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# Resonantly overcoming metal opacity

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The near-perfect response of electrons in metals to low-frequency electromagnetic fields makes even a sub-skin-depth film almost completely opaque to microwave radiation. Here, it is experimentally demonstrated that by surrounding a ~60 nm aluminium film with an array of thin resonant cavities, over 35% of the microwave radiation incident can be transmitted over a discrete set of narrow bands. This represents an enhancement of ~1000 times over an isolated film and allows for a frequency selective screen with a thickness less than 1/70th of the operating wavelength that may be tuned through choice of resonant geometry. © *2013 American Institute of Physics*.
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Since Ebbesen *et al.*[1] provided the evidence for resonantly enhanced transmission through arrays of subwavelength-size apertures in metals in 1998, there has been a great resurgence of interest in the electromagnetic properties of textured metallic films. At millimetre wavelengths, arrays of subwavelength holes in metallic substrates[2] or single holes with surface topography[3] allow for strong transmission enhancement over a narrow frequency band, with the enhancement mechanism predominantly attributed to diffraction enhancing the evanescent fields within the hole. Untextured metallic films have also attracted some interest, including a relatively recent study in the visible domain that utilised quarter–wavelength thick impedance matching layers to achieve enhanced transmission[4] through an otherwise opaque metal layer. Taking these ideas to the microwave regime would clearly result in ~centimetre-thick and relatively cumbersome structures. Indeed, a similar concept has been known for many years, which employs three-dimensional wavelength-sized resonant cavities, and has been used in the design of microwave transmission spectrometers.[5] However, in the present study, we utilise an extension of the idea developed by some of the current authors[6] to greatly reduce the sample thickness of microwave absorbers. The essence of the idea is to use an array of parallel closely spaced metallic strips that support a series of standing wave resonances in the plane of the structure, rather than perpendicular to it. The placement of a metallic layer at the centre of the thin cavities formed between the strips, in the plane of the structure, may be considered analogous to the inclusion of a tunnel barrier in a quantum mechanical system.[4] Using diffraction to efficiently couple radiation into a waveguide mode is certainly not new. Tien published on this subject in 1977,[7] and more recently, such an approach has been extensively studied for the improvement of solar cell efficiency[8–10] (*and references therein*). But here, the resonance of the cavity provides a method to match impedance and hence provide enhanced transmission across the thin film, three orders of magnitude stronger than that obtained through the thin metal layer in isolation.

The experimental sample is comprised of two polyester film (Mylar®) sheets ($d_t = 75\,\mu$m thickness), one of which is coated with $m_t = 60$ nm of aluminium, arranged to give a polyester-aluminium-polyester tri-layer. The continuity of the aluminium layer and its thickness were checked and measured using a scanning electron microscope. This region is surrounded by two periodic structures (gratings above and below) comprised of strips of copper $w = 3.68$ mm wide and $c_t = 17\,\mu$m thick, arranged with a periodicity $\lambda_g = 3.80$ mm. The gratings were fabricated by standard printed-circuit-board etching of copper coated (single sided), 0.80 mm-thick, FR4 laminates. The etched printed circuit board (PCBs) were arranged such that the FR4 was the outermost layer, hence there was only a 75 $\mu$m dielectric layer between each grating and thin metal film. (In principle, an overall sample thickness could be below 200$\mu$m, as shown by Figure. 1).

The sample, of surface area 165 mm × 255 mm, was sandwiched between two sheets of 7.44 mm thick acrylic plastic and fastened around the edges with nylon screws. This was required to ensure that the sample as a whole was flat and air pockets at the centre of the structure were reduced to a minimum. The experimental transmission spectra of microwave radiation, with its electric field perpendicular to the slits, incident normally ($\theta = 0$) upon the sample, are shown in Figure 2.

Transmission of ~35%, normalised to the intensity recorded without a sample, is achieved at resonance. This equates to an enhancement of some 1000 times, compared with that

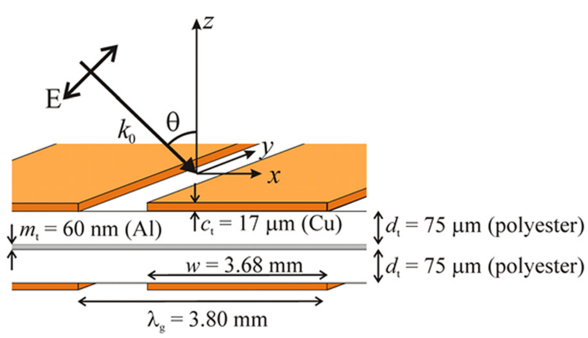


FIG. 1. Schematic cross-section through the sample, illustrating the plane of incidence, coordinate system, polar angle $\theta$, pitch, $\lambda_g$, and the thickness of the layers. The patterned copper layer is etched from a single sided FR4 PCB laminate. These PCBs form the outermost layers of the sample, with the patterned copper layer facing inwards. For clarity, the 0.8 mm thick FR4 substrate is not shown.

 

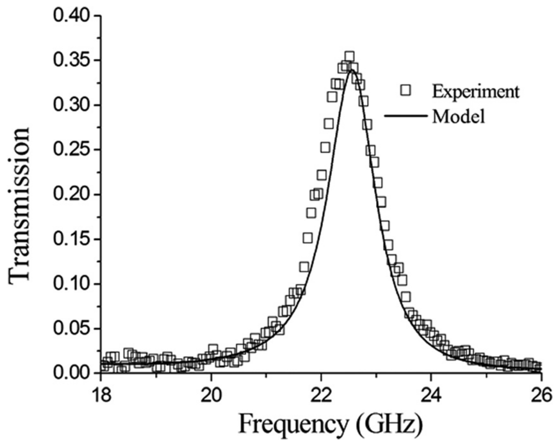


FIG. 2. Normal incidence ($\theta = 0$), microwave electric field perpendicular to the slits, transmission data compared with FEM model predictions for the fundamental mode. The modelled data use the sample dimensions discussed previously and incorporates a small (10 $\mu$m-thick) air gap at the metal layer due to imperfections in sample design and limitations in assembly.

expected for transmission through the isolated metal film (calculated using a Fourier modal method model,[11] with $\varepsilon_{Al} = -10^4 + 10^7 i$).

Material parameters for the various dielectrics in the system were determined by undertaking independent characterisation measurements, the results of which were fitted to the predictions of a finite element method (FEM) numerical model.[12] The Fabry-Perot like transmission resonances in the transmission spectra of one of the acrylic plastic layers were utilised to determine its permittivity, ($\varepsilon = 2.6 + 0.15i$), while the real part of the polyester permittivity was characterised by filling the gap between two metallic plates with the polyester, following a similar method to Ref. 13 ($\varepsilon = 2.6$). The loss in the polyester was negligible. The FR4 parameters ($\varepsilon = 4.1 + 0.082i$) were determined by pressing one of the patterned PCBs onto a flat metal plate, and recording the resonances in reflectivity spectra and numerically fitting this data, as described in Ref. 6. These parameters, together with the Drude value of the permittivity of bulk aluminium ($\varepsilon = -10^4 + 10^7 i$), and the geometric parameters described above were used in the FEM numerical model to predict the transmission through the aluminium film and surrounding structure. The model also incorporates a small (10 $\mu$m-thick) air gap between the aluminized polyester and the bare polyester layers, due to imperfections in sample design and assembly. Without the inclusion of this extra layer in the model, the resonance is near-identical in shape and height compared to that shown in Figure 2, but shifted somewhat to lower frequencies by ~1.0 GHz. Notice also that the transmission maximum is slightly asymmetric with the high frequency side of the resonance transmitting less than the low frequency side; this is due to the resonant response being superimposed on the capacitive low-pass frequency selective behaviour of the arrays of disconnected metal elements, see, e.g., Ref. 14.

Numerical FEM modelling of the electromagnetic fields shows the peak in transmission to occur at the resonance of the fundamental mode supported in between the copper strips. This mode, excited by the evanescent diffracted fields at the surface of the patterned copper layer, corresponds to a half wavelength quantisation associated with the copper strip width, $w$. The electric and magnetic fields are separated both spatially and temporally within the polyester region, with the electric fields strongly enhanced at the edges of the strip (Figure 3), and thus regions of very high magnetic field are localised at the centre of the slit cavities. Power transferred into the metal is proportional to the square of the magnitude of the magnetic field. The magnetic field penetrates across the metal film layer, since its thickness is much smaller than the skin depth, thereby exciting the resonance on the transmission (lower) side of the aluminium film. The two resonators are strongly coupled together, oscillate in phase, and reradiate in to free space, via diffraction at the copper slits. Note however, that the E field magnitude has reduced in the lower half of the split cavity.

It is important to re-emphasise here that the isolated aluminium film is opaque to radiation due to a large impedance mismatch between the film and free space (not due to a skin depth effect). Therefore, since the resonance essentially provides an impedance matching mechanism, one may naively argue that 100% transmission should be expected on this condition. However, the large imaginary component of the aluminium's dielectric constant ($10^7 i$) results in rapid absorption of the penetrating energy and places a limit on the transmission. Figure 4 illustrates the dependence of the modelled peak transmission of the fundamental mode on the thickness of the thin metal film, using the aforementioned Drude parameters for aluminium. These predictions were obtained using a Fourier modal method.[15] The transmission intensity falls rapidly as the film thickness is increased, being less than 1% for thicknesses of 1000 nm or greater. The Drude parameters for the aluminium's permittivity give a good agreement between modelling and our experimental results for 60 nm films (~35%), but these parameters may not be applicable for much thinner films. For very thin films, the classical resistivity size effect will become significant, while grain boundary scattering may contribute substantially to the resistivity, and the film may even become discontinuous. It is clear however that decreasing the film thickness will result in an increase of the peak transmission.

Optimisation of the resonantly transmitting system using the FEM model is shown by Figure 4 *inset*. Here, the FR4 core is given a loss tangent identical to the commercially available Neltec NY9208 PCB medium (($\varepsilon_i$ / $\varepsilon_r = 0.0006$)

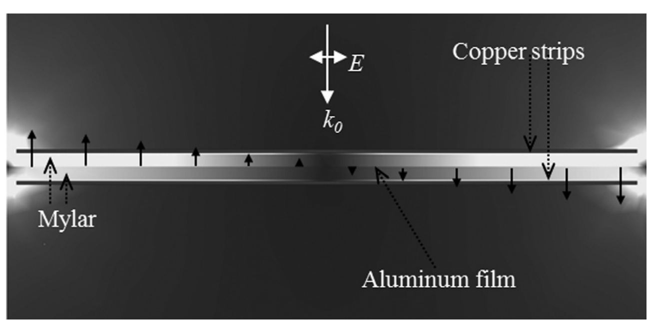


FIG. 3. Predictions of the time-averaged electric (E) field on resonance (colour gradient) together with a schematic representation of the electric vector orientation at a phase corresponding to maximum field enhancement. Red regions correspond to field enhancements in excess of 10 times the incident field.

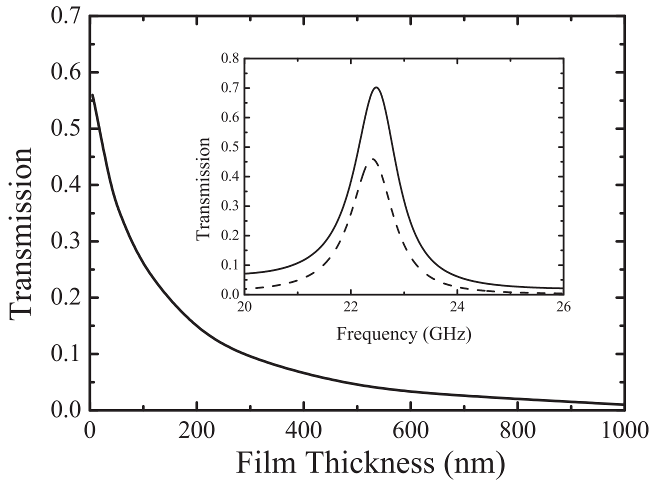


FIG. 4. Predictions of the dependence of the peak transmission intensity of the fundamental mode on the aluminium film thickness, modelled using the Fourier modal method.[14] The complex permittivity of the aluminium has been set as $\varepsilon = -10^4 + 10^7 i$. *Inset:* Optimisation of the resonantly transmitting system using the FEM model. Replacing the FR4 core with a low loss dielectric (dashed line) and then reducing the film thickness to 20 nm (solid line results in a transmission efficiency of 71%).

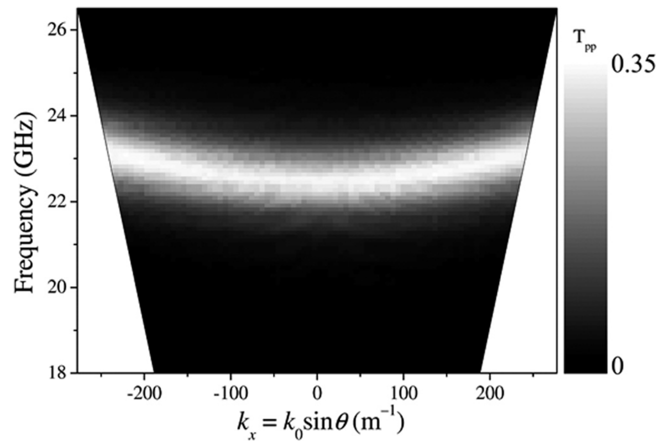


FIG. 5. Experimental transmission measurements for p-polarised (TM) radiation in the region of the fundamental mode for $-15° < \theta < 15°$.

dashed line). The reduction of this loss channel results in a 12% increase in transmission on resonance. Reducing the film thickness from 60 nm to 20 nm (solid line) further increases the transmission efficiency, with 71% of the incident radiation being transmitted on resonance through the otherwise opaque metal film.

Figure 5 shows the experimentally measured p-polarised (transverse magnetic, B field parallel to the slits) transmission results for incidence angles up to 15° from normal. The frequency, position, and width of the mode remain fairly constant across this angle range. The mode rises in frequency slightly at higher angles due mainly to the small phase difference being imparted across the slit openings, which will be reduced by a reduction in the slit width. In addition to the fundamental mode, the system also supports higher frequency modes associated with the multiples of half-wavelength quantisation in strip width, $w$. These higher order modes are less strongly coupled however. Further, due to symmetry arguments, only odd order modes will be coupled to at normal incidence since even number modes would require a phase variance in the incident wave across $w$. Initial modelling (not presented) also shows that a two dimensional array of square or circular patches will provide a polarisation and largely azimuth angle invariant response.

In conclusion, ~35% resonant transmission of microwaves through a thin (1/70th of the operating wavelength) resonant structure containing an otherwise opaque continuous metal film has been experimentally recorded and results found to be in good agreement with modelling. This transmission is some 1000-times that expected through the stand-alone thin film, occurring over a discrete narrow band of frequencies that may be tuned through variation of the cavity geometry. Optimisation of the system using the finite element method model shows resonant transmission of 71% to be achievable using low loss dielectrics and a 20 nm thick aluminium film. The standing wave resonances within the resonant cavities on the illuminated side of the thin metal layer couple through the layer exciting an equivalent resonance in cavities on the other side of the film, which then subsequently reradiates into the transmission space. It is also suggested that an incident angle and polarisation invariant response is readily obtainable.

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