AIP Journal of Applied Physics

Metamaterial tunnel barrier gives broadband microwave transmission

Celia A. M. Butler, Ian R. Hooper, Alastair P. Hibbins, J. Roy Sambles, and Peter A. Hobson

Citation: Journal of Applied Physics **109**, 013104 (2011); doi: 10.1063/1.3525557
View online: http://dx.doi.org/10.1063/1.3525557
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/109/1?ver=pdfcov
Published by the AIP Publishing

Metamaterial tunnel barrier gives broadband microwave transmission

Celia A. M. Butler,[1,a)] Ian R. Hooper,[1] Alastair P. Hibbins,[1] J. Roy Sambles,[1] and Peter A. Hobson[2]
[1]*Electromagnetic Materials Group, School of Physics, University of Exeter, Exeter, Devon, EX4 4QL, United Kingdom*
[2]*QinetiQ, Cody Technology Park, Farnborough, Hampshire GU14 0LX, United Kingdom*

(Received 3 September 2010; accepted 6 November 2010; published online 6 January 2011)

A simple structure comprising a metal mesh, symmetrically surrounded by subwavelength thickness dielectric layers, is shown to give near total microwave transmission over a broad frequency range. The mesh may be considered to be a tunnel barrier since it behaves as an ideal plasmonic metamaterial with a negative effective permittivity and no loss. The introduction of the mesh into the dielectric cavity imposes a finite gradient on the electromagnetic fields at the two mesh-dielectric interfaces. This defines a finite wavelength of the zeroth order Fabry-Pérot-type mode, which would otherwise be infinite. Suitable choice of the mesh parameters yields a broad band of near total transmission associated with the overlap of this zeroth order mode with that of the first order half-wavelength Fabry-Pérot-type resonance. © *2011 American Institute of Physics*.
[doi:10.1063/1.3525557]

I. INTRODUCTION

The microwave response of metal meshes has been extensively studied since the mid-20th century. Such regular arrays of holes have been optimized for use as frequency selective surfaces and bandpass filters based upon the transmission peak that occurs near the hole cut-off frequency.[1–5] Below this cut-off frequency the grids essentially behave as imperfect mirrors with evanescently decaying electromagnetic (EM) fields in the holes, as predicted by Bethe,[6] and for this reason have historically attracted little interest. However, Ebbesen *et al.*'s[7] observation of enhanced optical transmission (EOT) via tunneling of the EM fields associated with surface waves (surface plasmons) through perforated metal films has changed this view. Their work helped to ignite interest in the field of patterned and perforated metal structures, which were part of the reinvention of "metamaterials", and remain highly topical to this day.

The mesh considered in this study is explored in the non-diffracting regime, i.e., the periodicity of the grid, and therefore also the size of the holes are subwavelength (no propagating orders). Recently much work has been conducted on subwavelength meshes demonstrating narrow band resonant EOT for wavelengths near the diffraction edge.[8,9] This EOT is a tunneling phenomenon mediated by diffractively coupled surface waves at each of the metal mesh–dielectric boundaries, coupled by evanescent fields within the subwavelength holes. Both Dragila *et al.*[10] and Ortuño *et al.*[11] studied the dielectric clad metal mesh structures in this regime and observed surface-wave-induced transparency. However, the broadband enhanced transmission observed in the present study cannot be attributed to the excitation of diffractively coupled surface waves due to the very subwavelength nature of the structures considered.

The EM fields in the holes decay near exponentially, which is analogous in character to the fields in a plasmonic metal with a Drude-like dispersion in the visible domain, i.e., these holey metal layers may be represented via a large negative real effective permittivity.[12] However, unlike a real plasmonic metal, these metamaterials have an imaginary effective permittivity equal to zero. Hooper *et al.*[13] recently considered a plasmonic metal clad in thin dielectric in the optical regime and noted the parallel between this system and a quantum mechanical tunnel barrier. A quantum mechanical tunnel barrier must have a potential greater than zero, which is equivalent optically to $-n^2k_0^2>0$. This can be created if the material that is to act as the tunnel barrier has a purely imaginary refractive index (i.e., an ideal metal). Hooper *et al.* showed that the second and third order Fabry-Pérot mode[14] of the dielectric cavity merged into a composite mode as the tunnel barrier thickness increased (see Fig. 2 in Ref. 13). The authors employed an idealized analytical system with the optical plasmonic metal represented as a large negative permittivity with no loss to gain insight into the nature of these modes. It is not possible to fabricate this idealized structure in the visible regime due to the inherent loss of optical plasmonic metals (such as silver) as well as fabrication and experimental restrictions. Here, we mitigate these restrictions by employing a subwavelength metal mesh as a plasmonic-like metamaterial in the microwave regime. This produces a zero loss tunnel barrier that can be easily experimentally realized, enabling a detailed investigation into the lower frequency Fabry-Pérot-type modes and for normal incidence radiation.

Similar structures for transmission through tunnel barriers have been considered where a mesh has been surrounded by layers of metamaterials. Zhou *et al.*[15] used a resonant "H shaped mesh" that is represented as an effective medium, with a high permittivity ($\varepsilon_{\mathrm{real}}\sim 4$). These metamaterial layers allow the EM wave to tunnel through the negative permittivity metal mesh producing two resonant peaks which exhibit transmittance, due to enhanced tunneling over a frequency

[a)]Electronic mail: celia.butler@ex.ac.uk.

range of approximately 1 GHz. Zhou *et al.* also investigated the effect of changing the air gaps between the layers of the structure to show tuning of the two individual modes. In addition Hou *et al.*[16] have undertaken a study where subwavelength split ring resonators (SRRs) were fabricated around foam balls and held in an array orientated normal to the metal mesh. When subwavelength SRRs are arranged as an array, the combined response exhibits a large negative permeability over a narrow frequency range.[17] Further, when the SRR arrays are positioned either side of a subwavelength metal mesh (which exhibits a negative permittivity) a narrow transmittance peak is observed due to a negative refractive index (negative permittivity and negative permeability). Two further narrow peaks are observed at higher frequencies as in this regime the SRR arrays no longer have negative permeability but act as high permittivity dielectric layers which facilitate the EM wave tunneling through the metal mesh.

Of direct relevance to this present study is an analytical and numerical investigation by Lomakin and Michielssen[18] in 2005 that provides a very thorough discussion of enhanced transmission through a subwavelength mesh sandwiched between two dielectric plates. It is shown that resonant modes can be supported by the mesh coupled to standing waves in the dielectric layers. Here two regimes are explored, referred to as the "single resonance" and "double resonance" regimes. In the single resonance regime the incident wave couples to a resonant mode in a single dielectric layer (top or bottom), the resultant resonant feature is very narrow in frequency and does not give 100% transmission. In the double resonance regime, two resonant modes exhibiting 100% transmission are observed where the incident wave couples to standing-wave-like solutions in both dielectric layers. This study went on to vary the parameters in the system, demonstrating that both regimes may be supported for symmetric as well as asymmetric dielectric cladding, and more importantly exploring the transition from infinitesimally thin to very thick perforated metal plates: for very thin plates the higher frequency mode is much narrower, whereas for very thick plates only one mode is observed with reduced magnitude. This study is in excellent agreement with the numerical and experimental results presented herein.

In this study we concentrate our efforts on experimentally observing the lowest Fabry-Pérot modes studied in the aforementioned numerical and analytical work. In particular we focus our efforts on providing a thorough explanation of the lowest frequency mode and explore its origin as the "zeroth order" Fabry-Pérot mode. By demonstrating that the metal mesh may be considered as a metamaterial with a large negative real effective permittivity and no loss we also demonstrate that these two noninteracting modes can be brought together by manipulation of the sample geometry to result in a novel, broad transmitting band.

II. EXPERIMENTAL MEASUREMENT

In order to investigate the lowest order modes of an ideal tunnel barrier system in the microwave regime, experiments were performed using the sample shown in Fig. 1 which comprises a copper subwavelength square array of square air

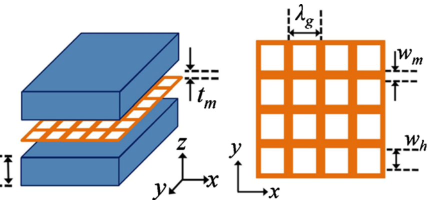

FIG. 1. (Color online) Left: exploded schematic of the experimental sample metallic mesh of thickness t_m=18 μm, between two low loss dielectric layer t_d=3.17 mm thick. Right: copper subwavelength mesh has a pitch λ_g=5.00 mm, hole width w_h=4.85 mm and therefore a metal "bar" width of w_m=0.15 mm.

filled holes of width w_h=4.85 mm and pitch λ_g=5.00 mm (referred to as the mesh). This 18 μm thick (t_m) mesh is sandwiched between two low loss dielectric layers (Nelco NX9255; $\varepsilon_{real}\sim 3$) of thickness t_d=3.175 mm. (The relative permittivity and dielectric loss tangent were obtained by numerically fitting the transmission spectrum of experimentally measured Fabry-Pérot mode resonances of blank sheets of dielectric over the frequency range 5–26 GHz).

The experimentally measured normal incidence transmittance of this sample is shown (black circles) in Fig. 2, together with a best fit from a finite element method (FEM) numerical model (continuous line). (Note: to fit the experimental data a dielectric thickness of 3.15 mm was used, consistent with the experimental average thickness of 3.175 ± 0.030 mm.) A clear band of near-complete transmission is observed over the frequency range 7–15 GHz. This structure exhibits greater than 300% transmission enhancement when compared to the FEM modeled response of a single freestanding mesh with no dielectric cladding (dashed line). The single freestanding mesh response was originally predicted by Bethe[6,19] in 1944, and its transmission is dependent upon both the hole size and pitch of the mesh and scales as $(w_h/\lambda_g)^4$.

III. ANALYSIS

Numerical modeling gives physical insight into the origins of the broad highly transmitting region, showing it to be comprised of two modes with their overlap summing to give

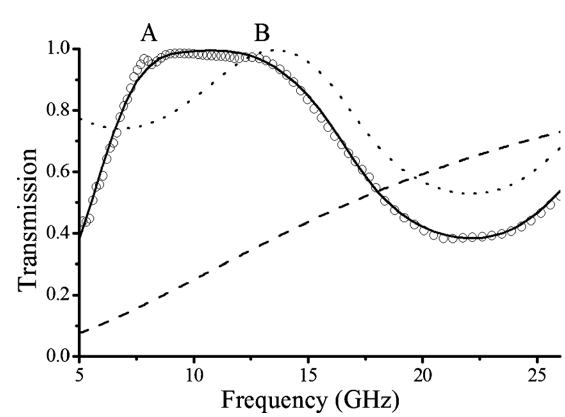

FIG. 2. Experimentally measured (circles), and numerically modeled (continuous line) normal incidence transmittance for the dielectric-clad subwavelength mesh shown in Fig. 1. The dashed line is the numerically modeled response of the unclad subwavelength mesh in free space and the dotted line is the modeled response of the sample without the metal mesh layer.

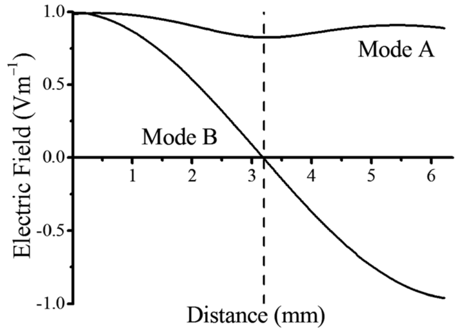

FIG. 3. Electric field profile for the two modes labeled as A and B in Fig. 2 plotted along a line in the z direction which passes through the center of a hole in the subwavelength mesh. Mode A was plotted at 7.42 GHz and mode B was plotted at 12.06 GHz.

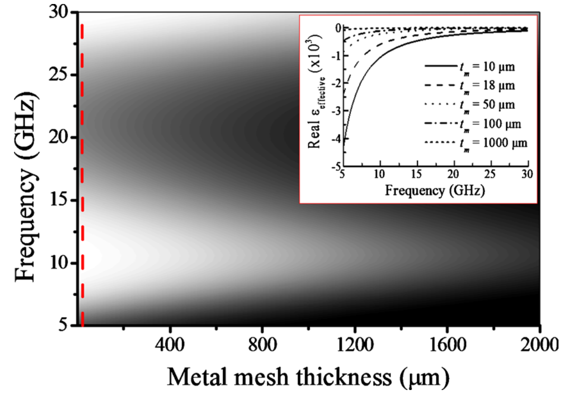

FIG. 4. (Color online) Transmission as a function of frequency and tunnel barrier thickness for the dielectric clad metal mesh where the dielectric has a thickness t_d=3.175 mm, and a relative permittivity ε_{real}=3 and the metal mesh is represented by frequency and thickness dependent effective permittivity following a Drude-like character with no loss. Note: black 0%, white 100% transmission. Inset: a selection of frequency dependent effective real permittivities for varied metal mesh thicknesses.

a transmissivity much higher than that of an isolated mesh (dashed line in Fig. 2). There is a low frequency mode centered about point A in Fig. 2 and a higher frequency mode centered about point B. Since the frequencies of both modes are below the cut-off frequency of the holes, their EM fields within the mesh layer are evanescent.

Point B defines the upper edge of the highly transmitting band, the electric field at this frequency being plotted in Fig. 3 for a line taken through the center of a subwavelength hole in the propagation direction. This mode is essentially the first order (half wavelength) Fabry-Pérot mode of the dielectric block. This is unsurprising as for a block of dielectric 6.35 mm thick with no mesh, Fabry-Pérot-type modes[14] are expected and duly observed (dotted line in Fig. 2) with the first order mode occurring at 13.5 GHz, just above point B. The addition of a very thin subwavelength mesh has almost no influence on this mode as the evanescent decay of the EM fields within the mesh couple between the front and back faces where the electric field forms an asymmetric mode with a sinh character which passes through zero at the center of the holes (in z). This mode within the mesh couples to the standing waves in the dielectric, forming an asymmetric mode in the overall structure (relative to the center of the structure in z).

It is mode A, the low frequency edge of the enhanced transmission band, which is the most intriguing. In the same way as we have considered mode B to be a modification on the first order Fabry-Pérot mode, mode A can be considered as a perturbation of the zeroth order Fabry-Pérot mode. Without the mesh acting as a tunnel barrier, the zeroth order Fabry-Pérot mode of the dielectric is supported at an infinite wavelength with a uniform EM field profile across the dielectric cavity. However, when the tunnel barrier is introduced the standing waves in the dielectric couple via the evanescent fields supported in the mesh, and give rise to a symmetric mode of the whole system and a cosh-like electric field distribution. Figure 3 illustrates the predicted electric field profile of mode A, plotted along a line through the center of one mesh hole. Here, the cosh-like function extends far beyond the confines of the mesh (represented by a vertical black dashed line) due to the slow gradient across the mesh–dielectric boundaries. The thickness of the mesh, size of the pitch and hole filling fraction, dictate the fields and their gradients at the mesh–dielectric interface. The matching condition at this interface therefore defines the mode's apparent wavelength in the dielectric, which is much greater than twice the overall sample thickness (i.e., the naïve Fabry-Pérot wavelength), and therefore its resonant frequency. As expected, mode A is highly sensitive to these three mesh parameters and this allows for a substantial degree of freedom in dictating the low frequency edge of the transmission band.

In Fig. 4 the transmissivity arising from these two modes is plotted as a function of frequency and metal mesh (tunnel barrier) thickness using Fresnel equations. Effective parameters of the mesh were obtained by numerically fitting Fresnel predictions to modeled (modal matching method) reflection and transmission spectra for freestanding metal meshes. These effective parameters reveal a large negative permittivity at low frequencies which follows a Drude-like dispersion with an imaginary permittivity equal to zero. Frequency dependent effective parameters were obtained for each metal mesh thickness (see Fig. 4 inset). In Ref. 13 the variation in the tunnel barrier thickness corresponds to variation in the real thickness of the optical metal. In our study variation of the effective tunnel barrier thickness which corresponds to a change of the coupling across the mesh, can be achieved by either changing the real thickness of the mesh and/or the filling fraction of the hole with respect to the pitch. Figure 4 shows that the higher frequency mode B is only weakly frequency dependent on changes in the mesh thickness. This is because the electric field within the subwavelength holes of the metal mesh is near zero for this mode, as shown in Fig. 3. However for the low frequency mode A, the high regions of electric field are concentrated within the subwavelength holes of the metal mesh, so by increasing the thickness of the metal mesh mode A rises in frequency toward mode B reducing the transmission bandwidth. The response of the sample thickness studied experimentally here is indicated by the vertical dashed line near the origin in Fig. 4.

It is also instructive to establish how the highly transmit-

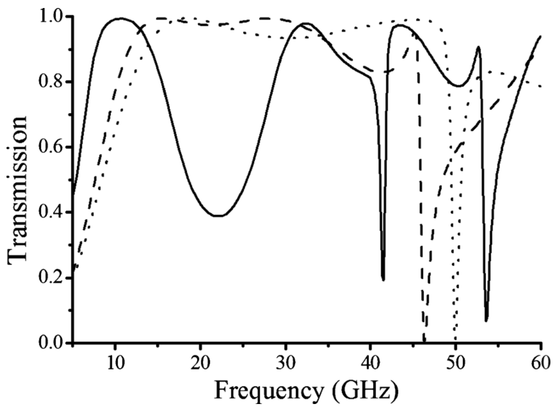

FIG. 5. FEM modeled normal incidence transmittance for the metal mesh clad in dielectric of varying thickness: 3.15 mm (continuous line); 1.5 mm (dashed line), and 1 mm (dotted line).

ting region varies with dielectric parameters. By increasing the permittivity of the dielectric layers while reducing the thickness, the electrical length $(t_d\sqrt{\varepsilon_r})$ is kept constant, modes A and B may be clearly separated (not shown). This separation arises from the increased reflectivity at the air-dielectric boundary giving sharper modes. Also the low frequency mode has reduced in frequency due to the increase in the field gradient at the mesh–dielectric interface.

By decreasing the dielectric thickness (t_d) alone the pass band width may be increased while maintaining a high level of transmission. This effect is shown in Fig. 5 where, as the thickness decreases, we see mode A increases only slightly in frequency as the response of this mode is dominated by the gradient at the mesh–dielectric boundary, and therefore the reduction in the thickness of the dielectric only weakly perturbs it. By contrast, mode B is almost entirely dependent upon the partial standing waves in the dielectric layers. As the thickness of the dielectric decreases this mode moves to much higher frequencies. Mode B also broadens as the reflectivity at the air–dielectric boundary reduces with increasing frequency. Through a suitable choice of parameters a pass band with a width >20 GHz, with a transmission of almost 100% may be experimentally realized in this three layer system. The upper bound of this pass band is largely only limited by the onset of diffraction which is determined by the pitch of the mesh.

IV. CONCLUSIONS

The transmission response of a structure composed of a subwavelength metal mesh symmetrically clad in dielectric layers has been experimentally measured and explained using a combination of numerical and analytical modeling. The experimentally observed broad, highly transmitting band was shown to be due to the superposition of two non-interacting modes. Both modes are derived from Fabry-Pérot modes of the dielectric cladding. Below the cut-off frequency of the subwavelength holes the metal mesh may be considered as a plasmonic metamaterial with a frequency dependent effective permittivity similar in character to a plasmonic optical metal with a Drude-like dispersion. However, in this structure there is no loss so the imaginary part of the effective permittivity is zero, and therefore this structure may act as an ideal tunnel barrier. The electrical field profile for Mode B reveals a small modification to the first order (half wavelength) Fabry-Pérot mode in the dielectric, through the introduction of the metal mesh the evanescent fields which couple between the front and back faces of the mesh to form an asymmetric sinh-like mode. Mode A, more surprisingly, reveals a symmetric (cosh-like in the mesh holes) mode which is derived from the zeroth order Fabry-Pérot mode of the dielectric. Without the metal mesh this mode would exist at infinite wavelength; by introducing a tunnel barrier the EM fields within the structure are quantized. The corresponding wavelength is *much* greater than twice the thickness of the structure. Analytical modeling shows a rise in frequency of mode A as the metal mesh thickness increases. The combination of these two modes gives a transmission pass band with a transmission coefficient almost equal to 1 for the frequency range 7–15 GHz. By suitable optimization of parameters this near unity transmission band could be maintained over ∼50% of the frequency band (>20 GHz) below diffraction.

ACKNOWLEDGMENTS

The authors wish to acknowledge the financial support of QinetiQ and the EPSRC (U.K.) for funding CAMB through the Industrial CASE scheme (no. 08000346).

[1]P. A. R. Ade, G. Pisano, C. Tucker, and S. Weaver, Proc. SPIE **6275**, 62750U (2006).
[2]J. M. Lamarre, N. Coron, R. Courtin, G. Dambier, and M. Charra, Int. J. Infrared Millim. Waves **2**, 273 (1981).
[3]R. Ulrich, Appl. Opt. **7**, 1987 (1968).
[4]T. Wu, *Frequency Selective Surfaces and Grid Arrays* (Wiley, New York, 1995).
[5]B. A. Munk, *Frequency Selective Surfaces: Theory and Design* (Wiley, New York, 2000).
[6]H. Bethe, Phys. Rev. **66**, 163 (1944).
[7]T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, Nature (London) **391**, 667 (1998).
[8]F. J. Garcia-Vidal, L. Martin-Moreno, T. W. Ebbesen, and L. Kuipers, Rev. Mod. Phys. **82**, 729 (2010).
[9]J. Bravo-Abad, L. Martin-Moreno, F. J. Garcia-Vidal, E. Hendry, and J. Gomez Rivas, Phys. Rev. B, **76**, 241102(R) (2007).
[10]R. Dragila, B. Luther-Davies, and S. Vukovic, Phys. Rev. Lett. **55**, 1117 (1985).
[11]R. Ortuño, C. Garcia-Meca, F. J. Rodriguez-Fortuno, J. Marti, and A. Martinez, Opt. Express **18**, 7893 (2010).
[12]J. B. Pendry, L. Martin-Moreno, and F. J. Garcia-Vidal, Science **305**, 847 (2004).
[13]I. R. Hooper, T. W. Preist, and J. R. Sambles, Phys. Rev. Lett. **97**, 053902 (2006).
[14]C. Fabry and A. Pérot, Ann. Chim. Phys. **16**, 115 (1899).
[15]L. Zhou, W. Wen, C. T. Chan, and P. Sheng, Phys. Rev. Lett. **94**, 243905 (2005).
[16]B. Hou, H. Wen, Y. Leng, and W. Wen, Appl. Phys. Lett. **87**, 201114 (2005).
[17]D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, Phys. Rev. Lett. **84**, 4184 (2000).
[18]V. Lomakin and E. Michielssen, Phys. Rev. B **71**, 235117 (2005).
[19]R. Gordon, Phys. Rev. A **76**, 053806 (2007).