Manipulation of mechanical motion at the micro-scale has been attracting continuous attention, leading to the successful implementation of various strategies with potential impact on classical and quantum information processing. We here propose an approach based on the interplay between a pair of localized mechanical resonators and travelling surface acoustic waves (SAW). We demonstrate the existence of a two-sided interaction, allowing to use SAW to trigger and control the resonator oscillation, and to manipulate the elastic energy distribution on the substrate through resonator coupling. Observation of the vectorial structure of the resonator motion reveals the existence of two coupling regimes, a dipole-dipole-like interaction at small separation distance versus a surface-mediated mechanical coupling at larger separation. These results illustrate the potential of this platform for coherent control of mechanical vibration at a resonator level, and reciprocally for manipulating SAW propagation using sub-wavelength elements.

The micromechanical resonators used in this study and depicted in Figure 1 are fabricated using ion-beam induced deposition (IBID) out of a platinum metal-organic precursor on a lithium niobate substrate. They consist in cylindrical pillars with a diameter of 4.4 μm and a height of about 4 μm, taking note that an uncertainty on the pillar dimensions of the order of 3 to 4% is to be expected, given the accuracy of both the fabrication process and the scanning electron microscope imaging (SEM) capabilities. The piezoelectricity of the supporting material is exploited to achieve all-electromechanical harmonic coupling. Observation of the vectorial nature of the interaction reveal an unexpected coupling scheme that can be tuned from near-field-like coupling to sheer surface-mediated mechanical coupling. Hybridization of the traveling surface wave with the resonating pillars also results in the possibility to manipulate the elastic energy distribution at the substrate surface. These results, obtained at room temperature and ambient pressure, illustrate the potential of the proposed platform for the coherent and highly-localized control of mechanical vibrations.

The control of mechanical vibrations in mesoscopic objects has a long-lasting and fruitful history in the context of classical physics. In recent years, the suggestion that the very same systems could serve as a basis for investigation of quantum-related effects has been gaining momentum. Nanomechanics, optomechanics, quantum acoustics are fields of growing interest from fundamental as well as practical perspectives, with highlighted applications to sensing [1–3] or to information processing [4–7]. The development of such complex mechanical architectures requires an exquisite engineering of, and a control over, the vibration properties of the mechanical resonators at play. This entails, amongst other, coherent control of their oscillations [8, 9], fine-tuning of their coupling characteristics to other mechanical systems or to other physical degrees of freedom [10–12], or control over dissipative and non-linear effects [13, 14]. Several works report on successful implementation of coherent manipulation of the mechanical features of micro- or nano-systems, based on coupling induced by effects as diverse as sheer mechanical coupling, radiation-pressure, stress or strain-mediated coupling, within the frames of linear or non-linear interactions [15–18]. The combination of different resonators in addition allows considering a scaling up of the underlying principles to resonator arrays, and hence to processing systems with a higher level of elaborateness [19–22]. Recently, the vibration of the surface of a supporting substrate itself has been considered as a potential vector for quantum information transport, an idea that has come true in classical bulk or surface acoustic wave devices cooled down to cryogenic temperatures [23–29]. In this context, we propose to highlight the capability of a hybrid platform merging SAW and coupled mechanical resonators allowing in a reciprocal manner to coherently control the resonator motion and to manipulate surface acoustic wave (SAW) propagation at a sub-wavelength scale. Partly inspired by plasmon hybridization and coupling mechanisms [30–32], we explore a coupling process involving the first flexural modes of two mechanical resonators excited by SAW impinging at different incidence angles. We first investigate an experimental system mimicking the behavior of plasmonic nanoparticle dimers by adopting a small separation distance between the mechanical resonators. Direct imaging of the vectorial nature of the interaction reveal an unexpected coupling scheme that can be tuned from near-field-like coupling to sheer surface-mediated mechanical coupling. Hybridization of the traveling surface wave with the resonating pillars also results in the possibility to manipulate the elastic energy distribution at the substrate surface. These results, obtained at room temperature and ambient pressure, illustrate the potential of the proposed platform for the coherent and highly-localized control of mechanical vibrations.

Coherent interplay between surface acoustic waves and coupled mechanical resonators: from plasmon-like to surface mediated coupling

Laetitia Raguin, Olivier Gaiffe, Roland Salut, Jean-Marc Cote, Valérie Soumann, Vincent Laude, Abdelkrim Khelif and Sarah Benchabane

Institut FEMTO-ST, CNRS, Université de Bourgogne Franche-Comté
15B Avenue des Montboucons, F-25030 Besançon Cedex, France

scanning interferometry provides extensive information...
on the device response under coherent harmonic drive.

The frequency response of a single, isolated microresonator subjected to an incident Rayleigh wave is first investigated as a reference. It exhibits a Lorentzian line shape, as shown by the data reported in Figure 1. The resonance is centered at a frequency of 70.54 MHz, a value that corresponds well to the computed eigenfrequency value for the first flexural mode of the resonator. The quality factor is about 35, leading to a quality factor - frequency ($Q - f$) product of the order of $10^9$. The unavoidable geometrical asymmetries in resonator shape and clamping conditions are low enough to result in an inability to observe a degeneracy lifting of the two mechanical polarization of the first flexural mode at such $Q$-factor levels. The nature of the vibration is confirmed by the experimental field map taken at resonance and depicted as an inset. The displacement field along the $z$-axis reaches an amplitude as high as 16 nm, for an impinging surface wave amplitude smaller than 1 nm. The resonator is therefore set into vibration by the hybridization of the propagating impinging surface wave with a pillar eigenmode. This, along with the strong localization of the elastic energy at the pillar vicinity and the dipolar characteristics of the first flexural mode make this system bear a striking resemblance to plasmonic nanoparticles. The eigenmode orientation, here with a nodal line making a $\pi/4$-angle with respect to the impinging wave vector, remains the same over the entire pillar response frequency range. It however should be noted that excitation of different isolated pillars exhibiting the same geometrical characteristics led to vibrations either along the incident wave vector, or at the orthogonal or diagonal directions. It is then assumed that the incident wave vector forces a preferential vibration axis for the cylindrical resonator, although this latter remains free to vibrate on one of its two degenerate eigenmode or on a combination of the two orthogonal polarizations.

Resonator-to-resonator coupling is then investigated in pillar pairs fabricated through a parallel IBID-growth process to reduce fabrication discrepancies. The resonators are solely interconnected by the supporting substrate surface, without any additional clamping point. Three case studies are considered, as illustrated in Figure 1d-e: a longitudinal coupling scheme, where surface acoustic waves propagate along the inter-resonator axis (Fig. 1d); a transverse coupling scheme, with waves propagating in the orthogonal direction (Fig. 1e); and a diagonal case, where the incident wave vector forms an angle of $\pi/4$ with the inter-resonator axis (Fig. 1f). The gap distance is first set at 1.5 µm for the three configurations, i.e., to a distance about equal to a third of the pillar diameter. The distance was essentially chosen out of technological concerns, as the gap is large enough to ensure a very good repeatability of the growth process for such a pillar height. In all three cases, the frequency response of each pillar is measured independently. Raw data are provided, corresponding to data taken every 10 kHz; the lines with markers are obtained after filtering out the frequency-dependent elastic wave source noise and serve as a guide for the eye.
Figure 2. **Diagonal incidence.** (a) Left: Experimental frequency responses of the 1.5 \(\mu m\)-spaced pillars of the pair in the 45\(^\circ\)-configuration. Right: Out-of-plane displacement field maps on the pillar surface for typical excitation frequencies: 69.99 MHz (A), 71.81 MHz (B) and 72.37 MHz (C). Bottom: Corresponding phase maps on the top of the pillars. The scan area is 13 \(\mu \text{m} \times 13 \mu \text{m}\), with a step size of 200 nm. (b) Left: Simulated frequency responses of 1.5 \(\mu m\)-spaced pillars of the pair in the 45\(^\circ\)-configuration, obtained by extracting the maximum out-of-plane amplitude on top of each pillar. Right and bottom: corresponding displacement maps (\(|u_z|\) and \(\arg(u_z)\) respectively) for typical resonance frequencies: 75.25 MHz (A), 78.40 MHz (B) and 79.65 MHz (C). The dimensions of the maps are 12 \(\mu \text{m} \times 12 \mu \text{m}\).

The frequency response and field maps obtained for the diagonal case are reported in Figure 2a. Splitting into three different modes is observed for the two resonators. This frequency splitting is independent of the drive power, at least within the range of excitation power used within the experiments comprised between -20 to +20 dBm. The first resonance, labeled (A) and appearing at a frequency \(f = 69.99\) MHz exhibits a Lorentzian line shape and a quality factor of 38, making the response very similar to the one obtained for a single pillar displayed in Figure 1f. The two other modes (labeled (B) and (C) at \(f = 71.81\) MHz and \(f = 72.37\) MHz, respectively) exhibit an asymmetric line shape, which, along with increased quality factors around 140 and 110 respectively for \(P_1\), are characteristic of resonator coupling. The amplitude measurements reported in Figure 2a confirm that the nature of the mode remains unchanged as the two resonators still vibrate on a fundamental flexural mode. Phase measurements show that the mechanical system here behaves as a pair of coupled dipoles: the two lower energy resonances at frequencies labeled (A) and (B) correspond to degenerate repulsive dipole modes, with pillars respectively in-phase and out-of-phase and exhibiting orthogonal polarizations. The third mode, observed at point (C), corresponds to an attractive dipole interaction with the pillars vibrating in the direction orthogonal to the inter-resonator axis. These experimental observations can be compared with finite element method (FEM) simulations results reported in Figure 2b, that displays three separate peaks including two with higher quality factors. The simulations were performed using material constants previously determined by independent characterizations [33], see Supplementary Information. Discrepancies on resonance frequency values can be accounted for by errors committed on pillar height and on IBID-Pt material constants, these parameters having a very strong influence on the coupled pair response. The numerical out-of-plane displacement and phase maps (\(|u_z|\) and \(\arg(u_z)\) respectively) for the three modes are also displayed. If the overall behavior in reasonable agreement, the influence of the incident wave source seems more significant in the numerical simulations. The orientation of the pillar vibration indeed deviates from the direction defined by the inter-resonator axis, which results in a mode polarization exhibiting a component in the direction parallel to the impinging surface elastic wave front. This points to a stronger surface-to-resonator coupling than the one observed in the experiments where the dipole-dipole interaction clearly prevails. The simulations in addition point at a degeneracy of the in-phase attractive and repulsive modes that vibrate along the inter-resonator axis, with a mode exhibiting an orientation at the trailing edge of the resonance orthogonal to the one at the leading edge, with a rotation occurring at resonance. Experimentally, only the lower energy, bonding-like state is observed.

We then investigate a different incident wave vector to evaluate the possibility to tune the resonator coupling mechanism. For this purpose, we focus on a longitudinal excitation, for which the surface acoustic wave propagates along the inter-resonator axis. Each resonator now exhibits two modes instead of the three observed for the diagonal incidence. The resonance profile is strongly asymmetrical in all cases, as shown in Figure 3. The mode identification here needs to be assisted by field map measurements, the mode splitting being too weak for an
unequivocal discrimination of the different modes. This allows to observe that frequency labeled (A) corresponds to a mode that is assumed to be an anti-symmetrical low energy, bonding dipole state. The measurements also show the existence of a second state, corresponding to frequency label (B), where the vibration direction of the two-pillar ensemble is rotated by \( \pi/2 \) compared to the lower frequency mode, which reminds of what was previously observed for modes (A) and (B) in the case of the diagonal incidence. The direction of the excitation source therefore rules out the third, anti-symmetrical mode, as well as its orthogonal polarization, that would impose to one of the pillar to vibrate out-of-phase with the incident source. Yet, if the pillar vibration direction is strongly influenced by the incident SAW wave vector, the direction is not as pure as the one expected from numerical simulations that quite naturally, and exclusively, predict a nodal line parallel to the impinging wavefront, regardless of the drive frequency. This may be accounted for by an increased surface-mediated mechanical coupling favored by the wave vector direction that would tend to increase the coupling strength, hence forcing the pillars toward an avoided crossing configuration.

The case of a transverse excitation where the inter-resonator axis is orthogonal to the source propagation direction is now reported in Figure 4a. As expected, only two modal signatures appear in the measured frequency response, a lower frequency mode, with amplitude levels and quality factors comparable with those of a single pillar, and a higher frequency, higher Q-factor mode, at least in the case of pillar P5 for which the Q reaches 85. The frequency difference between the two modes of P5 labeled (A) and (C) corresponds to the frequency difference previously measured in the diagonal-incidence case between the first and the third mode of P1. If this frequency behavior agrees well with the numerical simulations, the retrieval of the vectorial characteristics of the mechanical modes through elastic field map measurements reveals unexpected features. First, the two resonators vibrate sequentially, leading to a switching of the elastic energy distribution from one resonator to the other as a function of frequency, hence allowing RF-driven mechanical mode swapping. Second, experimental observations do not meet the expectations of the FEM model. This latter predicts a single vibration orientation for the two resonators, whatever the excitation frequency, with the pillars vibrating either in-phase or out-of-phase with a vibration direction locked by the incident wave source. This is for instance experimentally observed at a frequency of 67.02 MHz (labeled (A)). Such polarization states would correspond to pure bonding and anti-bonding states and would match well a dipolar approach of the problem. Yet, experimentally, as soon as the two pillars reach resonance, the pillar pair enters a rather unstable regime dominated by a quasi-circular polarization state, pointing at a degeneracy of two orthogonally-polarized vibration modes, a behavior reminiscent of bifurcation in non-conservative systems \[38\], although no dependence on the acoustic pump power of this polarization state could be observed in the experiments. The demonstration is in addition here incomplete, as the handedness of these polarization states is still to be determined.

For both longitudinal and transverse excitation schemes, the proposed surface wave coupled resonator pairs therefore exhibit a behavior with a description that stands in between the classical picture of inter-particle interaction usually adopted in plasmonics and the usual theory of mechanical resonator coupling based on harmonic oscillators. They indeed combine surface-plasmon-like features, deriving from the hybridization of the excitation surface wave propagating on the supporting substrate into particles separated by a gap within the plasmon coupling limit \[37\], with pillar-to-pillar interaction linked to sheer mechanical clamping.

To investigate further the influence of a surface-mediated mechanical coupling, additional pairs of pillars with an increased separation distance were fabricated. The gap was set to 6 µm, a distance chosen in the light of previous characterizations of an isolated resonator and corresponding to the extent of the displacement field as induced by the pillar vibration on the supporting surface \[39\]. Figure 4b reports the results obtained for a transverse excitation. The resonance shape for each pillar is now closer to the one measured for a single resonator. The respective blue and red-shifts of each resonator response respective to the one of an isolated pillar cannot be unambiguously assigned to resonator-to-resonator coupling, as, again, a difference in the pillar height is not unlikely. Yet, the broadening of the response, clearly visible for pillar P8, suggests that the two resonators remain

Figure 3. Longitudinal excitation. Experimental frequency responses of the 1.5 µm-spaced pillars of the pair in the longitudinal configuration. Bottom: Experimental out-of-plane displacement field maps for typical frequencies: 67.43 MHz (A) and 67.90 MHz (B) (D). The scan area is 14 µm × 8 µm, with a step size of 200 nm.
coupled. This is confirmed by the experimental displacement field maps displayed in Figure 4: the elastic energy distribution swaps again from one resonator to the other as a function of drive frequency, going through a clear avoided crossing here observed at $f = 67.37$ MHz. Outside this point, the resonators tend to orient in the direction either parallel or orthogonal to the incident surface wave vector, showing that the increased spacing lifts the degeneracy observed in the same excitation configuration with a 1.5 $\mu$m gap. A longitudinal excitation of a similar pillar pair, not reported here, leads to the observation of the same coupling scheme, with each pillar adopting its two orthogonal states and passing through an avoided crossing point. Interaction between the two pillars through the substrate surface is then expected and demonstrated to occur in the field maps displayed in Figure 5, reporting measurements in the case of a transverse (Fig. 5a) and a longitudinal (Fig. 5b) excitation. This interaction reciprocally leads to a channeling of the elastic energy at the substrate surface. The amplitude of out-of-plane component of the surface displacement is of the order of 0.5 nm, a value directly comparable to the one of the incident Rayleigh wave. Resonator-to-resonator coupling therefore leads to a deeply sub-wavelength confinement of surface acoustic waves with a localization directly conditioned by the direction of vibration of the pillars.

The overall behavior observed for a 6-$\mu$m-gap suggests that mechanical coupling now prevails, the obtained results echoing those observed for instance while considering the coupling between nanomechanical string or beam resonators. In contrast with the interaction observed at smaller separation distance, increasing the gap leads to a system that can rather be described as a four-mode coupled resonator system, rather than as a set of coupled dipoles. This kind of transitions to different coupling regimes is common to both plasmonics and...
and nanomechanics [15]. It is a good illustration of the wealth of mechanisms involved in the proposed SAW-based platform, leading to an incapacity to describe the SAW-mediated resonator-to-resonator interaction by a unique simple model, as neither a discrete dipole, nor a harmonic oscillator approach manage to give a general picture of the experimental observations. The used FEM model also fails to account for the polarization states of the resonators, although the frequency responses can be well anticipated whatever the considered configuration. This shows the relevance and importance of a direct observation of the spatial and vectorial behavior of the resonator motion for the interpretation of the coupling mechanisms at play, as was previously pointed out for optomechanical systems [40]. This also obviously highlights the need for a more complete model, encompassing both dissipation and potential nonlinearities, in addition to the already complex picture obtained by the current consideration of the surface wave propagation, the substrate anisotropy and piezoelectricity, and the full geometry of the mechanical resonators.

In summary, we proposed to combine the mechanical degree of freedom offered by micromechanical resonators to the capabilities enabled by propagating surface acoustic waves to build a reciprocal system allowing either to coherently control mechanical systems through SAW, or rather, to channel SAW propagation at the substrate surface through resonator-to-resonator coupling at a sub-wavelength scale. The core component of the investigated system is a pair of coupled resonators taking the basic shape of cylindrical pillars. By tuning the resonator-to-resonator distance as well as the impinging SAW wave vector orientation, switching between different coupling schemes could be observed, with features unveiled thanks to a full retrieval of the vectorial nature of the interaction obtained through direct imaging of the resonator motion. At low separation distance, dipole-dipole interaction seems to predominate and the SAW wave vector mostly acts as a means to select the active coupled mode, in a way clearly reminiscent of plasmonic coupling of nanoparticles. At higher separation distances, mechanical coupling becomes preponderate. In this case, the coupling mechanism seems insensitive to the SAW propagation direction and clear avoided crossings are observed. A numerical model based on the finite element method was used and shown to exhibit good agreement with the observed frequency response. The model however fails to account for the mode shapes, that could here be directly experimentally observed. Further developments are then required, that would first and foremost aim at the inclusion of dissipation and non-linearities. Such a complete description could allow exploiting the richness and unique features of the proposed platform for the coherent control of complex mechanical systems but also, conversely, for the control of the displacement and hence strain distribution on a substrate surface. This control could further be enhanced by tuning both the resonator shape and material, in view of increasing the quality factor. It could also be possible to bring additional degrees of tunability to the coupling by a thorough exploitation of the SAW excitation, for instance by controlling the acoustic power and therefore the involved strain and electric potential or by inducing bias voltages. It should finally be mentioned that the experiments were performed at room temperature and ambient pressure, far from the quantum limit. The experimental platform formed by such mechanical resonators is however readily scalable down to the nanoscale. This would result in systems with increased quality factors at higher operating frequencies, two essential ingredients that would make them suitable for applications to the burgeoning field of quantum acoustics.

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