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Acoustic resonant transmission through acoustic gratings with very narrow slits: Multiple-scattering numerical simulations

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It is shown that the transmission resonance of acoustic waves for an incident wavelength larger than the period of the grating exists in acoustic gratings with very narrow slits similar to that of optical subwavelength systems. The results are obtained by multiple-scattering numerical simulations. The physical origin for such an acoustic transmission resonance is also analyzed.

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In recent years, headway has been made in the study of the transmission of light through subwavelength metallic apertures. Several experiments[1] have reported that the transmission of light through metallic films perforated by arrays of subwavelength holes can exhibit extraordinary magnitude, which cannot be predicted by conventional aperture theory.[2] Subsequently, some works[3–13] have shown that similar extraordinary optical transmission effects can also be found in transmission metallic gratings with very narrow slits. It is believed that this extraordinary transmission effect has potential technological applications.[14,15]

However, the physical origin of the transmission resonance aroused some interest[3–13,16,17]. Porto *et al.*[4] proposed that two separate mechanisms were important: either the excitation of a cavity resonant mode, or resonant coupling between surface plasmons on both sides of the grating. These latter mechanisms can also occur for two-dimensional gratings with holes.[16] Subsequently, Treacy[5] applied the dynamical diffraction theory to explain this kind of phenomena independently. Cao and Lalanne[6] have pointed out that the coupling between the surface plasmons is not the prime effect and has a negative impact on the extraordinary transmission. Some works[7–11] have also shown that the Fabry-Pérot resonant cavity modes are responsible for the extraordinary transmission. In contrast, Barbara *et al.*[12] have shown that a model with plasmons on the incident side only explains this phenomenon very well. Recently, Pendry *et al.*[13] believed that they had resolved such a longstanding debate. They found that there are not two separate mechanisms for such an extraordinary transmission. The subwavelength holes or slits spoof surface plasmons that play the same resonant role.

Such a surface plasmon originates from the interaction of electromagnetic field with the free electrons of metal. It has some unique properties, which the other classical waves such as acoustic waves may not posses when they radiate on the metal surface. Then, it is natural to ask whether or not the extraordinary transmissions for other classical waves exist. If the extraordinary transmissions of light arise from the unique interaction form of the electromagnetic field with free electrons, one may conclude that the phenomenon may not exist for the other types of classical waves. Therefore, there are two motivations for the investigations of the extraordinary transmission of the other classical waves. First, it can provide more information about the origin of such an extraordinary phenomenon. The second motivation is the possibility of applications. If the extraordinary transmission is found for the other classical waves, it is valuable and can lead to other applications.

Based on these considerations, in this paper we investigate the transmission of acoustic waves through the narrow slit system. Thus, we take an acoustic grating consisting of cylinders, as shown at the top of Fig. 1. The period of the grating and the radius of the cylinders are denoted by a and R, respectively. The incident wave propagates in the X direction and the grating periods are in the Y direction. In fact, reflection and transmission acoustic gratings have been analyzed for many years.[18] However, transmission acoustic gratings with very narrow slits remain to be treated in detail.

We first calculate the transmission properties of acoustic waves for the grating systems for various sizes of the scatterer by using a highly efficient and accurate multiple-scattering method.[19] The source is developed by passing a

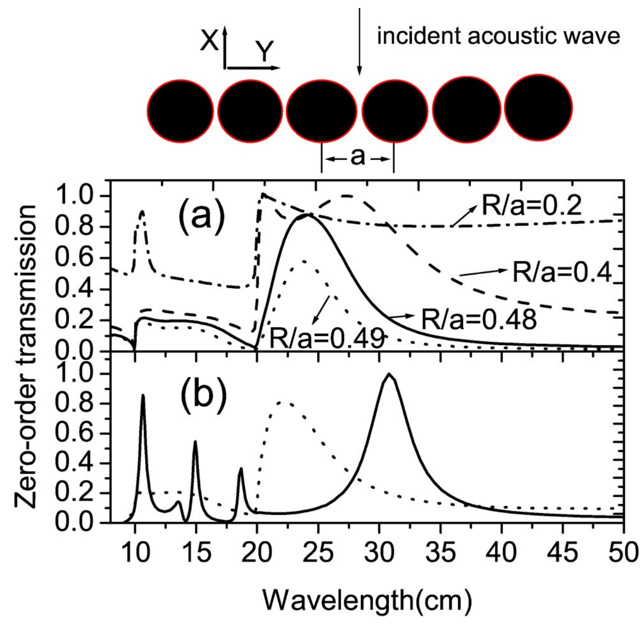

FIG. 1. Zero-order transmission spectra of an acoustic wave through a steel cylinder grating in an air background for different sizes of scatterer for normal incidence. Solid, dotted, dashed, and dashed-dotted curves correspond to the cases of $R/a=0.48$, 0.49, 0.4, and 0.2, respectively. a is taken as 20 cm. (b) The corresponding cases of $R/a=0.48$ for steel grating in a water background (dotted line) and a water cylinder grating in a mercury background (solid line).

plane wave through an open slit in front of the sample. The width of the slit is about 20% smaller than the sample width to avoid the scattering at the sample edges. The widths of the sample are sufficiently large, such as $100a$ with $a=20$ cm, to ensure sufficient angular resolution. Figure 1(a) shows zero-order transmission for acoustic waves normally incident on steel gratings in an air background as a function of the wavelength (λ) of the incident wave. Four kinds of grating with different sizes, (R/a), have been studied. The density and sound velocity ratios for steel and air are taken as $\rho_s/\rho_a=7800$ and $c_s/c_a=17.9$, respectively. The calculated results for those acoustic gratings are plotted as a solid curve ($R/a=0.48$), a dotted curve ($R/a=0.49$), a dashed curve ($R/a=0.4$), and a dashed-dotted curve ($R/a=0.2$), respectively. The corresponding cases of $R/a=0.48$ for the steel grating in a water background (dotted line) and the water cylinder grating in a mercury background (solid line) are also shown in Fig. 1(b).

It is seen from Fig. 1 that the Rayleigh minima of Wood's anomaly are clearly visible at the onset of each new diffraction order for all cases. This is the general feature of the gratings.[18] In the following, we focus attention on the long wavelength. When the wavelengths are larger than the grating period ($\lambda > 20$ cm), the transmission properties of the acoustic waves through the gratings depend on the size of scatterer and the distance between them. For small size scatterers ($R/a=0.2$), high transmission is obtained for the entire long wavelength region, which can be explained by the effective medium theory. With the increase of the size of the scatterer, the situation is different. When the width of the slits between two adjacent cylinders becomes small, such as for $R/a=0.48$ or $R/a=0.49$, the transmission resonances appear. The phenomenon is similar to those in optical subwavelength structures.[1–17]

Extraordinary acoustic transmissions similar to those of the optical systems are also obtained in the angular dependence of transmission spectra. Figure 2 shows the zero-order transmission spectra of acoustic waves as a function of the incident angle in the single-layer steel grating with $R/a=0.48$ in the air background. Solid lines, dashed lines, dotted lines, dot-dashed lines, and short dot lines correspond to the incident angles $\theta=0°$, 5°, 10°, 15°, 20°, respectively. It is seen that the zero-order transmission is sensitive to the incident angle. With a small change of the incident angle, the resonant peaks change in intensity and move in position, which is quite similar to the light propagation on metallic gratings with narrow slits and metallic films perforated by arrays of subwavelength holes.[1–17] This gives important information for the excitation of the transverse coupled acoustic modes. If k_t is the wave vector of excited mode, it can be expressed as $k_t=k_y \pm nG_y$ for the single-layer acoustic grating. Here $k_y=(2\pi/\lambda)\sin\theta$ is the component of the wave vector of the incident acoustic wave along the direction of grating period, $G_y=2\pi/a$ is the grating momentum to the wave vector, and n is the order of the mode. Therefore if the angle of incidence is varied, the incident radiation excites different coupled acoustic modes that lead to the changes of resonant peaks.

To understand the phenomenon further, we take two steps.

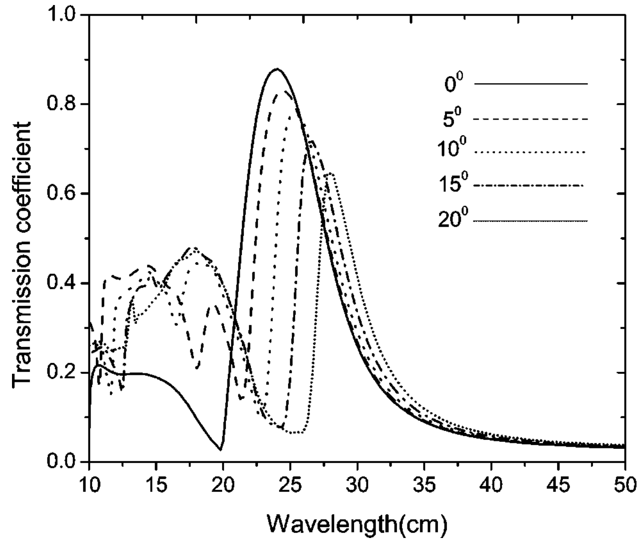

FIG. 2. Zero-order transmission spectra as a function of the incident angle of an acoustic wave through a steel cylinder grating with $R/a=0.48$ in an air background. Solid, dashed, dotted, dashed-dotted, and short dot curves correspond to $\theta=0°$, 5°, 10°, 15°, and 20°, respectively.

The first step is to add other layers of cylinders, that is, to change from a single-layer grating to a multilayer system. We study the transmission properties of acoustic waves through these systems for different thicknesses of the layer and observe the change of the transmission resonance with the increase of thickness of the layer. The second is to solve the eigenmodes of the single-layer grating and see whether or not the transverse coupled modes are excited. For comparison, the transmission coefficients for the single-layer (solid curves) and the three-layer (dotted curves) steel gratings in the air background are plotted in Fig. 3(c). We note that the transmission resonances still exist in the three-layer (deep) gratings. Comparing the results for the single-layer grating with those for the three-layer grating, we find that the transmission intensities around the maxima points do not reduce with the increase of sample thickness; there are two resonant peaks due to the coupling between different layers. With the increase of the number of systems, the grating systems become sonic crystals, which have been extensively investigated in recent years.[20–25] In order to compare the transmission resonances of acoustic waves in the acoustic gratings with those in the sonic crystals, we plot the band structure of the corresponding sonic crystals with $R/a=0.48$ in Fig. 3(a). Dispersion curves for the single-layer grating along the Y direction are also given in Fig. 3(b). Dark dots represent the positions of the transmission peaks, which are shown in Fig. 2.

Agreements between the eigenmodes of the grating and the transmission peaks have been observed, indicating that the excitations of these transverse coupled resonant modes are responsible for the phenomenon of the extraordinary acoustic transmission. It is interesting that the peak of resonant transmission in the acoustic gratings and the lower eigenmode at $k_y=0$ of Fig. 3(b) correspond to the flat band along the XM direction of the sonic crystals. The XM direc-

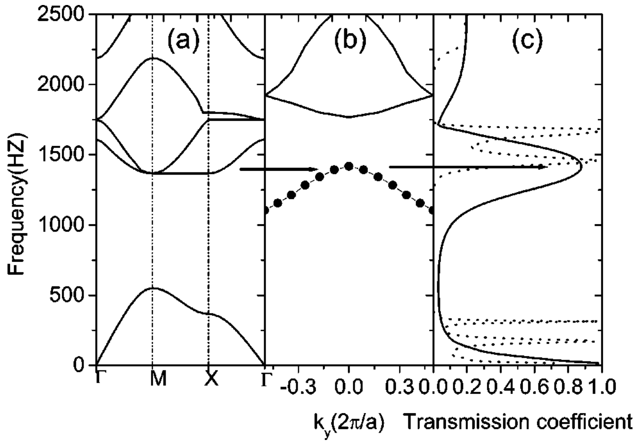

FIG. 3. Calculated band structure of an acoustic wave for a square lattice of a steel cylinder with $R/a=0.48$ in an air background. (b) The dispersion curves for the corresponding single grating along the direction of the grating period. Dark dots represent the positions of the transmission peaks as a function of incident angles, which are shown in Fig. 2. (c) The transmission coefficients for the grating systems. The solid curve corresponds to the single-layer case and dotted curve to three-layer case. The frequencies are in units of Hz.

tion is normal to the acoustic propagating direction (ΓX direction). The dark arrows in Fig. 3 mark the corresponding relation between them. These indicate that the transverse coupled resonant acoustic modes can also be observed in the sonic crystals.[20–25]

These transverse resonant modes come from the coupling of local resonant modes around a single cylinder. That is to say, when the incident acoustic waves radiate on a single "rigid" cylinder, the resonant modes can be excited around the surface of the cylinder. If we arrange these cylinders to single-layer gratings with very narrow slits, these resonant modes around the single cylinder will couple each other to form the transverse coupled acoustic modes. When the acoustic waves incident on the gratings, they are coupled to these excited transverse coupled modes, which leads to the appearance of the extraordinary transmission. In other words, the transverse coupled acoustic modes induce the extraordinary acoustic transmission. This is similar to the cases of optical subwavelength systems, in which the surface electromagnetic modes with a plasmonlike behavior (so-called spoof plasmons) induce the extraordinary optical transmission, as has been pointed out in Ref. 13.

In order to obtain further insight into the characteristics of the phenomenon, we also calculate the field distributions of

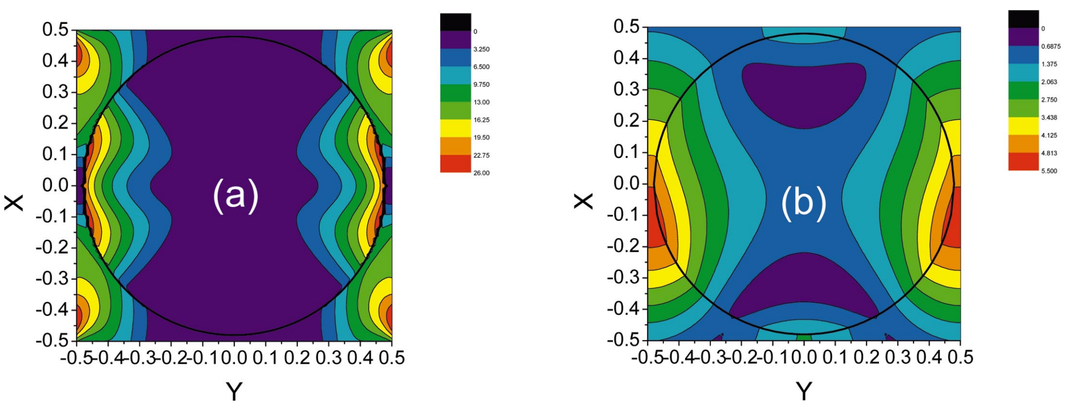

FIG. 4. (Color) (a) Intensity distribution of a pressure field (in arbitrary units) for an eigenstate in a unit cell at the band edge. (b) The magnitude of the transmitted pressure field (in arbitrary units) for the single-layer steel grating in an air background at the maxima point of transmission. The regions of field intensity are for one period, which corresponds to (a). The parameters are the same as in Fig. 3.

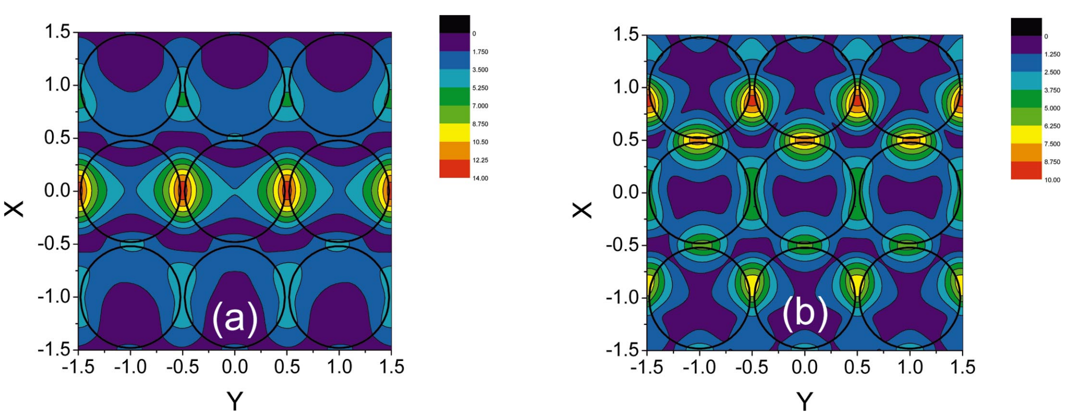

FIG. 5. (Color) (a) and (b) correspond to the distributions of the transmitted pressure field (in arbitrary units) at two maximum points of transmission for a three-layer grating, respectively. The regions of field intensity are for three periods for both cases. The parameters are the same as in Fig. 3.

the system. In the following, we will plot the pressure fields as Refs. 19 and 21 have shown, which is different from the cases of the displacement fields. For the displacement fields, they must exactly vanish inside the rigid cylinder. However, for the pressure fields, they do not vanish due to the continuity at the boundary of the cylinders. First, the intensity pattern of eigenmodes of the pressure field in a unit cell at $2X$ point of the band edge is plotted in Fig. 4(a), which corresponds to the peak of resonant transmission in the acoustic gratings. The corresponding transmitted field for the single-layer steel grating in the air background at the maxima point of transmission ($f \approx 1410$ Hz) is given in Fig. 4(b). Comparing them, we find excellent agreement, which means that the eigenmodes are actually excited. The properties of such excitation can be seen more clearly from the field distributions of the transmitted wave of the three-layer system. Figures 5(a) and 5(b) correspond to the three-layer cases at two maxima points (1462 Hz and 1666 Hz) of transmission, respectively. The fields are for three grating periods. That is to say, they are in an area of $3a \times 3a$ space around the center of the sample. It is interesting that two kinds of excitation mode, symmetric and antisymmetric, are observed clearly. The symmetric mode is shown in Fig. 5(a) where the excitation on the middle layer is strong, whereas, Fig. 5(b) corresponds to the antisymmetric mode with maxima on the top and bottom layers. For both cases, the transverse coupled resonant modes along the Y direction are demonstrated. These analyses imply that we should understand the origin of the extraordinary transmission from unified view instead of two separate mechanisms, which has been pointed out in Refs. 13 and 5.

In summary, we have performed an exact numerical simulation of the transmission behaviors of an acoustic wave through single-layer and multilayer acoustic gratings with very narrow slits. We have found that the transmission resonances for the wavelengths larger than the period of the grating exist in these systems similar to those of the optical subwavelength systems. These extraordinary transmissions for acoustic waves in the acoustic gratings may have important applications to ultrasonic devices. The physical origin of such a phenomenon has been analyzed, which the excitations of transverse, coupled resonant acoustic modes along the direction of grating period cause the resonant transmissions. Therefore, we can control such an extraordinary transmission of acoustic waves by tuning these transverse resonance modes.

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