittivity and permeability are analyzed by solving Maxwell’s equations. Metamaterials can enhance the intensity of the evanescent waves in the cladding without altering the propagation constant of the waveguide for both TE and TM modes. This is a unique property of metamaterials. The enhancement effect is due to surface polaritons occurring at the boundary between the metamaterials and the cladding, and can be applied to integrated waveguide devices to improve their performances. Gang Chen’s group has also begun the fabrication of thin films of split ring resonators and Swiss-roll structures in order to create negative refraction in the 30-50 µm range. The critical dimensions of the structures are limited by the lithographic system used at MIT (500nm).

New Physics in Metamaterials

(1) Generalization of the perfect lens effect to higher dimensions and curved surfaces (John Pendry)

The original perfect lens consisting of a slab of negative refractive material of infinite transverse size is essentially one dimensional. It also has the restrictive character that the size of the image formed is identical to that of the source. In other words, the magnification in the system is unity. In order to obtain a magnification different from unity, curved surfaces will necessarily have to be involved (which will break the translational symmetry parallel to the surface of the lens and enable magnification). As we have already shown, the role of the surface plasmon modes is crucial to the operation of the perfect lens. Since the dispersion of the surface states on a curved surface will be different from that on a planar surface, we concentrate on finding certain curved geometries where the perfect lens effect becomes possible.

![Figure 4](image-url)

**Figure 4.** A cylindrical annulus of material, dielectric constant $\varepsilon = -1$. (a) The annulus contains two charges, $\pm q$, one charge at the origin, the other at distance $r_1$ from the origin. (b) A charge $+q$ sits at a distance $r_2$ from the origin, beyond the annulus.
Particularly Pendry’s group concentrates on the near field limit where all the length scales of the problem are much smaller than a wavelength. In this limit the surface plasmons on the surface of a metallic cylinder become degenerate just as in the case of the slab. We note that in the near-field limit or the electrostatic limit only the dielectric properties of the system are important. They have shown that a cylindrical annulus with negative dielectric constant of $\varepsilon = -1$ has the property of projecting sources from the interior to the exterior (or vice versa) – See Figure-1.

![Diagram](image)

**Figure 5.** (a) The starting configuration of a single line charge and image to which we apply a conformal transformation to produce the configuration shown in (b). A slightly different choice of the parameters in the transformation leads to a configuration of two touching cylinders imbedded in the infinite negative medium. An object within one cylinder is refocused inside the second cylinder.

The system in figure 1 has a magnification of

$$\left( \frac{a_2}{a_1} \right)^2 \tag{1}$$

for projecting sources from inside the annulus to outside and a demagnification of

$$\left( \frac{a_1}{a_2} \right)^2 \tag{2}$$

for projecting sources from outside to inside, where $a_1$ and $a_2$ are the internal and external radii of the annulus.

Further we generate a whole class of two-dimensional lenses for the near-field with curved geometries by conformal transformations of the original slab lens. The extreme near-field of a source is described effectively by the Laplace equation which is invariant under a conformal transformation.
Hence we can obtain very efficiently several new kinds of lenses by conformal transformations. **Pendry’s group** recognize that the cylindrical annulus is just one example of this class. We also have explored a few more configurations of this class (see for example, figure-2) and the possibility of locally amplifying electric fields using these lenses. Although these lenses would work for the extreme near-field radiation, we note that they would be very inefficient outside the regime of the approximation.

As has been said before, only the use of curved surfaces can change the magnification of the image. It is possible to make a perfect magnifying glass that acts on both the radiative and near-field components by using a cylindrical annulus whose dielectric and magnetic permeability tensors are specified functions of the spatial coordinates. Ward and **Pendry** have shown earlier [A.J. Ward and J.B. Pendry, J. Mod. Optics. 43, 773 (1996)] that changing the geometry using a co-ordinate transformation amounts to changing the \( \varepsilon \) and \( \mu \) in the system. Make a co-ordinate transformation

\[
q_1(x,y,z), \quad q_2(x,y,z), \quad q_3(x,y,z).
\]

where \((q_1, q_2, q_3)\) are the new co-ordinates. Assuming the transformation to be diagonal for simplicity and rewriting the Maxwell’s equations in the new co-ordinate system,

\[
\nabla \times \mathbf{E} = -\mu' \mu_0 \frac{\partial \mathbf{H}}{\partial t}, \quad \nabla \times \mathbf{H} = \varepsilon' \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}
\]

We find that the form of the Maxwell’s equations do not change. But the \( \varepsilon \) and \( \mu \) in the new co-ordinate frame are given by

\[
\varepsilon_j' = \varepsilon_j \left( \frac{Q_1 Q_2 Q_3}{Q_i^2} \right), \quad \mu_j' = \mu_j \left( \frac{Q_1 Q_2 Q_3}{Q_i^2} \right)
\]

where

\[
Q_i^2 = \left( \frac{\partial x}{\partial q_i} \right)^2 + \left( \frac{\partial y}{\partial q_i} \right)^2 + \left( \frac{\partial z}{\partial q_i} \right)^2
\]

\[
E_j = Q_j E_j, \quad H_j = Q_j H_j.
\]

*To show that a cylindrical annulus can act as a perfect lens, we make a co-ordinate transformation from the Cartesian slab geometry into cylindrical co-ordinates as follows:*

\[
x = r_0 \exp(l/l_0) \cos \phi, \quad y = r_0 \exp(l/l_0) \sin \phi, \quad z = r_0 Z.
\]

In this new frame the transformed values of the \( \varepsilon \) and \( \mu \) for the perfect lens solution turn out to be

\[
\varepsilon_r = \mu_r = -1, \quad \varepsilon_\phi = \mu_\phi = -1, \quad \varepsilon_z = \mu_z = -n_0^2/r^2, \quad a < r < b,
\]

\[
\varepsilon_r = \mu_r = +1, \quad \varepsilon_\phi = \mu_\phi = +1, \quad \varepsilon_z = \mu_z = +n_0^2/r^2, \quad a > r > b
\]

and the solution of the Maxwell’s equations is

\[
H_z = H_0 z r^{\frac{\pm ik_z}{r}} \exp \left( i m_\phi \phi + i k_z z - i\omega t \right)
\]

where

\[
k_z^2 + m_\phi^2 + n_0^2 k_z^2 = n_0^2 \omega^2 c_0^{-2}
\]

Thus, we have a perfect lens solution for a cylindrical geometry in the plane normal to the axis of the cylinders. We note that the \( \varepsilon \) and \( \mu \) become functions of the spatial co-ordinates both inside and outside the annulus. However, if the electric field is everywhere perpendicular to the cylinder axis, \( \varepsilon_z \) is irrelevant and \( \mathbf{H} \) is everywhere parallel to the cylinder axis. If, in addition, we neglect the magnetic field (electrostatic limit) \( \mu_z \) is also irrelevant and therefore we retrieve our previous result obtained by conformal mapping of the slab geometry into the cylindrical geometry.
The original perfect lens comprised of a slab of negative index material with $\varepsilon = -1$ and $\mu = -1$. Pendry’s group have now shown that focussing can occur for more general conditions. If $z$ be the lens axis and

$$
\varepsilon_2(x,y) = -\varepsilon_1(x,y), \quad \mu_2(x,y) = -\mu_1(x,y),
$$

where $\varepsilon_2$ and $\mu_2$ are the dielectric constant and the magnetic permeability of the negative slab medium ($0 < z < d$) and $\varepsilon_1$ and $\mu_1$ are the dielectric constant and the magnetic permeability of the positive slab ($-d < z < 0$) respectively, then we get an ideal image on the plane $z = d$ plane of whatever is there on the $z = -d$ plane. It is as if the effect of the spatially varying positive medium is completely cancelled out by the negative medium with a similar spatial variation and equal thickness. Optically the effect of the combined slab vanishes. We can also relax the condition of invariance along the lens axis to any region that is mirror-antisymmetric about a plane with respect to these complementary media.

The result can be generalised to the case where $\varepsilon, \mu$ and tensors,

$$
\varepsilon = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{bmatrix}, \quad \mu = \begin{bmatrix} \mu_{xx} & \mu_{xy} & \mu_{xz} \\ \mu_{yx} & \mu_{yy} & \mu_{yz} \\ \mu_{zx} & \mu_{zy} & \mu_{zz} \end{bmatrix}
$$

(12)
except that now the complementary media have the form,

\[
\begin{pmatrix}
\varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\
\varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\
\varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz}
\end{pmatrix}, \quad
\begin{pmatrix}
\mu_{xx} & \mu_{xy} & \mu_{xz} \\
\mu_{yx} & \mu_{yy} & \mu_{yz} \\
\mu_{zx} & \mu_{zy} & \mu_{zz}
\end{pmatrix}
\]

\[\varepsilon_2 = \begin{pmatrix}
-\varepsilon_{xx} & -\varepsilon_{xy} & +\varepsilon_{xz} \\
-\varepsilon_{yx} & -\varepsilon_{yy} & +\varepsilon_{yz} \\
+\varepsilon_{zx} & +\varepsilon_{zy} & -\varepsilon_{zz}
\end{pmatrix}, \quad
\mu_2 = \begin{pmatrix}
-\mu_{xx} & -\mu_{xy} & +\mu_{xz} \\
-\mu_{yx} & -\mu_{yy} & +\mu_{yz} \\
+\mu_{zx} & +\mu_{zy} & -\mu_{zz}
\end{pmatrix}, \quad 0 < z < +d
\]

Figure 8. We show the phase of the transmitted wave, the transmittance \(|T|^2\) and reflectance \(|R|^2\) for the P- and S-polarised waves for the case defined by equation (14). (a) and (b) are for \(\lambda_e = \lambda_\mu = 0.9\mu m\), \(\lambda = 4.54\mu m\) (low energy). (c) and (d) are for \(\lambda_e = \lambda_\mu = 1.8\mu m\) and \(\lambda = 0.617\mu m\).

They have verified these predictions with numerical simulations using the transfer matrix method. Within the accuracy of the simulations, there is very good agreement with the analytical theory. In Fig. 8, we show the results of our simulations for a medium with periodically varying \(\varepsilon\) and \(\mu\) along \(x\) and invariant along the \(y\) coordinate as below:
\( \varepsilon = -1.0 - \frac{|z|}{d} \sin^2 \left( \frac{2\pi x}{\lambda_\varepsilon} \right), \quad |z| < d \)

\( \varepsilon = +1.0 + \frac{2d - |z|}{d} \sin^2 \left( \frac{2\pi x}{\lambda_\varepsilon} \right), \quad d < |z| < 2d \)

\( \mu = -1.0 - \frac{|z|}{d} \sin^2 \left( \frac{2\pi x}{\lambda_\mu} \right), \quad |z| < d \)

\( \mu = +1.0 + \frac{2d - |z|}{d} \sin^2 \left( \frac{2\pi x}{\lambda_\mu} \right), \quad d < |z| < 2d \)

(14)

It can be seen that the deviation of the transmittance from unity, reflectance from zero and the phase of the transmitted wave at the image plane from zero are very small thus confirming our generalized lens theorem.

(2) **Possibility of sub-wavelength imaging using photonic crystals** (In collaboration with C. Luo, S.G. Johnson and J.D. Joannopoulos at MIT)

The problem of sub-wavelength imaging using the negative refractive effect with photonic crystals was examined. It was noted that the existence of photonic states bound to the lens surface was the key to the amplification of the evanescent waves and negative refractive index is not essential to the perfect lens problem. The photonic crystal imposes a natural cut-off to the maximum transverse wave vector for which there is amplification and this is when the transverse wave vector becomes comparable to the underlying Bragg vector due to the periodicity of the crystal.

(3) **Designing synthetic magnetic media that emit radiation with a purely magnetic character** (In collaboration with M.L. Povinelli, S.G. Johnson and J.D. Joannopoulos at MIT)

The possibility of designing synthetic magnetic media that emit radiation with a purely magnetic character has been explored. By identifying point defect modes in a 3D photonic crystal whose local field pattern resembles an oscillating magnetic moment, it is shown that modes can be designed with a primarily magnetic multipole character in the far field: over 98% of the emitted power goes into magnetic multipole radiation. It should be noted that these photonic crystals that exhibit magnetic properties have completely non-magnetic constituents and can be designed to operate without losses even at optical frequencies unlike natural paramagnetic and ferromagnetic media.

During the past year Joannopoulos’ group have been 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 metamaterials with novel dielectric and magnetic responses.
In this regard we have designed a new defect state in a 3D photonic crystal that emulates the behavior of a single oscillating magnetic multipole even though there is no magnetic material involved with the structure. This defect state is shown in Fig. 9 and will eventually be investigated experimentally by the Schutz/Smith and Chen groups.

![Figure 9](image)

**Figure 9.** Snapshot of Magnetic and Electric field density associated with a photonic crystal defect that possesses over 98% oscillating magnetic multipole character.

We have also performed studies of negative refraction of electromagnetic waves in photonic crystal systems as interesting alternatives to the left handed materials that can work both at microwave and optical frequencies. In a collaborative effort with Pendry, Joannopoulos' group has shown that single-beam negative refraction in photonic crystals is possible for all incoming angles in a regime of positive effective index of refraction. In particular, we focus on the lowest photonic band near a Brillouin zone corner furthest from $\Gamma$. Interestingly, this band has a positive group velocity but a negative photonic “effective mass”. The frequency range is chosen so that for all incident angles, one

![Figure 10](image)

**Figure 10.** A pulsed oscillating point-dipole on the top of a slab of 3D photonic crystal superlens passes through and is focussed to an oscillating point image at the bottom. Top and bottom panels refer to two different crosssections are shown.
obtains a single negative-refracted beam. We call this effect All-Angle Negative Refraction (AANR) and have determined the set of sufficient criteria for its observation. To illustrate this phenomenon, we succeeded in designing and numerically simulating a photonic crystal micro-superlens. This structure has now been fabricated by the Chen group and is being tested by the Schultz/Smith group.

They have also succeeded in extending these ideas to 3D photonic crystal systems. To realize AANR in 3D, sufficient criteria are: 1. the frequency range be near a negative “photonic-mass” region; 2. the frequency range be below the diffraction threshold; 3. the photonic-crystal constant-frequency contour be all-convex and larger than that of air; and 4. the symmetry of the photonic modes allow good coupling with incident wave. Clearly, this is only possible in the first few bands. A rough rule for determining the optimal geometric lattice for AANR is just to maximize the number $N$ of nearest-neighbor reciprocal-lattice sites to a critical wave vector $C$. If AANR is to be realized in the fundamental (i.e. the first two) bands, then $C$ is a corner of the first Brillouin zone. In this case, a simple-cubic (SC) reciprocal lattice with $N = 8$ should be used, resulting in a SC photonic crystal with (111) surface termination. If AANR is to be realized in the next higher bands, then $C$ is a corner of the second Brillouin zone, which in most lattices is just $G$ after translation by a reciprocal-lattice vector. This is the usual effective negative-index situation, and the Face-Centered Cubic (FCC) reciprocal lattice which has $N = 12$ should be chosen, giving a Body-Centered Cubic (BCC) structure in real space. To illustrate this phenomenon, we succeeded in designing and numerically simulating a BCC photonic crystal micro-superlens in 3D. The results are shown in Figure 10. We are currently working with the Chen and Schultz/Smith groups to eventually fabricate this photonic crystal superlens and experimentally demonstrate its performance.

Finally, in our continuing studies of photonic crystals as alternates for metamaterial systems at optical frequencies, we have discovered dramatic and novel behavior of Cerenkov radiation in a photonic crystal. When a charged particle travels inside a medium, it can drive the medium to emit coherent electromagnetic energy called Cerenkov Radiation (CR). Extensively utilized in particle detectors and counters, CR in a conventional material possesses three key characteristics: it occurs only when the particle’s velocity exceeds the medium’s phase velocity, the energy propagates only in the forward direction, and there is a forward-pointing conical wavefront. One possibility for unusual CR is in a

![Figure 11. Snapshots of field densities associated with a charged particle traveling through a photonic crystal with various velocities.](image)
medium with simultaneously negative permittivity and permeability, where CR is predicted to flow backwards, i.e. opposite to the particle velocity. Another possibility exists near a periodic structure, where simple Bragg scattering of light can give rise to radiation without any velocity threshold. This was first confirmed by Smith and Purcell in early experiments with electrons traveling near the surface of a metallic grating. A photonic crystal, where very complex Bragg scattering is possible, presents a further new medium for unusual photon phenomena. In this work, we have discovered a surprising variety of CR radiation patterns that can occur in a single photonic crystal for different particle-velocity regimes. These patterns are shown in Figure 11. Within one particle velocity range, we can reverse the overall cone that encloses all traveling electromagnetic energy. In another velocity regime, they find a backward-propagating CR behavior reminiscent of that predicted in the negative-index materials. They are currently working with the Schultz/Smith and Chen groups to see if experiments might be feasible. Interesting potential applications include velocity sensitive particle detection and radiation generation at selectable frequencies.

(4) Investigations of Indefinite Media (UCSD)

During the past year, UCSD has continued a general exploration of wave propagation in indefinite media, including investigations into variety of applications of indefinite media, including spatial filtering, near-field refocusing and lens design. Indefinite media are anisotropic media, for which not all of the principal elements of the permittivity and permeability tensors have the same algebraic sign.

![Diagram](image)

**Figure 12:** (Left) A bilayer of indefinite media can be used to perform subdiffraction limited imaging. Two electromagnetic sources, each λ/20 in width and λ/10 apart, on the left of the bilayer are imaged on the right side of the bilayer as shown. (Right) An example of spatial filtering. Three beams are incident on a slab consisting of four layers of different types of indefinite media. The result is that certain angles are transmitted while others are entirely reflected.

Indefinite media significantly expand the range of possible wave propagation behavior available in metamaterials. As is often the case with anisotropic media, the phase and group velocities associated with a propagating wave are not generally parallel or antiparallel, as is the case with positive and negative definite media. Rather, there is an arbitrary angle between the phase and group velocities for waves propagating in indefinite media. Normally such media would not couple well to free space, but by combining different types of indefinite media, the materials can be matched to free space and their unusual properties exploited. As shown in Eqs. (12)-(14), Pendry’s group is exploring the imaging theory in generalized indefinite media.
Two applications of indefinite media are shown in the figure below. On the left-hand side, we present an analytically calculated field plot demonstrating near-field refocusing by a bilayer composed of two types of indefinite media. Two sources are placed on the left-most side of the bilayer, each $\lambda/20$ in width and spaced $\lambda/10$ apart. The particular property of the indefinite medium used here is that near-field (evanescent) components in free space couple to propagating modes within the indefinite media; the dispersion properties of the material indicate that these near fields are channeled into “resonance cones”, visible in the figure as the (darker) regions of high field intensity. By combining positive and negative refracting indefinite media, the image from the left-hand side of the bilayer is transmitted, along with the sub-diffraction limited resolution, to the right-hand side of the bilayer.

The right hand side of Figure 12 shows a spatial filtering application, in which layers of indefinite media are used to form an angle-selective surface. In this case, four layers of indefinite media are used, two to form a compensated high-pass spatial filter, and two to form a compensated low-pass spatial filter.

During the past year, **UCSD** purchased a rapid circuit board prototyping machine under ONR funding, which is uniquely suited for the fabrication of test indefinite media structures appropriate for the UCSD 2-D scattering chamber. As we move forward to actual experiments involving negative refractive and indefinite metamaterials, design and fabrication of actual materials can become a bottleneck. What will be needed will be many iterations between simulation and test structures to develop an understanding of the true possibilities and limitations associated with metamaterial designs. UCSD has now begun that process; an illustration is shown in Figure 13, which shows simulated focusing by a double-concave parabolic indefinite media lens, and the structure that will be used for experiments.

![Simulation of Isotropic and Anisotropic Negative Refractive Materials (UCSD)](image)

(5) Simulation of Isotropic and Anisotropic Negative Refractive Materials (UCSD)

In the last year, **UCSD** has further developed the ability to simulate wave scattering from isotropic and indefinite negative refractive media. In conjunction with Professor John Pendry, UCSD is currently working to apply these methods to simulate configurations of negative and positive refractive index materials that might lead to unusual phenomena or devices, based on the insight from initial analytical calculations. In the last year, UCSD has performed a preliminary confirmation of a theorem developed by Pendry and Ramakrishna: that an inhomogeneous medium (medium 1)
composed of negative and positive index media, could be compensated by an equal length of medium (medium 2) for which $\varepsilon_2(-r)=-\varepsilon_1(r)$ and $\mu_2(-r)=-\mu_1(r)$. A second geometry of interest is the corner reflector, in which a quadrant of space is filled with a material with index of $n=-1$. The corner reflector has similar properties to the “perfect lens”, so that the fields associated with a nearby electromagnetic source are refocused to other positions, including the near-fields. In addition to these more recent explorations, UCSD has now simulated a variety of wedge, slab and lens geometries for various studies.

(6) Metallic Metamaterials (Yablonovitch’s group)

Yablonovitch group’s primary research interest has been the conception and design of near-field optical structures that take advantage of surface plasmon excitation. The dispersion curve for a thin film of silver on a sapphire substrate is illustrated in Fig. 14 below as a function of film thickness. The dispersion curve clearly indicates that plasmons at ultraviolet frequencies ($E \sim 3$ eV) possess wavelengths corresponding to free x-rays ($\lambda \sim 100$ eV/c). Surface plasmons are thus excitations that can be used to resolve features below the far-field limit of optical radiation; it is the resonance of surface plasmons in thin films that the perfect lens for the near-field utilizes. We expect that other lens structures with greater functionality can take advantage of the very short wavelength of surface plasmons, and we are working towards the design of such structures.

![Surface Plasmons - Symmetric Mode](image)

**Figure 14.** Dispersion relation for the symmetric surface plasmon supported by a thin silver film coating of a sapphire substrate. The film thickness determines the coupling of plasmons on opposite surfaces, thus influencing the symmetric plasmon dispersion.

Their collaborative effort has focused on discussions of a theoretical nature with Prof. Pendry. A product of this discourse was the notion that surface plasmon dispersion can be tuned through precise control of the metal film thickness supporting the plasmon modes. Further discussions have elucidated other factors that must be considered in thin film structure design, in particular heat dissipation and film thickness tolerances are of critical import.
(7) Extensive investigations of the optics of evanescent waves (superlens)

Excitation of the rich degenerate states of surface plasmon on metamaterials offers the opportunity to access the deep sub-wavelength information using superlens. Following the work on the amplification of evanescent waves using superlens, Zhang’s group is devising a set of experiments toward further understanding on configuration and manipulation of plasmon optics (Fig. 15). First, silver samples are cross-sectioned using FIB to evaluate their granular structure and the contribution to the scattering of evanescent waves. The results on evaporated silver film support the assumption of surface scattering from silver-air interface that dominates the coupling from propagating waves to evanescence, a critical requirement for the demonstration of superlens. Meanwhile, the experiments of oblique incidence on silver film are ongoing to investigate the angular dependence of the dipole emissivity of the near-field object.

![Figure 15](image)

Figure 15. Left: The Fourier transformed roughness spectrum of 50nm silver film as probed by AFM. Inset, a cross-sectional TEM picture of 50nm silver film for comparison. Right: The experiments of oblique incidence on silver film are ongoing to investigate the angular dependence of the dipole emissivity. Shown here is the computed dipole function $|W_p(\theta, \theta_0)|^2$ when incident angle $\theta_0$ varies from $0^\circ$ to $20^\circ$.

(8) Goos-Hanchen Shift at the Interface between Left-handed and Right-Handed Materials

Goos-Hanchen shifts due to total reflections at the interface between left-handed media and right-handed media are analyzed. When incident medium and transmitting medium are both left-handed or both right-handed, the Goos-Hanchen lateral shift direction is parallel to the direction of in-plane energy flux of the incident beam. When one medium is left-handed while the other one is right-handed, the Goos-Hanchen shift is anti-parallel to the direction of in-plane energy flux of the incident beam. The Goos-Hanchen shifts have to be taken into account in designing of waveguides associated with metamaterials.

Electromagnetic Characterization and Devices

Metamaterial Characterization

(1) Characterization and Analysis of THz Structures

UCSD has also contributed to the measurement and analysis of the UCLA THz metamaterial samples. These samples have included both split ring resonator media, as well as both static and reconfigurable wire media. Preliminary work suggests that there is indeed a magnetic effect from the
split ring resonators (SRRs), although at the moment the SRRs are only deposited on a surface rather than forming a bulk medium. UCSD has formulated an analysis of the scattering geometry and shown that the recovered reflectance curves are indeed consistent with the SRRs having a magnetic response.

(2) Measurement of the MIT All-Angle Negative Refractive Photonic Crystal

During the last year, a photonic crystal was designed and fabricated by the MIT groups, and sent to UCSD for testing. Photonic crystals represent an alternative approach to realizing negative refraction, although the mechanism is quite different. In particular, photonic crystals are highly inhomogeneous materials that are not easily described by continuous bulk parameters. This difference has been manifested in the initial microwave experiments performed on the MIT sample, which is expected to exhibit refocusing of a nearby line-source with subwavelength resolution. Indeed, the data that has been taken on the sample has shown there are definite frequency regions for which a very narrow focal spot can be achieved. The plots in Figure 16 below indicate that the overlap with theoretical calculations from MIT is excellent for both free space and across the PBG sample. However, the experimentally observed frequencies where the superresolution exists do not necessarily coincide with the frequencies predicted from the simulations. This is not unexpected, as very small changes to the photonic crystal surface structure can lead to large changes in the surface band structure. During the coming year, UCSD will continue to work with MIT to understand the

Figure 16: (Top) The MIT PBG sample next to a coaxial antenna. (Left) Numerically calculated and experimentally measured field plots at a position 37 mm from the antenna source. (Right) Numerically calculated and experimentally measured field plots 37 mm away from an antenna source, placed on the opposite side of a PBG structure. The wavelength is ~49 mm.
issues associated with using photonic crystals to observe phenomena associated with negative refraction.

(3) Development of NSOM (near field scanning optical microscopy) for optical diagnostics of local density of state (LDOS) of metamaterials

A near-field scanning optical microscope, in combination of optical spectroscopy, is being developed at Zhang’s group. The bent optical fiber tips are manufactured and assembled onto a customer designed piezoelectric driving tip holder. The quality of near-field probes will be critical to the NSOM imaging and spectroscopic resolution. To this end, we are optimizing the tip manufacturing processes on homemade apparatus. Using FIB, we further fabricated some plasmonic nanostructures that have demonstrated extraordinary far-field light transmission at specific wavelengths. We plan to probe the near-field spectral characteristics of these structures as to initiate the efforts of optical diagnostics of local density of state (LDOS) of metamaterials. Zhang/Yablonovitch’ group is going to collaborate on the theoretical aspect of local density of state (LDOS) of metamaterials.

Metamaterial Devices

(1) Demonstration of working tunable plasmonic filters in 1-2 THz

Zhang’s group synthesized two generations of tunable plasmon wire samples embedded in elastomeric substrates (PDMS) (Fig 17). The preliminary mechanical test on PDMS molded THz plasmonic filter demonstrates an elastic deformation more than 100%, with Poisson ratio 0.28. A special sample mount is machined to demonstrate the tunability of the thin wire devices in FTIR system. The preliminary measurement of these samples indicates the red-shift of plasmonic edge when the samples experience elongation, and efforts are ongoing to optimize the device performance.

![Figure 17](image)

**Figure 17.** Left: Optical image of tunable plasmonic wires molded in PDMS. Right: The preliminary transmission FTIR experiment demonstrates a red-shift of plasmonic edge when the samples undergo elongation.

(2) Refinement of the Transmission Line (TL) Approach of Metamaterials

We have significantly improved our understanding of metamaterials using the TL approach. Any physical structure necessarily includes LH and right-handed (RH) contribution due to the presence of natural RH effects, so that we introduced the term composite right/left-handed (CRLH) to designate the most general type of metamaterial. Typically, a CRLH material is LH at low frequencies and RH at higher frequencies with a transition frequency characterized by an infinite guided wavelength. Such a structure is represented in Fig. 18. Fig. 19 shows a typical analytical dispersion relation and
dispersion diagrams, showing the existence of a gap between the LH/RH ranges only in the case of unbalanced component values.

\[ \cos(\beta \omega) = 1 - \frac{1}{2} \left[ \frac{1}{\omega^2 L_C + \omega^2 L_L} - \left( \frac{L_C}{L_L} \frac{C_L}{C_C} \right) \right] \]

\[ v_e = \frac{a^2 \sin(\beta \omega)}{\omega L_C, \omega L_L} \]

\[ \Gamma: \alpha_1 = \frac{1}{\sqrt{L_C}}, \alpha_2 = \frac{1}{\sqrt{L_L}} \]

if \( L_C = L_L \), then \( \alpha_1 = \alpha_2 \)

i.e. no GAP!

Figure 18: Artificial 1D (straightforwardly extendable to 2D) CRLH-TL (red: RH; blue: LH).

Figure 19: CRLH-TL important formulas, dispersion diagram, 2D-case dispersion diagram for balanced and unbalanced case.

(3) Backfire-to-Endfire CRLH leaky-wave (LW) antenna

Figure 20: Backfire-to-endfire leaky-wave CRLH antenna. Antenna structure and behavior, measured radiation patterns at 3.5, 3.9 and 5 GHz, and measured scanned angle versus frequency characteristic. The CRLH LW antenna was one of the major findings of our research. It emerged as a direct consequence of Fig. 19 plus the presence of the radiation cone, in which modes are complex and leaky. The structure (interdigital C, shorted stub L) and performances of this antenna are presented in Fig. 20. In addition, a diversity of frequency/angle-agile reflectors integrating this antenna and based on heterodyne mixing were designed and demonstrated experimentally. A 2D reflector using simply shorted/matched terminations was also demonstrated.

(3) Microwave 1D Components

Many novel 1D components were invented, analyzed and demonstrated experimentally. Two examples are shown in Figs. 21 and 22. Fig. 21 shows a CRLH/RH coupled line coupler characterized
by arbitrarily tight coupling (virtually up to 0dB!) over 30% bandwidth, whereas conventional coupled-line couplers exhibit very poor coupling (typically less than 10dB). A CRLH/CRLH coupler was also investigated and shown to present similar performances. The exceptionally high level of coupling is due to the amplification of transverse evanescent waves. Fig. 23 shows a dual-band branch line coupler that can be designed to an arbitrary pair of frequencies, whereas the conventional branch line is restricted to odd harmonic frequencies (i.e. $f_0$ and $3f_0$). The key idea is to exploit the additional degree of freedom of the frequency offset from DC provided by the CRLH-TL (Fig. 19). A dual-band rat-race coupler based on the same principle was also demonstrated. Also, dual mode and enhanced-bandwidth components were discovered.

**Figure 21**: Broadband tight (here 0-dB) coupled-line RH/LH coupler and measured S-parameters.

**Figure 22**: Dual-band branch line coupler. Prototype, measured magnitude response, and phase response.

(4) Two-Dimensional Structures

The 1D-TL approach was rigorously extended to 2D-TL and a complete theory (e.g. Fig. 19, third graph) was established to describe all the properties of 2D metamaterials. One of our findings was the existence of a strong energy concentration at the interface between RH/LH media at the transition frequency where the two media have the same EM density, as illustrated in Fig. 23. We speculated that this phenomenon might be an extension of the conventional surface plasmon, where the permeability of the plasma would be negative. A preliminary naïve description has raised the question of the possible existence of radiative palmons, which may lead to extremely small antennas.
Figure 23: RH/LH interface plasmon phenomenon. Interface, dispersion relation, and voltage magnitude/phase obtained by 2D circuit simulation.

We have also proposed and demonstrated an anisotropic structure with RH characteristics (positive refractive index) in one direction and LH (negative refractive index) characteristics in the other orthogonal direction.

Figure 24: Capacitively enhanced mushroom structures. Open and closed case with corresponding full-wave dispersion diagrams

Another extensive research line was dealing with the 2D mushroom structure shown in Fig. 24, where it can be seen that this structure supports a fundamental mode which is LH along most of the spectral region. In the open case, the mode couples to the TM air line down to DC, while in the closed case it is purely LH.
Finally, we were able to discover an open 2D textured structure which supports radiative modes and can therefore be used as a 2D leaky-wave antenna. This structure is shown in Fig. 25 along with its dispersion diagram. Initial radiation patterns measurement confirm the expected full-space scanning capability of this structure.

![Textured interdigital leaky-wave radiating surface and corresponding dispersion diagram.](image)

**Figure 25:** Textured interdigital leaky-wave radiating surface and corresponding dispersion diagram.

### 4 Synergy and Interactions

During this year, there have been many formal and informal interactions among members of our MURI team. At whole project level, three teleconferences have been arranged to facilitate the interaction among teams. Especially, the teleconferences offer the opportunities for students and postdocs to present their results. The collaborative efforts among the team members have been summarized in the following table.

<table>
<thead>
<tr>
<th>Participants</th>
<th>Activities</th>
</tr>
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<tbody>
<tr>
<td>UCLA interactions</td>
<td></td>
</tr>
<tr>
<td>Zhang/Itoh</td>
<td>Dr. Caloz’s presentation at Zhang’s group (Jan. 24, 2003)</td>
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<tr>
<td>Zhang/Smith/Basov</td>
<td>THz metamaterials characterization</td>
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<tr>
<td>Zhang/Chen</td>
<td>Zhang’s student gave a seminar in Chen’s group</td>
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<tr>
<td></td>
<td>Four physical meeting between Chen and Zhang and frequent discussion</td>
</tr>
<tr>
<td>Zhang/Pendry/Smith/Schultz</td>
<td>Visits and discussions on superlensing and enhancement of evanescent waves</td>
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<tr>
<td>Zhang/Yablonovitch</td>
<td>Discussion on Plasmonic imaging and super lensing</td>
</tr>
<tr>
<td>Zhang/Joannopoulos</td>
<td>Povenilli visit Zhang’s Lab and discuss about magnetic dipole radiation in PBG</td>
</tr>
<tr>
<td>MIT Interactions</td>
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<tr>
<td>Joannopoulos/Chen</td>
<td>Collaboration on AANE</td>
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<tr>
<td></td>
<td>Luo gave a seminar at Chen’s group</td>
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<tr>
<td>Joannopoulos/Chen/Schultz/Smith</td>
<td>Design, fabrication, and characterization of AANR</td>
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<tr>
<td></td>
<td>Visit from UCSD group</td>
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<tr>
<td>Joannopoulos/Pendry/Schultz/Smith</td>
<td>Joint publication on AANR</td>
</tr>
<tr>
<td>Joannopoulos/Zhang</td>
<td>Povenilli visit Zhang’s lab and discuss about magnetic dipole radiation in PBG</td>
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<tr>
<td>Collaboration</td>
<td>Description</td>
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<tr>
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</tr>
<tr>
<td>Imperial College Interactions</td>
<td>Discussion and collaboration. Visits by Pendry and Ramakrishna to UCSD. 2 month sabbatical by Pendry at UCSD. Three publications.</td>
</tr>
<tr>
<td>Imperial college and UCSD</td>
<td>Discussion and collaboration. Visits by Pendry and Ramakrishna to UCSD. 2 month sabbatical by Pendry at UCSD. Three publications.</td>
</tr>
<tr>
<td>Imperial college and MIT</td>
<td>Discussions and collaboration. Three joint publications.</td>
</tr>
<tr>
<td>Imperial college and UCLA</td>
<td>Visits by Pendry and Ramakrishna – Seminars and discussions on the perfect lens and other topics.</td>
</tr>
<tr>
<td>UCSD Interactions</td>
<td>Three visit to UCLA and on visit by Dr. Caloz to UCSD. Visit the group of Itoh to understand relationship of the transmission line approach to metamaterials versus the materials approach.</td>
</tr>
<tr>
<td>Smith/Starr/Itoh/Caloz</td>
<td>Host Pendry for sabbatical.</td>
</tr>
<tr>
<td>Schultz/Smith/Pendry</td>
<td>Collaborative effort on experimental measurement of AANR.</td>
</tr>
<tr>
<td>Mock/Schultz/MIT</td>
<td>Discussion with Pendry and Ramakrishna regarding practical implementations of the “perfect lens”. Two visit by Pendry and one visit by Ramakrishna.</td>
</tr>
<tr>
<td>Smith/Schurig/Pendry</td>
<td>Teleconference, email and visits with members from Zhang’s group. Members from the UCSD group have made several visit to UCLA, and many members from Zhang’s group have come to work at UCSD facilities. The primary focus of this interaction has been the design, fabrication and characterization of metamaterial structures designed for THz frequency.</td>
</tr>
<tr>
<td>Schultz/Smith/Padilla/Zhang</td>
<td>Introduce Prof. Basov work and experimental capability to Zhang. Made a fund transfer to aid Prof. Basov join in THz frequency effort.</td>
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