Enhanced Millimeter Wave Transmission Through Quasioptical Subwavelength Perforated Plates

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***Abstract*—In this paper, we show that the phenomenon of extraordinary transmission through arrays of subwavelength holes, present in the optical regime, is also present in the millimeter wave range. After presentation of the theoretical foundations of the enhanced transmission, measurements of the transmission response have been performed on different samples by using a millimeter wave quasioptical vector network analyzer in the range between 45 and 110 GHz. The prototypes have been fabricated in Aluminum plates with several thickness and different hole diameters drilled by using a laser machine. Good agreement between theory and experiment is obtained, with clear signals of the existence of resonant transmission at wavelengths close to the period of the array. Possible applications in frequency selective surfaces and near-field imaging are envisaged.**

***Index Terms*—Extraordinary transmission, metamaterials, millimeter waves, perforated plates, quasioptics, subwavelength.**

I. Introduction

RECENTLY, the research of space-periodic structures has been refreshed by its potential applications in the emergent research topic of artificial materials and Metamaterials [1]. Perforated plates fit into this category, although they have attracted attention since mid of last century, due mainly to their properties as selective filters. They show typically a bandpass behavior. The low cutoff frequency is given by the hole electromagnetic cutoff, whereas the high cutoff frequency is due to the redistribution of energy caused by the periodic array when a new diffraction order becomes propagating. More precisely, denoting the hole cutoff wavelength by λ_c, the lattice parameter by L and the wavelength by λ, perforated plates act as bandpass filters for $L < \lambda < \lambda_c$. This property has been studied in several frequency regimes as microwave [2], far infrared [3], mid infrared [4] and infrared [5].

The discovery of the phenomenon of extraordinary optical transmission (EOT) observed in two-dimensional (2-D) arrays of subwavelength holes perforated in optically thick metallic films [6], has opened the possibility of using subwavelength apertures for a variety of optoelectronic applications like imaging systems.

Notice that, although initially EOT was found in perforated plates, there were two main differences with previous works. First, experiments were performed in the optical regime, and second, the geometrical parameters defining the structure were such that $\lambda_c < L < \lambda$.

This parameter range had not, up to our knowledge, been studied before Ebbesen's experiment, perhaps because nothing remarkable was expected for wavelengths beyond cutoff. EOT come, therefore, as a surprise which already the first experiments [6] showed to be related to surface electromagnetic resonances present in the corrugated metallic surface, but the transmission mechanism was unclear.

Several subsequent theoretical works analyzed the one-dimensional (1-D) analog of Ebbesen experiment (array of subwavelength slits) [7]–[9], which were able to capture some of the physics of the problem (the presence of corrugated metal surfaces) but not all of it as, contrary to the situation for sub-wavelength holes, slits present a propagating TEM mode for all frequencies.

Fully three-dimensional (3-D) theoretical studies of EOT in hole arrays was reported in [10] and, by some of the authors of this paper in [11]. The conclusions of these two works were different, whereas in [10] EOT was assigned to an essentially propagating mode appearing in the hole array which exists only when a realistic dielectric constant for the metal is considered, in [11] EOT is adscribed to the existence of leaky surface electromagnetic (EM) modes on both surfaces that couple through the evanescent waveguide modes present in the subwavelength holes. Furthermore, it was found in [11] that these leaky modes, and therefore EOT, are present even when the metal is considered as perfect, i.e., when it is assumed that no EM field can exist inside the metal. This is not a trivial statement, as it is well known that a flat *perfect*-metal surface does not support surface EM modes. However, the presence of holes in a perfect-metal surface provides an impedance to the surface of purely geometrical nature that may lead to the existence of the surface EM mode [12]. Of course, in a real situation, this geometrical impedance would be modified by a "dielectric" contribution, coming from the finite dielectric constant of the real metal.

Here we adhere to the formalism and results found in [11]. The presence of EOT also in the simplified perfect-metal model points out to the existence of EOT in other frequency regimes, as the millimeter wave range, where treating the metal as perfect is more justified than in the optical regime. In this paper we

Manuscript received May 26, 2004; revised November 3, 2004. This work was supported by CICYT under Contracts TIC2002-04528-C02-01 and TIC2002-04528-C02-02.

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Digital Object Identifier 10.1109/TAP.2005.848689

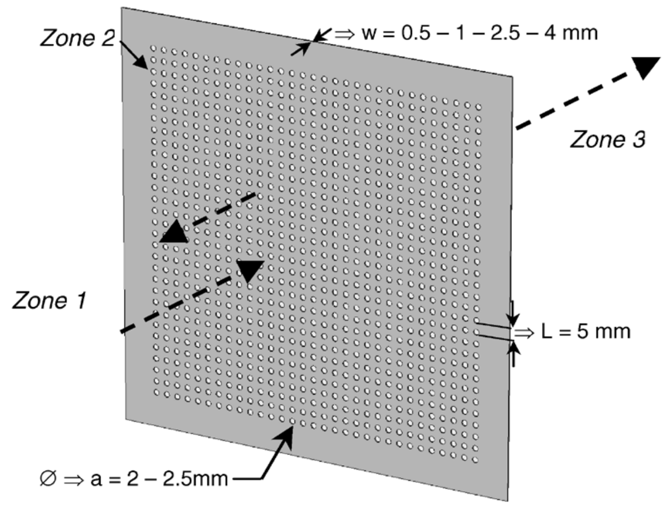


Fig. 1. Schematic of the considered problem where electromagnetic wave impinges on a perforated metallic film.

explore this possibility, both experimental and theoretically. We will demonstrate that extraordinary transmission also occurs in hole arrays in the millimeter range. Previously EOT had only been observed in the optical regime and in the THz regime for a doped semiconductor system, with a geometry somewhat different that supports TEM propagating modes [13]. This result also points out to the transferability to other frequency ranges of other phenomena related to EOT found in the optical range, such as EOT in single apertures [14] and beaming effects [15], [16]. This is an interesting result, both from the fundamental point of view and due to possible applications in frequency selective surfaces and near-field imaging.

II. Modelling the Electromagnetic Problem

Following the developments presented in [11], let us consider the general problem described in Fig. 1, where an electromagnetic wave is incident from a uniform medium 1, into a metal film (zone 2) of thickness h, perforated with circular holes of diameter a, periodically distributed in a square array of lattice parameter L. After zone 2, medium 3 is placed where the waves are measured. In the general case, the dielectric permitivity constants are ε_1 in medium 1, ε_2 inside the holes, and ε_3 in medium 3 but in this paper all three will be considered equal. The metal is characterized by a perfect conductor in our calculations. This approximation is more justified in the millimeter wave range than in the optical range of [6], since the considered frequencies are well below the plasma frequency of the metal.

As regards the incident wave, in this work we assume a normal incident plane wave impinging toward the metal film. By expanding the electromagnetic fields in their eigenmodes (considering both the wavenumber and polarization indexes) for each of the three regions of the problem above mentioned, a linear superposition of plane waves represents the total electromagnetic fields for regions 1 and 3. Bloch waves combining evanescent and, if there is any, propagating TE and TM waveguide modes represent the electromagnetic fields inside the holes.

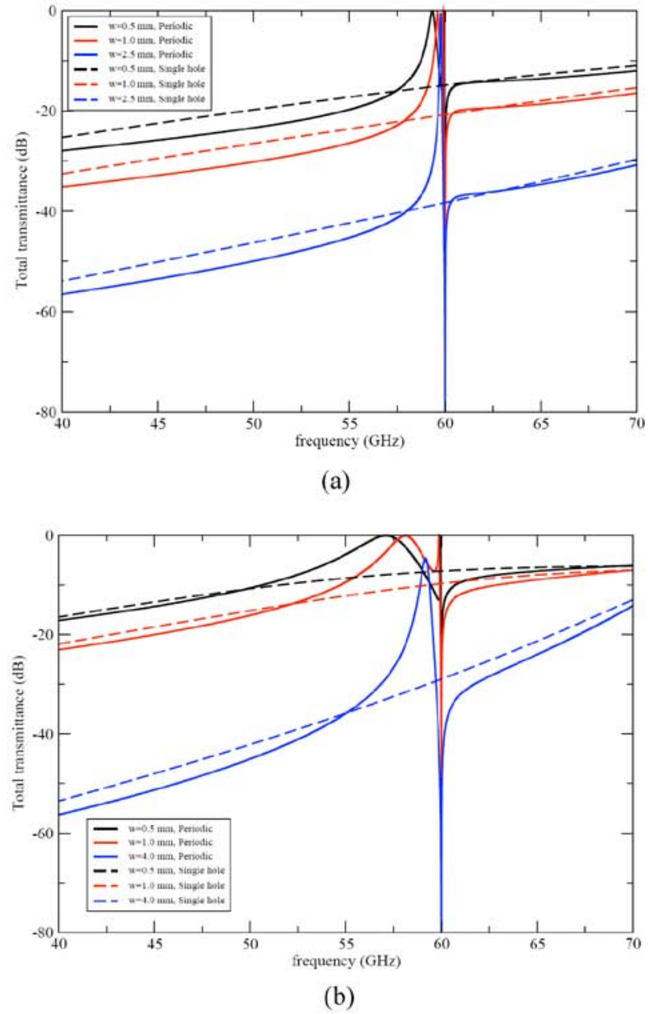


Fig. 2. Theoretical zero-order transmittance spectra in decibel scale as a function of frequency (in GHz) for (a) $a = 2$ mm for three different w's. $w = 0.5$ mm (black), $w = 1$ mm (red) and $w = 2.5$ mm (blue). (b) $a = 2.5$ mm for also three w's. $w = 0.5$ mm (black), $w = 1$ mm (red) and $w = 4$ mm (blue). The dashed curves correspond to the single hole case.

In spite of the fact that, an infinite number of modes are necessary in each region to a rigourous characterization of the electromagnetic problem, if we consider the number of parallel wave vector components the convergence is achieved quickly. Details of the theoretical framework can be found in [11].

In Fig. 2, results of the numerical simulations for the total transmittance, T, at normal incidence for different cases are presented. The array has a lattice constant, d, of 5 mm, two different hole diameters, a: 2 and 2.5 mm, and different plate thicknesses. As shown in Fig. 2(a) and (b), the total transmittance exceeds by orders of magnitude the results predicted by a theory based on independent holes [17]. It is worth noting that, although the phenomenon of extraordinary transmission is present for the two different diameters studied, the shape of the transmission curves is dramatically dependent on a. Basically, the transmission peaks become narrower as the diameter of the holes decreases. This is due to the fact that the electromagnetic coupling between the incident plane wave and the excited eigenmodes inside the holes is strongly dependent on a.

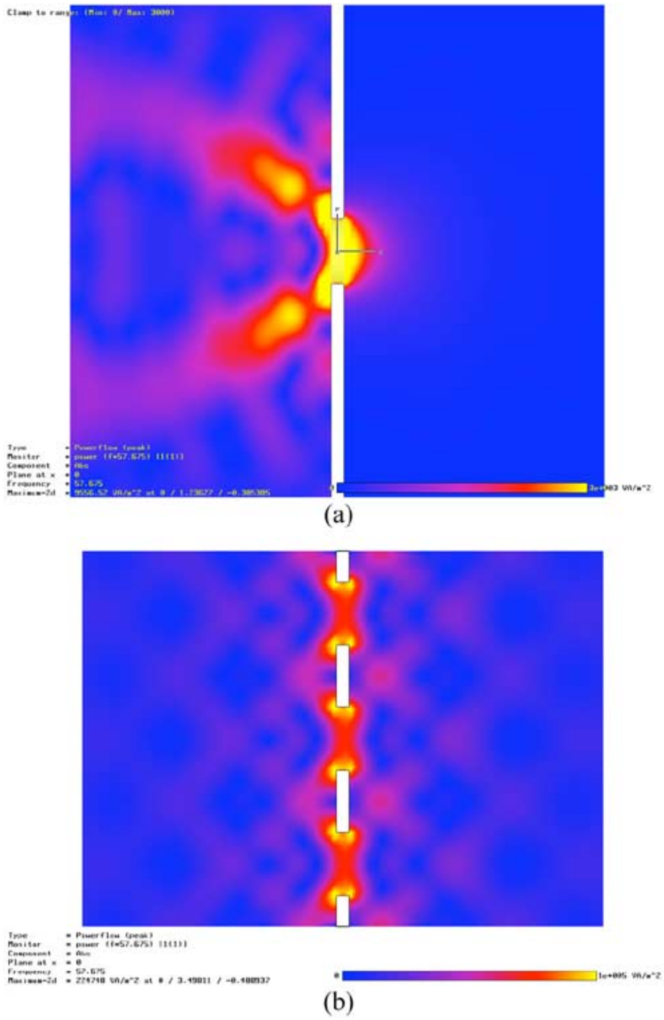


Fig. 3. (a) Power flow across a single hole and (b) power flow across the infinite hole array for the plate with $a = 2.5$ mm, $w = 0.5$ mm calculated at the resonance frequency, 57.675 GHz.

To show graphically the enhancement in the power profile coupled across the holes, simulations using the Finite Integration Method CST Microwave Studio commercial code have been carried out, see Fig. 3.

In order to analyze the origin of the transmission peaks observed in Fig. 2(a) and (b), we will use a highly simplified version of the model, which can be analytically worked out, that shows the same behavior in the regime of interest of $\lambda \geq L \gg a$. If a strong truncation in parallel wave vectors is done, in regions 1 and 3 only first-order diffraction is considered, i.e., the possible wave vectors in the direction of the incoming electric field, x, are $k_{x0} = 0$ and $k_{x\pm 1} = \pm 2\pi/L$. In region 2, where all modes are evanescent for $\lambda > 1.7a$, only the most slowly decaying evanescent mode, the TE_{11} mode of the circular waveguide, is taken into account. It follows from [11] that the main effect of truncating the number of modes is a small unimportant shift in the position of the transmission peaks. In order to further simplify the discussion, we consider the ideal nonabsorbing case. Finite absorption merely reduces the height of the peaks (for zero absorption the transmittance can be as large as 100%) without altering the physical picture.

Within this minimal model, the zero-order transmission coefficient (t_{00}) can be written as a typical Fabry-Perot expression

$$t_{00} = \frac{\tau_{01}^{12} \exp(-|q_{z1}|h) \tau_{10}^{23}}{1 - \rho^2 \exp(-2|q_{z1}|h)} \tag{1}$$

where τ_{01}^{12} is the fraction of the amplitude for the incident wave impinging from region 1 to be transmitted through the holes of a semi-infinite region 2; ρ is the reflection amplitude of a evanescent wave with purely imaginary wavenumber $j|q_{z1}|$ (the TE_{11} mode of the circular waveguide) coming from region 2 and approaching the interface between regions 2 and 1. Finally, τ_{10}^{23} is the fraction of the amplitude of this evanescent mode to be transmitted from region 2 to region 3. Referring to the extraordinary transmission, transmittance peaks ≈ 1 suggest the presence of resonant phenomena. This idea is reinforced by the presence of a multiple scattering denominator in (1) that could be close to zero. However, the Fabry-Perot condition for resonant denominator seems never to be fulfilled as $\exp(-2/q_{z1}/h) \ll 1$ in the sub-wavelength regime considered. But, this decrease in amplitude could be compensated by an amplitude boost at the interfaces, that is, if ρ is larger than one. This counter-intuitive behavior is not forbidden by energy conservation rules when dealing with evanescent modes. Actually, it can be shown (see [11] for further details) that the the modulus of the reflection coefficient for the evanescent wave impinging from the interior of the hole can be much larger than one at frequencies close to the resonant frequency of a surface EM mode of the decorated $(\mathrm{surface} + \mathrm{holes})$ metal-vacuum interface. In some sense we can state that at these resonant frequencies, the metal-vacuum interface acts as a "supermirror" for evanescent waves. Therefore, the origin of the transmission peaks observed in Fig. 2(a) and (b) at frequencies close to 60 GHz are associated to the excitation of two coupled surface EM modes. Note that in the millimeter wave range the resonant condition for the excitation of the surface EM mode appears at wavelengths very close to the period.

At this point, in the results shown in Fig. 2, it is noticeable the presence of the characteristic transmission minimum appearing for wavelengths smaller than the ones at which the transmission resonance appears. These are the anomalies observed by Wood in 1902 when measured optical gratings, see [18]. During the times of Wood's research it was not possible to understand these anomalies today associated to the change of the number of radiant diffraction orders. In an infinite periodic system, these minima are expected to appear at a period identical to the free space wavelength.

III. Finite Structures

All the preceding theory has been applied for infinite perforated plates. As a previous step before the experiment, finite structures need to be simulated. To make this study we have applied a theoretical formalism recently developed by some of the authors that is able to analyze the optical properties of finite collections of holes drilled in a metallic film [19]. As in the theoretical framework developed for infinite 2-D arrays of holes, in this formalism we apply a modal expansion of the EM fields (plane wave in vacuum regions and TE/TM modes inside the holes).

By matching the EM fields appropriately on all interfaces (we also assume perfect matching boundary conditions to simplify the calculations), we end up with a set of linear equations for the expansion coeficients of the EM-fields at the diferent holes of our structure. Once these coeficients are obtained, the total transmittance through the 2-D subwavelength hole array can be finally calculated. In both panels of Fig. 4, we show the total transmittance spectra for the six 31×31 arrays of holes analyzed as obtained with our new theoretical tool.

It can readily be seen that the peak of extraordinary transmission appears around the frequency predicted for the infinite case. Transmission always decreases as the thickness of the plate grows. This agrees with the assumption of an evanescent mode inside the holes. It is important to note that there is almost total transmission for the structure with hole diameter $a = 2.5$ mm and plate thickness $w = 0.5$ mm. On the other hand, the plates with holes of diameter $a = 2$ mm have a transmission peak of around -7 dB for the best case. Wood's anomaly is also present in these simulations, although it is not clearly emphasized. As typically happens in finite systems, it is slightly shifted toward higher frequencies [20]–[22].

It seems that making the sample finite implies a loss in spectral resolution in the frequency response. Evidently, a lower frequency resolution flattens somewhat the narrowest peaks in the spectra. As a consequence of this flattening, the maximum of transmission falls dramatically for very narrow peaks. A comparison between Fig. 2(a) and (b) shows that transmission peaks are much narrower for small holes. In accordance with this interpretation, the level of signal in Fig. 4(a) is much smaller than in Fig. 4(b). Moreover, in infinite structures, Wood's anomaly appears as an abrupt fall of power within a very narrow frequency range. In consequence, it is softened in finite structures.

Following the aforementioned interpretation, in order to catch the finest details of the spectrum, the illumination should impinge on a larger effective area. This can be accomplished either by constructing larger samples maintaining the size of the holes or by increasing the diameter of the holes maintaining the size of the array. The latter statement is a complementary explanation for the high level of signal seen in Fig. 4(b) compared to the low level presented in Fig. 4(a).

Experimental verification will be realized in the following in order to verify if it appears the same phenomena that has been demonstrated in the optical frequency band.

IV. Experimental Set-Up and Measurements

Several prototypes have been fabricated in square aluminum plates with 31×31 holes and different thicknesses (w) (ranging from 0.5 mm to 4 mm) by a laser machine drilling the holes with the required diameters and periodicity. Some conical deviation from the theoretical cylindrical form is unavoidable because of the fabrication process, but the theoretical average diameter has been preserved with a tolerance of ± 50 micrometers. In all cases analyzed, the array has a lattice constant, d, of 5 mm with the same tolerance and two different hole diameters, a, are considered: 2 and 2.5 mm, see Fig. 5.

Transmission of millimeter waves through these structures is measured by using an AB Millimeter Quasioptical Vector Network Analyzer in the frequency range between 45 and 70 GHz. Details of the instrumentation can be found in [23]. In Fig. 6(a)

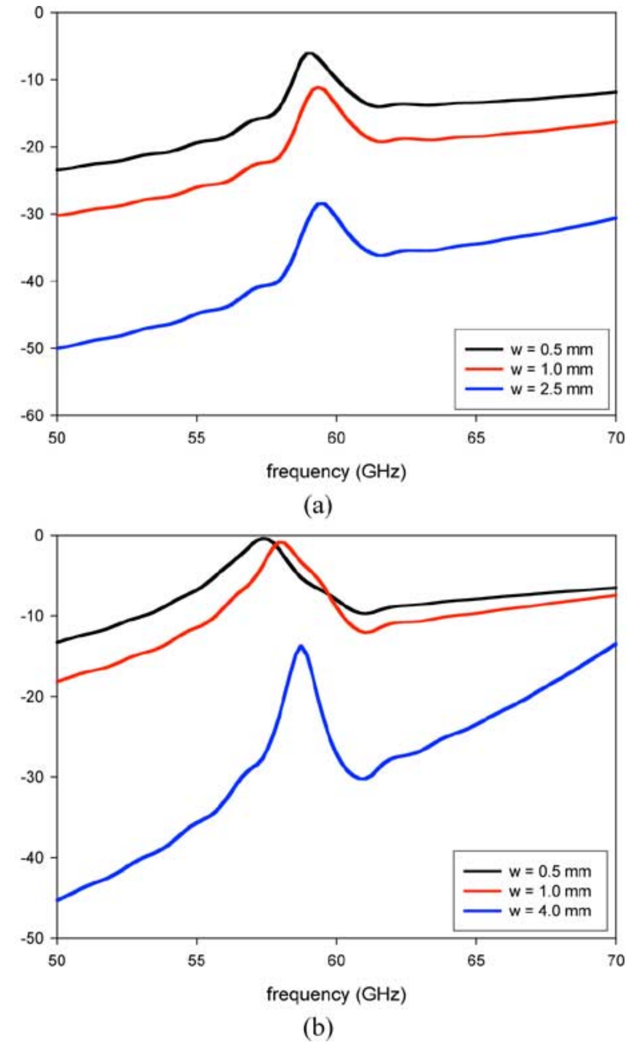


Fig. 4. Numerical simulation of finite size 31×31 hole array total transmittance for (a) $a = 2$ mm and three different w's. $w = 0.5$ mm (black), $w = 1$ mm (red) and $w = 2.5$ mm (blue) and for (b) $a = 2.5$ mm and three w's. $w = 0.5$ mm (black), $w = 1$ mm (red) and $w = 4$ mm (blue).

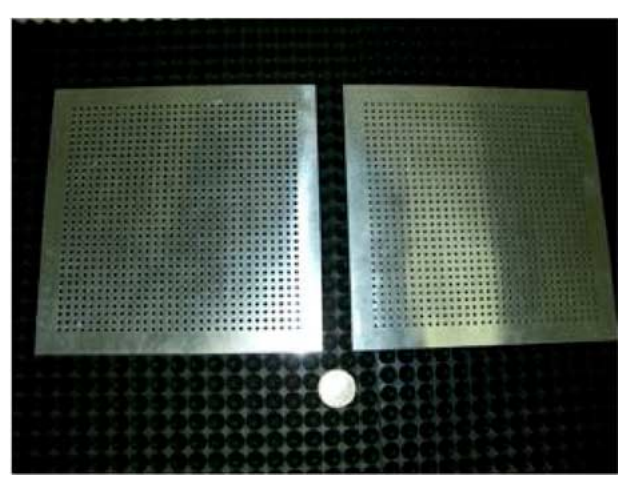
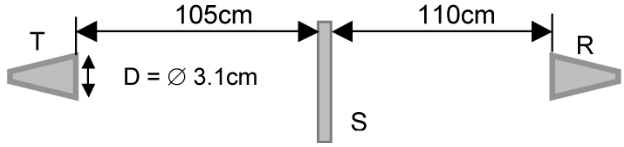


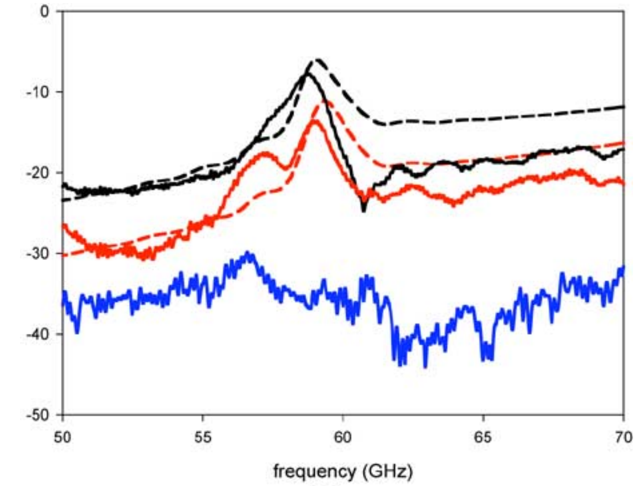
Fig. 5. Photograph of the samples analyzed in the experiments with hole diameters $a = 2$ and 2.5 mm.



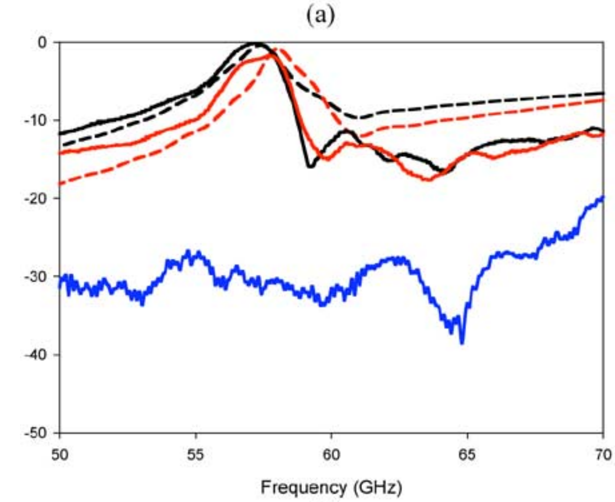
(a)

(b)

Fig. 6. (a) Schematic of the whole experimental setup. (b) Photograph of the source antenna (T) and the sample (S) covered with absorbing material to avoid diffraction. The receiving antenna is not shown.



(a)



(b)

Fig. 7. Experimental transmittance spectra for (a) $a = 2$ mm for three different w's. $w = 0.5$ mm (black), $w = 1$ mm (red) and $w = 2.5$ mm (blue). (b) $a = 2.5$ mm for also three w's. $w = 0.5$ mm (black), $w = 1$ mm (red) and $w = 4$ mm (blue). Also shown the theoretical predictions of Fig. 4 for the plates with thickness $w = 0.5$ mm (dashed black) and $w = 1$ mm (dashed red).

we show a schematic of the experimental set-up. The measurement procedure follows the next sequence: a vertically polarized pure gaussian beam [24] is generated by a corrugated horn antenna (T) with a beamwaist of 0.9 times the horn diameter; this beam propagates up to the sample under test (S) and the transmitted beam is collected by another corrugated horn antenna (R). The beam radius of the gaussian beam incident on the sample is about 16 cm for the worst case (45 GHz). This ensures a good illumination of the hole array. In order to avoid spurious effects due to diffraction the sample is covered with dielectric absorbing material. The photograph with the transmitting antenna (T) and the covered sample (S) is shown in Fig. 6(b). The calibration is made by simply removing the sample and maintaining the rest of the whole set-up. After getting the base the calibration is checked with the measurement of the free space propagation.

Samples were measured with the aforementioned experimental set-up. The results of the measurements are shown in Fig. 7.

V. Discussion of the Results

The underlying physical mechanism responsible of this extraordinary effect, namely, a wave resonance process through the surface EM modes formed on each metal-dielectric interface, has been identified. If we compare simulation results of Fig. 4 with experimental ones of Fig. 7, some conclusions follow. First, it is clear that for thin plates ($w = 0.5$ and 1 mm) the experiment is in very good agreement with the numerical prediction. It has been included in Fig. 7 those theoretical curves in order to simplify the comparison. The level of the transmittance is of the same order all along the spectum. The extraordinary transmission peaks are somewhat shifted from the prediction frecuencies. The bandwith of the passband is very similar. Second, Wood's anomaly is more emphasized in the experiment than in the simulation, and is effectively shifted toward lower frequencies. Third, for thick plates (blue curves of Fig. 7) the peak of transmission is somewhat hidden by the noise threshold of the measurement device.

It is worth to note that for a reasonably high number of illuminated holes and a thin enough plate we can get total transmission at resonance. This is what happens for the sample with $a = 2.5$ mm and $w = 0.5$ mm. We have experimentally explored this case in more detail. The frequency range for the measurement has been extended up to 110 GHz, using another set of twin corrugated horn antennas. The result of this experiment is shown in Fig. 8. It is compared to the zero-order transmittance of an infinite hole array with the same parameters. Apart from very fine frequency details, the finite structure behaves qualitatively as the infinite one. Note the presence of Wood's anomaly around

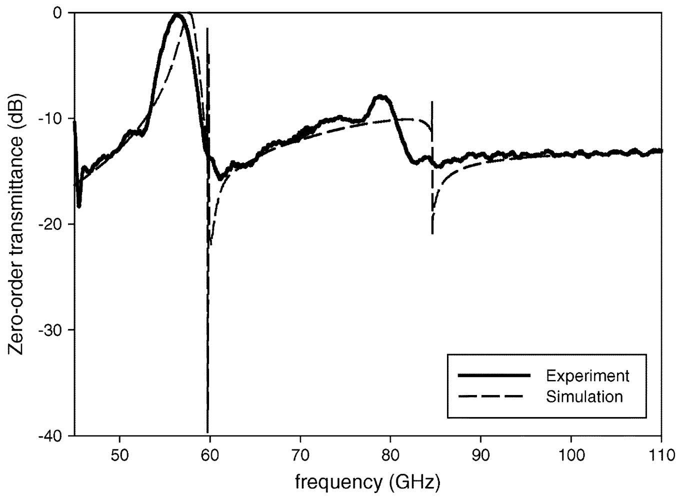


Fig. 8. Theoretical spectrum of the infinite structure (dashed) and experimental reponse of the 31×31 hole array (solid) extended up to 110 GHz for parameters $a = 2.5$ mm and $w = 0.5$ mm.

60 GHz as expected and the second relative maximum with similar amplitude.

VI. Conclusion

In conclusion, we have demonstrated that the phenomenon of extraordinary electromagnetic wave transmission through arrays of subwavelength holes perforated in optically thick metallic films is also present in the millimeter range of the EM spectrum. By combining experiments and theory, we have shown how the underlying physical mechanism is also the same than the one discovered in the optical regime.

This experimental finding suggests that the effects related to the phenomenon of enhanced electromagnetic waves transmission (enhanced electromagnetic waves transmission through a single aperture, beaming and focusing electromagnetic waves by texturing periodically the vicinity of a single aperture) previously reported in the optical regime could also be found in other EM ranges, in particular in the millimeter and microwave regimes.

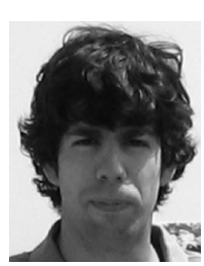
The verification of this hypothesis will open up some potential applications in millimeter waves like narrow bandwidth frequency selective surfaces or near-field imaging.

Acknowledgment

M. Beruete and M. Sorolla are indebted to J. D. Baena, Universidad de Sevilla in Spain, for the fruitful discussions related to frequency selective surfaces.

References

[1] S. Tretyakov, *Analytical Modeling in Applied Electromagnetics*. Boston, MA: Artech House, 2003.
[2] F. Keilmann, "Infrared high-pass filter with high contrast," *Int. J. Infrared and Millimeter Waves*, vol. 2, pp. 259–272, Apr. 1981.
[3] A. Mitsuishi, Y. Otsuka, S. Fujita, and H. Yoshinaga, "Metal mesh filters in the far infrared region," *Jpn. J. Applied Phys.*, vol. 2, pp. 574–577, Sep. 1963.
[4] R. Ulrich, "Far-infrared properties of metallic mesh and its complementary structure," *Infrared Phys.*, vol. 7, pp. 37–55, 1967.
[5] C. M. Rhoads, E. K. Damon, and B. A. Munk, "Mid-infrared filters using conducting elements," *Appl. Opt.*, vol. 21, p. 2814, 1982.
[6] T. W. Ebbesen, H. J. Lezec, H. Ghaemi, T. Thio, and P. A. Wolf, "Extraordinary optical transmission through sub-wavelength hole arrays," *Nature*, vol. 391, pp. 667–669, Feb. 1998.
[7] U. Schroter and D. Heitmann, "Surface-plasmon-enhanced transmission through metallic gratings," *Phys. Rev. B*, vol. 58, pp. 15 419–15 421, 1998.
[8] M. M. J. Treacy, "Dynamical diffraction in metallic optical gratings," *Appl. Phys. Lett.*, vol. 75, pp. 606–608, 1999.
[9] J. A. Porto, F. J. García-Vidal, and J. B. Pendry, "Transmission resonances on metallic gratings with very narrow slits," *Phys. Rev. Lett.*, vol. 83, pp. 2845–2848, Oct. 1999.
[10] E. Popov, M. Neviere, S. Enoch, and R. Reinisch, "Theory of light transmission through subwavelength periodic hole arrays," *Phys. Rev. B*, vol. 62, pp. 16 100–16 108, Dec. 2000.
[11] L. Martín-Moreno, F. J. García-Vidal, H. J. Lezec, K. M. Pellerin, T. Thio, J. B. Pendry, and T. W. Ebbesen, "Theory of extraordinary optical transmission through subwavelength hole arrays," *Phys. Rev. Lett.*, vol. 86, pp. 1114–1117, Feb. 2001.
[12] J. B. Pendry, L. Martín-Moreno, and F. J. García-Vidal, "Mimicking surface plasmons with structured surfaces," *Science*, vol. 305, p. 847, Aug. 2004.
[13] J. Rivas, C. Schotsch, P. H. Bolivar, and H. Kurz, "Enhanced transmission of THz radiation through subwavelength holes," *Phys. Rev. B*, vol. 68, p. 201 306, Nov. 2003.
[14] F. J. García-Vidal, H. J. Lezec, T. W. Ebbesen, and L. Martín-Moreno, "Multiple paths to enhance optical transmission through a single subwavelength slit," *Phys. Rev. Lett.*, vol. 90, p. 213 901, May 2003.
[15] H. J. Lezec, A. Degiron, E. Devaux, R. A. Linke, L. Martín-Moreno, F. J. García-Vidal, and T. W. Ebbesen, "Beaming light from a subwavelength aperture," *Science*, vol. 297, pp. 820–822, 2002.
[16] L. Martín-Moreno, F. J. García-Vidal, H. J. Lezec, A. Degiron, and T. W. Ebbesen, "Theory of highly directional emission from a single subwavelength aperture surrounded by surface corrugations," *Phys. Rev. Lett.*, vol. 90, pp. 167 401–0, Apr. 2003.
[17] A. Roberts, "Electromagnetic theory of diffraction by a circular aperture in a thick, perfectly conducting screen," *J. Opt. Soc. Amer. A*, vol. 4, pp. 1970–1983, Oct. 1987.
[18] R. W. Wood, "On a remarkable case of uneven distribution of light in a diffraction grating spectrum," *Phil. Mag.*, vol. 4, pp. 396–408, 1902.
[19] J. Bravo-Abad, F. J. Garcia-Vidal, and L. Martin-Moreno, "Resonant transmission of light through finite chains of subwavelength holes," Phys. Rev. Lett., vol. 93, pp. 227401–227404, Nov. 2004, to be published.
[20] A. Hessel and A. A. Oliner, "A new theory of woods anomalies on optical gratings," *Appl. Opt.*, vol. 4, no. 10, pp. 1275–1297, 1965.
[21] T. K. Wu, *Frequency Selective Surface and Grid Arrays*. New York: Wiley, 1995.
[22] B. A. Munk, *Frequency Selective Surfaces—Theory and Design*. New York: Wiley, 2000.
[23] P. Goy, M. Gross, and S. Caroopen, "Millimeter and submillimeter wave vector measurements with a network analyzer up to 1000 GHz. Basic principles and applications," in *Proc. 4th Int. Conf. on Millimeter and Submillimeter Waves and Applications*, San Diego, CA, Jul. 20–23, 1998.
[24] P. F. Goldsmith, *Quasioptical Systems-Gaussian Beam, Quasioptical Propagation, and Applications*. Piscataway, NJ: IEEE Press, 1998.



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Luis Martín-Moreno, photograph and biography not available at the time of publication.

J. Bravo-Abad, photograph and biography not available at the time of publication.

F. J. García-Vidal, photograph and biography not available at the time of publication.