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Local resonances in phononic crystals and in random arrangements of pillars on a surface

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The propagation of surface acoustic waves in two-dimensional phononic crystals of pillars on a surface is investigated experimentally for hexagonal and honeycomb lattice symmetries. A random array of pillars is also compared to the periodic phononic crystals. Taking into account that the geometrical and physical characteristics of the pillars are the same in all cases, it is shown that the locally resonant band gap in the low frequency range is almost independent of periodicity and resilient to randomness. In contrast, the Bragg band gap disappears with the random array. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4820928]

During the last decades, a great deal of effort has been made to achieve control of acoustic wave propagation within periodic structures. Unlike inside homogeneous media, in which they travel with the same velocity regardless of frequency, acoustic waves inside periodic media can be strongly slowed down or prohibited to propagate within frequency band gaps, thanks to the adequate choice of the physical and geometrical properties of both scatterers and host matrix.[1] The so-called phononic crystals can therefore play the role of perfect mirrors, filters, collimators, and lenses. Further functionalities such as waveguiding or trapping of the acoustic energy in high-Q resonators can be readily obtained using linear or isolated defects, respectively.[2,3] There are two main physical mechanisms at the origin of phononic band gaps: Bragg interference of scattered waves and hybridization of local resonances. In the former case, a strong impedance mismatch between inclusions and host matrix is usually required to build broad acoustic band gaps. Furthermore, a well-controlled periodic arrangement must be considered to obtain destructive interference: the effect is coherent and the precise distance between two neighbouring scatterers conditions, the band gap characteristics. In the latter case, band gaps open up as a result of hybridization of the local resonances of each individual unit cell with the continuum modes of the host matrix.[4–8] Therefore, the inclusion in the unit cell is no longer considered to be scatterer, but rather a resonator. It has been demonstrated that local resonances can be excited even when the wavelength is quite long compared to the period. The ratio of these distances can even attain several orders of magnitude. Whenever neighboring resonators have a small crosstalk, locally resonant band gaps are expected to depend weakly on periodicity or on the direction of propagation. In addition to presenting band gaps, resonator arrays can form acoustic metamaterials, that is, homogenized artificial materials exhibiting unprecedented functionalities not yet found in nature, such as negative mass density, negative moduli, or negative refractive index. Acoustic metamaterials hence greatly broaden the ways of handling acoustic waves.

In this letter, we examine experimentally the resistance to lattice symmetry and randomness of the locally resonant band gap of a phononic crystal of pillars sitting on a semi-infinite substrate. A similar system was considered by the same authors previously,[9] but in the square-lattice periodic arrangement, for which a locally resonant and a Bragg band gap could be observed and characterized. Here, the locally resonant band gap is shown to remain almost unchanged for a triangular-lattice, a honeycomb-lattice, and even a randomly distributed array of pillars.

Micro-fabricated phononic crystals operating in the hundreds of MHz to the GHz range are interesting for radio-frequency signal processing.[10] Phononic crystal for surface acoustic waves have been demonstrated by drilling holes in a solid substrate.[11–13] Phononic crystal slabs defined by etching holes in free-standing membranes have also been put forward because their finite dimension in the third direction provides natural confinement of the energy of Lamb waves.[14–18] Hollow inclusions are efficient scatterers that lead to the appearance of Bragg band gaps; they do not support, however, local resonances. Recently, a particular attention has been brought to the propagation of guided waves in periodic structures of pillars.[9,19–22] It was demonstrated theoretically and experimentally that such structures exhibit locally resonant band gaps at the low frequency regime that can be tuned by changing the physical and geometrical features of the pillars. It is, however, worth noting that coupling between guided waves in the matrix and the resonances in the pillars differs in the case of surface (Rayleigh) waves and membrane (Lamb) waves. Because of flexural motion in membranes, coupling between adjacent pillars is always rather strong. As a result, locally resonant band gaps for Lamb waves depend on the lattice symmetry.[23] In contrast, a semi-infinite substrate is much stiffer, resulting in potentially less coupling between adjacent pillars. It was shown theoretically that the locally resonant band gap is almost independent of the symmetry of the lattice.[24]

In the experimental setup depicted in Figure 1, a pair of identical wide-bandwidth chirped interdigital transducers are

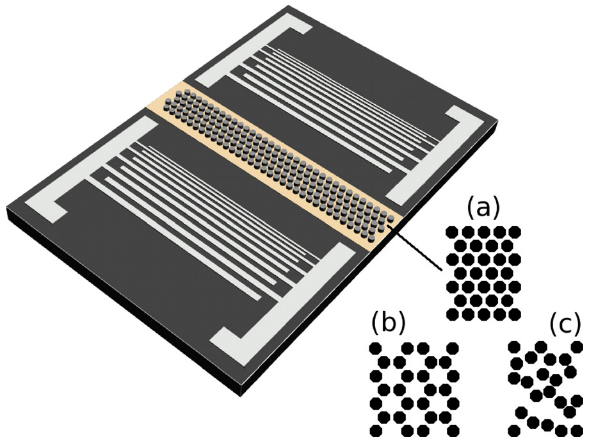

FIG. 1. Schematic of the experimental setup used for investigating the propagation of surface phonons in a periodic array of pillars on a semi-infinite substrate. The nickel pillars shown as an inset have a radius of 3.2 μm and a height of 4.7 μm. They are arranged according to a square lattice with a pitch of 10 μm. Two chirped interdigital transducers generate and detect surface phonons thanks to the piezoelectric properties of the lithium niobate substrate. The yellow color under the pillars represents the thin copper film used to insure electrical contact during the electroplating process necessary for pillar growth.

placed on both sides of an array of pillars. Rayleigh surface acoustic waves are launched and detected using the piezoelectric properties of the substrate. We choose a Y + 128 rotated lithium niobate ($LiNbO_3$) wafer and consider propagation along the X-crystallographic direction, in order to obtain both high piezoelectric coupling and absence of leaky surface acoustic wave generation. The pillars are 4.7 μm high and have a radius of 3.2 μm. Pillar fabrication was described in Ref. 9. Both triangular and honeycomb phononic crystals have a pitch $a = 10\,\mu$m. The random array of pillars was generated from the honeycomb array by randomizing the position of each pillar following a uniform distribution. It obviously possesses no symmetry. It has been shown that the height of the pillars is the main factor conditioning the position of the locally resonant band gap, while the Bragg band gap position is mostly determined by the pitch of the periodic array.[21] In particular, the higher the pillars, the lower the LR band gap frequency. We chose the height of the pillars so that the LR band gap is markedly lower than the Bragg band gap, in order to avoid any confusion between the two effects.

Electrical transmission measurements are shown in Figure 2 for the different samples. Transmission in the absence of pillars, displayed in Figure 2(a), characterizes the response of the delay line as given by Rayleigh surface acoustic waves propagating freely on the surface and serves as a reference. The bandwidth of the transducer pair extends from 65 MHz to 130 MHz, with a dynamic range in excess of 30 dB. Transmission through the triangular-lattice PC is shown in Figure 2(b). This transmission is close to the reference transmission for frequencies ranging from 65 MHz to 75 MHz and from 90 MHz to 130 MHz. Outside these ranges, a dip reaching an extinction ratio of about 20 dB at 80 MHz is identified. It is worth noting that the square-lattice PC of pillars investigated in Ref. 9 gave rise to a LR band gap in the same frequency range.

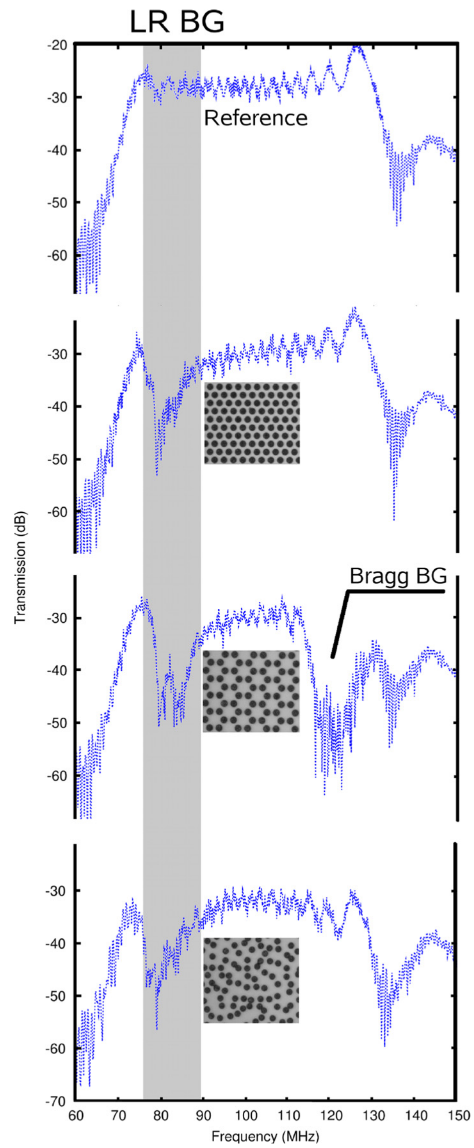

FIG. 2. Measured electrical transmission S_{12} as a function of frequency for (a) a pair of chirped interdigital transducers (IDTs) operating in a delay line configuration without PC, hence serving as a reference, (b) with a triangular lattice PC, (c) with a honeycomb lattice PC, and (d) with a randomly distributed pillar array. The grey region represents the common position of the locally resonant band gap. Optical microscope images of each pillar array are shown as insets.

Transmission through the honeycomb-lattice PC in Fig. 2(c) also reveals a dip around 80 MHz, immediately followed by a second dip of similar depth around 85 MHz. As a possible explanation, we point at the coupling mechanisms at play here, that combine both hybridization and cross-talk effects resulting from an evanescent coupling between adjacent resonators. We will suppose for the sake of simplicity that the pillars are all identical, therefore, showing the same intrinsic resonance frequency. In the case of sufficiently spaced resonators, the hybridisation mechanism alone should in principle result in the appearance of a well-defined, narrow resonance with a frequency that is only determined by the coupling of the modes of the resonators to the surrounding continuum. Cross-talk between resonators results in a splitting, with a frequency shift, of this resonance: in an infinite,

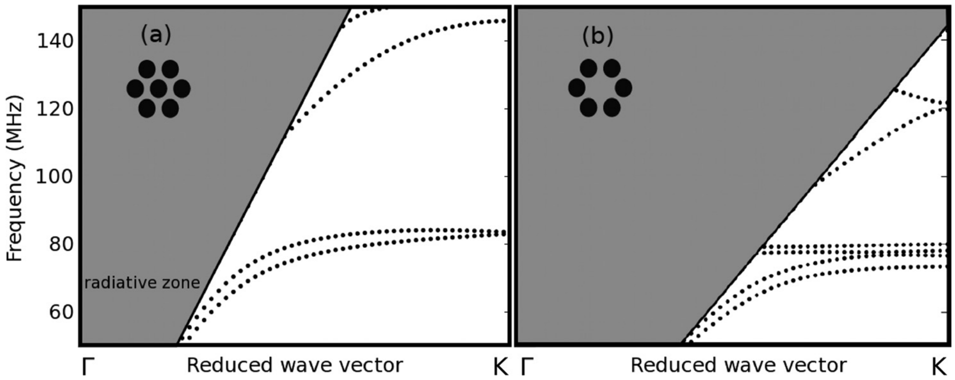

FIG. 3. Band structure of a periodic array of nickel pillars on a lithium niobate substrate computed using a finite element method along ΓK of the highest symmetry directions of the first Brillouin zone. The array is arranged according to (a) triangular and (b) honeycomb lattices with a pitch $a = 10\,\mu$m. The radius of the pillar is $r = 3.2\,\mu$m and the height is $h = 4.7\,\mu$m. The grey region indicates the radiative region, or sound cone of the substrate.

random array, the resonances would form a continuum with a frequency spread directly dependent on the coupling strength range. Coming back to the measurements reported here, in the case of a square or a triangular lattice, where the spacing between resonators is constant and equal to a, a single dip appears, though it is in the case considered here even more broadened by the dispersion in pillar height. Now, in the case of a honeycomb lattice, neighboring pillars are separated by either a or $\sqrt{3}a$ in the first approximation. We thus may attribute the existence of a system of two dips in the honeycomb case to this symmetry breaking. Furthermore, another band gap is identified in Fig. 2(c) between 110 MHz and 125 MHz. This is the first Bragg band gap, that here, in contrast with the case of the square[9] and the triangular lattices, appears within the bandwidth of the chirped IDTs. The period of the honeycomb PC is indeed $\sqrt{3}a$, whereas it is a for both the square and the triangular PC, hence leading to a Bragg band gap appearing at lower frequency.

We present in Figure 3, the numerical calculations performed using the finite element method of the band structure for surface acoustic waves in the triangular and honeycomb lattices. Anisotropy and piezoelectricity of the host matrix were taken into account. The radiative zone is indicated with the grey sound cone limited by the dispersion of the slowest bulk wave propagating in the substrate. Since surface acoustic waves propagate with velocities lower than bulk waves, the expected surface guided modes are supposed to be observed outside the radiative region. For frequencies well below 80 MHz, the presence of the pillars does not affect significantly the propagation of surface acoustic waves and this latter travel at Rayleigh velocity. When the resonance is reached, guided modes are slowed down leading to the occurrence of locally resonant band gaps. We can see clearly that the position of the band gap doesn't depend on the lattice symmetry. However, because of considering two pillars in honeycomb unit cell, the surface acoustic energy is split leading to a degeneracy lifting and the showing of further flat bands. Moreover, the lattice symmetry remains important to control the dispersion and to build further band gaps. Indeed, close to 120 MHz, surface guided modes propagate in the dispersive triangular lattice but are prohibited to propagate in the honeycomb.

In order to confirm the independence of the position of the LR band gap with periodicity, we also considered the case of randomly distributed pillars on the surface. The transmission in Fig. 2(d) again shows a clear dip around 80 MHz. This dip is more uniformly distributed in frequency than the one observed with periodic phononic crystal samples. This observation is in accordance with the former phenomenological discussion of hybridization, if one considers that the distance between pillars and hence their coupling is randomly distributed.

We plot in Fig. 4, the transmission for three randomly arranged pillar arrays with different heights, but with the same radius and an identical spatial distribution. It is clear that the LR frequency band gap shifts as a function of the height, changing from 80 MHz for $h = 4.7\,\mu$m to 95 MHz for $h = 4.1\,\mu$m, and to 110 MHz for $h = 3.5\,\mu$m. The LR frequency times pillar height roughly follows the law $fh \approx 380\,$m/s. Consequently, by creating random arrays of pillars on the top of a flat surface with a graded variation of the LR frequency, broad band gap structures could, in principle, be achieved.

In summary, we have investigated experimentally the propagation of surface acoustic waves in phononic crystals of pillars on a surface with different lattice symmetries, but also in random arrays of pillars. It is found that surface acoustic waves are prohibited to propagate in a locally resonant frequency band gap that is mostly dictated by the height of the pillars, and thus can be made significantly lower than the Bragg band gap. Furthermore, in contrast to Bragg band gaps, the locally resonant frequency band gap does not depend on the lattice symmetry and is strikingly resilient to randomness

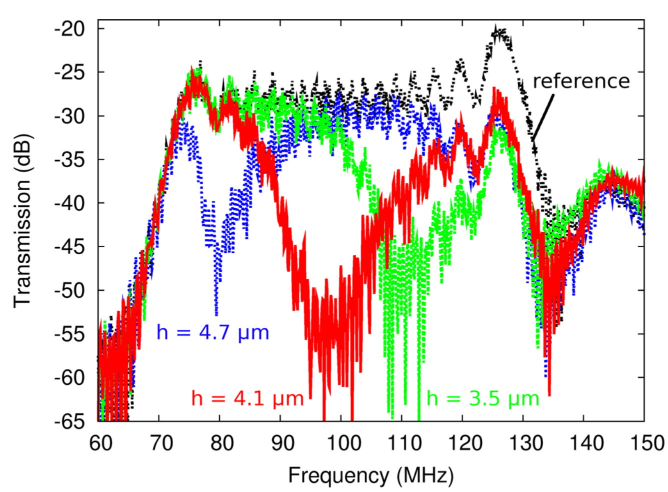

FIG. 4. Measured electrical transmission S_{12} as a function of frequency for chirped interdigital transducers (IDTs) operating in a delay line configuration without (reference in black dotted line) and with randomly distributed pillar arrays with different heights (4.7 μm in blue, 4.1 μm in red, and 3.5 μm in green).

of the pillar positions. These observations suggest a practical way to prohibit surface acoustic wave propagation by placing random arrays of pillars on the surface, where the overall band gap can be tuned by grading the LR frequency of each pillar. Applications to acoustic wave filters as well as to phononic crystal sensors, for instance, can be foreseen.

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