Laminated Photonic Band Structures with High Conductivity and High Transparency: Metals Under a New light

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ABSTRACT

We have developed a new transparent conductor based on one-dimensional metal-dielectric photonic band gap structures. Thin-film metal-dielectric filters containing at least 150nm of silver have been fabricated, with transmittance greater than 50\% over the 500-600nm waveband, and sheet resistance of $\sim 0.1$ Ohm/Square. Theoretical calculations predict at least 25\% transparency levels for structures that contain $1/2$ $\mu$m of silver, and transparencies that approach 80\% for structures that have in excess of 100 nm of silver. Some applications for transparent, conducting films include antennas embedded in windshields, electrodes on flat panel displays, electromagnetic shielding, and solar window panes, to name a few.

The study of electromagnetic wave propagation at optical frequencies in metals has never been tackled in the past because it was never thought to be very interesting. The reason is simple and well known: metals are highly reflective (and absorptive) at nearly all wavelengths of light. For example, static fields are rejected from the surface of a metal, while all other frequencies of interest, from microwaves to ultraviolet light, are reflected. One of the more significant optical properties of a metal is the skin depth [1,2]. The skin depth is a measure of the distance from the surface such that the magnitude of the electric field has decreased to approximately 1/3 of the value at the surface. Since metals are very dispersive, the skin depth is a strong function of frequency. For example, the skin depth of silver and other metals such as copper, aluminum, and gold, at optical frequencies is approximately 10nm. At microwave frequencies, the skin depth increases to approximately 1$\mu$m. It is therefore clear that metals attenuate electromagnetic waves very well, more so at high frequencies.
Since metals are highly reflective, their use in photonic band gap crystals was never contemplated at optical frequencies. To be sure, metals have been used to describe two and three-dimensional photonic crystals at microwave frequencies [3-5]. However, the role of the metal in those cases, which was arranged to form wire meshes, or as small metal spheres embedded in a dielectric crystal, fulfilled the more traditional role of scatterers of incident waves. Therefore, the filtering capabilities of the devices proposed in references [3-5], for example, come about because the scatterers are strategically located inside a dielectric matrix to produce pass bands and band gaps for incident, microwave radiation. In contrast, we have discovered a simple resonance tunneling mechanism that allows optical waves to propagate through a series of metal layers containing one half micron of silver or more, without incurring reflection or absorption losses that are traditionally associated with these systems [6,7].

Previously, it was thought that multi-layer stacks containing alternating layers of metal and dielectric materials would not exhibit a photonic band gap structure. It was expected that all electromagnetic radiation would be reflected or absorbed, and none transmitted. Indeed, layered metal-dielectric stacks have been proposed to make better reflectors of light at visible wavelengths [8]. For example, a single silver film 40nm thick transmits only 7% of the incident radiation for wavelengths in the visible range. Therefore, it would be counterintuitive to add metal layers in order to form a multi-layer metal-dielectric stack to enhance and/or widen the transmittance band. In fact, the resonant tunneling that we describe below can enhance the transmission by several orders of magnitude. The periodic nature of the metal-dielectric lattice causes the light to propagate through the metal layers with extremely low losses.

A related device exists in electronics, the resonant tunnel diode, which contains a single barrier that the electrons tunnel through. An interesting feature of the resonant tunneling process in a metal-dielectric photonic band gap crystal is that the tunneling efficiency is very low for a single metal layer, enhanced tunneling is only evident if two or more metal/dielectric periods are present. A surprising fact is that the transmission through the metal-dielectric photonic band crystal may actually increase, as more metal layers are deposited [7]. In addition, the center wavelength, width, and sharpness of the transparency window for the metal-dielectric photonic band gap crystal is adjustable and generally dependent on the thickness and the number of the metal-dielectric layers.

Resonant tunneling occurs for those wavelengths that are resonant with the metal cavities that are stacked together to form the photonic band gap structure. Metal layer separation is chosen to be
approximately $\lambda/2$, where $\lambda$ is the tunneling wavelength. Since the index of refraction for most metals is of order unity or less in the visible range, interference effects conspire to allow mostly unimpeded propagation of light with minimal scattering and absorption losses [6,7]. Resonant tunneling can be observed in the simple case of a metallic Fabry-Perot cavity. We depict this situation in Fig.1, where we plot the transmission as a function of the separation between two metal layers approximately 40nm thick. Plate separation has been scaled to a reference wavelength of 1$\mu$m, and we use the parameters for silver at $\lambda=1\mu$m [9]. In Fig.1, a transmission resonance can be observed near but not exactly multiples of $\lambda/2$. This is due to the finite thickness of the metal walls. What is surprising is that the addition of more layers does not reduce the maximum transmission [7]. Perhaps another of the most unique features of the transparent metal is the ability to have a tunable, single pass band and block all other radiation from static fields to soft X-rays. This remarkable property is a result of the highly dispersive nature of metals.

**Figure 1:** Transmission coefficient vs cavity length calculated for a simple metallic Fabry-Perot cavity having 40-nanometer thick metal walls. A transmission resonance occurs when the condition $2X=n\lambda$, where $n$ is an integer, is approximately satisfied, as expected. Although we do not show this here, adding more periods generates the band structure, with as many resonances within a pass band as there are periods. **Inset:** Schematic representation of the structure, and the regions where we seek solutions for the wave equation.
Several metal-dielectric photonic band crystals were grown to demonstrate this new remarkable technology. In one case, a photonic band crystal consisting of a 5-period lattice of silver and magnesium fluoride was grown containing a total metal thickness of 150nm. This is more than 10 optical skin depths of metal, and will serve to illustrate the fact that resonant tunneling can greatly enhance the transmittance.

The sample was grown in a standard thin-film thermal evaporator with dual sources. Corning 2947 glass, 2.5cm by 7.5cm was used as the transparent substrate. The substrate was not temperature controlled during the growth. Instead of growing a sample with uniform periodicity as in our earlier work [7], the silver layers had a chirp in the thickness. The chirp serves to smooth out oscillations in the transmittance spectrum. Starting from the substrate, the silver layer thicknesses were 20nm, 35nm, 40nm, 35nm, 20nm, respectively. The magnesium fluoride layers were all 145nm thick, except for the final top layer, which was 75nm thick. The thinner, topmost magnesium fluoride layer plays the role of an anti-reflection coating, and it enhances the transmittance by 10% compared with a layer 145nm thick. However, we have made no attempt to further optimize the transmission beyond this simple step.

The layer thicknesses were measured in situ by a quartz crystal thickness monitor. The thickness monitor was calibrated by profilometry measurements as well as optical transmittance measurements. Essentially, the 5-period sample consists of four coupled Fabry-Perot cavities. Since each individual metal layer is nearly three optical skin depths thick, the cavities are weakly coupled and nearly degenerate. The result will be a relatively narrow transmission band, approximately 100nm wide. The center of the transmission band for this sample can be found at approximately 520nm, at green wavelengths. We have shown previously [6] that by using thinner metal layers, 10nm thick, the cavities are strongly coupled and the degeneracy is removed. In that case, a 400nm wide transmission band was obtained across the visible spectrum with 70% transmittance.

The optical transmittance of the chirped sample is shown in Fig.2. At a wavelength of 500nm, the transmittance of the metal-dielectric photonic band sample is 17,000 time greater than for a single silver film containing the same amount of silver, 150nm. The transmission resonance at a wavelength of 330nm is near the plasma frequency for silver and is not due to the photonic band geometry. At frequencies above the plasma frequency, according to the simple Drude model the metal should be transparent. However, interband transitions lead to absorption, and in this region metals behave more like lossy dielectrics. Therefore, any other pass bands expected at higher frequencies for lossless materials are removed due to interband transitions.
The view through the sample just described is shown in Fig. 3. In the picture, we compare the transmission through the transparent metal stack and from a bulk, 150nm silver layer. The view is clearly unobstructed through the transparent metal filter (bottom); the solid metal layer is almost completely opaque. The thickness of the dielectric components is not exactly uniform across the sample; this explains the light blue tones that emerge near the right edge of the sample.

We note that the transmission resonance at 330nm can be removed without significantly changing the pass band at 500nm by replacing one of the silver layers with an appropriate thickness of gold or copper, for example, which have slightly lower plasma frequency. An unusual feature of the spectrum in Fig. 2 is that the pass band shuts-off after 600nm. In ordinary dielectric-dielectric photonic

**Figure 2.** Theoretical (solid) and experimental (dashes with solid squares) curves for a 5-period metal-dielectric stack. The structure depicted in the inset of the figure. It is chirped, with 145nm MgF2 layers, and 20,35,40,35,20 nm Ag layers, respectively, and an outer MgF2 layer 75 nm thick.

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band gaps, the pass band extends all the way to static fields. In metal-dielectric band gaps, the pass band closes due to the highly dispersive nature of metals. The result can be a single pass band with stop bands extending down to static fields and soft X-rays. The pass bands can be tuned to higher or lower frequencies by adjusting dielectric layer thicknesses [6,7].

Microwave transmission measurements were performed on our samples from frequencies ranging from 8 to 20GHz. As expected, the microwave power transmitted through the sample was at the noise floor for the measurement apparatus, -35dB. As we mentioned earlier, this result follows from the fact that the optical potential step at microwave frequencies is essentially infinite. Therefore, large skin

**Figure 3.** Photograph of a transparency placed on an overhead projector. The writing is covered by two samples: a uniform, 150nm silver layer (top), and our transparent, multilayer stack (bottom) described in Fig.2.
depth values do not necessarily correspond to the ability to transmit radiation. To compare the shielding capabilities of metal-dielectric photonic band structures with the industry standard for transparent conductive films, indium tin oxide (ITO), another measurement was performed with commercially available ITO. The ITO reduced the transmitted power by only -3dB.

Another important property of the sample is the electrical sheet resistance. Sheet resistivities for ITO range from 5-100ohm/sq. Measurements on metal-dielectric photonic band samples showed that the sheet resistance is equal to the resistivity of bulk silver divided by the total metal film thickness. This means that a metal-dielectric photonic band sample containing a total of only 100nm of silver will have a sheet resistance <0.2 ohm/sq. It was determined that the silver layers in the silver/magnesium fluoride samples were in electrical contact, probably as a result of pinhole defects in the magnesium fluoride. It would also be possible to use other materials between the metal layers that are slightly conducting to establish contact between metal films, or by shorting all metal layers together at the edge.

In Fig.4 we plot the predicted transmissive properties of a 20-period metal-dielectric stack that contains 1/2µm of silver. Metal layers are each taken to be 25nm thick, while the dielectric material is TiO₂. Each dielectric layer is approximately 72nm thick. It is clear that even with what can be considered an extremely large amount of metal, the stack is still approximately 25% transmissive over a

1/2 µm of Ag

![Figure 4](image)

**Figure 4.** Theoretical transmittance vs wavelength for a 20-period Ag(25nm)/TiO₂(72nm) stack, containing 1/2µm of silver (solid blue line). The red curve is the transmittance through a 1/2µm bulk silver layer.
bandwidth in excess of 100nm. The conductivity of a metal layer 1/2µm thick is approximately 0.04 ohm/sq, which is negligible for most practical applications.

In Fig.5, we show the transmissive properties of a 6-period Ag(16nm)/TiO$_2$(72nm) multi-layer stack. The first and last TiO$_2$ layers are approximately 38nm thick. This departure from periodicity can give dramatically better results compared to the strictly periodic structure. We note that in this case sheet resistance is approximately 0.2ohm/sq, and transmission levels reach 80% in the visible range. Further improvements in transmission may be achieved with a systematic optimization procedure.

![Figure 5](image)

**Figure 5.** Theoretical transmittance vs wavelength for a 6-period Ag(16nm)/TiO$_2$(72nm) stack. The sheet resistance of this sample is predicted to be 0.2 ohm/sq, similar to that measured and reported in ref.[7].

In conclusion, a remarkable resonance tunneling mechanism allows the propagation of a selected wavelength range through a metal-dielectric photonic band gap structure, visible light in particular. Using this arrangement, we have shown that it is possible to obtain highly conductive, transparent films that find applications in sensor protection, UV protective films, embedded antennas, electromagnetic...
shielding, thermal management in heat reflecting windows, and in transparent, conductive display technology. From a more fundamental point of view, this newly discovered effect opens new avenues of research in the study of electromagnetic field propagation in metals, including diffraction and nonlinear effects, with more surprises to be revealed.

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