AIP Applied Physics Letters

Influence of the hole filling fraction on the ultrasonic transmission through plates with subwavelength aperture arrays

Héctor Estrada, Pilar Candelas, Antonio Uris, Francisco Belmar, Francisco Meseguer et al.

Citation: Appl. Phys. Lett. **93**, 011907 (2008); doi: 10.1063/1.2955825

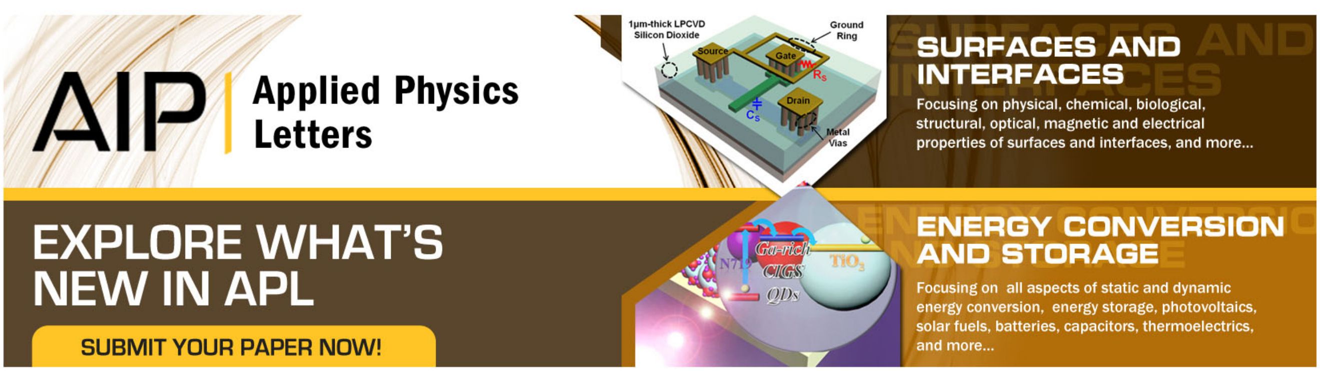
View online: http://dx.doi.org/10.1063/1.2955825

View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v93/i1

Published by the American Institute of Physics.

Related Articles

Additional information on Appl. Phys. Lett.



Influence of the hole filling fraction on the ultrasonic transmission through plates with subwavelength aperture arrays

Héctor Estrada,[1,3] Pilar Candelas,[1] Antonio Uris,[1] Francisco Belmar,[1]
Francisco Meseguer,[1,3,a)] and Francisco J. García de Abajo[2,a)]
[1]*Centro de Tecnologías Físicas, Unidad Asociada ICMM-CSIC/UPV, Universidad Politécnica de Valencia, Av. de los Naranjos s/n, 46022 Valencia, Spain*
[2]*Instituto de Óptica-CSIC Serrano 121, 28006 Madrid, Spain*
[3]*Instituto de Ciencia de Materiales de Madrid (CSIC), Cantoblanco, 28049 Madrid, Spain*

(Received 9 May 2008; accepted 16 June 2008; published online 9 July 2008)

We report on the large impact of the hole filling fraction on the ultrasonic transmission spectra of periodic subwavelength hole arrays. We demonstrate both theoretically and experimentally that transmission peaks become narrower as the filling fraction decreases. Our results are consistent in plates with different thickness values and provide a route map for the design of plates with tailored acoustic transmission profiles. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2955825]

The past decade has witnessed increasing interest in extraordinary optical transmission (EOT) through subwavelength apertures in metallic plates after the pioneering demonstration of this phenomenon,[1] whereby periodic arrays of subwavelength holes drilled on a metal film were shown to transmit much more light per hole than expected from Bethe's theory[2] for a single opening. This effect occurred at specific wavelengths strongly correlated with the periodicity. EOT has been reported in one- and two-dimensional gratings in numerous theoretical and experimental studies[3–8] and over a wide range of wavelengths.[9,10] Several mechanisms have been identified that contribute to EOT, such as surface plasmon resonances,[11,12] cavity resonances,[13] and dynamical diffraction,[4] all of them describable using a simple analytical formulation.[13]

Similar to light, the wave nature of sound can be exploited to produce extraordinary acoustic transmission, which has been recently studied in one- (slit) and two-dimensional (hole) apertures.[14–16] In this context, we have recently shown that perforated plates do not only exhibit high transmission but also Wood anomalies dictated by the condition of a diffracted beam becoming grazing and leading to extraordinary sound attenuation well beyond that predicted by the mass law equation (i.e., perforated plates shield sound more effectively than nonperforated ones[17]), which may find application to underwater sound screening structures. The purpose of this letter is to show through both theory and experiment that the filling fraction has a large impact on the ultrasound spectra of periodic subwavelength hole arrays and to further assess the dependence of the transmission on geometrical parameters of the hole array. The filling fraction for a square array is given by $f=\pi d^2/4p^2$, where d is the hole diameter and p is the lattice period [Fig. 1(b)]. An increase in p leads to a decrease in the filling fraction when the hole diameter remains constant. We model the plate in the hard-solid limit to calculate the transmission spectrum. The pressure field φ defining the acoustic wave satisfies the scalar field equation in the fluid outside the plate material, $(\nabla^2+k^2)\varphi=0$, where $k=2\pi/\lambda$ and λ is the sound wavelength in the fluid. The hard-solid approximation consists in neglecting the penetration of the sound into the solid plate, which results in the condition that the normal derivative of φ vanishes at the solid-fluid interface. The pressure φ is obtained upon expansion in terms of cylindrical cavity modes and plane waves inside and outside the hole, respectively. The expansion coefficients are then obtained from the continuity of φ and its derivatives at the hole openings and the vanishing of the normal derivative of φ elsewhere in the solid-fluid interfaces. The converged numerical results presented here are obtained considering 100 evanescent diffraction orders and 11 hole modes. We show in Figs. 2(a)–2(d) calculated transmission spectra at normal incidence for square hole arrays and four different values of the plate thickness. Full transmission is achieved in the four cases, mediated by coupling to Fabry-Pérot resonances of the hole cavities and modulated by interaction among holes. Actually, more resonant modes (and consequently more transmission maxima as well) show up as the thickness of the plate increases. It can also be observed that the transmission peaks become narrower as the filling fraction decreases, that is, as the period of the hole array p increases. This behavior resembles that of diffraction gratings:[18] the spectral lines become sharper as the filling fraction decreases. We also find a minimum transmission in Figs. 2(a)–2(d) originating in the Wood anomalies,[19] first observed by Wood when characterizing optical gratings. Near the Wood anomaly, perforated plates shield sound much more efficiently than nonperforated ones.[17] As the filling fraction is increased by reducing the periodicity, the Wood anomaly moves toward smaller wavelength values. This displacement clearly influences the posi-

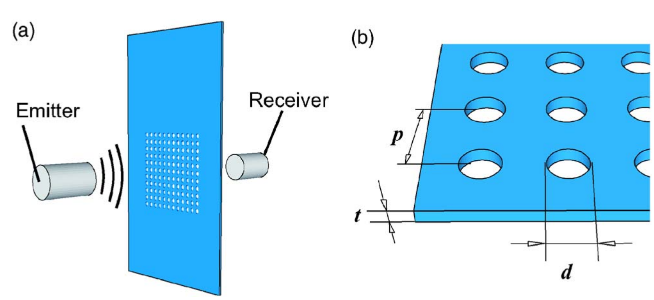


FIG. 1. (Color online) (a) Diagram of the measurements and (b) geometrical parameters of the perforated plates.

[a)]Authors to whom correspondence should be addressed. Electronic addresses: fmese@fis.upv.es and jga@io.cfmac.csic.es.

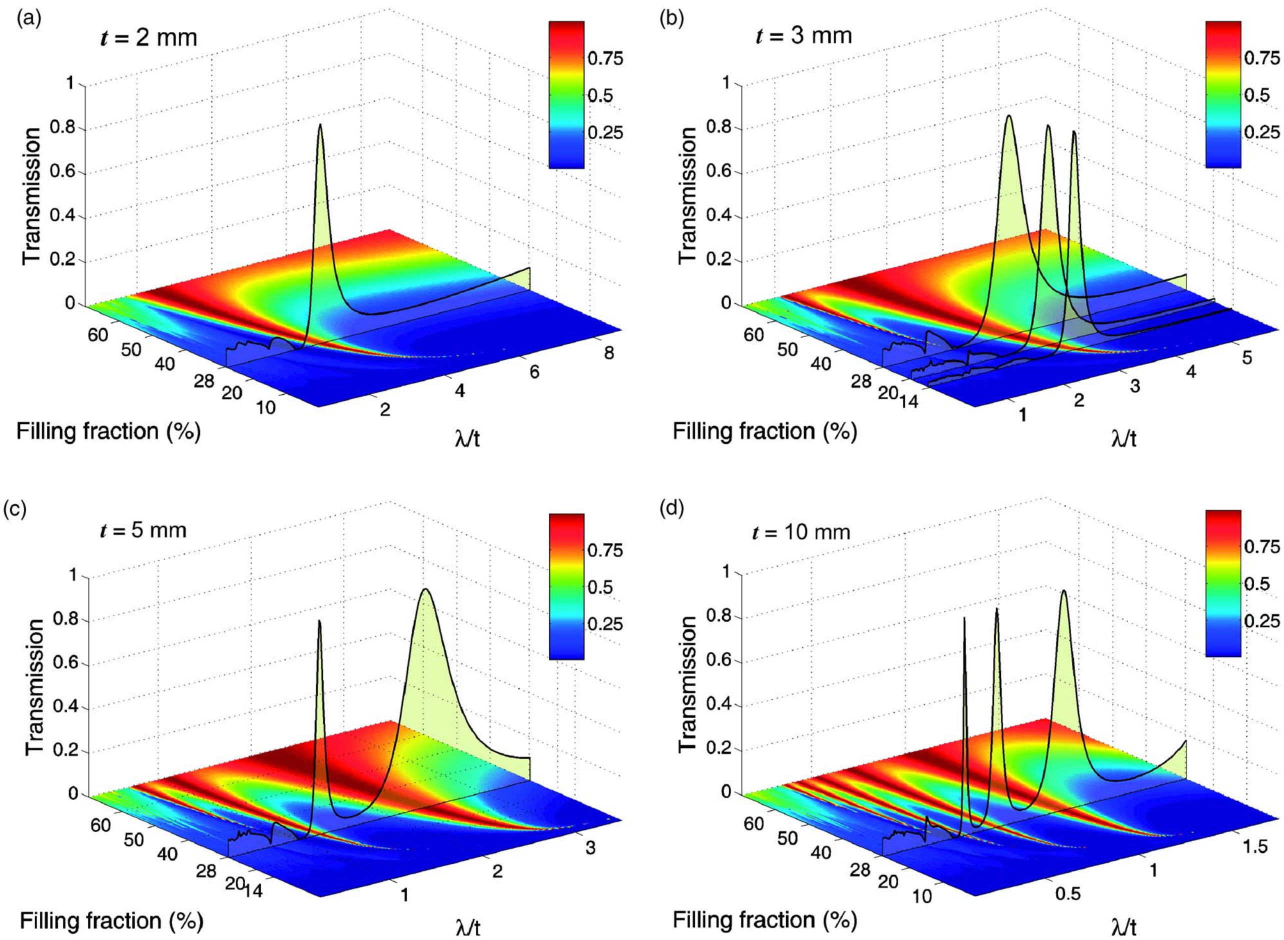


FIG. 2. (Color online) Calculated transmission of periodically perforated plates as a function of both wavelength normalized to the plate thickness, λ/t, and filling fraction (color contour plots). Different plate thicknesses have been considered: (a) $t=2$ mm, (b) $t=3$ mm, (c) $t=5$ mm, and (d) $t=10$ mm. The slices are the same as in the contour plots and correspond to the configurations measured in this paper.

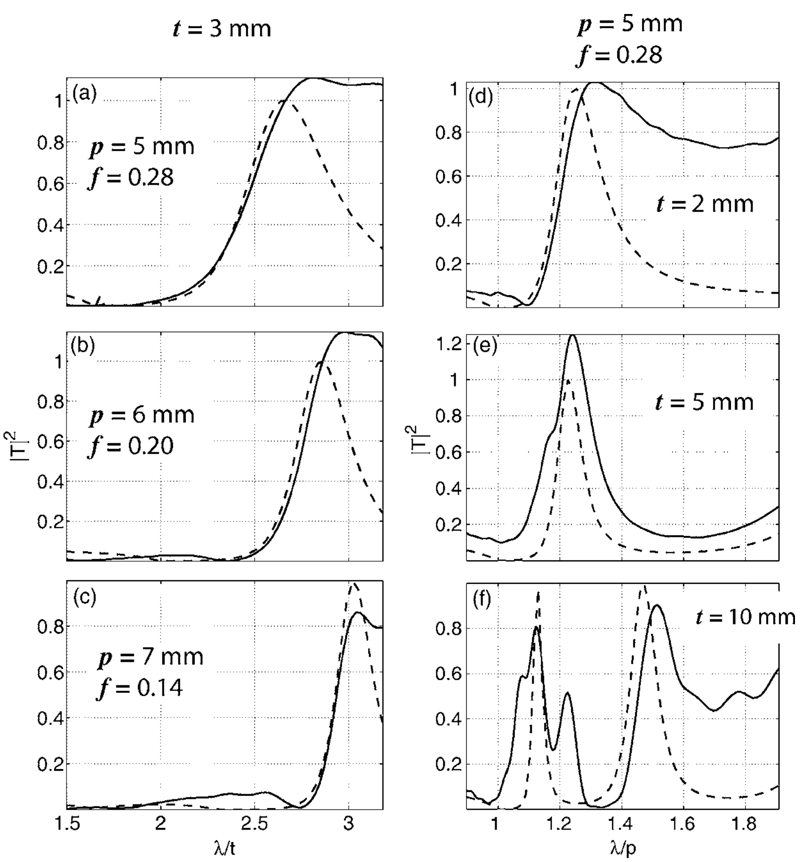


FIG. 3. Measured (solid curves) and calculated (broken curves) transmissions of plates perforated by a square array of holes with diameter $d=3$ mm. (a)–(b), and (c) are for a plate with thickness $t=3$ mm and different periods [see Fig. 2(b)]. (d)–(f) are for plates with periodicity $p=5$ mm and different thickness values [see Figs. 2(a), 2(c), and 2(d), respectively].

tion of full transmission peaks. Similar results can be obtained by varying the filling fraction through d while keeping p constant, but in that case the Wood anomaly remains at the same wavelength, roughly independent of the filling fraction. In order to corroborate our numerical results, we have performed measurements on 200-mm-wide, 350-mm-long aluminum plates perforated with holes of diameter $d=3$ mm and immersed in water. The holes were distributed in a square lattice with periods $p=5$ mm, $p=6$ mm, and $p=7$ mm, corresponding to filling fractions $f=0.14$, $f=0.20$, and $f=0.28$, respectively. The experimental setup is based on the ultrasonic immersion transmission technique. We use a couple of transmitter/receiver ultrasonic Imasonic immersion transducers with 32 mm in active diameter and −6 dB bandwidth between 169 and 330 kHz, corresponding to wavelengths in the 4.5–8.8 mm range in water. Each transducer is located at a distance of 90 mm from the clamped perforated plate and aligned for normal incidence. An estimate of the transmission spectrum is then obtained from the power spectra of the signal normalized to the reference signal measured without the plate. This normalization leads to transmission values slightly above 100% in some cases, which we attribute to the finite size of the incident wave, so that the wave front generated by the transducer is not perfectly plane. Figures 3(a)–3(f) show a comparison between calculated and measured transmission spectra for different values of the lattice period p and the plate thickness t. The measurements are in good agreement with the calculated results. Some differences between theory and experiments exist though. In particular, the measured transmission peaks are broader than the calculated ones, possibly due to experimental errors and dissipative losses that have not been taken into account in the calculation model. In some cases [Figs. 3(a), 3(d), and 3(f)], the measured transmission remains high at the largest values of λ while the model predicts low transmission values. This difference can be explained as the effect of the finite impedance ratio between the plate and the fluid that implies coupled vibrations of the former. Finally, extra peaks appearing in the thickest plate [see Fig. 3(f)] are not accounted for by the theory, as they arise from coupling to $k_{\parallel}=0$ Lamb modes. Those modes appear in the spectral region of interest for the case of the thickest plates[20]. A more sophisticated theory taking into account plate modes could provide additional insight into the complex interplay between lattice-resonance modes[13] (Wood anomalies) and homogeneous-plate modes (Lamb and Scholte modes). It is clear that the measured transmission peaks become narrower as the filling fraction decreases, and consequently there is an increase in the Q-factor near the peak maxima. Finally, the displacement of the Wood anomaly is clearly resolved in Figs. 3(a)–3(c).

In conclusion, we have shown that the aperture filling fraction, which is related to the lattice period of perforated plates with square subwavelength hole array, has great influence on the shape and position of transmission features. It is found that the transmission peaks become narrower as the filling fraction decreases, and consequently there is an increase in the Q-factor associated with the coupled-hole cavities near the peak maxima. Similar results have been observed when the plate thickness increases. Calculated results are in good agreement with experiment. These results can be of interest in the development of underwater sound screening materials and in guiding and controlling ultrasound through perforated plate structures.

Note added in proof. During the proof correction process, the authors were aware of another work[21] related to the theoretical model treated in this paper.

This work has been supported by the Spanish MEC (MAT2006-03097, NAN2004-08843-C05-05, and Consolider Nanolight CSD2007-046) and the CSIC (PIF Project No. 200560F0071). H.E. acknowledges a CSIC-JAE scholarship.

[1] T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, Nature (London) **391**, 667 (1998).
[2] H. A. Bethe, Phys. Rev. **66**, 163 (1944).
[3] J. A. Porto, F. J. García-Vidal, and J. B. Pendry, Phys. Rev. Lett. **83**, 2845 (1999).
[4] M. M. J. Treacy, Appl. Phys. Lett. **75**, 606 (1999).
[5] Y. Takakura, Phys. Rev. Lett. **86**, 5601 (2001).
[6] F. Yang and J. R. Sambles, Phys. Rev. Lett. **89**, 063901 (2002).
[7] A. Barbara, P. Quémerais, E. Bustarret, and T. Lopez-Rios, Phys. Rev. B **66**, 161403 (2002).
[8] C. Genet and T. W. Ebbesen, Nature (London) **445**, 39 (2007).
[9] J. Gómez Rivas, C. Schotsch, P. Haring Bolivar, and H. Kurz, Phys. Rev. B **68**, 201306 (2003).
[10] S. Selcuk, K. Woo, D. B. Tanner, A. F. Hebard, A. G. Borisov, and S. V. Shabanov, Phys. Rev. Lett. **97**, 067403 (2006).
[11] L. Martín-Moreno, F. J. García-Vidal, H. J. Lezec, K. M. Pellerin, T. Thio, J. B. Pendry, and T. W. Ebbesen, Phys. Rev. Lett. **86**, 1114 (2001).
[12] W. L. Barnes, A. Dereux, and T. W. Ebbesen, Nature (London) **424**, 824 (2003).
[13] F. J. García de Abajo, Rev. Mod. Phys. **79**, 1267 (2007).
[14] J. Christensen, A. I. Fernandez-Dominguez, F. de Leon-Perez, L. Martin-Moreno, and F. J. Garcia-Vidal, Nat. Phys. **3**, 851 (2007).
[15] B. Hou, J. Mei, M. Ke, W. Wen, Z. Liu, J. Shi, and P. Sheng, Phys. Rev. B **76**, 054303 (2007).
[16] M.-H. Lu, X.-K. Liu, L. Feng, J. Li, C.-P. Huang, Y.-F. Chen, Y.-Y. Zhu, S.-N. Zhu, and N.-B. Ming, Phys. Rev. Lett. **99**, 174301 (2007).
[17] H. Estrada, P. Candelas, A. Uris, F. Belmar, F. J. G. de Abajo, and F. Meseguer, Phys. Rev. Lett. (to be published).
[18] D. H. Towne, *Wave Phenomena* (Dover, New York, 1967).
[19] R. W. Wood, Philos. Mag. **4**, 396 (1902).
[20] H. Estrada, P. Candelas, A. Uris, F. Belmar, F. J. G. de Abajo, and F. Meseguer, arXiv:0805.0981v1.
[21] J. Christessen, L. Martin-Moreno, and F. J. Garcia-Vidal, Phys. Rev. Lett. **101**, 014301 (2008).