CHIN. PHYS. LETT. Vol. 33, No. 4 (2016) 044302

Extraordinary Acoustic Transmission in a Helmholtz Resonance Cavity-Constructed Acoustic Grating *

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(Received 21 January 2016)

We investigate both experimentally and numerically a complex structure, where 'face-to-face' Helmholtz resonance cavities (HRCs) are introduced to construct a one-dimensional acoustic grating. In this system, pairs of HRCs can intensely couple with each other in two forms: a bonding state and an anti-bonding state, analogous to the character of hydrogen molecule with two atoms due to the interference of wave functions of sound among the acoustic local-resonating structures. The bonding state is a 'bright' state that interferes with the Fabry–Pèrot resonance mode, thereby causing this state to break up into two modes as the splitting of the extraordinary acoustic transmission peak. On the contrary, the anti-bonding state is a 'dark' state in which the resonance mode remains entirely localized within the HRCs, and has no contribution to the acoustic transmission.

PACS: 43.35.+d, 43.20.+g, 43.40.+s DOI: 10.1088/0256-307X/33/4/044302

Optical metamaterials have recently sparked broad interest in the scientific community, due to the expected fascinating physical effects and promising applications in various fields.[1–10] As a counterpart of optical metamaterials, myriad interesting phenomena have been discovered with studies of acoustic metamaterials recently, including negative refraction,[11–16] sub-diffraction limited acoustic focusing[17–19] and imaging,[20,21] acoustic cloaking,[22–26] topological protected[27–31] and PT symmetric[32–34] one-way transmission, as well as extraordinary acoustic transmission (EAT)[35–39] and the sound beaming associated with the excitation of acoustic surface evanescent waves (ASEWs).[40–43] In particular, the discovery of the EAT offers scientists a new approach to design and engineering the propagation of sound in sub-wavelength acoustic structures that can resonantly couple with the ASEWs. Hitherto, since the suggested structures are simply one-dimensional (1D) or two-dimensional (2D) acoustic gratings, there are only a few freedoms to manipulate the excited resonance and thus engineer more challenging acoustic devices based on the EAT or ASEWs. It is therefore necessary to investigate the acoustic metamaterials intrinsically consisting of periodically arranged local resonators.[19,39,44] In such a circumstance, the short range local resonance can be efficiently connected with the long range ASEWs. These couplings between the short and long range resonances are expected to drastically modulate the inherent dispersions of the acoustic metamaterial, thereby leading to promising applications.

In this Letter, we introduce a novel one-dimensional (1D) acoustic grating consisting of periodically arranged Helmholtz resonance cavities (HRCs) which typically support local resonances.[44] Analogous to the character of hydrogen molecule with two atoms, due to the interference of wave functions of sound among the acoustic local-resonating structures, two distinct acoustic states corresponding to different energy levels are formed: one is the bonding state which can be intensely coupled with the fundamental Fabry–Pèrot (FP) resonance within the apertures of the 1D grating, and the other is an anti-bonding state in which every HRC is entirely isolated from each other. This composite 1D acoustic grating as well as its resonance modes have been carefully investigated by both numerical and experimental efforts as follows.

First of all, the schematic diagram of a conventional 1D acoustic grating (made of photosensitive resin with mass density and elastic modulus equaling to 1.3 g/cm^3 and 2765 MPa, respectively) is illustrated in Fig. 1(a), in which w denotes the aperture width, d represents the period along the x direction, and t stands for the grating thickness. The corresponding transmission spectra of this acoustic grating are calculated by a finite element method (by using commercial software COMSOL multi-physics), as shown in Fig. 1(b), with different values of w, while keeping $d = 4.5$ mm and $t = 4$ mm as constants. It is clearly seen that when the aperture width is adjusted from 0.5 mm to 2.5 mm, the frequency width of the

*Supported by the National Basic Research Program of China under Grant Nos 2012CB921503, 2013CB632904 and 2013CB632702, the National Natural Science Foundation of China under Grant No 1134006, the Natural Science Foundation of Jiangsu Province under Grant No BK20140019, the Project Funded by the Priority Academic Program Development of Jiangsu Higher Education, and the China Postdoctoral Science Foundation under Grant Nos 2012M511249 and 2013T60521.

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extraordinary transmission peak is broadened while the position of peak shifts inconspicuously. This phenomenon occurs due to the fact that all the studied apertures with different widths act as a single mode waveguide and thus the acoustic modes inside these apertures share almost the same wavenumber,[43] indicating the independence of the FP resonance modes on the aperture widths. It is therefore highly desirable to introduce more resonant mechanism to reinforce the manipulation of the FP resonance within the aperture as well as other relevant effects, such as the EAT.

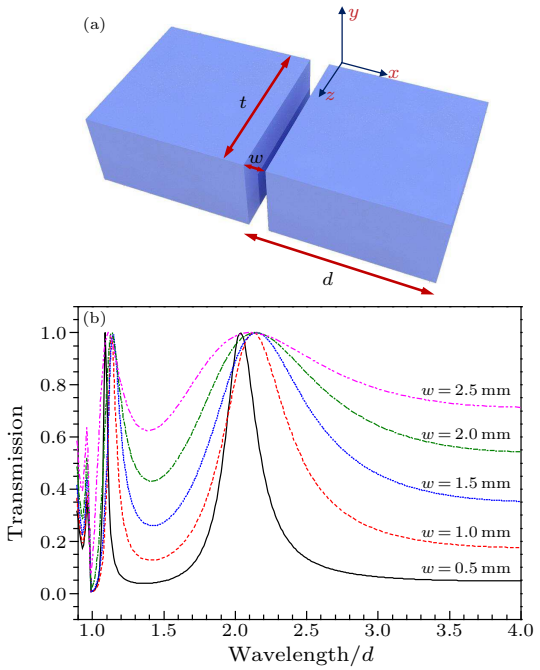

Fig. 1. (a) Illustration of the normal 1D acoustic grating, in which w denotes the aperture width, d represents the period along the x direction, and t stands for the grating thickness. (b) Calculated transmission spectra of the grating with different values of w, where $d = 4.5$ mm and $t = 4$ mm.

Our proposed 1D acoustic grating with the HRCs is demonstrated in Fig. 2(a), in which w denotes the aperture width, d represents the period along the x direction, t stands for the grating thickness, e, f, g and h refer to the detailed geometrical parameters as labeled. The practical sample of this composite acoustic grating is manufactured from photosensitive resin by using the stereo lithography technique, as shown in Fig. 2(b), in which $w = 0.5$ mm, $d = 4.5$ mm, $t = 4$ mm, $e = 1$ mm, $f = 0.75$ mm, $g = 2$ mm and $h = 0.5$ mm. In the experiment, the acoustic transmission spectra of this grating are measured by a measurement package of the 3560C Brüel & Kjær pulse sound and vibration analyzers. The transmission spectrum as a function of the sound-wavelength/grating-period (d) for normal incidence is shown in Fig. 2(c). The experimental results (black solid) agree well with the calculated results (red dashed) by the finite element method.

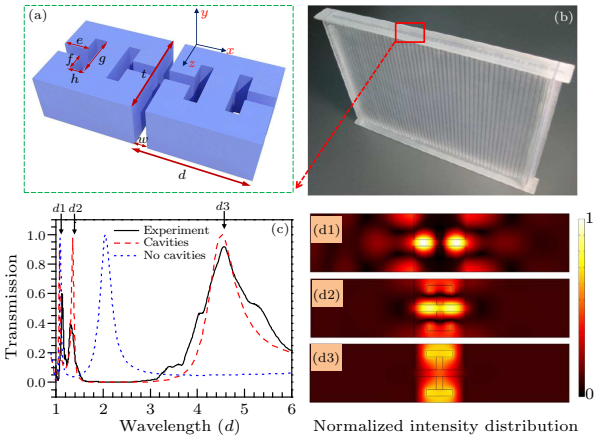

Fig. 2. (a) Illustration of 1D acoustic grating made of HRCs, in which w denotes the aperture width, d represents the period along the x direction, t stands for the grating thickness, e, f, g and h refer to the detailed geometrical parameters of HRCs. (b) The practical sample, for $w = 0.5$ mm, $d = 4.5$ mm, $t = 4$ mm, $e = 1$ mm, $f = 0.75$ mm, $g = 2$ mm and $h = 0.5$ mm. (c) Experimental (black solid curve) and numerical (red dashed curve) transmission spectra for the grating shown in (b). Blue dotted curve represents the numerical calculated transmission spectra for the grating without HRCs. (d) Spatial intensity distribution of the pressure field for the HRC grating at different wavelengths of $1.07d$ (d1), $1.355d$ (d2) and $4.51d$ (d3).

Distinguished from results without the HRC grating where only two transmission peaks were observed (blue dashed curve in Fig. 2(c), and black solid curve showing the experimental results from our previous work[43]), there exist three transmission peaks when we introduce an HRC grating in the measurement. The low-frequency resonant peak (with larger wavelength) of the original grating splits into two resonant peaks in the presence of HRC grating. However, the high-frequency resonant peak (with smaller wavelength) remains the same. This splitting is attributed to the dependence of the high-frequency resonant peak on the second-order FP resonance mode, which barely couples to the HRC modes and is of a low-frequency peak on the fundamental FP resonance inside the aperture, which can be strongly coupled to the HRC modes. To gain deeper insight into this phenomenon, we map the calculated distribution of the acoustic pressure fields around the HRC grating at the wavelengths of $1.07d$, $1.355d$ and $4.51d$ in Figs. 2(d1)–2(d3), respectively, corresponding to three different resonant transmission peaks. At the wavelengths of $1.07d$ (as shown in Fig. 2(d1)), periodic oscillation of the pressure field on the grating surface can be observed, and the acoustic fields are highly localized inside the aperture with negligible intensity inside the HRCs, suggesting the simultaneous excitation of the ASEWs associated with the second order FP resonance inside apertures. At the wavelengths of

1.355d (as Fig. 2(d2)), the ASEW could also be observed though not as evident as that in Fig. 2(d1). Inside the aperture, the acoustic field clearly demonstrates a character of the fundamental FP resonance as the acoustic energies are mainly localized inside the aperture with relatively small contribution inside the HRCs. This transmission peak arises due to the corporate coupling of the ASEWs, the fundamental FP resonance and the HRC resonance at the same time. At the wavelengths of 4.51d (as Fig. 2(d3)), it can be seen that the ASEWs completely disappear, and most of the acoustic energies are confined inside the HRCs with relatively weak coupling between the fundamental FP resonance and the HRC resonance, indicating a dominant local-resonant character.

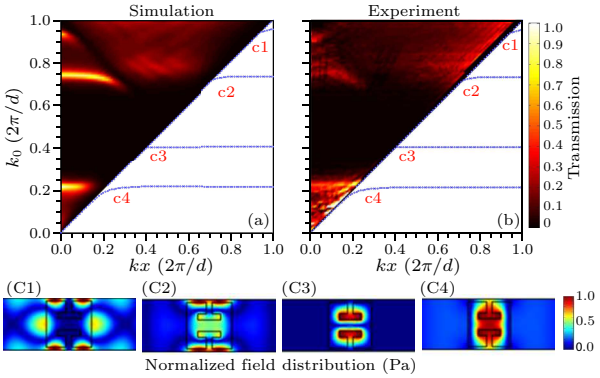

Fig. 3. Left part in (a) simulation and (b) experiment: transmission as a function of wave number k_0 and k_x. Right part in (a) and (b): dispersion for the 1D HRC acoustic grating. (c1)–(c4) Field distributions for resonant modes at $\frac{k_0 d}{2\pi}$ of 0.22, 0.40, 0.74 and 0.93, respectively.

To further investigate the EAT phenomenon associated with our proposed HRC grating, the dispersion relation of this periodic grating is calculated as shown in Fig. 3 (in both Figs. 3(a) and 3(b)) as the dependence of free space wave number k_0 on k_x, compared with the corresponding transmission spectra (as the thermal graph denotes in both Figs. 3(a) and 3(b) for simulation and experimental results, respectively). Here k_x is parallel to the grating surface and is set proportional to $\sin\theta$, where θ indicates the acoustic incident angle. Consistent with Fig. 2, there are three transmission peaks clearly observed at $k_x = 0$ (the situation of normal incidence), shown in the left part of Figs. 3(a) and 3(b). However, these three peaks present completely different angular dependencies: the resonance peak at $\frac{k_0 d}{2\pi} = 0.22$ ($\lambda = 4.51d$) is insensitive to angular variation, while the other two resonance peaks close to Wood's anomaly $\left(\frac{k_0 d}{2\pi} = 0.22 = 1\right)$ (Wood discovered in 1904: on many diffraction gratings narrow spectral regions showed sharp change of energy diffracted[45]) are strongly dependent on the incident angles. Red shift of these two peaks can be observed as the incident angle θ increases (which are not very obvious while still perceptible in the experimental results), suggesting the dominant role of the ASEWs on the surface of the 1D HRC grating. Here the wave vectors of the ASEWs can be expanded as $k_{xm} = \frac{2\pi}{\lambda}\sin\theta \pm mG_x$,[43] where $G_x = \frac{2\pi}{d}$ is the grating vector, and m is the order of the acoustic diffraction. The variation of the incident angle θ influences the features of the ASEWs as well as the coupling between the diffractive waves and the localized resonant modes (coupled FP and HRC resonances), which jointly affect the extraordinary transmission peaks.

The coupling between the diffractive modes and these localized resonance modes can be clearly indicated from the right parts of Figs. 3(a) and 3(b), which show a distinct anticrossing feature (crossing bands with modes in similar spatial symmetries interacted with each other, thus open an anti-crossing gap in the band structure[46,47]) between the linear air-line dispersion and the nearly flat dispersion of the localized resonance. This kind of coupling can result in a new 'polariton' with sub-wavelength acoustic surface dispersion (also called the ASEW[43]). Although three peaks can be observed in the transmission spectra, four eigenmodes exist in the dispersion of HRC grating, within the interested frequency range, at $\frac{k_0 d}{2\pi} = 0.22$, 0.40, 0.74 and 0.93, respectively. It is evident from the corresponding acoustic field distribution that the mode at $\frac{k_0 d}{2\pi} = 0.40$ is localized entirely for it presents an isolated energy distribution inside every individual HRCs, without being coupled to the FP mode supported by the apertures. Therefore, this resonant mode shows no radiation efficiency and is strongly localized due to its effective negative modulus[44] and its large impedance mismatch, leading to the negligible sound transmission. Intuitively, the unit cell of our HRC grating consisting of two cavities acts similarly to the hydrogen molecule with two atoms, possessing both the bonding and anti-bonding eigen states. In the anti-bonding state, wave functions of the acoustic fields are localized and isolated in the individual HRC and there is hardly any coupling between each other or with the FP mode inside the aperture, like the mode at $\frac{k_0 d}{2\pi} = 0.40$. This kind of anti-bonding state can be referred as a 'dark' state or a deaf mode[48,49] that cannot directly couple with free space radiation. However, in the bonding state, there exists a coupling between the acoustic fields in two HRCs creating unified resonant modes that interfere with the fundamental FP modes as well. Recently, this quantum analog (energy levels) has brought great scientific impact into the field of acoustic metamaterial from acoustic Zeeman effects in moving media,[32] acoustic Raman scattering,[51] and quantum spin Hall effect for acoustic topological insulators.[27–31] The interference with the FP modes results in a mode split

and the acoustic fields are consequently more localized in either the HRCs or the grating apertures, showing one symmetric and one anti-symmetric mode at different frequencies: $\frac{k_0 d}{2\pi} = 0.22$ and 0.74, respectively. Both the modes are referred to as the 'bright' states that can contribute to the EAT.

In conclusion, we have proposed an acoustic grating made of HRCs and investigated its corresponding ultrasonic properties. Within this composite structure, pairs of HRCs strongly couple with each other by either a bonding state or an anti-bonding state, similar to the behavior of hydrogen molecule with two atoms. The dispersion of this acoustic HRC grating further reveals that the bonding state can strongly interfere with the ASEWs as well as the incident acoustic field via the FP resonance supported by the grating aperture, hence demonstrating a transmission peak in the spectrum (therefore it is called the 'bright' state). However, the anti-bonding state is highly confined in the HRCs and is completely isolated to the FP resonance, showing a zero transmission character (therefore anti-bonding state is called the 'dark' state). It is expected to realize the acoustic counterpart of electromagnetically induced transparency[50] if the 'bright' and 'dark' resonant modes in the proposed HRC grating are carefully engineered. These effects may have potential applications in ultrasonic device design such as acoustic microscope, superlens,[19] hyperlens,[20] acoustic filters, acoustic collimators, and compacted acoustic devices with sub-wavelength.

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