

## Nanoscale Metallic Photonic Crystals: Fabrication, Physical Properties, and Applications

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### Introduction and Objectives

Metallic photonic crystals (MPCs) have a number of unique properties due to the presence of a high conductivity and a plasma frequency in the metal constituent. It is desirable to investigate the physical properties of MPCs in the visible spectrum in order to reduce losses in the metal, therefore requiring periodicity on the nanoscale. Our team is concentrating on two physical embodiments of MPCs: 2-D nanostructured metallic films and 3-D metal-infiltrated opals. We are experimentally and theoretically studying a number of physical properties of these MPCs and are investigating possible applications.

### 2-D MPCs

Two-dimensional structures are fabricated using electron beam lithography. One example is shown in Figure 1, along with linear transmission versus incident angle through the otherwise

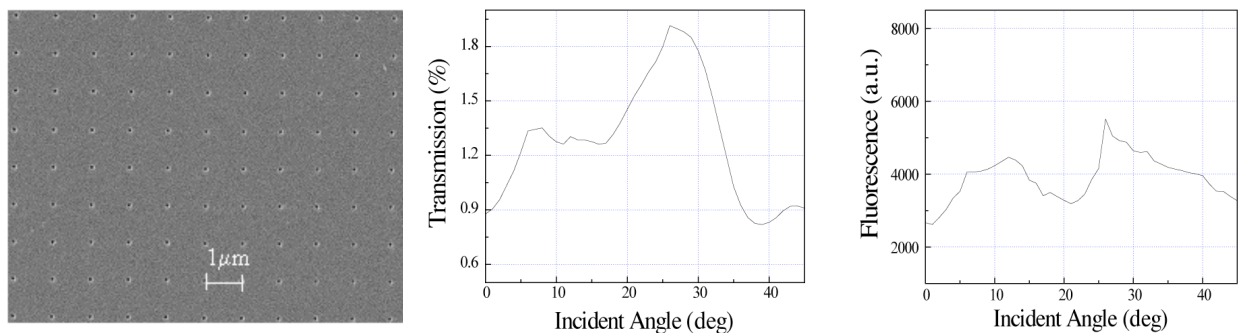


Figure 1. Fabricated 2-D MPC in 60 nm thick gold film (left). The apertures are 100 nm in diameter and the lattice constant is 1 micron. Transmission at 635 nm through the sample versus incident angle (center). Transmitted fluorescence from a Cy-5 labeled avidin monolayer through the sample (right).

opaque film. One of our goals is to better understand the phenomenon of enhanced light transmission through these samples and to determine what applications might result. There are two contributions to the light transmission: light transmitting directly through the apertures, and light coupling into and out from surface plasmon modes through the periodicity of the grating, which results in distinct resonance features (this coupling can be considered as the result of leaky mode propagation within a plasmonic crystal). It is widely believed that under the conditions of resonant transmission, light intensity within the apertures is enhanced. In order to demonstrate that effect, a fluorescing monolayer was applied to the front side of the sample, with fluorescence collected through the back side; the fluorescence intensity as shown in Figure 1. From these measurements, the total fluorescence output normalized to the aperture fill-fraction is 40 times greater than anticipated, suggesting a 40 times enhancement of incident light intensity

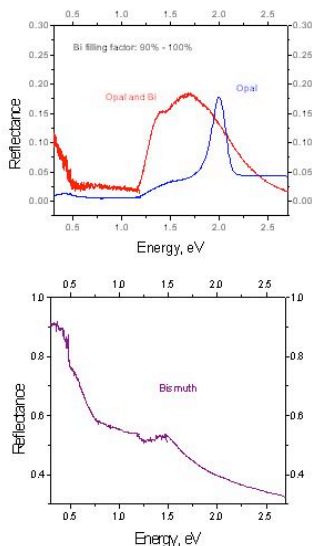
within each aperture. Based upon these results [2], we are pursuing three application directions: fluorescence biosensing, organic light-emitting diodes (OLEDs), and enhanced nonlinear optical effects. The demonstration of fluorescence enhancement suggests that the light emission efficiency of OLEDs could be improved upon application of the organic layer to periodic metallic structures. This possibility is currently under investigation. For the demonstration of enhanced nonlinear effects, a nonlinear material should be placed within the apertures because that is where the intensity enhancement occurs. The nonlinear effects that will experience the greatest net enhancement are those that scale as intensity-squared or greater, as the intensity-enhancement fill-fraction product is less than one, but the intensity-squared fill-fraction product is greater than one. We are currently performing studies of native second-harmonic generation and two-photon induced fluorescence from a labeled monolayer with these structures.

Additional physical property studies are being performed with metals, such as cobalt, that exhibit magneto-optic effects. With these magnetic metals, we anticipate that light coupling through the structure will occur via magneto-plasmons, which may have somewhat different properties and dispersion relations as compared to surface plasmons. We plan to measure the spectra of magnetic constants through the 2-D magnetic metallic PC and light transmission through these structures versus external magnetic field.

### 3-D MPCs

Three-dimensional structures are fabricated by infiltrating synthetic opals with a variety of metals. The goal is to study their optical, magnetic and transport properties. We have been successful in synthesizing silica balls of diameters ranging from 100 to 800nm with less than 5% dispersion. Thin opal films with large surface area have been successfully fabricated using self-assembly. An oven was constructed to infiltrate various metals such as Gallium and Indium; infiltrated Ga/opal PCs have been already fabricated. In addition we have collaborated with a group at UT Dallas for infiltration of other metals into opals, such as Bismuth.

Visible range reflectance of opal infiltrated with Bi



The optical reflectivity spectrum of metallic opal PCs have been measured as a function of angle in the visible to near IR spectral range, and in the mid to far IR spectral range. Figure 2 shows the visible/near IR reflectivity spectra of opal PC, Bismuth, and Bismuth infiltrated opal PC. The reflectivity of Bi in opal PC is very different from that in the opal and Bi metal alone. The spectrum has a well-defined Bragg stop band at 1.5 eV, which is much broader and more red-shifted compared with that of the opal PC. This is due to the larger dielectric constant mismatch between the silica and Bi. In addition the Bismuth infiltrated opal PC spectrum shows a dramatic increase towards low energy, which may be the signature of a 'cut-off' energy, reminiscent of the plasma edge of metals. Additional spectra will be obtained with other metallic-opal PCs and over a broader spectral range from 100 to 30,000  $\text{cm}^{-1}$ .

To investigate the network connectivity of the metallic-opal

PCs, we also measured their electrical resistance,  $R$  vs. temperature,  $T$ . Although most of the metallic- opal PC samples show metallic type  $R(T)$  behavior, where  $R$  increases with  $T$ , some other interesting properties, such as marked phase transitions also occur; for Bismuth opal PC, phase transition occurs near 40 K..

### Theoretical Studies

An analytical theory of low frequency electromagnetic waves in small metal volume fraction MPCs has been developed [3,4]. The evidence of the existence of such waves has been found recently via experiments and computations. We have obtained an exact dispersion equation and studied the cutoff frequency as a function of parameters of the MPC. Recent experimental and computational results are in a perfect agreement with our analytical expressions. We have also shown that a simple explanation of the negative refraction in the compound system of the MPC and split ring resonators (SRR's), based upon the permittivity of the MPC and the negative permeability of the SRR's, does not work because negative permeability blocks the propagation of EM waves in the MPC .

We have also shown that the popular opinion that left-handed media (LHM) are characterized by a negative refractive index is misleading [5]. Since  $n$  does not enter into Maxwell's equations and boundary conditions, any medium may be described by both positive and negative  $n$ . However, to use negative  $n$  one should alter some traditional electrodynamics definitions.

We have also proposed a new type of lens similar to the Veselago lens (Fig. 3a) which consists of a slab of a LHM embedded into a RM with the same  $n$  and impedance  $Z$ . Due to negative refraction at the LHM-RM interface, this lens images stigmatically three-dimensional domains. In the proposed novel lens only  $n$  is the same for both materials. Therefore, this lens is easier to make. Lens of the new type has multiple foci and might be useful for 3D imaging (Fig. 3b).

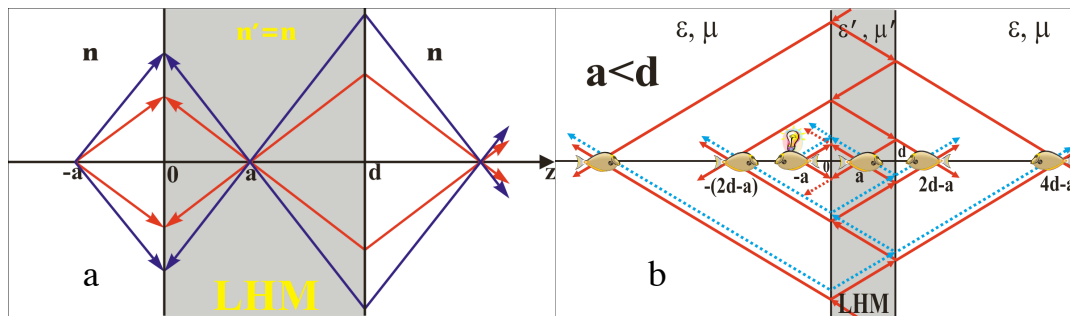


Fig. 3. Veselago lens (a) and a novel lens (b). Object is marked by the bulb.

### References

- [1] For further information about this project, see < <http://www.physics.utah.edu/~opalgroup> >, or email <opalgroup@physics.utah.edu>.
- [2] Y. Liu and S. Blair, "Fluorescence enhancement from an array of sub-wavelength apertures," accepted to Optics Letters, (2003).
- [3] A. Pokrovsky and A. Efros, Phys. Rev. B **65**, 045110 (2002)
- [4] A. Pokrovsky and A. Efros, Phys. Rev. Lett. **89**, 093901 (2002).
- [5] A. Pokrovsky and A. Efros, Solid State Comm. **124**, 283 (2002).