Metal/Dielectric Photonic Crystal with Broadband Transparency for Propagating and Evanescent Waves

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Abstract: Strongly coupled metal/dielectric cavities with anti-reflection coatings at the entrance and exit faces provide a very broad transmission band for both the evanescent and propagating waves. Power lost through the super-resolution process is also examined.

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Pendry[1] showed that a simple metal film displayed negative refraction of the Poynting vector for TM polarized light and was capable of supporting evanescent waves. This unique combination resulted in a flat superlens that could image an object with a resolution beyond traditional glass lenses which support only propagating waves. The performance limit of the metallic superlens was associated with the losses in the metallic film.

In order to overcome the losses associated with a single metal film, Ramakrishna *et al.* designed a superlens based on a multilayer metal-dielectric stack having thin metal layers[2]. This new combination of a positive and negative dielectric constant material results in a slightly different type of superlens. Instead of having a focus inside of the metal film, the new geometry balanced the negative and positive refraction of the Poynting vector in consecutive layers. This leads to a waveguide-type effect that carries the propagating and evanescent waves through the structure without the usual diffraction.

Since the introduction of the metallo-dielectric superlens there have been numerous attempts to design structures with high transmittance for the evanescent waves[3-6]. However, very little has been said about the transmittance of the propagating waves and the bandwidth of the lens.

The structure we examine is a 1-dimensional metallo-dielectric photonic crystal (1-D MDPC) based on Ag/GaP. These 1-D MDPC are known to have a very low sheet resistance (~0.1 ohm/sq) due to the high fraction of metal in the multilayer stack[7]. In general, most of the interest in photonic crystals has concentrated on the unique properties of the band gap and the band edges, but for MDPC the interest is on the pass band precisely because of the unusual combination of broadband, high transmittance and high electrical conductivity, hence they are often called "transparent metals."

The concept of a transparent MDPC is based on a series of strongly coupled metal-dielectric Fabry-Perot cavities[8,9]. As an example, we start with a single cavity of Ag/GaP/Ag (22 nm/35 nm/22 nm) surrounded by air. Adding another period of GaP/Ag results in 2 coupled cavities and removes the degeneracy causing the single resonance at 570 to split into 2 resonances at 490 nm and 620 nm. The amount of the splitting depends on the thickness of the Ag layers, with thinner layers providing a larger separation in the transmission resonances. Adding another period results in 3 coupled cavities and 3 resonances and so on for more periods.

While the transmittance of the periodic MDPC is large, it can be improved by the addition of antireflection coatings. The AR coating is simply ½ the thickness of the dielectric spacer and of the same material.

In the following we compare 3 geometries, a Periodic MDPC [6 periods of Ag/Gap (22 nm/35 nm)], a Symmetric MDPC [5.5 periods of Ag/GaP (22 nm/35 nm)], and a Transparent Metal MDPC [5.5 periods of Ag/Gap (22 nm/35 nm) with 17 nm thick GaP AR coatings on the entrance and exit faces]. All three structures have the same amount of Ag, 132 nm total thickness equally divided into 6 layers.

Fig. 1 is a 3-D plot of the transmittance versus wavelength and k_x/k_o. To save space we plot the 3-D transmittance for the transparent metal MDPC and the periodic MDPC. The symmetric MDPC is only slightly better than the periodic MDPC. The notable feature in Fig. 1 is the broadband, high transmittance of the propagating and evanescent waves for the transparent metal MDPC. The five resonances associated with the five coupled cavities are clearly evident. It is surprising that the AR coatings can have such a drastic effect on the transmittance of the propagating and evanescent waves over a broad range of wavelengths.

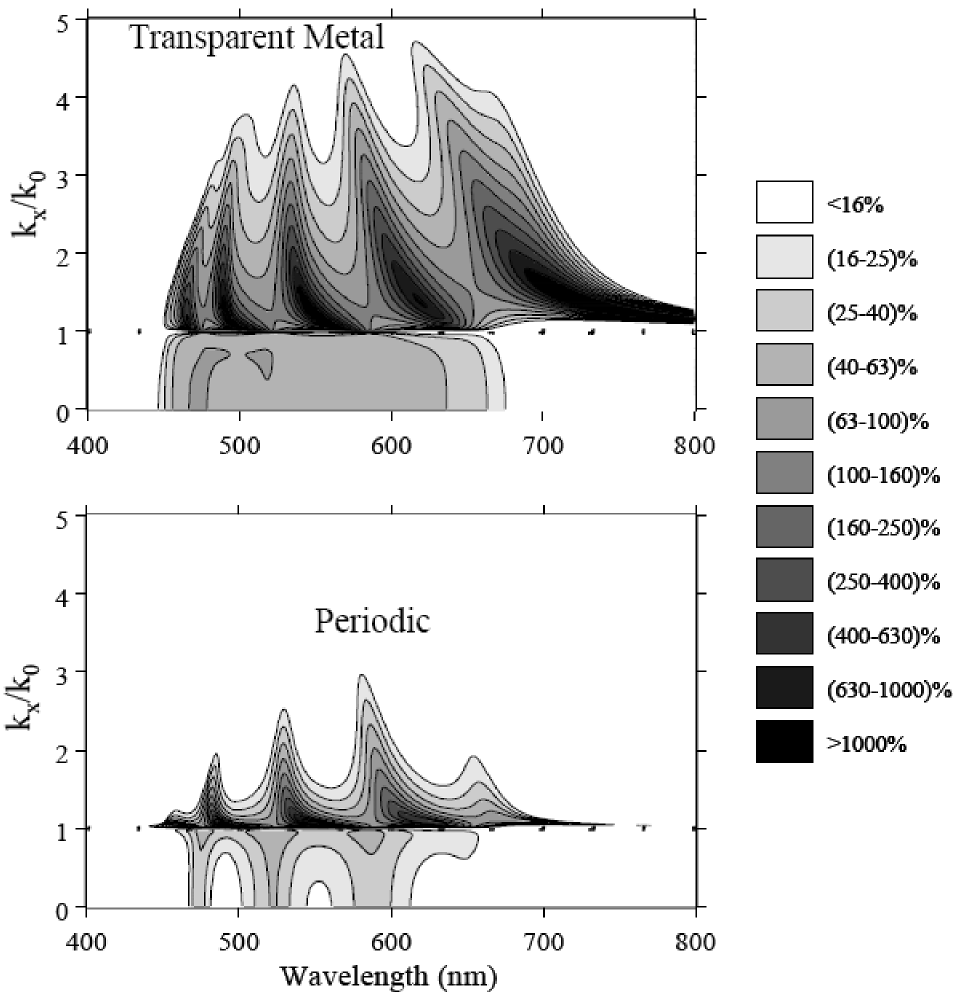

Fig. 1) Topographic 3-dimensional plot of the transmittance versus wavelength and k_x/k_o for the transparent metal MDPC and the Periodic MDPC. The lowest contour line indicates a transmittance of 16%. Note that the contour lines are not uniformly spaced to include the wide range of transmittance values.

The super-lensing properties were examined by imaging 2 slits separated by less than $\lambda/2$ in free space. As an example, we look at a wavelength of 532 nm and compare all three MDPC. Fig. 2 shows the image formed by the three lenses and also the case of the transparent metal MDPC, but without evanescent components (diffraction limited). The slits (40 nm wide with a center to center spacing of 140 nm) are placed at the entrance of the lens (but in free space) and the image plane is located 50 nm beyond the end face of each lens. Although each lens contains six, 22 nm thick Ag films, the lenses have slightly different lengths due to the different geometries. The result is that the distance from the object plane to the image plane is 357 nm, 391 nm, and 392 nm for the symmetric, transparent metal, and periodic MDPC, respectively. The transparent metal MDPC provides >95% contrast for the two slits at a slit separation of $\lambda/4$. The other two lenses are only slightly better than the diffraction limited case.

It has been noted previously that the interference of propagating waves and evanescent waves can cause circulation in the Poynting vector[5]. Remnants of the vortices can be seen in Fig. 2 for the slightly negative components of S_z at a distance of ~200 nm from the center of the slits. The presence of vortices is an indication that evanescent waves are contributing to the resolution of the lens.

Images similar to those shown in Fig. 2 were calculated throughout the transparency band of the transparent metal lens. It was found that over the wavelength range of 500 nm to 650 nm, the transparent metal lens could resolve two 40 nm wide slits with a contrast >80% and slit separation of <λ/2.5 where lambda is the free space wavelength for the incident radiation. At most wavelengths, the slit separation was ~λ/4. In addition, the transmittance for the normal incidence propagating waves was ~ 50% over the super-lensing band, Fig. 1.

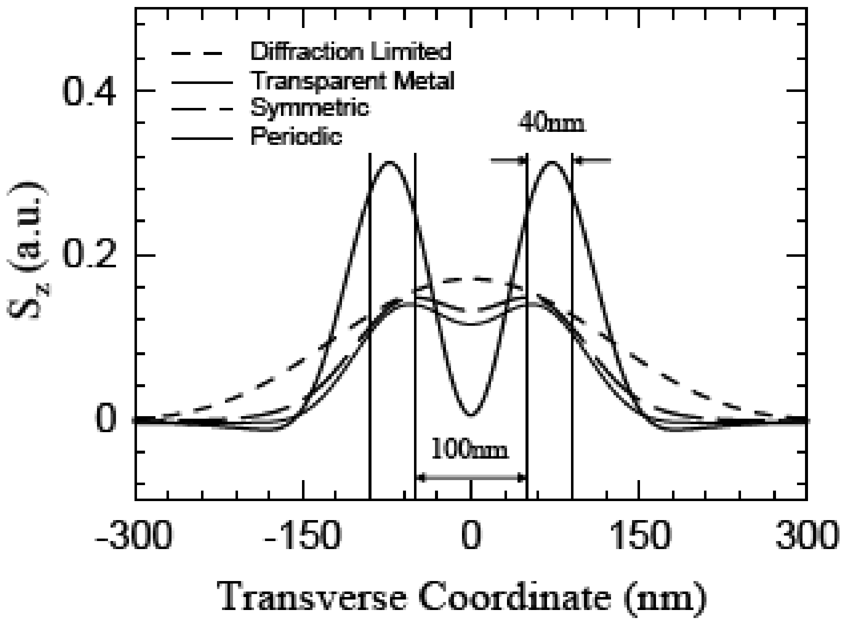

Fig 2) Image formed by the lenses for 2 slit sources at a wavelength of 532 nm. The center to center slit separation is λ/4. The image plane is 50 nm from the end of the lens. The diffraction limited case is for the transparent metal but without the evanescent components included in the calculation.

It is worthwhile mentioning that the single Fabry-Perot cavity (Ag/GaP/Ag) has good transparency for the propagating and evanescent waves in the region of 575 nm to 625 nm. Although the single cavity lens is short, only 79 nm, it provides the basic building block of the transparent metal lens.

We have also calculated the ohmic losses associated with the excitation of the surface plasmon modes responsible for the super-lensing process. We find that the losses are strongly dependent on the proximity of the lens with respect to the source. A value of 100% transmittance for the evanescent waves does not imply these components are transmitted without power loss. In fact, the losses for the evanescent components can exceed the losses associated with the propagating waves.

As a final note, the transparent metal approach is based on relatively thick metal films that can be fabricated by traditional deposition techniques.

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