Enhanced millimeter-wave transmission through subwavelength hole arrays

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We explore, both experimentally and theoretically, the existence in the millimeter-wave range of the phenomenon of extraordinary light transmission through arrays of subwavelength holes. We have measured the transmission spectra of several samples made on aluminum wafers by use of an AB Millimetre quasi-optical vector network analyzer in the wavelength range 4.2–6.5 mm. Clear signals of the existence of resonant light transmission at wavelengths close to the period of the array appear in the spectra. © 2004 Optical Society of America

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The discovery of the phenomenon of extraordinary optical transmission (EOT) observed in two-dimensional (2D) arrays of subwavelength holes perforated in optically thick metallic films[1] has opened up the possibility of using subwavelength apertures for a variety of optoelectronic applications. Previous theoretical work[2] on Ebbesen's experiment assigned the EOT phenomenon to the excitation of surface electromagnetic (EM) modes occurring on corrugated metal surfaces. Furthermore, these modes (and EOTs) were found to appear even in a simpler model where the metal was treated as a perfect conductor.[2,3] These surface leaky modes are similar to the ones appearing in perfectly conducting sinusoidal gratings.[4] As the perfect conductor approximation should be even more valid for larger wavelengths, the possibility of the existence of EOT in other ranges of the EM spectrum was pointed out in Ref. 2. Moreover, recently there have been experimental studies of EOT in the terahertz regime in doped semiconductors[5] and in metals[6–8] that seem to suggest that EOT is also present in this frequency regime.

Here we move a step further by studying, both experimentally and theoretically, the transmission of EM radiation through 2D arrays of subwavelength holes in the millimeter-wave range. To carry out our analysis we fabricated several prototypes in aluminum wafers of different thicknesses (w), ranging from 0.5 to 4 mm. All the square arrays (31×31) have a lattice constant (d) of 5 mm, and two different hole radii (R) are considered: 1.25 and 1 mm [see Fig. 1(a)].

It is important to note here that, before the experiment by Ebbesen *et al.*,[1] there were experimental studies of transmission of light through arrays of holes in the far-infrared,[9] mid-infrared,[10] and infrared[11] ranges. However, these previous experiments were performed for hole sizes and lattice constants (d) such that d was

(a)

(b)

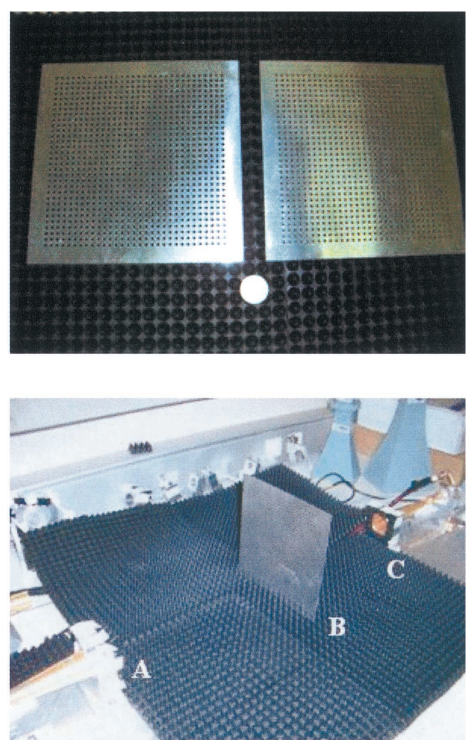

Fig. 1. (a) Photographs of two of the six samples analyzed in the experiment (left, $R = 1.25$ mm, $w = 0.5$ mm; right, $R = 1$ mm, $w = 0.5$ mm). (b) Photograph of the experimental setup: A, corrugated horn antenna acting as source of millimeter waves; B, sample; C, receptor antenna.

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smaller than the cutoff wavelength (λ_c). EOT appears essentially for $\lambda = d$ and when the modes inside the hole are evanescent, i.e., when $d > \lambda_c$.

Let us first discuss the theoretical predictions for the transmittance spectra given by the framework described in Ref. 2 for the study of EOT in the optical range. Within this formalism, we consider a metal film perforated by an infinite 2D square array of holes. Because aluminum behaves as a quasi-perfect conductor in the millimeter-wave regime, we simplified our formalism by considering the perfect metal boundary conditions at all interfaces forming the structure. Within the perfect metal boundary condition approximation, this theoretical framework is rigorous, being equivalent to one developed some time ago for studying inductive grids.[12]

In Fig. 2 we show our numerical simulations for the zeroth-order transmittance spectra of infinite arrays of holes corresponding to the six samples fabricated. In all the calculations we assume that a normally incident plane wave is impinging at the perforated metal film. Figure 2(a) displays the cases with $R = 1.25$ mm ($\lambda_c = 0.85d$) and three different thicknesses, and in Fig. 2(b) the three corresponding transmittance spectra with $R = 1$ mm ($\lambda_c = 0.68d$) are shown. In the region $\lambda/d \approx 1$, the calculations shown in Fig. 2 predict the appearance of EOT resonances. For each of the thinner samples considered ($w = 0.5$, 1.0 mm), the two surface EM resonances excited at the two surfaces of the metallic film are coupled, leading to two transmission peaks that reach 100%.[2] However, for the thicker samples analyzed ($w = 4.0$ mm for $R = 1.25$ mm and $w = 2.5$ mm for $R = 1$ mm), this EM coupling is negligible and only one transmission peak appears in the spectra.

Transmission through our samples is measured by using an AB Millimeter quasi-optical vector network analyzer in the frequency range 40–110 GHz. In Fig. 1(b) we show a photograph of the experimental setup. A vertically polarized pure Gaussian beam is generated by a corrugated horn antenna, A. This beam propagates to the sample, B, that is located 166 cm from the antenna. The diameter of the beam waist at the sample location is ~50 cm at the wavelength range of interest. In this way the illumination of the hole arrays is rather uniform. The transmitted beam is finally collected into a horn antenna, C, that is placed 105 cm from the sample. The samples are embedded into a sheet of millimeter-wave absorbing material [not shown in Fig. 1(b) for illustrative purposes] such that any possible diffracted beam generated by the edges of the samples is absorbed by the sheet and not collected by the receiver antenna, C.

Figure 3 shows experimental transmission spectra obtained for the six different samples analyzed. We represent the collected transmission power, T (normalized to the collected power when no sample is present) as a function of wavelength, when the holes have radius $R = 1.25$ mm [solid curves in Fig. 3(a)] and when $R = 1$ mm [solid curves in Fig. 3(b)]. In the case of $R = 1.25$ mm and $w = 0.5$ mm [black curve in Fig. 3(a)], the transmission at resonance (located at a λ value slightly larger than d) can be as large as 95%, although the holes occupy only 20% of the unit cell. For $R = 1.25$ mm and $w = 1$ mm (solid red curve), the transmission resonance also appears, reaching 65% at maximum. This kind of transmission resonance is also present in the thinner samples [$w = 0.5$ mm and $w = 1$ mm; see Fig. 3(b)] of the arrays of holes with smaller radius ($R = 1$ mm), but the associated transmittance peaks are much lower than the ones obtained for $R = 1.25$ mm. For the thicker films analyzed ($w = 4.0$ mm for $R = 1.25$ mm and $w = 2.5$ mm for $R = 1$ mm), the collected power is extremely small and no fingerprints of transmission resonances are observed. As the measured transmission resonances appear in a frequency range in which the holes support only EM evanescent waves, we can safely conclude that EOT also takes place in the millimeter-wave range, as predicted by theory.

However, there is strong disagreement between theory and experiment with regard to the absolute value of the transmission peaks. A possible reason for this disagreement could be the intrinsically finite size of our arrays (31 × 31). To explore this possibility in more detail we applied a theoretical formalism recently developed by our group that is able to analyze the optical properties of finite collections of holes drilled in a metallic film.[13] In this method we first assume an artificial square supercell with sides L that contains the $N \times N$ array of holes ($L > Nd$). Then we apply a modal expansion of the EM fields (plane waves in vacuum regions and TE or TM modes inside the holes[14]),

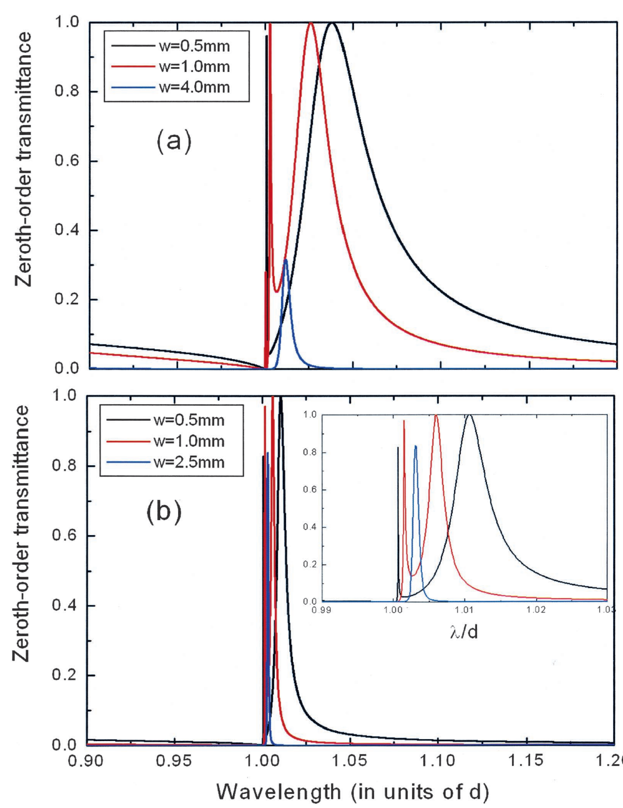

Fig. 2. Theoretical zeroth-order transmittance spectra corresponding to different infinite hole arrays with (a) $R = 1.25$ mm and (b) $R = 1$ mm. The inset in (b) represents the same physical quantity but for a smaller range of wavelengths.

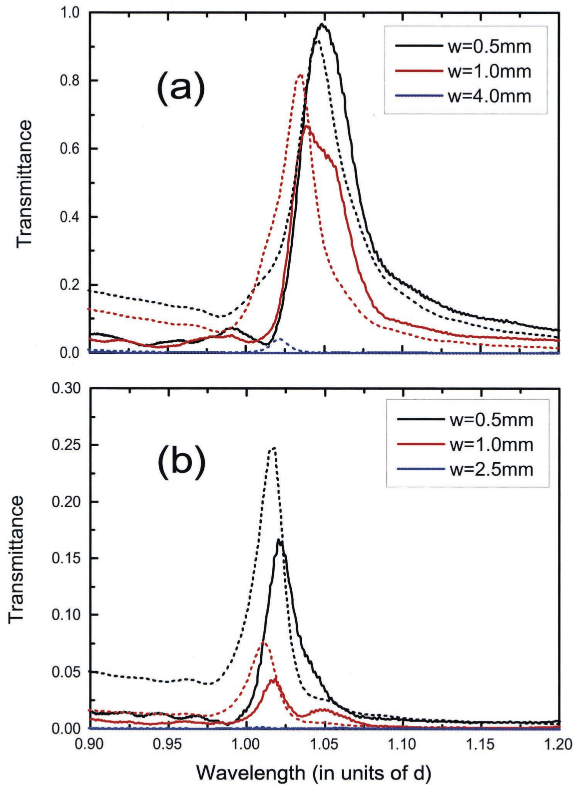

Fig. 3. Experimental transmittance spectra (solid curves) and theoretical total transmittance curves (dashed curves) for the 31×31 arrays corresponding to the same geometric parameters as in Fig. 2. Different hole arrays with (a) $R = 1.25$ mm and (b) $R = 1$ mm are analyzed.

and we match these fields, taking into consideration the perfect metal boundary condition. At the end of this procedure a set of linear equations for the expansion coefficients of the EM fields at the different holes of our structure is established. As the considered supercell is fictitious, we have to take the limit $L \rightarrow \infty$ in the different terms appearing in this set of linear equations. Once the expansion coefficients are obtained, the total transmittance through the 2D subwavelength hole array can be calculated.

The dashed curves in Fig. 3 show the total transmittance spectra for the six 31×31 arrays of holes as obtained with our new theoretical tool. If we compare the theoretical results for the 31×31 arrays (dashed curves in Fig. 3) with the corresponding results for infinite arrays (Fig. 2), there are two main changes. First, the very narrow transmission peaks appearing at $\lambda \approx d$ for the infinite arrays are not present in the spectra of finite arrays. Second, there is a strong reduction of the transmission peaks when going from infinite arrays to finite ones; this reduction is more dramatic for the structures with $R = 1$ mm than for the arrays with $R = 1.25$ mm. These two changes lead to a much better agreement between theoretical predictions and experimental results (see Fig. 3). This good agreement allows us to state that the strength of transmission resonances associated with the EOT phenomenon observed in subwavelength hole arrays is basically controlled by the size of the arrays.

In conclusion, we have demonstrated that the phenomenon of extraordinary EM transmission through arrays of subwavelength holes is also present in the millimeter-wave range. Moreover, we have also shown that one of the key parameters to observe this phenomenon is the number of periods of the array.

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13. J. Bravo-Abad, F. J. García-Vidal, and L. Martin-Moreno are preparing a manuscript titled "Resonant transmission of light through finite chains of subwavelength holes."
14. As we are working in the subwavelength regime, considering just the two least decaying modes in each hole is enough to obtain accurate numerical results.