Enhanced millimeter wave transmission through subwavelength hole arrays

M. Beruete and M. Sorolla
Departamento de Ingeniería Eléctrica y Electrónica, Universidad Pública de Navarra, E-31006 Pamplona, Spain.

I. Campillo and J.S. Dolado
Labein Centro Tecnológico, Cuesta de Olabeaga 16, E-48013, Bilbao, Spain.

L. Martín-Moreno
Departamento de Física de la Materia Condensada, ICMA-CSIC, Universidad de Zaragoza, E-50009 Zaragoza, Spain.

J. Bravo-Abad and F.J. García-Vidal
Departamento de Física Teórica de la Materia Condensada, Universidad Autónoma de Madrid, E-28049 Madrid, Spain.

In this letter, 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 using an AB Millimetres TM Quasioptical Vector Network Analyzer in the wavelength range between 4.2mm to 6.5mm. Clear signals of the existence of resonant light transmission at wavelengths close to the period of the array appear in the spectra.

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, has opened up the possibility of using subwavelength apertures for a variety of optoelectronic applications. A previous theoretical work 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 EOT) were found to appear even in a simpler model where the metal was treated as a perfect conductor. These surface leaky modes are similar to the ones appearing in perfectly conducting sinusoidal gratings. As the perfect conductor approximation should be even more valid for larger wavelengths, the previously cited work pointed out to the possibility of the existence of EOT in other ranges of the EM spectrum. Moreover, very recently, there have been some experimental studies of EOT in the THz regime in doped semiconductors and in metals 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 millimetric wave range. In order to carry out our analysis, several prototypes have been fabricated in aluminum wafers of different thicknesses, ranging from 0.5mm to 4mm. All square arrays (31 × 31) have a lattice constant (d) of 5mm and two different hole radius (R) are considered: 1.25mm and 1mm (see Fig.1a).

It is important to note here that, before Ebbesen experiment, there were experimental studies of transmission of light through arrays of holes in the far infrared, mid infrared and infrared ranges. However, these previous experiments were performed for hole sizes and lattice constants (d) such that d was smaller than the cut-off wavelength (λc). EOT appears essentially λ = d, but when the modes inside the hole are evanescent, i.e., when d > λc.

Let us first discuss the theoretical predictions for the transmittance spectra given by the framework described in 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. As aluminum behaves as a quasi-perfect conductor in the millimeter wave regime, we have simplified our formalism by considering perfect metal boundary conditions (PMBC) at all interfaces forming the structure. Within the PMBC approximation, this theoretical framework is rigorous, being equivalent to the one developed some time ago for studying inductive grids.

In Fig. 2 we show our numerical simulations for the zero-order transmittance spectra of infinite arrays of holes corresponding to the six samples fabricated. In all calculations we show in this paper we assume that a normal incident plane wave is impinging at the perforated metal film. Panel (a) displays the cases with R = 1.25mm (λc = 0.85d) and three different thicknesses and in panel (b) the corresponding three transmittance spectra with R = 1mm (λc = 0.68d) are shown. In the region λ/d ≈ 1, calculations rendered in panels 2a and 2b predict the appearance of EOT resonances. For each of the thinner samples considered (w = 0.5mm and w = 1.0mm), the two surface EM resonances excited at the two surfaces of the metallic film are coupled, leading to two transmission peaks that reach 100%. However, for the thicker samples analyzed (w = 4.0mm for R = 1.25mm and w = 2.5mm for R = 1mm), this EM coupling
transmission through our samples is measured by using an AB Millimeter\textsuperscript{TM} Quasioptical Vector Network Analyzer in the frequency range between 40 to 110GHz. In Fig.1b we show a photograph of the experimental set-up. A vertically polarized pure gaussian beam is generated by a corrugated horn antenna (A). This beam propagates up to the sample (B) that is located at 166cm to the antenna. The diameter of the beam waist at the sample location is around 50cm 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 at 105cm from the sample. The samples are embedded into a sheet of millimeter wave absorbing material (not shown in Fig.1b for illustrative purposes) in such a way 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).

Fig.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 $R = 1.25\text{mm}$ (top panel, full lines) and when $R = 1\text{mm}$ (bottom panel, full lines). In the case of $R = 1.25\text{mm}$ and $w = 0.5\text{mm}$ (black curve in panel a), the transmission at resonance (located at $\lambda$ slightly larger than $d$) can be as large as 95% although the holes only occupy 20% of the unit cell. For $R = 1.25\text{mm}$ and $w = 1\text{mm}$ (red full curve), the transmission resonance also appears, reaching 65% at maximum. This kind of transmission resonances is also present in the thinner samples ($w = 0.5\text{mm}$ and $w = 1\text{mm}$, see panel b) of the arrays of holes with smaller radius ($R = 1\text{mm}$) but the transmittance peaks associated are much lower than the ones obtained for $R = 1.25\text{mm}$. For the thicker films analyzed ($w = 4.0\text{mm}$ for $R = 1.25\text{mm}$ and $w = 2.5\text{mm}$ for $R = 1\text{mm}$), 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 only support EM evanescent waves, we can safely conclude that EOT also takes place in the millimeter wave range, as theory predicted.

However, there is a strong disagreement between theory and experiment as regards the absolute value of the transmission peaks. A possible reason for this disagreement could be originated by the intrinsic finite size of our arrays ($31 \times 31$). In order to explore in more detail
FIG. 3: Experimental transmittance spectra (full lines) and theoretical total transmittance curves (dashed lines) for the 31 \times 31 arrays corresponding to the same geometrical parameters as in Figure 2. Different hole arrays with $R = 1.25$ mm in (a) and $R = 1$ mm in (b) are analyzed.

In both panels of Fig. 3 (dashed curves), we show the total transmittance spectra for the six 31 \times 31 arrays of holes as obtained with our new theoretical tool. If we compare the theoretical results for the 31x31 arrays (dashed lines in Fig.3) with the corresponding ones for infinite arrays (Fig.2) there are two main changes. Firstly, the very narrow transmission peaks appearing at $\lambda \approx d$ for the infinite arrays are not present in the spectra of finite arrays. Secondly, 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 to 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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\[ \text{[12]} \text{ As we are working in the subwavelength regime, considering just the two least decaying modes in each hole is enough to obtain accurate numerical results.} \]