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Nonleaky surface acoustic waves on a textured rigid surface

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Through a systematic theoretical analysis, we find that coarse corrugations textured on rigid surfaces are preferred to realize highly confined surface acoustic waves over a broad frequency range. To give a direct validation for the existence of the nonleaky surface waves, we have experimentally measured the dispersion relation. The experimental result agrees excellently with the theoretical one. Extensive applications of such artificial surface waves can be predicted because of the flexibility in design.

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After the discoveries of the optic transmission enhancement and directional beaming effect through two-dimensional arrays of subwavelength metallic structures,[1,2] the physical origins of these extraordinary wave phenomena have sparked extensive discussions due to the rich physics and potential applications.[3–5] Near the visible frequency region, it is now widely accepted that the resonant excitation of surface plasmon polaritons (SPPs) on metallic surfaces plays an important role. Parallel studies have been extended into acoustic systems and similar phenomena have also been observed.[6–12] Besides the perforated *hard* plates[6–8] where the individual cavity modes as well as the collective couplings among them are responsible for the acoustic transmission enhancement, the *elastic* plate structures have also been investigated, in which the resonant excitation of the intrinsic plate modes[10,11] and surface acoustic waves (SAWs)[12] results in the exotic transmission response.

It is well known that a planar interface between two semi-infinite homogenous media may sustain SAWs,[13] such as Stoneley surface waves. In the past few years, the SAWs created in periodically corrugated surfaces have aroused great attention due to the additional degrees of freedom in design.[14–17] Recently, it has been reported that even in the perfectly conducting limit, the metal textured with subwavelength structures can also support strongly localized surface waves.[18–20] Unlike regular surface waves, the dispersion of such electromagnetic surface waves (frequently referred to as "spoof" or "designer" SPPs) depends greatly on the geometrical parameters of the structure. The "designer" SPPs in such electromagnetically rigid systems have an acoustic counterpart as well. By using a finely textured rigid plate, Christensen *et al.*[21] have theoretically studied the acoustic transmission enhancement associated with the beam collimation effect. A similar system is further discussed in the experiment by Zhou *et al.*[22] However, the "designer" SAWs (DSAWs) involved in their work are leaky and hence, at least in some sense, not true surface waves. In this Brief Report, we aim at designing a rigid surface structure that supports highly confined DSAWs and validate such nonleaky surface waves by experimentally measuring the dispersion relation of the system.

In fact, the geometry-induced DSAWs have already been studied by a modal model two decades ago.[23] To obtain a direct understanding of such kinds of SAWs, by using the modal model we have calculated the dispersion relations for the rigid surface corrugated with a one-dimensional (1D) periodical array of rectangular grooves. Figure 1 shows the numerical results for the systems with different geometric parameters, with p, w, and h being the period, width, and depth of the rectangular grooves, respectively. Here the horizontal axis denotes the wave vector of the surface wave k_s, and the vertical axis represents the wave vector of the background k_0 (which corresponds to frequency), respectively. It is observed in Fig. 1(a) that for a finely textured system, for example, $w = h = 0.1p$ (red solid line, the situation considered in Ref. 22), the dispersion curve is extremely close to the background one (black dashed line), indicating a character of weak surface localization. The deviation becomes remarkable as the groove depth increases. In addition, for the deep groove case (e.g., $h = 1.5p$, blue dash-dotted line) the dispersion curve separates into many branches. The phenomena can be well understood since the DSAWs result from the coupling among the acoustic waves localized in the cavities. As the resonant frequency of the cavity modes ($k_0 h = n\pi/2$, with n being the odd number) approached, the resonance effect of the individual cavity becomes striking, and hence the dispersion curve is flattened and deviates considerably from the background one; the deviation reduces as the frequency goes gradually away from the cavity resonance, where the collective coupling takes a dominant role. The crossover between the two situations is determined by the groove width: the wider the cavity is, the broader the crossover is induced by the stronger coupling among the cavities. The broadened crossover also accompanies a large deviation of the band edge frequency from the predicted cavity resonance (see the horizontal black dotted line). This is manifested by the dispersion curves in Fig. 1(b) for the systems with identical groove depths but different groove widths. Therefore, the rigid surface corrugated with deep and wide grooves (with respect to the period) is preferred to realize the highly confined DSAW over a broad frequency range (with respect to the resonance frequency of the first cavity mode). Note that we aim at the nonleaky DSAW and thereby only consider the dimensionless frequency below $k_0 p/2\pi = 0.5$, above which the DSAW turns leaky because of the band-folding effect induced by the periodicity of the surface structure. The leaky case has been discussed in Refs. 21 and recently.

To validate the existence of the highly confined DSAWs, we have experimentally measured the dispersion relation for a coarsely textured rigid surface. As schematically illustrated in

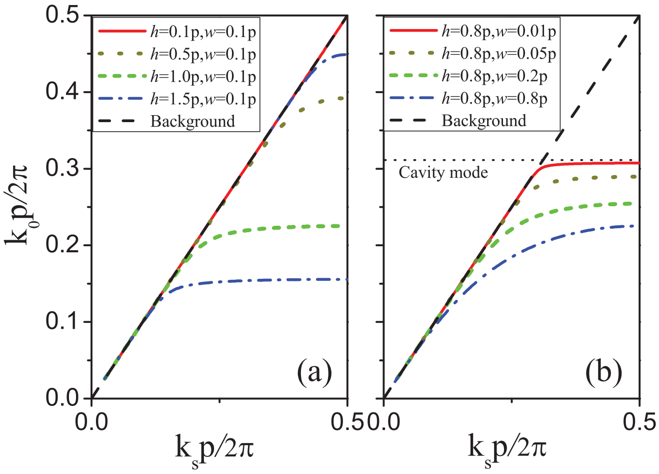

FIG. 1. (Color online) Dispersion curves for the systems made of rigid surfaces textured with a 1D periodical array of rectangular grooves, where p, w, and h are the period, width, and depth of the grooves. The horizontal black dotted line in Fig. 1(b) denotes the frequency predicted by the first cavity mode for the given groove depth.

Fig. 2(a), our sample is made of an air-surrounded epoxy plate textured with a 1D periodical array of rectangular grooves (along the x direction), where the total plate thickness $t = 1.7$ cm, the structural period $p = 2$ cm, the width $w = 1.2$ cm, and the depth $h = 1.2$ cm for the grooves. The total length and width of the sample are 80 cm (thus covering 40 periods) and 15 cm, respectively. For the convenience of description, we define $x = 0$ in the middle of the sample along the horizontal direction and $z = 0$ on the top of the gratings [see Fig. 2(a)]. Considering the great mismatch of the acoustic

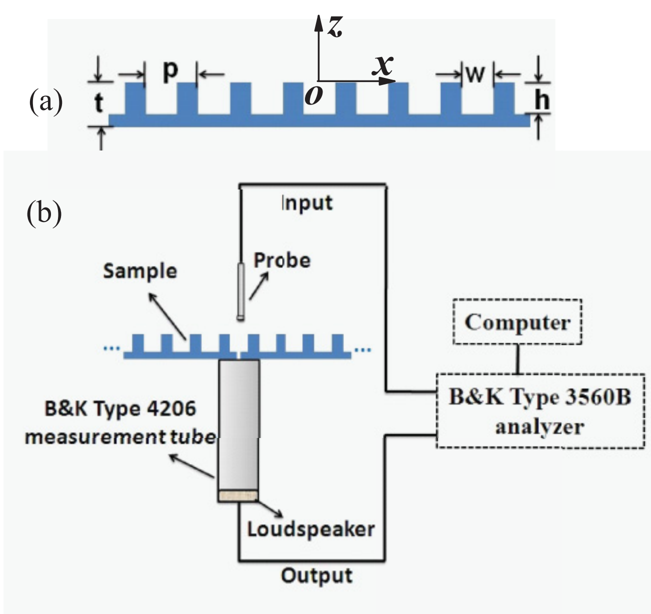

FIG. 2. (Color online) Schematic illustrations for (a) the sample consisting of an air-surrounded epoxy plate textured with a 1D periodical array of rectangular grooves along the x direction, with the geometric parameters given in the text, and (b) the experimental setup used for scanning the pressure field.

impedances between the epoxy and air, the structured plate can be viewed as a perfectly rigid body. Our experimental setup is illustrated in Fig. 2(b). The unstructured surface of the sample is closely glued on the exit of the impedance/transmission loss measurement tube (B&K Type 4206) with diameter 10 cm. A slit of width 0.2 cm, which is much smaller than the wavelength under consideration, is opened in the middle (i.e., $x = 0$) of the finite sample. The acoustic signal transmitted through the narrow slit resembles a line source and can excite the DSAW if it indeed exists. The distribution of the pressure field behind the sample can be scanned by a probe microphone (B&K Type 4187) of radius 0.32 cm. The acoustic signals sent from the measurement tube and received by the probe microphone are analyzed by a multianalyzer system (B&K Type 3560B). The experimental measurement is performed within the frequency range of 1–10 kHz, corresponding to a wavelength region of 3.4–34 cm.

In Fig. 3(a) we present a typical near-field pressure distribution measured at the frequency 4.78 kHz (corresponding to the dimensionless frequency $k_0p/2\pi \simeq 0.274$). Considering the symmetry, we only provide the data on the side of $x > 0$. One observes that the pressure field decays quickly away from the sample, mimicking the behavior of the intrinsic SAWs on a flat interface (e.g., Stoneley surface waves). This new type of surface waves (i.e., DSAWs) is believed to be created by the textured structure since the flat rigid surface itself prohibits any

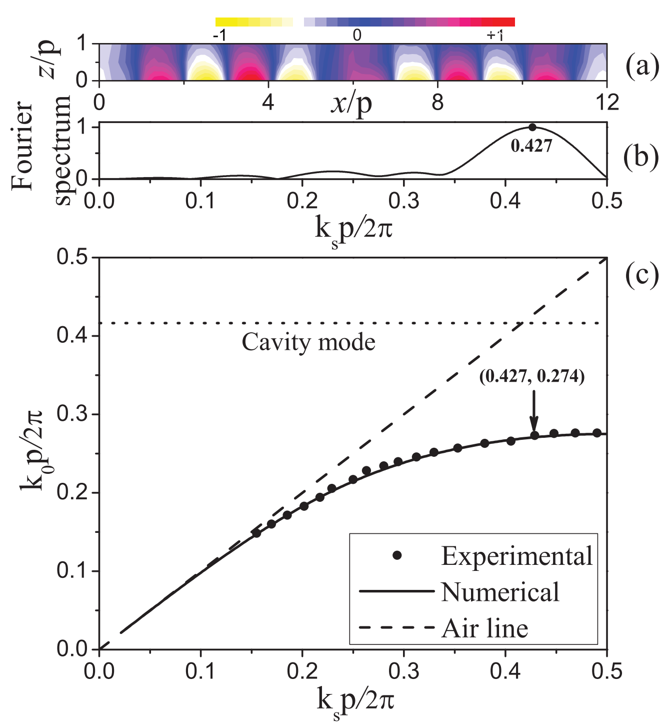

FIG. 3. (Color online) (a) A typical pressure field distribution measured around the structured surface at the dimensionless frequency $k_0p/2\pi \simeq 0.274$. Here the pressure is normalized by the maximum of the pressure amplitude. (b) The 1D Fourier transformation spectrum of the pressure for $z = 0$. (c) The experimental dispersion curve (circle) for the sample, compared with the numerical result (solid line) and the air line (dash line), where the horizontal dotted line denotes the frequency predicted by the first cavity mode.

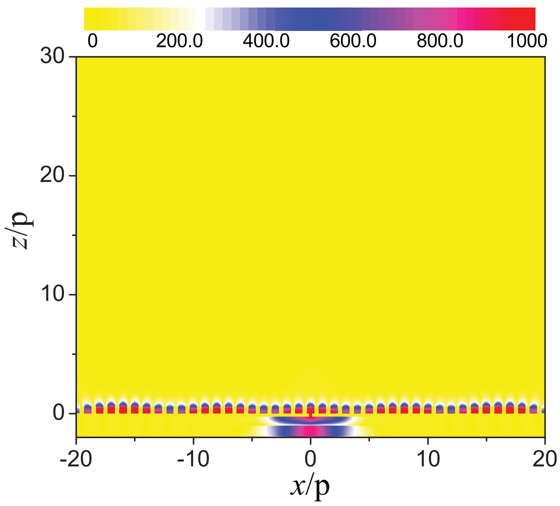

FIG. 4. (Color online) The numerical far-field distribution of the pressure amplitude (in arbitrary units) at the dimensionless frequency $k_0 p/2\pi = 0.274$.

SAW. To obtain the wave vector of the DSAW k_s for the given frequency, we implement a 1D Fourier transformation along the x direction for the near field. Figure 3(b) shows the result for $z = 0$. The position of the leading peak in the Fourier spectrum gives a good estimation for k_s ($k_s p/2\pi \simeq 0.427$), ignoring the broadening induced by the finite size effect. Repeating the process for different frequencies, we can obtain the dispersion relation of the sample, as shown by the circle in Fig. 3(c). It agrees excellently with the numerical result (solid line). Both dispersion curves lie below the air line and exhibit a general feature of the nonleaky surface waves.

Although strong near-field enhancement has also been observed in similar rigid structures, see Refs. 21 and 22, the far-field radiation property differs from the current situation due to the essentially different physics involved. In those works, the dimensionless frequency focused is above $k_0 p/2\pi = 0.5$, where the related DSAW must be leaky; in particular, when the frequency approaches $k_0 p/2\pi = 1$, the leaky DSAW at wave vector $k_s = 0$ is resonantly excited by the acoustic wave emitted from the narrow slit, associated with a striking directional beaming effect along the normal direction of the structure. In our case, however, the DSAW is nonleaky and thereby it can only be excited in an evanescent way. To verify this, we have conducted the finite-difference time-domain method to obtain the far-field pressure distribution by launching a Gaussian beam normally onto the sample at the dimensionless frequency $k_0 p/2\pi = 0.274$. As displayed in Fig. 4, the pressure amplitude decays quickly away from the structure surface.

In summary, with geometric parameters carefully engineered, the highly confined nonleaky DSAWs can be created on a coarsely textured rigid surface. The existence of such surface waves has been validated experimentally by measuring the dispersion relation. Compared to the regular nondispersive Stoneley surface wave[13] that arises from the contrast of the material properties between the constituent ingredients, the dispersion of the DSAW can be well designed by the geometric parameters of the textured structure. This merit endows the DSAWs with potential applications, such as in acoustic integrated devices or in ultrasonic detection devices.

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