SPIM

Projet de Mémoire

école doctorale **sciences pour l'ingénieur et microtechniques**

UNIVERSITÉ DE FRANCHE-COMTÉ

RADIO-FREQUENCY PHONONICS

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INTRODUCTION

More than two decades ago, inspired by the rise and success of photonic crystals, mechanical vibrations in periodic structures were considered anew, giving birth to the field of phononic crystals and later to the one of acoustic metamaterials. Engineering two and three-dimensional structures led to unique dispersion features: periodicity induced acoustic or elastic band gaps due to Bragg scattering; introduction of defects allowed the demonstrations of strong wave localization in cavities or waveguides; dispersion engineering opened the path towards slow sound, sub-wavelength focusing or self-collimation. The very nature of elastic and acoustic waves, their natural extension over a widest scale of wavelength and hence frequencies, promised many potential fields of use for phononic crystals, ranging from structural vibrations to radio-frequency telecommunications, through micro-electromechanical systems and underwater and medical acoustics, to name but a few. The physics of phononic crystals was further enriched by the concept of locally-resonant crystals, where the resonance properties of the scattering unit played the leading role in band gap formation. The characteristic dimensions of the crystal unit cell could then be brought to the sub-wavelength scale, which paved the route to acoustic and elastic metamaterials. Phononic crystals and elastic metamaterials have now reached some degree of maturity and the capacity to control elastic or acoustic wave propagation has attained unprecedented levels.

The aim of this manuscript is to give a brief account of my contribution to this thriving field. A wide part of my research activities actually relates to Phononics at the micron-scale and seeks to engineer elastic wave propagation in the radio-frequency range. These activities were greatly favoured by the rich context offered by FEMTO-ST, that has been my host laboratory during my PhD years and during the overwhelming majority of my career. My PhD thesis work was indeed dedicated to the demonstration of the existence of phononic band gaps, most notably for surface acoustic waves (SAW) in the hundred of MHz range. A large part of my later activities, and of my research today, still revolves around the wide ambition to harness SAW propagation, first using strategies based on phononic crystals, but also, and more recently, by investigating the possibilities offered by concepts borrowed from nanoelectromechanical systems. Outside the sheer interest this may trigger in the domain of radio-frequency acoustics, controlling SAW propagation in micron-scale structures allows considering interactions with other physical degrees of freedom. As it will be detailed later, we have tried to exploit this characteristics in the context of acousto-optical interactions, in the classical or confined regimes. We will however see that this potential for interaction can be exploited in a number of physical domains, which has recently generated a renewed interest in controlling high-frequency acoustic wave progapation.

This report provides a synthetic description of my post-doctoral research, mostly as a CNRS research scientist at FEMTO-ST. As a preamble, a curriculum vitæ and a summary of my doctoral thesis work are provided. I will then summarize my activities, settling their decription in an international context. Chapter 4 will then discuss my research perspectives, on a mid-term basis. The last part of the manuscript is dedicated to a more factual presentation of my institutional responsibilities, my contribution to research management and my involvment in teaching and education. A complete list of publications is also appended to the present document.

1 CURRICULUM VITAE

PERSONAL INFORMATION

Name:	Sarah BENCHABANE
Date of birth:	10 October 1980 (39 years old)
Nationality:	French

CURRENT POSITION

CNRS Research Scientist (*Chargée de recherche classe normale)*
Institut FEMTO-ST - Département MN2S
15b avenue des Montboucons
25 030 Besançon cedex

Main research topics: Phononic Crystals, Nanophononics, phoxonic crystals and optomecanics, acousto-optical interactions, micro- nano-technology.

PAST POSITION

2007	Postdoctoral research scientist, Nanophotonics/Optoelectronics group (Prof. V. Pruneri), Institut de Ciències Fotòniques (ICFO), Spain. **Research topic:** Acousto-optical interactions and devices in ferroelectric materials.

EDUCATION

2003 - 2006	**Ph.D. in Engineering** Université de Franche-Comté - Institut FEMTO-ST, dpt. DPMO - Besançon, supervised by Vincent Laude and Abdelkrim Khelif Title: *Guiding and filtering waves in phononic crystals*.
2002-2003	**Master's Degree** (DEA) Optics & Optoelectronics - Université Jean Monnet - S^{t} Etienne, France. Internship at the University of Strathclyde (Glasgow, UK)
2001-2002	**MPhys in Applied Physics (Optoelectronics & Laser Engineering)**, Heriot-Watt University - Edinburgh (U.K.) / U. Jean Monnet - S^{t} Etienne (France)

INSTITUTIONAL RESPONSIBILITIES

2018 - now	Head of the GdR CNRS *Métamatériaux acoustiques pour l'ingénierie* (GdR META, n°3759).
2016 - 2018	Co-founder and deputy head of the GdR CNRS *Métamatériaux acoustiques pour l'ingénierie*.
2012 - 2017	Executive board member of the FEMTO-ST technology center (1300 m^2 clean-room, part of the French Renatech network).
2008 - 2012	Member of the scientific steering committee of the FEMTO-ST technology center.

AWARDS

- Juan de la Cierva Fellowship (Spain), grant declined following my admission at CNRS (2007).
- CNRS Bronze Medal 2012.
- *Prime d'excellence scientifique* (PES) du CNRS (2013).
- Selected for the *Cursus Jeunes Talents* of the CNRS in 2016.

PUBLICATIONS

- 43 articles in international peer-reviewed journals.
- 23 invited talks (13 as first author).
- 22 international conferences with proceedings.
- 3 book chapters.

TEACHING ACTIVITIES

2009-2016	17h lecture/year – Acousto-optics, Master PICS, Univ. Franche-Comté.
2017 - now	15h lecture/year – Acoustical microsystems, Master MIR, Univ. Franche-Comté.
2003 - 2006	60h lecture/year – IT for 2^{nd}-year students in information & communication.

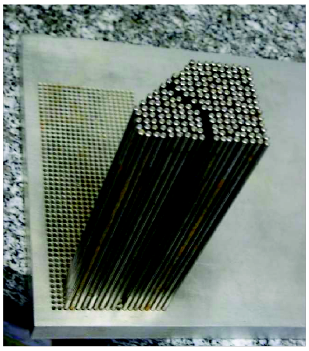
2
DOCTORAL THESIS

2.1 Summary

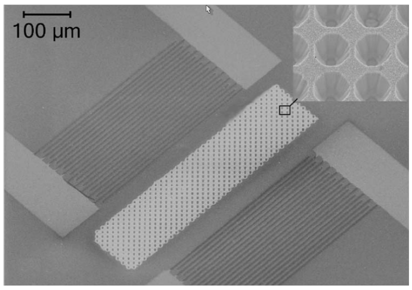
I obtained a PhD in Engineering Sciences at the Université de Franche-Comté, after completion of a thesis work conducted at FEMTO-ST from 2003 to 2006, under the supervision of Abdelkrim Khelif and Vincent Laude. A research track dedicated to phononic crystals had been introduced a couple of years earlier in the host laboratory as part of the activities of the *Acoustics & Microsonics* group, then well-renowned for its activities on radio-frequency surface acoustic wave (SAW) devices. The field of phononic crystals itself was still in its infancy and experimental demonstrations of phononic band gaps and waveguides for bulk waves in crystals operating in the audible and lower ultrasonic regime frequency opened at the time perspectives as promising as those offered by their photonic counterparts, that were then incontestably dominating the landscape of periodically-structured materials. In this context, the broad aim of this PhD was to investigate further the capabilities of phononic crystals for the implementation of guiding and filtering functions. Its major objective, however, was to demonstrate that the existing proof-of-concept experiments performed on bulk waves in the ultrasonic regime could be transposed to surface acoustic waves in integrated devices. The targeted structures were to exhibit characteristic dimensions in the micron-scale and operating frequencies of the order of a few hundreds of MHz, i.e. compatible with a range of wireless communication SAW devices.

The first part of my thesis work was dedicated to the implementation of further experiments in the lower ultrasonic regime. The considered experimental structure consisted in a periodical arrays of steel rods immersed in water, as shown in Figure 2.1a and had been used by the group before to demonstrate both phononic band gaps and waveguides [T9]. The lattice parameter was of the order of a millimeter, leading to an operating frequency of the order of a few tens of kilohertz. Within the course of the PhD, these crystals were used to investigate the coupling between modes guided along a line defect of the crystal and cavity modes hosted by grafted stubs [T4].

In a second part, we focused on the demonstration of the existence of phononic band gaps for surface acoustic waves. The idea was to benefit from the intrinsic confinement of SAW close to the substrate surface to build an equivalent 2.5-D phononic crystal out of a two-dimensional periodical structuring of the substrate. Lithium niobate was chosen as the matrix material, mainly for his strong piezoelectric coupling coefficients, but also for the potential it offered for later investigation of enhanced acousto-optical interactions through phononic wave guiding or confinement. From an experimental point of view,



(a)



(b)

Figure 2.1: (a) Ultrasonic phononic crystal obtained by inserting steel rods into a rigid perforated plate. The crystal period is 3 mm. (b) Scanning electron microscope image of a phononic crystal for surface acoustic waves. The structure, consisting of 9 μm diameter air holes with a 10 μm pitch, is surrounded by a pair of IDTs to ensure surface wave transduction. The inset in the top-right corner shows a more detailed view of the holes etched in the lithium niobate single crystal substrate.

using a piezoelectric single-crystal would enable the realisation of experiments in which the sources and detectors of acoustic waves could be embedded with the phononic crystal itself. I carried out the experimental part of the study, which involved among other things phononic crystal fabrication using clean room processes (Figure2.1b). In particular, I had to develop a process for lithium niobate dry etching. I then designed and fabricated the IDTs necessary to perform an electrical characterization of the crystal. This work has led to the demonstration of the existence of a complete band gap for SAW, in good agreement with theoretical predictions [T2]. I also initiated a collaboration with the Helsinki University of Technology (Finland) in view of performing optical characterisation of the elastic energy distribution in our devices. These first experiments constituted a preliminary but successful assessment of the relevance of optical interferometry for the investigation of SAW propagation in phononic crystals [T1].

The last part of this thesis aimed at laying the foundations of a set activities at the interface of Acoustics and Optics in view of investigating acousto-optical interactions in simultaneously photonic and phononic band gap materials. We more specifically focused on the potential implementation of the concept in photonic crystal fibers. A theoretical demonstration of the possible existence of adequate structurations allowing for the simultaneous observation of both optical and elastic band gaps in such fibers had indeed been performed within my host research group [T6]. I paid closer interest to the theoretical study of the guided mode acousto-optical interaction itself, by comparing a formal approach based on the Pockels theory and another one describing the interaction as a parametric process. Without constituting a significant breakthrough, this work at least highlighted the importance of the chosen formalism in this particular configuration that involves highly confined optical and acoustic fields with well-defined mode shapes, compared to usual acousto-optical systems where the elastic wave spatial expansion is considered as infinite. A matching experimental study was also considered, through various - and unprosperous - attempts to realise an integrated on-fibre acoustic transducer by depositing a piezoelectric thin film (here, aluminium nitride) on the fibre circumference. We will see that this pursuit of simultaneous phononic and photonic band gaps stretches beyond this PhD work: it has been and still is a guiding line of my post-doctoral research activities.

2.2 List of Publications related to the post-graduate period

International peer-reviewed journal articles

T1. K. Kokkonen, M. Kaivola, S. Benchabane, A. Khelif, and V. Laude, "Scattering of surface acoustic waves by a phononic crystal revealed by heterodyne interferometry," Appl. Phys. Lett. **91**, 083517 (2007).

T2. S. Benchabane, A. Khelif, J.-Y. Rauch, L. Robert, and V. Laude, "Evidence for complete surface wave band gap in a piezoelectric phononic crystal," Phys. Rev. E, **73**, 065601(R) (2006).

T3. Y. Pennec, B. Djafari-Rouhani, J.O. Vasseur, H. Larabi, A. Khelif, A. Choujaa, S. Benchabane, and V. Laude, "Acoustic channel drop tunneling in a phononic crystal," Appl. Phys. Lett. **87**, 261912 (2005).

T4. S. Benchabane, A. Khelif, A. Choujaa, B. Djafari-Rouhani, and V. Laude, "Interaction of waveguide and localized modes in a phononic crystal," Europhys. Lett. **71**, 570 (2005).

T5. V. Laude, M.Wilm, S. Benchabane, and A. Khelif, "Full band gap for surface acoustic waves in a piezoelectric phononic crystal," Phys. Rev. E **71**, 036607 (2005).

T6. V. Laude, A. Khelif, S. Benchabane, M. Wilm, Th. Sylvestre, B. Kibler, A. Mussot, J. M. Dudley, and H. Maillotte, "Phononic bandgap guidance of acoustic modes in photonic crystal fibers," Phys. Rev. B **71**, 045107 (2005). Selected by the Virtual Journal of Nanoscale Science & Technology **11** (2005).

T7. A. Khelif, A. Choujaa, S. Benchabane, B. Djafari-Rouhani, and V. Laude, "Experimental study of guiding and filtering of acoustic waves in a two dimensional ultrasonic crystal," Z. Kristallogr. **220**, 836 (2005).

T8. M. Schmid, S. Benchabane, F. Torabi-Goudarzi, R. Abram, A.I. Ferguson et E. Riis, "Optical in-well pumping of a vertical-external-cavity surface-emitting laser," Appl. Phys. Lett., **84**, 4860 (2004).

T9. A. Khelif, A. Choujaa, S. Benchabane, B. Djafari-Rouhani et V. Laude, "Guiding and bending of acoustic waves in highly confined phononic crystal waveguides," Appl. Phys. Lett. **84**, 4400 (2004).

Invited Papers

1. S. Benchabane, A. Khelif, L. Robert, J. Y. Rauch, Th. Pastureaud, and V. Laude, "Elastic band gaps for surface modes in an ultrasonic lithium niobate phononic crystal," in Photonic Crystal Materials and Devices III, Proc. Soc. Photo.-Opt. Instrum. Eng. 6182, 618216 (Strasbourg, France, 2006).

International conferences with proceedings

1. V. Laude, N. Khelfaoui, D. Gérard, C. F. Jerez-Hanckes, H. Moubchir, S. Benchabane, and A. Khelif, "Anisotropic Wave- Surface Shaped Annular Interdigital Transducer," IEEE Ultrason. Symp., 2115 (New York, 2007).

2. A. Khelif, F.-L. Hsiao, S. Benchabane, A. Choujaa, B. Aoubiza, and V.Laude, "Ultrasonic and hypersonic phononic crystals," in Photonic Crystal Materials and Devices VII, Proc.Soc. Photo.- Opt. Instrum. Eng. 6901, 69010B-10 (2008).

3. D. M. Profunser, O. B. Wright, O. Matsuda, U. Lang, A. Khelif, S. Benchabane, V. Laude, "Hypersonic SurfaceWaves Scattered in Air-Silicon Microstructured Phononic Crystals," IEEE Ultrason. Symp., 501 (Vancouver, 2006).

4. D. Gachon, G. Lengaigne, S. Benchabane, H. Majjad, S. Ballandras, and V. Laude, "High frequency bulk acoustic wave resonator using thinned monocrystalline lithium niobate," Europ. Time Freq. Forum Proc., 810 (Braunschweig, 2006).

5. S. Benchabane, A. Khelif, W. Daniau, L. Robert, V. Pétrini, B. Assouar, B. Vincent, O. Elmazria, J. Krüger, and V. Laude, "Silicon phononic crystal for surface acoustic waves," IEEE Ultrason. Symp., 922 (Rotterdam, 2005).

6. Y. Pennec, B. Djafari-Rouhani, A. Khelif, A. Choujaa, J. Vasseur, S. Benchabane, H. Larabi, and V. Laude, "Channel drop process of elastic wave in a two dimensional phononic crystal," IEEE Ultrason. Symp., 69 (Rotterdam, 2005).

7. V. Laude, M. Wilm, S. Benchabane, and A. Khelif, "Full band gaps for surface acoustic waves in piezoelectric phononic crystals," IEEE Ultrason. Symp., 1046 (Montréal, 2004).

3
POST-DOCTORAL RESEARCH ACTIVITIES

3.1 Summary

A significant part of my research activities has been and still remains devoted to attempts of controlling propagation of surface acoustic waves in the radio-frequency (RF) regime. If the incentive was initially to explore the potential of phononic crystals for signal processing, the aim and scope has widened and I am now seeking to harness SAW propagation in order to fully exploit the capabilities offered by this powerful information carrier.

3.2 Prelude: a personal perspective

I have been involved in the field of Phononics at FEMTO-ST since my recruitment first as a PhD student in 2003, then as a full-time CNRS researcher in 2008 after a year spent as a post-doctoral researcher at the Institut de Ciències Fotòniques in Spain. The research activity was launched back in 2002, under the impetus of Abdelkrim Khelif and Vincent Laude, both Research Scientists at CNRS, and was hosted by a research group specialised in radio-frequency acoustics and ultrasonics, with strong expertise in surface acoustic wave (SAW) and bulk acoustic wave (BAW) devices. The group was at the time gaining additional recognition for its pioneering works on phononic crystals theory and modeling. It also was the stage for early demonstrations of phononic band gaps in the ultrasonic regime, notably in millimeter-scale structures immersed in water. My initial contribution to the field, as a PhD student, was to participate to the launching of a set of activities merging phononic crystals and surface acoustic wave devices. My primary contribution as a CNRS researcher, has been to expand the group's activities dealing with phononics at the micron-scale towards the hypersonic regime, taking charge of technological and experimental aspects of the related conducted projects. This was made possible through the availability of a technological center member of the French Basic Research network at FEMTO-ST and through the scientific autonomy that was granted to me upon my recruitment as a CNRS research scientist.

My activities have then been strongly marked by a continuous drive to control radio-frequency elastic wave propagation at the micro- and nanoscale and can be depicted as three inter-related research lines. The first one pertains to the experimental demonstration of phononic crystals and devices at the micron-scale. The second relate to the use of the developed structures and concepts in the context of simultaneous photonic-phononic crystals and of acousto-optics. The third one seeks to merge concepts stemming from phononics or acoustic metamaterials with principles and ideas borrowed from the wider mechanical and nanomechanical research community. This research axis is well in line with the general development of the fields of Phononic crystals and elastic metamaterials. It is also widely driven by a latest, general re-assessment of the potential of radio-frequency elastic waves for applications lying beyond their usually admitted and historical fields of dominion, with the ambition to exploit the rich physics involved by the intrinsic coherent coupling of mechanical vibrations with other physical degrees of freedom.

This Chapter is therefore naturally organized along three corresponding sections, following a more generic introduction and state-of-the art, presented in Section 3.3. Section 3.4 summarizes our contribution to surface acoustic wave phononic crystal and waveguides in the radio-frequency regime. Section 3.5.1 is an account of our attempts to exploit these phononic structures for the obtaining of simultaneous photonic and phononic band gaps, in view of contributing to the field we then termed *Phoxonics* – a word that has definitely lost the semantic battle, the wording *Optomechanics* having widely prevailed since then. Last, Section 3.6 highlights more recent developments dedicated to the localized and coherent control of elastic vibration in micron-scale features.

3.3 General context and positioning: radio-frequency phononics

Over the past thirty years, the tremendous technological advances in micro- and nano-manufacturing processes has led to a massive resurgence of interest in the manipulation of mechanical vibration at small scales, resulting in significant progress in diverse areas of applied and fundamental science. Micro-electromechanical systems (MEMS) in particular have reached an unprecedented level of maturity over a significantly short time scale: they are now to be found in virtually any electrically-powered device, as long as the tiniest level of smartness or agility is required. Amongst the most striking examples of such rapid developments stand surface acoustic wave devices (SAW). SAW devices are ubiquitously used in modern wireless communication systems, where most analog radio-frequency filtering functions are performed through bulk or surface electro-acoustic devices. A mere decade separates the publication of the seminal paper by White & Voltmer [1] from their massive development as TV filters, quickly followed by their prevalent use in radio-frequency (RF) signal processing [2]. The elegance of the concept of interdigital transducer (IDT) and their relative ease of fabrication are an integral part of this success. But SAW devices offer a desirable number of characteristics. They can operate in the GHz regime, exhibit large bandwidth and can be confined in high-quality-factor resonators. They have a low propagation speed, increasing processing time and yielding long delays over compact structures. SAWs are therefore extremely well-suited as on-chip RF signal processors.

The emergence of phononic crystals in the 1990's and the subsequent demonstrations in the audible or ultrasonic range of phononic filters, waveguides or even multiplexers promised unparalleled ways of steering the course acoustic and elastic waves. It suggested the possibility to implement advanced signal processing functionalities over *phononic chips*, mirroring similar developments in photonics. The phononic crystal community then turned to attempts to apply the early theory and experiments developed for bulk waves in the lower frequency regime to bulk and guided-waves in the radio-frequency range, or, rather, in the hypersonic regime, as the community would rather name it. The objective here was two-fold: to demonstrate and exploit the specific features of acoustic wave propagation within this frequency range, but also to assess whether such RF phononic devices could result in a significant enough breakthrough with respect to the well-established, highly-robust and very effective conventional high-frequency surface acoustic wave (SAW) and bulk acoustic wave (BAW) devices. Transposing the physical concepts underlying phononic crystals and band gaps to RF electro-acoustical devices could in addition be made significantly easier by the already acute understanding of dispersion engineering and Bragg band gaps in one-dimensional structures by RF filter designers, acquired upon years of advanced industrial developments. To quote but a few examples, surface acoustic wave transducers and reflectors rely on periodical arrays of metal electrodes fulfilling the Bragg condition, and solidly-mounted bulk acoustic wave resonators (SMR) use a stack of alternating layers of materials with contrasting elastic constant and mass densities to confine bulk waves in a piezoelectric thin film.

The first experimental demonstration of phononic crystals in the hypersonic regime is admittedly the work of Gorishnyy *et al.* [3]. The proposed structure consisted in a three-dimensional periodical system based on a triangular lattice of air holes directly formed in a thick photoresist coated on a glass plate. The corresponding band diagram was characterised using Brillouin light spectroscopy and a band gap in the 2-GHz range, as well as band folding at the edge of the Brillouin zone could be demonstrated. Other early demonstrations based on similar pump-probe techniques confirmed these findings, as in [4–6].

Configurations based on guided waves appeared at a slightly later stage, following a series of theoretical papers focused on demonstrating that complete surface wave band gaps could be obtained in two-dimensional crystals [7, 8]. An appealing solution at the time lied in the combination of surface acoustic waves with piezoelectric single-crystal substrates such as quartz, lithium tantalate ($LiTaO_3$) or lithium niobate ($LiNbO_3$) that offer unmatched piezoelectric and electro-mechanical coupling properties. These interesting features were however counter-balanced by the difficulty of processing these materials using standard micromachining technologies. Fabrication stood as a challenge, while design was not made easier: the strong anisotropy of acoustic wave propagation inherent to piezoelectric materials, combined with the quasi-systematic mixing of shear and longitudinal polarisations, put tighter constraints on the geometrical parameters of the periodical structure itself [8, 9].

The first experimental demonstration of a phononic band gap for surface acoustic waves was therefore proposed on a silicon substrate, a more technologically appealing alternative, as regards both fabrication and integration capabilities. Wu *et al.* proposed to associate the silicon substrate to a piezoelectric thin film, here zinc oxide, to excite surface waves using interdigitated transducers [10]. They demonstrated the existence of a directional band gap for SAW at frequencies in the 100 MHz range. This was followed by the experimental demonstration of complete band gaps for surface acoustic waves propagating on a single-crystal lithium niobate substrate by our group at FEMTO-ST, within the course of my PhD work. This work also evidenced the occurrence of significant transmission loss at frequencies supposedly lying above the band gap. The corresponding acoustic modes were actually located above the so-called *sound line* – defined by the dispersion relation of the bulk mode with the lowest velocity – and were hence subject to radiation to the bulk. SAW band gaps based on Bragg scattering have been investigated by a number of groups since then, with the persistent concern of higher frequency losses [11–14]. Convincing demonstrations of phononic crystal SAW resonators were nevertheless reported [15, 16].

A potential way out of this "sound line issue", compatible with a number of existing electro-acoustic devices, was then to make use of Lamb waves, by considering propagation in thin slabs of solids. An increasing research effort was then directed towards phononic crystal slabs and the natural vertical confinement offered by membranes (see for example [17–28]). A particularity of phononic slabs is their supporting the propagation of a host of modes: symmetric and anti symmetric Lamb waves as well as shear horizontal plate waves. This produces a much more complex band structure than three-dimensional phononic crystals or than phononic crystals for surface waves. The existence of *deaf bands* linked to the lack of matching symmetry between the source, the propagating Lamb waves and the Bloch mode of the crystal can lead to extended attenuation ranges [25–27] which proves highly beneficial in most applications, where phononic crystals are expected to act as frequency filters or reflectors. This has been exploited for the demonstration of phononic crystal slab devices, such as Fabry-Pérot phononic cavities or waveguides [29–31], leading to elastic wave resonators with reduced fingerprints and quality factors comparable to those observed for traditional contour mode resonators. These works have been finding an increasing echo within the MEMS community, where confinement of elastic energy in a membrane is a recurring challenge. Conventional approaches make use of tethers, that provide mechanical isolation of the membrane from the supporting substrate. The added-value of a solution based on phononic crystals here does not lie in an increased confinement or in a miniaturisation of the system, it lies in the possibility to reduce, to some extent, anchor loss usually linked to these tethers [32–34]. This solution is mostly appropriate when heat management is an issue.

Lamb-wave-based resonators, however, cannot to date fill-in the functions delivered by SAW devices in RF communication systems. As such, finding a way to overcome the high-frequency propagation losses previously observed in SAW phononic crystals remained relevant. A solution was found through the concept of locally-resonant metamaterials, initially introduced in the 2000's as a means to overcome the size limitations for acoustic band gap materials in the audible regime imposed by Bragg scattering conditions [35]. An appropriate choice of unit cell could similarly lead to a lowering of the band gap frequency well below the sound line[1]. It was then shown that phononic crystals of thick metal pillars deposited on a homogeneous surface could exhibit hybridisation gaps caused by local resonances of the pillars in addition to the Bragg band gaps caused by the periodicity of the array [38–41]. Other resonator geometries were used and shown to result in the opening of lower frequency band gaps [42, 43]. The main

[1]Quite strikingly, a similar idea of using mechanical resonators to slow down SAW propagation was first exploited in the 1970's as a tool to manage dispersion properties of travelling radio-frequency surface acoustic waves [36, 37].

drawback of locally-resonant crystals for radio-frequency applications in their intrinsic sub-wavelength character, that make their implementation in the GHz frequency range difficult from a technological point of view.

Gaining a full control on elastic wave propagation in the hypersonic regime through material engineering is therefore still an open and difficult issue. An honest statement here would be to admit that phononic crystals and acoustic metamaterials have up to now failed to meet the stringent standards of the radio-frequency SAW and BAW industry. The pursuit of this objective has however yielded demonstrations that are now finding some echo in the MEMS community, as mentioned earlier, but also as a more general means of controlling small wavelength elastic waves. SAW and BAW are indeed mechanical vibrations. As such, they are intrinsically coherent and can coherently couple to a number of other physical degree es of freedom. Controlling elastic wave propagation and confinement is then a problem that extends far beyond the only field of acoustics or electro-acoustics. This has been thoroughly exploited for instance by semiconductor physicists to achieve charge transport, either through the mechanical displacement itself, or via the carried electrical potential [44–49], or in Optomechanics [50, 51]. It is now returning to the forefront of the concerns of solid-state physicists, e.g. in the contexts of quantum acoustics [52–58], interactions with spins or magnetic excitations [59–64]. Novel MEMS-based architectures are being introduced to control RF elastic waves, yet expanding the range of possibilities [59, 65–68]. This will most certainly contribute to widening the prospects for high-frequency phononic crystals and elastic metamaterials, bringing along a yet unforeseen number of challenges [69].

We have given here a brief and non-exhaustive overview of the evolution of the research landscape of phononic crystals for guided waves in the radio-frequency regime. The reader will most probably note while going through the following sections that our own research activities have been evolving along these very same "historical" lines. Our objective has ultimately remained to finely steer the course of surface elastic waves, that are undoubtedly extraordinary information carriers with an outstanding capability to couple to other physical systems. This has led us to work on the demonstration of hypersonic phononic crystals, to implement different strategies for surface acoustic wave guiding and to exploit the commensurability of the wavelengths of radio-frequency elastic waves and optical waves to aim at enhanced acousto-optical interactions. It is now pushing us to seek the finest control and confinement of elastic energy at the micron-scale in order to provide a rich and versatile physical interface for different types of interactions. And this concern will also be at the core of my research projects during the coming years, bearing renewed challenges and excitement.

3.4 Phononic crystals for surface acoustic waves

A significant part of my earliest activities as a CNRS research scientist was clearly in line with my Ph.D. thesis work dedicated to the demonstration of phononic band gaps for surface acoustic waves in the radio-frequency regime. We had indeed demonstrated the existence of an omnidirectional band gap at a frequency about 200 MHz. The point was then to transpose the device operation frequency to the GHz range, i.e. for wavelength of the order of one micrometer. The objective here was twofold: we were aiming at bringing phononic devices closer to the wireless communication frequency regime and serving our later ambition to realise artificial crystals exhibiting both simultaneous photonic and phononic band gaps.

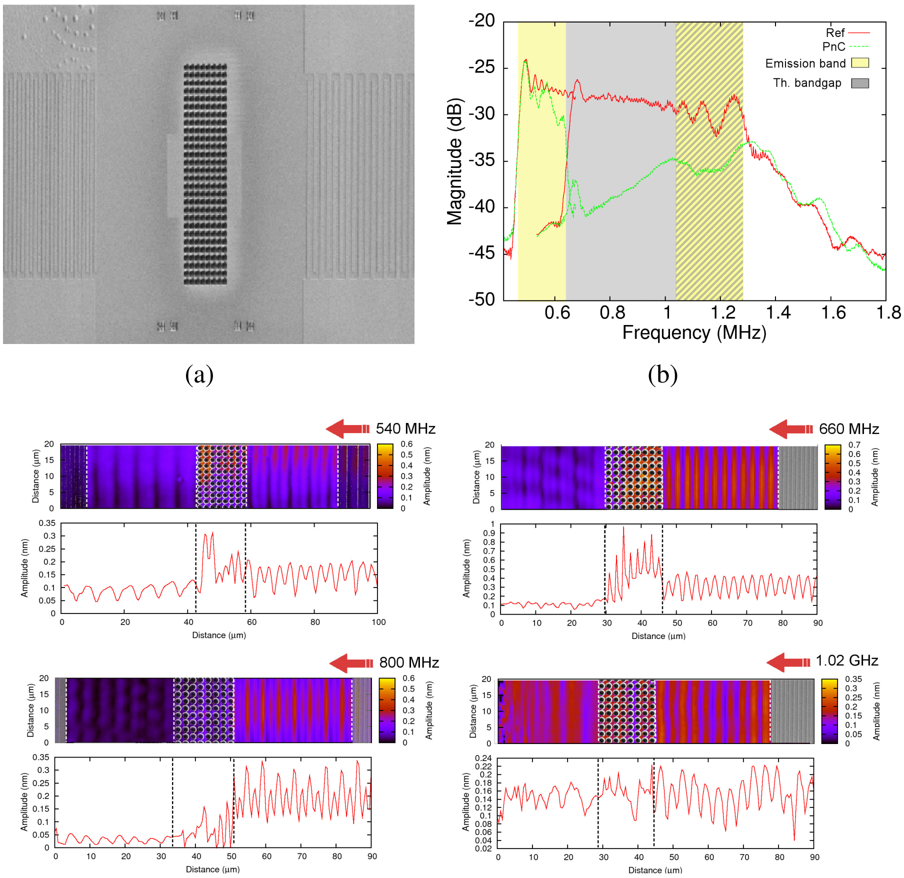
The conceptual and theoretical basis seemed sound at the time, but reaching a successful outcome still required us to tackle a number of issues raised by our earlier experimental investigations. The first challenge simply pertained to the technological and experimental developments required to increase the operating frequency of phononic devices, that were at the time limited to a couple of hundreds of MHz. The second was of more fundamental character and derived from the observation of significant losses due to radiation of SAW to the bulk of the substrate at frequencies lying beyond the sound line. We will see that this last point has led us to investigate two different mechanisms for band gap formation: conventional Bragg scattering and local resonances.

3.4.1 Hypersonic crystals in the Bragg regime

The general mechanism for band gap formation in a phononic crystal operating in the Bragg regime is multiple interference. Bragg band gaps originates from destructive interferences occurring when an impinging elastic or acoustic wave scatters on the periodically-spaced inclusions constituting the crystal. The typical length-scale of the crystal conditions the operation wavelength and hence its operation frequency. Bringing phononic crystals to radio-frequency applications or merging them with photonic devices therefore required addressing at least a common base challenge, yet to be addressed in the literature at the time: the obtaining of band gaps in the GHz regime, hence with crystal features exhibiting dimensions in the micrometer range.

Phononic crystals for surface acoustic waves

One of our ambition in this context was to implement our demonstrations on lithium niobate ($LiNbO_3$), a material featuring an almost unique combination of elastic, piezoelectric and optical properties. Lithium niobate is an extremely mature, and therefore low-cost material, extensively used in the RF acoustics and optoelectronics industry. It exhibits, amongst others, piezoelectric coefficients at least 10 times higher than alternative candidates for integrated acousto-optical applications such as gallium arsenide or indium phosphide (e_{14} respectively equal to 3.7, 0.15 and $3.5{\cdot}10^{-2}$ C/m^2). An appropriate choice of the crystallographic orientation in addition allows ensuring single-mode excitation of surface acoustic waves. These appealing physical properties come, however, at a certain technological cost: micro-machining lithium niobate is an open problem, even to date, and there has not been any consensus on a suitable processing method or base chemistry. The results obtained in [T2] were yet encouraging enough to warrant a transposition to the GHz range, keeping in mind, however, that the realisation of an almost two-dimensional phononic crystal exhibiting hole depths much larger than the SAW penetration depth was most probably out of reach. This entailed considering our phononic devices as constituted by a phononic crystal layer standing on a semi-infinite substrate. Radiation to the bulk of the substrate were to be expected for frequencies lying above the sound line,



(a) (b)

(c)

Figure 3.1: (a) Scanning electron microscope image of a square-lattice hypersonic crystals made of air holes etched in a lithium niobate substrate, surrounded by a pair of chirped IDTs for signal emission and detection. (b) Measured elastic wave fields propagating through the phononic crystals for excitation frequencies at the band gap edge (660 MHz), below (540 MHz), within (800 MHz) and above (1.02 GHz) the band gap. In each case, the emitting transducers is at the right hand side and a SEM image of the actual crystal and transducers is overlaid to the field map. The amplitude data are averaged along the IDT acoustic aperture and the resulting line profiles along the wave propagation direction are displayed.

that is, roughly, for frequencies above the phononic band gap. The question was rather to observe at least a band gap and to evaluate the extent of this loss mechanism, in the prospect of realisation of phononic waveguides or cavities. To this aim, we designed and fabricated phononic crystals on lithium niobate wafers in the X-crystallographic orientation. Focused ion beam milling was chosen to build a square lattice of 2 μm-diameter, 2.3 μm-deep air holes arranged with a period of 2.2 μm. Chirped electro-acoustic delay lines were used for the excitation of surface-guided waves, while detection was performed both electrically and by mapping the displacement fields by laser scanning interferometry (see Section 3.7.1 for further details). Two chirped interdigitated transducers were

required to cover the frequency band of interest, hence calling for the fabrication of two *identical* - as identical at least, as our fabrication processes allowed - phononic crystals. Figure 3.1a displays a scanning electron microscope (SEM) image of the structure, along with the electro-acoustic measurements performed using radio-frequency probe testing (Fig. 3.1b). Transmission through delay lines devoid of any phononic crystals were taken as a reference. A good overlap between the two signals can be observed at frequencies below 650 MHz. Beyond this frequency, the electrical response is strongly attenuated, with an extinction ratio of the order of 13 dB. Partial re-transmission occurs from a frequency of about 1 GHz, without however bringing indisputable evidence of surface modes above the band gap. Direct measurement of the elastic displacement field by optical interferometry confirmed the existence of a hypersonic band gap, that was demonstrated to range from 0.65 to 1.1 GHz. The field maps also allowed to observe a 75% signal transmission above the band gap exit frequency, as reported in Figure 3.1c, that could not be resolved through electro-acoustical measurements. This is in all likelihood due to a phase mismatch between the elastic wave front at the crystal output and the shape and phase of the interdigitated fingers constituting the electro-acoustic transducer.
This work hence demonstrated the feasibility of band gap devices for surface-guided waves at near-gigahertz frequencies. The proposed phononic crystal indeed behaved as an effective mirror for frequencies lying within the band gap and transmission of SAW through the periodical array of holes could be observed below, but more significantly above the band gap, even for frequencies inside the sound cone.

The limitations raised by radiation losses to the bulk however pushed an increasing part of the Phononics community, the Phononics group at FEMTO-ST included, to turn to phononic crystals slabs.

Phononic crystals for Lamb waves

In collaboration with the CEA-LETI, we investigated the possibility to demonstrate the existence of a complete band gap for Lamb waves in the GHz regime. This time, the crystal was fabricated by etching holes in a aluminium nitride (AlN)/silicon dioxide (SiO_2) suspended membrane (AlN thickness: 2 μm, SiO_2 thickness: 0.5 μm). The 2-μm-diameter air holes were arranged on a square lattice with a period of 6.6 μm. Numerical calculations performed using the finite element method predicted a band gap between 776 and 828 MHz. The electrical measurements however showed an attenuation of the transmission between 600 and 900 MHz. This was accounted for by the mismatch between the symmetry of the source, an elliptically-polarized S0 Lamb wave and some of the Bloch modes of the crystal.

Mode conversion at the crystal boundary were also thought to result in non-piezoelectrically coupled A0 and SH0 modes that cannot be detected through electrical means. Optical measurements further confirmed the existence of the band gap, by showing a strong attenuation at the output of the crystal and a reflection pattern at the input. From a practical point of view, this work demonstrated the possibility to combine band gaps and deaf modes of the structure to increase the effective attenuation bandwidth of the crystal, here resulting in fractional bandwidth above 40% [P14].

If hypersonic band gaps for both SAW and Lamb waves could be demonstrated, the characteristics exhibited by the proposed phononic devices were not even remotely meeting the requirements of the RF communication industry. In the case of SAW phononic crystals, the 25% transmission loss above the band gap exit frequency ruled out their use as filters. The losses within the band gap linked to radiation of SAW to bulk waves in the substrate, not characterized, but unavoidable due to fabrication imperfections and limited hole depth, made them unsuitable for genuine, applications to resonators. The natural confinement offered by membranes first appeared as an appealing way to circumvent the radiation to the bulk issue. Very nice demonstrations of phononic slab devices were indeed reported in the literature by different groups, that were particularly active in the 2008 to 2013 period, as mentioned in Section 3.3. But this benefit of intrinsic vertical confinement is offset by the difficulty to control the number of modes that propagate in an adequately proportioned membrane, leading to possible mode conversions. Anchor loss observed in such slab devices are also detrimental. These two concerns make even conventional plate-wave resonators (or Lamb-wave resonators, or contour-mode resonators as they are also termed) struggle yet to rival SAW-based components. The point was then either (or both) to look for alternative mechanisms of bang gap formation or to identify a pathway for which Phononics could be considered as a technology disruptive enough to tolerate reduced filtering performance.

3.4.2 Locally-resonant phononic crystals

The phononic crystals investigated since then relied on the use of periodically arranged structures, consisting of inclusions embedded in a matrix with contrasting elastic constants and density. Bragg scattering is then responsible for band gap formation, making the forbidden elastic wavelength directly commensurable with the crystal period.

As previously mentioned, Liu and co-workers however introduced in 2000 an alternative band gap opening mechanisms that consists in exploiting the intrinsic resonances of the crystal inclusions [35]. The band gap frequency now originates from the coupling between the individual resonances of the inclusions and the propagating modes of the surrounding homogeneous medium. The location of these hybridisation gaps is therefore conditioned by the resonance frequency of the individual resonators alone. This notably allows one to drastically reduce the size of the overall structures in the low frequency regime as designing crystals with lattice constants smaller by several orders of magnitude than the elastic or acoustic wavelength becomes conceivable. Periodicity is no longer a prerequisite. The deep sub-wavelength character of the elementary features allows considering the structure as an homogeneous effective medium, that can be described, at least in the long wavelength approximation, by effective parameters, as e.g. effective mass densities or elasticity moduli. As such, locally-resonant phononic crystals were amongst the first demonstration of the soon-to-become acoustic metamaterials.

Locally-resonant phononic crystals were initially investigated within the frame of bulk waves in isotropic materials. The concept was then transposed to slabs and low-frequency band gaps and wave guiding were successfully reported in phononic crystals constituted by cylindrical dots or pillars deposited on the slab surface, as in [19–21].

We expanded the concept of locally-resonant phononic crystals to semi-infinite media,

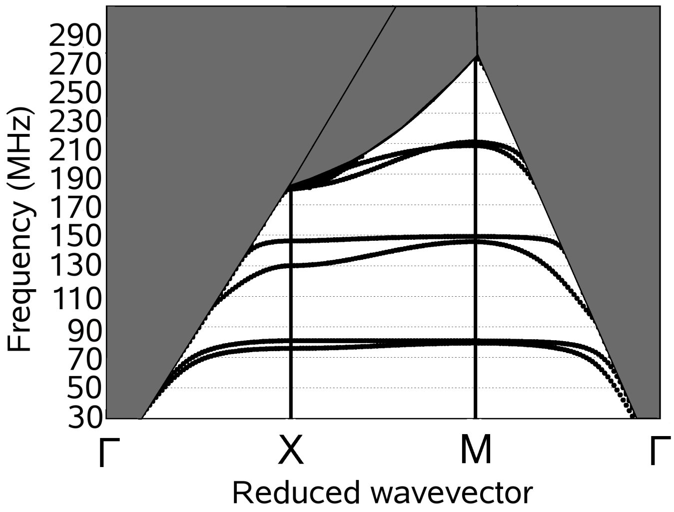


Figure 3.2: Band structure of a periodic array of nickel pillars on a lithium niobate substrate computed using a finite element method along the highest symmetry directions of the first Brillouin zone. The array is arranged according to a square lattice with a pitch $a = 10$ μm. The radius of the pillar is $r = 3.2$ μm and the height is $h = 4.7$ μm. The gray region indicates the radiative region, or sound cone of the substrate.

first through theoretical and numerical investigations [P24] then by means of experimental demonstrations, notably in the frame of Younes Achaoui's Ph.D. thesis (2007-2011), supervised by Abdelkrim Khelif and Vincent Laude [P19]. The base structures for our investigations relied on square arrays of pillars deposited atop a semi-infinite substrate. Numerical and theoretical investigations were first performed on monolithic samples made of silicon. The experimental demonstration was performed on nickel pillar arrays with a diameter of 6.4 μm, a pitch of 10 μm and a height of 4.7 μm. In this case, a low-frequency band gap was found, in addition to the Bragg band gap set by the crystal periodicity. The band structure for surface-guided waves, reported in Figure 3.2, shows the occurrence of flat bands at a frequency of about 80 MHz, that define the locally-resonant band gap. This frequency corresponds to the first resonance frequency of the pillars, while the second resonant mode can be seen to occur at about 150 MHz. This low-frequency band gap is defined by surface-guided modes induced by the resonating pillars that exhibit modal shapes and polarisations that cannot be supported by a free, homogeneous surface, such as, notably, an in-plane polarized wave and a transverse wave with sagittal polarisation. These modes are therefore located in the non-radiative region of the substrate and have a strong dependency on the resonator geometrical parameters, their height in particular. The low group velocity of these modes are characteristic of energy storage within the resonators, which could be confirmed by direct observation of the elastic field by optical interferometry, as displayed in Figure 3.3. The field maps indeed show a strong enhancement of the amplitude of the vibration at the first pillar, followed by an exponential decay toward the exit of the phononic crystal. The observed modal shape is characteristic of an individual pillar resonance. As expected, this low-frequency band gap is independent of the periodicity of the pillar arrangement, which was experimentally demonstrated through

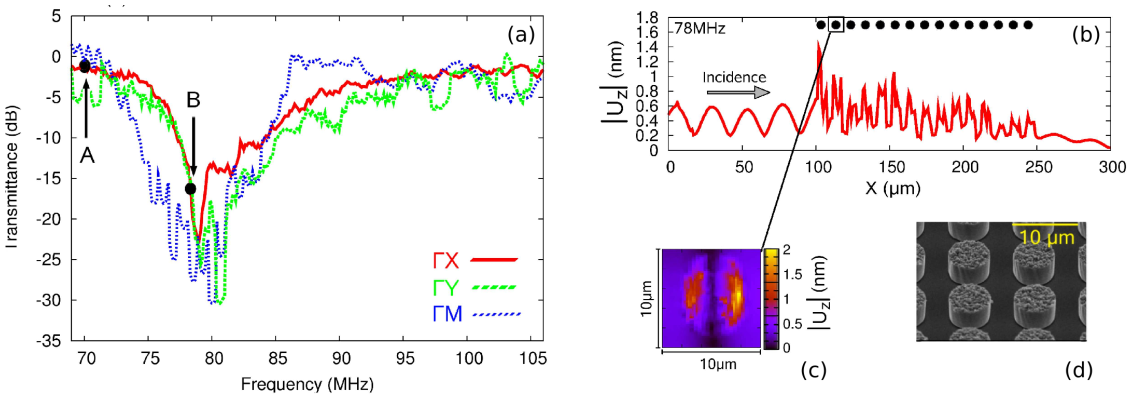


Figure 3.3: (a) Experimental transmittance of the periodic array of Ni pillars for the three highest symmetry directions of the first Brillouin zone. The transmission dip around 78 MHz is the signature of a complete locally-resonant band gap for surface elastic waves. (b) Averaged cross section of the displacement of the surface, as measured using heterodyne optical interferometry for a frequency of 78 MHz (point B). (c) Measured modal distribution of the second pillar at the frequency of the transmission dip. (d) Scanning electron microscope image of the Ni pillars constituting the crystal.

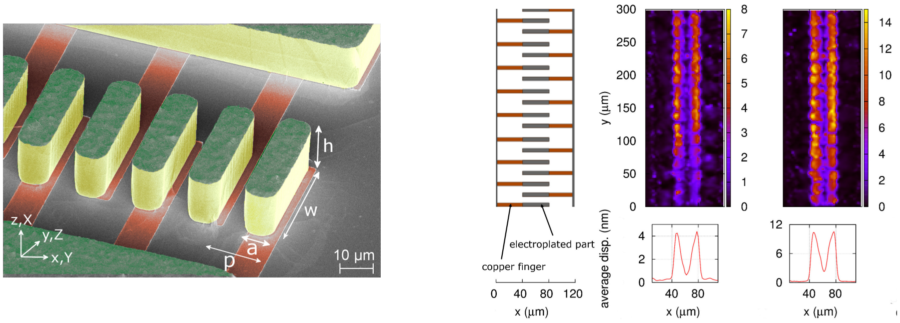
the fabrication and characterisation of a locally-resonant *crystal* consisting in a random arrangement of nickel pillars [P8]. A Bragg band gap was also observed from 150 to 180 MHz, hence at a frequency almost twice as large as the one of the locally-resonant band gap.

Locally-resonant band gaps hence opens a possibility to trap the elastic energy at the substrate surface, hence providing a route to circumvent the radiation loss issue. Choosing to operate at lower frequencies compared to the one imposed by Bragg scattering moreover allows defining surface-guided waves at the exit of the band gap that remain outside the sound cone. This comes, however, at the expense of the operating frequency, as it requires the fabrication of sub-wavelength inclusions, making it difficult to reach the GHz regime. We will however see that there is more to expect from exploiting surface-wave coupled mechanical resonances, outside the mere context of phononic band gaps in Section 3.6. But for now, we are left with the definition of yet another limitation to be overcome to make phononic band gap materials worth being considered for conventional radio-frequency applications. Still, if the path to genuine phononic SAW resonators remains a tedious one, the possibilities phononic crystals offer to confine the elastic energy within wavelength-sized volume, or to perform dispersion engineering open unprecedented prospects for controlling elastic energy distribution.

3.4.3 Phononic wave guides for surface acoustic waves

High-Aspect Ratio transducers

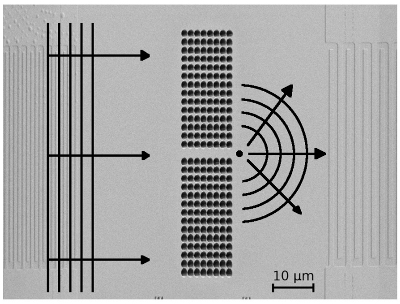
The investigation of locally-resonant phononic crystals can somehow be seen as a refinement of the so-called *mass-loading* effect for elastic energy trapping and confinement.



(a) (b)

Figure 3.4: (a) Scanning electron microscope image of a W1 HAR IDT (w=2p=1) with h=2p=0.43 and p=18 μm (false colors). The plating was limited to the acoustical aperture length and to the IDT bus bars. (b) Out-of-plane mechanical displacement and average displacement along the IDT for the first two modes.

Surface acoustic wave propagation can indeed be easily perturbed by any structuring of the surface of a semi-infinite medium. This specificity, linked to the strong confinement of the elastic energy at the air/solid interface, has been widely exploited in view of achieving SAW propagation control. In some sense, locally-resonant phononic crystals can be seen as extensions of earlier works exploiting coupling between SAWs and arrays of mechanical resonators to slow down wave propagation by creating corrugations on the surface of the substrate [36]. Such corrugations could also induce shear horizontal (SH) waves that cannot be excited on a homogeneous surface, hence demonstrating the potential brought by surface structuring for the control or the generation, using mass-loaded interdigital transducers, or high-aspect ratio (HAR) transducers [70] of the polarisation properties of surface-guided waves. But where mass-loading affects the dispersion properties of the propagating wave, regardless of the operating frequency, local resonances allow for an enhanced energy trapping at the substrate surface specifically at the vicinity of the inclusion resonance frequency.
Within the context of the PhD work of Ludovic Socié (2010-2014), and inspired by our contribution to SAW locally-resonant phononic crystals, we proposed to take the concept of HAR transducer a step further by increasing the lateral confinement within an HAR transducer by reducing the width of the acoustical aperture down to a single wavelength. This resulted in the possibility to generate slow surface modes, exhibiting velocities as low as 1015 m/s for the first resonance, while Rayleigh waves in the material propagate at a speed of 3940 m/s. These pseudo-surface waves exhibit a general polarisation, involving vertical and shear horizontal components, as opposed to the sagittal polarisation of pure surface waves. Elastic field maps further revealed that the elastic energy was mostly distributed in the mass-loaded areas, leading to diffractionless confinement, even for very low acoustic apertures, as illustrated in Figure 3.4. The strong wave vector and polarisation mismatch between these low-velocity modes and the expected velocity for the semi-infinite substrate however prevented coupling to the surrounding homogeneous surface, making these kind of structures rather suitable for applications to resonators, rather



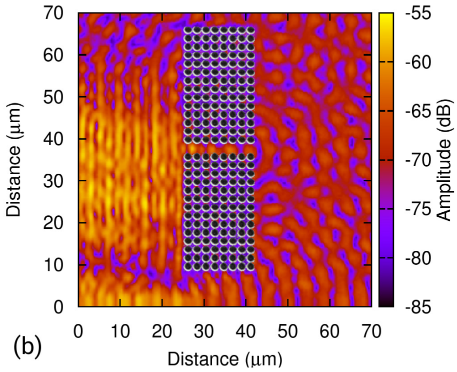


Figure 3.5: (a) Scanning electron microscope image of a phononic wave guide device with an eight-period-long crystal consisting of a square lattice of air holes etched into lithium niobate. The chirped transducers are visible at the left and right edges of the picture. A schematic drawing of the expected wave fronts launched by the source transducer and as leaving the structure after propagation through the wave guide are also shown.(b) Measured elastic wave field amplitude maps for excitation frequencies located inside the band gap (820 MHz). A semi-transparent scanning electron microscope picture of the holes overlays the measurement data.

than to transducers or genuine waveguides. The low velocities of these confined modes in addition limits the operating frequency of potential devices as compared to devices operating on Rayleigh waves or conventional pseudo-surface acoustic waves.

Phononic crystal waveguides

We have also investigated in parallel the possibility to achieve SAW propagation control in the GHz range in a classical, air/solid phononic crystal wave guide. The phononic wave guide was fabricated by introducing a one-period wide line defect in a crystal very similar to the previously proposed square-lattice structure (see section 3.4.1 and [P17]). The crystal therefore consisted in an array of 8×28 holes, with a diameter of 1.9 μm, a lattice constant of 2.1 μm and an estimated hole depth of about 2.5 μm. The defect-free phononic crystal showed a band gap from 650 to 950 MHz, as extracted from both electrical and optical characterisations. The electrical response of the wave guide sample, as characterized by radio-frequency probe testing, is strikingly similar to the one those observed for the defect-free phononic crystal. The entrance of the band gap lied at about 670 MHz, the exit cannot be inferred from these scattering parameter measurements. The guided modes, however, do not leave any signature on the radio-frequency measurements.
SAWs guided by the line defect could however be observed by laser scanning interferometry, as reported in Figure 3.5. At 820 MHz, a frequency within the band gap, the output field featured an interference pattern between a spherical wave issuing from the phononic wave guide and waves bypassing the phononic crystal, due to the limited lateral dimension of the crystal compared to the acoustical aperture of the input interdigitated transducer. No direct contribution of the plane wave source could be observed at the output. The incoming elastic field was transmitted through the wave guide, resulting in a

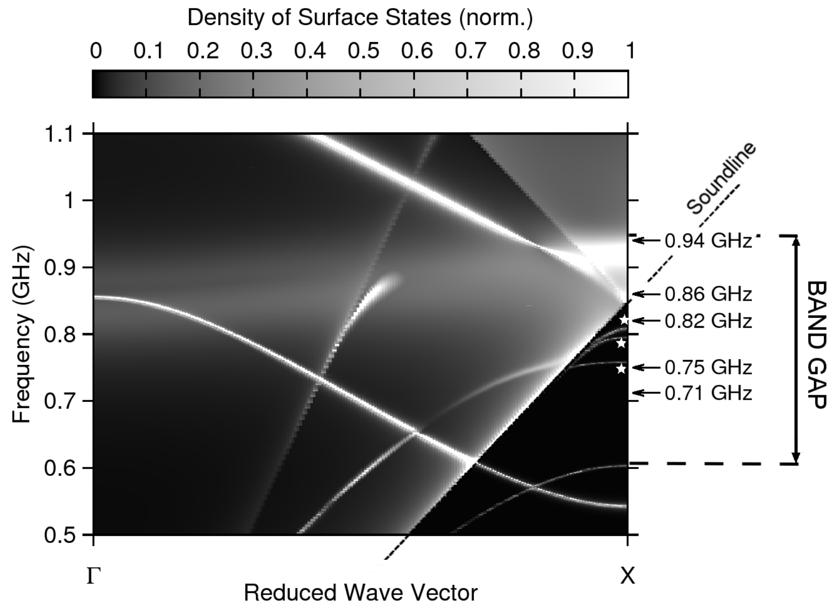


Figure 3.6: Density of surface states of radiative and non-radiative surface-guided modes propagating in the ΓX direction for a finite depth phononic wave guide. The computation assumes 2.5 μm-deep and perfectly cylindrical holes. The frequencies displayed on the left-hand side correspond to the excitation frequencies used in the experiments presented in Fig. 3.5. The white $\star$ symbols indicate the branches corresponding to the expected guided modes below the sound cone.

point source like emission spot at the output of the line-defect. A standing wave pattern was in addition observed inside the wave guide, probably resulting from the interference of two guided counter-propagating Bloch waves. At 940 MHz, a different transmission mechanism seemed at play. A modulation fringe pattern was still visible inside the wave guide but the free surface at the output supported ripples rather than highly contrasted fringes. The main contribution at the output was that of a plane wave directly incoming from the source and passing through the crystal. Additional scans demonstrated the strongly multimode character of the proposed W1 phononic waveguides. Wave guiding could indeed be observed at a number of frequencies, particularly in the 800–860MHz range and at about 750 MHz, although with different guiding strengths. The used optical measurements in addition underestimated the number of guided modes, by ruling out in-plane polarized waves or waves that can be polarisation-converted at the crystal interface. The calculation of the density of surface states presented in Figure 3.6 was in reasonable agreement with the experiments. The simulations predicted several guided waves with flat dispersion, particularly in the upper frequency range of the band gap, echoing the variety of modes experimentally observed between 800 and 860 MHz. Other guided modes could be spotted around 770 MHz, corresponding to those located at about 750 MHz in the experimental data. One of the most striking feature of these dispersion calculations lied in the density of surface states obtained for frequency lying within the sound cone. The predicted modes closely resemble leaky surface-waves, with a significant contribution at the substrate surface and a reasonable transmission above the sound line can be expected. The experimental observations of surface wave propagation through the crystal by optical interferometry were in good agreement with these predictions. Failure to observe these guided modes in the electrical response of the transducer was, again, most likely due to a wavefront mismatch between the cylindrical wavefront stemming from the output of the phononic wave guide and the straight-crested shape of the receiving interdigital transducer. This wavefront and phase mismatch prevented efficient regeneration of electrical signal by mechano-electrical conversion along the metal fingers.

3.4.4 Conclusion

This experimental demonstrations of surface wave band gap and wave guiding in a micron-scale phononic crystal structure operating in the hypersonic regime were the first of their kind at the time. They unveiled part of the potential of phononic crystal for advanced signal processing, a potential yet to be exploited: clearly, failure to recover an electrical signal at the output of the crystal in a straightforward manner remained a significant shortcoming. But there was another, promising lesson learnt from this early work: surface elastic waves could be efficiently confined within micron-sized defects. In other words, SAW could be confined and controlled within structures exhibiting characteristic dimensions commensurable with those of photonic crystals. This opened the possibility to design artificial crystals with simultaneous photonic and phononic band gap, in view of observing enhanced, or even unexpected classes of acousto-optical interactions.

3.5 Phoxonic crystals, optomechanics and highly-confined acousto-optical interactions

The core of my research activity since completion of my Ph.D. has been driven by a broad, and, as we will see, demanding goal, that I pursued with mitigated success, to say the least: exploring and exploiting the potential of micron-scale phononics for the implementation of enhanced elasto-optical interactions. The idea then was to develop the concept of *phoXonic crystals*, a class of man-made materials exhibiting simultaneous photonic and phononic band gaps. This research track was strongly inspired by pioneering works in semi-conductor superlattices, notably by the one reported by Trigo *et al.*in 2002 [71]. In this article, the authors reported on a one-dimensional doubly-resonant cavity ensuring the confinement of photons and Raman-generated high frequency phonons drawing attention to an obvious, yet thoroughly missed property: optical and elastic waves could be confined within a same volume, provided the operating frequency of the two types of waves, and hence their respective wavelength is adequately chosen. The subsequent works of P. Santos' group in the Paul Drude Institut, Berlin, introduced still greater latitude in the management of the interaction by using surface acoustic waves to modulate the properties of light propagating in 1D semiconductor superlattices [72]. Pivotal progress was made in 2005, with the proposition made by Prof. Russell's group at the University of Bath to extend these highly confined acousto-optical interactions to a bi-dimensional configuration. They indeed experimentally demonstrated that elastic waves could be confined in defect modes of a photonic crystal fibre preform with a lattice parameter of some tens of microns [73, 74], leading to simultaneous confinement of sound and light in two dimensions. This increase in dimension allowed to introduce an additional parameter, that could be tuned by an appropriate choice of periodical structure: dispersion. These findings were confirmed by a second theoretical analysis by A. Khelif *et al.* [75]. Laude *et al.* even proposed a fibre core geometry that would allow for simultaneous photonic and phononic crystal wave guiding [76]. It should be mentioned here that, even to date, there is no experimental report on genuine phoxonic wave guiding in actual photonic crystal fibres, although a significant number of works report on the control of guided acoustic waves or of acoustic resonances usually generated via nonlinear optical effects (e.g. Brillouin scattering or electrostriction), as in, e.g. [77–80].

The transposition of such an idea to two-dimensional and three-dimensional crystals can be dated back to 2006, when E. L. Thomas' group at the Massachusetts Institute of Technology theoretically demonstrated that phoxonic band gaps and cavities could be obtained in two-dimensional square- or hexagonal-lattice crystals made of air holes in a silicon matrix [81]. Akimov *et al.* then reported on modulation of light using hypersonic frequency elastic waves in a 3D phoxonic crystal made of silica spheres [82], without, however, demonstrating unambiguously the existence of simultaneous band gaps. In 2007, then, experimental reports of phoxonic band gaps and cavities were yet to be made.

The results obtained on microsonic and hypersonic crystals, the background of the Phononics team members in Optics and Condensed Matter physics, the presence, within the FEMTO-ST institute, of research groups involved in photonics, naturally pushed us to investigate further this concept of phoxonic crystals. The ingredients at hand seemed indeed to constitute a most favourable ground for investigations of both theoretical and experimental aspects. This pursuit of phoxonic band gaps then became one of my core research theme. We will see that this activity was accompanied by developments on more general aspects of confined acousto-optical interactions, that I actually started to investigate prior to my joining the CNRS.

3.5.1 Acousto-optical interactions in integrated optical devices

Acousto-optical interactions in domain-inverted ferroelectric crystals

Within the frame of my post-doctoral period at the Institut de Ciènces Fotòniques (ICFO), as a member of Prof. Valerio Pruneri's research group, we investigated the possibility to exploit domain-inverted structures in ferroelectric crystals, most notably lithium niobate, for the realisation of surface acoustic wave-based electro-acoustic and subsequently acousto-optical devices. This work constituted the core of the PhD thesis of Dr Didit Yudistira, then a Ph.D. student at the Universitat Politècnica de Catalunya. I was involved in the supervision of Dr Yudistira's thesis during my post-doctoral stay, but also after my recruitment at FEMTO-ST. We indeed maintained a level of collaboration with ICFO through a Didt Yuditira's 6-month-stay in 2008-2009 and through the obtaining of

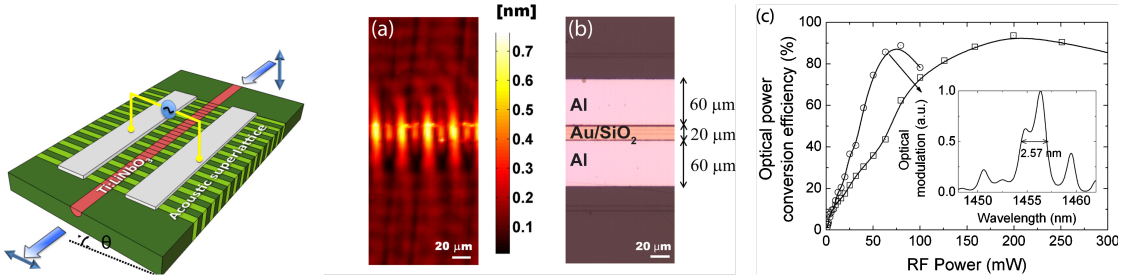


Figure 3.7: Left: Schematic of the proposed ASL-based acousto-optical tunable filter. Left: (a) Displacement profile of confined SAW field scanned with laser interferometry at RF of 187.5 MHz. (b) A photograph of the sample taken from a microscope in the same scale. (c) Optical power conversion efficiency as a function of electrical (RF) power: for mass-loaded sample (circles) and unloaded, reference, samples (rectangles). The inset shows output optical intensity modulation as a function of optical wavelength measured on mass-loaded sample at RF power of 63 mW and frequency of 187.5 MHz.

a *Partenariat Hubert Curien* in 2010.

The basic idea here was to exploit domain inversion of lithium niobate for applications to electro-acoustics and acousto-optics. Ferroelectric crystals can indeed be appropriately micro-structured through domain inversion [83]. In domain-inverted materials, the physical tensors with odd rank, such as the nonlinear optical or the piezoelectric tensor, change their signs from one domain to the next, whereas the even-rank tensors such as the permittivity one remain unchanged. In the so-called periodically-poled materials, domain inversion is usually achieved by electrical poling of the substrate material in a periodical fashion. Such structures have been extensively used in nonlinear optical frequency conversion devices, to achieve, e.g. quasi-phase-matched second harmonic generation or optical parametric amplification [83,84]. They have also been used in electro-optical devices [85,86]. Periodically-poled materials in addition present a potential for the realisation of electro-acoustic devices. It has indeed been shown as early as in 1992 that periodically-poled materials could operate as acoustic superlattices (ASLs) capable to generate and support bulk or Lamb elastic waves [87–89], exhibiting operating frequencies directly conditioned by the periodicity of the ferroelectric domains. Such periodically-poled acoustic superlattices were subsequently used as the basic constituting element of a bulk, monolithic acousto-optical tunable filter [90].

We searched to extend the concept and application of ASLs to surface acoustic wave devices, notably based on the offered capability to generate SAWs using uniform coplanar electrodes, instead of periodic electrodes as used in IDTs. In periodically-poled structures, the application of a uniform external electric field will subject the domain walls to a periodic strain resulting from the periodic change in the piezoelectric coefficient, effectively resulting in localized sound sources, and hence on elastic wave generation. In ASLs, the elastic wavelength is therefore directly given by the periodicity Λ of the lattice, resulting in a SAW frequency given by $f = v\Lambda$, where v is the acoustic wave velocity. A remarkable feature of these ASLs is then that the achievable SAW device operating frequency is twice that can be obtained from standard IDTs featuring the same electrode pitch. This is however counter-balanced by the reduced achievable resolution induced by the poling process itself. The use of coplanar electrodes, however, can be beneficial for the realisation of integrated acousto-optical devices: the SAW is indeed generated and naturally guided in the region in between the electrodes, making such a configuration particularly well-suited for collinear wave-guided acousto-optical interaction.

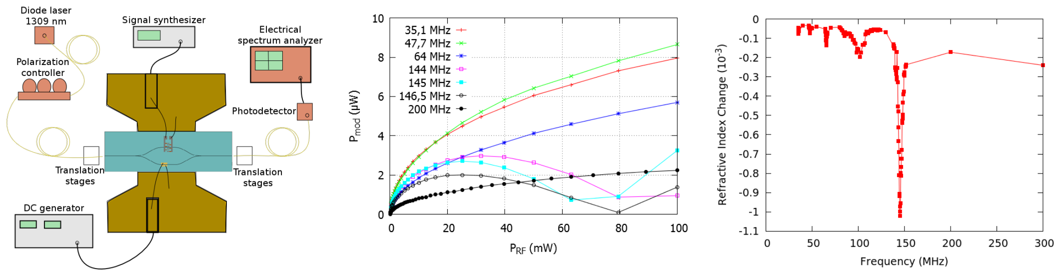
We have therefore demonstrated the direct generation of Rayleigh surface acoustic waves in an ASL made of periodically-poled lithium niobate (PPLN) in the ZX-crystallographic orientation. The coplanar electrode geometry forces the electric field to be confined in the crystal region between the electrodes. A first device, with a gap width of 100 μm and an operating frequency of 253 MHz allowed us to confirm that the effective electromechanical coupling coefficient remained similar to that obtained with standard IDTs (3%). The structure supports at least a symmetrical and an asymmetrical mode, as well as higher order modes as the gap distance increases. The resonance frequency of the first two modes becomes asymptotically closer as the gap width increases. Investigation of the mode profiles using laser interferometry showed that the symmetrical mode tends to be localized in the central region between the electrodes, whereas the anti-symmetrical mode is rather located below the electrodes [P30]. This localisation was exploited for the realisation of acousto-optical polarisation converters based on titanium-indiffused lithium niobate waveguides, as illustrated in Figure 3.7. Diffraction efficiency close to 90% could be obtained with drive power below 100 mW, leading to at least a ten-fold enhancement compared to their bulk counterparts [P27]. The power consumption of the device was in addition reduced by yet increasing the confinement of the elastic wave through mass-loading of the substrate surface [P21]. AO measurements revealed a three-fold improvement in power conversion efficiency on the mass-loaded sample with respect to unloaded ASL-based AO device.

Integrated acousto-optical modulator based on high aspect ratio interdigital electrodes

Along a similar line, we tried to use the high-aspect ratio transducers developed during the Ph.D. thesis of Ludovic Socié for the implementation of acousto-optical modulation functions.

We therefore worked on the realisation of an optical intensity modulator exploiting the elastic energy trapping capabilities of HAR-IDTs. The proposed device relied on an integrated Mach-Zehnder interferometer (MZI) consisting of optical waveguides obtained by annealed proton-exchange of a lithium niobate substrate in the X-crystallographic orientation. The acoustic modulation is applied through an 18-μm pitch HAR IDT on a single arm of the interferometer in a transverse configuration, as shown in Figure 3.8. The device was optically characterized in a butt-coupling configuration and the output signal monitored in both the time and frequency domains.

A strong slowing down of the acoustic wave velocity along with a tight confinement of the elastic displacement field in the electrodes was again observed, resulting in a wave velocity of 1200 m/s for the slowest mode. A leaky surface wave could also be excited at about 145 MHz. A modulation of the output optical signal was observed for each of the IDT resonance frequencies. The measured acousto-optical modulation amplitude was



(a) (b) (c)

Figure 3.8: (a) Schematic of the experimental set-up used for the characterisation of the proposed acousto-optical intensity modulator. (b) Measured acousto-optical modulation at each of the transducer resonance frequencies. (c) Static refractive index change observed from the shift in the channeled spectrum of the integrated Mach-Zehnder interferometer, obtained for a RF input power of 20 dBm.

however limited to 15% for a confined mode, and to 5% for the leaky SAW), mostly due to the non-optimized operation point of the used MZI. More unexpectedly, measurements performed at zero-frequency with an optical spectrum analyzer revealed a wavelength shift of the interferometer channeled spectrum reflecting a static modulation of the optical signal. This effect is directly linked to the electro-acoustic response of the HAR IDT and resulted in a shift as high as 20 nm at 145 MHz. The origin of this static shift could not be determined. Possible explanations could be found by investigating the thermo-optic effect or by considering charge accumulation at the electrode edge. These two hypotheses are yet to be explored, but the proposed configuration could open interesting prospects for the realisation of integrated acousto-optical devices and quite notably to acousto-optical tunable filters.

Acousto-optical modulation of a lithium niobate photonic crystal

The previously presented strategies for the realisation of enhanced acousto-optical devices relied on an increased confinement of the elastic energy at the vicinity of an optical wave guide. An alternative, as mentioned in the introduction to this Section, is to exploit the unusual dispersion features of photonic or phononic band gap materials. This specificity was investigated by colleagues of the Optics department of FEMTO-ST in 2006 in the context of electro-optical modulation. Roussey *et al.* indeed took advantage of slow light effects at the band gap edges of a two-dimensional lithium niobate photonic crystal to demonstrate enhanced electro-optical interactions [91]. Slow light effects in this case resulted in an increase in interaction time and therefore in effective interaction strength between the optical field and an externally-applied electrical field. An enhancement factor of the electro-optical modulation of 312 was obtained, leading to the demonstration of a highly-compact and efficient photonic modulator.

In collaboration with this research group, we investigated the acousto-optical equivalent of such a slow-light photonic modulator on an X-cut lithium niobate substrate [P26]. A square-lattice photonic crystal, designed to exhibit a band gap at 1.55 μm, was fabricated atop a proton-exchanged optical wave guide allowing guiding of transverse-electric (TE) polarized waves. The crystal was inserted within a SAW delay line, consisting of a pair of interdigital transducers launching Rayleigh waves propagating along the Z-axis of the $LiNbO_3$ crystal. Adjusting the phase between the two IDTs allowed to control the positions of the maxima of the elastic displacement field, allowing to adjust the point of maximum strain on the photonic crystal. Under such configuration, the strain and electric field accompanying the elastic displacement field on the piezoelectric substrate induced, respectively, an elasto-optical and an indirect electro-optical effect, leading to a change in dielectric constant, provoking a shift in the spectral gap position. The device was then expected to operate as a band-edge intensity modulator. Comparing the estimation of the expected refractive index change inferred from direct measurement of the elastic displacement field with the band gap shift actually induced by the SAW allowed us to demonstrate an acousto-optical enhancement factor of the order of 60, further illustrating the potential of slow-wave photonic devices for the realisation of highly-compact and low-power consumption active integrated optical devices.

The next, natural step, was then to bring these concepts a step further by working towards the demonstration of simultaneous photonic and phononic band gaps, combining the added-value of both confinement and dispersion management.

3.5.2 Phoxonic crystals

This section summarizes what has constituted the heart of my research activities over the first seven years as a CNRS researcher: the pursuit of phoxonic band gap materials, or more generally, of confinement of elastic and optical waves in ultimately small volumes. A number of tracks have been investigated, involving different substrate materials, but also different types of physical structures. None of them have up to now met a happy-ending, and the initial objective remains, to some variable extent, part of my current and potentially future concerns, not to say perspectives. There have however been, some notable contributions, and a number of lessons learnt that we try to summarize below.

Lithium niobate phoxonic crystals

The realisation of a lithium niobate phoxonic crystal has been one of the main driving objective of my post-doctoral period. These activities were mostly pursued within the context of the project *PhoXcry*, funded by l'Agence Nationale de la Recherche (ANR) from 2009 to 2013. I had at the time widely contributed to the writing of the corresponding research proposal. The project itself, coordinated by Vincent Laude, was involving, outside FEMTO-ST, the Institut de Microélectronique et de Micro- et Nano-technologie (IEMN) in Lille, the laboratoire de Physique de la Matière Condensée (LPMC) in Nice, and Thales R&T (Palaiseau). The search for lithium niobate phoxonic crystals was also at the core of Said Sadat Saleh's Ph.D. thesis (2007-2010), jointly supervised by Vincent Laude (Phononics group) and Maria-Pilar Bernal (Nano-optics group) of FEMTO-ST. One of the main achievement of Dr Sadat Saleh was to design a crystal geometry simultaneously hosting a photonic and a phononic band gap. The theoretical models involved

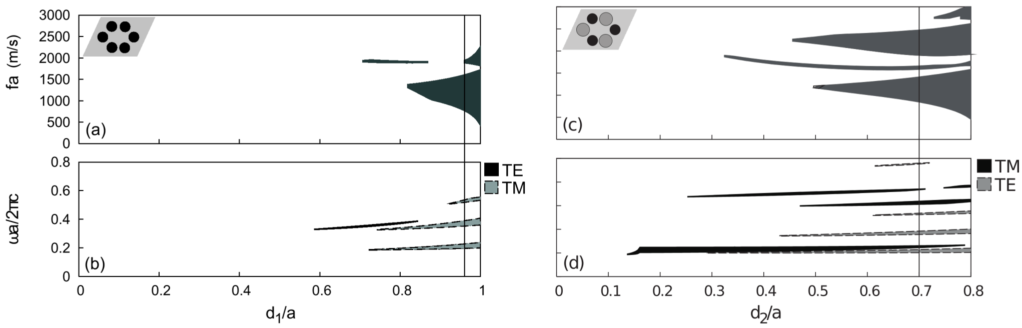


Figure 3.9: Phononic (a) and photonic (b) gap maps for a honeycomb lattice array of circular air holes in lithium niobate as a function of the diameter to pitch ratio d_1/a. Phononic (c) and photonic (d) gap maps for boron-nitride-like crystals made of circular air holes in lithium niobate, as a function of the diameter to pitch ratio d_2/a, for $\beta = d_1/a = 1.2$. Photonic gap maps are given for both the TM (black) and the TE (light gray) polarisations and are displayed in units of the normalized frequency ($\omega a/2\pi c$). Phononic band gaps are displayed in units of the product $f \cdot a$, where f is the acoustic frequency.

considered the electromagnetical and the elastic aspects in a independent fashion. Photonic band structures of different lattice types of crystals consisting of arrays of air holes on lithium niobate substrates were calculated using a finite-difference time-domain code, as developed by Prof. Fadi Baida at FEMTO-ST. Phononic band structures were obtained using a code relying on the plane-wave expansion method as developed by V. Laude. In both cases, the models remained two-dimensional. The design was driven by the practical concern of future realisation and characterisation of such a crystal. An operating optical wavelength of 1.55 μm was aimed at and the elastic wave frequency was due to remain at most in the low-GHz frequency range. These numerical investigations highlighted that the classical triangular and square lattices, as widely used, respectively, in the fields of photonics and phononics were quite ill-suited. Lowering the crystal symmetry yielded, as expected, better results, and the honeycomb or boron-nitride lattices eventually proved to be better candidates [P28], as illustrated in Figure 3.9. The anisotropy of lithium niobate, however, prevented to obtain a full photonic band gap, that is, a band gap whatever the optical wave polarisations. We therefore focused on the design of a crystal exhibiting a band gap for TE-polarized wave, this polarisation corresponding to the one typically guided by proton-exchange optical waveguides.

A honeycomb lattice crystal was therefore subsequently fabricated on a lithium niobate substrate, using focused ion beam milling. The air hole diameter was set to 1.1 μm for a pitch of 1.3 μm. The substrate integrated a proton-exchange optical wave guide and a pair of interdigitated transducers. The crystal characterisation led to the demonstration of a phononic band gap for surface-waves, as shown by electrical and interferometrical measurements of the elastic displacement field as reported in Figure 3.10. The phononic band gap extended from 670 to 790 MHz and exhibited features comparable with those obtained out of the previously mentioned hypersonic square-lattice crystal of Section 3.4.1 and reported in [P17]. We failed, however, to demonstrate unambiguously the existence of a photonic band gap. If an extinction of the optical signal and a modulation of the

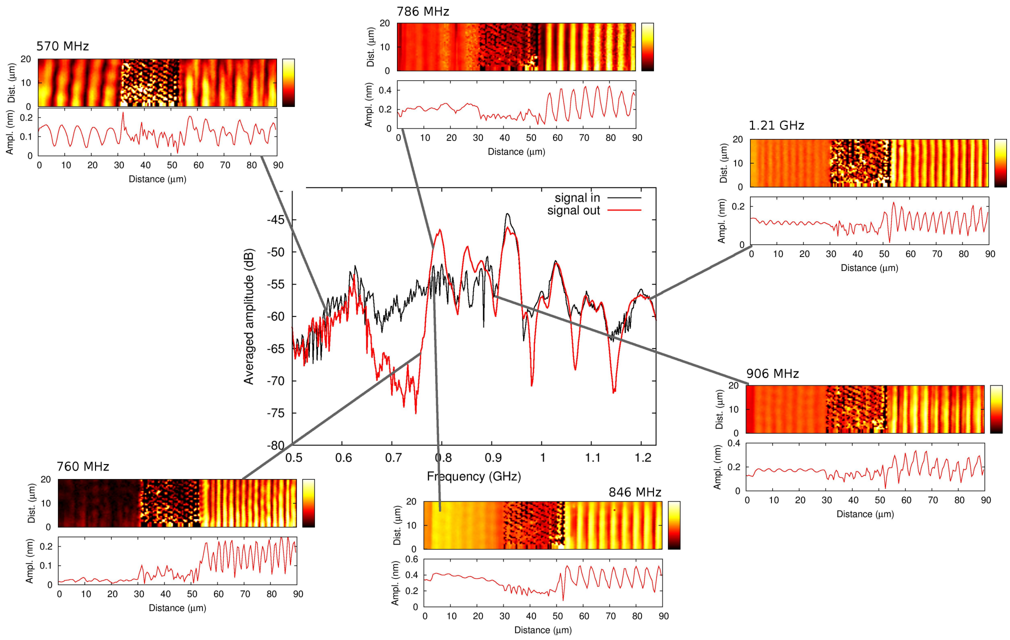


Figure 3.10: Normalized transmission through the phononic crystal obtained by heterodyne optical interferometry. The amplitude of the out-of-plane component of the surface wave displacement field is measured before and after the phononic crystal. The output amplitude is then normalized with respect to the input signal. The measurements are taken with a 1 MHz step in the 500 MHz to 1.25 GHz frequency range, that roughly corresponds to the operating frequency range of the chirped interdigital transducer. The frequencies at which the field maps presented have been taken are also reported.

optical response could be measured, they were this time attributed to optical losses and radiation to the bulk: one of the main limitations of the proposed approach actually lied in the combination of the limited hole-depth achievable on lithium niobate samples. In our case, the hole depth was estimated to be about 2 μm. The optical wave guide, however, was fabricated using conventional proton-exchange. In this case, the optical mode is buried a few microns away from the surface and the optical mode itself extends over a few microns, given the graded-index character of proton-exchanged wave guide. Even by carefully tuning the wave guide fabrication process, the optical mode extended at least a few microns away from the substrate surface. The guided mode was therefore experiencing a surface perturbation rather than the effect of a photonic crystal. An assumption is that this surface perturbation resulted in a change of effective refractive index, leading to radiation losses that resulted in transmission loss at 1.55 μm. This hypothesis was verified experimentally, although the matching theory was not developed at the time: changing the pitch of the crystal by maintaining a constant filling fraction did not shift the spectral response of the optical signal, while a change in filling fraction for a constant crystal pitch resulted in a shift of the cut-off frequency of the wave guide. We also investigated the effect of a DC modulation, by applying a static electric-field around the crystal. The optical response should indeed be modulated, but here again, this modulation was rather due to a modulation of the wave guide refractive index and hence of the wave guide cut-off frequency, independently of the photonic band gap.

These results questioned the relevance of using bulk lithium niobate crystal as the base material for the realisation of phoxonic crystals. The difficulty to achieve high-aspect ratio micron-scale structure on lithium niobate, combined with the requirements imposed by optical wave guiding, could not be easily overcome, leaving us to look for an alternative where the intrinsic properties of the substrates were to be sacrificed on the altar of technological feasibility.

Phoxonic crystal slabs

Our previous attempts on phoxonic crystal have led us, as one could have expected, to turn to the investigation of membrane-based devices. Slabs have the intrinsic capability to confine both optical and elastic waves, a property that has been widely exploited for photonic and phononic crystals alike.

We tried to explore this alternative within the frame of the European Future Emerging Technology (FET-Open) *Tailphox* (2009-2012), coordinated by Alejandro Martinez from the Universitat Politècnica de València. The objective here was to benefit from the availability of strategically-relevant and technologically-friendly silicon-on-isolator (SOI) substrates, that were already widely spread and used in the photonic crystal community. To this aim, we developed a number of numerical tools based on the finite element method, that allowed us to design suitable crystal geometries allowing to open phoxonic band gaps operating at optical telecommunication wavelengths. The honeycomb lattice proved once again particularly relevant [P16][P23]. The simultaneous obtaining of a phononic and photonic band gap raised some constraints on the substrate thickness, and the obtaining of a phoxonic crystals hence required respecting a well-defined lattice pitch/filling fraction/substrate thickness triplet. The defined geometries remained however, comfortably practical from a fabrication point of view, if we except the need to use SOI wafers with a custom device layer thickness of 400 nm to ensure operation at an optical wavelength of 1.55 μm.

The main technological bottleneck this time lied in the elastic transduction. One of the project objective was indeed to integrate electrically-pumped elastic sources on a phoxonic crystal slab.

Integration of elastic wave sources required a number of challenging technological steps, including the deposition of a piezoelectric thin film and the need to ensure process compatibility between the interdigital tranducer fabrication process and the phoxonic crystal slab process. Given the geometrical configuration of the considered samples (silicon slabs), interdigital transducers appeared as a natural choice to generate the Lamb waves sought after, much similarly to what was previously achieved during our collaboration with the CEA-LETI, mentioned in section 3.4. We also chose to work with Aluminum Nitride as a piezoelectric base layer.

If the fabrication of Lamb wave sources and delay lines operating at frequencies up to 5 GHz could be demonstrated on an AlN/400-nm Si layer stack (Figure 3.11), the difficulty of transposing the process to fully released Si membranes could not be overcome. Our incapacity to clear this hurdle prevented us to reach a successful experimental outcome within the project time frame.

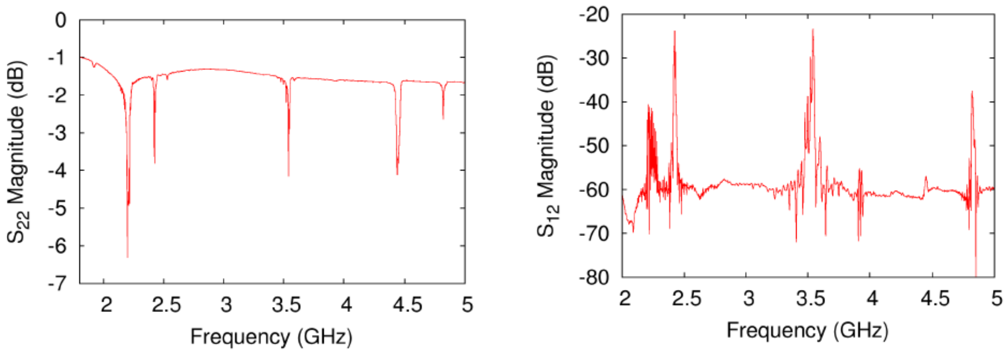


Figure 3.11: (a) Reflection scattering parameter measurements (S_{11}) of a transducer fabricated atop a 400-nm Si slab measured in the range 1.8 to 5 GHz range. Five modes, including one lying as high as 4.8 GHz are clearly visible. (b) Transmission scattering parameter measurements (S_{12}) of a corresponding delay line.

3.5.3 Conclusion

I have been pursuing, over the years, a number of attempts to demonstrate novel, or at least, enhanced acousto-optical interaction schemes. This wide objective remains topical and I will definitely keep the research track in the coming years.

Yet, my research work dedicated to phoxonic crystals has been characterized by underwhelming experimental results. The numerical achievements, led by Dr Vincent Laude which I have participated to some limited extent at an early stage, have most certainly earned the group an international recognition in the field. But experimental confirmation of these numerical findings are still lacking, and we have somehow failed as well to demonstrate indubitably the potential of Phoxonics in general to the then rising and now thriving field of Optomechanics. Still, the lessons learnt in these various attempts have allowed us to increase our experimental and technological potential. It has also opened a number of perspectives, our involvement in the community having widened our initial interests, focused on Phoxonics, to the larger field of optomechanics. The point now is to find an adequate platform allowing to exploit the elastic energy confinement offered by phononics. If phononic crystals obviously remain amongst the considered possibilities, an alternative could be to exploit the concept of local resonances in a somewhat different approach, outside the usual periodic or collective scheme. We will see that this topic has been at the center of my research activities for the past five years.

3.6 Surface-coupled phononic resonators

The concept of local resonances has been steadily gaining momentum in the field of phononics and acoustic metamaterials. The phononic-crystal literature has indeed witnessed significant progress in the understanding of the hybridisation mechanisms underlying the coupling between resonant scatterers and waves propagating in the surrounding continuous medium in both classical periodical phononic crystals and disordered media.

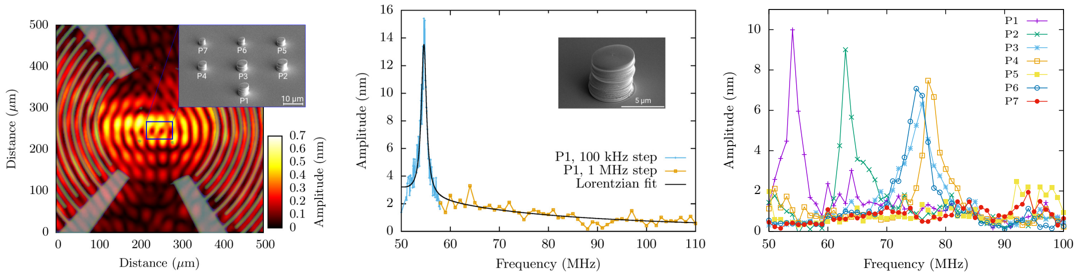
We, amongst others, have applied this concept successfully to surface acoustic waves, and it has also been shown that interaction between SAW and local resonators could also be used beyond wave propagation management, for instance to investigate contact resonance effects at the micron scale in granular materials [92, 93]. As already mentioned, such approaches can also be considered as extensions of earlier works exploiting coupling between SAWs and arrays of mechanical surface resonators to slow down wave propagation by creating corrugations on the surface of the substrate [36]. Theoretical investigations of the interaction between propagating Rayleigh waves with mechanical oscillators randomly distributed on the surface have also shown interesting dispersion characteristics, including anticrossings due to mode repulsion resulting from coupling of the surface wave with the resonator eigenmodes [94]. These features are very close to those observed when considering surface plasmon polaritons at single interface [95]. In acoustics or phononics, however, the local resonance concept has mostly been tackled as a way to control wave propagation through a collection of resonators, and works dealing with resonant elements are scarce [96]. The interaction of isolated resonators with a supporting surface is usually considered in the light of micromechanics where it is seen as an intense source of losses and considered as detrimental. Yet, similarly to what has been achieved in plasmonics [97], such an approach could make it possible to conceive phononic circuits capable of carrying the elastic energy in subwavelength structures. But considering the question in the light of micro- and nano-mechanics opens even larger perspectives. If arrangements of such individual locally-resonant structures can be used as a means to harness elastic wave propagation, surface acoustic waves can reciprocally be considered as a way to dynamically and coherently control the resonator motion.

We have therefore been working to try to unveil the potential lying behind this combination of micro- nano-scale resonators with surface acoustic waves with the initial objective to demonstrate the possibility to trap the elastic energy at a deep sub-wavelength scale. We have started a series of investigations aiming at producing and exploiting complex systems of surface-coupled mechanical resonators that we plan to exploit in the linear regime, for instance to demonstrate SAW wave guiding along a chain of micro-scale resonators; but also in the nonlinear regime, with the objective to achieve phononic parametric interaction in a very small volume. These activities have been led within the frame of a Young Researcher Project, *PhoRest* (Surface Coupled Phononic Resonators), funded by ANR, that I coordinated from December 2014 to March 2019. Most of the work reported on coupled resonators was part of Laetitia Raguin's Ph.D. thesis (2016-2019).

This Section of the manuscript gives a summary of the current achievements of what is still a work in progress. We will see that such hybrid platform, merging SAW and mechanical resonators, remains at the center of our mid- to long-term perspectives.

3.6.1 Surface wave coupling to single resonators

The very first step towards such development lied in the capability to demonstrate that SAW to resonator coupling can be used to excite discrete micron-scale mechanical resonators and to confine the elastic energy within [P3]. To this aim, a simple experimental system was investigated. A set of individual resonators were fabricated atop a lithium niobate substrate hosting interdigital transducers. We opted for ion-beam induced de-



(a) (b) (c)

Figure 3.12: (a) Measurement of the out-of-plane component of the displacement field generated by a chirped annular interdigitated transducer for an excitation frequency of 75 MHz. A microscope picture of the fingers and pads overlays the measurement data as a guide for the eye. Inset: scanning-electron-microscope image of the fabricated pillars. (b) Frequency response of pillar P1. The frequency step is refined to 100 kHz around the resonance. (c) Frequency response of the pillars shown in inset, obtained by retrieving the maximum amplitude of vibration of each resonator P1 to P7 as a function of excitation frequency. The frequency step is 1 MHz.

position (IBID) as a resonator fabrication method. In addition to serving the purpose of controlling the geometry of the fabricated resonators individually, the idea here was to contribute to the development of this deposition technique, that allows for unprecedented three-dimensional structuring capabilities with a potentially nanoscale accuracy (see Section 3.25). We will see that at this preliminary stage, we have been using this technology at a level well below its intrinsic capabilities. We indeed focused on simple, cylindrical pillars as test objects. The resonators exhibit dimensions ranging between 3 to 5 microns in both height and diameter. The choice of resonator dimensions is driven by the need to distinctly map the displacement field at the pillar surface using optical interferometry in order to retrieve the resonance mode shape. We used an FEI Helios Nanolab 600i Dualbeam FIB-SEM system readily available within the MIMENTO technology center of FEMTO-ST. The process development and sample fabrication are to be attributed to Dr Roland Salut, Nanotechnology Research Engineer within MIMENTO. A gas injection system (GIS) dedicated to platinum deposition was used to locally inject the trimethyl-(methylcyclopentadienyl)-platinum(IV) precursor on the sample. The resulting material is amorphous and its mechanical properties quite undocumented, we will see in Section 3.25 that they have stood at the core of an investigation of their own. The atomic composition of the system can however be readily characterized by energy-dispersive X-ray spectroscopy and that points at a ratio of 53% of platinum, 18% of gallium, and 29% of carbon. Independent investigation reported below, led to rough estimations of the density (10^4kg m^{-3}) and of the Young's modulus, that was estimated to range at about 100 GPa at this stage of the investigations. A SEM image of the resulting sample is reported in Fig 3.12a. The surface of the pillars is tilted with an angle of about 7° with respect to the substrate surface. This tilt angle is partly due to the injection nozzle position during the growth process. We will see that we have developed strategies at a later stage to yield better-controlled pillar geometries.

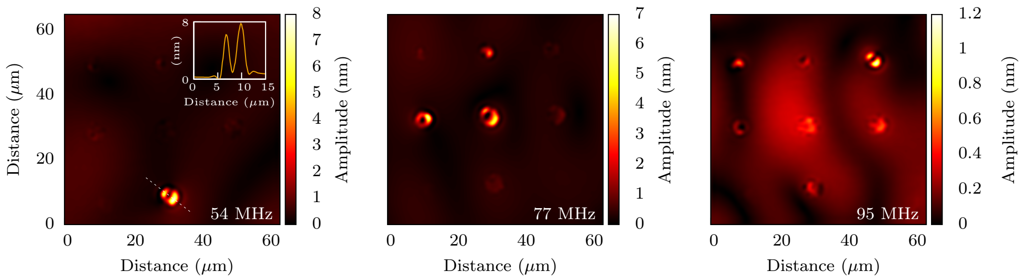


Figure 3.13: (a) (b) Out-of-plane displacement for excitation frequencies of 54 MHz, 77 MHz and 95 MHz. The scans cover an area of 60 μm $\times$ 60 μm with a 0.5 μm step size. Inset of (a): cross-section of the vibration amplitude for pillar P1 along the dotted line.

We here chose to focus on the excitation and detection of the first flexural mode of the resonator, for which radiation to the bulk is intrinsically low because of the dipolar character induced by the modal symmetry. A first approximation of the pillar resonance frequencies was obtained by considering a single pillar Pt-pillar sitting on a lithium niobate half-sphere and yielded resonance frequencies between 50 and 90 MHz. The resonators were then excited by a broadband quasi-annular interdigital transducer, operating at about 70 MHz with a 75% relative emission bandwidth.

The frequency response of one of the resonators is reported in Figure 3.12b. The resonance frequency is about 54 MHz. The quality factor of the resonator is about 40, leading to a quality factor-frequency product ($Q-f$) of the order of 10^9 at room temperature and ambient pressure. Surprisingly, the value compares well with those exhibited with much higher aspect ratio resonators used within the context of optomechanical experiments [98]. A striking feature lies in the recorded out-of-plane displacement field amplitude. The displacement is of the order of 14 nm, for a maximum of 1 nm at the substrate surface. Further optical characterisations of the entire set of micropillars, reported in Figure 3.12c show that each resonator responds at a specific frequency dictated by the geometrical characteristics of the fabricated structures. Five out of seven pillars exhibit a clear response in the frequency range of interest. The vibration amplitude of P5 and P7 is seven to eight times lower, as their resonance frequency is very close to the emission edge of the surface acoustic wave source. For pillars P1 to P4 and P6, the out-of-plane displacement is of the order of 8 to 10 nm for a maximum of 1 nm at the substrate surface. There is therefore a seven to ten-fold increase in amplitude, compared to the one measured for the incident Rayleigh wave. Figure 3.13 presents the displacement field maps obtained for excitation frequencies of 54, 77, and 95 MHz. A significant elastic field enhancement in the pillar with respect to the surface is revealed by the measurements, confirming that the elastic energy can be efficiently coupled through the substrate surface in the resonators under potentially radiative conditions. The vibration at the pillar surface features a nodal line at the center, as expected for a first-order flexural mode. This observation suggests that the excited mechanical resonances correspond to natural eigenmodes of the phononic resonators. The pillars are addressed independently as a function of drive frequency: the

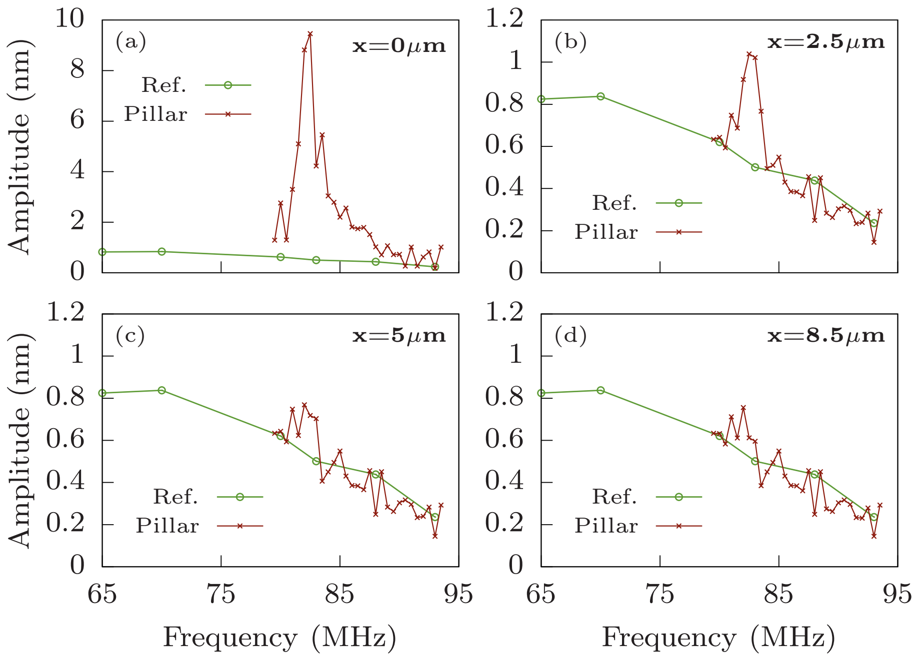


Figure 3.14: Displacement amplitude measured at the surface of a substrate hosting a 3.2 μm-diameter, 3.3 μm-high Pt pillar, obtained by retrieving the maximum amplitude of vibration as a function of excitation frequency and measured at different radial distances x to the pillar center. The response of the surface elastic wave excitation source obtained from a pillar-free sample is given as a reference.

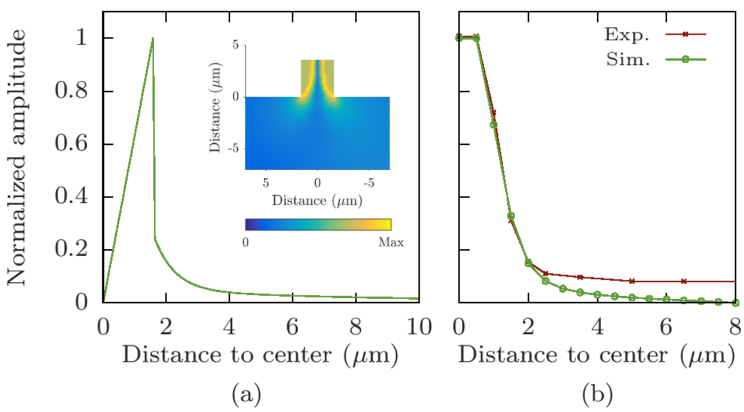
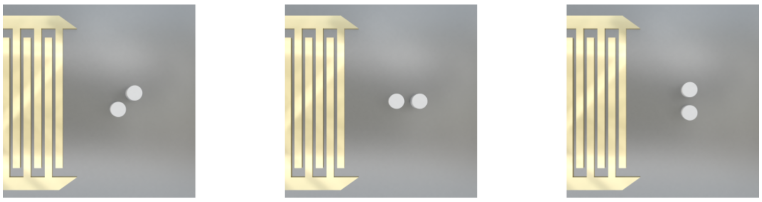


Figure 3.15: Elastic energy decay at the substrate surface as a function of distance to pillar center: (a) Simulation results obtained by cross-sectioning the elastic field maps obtained through time-harmonic simulations. The two-dimensional cross-section in inset shows the spatial distribution of the elastic energy within the pillar and beneath the substrate surface. (b) Comparison between experimental measurements and numerically convoluted simulation data.



(a) (b) (c)

Figure 3.16: Schematic of the proposed excitation schemes. Three impinging SAW wave vector directions are considered for excitation of the pillar pair, respectively corresponding to a diagonal (a), a longitudinal (b) and a transverse (c) coupling scheme; the gap distance is set to either 1.5 μm or 6 μm.

ability to control individually the geometrical properties of the resonators further provides a direct way to control dynamically the energy distribution at the substrate surface.

The confinement of the elastic energy within such resonators was then investigated. The displacement amplitude measured at the surface of a substrate hosting a 3.2-μm-diameter, 3.3-μm-high Pt pillar, at different radial distances to the pillar center are reported in Figure 3.14. The amplitude of displacement decays rapidly outside the pillar. The elastic energy decay measured experimentally fares well with associated numerical simulations developed by Dr Abdelkrim Khelif, reported in Figure 3.15. The displacement amplitude measured outside the pillar tends to the one at the free surface within a distance much lower than the characteristic wavelength of the excitation signal. This supports the achievement of a tight control of the spatial distribution of the elastic energy within such phononic resonators.

3.6.2 Surface-mediated resonator-to-resonator coupling

As a natural sequel of this work, we have investigated the influence of surface acoustic waves in the coupling mechanism between two neighbouring resonators [P1]. The investigation is still in progress, but a number of results have already been obtained.

The system under consideration simply consists in a pair of resonators. Again, to simplify the characterisation process, we have opted for cylindrical pillars with a diameter and a height of 4 μm. Several pairs were fabricated, with different separation distances. We will here focus on configurations with gap distances of 1.5 μm and 6 μm. Three excitation schemes are considered, as illustrated in Figure 3.16: a longitudinal coupling scheme, where surface acoustic waves propagate along the inter-resonator axis (Fig. 3.16b); a transverse coupling scheme, with waves propagating in the orthogonal direction (Fig. 3.16c); and a diagonal case, where the incident wave vector forms an angle of $\pi/4$ with the inter-resonator axis (Fig. 3.16a). The results obtained for a gap distance of 6 μm in the longitudinal and transverse configuration are reported in Figures 3.17a and b respectively. The broadening of the response, clearly visible for pillar P8, suggests that resonator-to-resonator coupling occurs. The experimental displacement field maps displayed show that the elastic energy distribution swaps from one resonator to the other as a function of drive frequency, going through a specific coupled state where the polarisa-

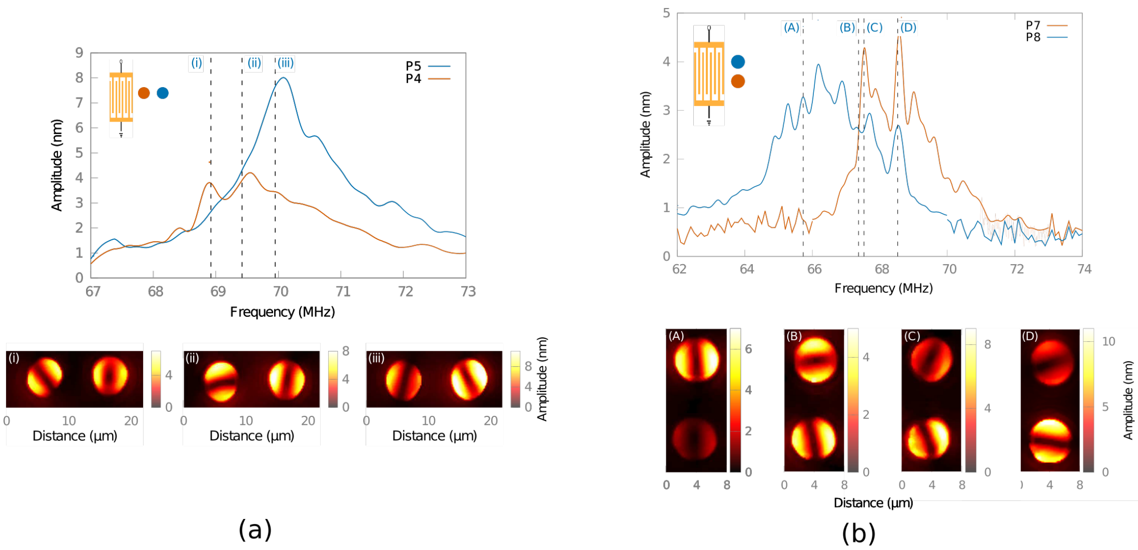


Figure 3.17: (a) Experimental frequency responses of 6 μm-spaced pillars in a longitudinal excitation configuration. Bottom: corresponding out-of-plane displacement field maps for typical excitation frequencies. The scan area is 8 μmm$\times$19 μmm, with a step size of 200 nm. (b) Same as (a) for a transverse excitation.

tions of the two pillar modes are orthogonal. This behavior is characteristic of the avoided crossings observed in classical, e.g. electrostatically-driven paired mechanical resonators. Outside this crossing point, the resonators tend to orient in the direction either parallel or orthogonal to the incident surface wave vector. The pillar pair behaves much similarly to a set of paired mechanical beams vibrating on a flexural mode, whatever the impinging SAW wave vector direction. Their behaviour then echoes the one observed when considering coupling between nanomechanical string or beam resonators [99, 100] and can be seemingly described as a four-mode coupled resonator system [100].

Interaction between the two pillars through the substrate surface is then expected and demonstrated to occur in the field maps displayed in Figure 3.18 in the case of a transverse (Fig. 3.18a) and a longitudinal (Fig. 3.18b) excitation. This interaction reciprocally leads to a channeling of the elastic energy at the substrate surface. The amplitude of the 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 localisation directly conditioned by the direction of vibration of the pillars.

Decreasing the spacing between two resonators however leads to a change in coupling regime. Figure 3.19 displays the results obtained for a pillar pair with a 1.5 μm gap distance for the three excitation directions. In the case of a diagonal incidence, splitting into three different modes is observed for each resonator. 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 3.12b. 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

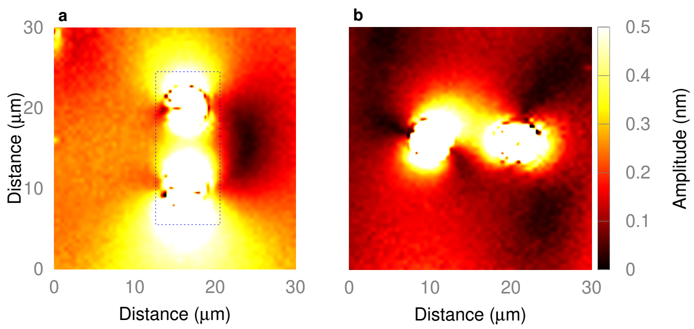
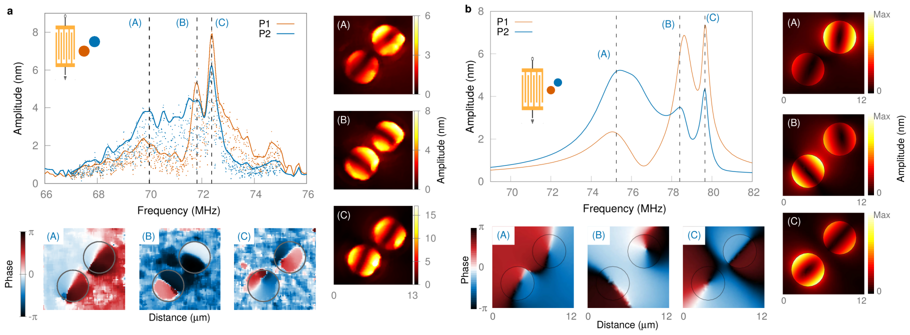


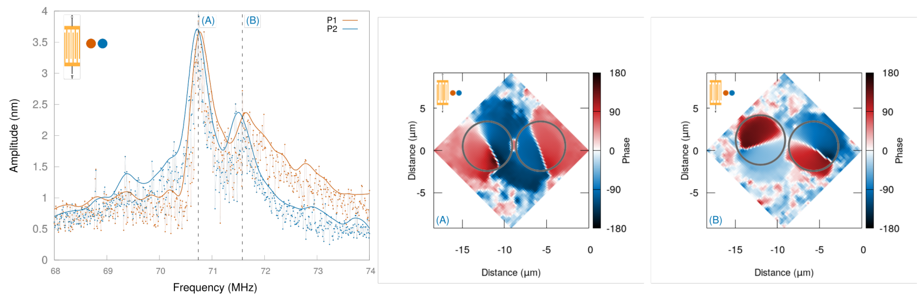
Figure 3.18: (a) Out-of-plane displacement field maps on the substrate surface for 6- μm-spaced pillars for (a) a transverse excitation at 68.53 MHz (mode D) and (b) a longitudinal excitation at 66.26 MHz. The scan area is 30 μm$\times$30 μm, with a step size of 500 nm. The color scale is saturated to highlight the field displacement at the substrate surface. The dashed rectangle indicates the area corresponding to the data reported in Fig. 3.17.

increased quality factors around 140 and 110 respectively for P1, are characteristic of resonator coupling. The displacement field measurements 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 repulsive dipole modes, with pillars respectively in-phase and out-of-phase and exhibiting orthogonal polarisations. 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. The observed response is actually very close to the one observed in plasmonic heterodimers [101]. Rather than a mechanical interaction, the system here interacts following a dipole-dipole like interaction. These experimental observations can be compared with finite element method (FEM) simulations results reported in Figure 3.19a (right), that displays three separate peaks including two with higher quality factors. 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 behaviour is in reasonable agreement, the influence of the incident wave source seems more significant in the numerical simulations. In the case of mode (i), the orientation of the pillar vibration indeed deviates from the direction defined by the inter-resonator axis, which results in a mode polarisation 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 dipole-dipole interaction prevails.

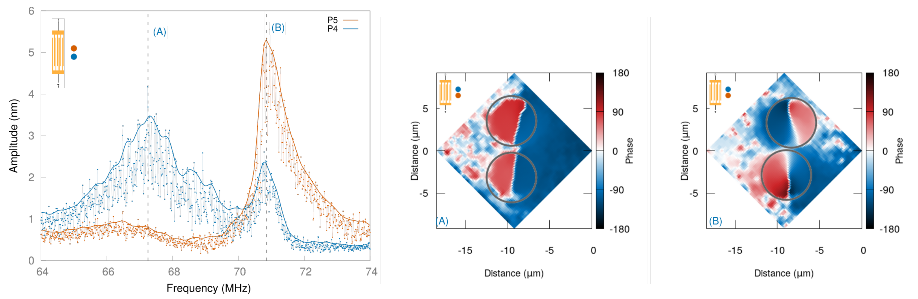
This dipole-like character of the interaction is further confirmed when exciting the resonator pair along a longitudinal or transverse direction. In each case, only two modes appear, instead of the three modes observed for a diagonal incidence. The direction of excitation therefore rules out some specific modes based on the mode symmetry and of



(a) Left: Experimental frequency responses of the 1.5-μm-spaced pillars of the pair for a diagonal excitation. 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 μmm$\times$13 μmm, with a step size of 200 nm. (b) Right: Corresponding simulated frequency responses and displacement and phase maps ($|u_z|$ and $\arg(u_z)$ respectively) for typical resonance frequencies: 75.25 MHz (A), 78.40 MHz (B) and 79.65 MHz (C).



(b) Experimental frequency responses of 1.5-μm-spaced pillars in the longitudinal-excitation configuration. Phase maps are given for frequencies equal to 70.74 MHz (i) and 71.58 MHz (ii), corresponding to the two modes of the resonator pair.



(c) Experimental frequency responses of 1.5-μm-spaced pillars in the transverse-excitation configuration. Phase maps are given for frequencies equal to 67.25 MHz (i) and 70.86 MHz (ii), corresponding to the two modes of the resonator pair.

Figure 3.19: Frequency responses of 1.5-μm-spaced pillars under different excitation conditions.

their potential incompatibility with the impinging elastic wave polarisation and direction. More specifically, in the case of a longitudinal incidence, frequency labeled (i) corresponds to a mode that behaves like a symmetrical dipole state, as shown by the corresponding phase maps. The measurements also show the existence of a second state,

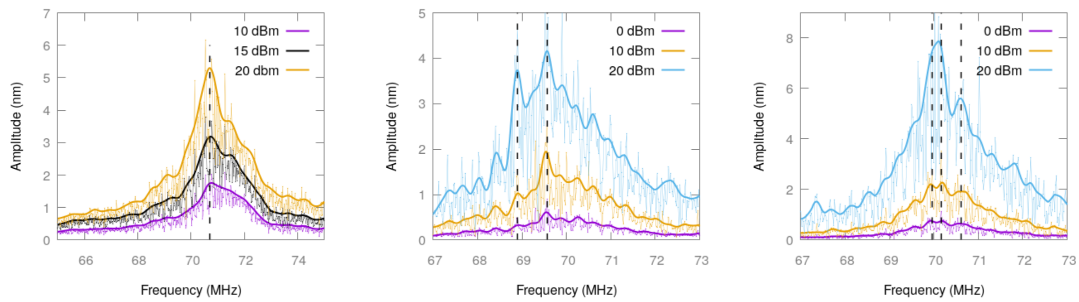
corresponding to frequency label (ii), where the vibration direction of the two-pillar ensemble is rotated by $\pi/2$ compared to the lower frequency mode. These two modes are similar to modes (ii) and (iii) in the case of the diagonal incidence. The direction of the excitation source therefore rules out mode (i).
Similarly, in the case of a transverse incidence, 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 (i) and (iii) corresponds to the frequency difference previously measured in the diagonal-incidence case between the first and the third mode of $P1$. The transverse excitation scheme therefore rules out mode (ii). Yet, if mode (i), observed at a frequency of 67.02 MHz, exhibits a pure dipolar behaviour, the pillar pair enters a rather unstable regime when the two pillars reach resonance, dominated by a quasi-circular polarisation state. This points at a degeneracy of two orthogonally-polarized vibration modes. This behaviour is reminiscent of bifurcation in non-conservative systems [102], and suggests the occurrence of non-linearities in the considered pillar pair systems, that we will discuss later.

The obtained results then point at the existence of two different coupling regimes as a function of the gap distance. With a 1.5-μm gap, the pillar pair seems to interact following rules similar to those observed for dipole-like states. For a 6-μm-gap, mechanical coupling seems to prevail, the resonators behavior echoing the one observed while considering, for instance, coupling between nanomechanical string or beam resonators [99, 100]. Increasing the gap then leads to a system that can rather be described as a four-mode coupled resonator system [100], rather than as a set of coupled dipoles. This kind of transitions to different coupling regimes is common to both plasmonics [103] and nanomechanics [104]. 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. In plasmonics, the critical gap parameter is usually defined in terms of particle diameter, that conditions the particle resonance frequency, and operating wavelength. In the proposed surface-acoustic-wave coupled resonators, that vibrate along a flexural mode, the relevant geometrical parameter is the resonator height, that conditions the pillar resonance frequency. This parameter is therefore to be correlated to the impinging SAW wavelength λ. The cases of 1.5 μm and 6 μm separation distances considered here, which correspond to about $\lambda/30$ and $\lambda/8$ respectively, lie unambiguously in the dipole-like or in the mechanical regime. The distinction between these two regimes is here made obvious by the observed polarisation states rather than by the only consideration of the frequency response. This shows the relevance and importance of a direct observation of the spatial and vectorial behaviour of the resonator motion for the interpretation of the coupling mechanisms at play, as was previously pointed out for optomechanical systems [102]. The used FEM model does not fully account for the polarisation states of the resonators. This 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.

3.6.3 Nonlinearities in surface coupled mechanical resonators: opening tracks

The observation of polarisation instabilities in the previously described pairs of resonators has led us to start investigating potential nonlinear effects in these systems. This study is yet at a very preliminary stage but the obtained results already open promising perspectives for the realisation of SAW-driven nonlinear MEMS devices.

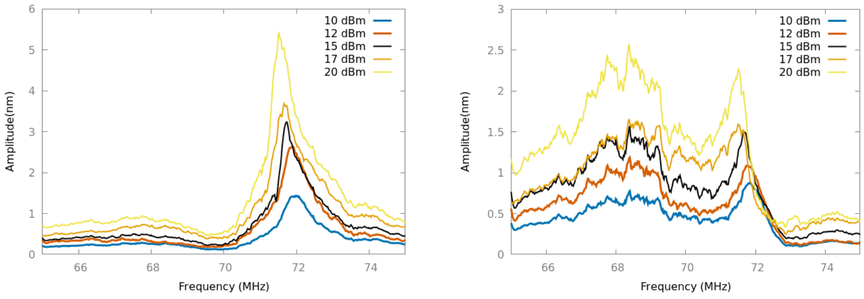
One should recall here that the resonators we have been using up to now had been designed to comply with our experimental constraints as far as the characterisation method went. This imposed the use of rather bulky (4 μm in diameter), low aspect ratio (equal to one) structures, which, obviously do not conform to the nonlinear mechanics ideals. And as expected, SAW excitation does not trigger any obvious nonlinearities when considering a single pillar, at least not in the range of available input RF power (up to 20 dBm). Figure 3.20a indeed shows the frequency response obtained from a single pillar, for different input powers. The resonance shape and frequency remains unchanged, there is no direct indication of a non-linear spring effect and hence of a Duffing-like effect. The same conclusions can be drawn from measurements of the behaviour of the pillar pair with a 6-μm gap distance. The position and width of the pillar pair resonances remain unchanged, only the amplitude of the pillar vibration is affected. The coupling mechanism is independent on the SAW amplitude, as expected for a pillar pair operating in a sheer mechanical coupling regime.



(a) (b) (c)

Figure 3.20: Experimental frequency responses (a) of a single pillar with a diameter of 4.4 μm and a height of about 4 μm excited by a SAW for different input powers applied to the IDT, (b) and (c) for two pillars within a pair with a 6 μm gap distance excited by a longitudinal SAW wave vector.

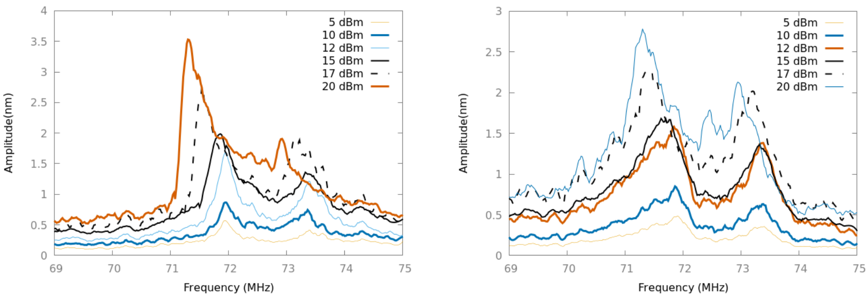
This observation does not hold, however, in the case of 1.5-μm-spaced pillar pairs, where SAW mediated dipole-like interaction was shown to be dominant. A similar investigation of the RF power-dependency was performed for the transverse and the longitudinal configurations. In the case of a transverse excitation, the frequency response of the resonators is only marginally affected by the SAW amplitude and only an extremely



(a) (b)

Figure 3.21: Experimental frequency responses of two pillars within a pair with a 1.5 μm gap distance excited by a transverse SAW wave vector at different RF input power. (a) Response of the first pillar. (b) Response of the second pillar.

moderate downshift of the frequency response for both pillars can be observed, as shown in Figure 3.21a. The case of a longitudinal excitation reported in Fig. 3.22b however exhibits features distinctive of a nonlinear system. The frequency downshift as a function of applied RF power is here clearly visible, the lowest frequency resonance, that corresponds to a symmetric mode of the pair being more affected that the higher frequency resonance, corresponding to an anti-symmetric mode; the line shape profile becomes more asymmetric, leading to a frequency instability area; and, strikingly, and as reported in Figure 3.23, a hysteresis phenomenon is observed for the first resonance when performing either upwards or downwards drive frequency sweeps.



(a) (b)

Figure 3.22: Experimental frequency responses of two pillars within a pair with a 1.5 μm gap distance excited by a longitudinal SAW wave vector at different RF input power. Response of pillar P4 (closest from the excitation source). (b) Response of pillar P5 (farthest from the excitation source).

The nonlinearities are therefore only observed unequivocally for a longitudinal excitation scheme. The absence of frequency dependence on the input power, for the single resonator, maybe linked to their low quality factors or to the lack of available RF power, seem to rule out Duffing-like nonlinearities in our experimental configuration. The increase in quality factor obtained by resonator-to-resonator coupling could help triggering non linear interactions, but the nonlinearities are only observed unequivocally for a lon-

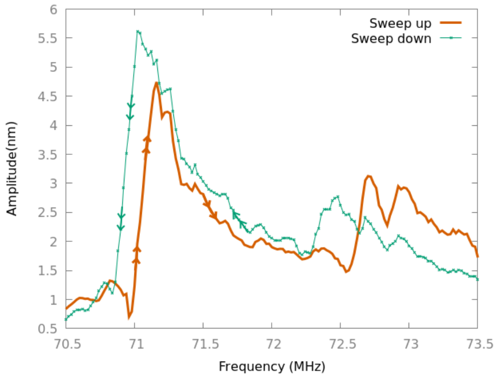


Figure 3.23: Comparison of up and down frequency sweeps for the first resonance of pillar P4 (closest to the excitation source) at an RF input power of 20 dBm. The frequency shift linked to the hysteresis cycle appears at about 70.9 MHz.

gitudinal excitation scheme. This dependency of the observed nonlinearities on both the SAW wave vector but also on the separation distance seem to point at a SAW-induced non linear coupling mechanism that we still need to describe from a theoretical and numerical point of view to increase our understanding of the phenomenon and exploit it accordingly.

3.6.4 Conclusion

We have been trying to put a slightly different twist to the local resonance concept by exploiting the possibility to couple surface acoustic waves of a surrounding homogeneous medium to deep sub-wavelength individual resonators. The observed elastic confinement and apparent field enhancement, the existence of dipole-like states, the observation of elastic energy channeling between neighbouring resonators make this system bear, as expected, strong analogy with plasmonic nanoparticles. It also supports a behavior far more characteristic of coupled micro- and nanomechanical devices, hence somehow bridging the gap between Phononics and Micro- Nano-mechanics. SAW can indeed be used to coherently control mechanical systems, adding another degree of freedom to the resonator geometry, as such, or as part of a more complex arrangement. By tuning the resonator-to-resonator distance as well as the impinging SAW wave vector orientation, switching between different coupling schemes can be achieved, an observation that was made possible by the possibility offered by direct imaging of the resonator motion to fully retrieve the vectorial nature of the interaction. The obtained results point at an even wider span of physical mechanisms, including most predictably, mechanical nonlinearities. The initial set of results obtained and reported above therefore only constitute a starting point: there is still indeed much to do to fully exploit the richness and unique features of the proposed platform for the coherent control of complex mechanical systems. Enhancing our numerical and theoretical modeling capabilities, improving our fabrication processes, expanding our characterisation capabilities will be required to meet the challenging expectations of our predicted framework: the experimental platform formed by such mechanical resonators is 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 to build highly versatile nanomechanical platforms, capable to operate in the classical, but also in the quantum regime. We will see the last Chapter of this manuscript that the investigation of mechanical quantum-like or genuinely quantum systems relying on the interaction between SAWs and mechanical resonators lie at the core of my research perspectives.

3.7 Instrumentation and technology for radio-frequency Phononics

My commitment to the realisation of hypersonic and hybrid photonic-phononic crystals has been driving my core research interest towards lower scale structures requiring a strong involvement in the development of micro-fabrication and appropriate characterisation techniques. We have for instance been putting significant effort into the setting-up of a laser scanning interferometer dedicated to displacement field measurement that has allowed us to gain a greater understanding on wave propagation phenomena in our phononic devices. The fabrication of the proposed hypersonic phononic devices also required us to resort to microfabrication technologies. This section illustrates typical developments revolving around these experimental and technological aspects.

3.7.1 Laser scanning interferometry

Surface acoustic wave electro-acoustic devices are usually characterised using radio-frequency probe testing, commonly through the measurements of electrical scattering parameters that allow retrieving the electrical admittance of the device. This extremely convenient method give valuable information on mechanical to electrical energy transduction, and hence indirectly allow detecting elastic wave transmission through a phononic structure in a classical source-crystal-detector configuration. In the rather prospective context of phononic devices, supplementing this electro-acoustic information with more direct characterisations of the elastic field distribution itself is highly beneficial: measuring this distribution both in the time and frequency domain can indeed allow retrieving fundamental features of the phononic device, e.g. wave localisation, mode shape, leakage mechanisms, phase information, and even dispersion relations.

Electro-acoustic devices operating in the higher ultrasonic regime are bound to exhibit mechanical displacements with very low amplitudes, well below the nanometer range even when operating in a forced excitation regime. This figure is fully within the detection limit of optical measurement methods. Optical interferometry is particularly well-suited for the amplitude and phase measurement of such micromechanical systems. This very robust technique allows for the detection of out-of-plane mechanical vibrations with sensitivities that can in principle reach 10^{-15} $\mathrm{m} \cdot \mathrm{Hz}^{-1}$ [105]. Homodyne interferometers have been in use since the end of the XIX$^{\text{th}}$ century, heterodyne configurations were most probably first proposed by Massey [106], and improved by Whitman and Korpel in 1969, through the use of early single-crystal acousto-optical Bragg cells [107].

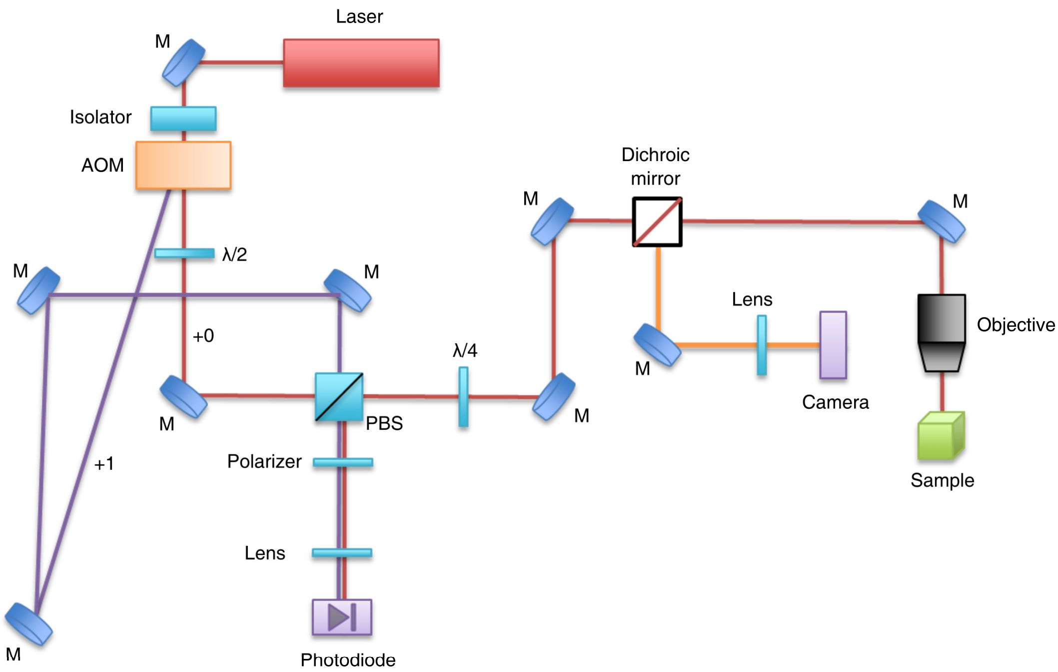


Figure 3.24: (a) Schematic of the Mach-Zehnder heterodyne laser scanning interferometer used for optical characterisations. (AOM = Acousto-Optic Modulator; PBS = Polarized Beam Splitter).

As already seen in the course of this manuscript, we have made an extensive use of heterodyne interferometry for the characterisation of surface acoustic wave propagation in phononic crystals in the GHz frequency range where displacement fields are regularly of the order of a few tens of picometers, first through a fruitful collaborations with K. Kokkonen, then with Aalto University of Technology in Finland, then through home-made interferometers. Our first experimental set-up was based on double-pass heterodyne Michelson interferometer as proposed by P. Vairac and B. Cretin from FEMTO-ST [108], following a very compact geometry, at the cost, however, of a number of geometrical restrictions. The ever-increasing need for high spatial resolution measurements with increased signal to noise ratio has pushed us to optimize the set-up, leading to the implementation of a Mach-Zehnder heterodyne interferometer directly inspired from [109], accompanied by a number of signal processing algorithms, particularly in the context of our recent work on surface coupled microresonators.

A schematic of the set-up is proposed in Figure 3.24. A linearly polarized, stabilized 633-nm HeNe laser is split into two frequency-shifted paths thanks to an acousto-optic modulator chosen for the large separation angle between the two diffraction orders after passing through an optical isolator. The first-order, frequency-shifted beam acts as the reference arm while the zeroth-order beam propagates to the sample and back. The zeroth- and first-order beams exhibits orthogonal polarisations. The reference beam is directly transmitted through the polarizing beamsplitter. The probe beam propagates through a half-wave plate, passes through the polarizing beamsplitter and is sent through a quarter-wave plate before reaching the sample. The laser beam is focused on the sample using a long-working distance microscope objective with a numerical aperture of 0.8, leading to a spot size of 650 nm. After reflection on the sample, the second pass through the quarter-wave plate allows to rotate the beam polarisation so that the probe beam is now reflected on the beamsplitter. This way, the two orthogonally-polarized beams are recombined. The resulting interference pattern allows to calculate the optical phase difference between the two paths and to determine the amplitude of the out-of-plane component of the sample surface vibration. The two interfering beams propagate through a linear polarizer to a fast photodiode. The signal collected by the photodiode is amplified and then either sent to an electrical spectrum analyzer for amplitude measurements or to an oscilloscope to perform a numerical modulation of the signal and extract the corresponding phase maps. Field maps are obtained by raster scanning the surface of interest for specific frequencies. The scanning of the sample is accomplished using computer-controlled nanometer precision linear positioners. The theoretical displacement measurement sensitivity associated with our current optical and electronic configuration is around $6\ \mathrm{fm} \cdot \sqrt{\mathrm{Hz}}$.

The combination of a harmonic excitation of a phononic structure using surface acoustic wave devices and laser scanning interferometry provides extensive information on the physical phenomena at play. In the context of phononic band gaps and waveguides, it has allowed us to demonstrate unambiguously wave filtering and transmission, in particular in specific cases where electrical measurements failed to allow for a full recovery of the propagating signal. In the framework of surface coupled phononic resonators, it allowed us to proceed to the direct observation of the vectorial nature of the interaction, giving complete information on the resonators mode shape and phase, notably allowing us to demonstrate unambiguously the occurrence of avoided crossings. These optical methods have then been one of our most valuable investigation tools.

3.7.2 Technological processes for surface acoustic wave phononic crystals and resonators

I have dedicated part of my activities to the development of various technological processes for the fabrication of phononic crystal devices. If the processes used for the realisation of SAW transducers are fairly standard, mostly based of classical optical or electron-beam lithographies, the fabrication of micron-scale phononic structures has been more challenging and has led us to address a number of technological bottlenecks, briefly summarised in the following sections.

Lithium niobate dry etching

The etching of high-aspect ratio patterns in non conventional single-crystals – one could probably substitute *other than silicon or III-V semiconductors* to *non-conventional*, incidentally – has been a long standing issue. There is, for instance no directly available process for etching lithium niobate, despite its being a key substrate in a number of applications ranging from integrated optics to radio-frequency acoustics. A number of methods have been proposed in the literature, and the field remains surprisingly active. In the context of hypersonic phononic (and of photonic) crystals, the difficulty is intensified by the need for sub-micron scale features in generally high filling fraction arrays.

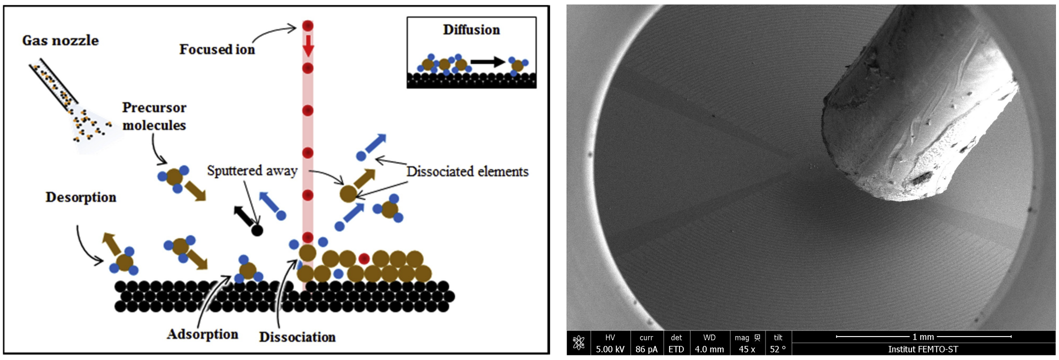
Our realisations of hypersonic phononic crystals presented in sections 3.4 relied on the use of focused ion beam (FIB) milling which has proven, up to now, to one be the most efficient way to produce sub-micrometric-sized holes on a $LiNbO_3$ substrate with high aspect ratios. As a general rule, aspect ratios up to five are achievable, and 300 nm diameter holes with a depth of 1.5 μm have been repeatedly obtained. Using plasma etching, however, is a more appealing method for the realisation of large scale structures, as opposed to the time-consuming, individual hole milling performed when operating FIB etching. We therefore engaged in a series of attempts to achieve lithium niobate dry etching, primarily through reactive ion etching in fluoride-based chemistries. The major and well-identified issue here relates to lithium fluoride (LiF) re-deposition, a non-volatile reaction byproduct that is known to decrease both the etch rate and the $LiNbO_3$/mask selectivity. This redeposition in addition limits the achievable sidewall slope angle and increases the wall roughness. To overcome this issue, we used in the course of my PhD thesis work a particular etch mask made of electropated Ni. A process was developed then using capacitively-coupled reactive ion etching (CCP-RIE), that allowed etching 10 μm diameter features with depths over 10 μm, whatever the lithium niobate crystallographic orientation, in a sulfur hexafluoride (SF_6) based plasma (selectivity with lithium niobate around 20). The process was however limited by the etching angle which actually decreases with the hole diameter (angle around 73° for a diameter down to 6 μm, even lower for smaller diameters [P31]). We therefore worked on the transposition of this process to the etching sub-micron features, this time using inductively-coupled plasma (ICP) RIE. ICP systems allows bringing the plasma and density control a step further and generally permits an increase of the anisotropic etching capability compared with CCP-RIE along with higher etch rates along with lower roughness. The outcome of these developments were this time definitely limited to the etch mask definition using our internal fabrication means: the achievable grain size of our electroplated Ni layers led to unacceptable sidewall roughness. In the lack of internal capabilities for metal dry-etching, the use of a lift-off process for the definition of evaporated or sputtered metal masks proved plainly limiting.

The issue remains open, then, and will probably be re-explored in the coming years. It will probably be relevant, however, to re-focus our process development to the etching of the rather recently introduced lithium-niobate-on-insulator (LNOI) substrates, both from an applicative and a technological perspective: these substrates are particularly suited for the realisation of integrated optical or Lamb-wave based devices and the etching of through-holes is expected to significantly ease the technological process.

Three-dimensional nanofabrication of mechanical resonators

One of the cornerstones of this work dedicated to SAW-mechanical resonator interaction is our capability to control the phononic resonators fabrication process.

We have chosen in this context to focus on ion-beam induced deposition (IBID), first introduced in the 1980's. IBID is an extension of electron-beam induced deposition (EBID): both can be described as chemical vapor deposition (CVD) processes, albeit of the very complex and not fully understood types [110]. In an IBID process, the ion beam is used to dissociate precursor molecules adsorbed at the sample surface. This dissociation process leads to the creation of a local, solid deposit constituted by the non-volatile compounds of the precursor molecule. This latter is injected as closely as possible to the ion beam collision area using a gas injection system (GIS) consisting of the association of a reservoir, a leak valve and a capillary. An injection nozzle with a diameter of the order of a few hundreds of nanometers allows controlling the direction, the flow rate and the local pressure of the injected vapour. The precursor is usually a metal carbonyl precursor with a vapour pressure of a few mbar at temperatures about 100 °C to ease this injection process. An IBID process is therefore dictated by the complex adsorption/desorption/diffusion/dissociation dynamics induced by the gas injection but also by the ion-beam characteristics (beam current/dwell time, acceleration voltage, types of electrons involved, milling rate, etc.). A schematic of the reaction as well as an actual image of the injecting needle inside the FIB chamber are reported in Figure 3.25.

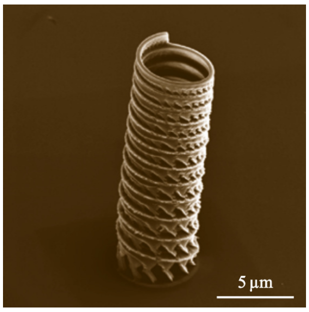


(a) (b)

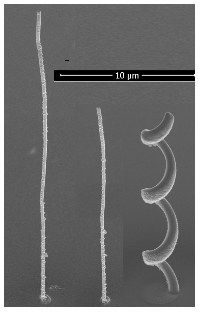
Figure 3.25: (a) Schematic illustrating the behaviour of precursor gas molecules on the substrate surface during an IBID process (from Lee *et al.*. [111]. (b) SEM view of the injecting noodle taken in the FIB/SEM chamber at MIMENTO.

Ion-beam induced deposition has been in use for quite some time now [112], but its potential for the fabrication of three-dimensional nanostructures has only been unveiled recently. Research works have mainly focused on the electrical properties of IBID-platinum, given its initial expected use for circuit repair. The mechanical properties of IBID materials remain little-known, exception made of a few inspiring papers published a few years back by groups at the University of Tokyo. They presented convincing demonstrations of the capabilities of the technology for growth of genuine three-dimensional micro- and nanostructures in IBID-carbon, as illustrated in Figure 3.26, along with characterisations of the material Young's modulus that could reach values up to 600 GPa under specific process conditions [113–115].

The MIMENTO technology center hosts a Helios Nanolab 600i Dualbeam FIB/SEM system from FEI equipped with five different gas injection systems (GIS). We initially set our choice on platinum (a naphtalene GIS for carbon deposition was subsequently acquired) and the phononic resonators used in our recent works are therefore made of IBID-Pt, obtained from a trimethyl-(methylcyclopentadienyl)- platinum(IV) precursor. It should be highlighted here that we have been operating the IBID process outside its usual scope of use: the resonators exhibit a diameter of a few microns, essentially dictated by



(a)

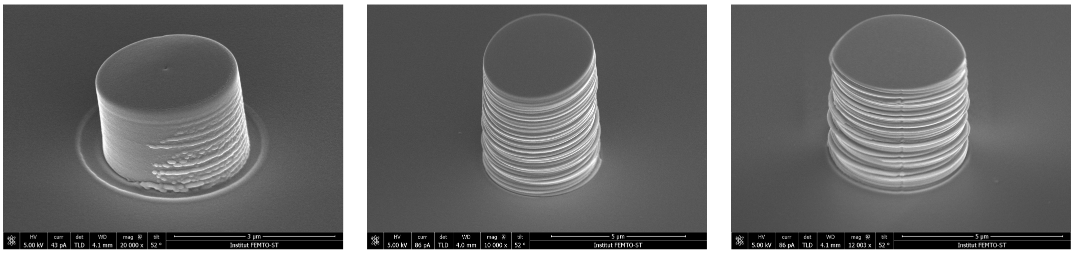


(b)

Figure 3.26: Illustration of the potential of IBID for three-dimensional nanofabrication. (a) Micro Tower of Pisa, from Matsui *et al.* [113]. (b) Examples of high-aspect ratio and three-dimensional structures fabricated using the FIB/SEM Dual Beam system at MIMENTO.

the characterisation methods used. The position of the injection needle in lateral and height distances from the coincidence point of the two beams was optimized to reach a compromise between growth speed and dimensional uniformity of the structures in the considered write field of 50 μm. The pillars were grown with an accelerating voltage of 30 kV and a probe current of 40 pA. The beam is scanned repetitively and at a high speed on the growth area to optimize the refreshment of the precursor. A SEM image of a typical resonator grown using this method is shown in Figure 3.27a. Applying a drift correction procedure during the growth process allows improving the overall pillar verticality, at the expense, however, of surface roughness (Fig. 3.27b). In order to improve further the planeity of the top surface and to gain a higher degree of control on the pillar height, their upper faces were polished by ion beam milling. A dedicated substrate holder was then designed and manufactured to bring the pillar orthogonal to the grazing ion beam, leading to the resonators shown in Figure 3.27c. The realisation of pillars within pairs required further adjustments to yield resonators as identical as possible. The resonators were grown simultaneously: the ion beam scans alternatively, at a (high) speed of 200 μm.s^{-1}, the two growth area, resulting in the production of twin pillars. Although both pillars within a set are processed within a single milling step, a difference in height of a few tens of nanometers between different pillars may remain. A typical pillar pair is reported in Figure 3.27c.

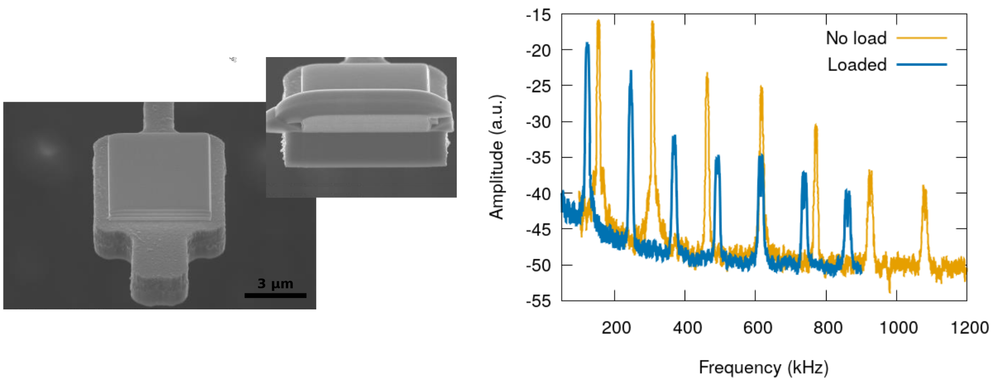
We have also started to establish an experimental protocol dedicated to the systematic and in-situ characterisation of the deposited materials basic mechanical properties. The mass density can be obtained by in-situ measurement in the FIB chamber of the resonance frequency of a cantilever beam, first unloaded, then loaded with a known volume of the deposited material. The mechanical vibration is measured following a method first proposed by Buks and Roukes [116] and takes advantage of our dual-beam FIB/SEM system: the electron beam of the electron optical column is focused on a point near the tip of the cantilever beam, here made of silicon or silicon nitride. No external sources are used, the beam is set into vibration by the noisy environment of the FIB/SEM system and naturally locks to its natural resonant frequencies. The beam vibration induces a contrast modu-



(a) (b) (c)

Figure 3.27: Scanning electron microscope images of a IBID-Pt pillar with a diameter of 4 μm and a height about 3.7 μm. (a) Deposition as is. (b) Compensation by drift correction. (c) Drift corrected pillar after surface polishing by FIB at grazing incidence.

lation of the signal detected by the secondary electron detector. This signal is sent and recorded by an electrical spectrum analyser. Under such "brownian" excitation, only the fundamental mode can be detected. Measuring higher harmonics, and hence improving our estimation of the frequency shift and hence of the mass density, would require an external excitation field (which is feasible but not implemented yet). Figure 3.28a displays one of the sample employed, and the corresponding measurement in the case of platinum. The measured frequency shift and the estimated volume lead to a mass density of about 10^4 kg.m^3. The Young's modulus is then estimated using the same measurements setup. To this aim, long aspect ratio resonators are fabricated, with typical diameters about 200 nm and heights of several micrometers (from 5 to 22, typically, as shown in Figure 3.29). The natural resonance frequency of the fundamental mode is again measured and the Young's modulus inferred by solving a simple Euler-Bernouilli equation, leading to Young's modulus around 60 to 70 GPa.



(a) (b)

Figure 3.28: (a) Scanning microscope images of a Si cantilever beam loaded with an IBID-Pt deposit. A cross-section of the edge platform is performed after each measurement to check the deposited volume. (b) Measurement of the unloaded and loaded beam resonance frequency of the first fundamental mode.

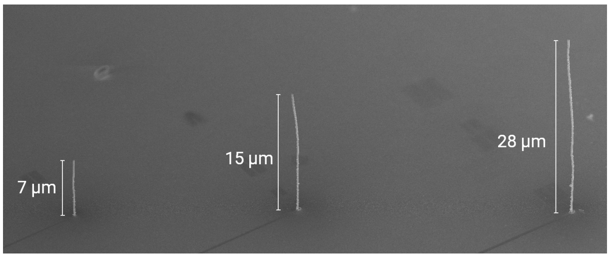


Figure 3.29: Typical high-aspect ratio cylindrical beams used for the in-situ characterisation of the mechanical properties of our IBID deposit. The beam diameter is 170 nm in all cases, the respective heights are about 7, 15 and 28 μm respectively.

The obtained mass density and Young's modulus values are in good agreement with those estimated through a comparison between the actual response and the numerical predictions of the surface-coupled resonators presented in Section 3.6. They also agree with preliminary results obtained by nano-indentation and corroborate the material analysis made by EDS. Accessing higher-order modes would, however, definitely improve the overal characterisation process: including an external excitation scheme is an obvious next step in this context.

These initial technological developments on ion beam induced deposition already served our recent work on surface-coupled phononic resonators. But IBID will constitute a major track of development in the coming years. One of main objective will be to work on the realisation of complex three-dimensional sub-micron structures with well-defined geometrical and mechanical properties in view of obtaining phononic resonators with tailorable mode properties (relative frequencies and lifetimes, in particular). Carbon will here be the material of choice, to take full advantage of achievable Young's modulus but also potential three-dimensional complexity.

4 PERSPECTIVES: PHONONICS FOR QUANTUM INFORMATION PROCESSING

I have dedicated the earliest part of my post-doctoral career to radio-frequency phononic crystals, conceived and sought after as micron-scale, integrable high-frequency counterparts of the successful sonic crystal and devices. It however occurred to us a few years ago, that the field of micron-scale Phononics, defined along such restrictive lines, will not manage to reach critical mass within the academic community. The shy performance of the experimental demonstrators reported in the literature, at the cost of complicated fabrication processes, did not trigger enough interest in the industry to warrant sustainable, significant development of viable phononic devices. But managing elastic wave propagation and mechanical energy distribution at the micron-scale opens prospects beyond the sheer achievement of device miniaturization, and this is indeed generating a much renewed interest towards hypersonic crystals and devices from the nanomechanics and condensed matter physics communities.

Our objective over the coming few years will then be to contribute to the field by merging physical concepts stemming from Phononics and Nanomechanics to implement on-chip, nano-electromechanical information processing devices in both the classical and the quantum regime. The work we are aiming at pursuing is in keeping with our activities dedicated to surface-coupled phononic resonators. We will exploit our recent results demonstrating the possible interaction between surface-propagating and localized mechanical vibrations to elaborate an experimental playground that will enable the coherent control of complex linear or non linear mechanical systems but also, reciprocally, the control of the displacement and hence strain distribution on a substrate surface. This will of course be exploited in the context of optomechanics or phoxonics, but we will take further advantage of the inherent, remarkable capability of mechanical vibrations to couple coherently to a variety of physical degrees of freedom to expand the potential of our phononic devices. In particular, clearly inspired by recent works reporting on acoustics in the quantum regime, we will aim at the development of an all-electromechanical single-phonon platform. This last point lies at the core of the project uNIQUE (Nanophononics for quantum Information processing), first submitted in February 2019, that was recently granted in the context of the 2019 European Research Council Consolidator Grant call.

4.1 Context

The tremendous technological advances in micro- and nano-manufacturing processes and the subsequent emergence of micro- and nano-electromechanical systems

(MEMS/NEMS) have opened prospects exceeding by far those initially anticipated, going well beyond the possibility to merely shrink the footprint of existing electromechanical devices. The intrinsically low mass of micro- and nano-scale resonators made them indeed naturally well-suited for the realization of highly sensitive detectors that were shown to exhibit quantum limited sensitivity [117–121]. In particular, the possibility to combine the mechanical and electromagnetic degrees of freedom has allowed to demonstrate quantum interfacing between mechanical and electromagnetic modes, leading for instance to the demonstration of zero-point motion [122], sensors with quantum limited sensitivity [123], reciprocal transduction between microwave and optical signals [51, 124–126], or remote entanglement of mechanical oscillators [127]. 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 [128–130], paving the route towards complex platform for both classical and quantum information processing.

This momentum has also, in a most cyclic development, pushed towards the development of all-mechanical quantum systems where coherent manipulation of the mechanical features of micro- or nanosystems was sought after in order to reach quantum-like behaviour, based on coupling induced by effects as diverse as mechanical coupling, radiation-pressure, stress or strain-mediated coupling, within the frames of linear or non-linear interactions [99, 104, 131–135]. Such systems present a strong potential in terms of device miniaturization and integration. Their long coherence time has also allowed to demonstrate their viability as quantum bits (or qubits) in a number of experiments [126, 127, 136–138]. They also inherently benefit from the remarkable capability of mechanical vibrations to couple coherently to a variety of physical degrees of freedom through their capability to affect stress, strain or electric-field, as in, among others [125, 139, 140], a deed that cannot be done by light.

Most of the works reported in the literature has then been focused on the exploitation of mechanical resonators, hosting, as such, what we could term *localised phonons*. We however know very well that SAW, and in particular SAW propagating on piezo-electric substrates, are extremely powerful conveyors of both mechanical and electrical energy. This has led semiconductor physicist to use surface acoustic waves to achieve charge transport and control [45–49], hence introducing SAW devices into the realm of condensed matter physics. These works have contributed to unveil the potential of SAW as an interface with a variety of solid-state quantum bits – qubits – such as quantum dots or neutral vacancy centers, these latter being sensitive to both strain and carried electrical potential. SAWs have lately gone another step into the field of fundamental physics: it has indeed been reported that elastic waves could be operated at a single-phonon level and therefore used as information carriers truly able to encode a quantum state [52, 53, 55, 56] and even to entangle it to a solid-state qubit, as recently reported by Prof. Cleland's group in 2019 [58], in an experiment demonstrating the transfer of a quantum state from a superconducting qubit to a distant one by a single-phonon SAW.

Despite the extremely novel and exciting character of quantum acoustics, the reported works do not take the measure of the full potential offered by surface acoustic waves as an information conveyor. The used SAWdevices are limited to simple transducers, or to two-port resonators. But interaction of a SAW with its supporting surface yields a

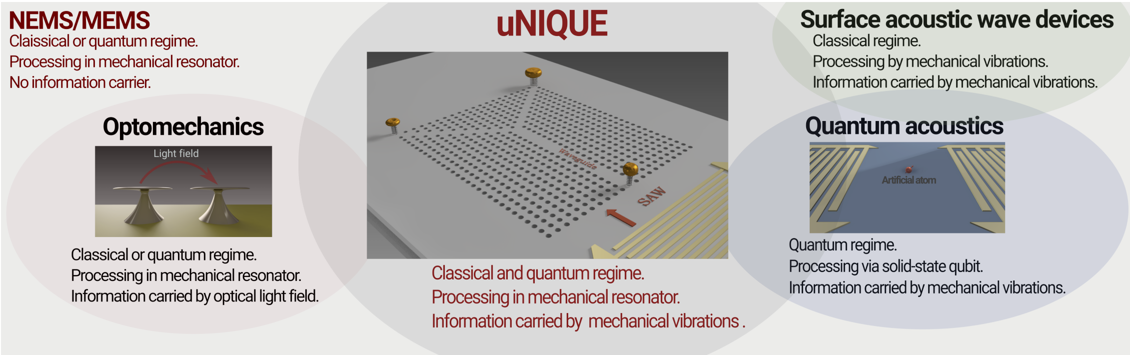


Figure 4.1: Positioning of the uNIQUE project proposal with respect to the current state-of-the-art. By merging concepts stemming from SAW devices, phononics, and nanomechanics, uNIQUE aims at building an on-chip acousto-mechanical platform, with a strong potential for hybridisation with a number of quantum systems. The project will investigate an all-mechanical alternative, where the qubit itself will be of mechanical nature. This specificity, associated with the potential of surface acoustic waves for information transport and of phononic crystals for wave propagation management, opens exciting prospects for quantum circuits, where remote entanglement could be mediated by SAW.

wealth of possibilities. The choice of materials, documented by years of advanced RF designing, associated with the wealth of possibilities offered by phononic crystals and elastic metamaterials can bring this recent field of *quantum acoustics* to new heights.

4.2 Objectives

Our overarching, most ambitious (not to say blue-sky) objective over the coming years, that constitutes the aim of the ERC CoG project uNIQUE, is to implement an on-chip, all-electromechanical quantum information processing platform where surface acoustic waves will be used to generate, prepare, convey and process quantum states. This platform will integrate advanced functionalities for SAW propagation and mechanical vibration control, notably based on phononic crystals and phononic resonators.

We will take full advantage of the possibilities offered to achieve SAW propagation management and will apply them to the quantum regime. We will involve a complete set of parameters for the design of our ideal quantum processing platform, including appropriate choice of the substrate, well-designed SAW sources and cavities and SAW confinement and waveguiding using phononic crystals or locally-resonant structures. This will lead to the demonstration of a highly versatile mechanical platform with a strong potential, in the long run, for hybridisation with a number of quantum systems. Reaching the single-phonon regime will require setting-up experiments in a cryogenic environment, ideally in the 10 to 50 mK range. Powering the device or performing in-situ optical characterization already are challenges of sorts under such experimental conditions. Solutions do indeed exist and single-phonon operation has been successfully reported a significant number of times in the literature, but the learning curve here is not to be neglected.

We will then design and fabricate mechanical resonators to be used as mechanical qubits. This will call for an exquisite control over the mechanical mode of the resonating structures and of their coupling to both the surface acoustic waves and the supporting substrate. We will use our expertise in phononics, surface acoustic wave devices and micro-nano-technology to get additional degrees of tunability of isolated mechanical resonators, by tailoring the resonator itself but also the mechanical and electro-acoustical properties of their environment. We will exploit the rich hybridization mechanisms induced by coupling the resonator eigenmodes to surface modes of the surrounding continuous medium. We will more specifically aim at a careful engineering of surface-coupled phononic resonators that will behave as electro-acoustically-driven two- or three-level systems, where parametric interaction can be used to achieve mechanical sideband cooling, as inspired by the works reported in [132]. We will seek to achieve this phononic parametric interaction first at room temperature. Obtaining phonon parametric interaction in a mechanical resonator calls for non-linearities, and indirectly for high-quality factors. It will therefore be critical to properly understand the damping and potential leakage mechanisms. This will require the improvement of our current FEM models, by taking into account finite-size of the substrate, the potential coupling to bulk waves in anisotropic, piezoelectric materials, the visco-elasticity of the materials at play and the system nonlinearities. Parametric interaction requires commensurable resonance frequencies in addition to well-controlled quality factors. The choice of the fabrication technology is then key. We will favor the use of ion-beam induced deposition and of carbon as a base material and develop fabrication processes allowing for a careful control of both the geometry and the mechanical properties of the resonators. Progress beyond the state-of-the-art will be required to exploit this technology to its full potential, in particular as regards the characterisation of the deposited material. Sub-micron sized resonators will be sought after, in order to reach higher quality factors. Characterizing the resonator response will then require us to develop specific experimental techniques for motion measurements at the nanoscale by either pushing to their limits usual and robust methods like optical interferometry or by using less conventional electron-based characterization means.

The experiments will then be transposed to the mK-range, with the objective to reach the single-phonon regime. If operating at cryogenic temperatures will obviously improve the resonators quality factors, a very challenging aspect resides in the fact that, contrarily to cooling using optical or microwave fields where decaying phonons are converted to photons, mechanical sideband cooling may result in a re-population of the thermal phonon bath. This may well affect the intrinsic capability of our system to maintain operation at the single-phonon level. We will therefore investigate how electro-acoustical dissipation mechanisms relying on the piezoelectricity of the substrate and on the use of travelling acoustic waves may be used to reduce this effect, although this may still appear as rather speculative given our current understanding of the phenomena at play.

We will then aim at the coupling of these hopefully mechanical qubits by traveling surface waves in the single-phonon regime. We will first investigate conventional SAW resonators and delay lines to reproduce the results previously reported in the literature [52, 55]. The challenge here will be to implement single-phonon detection schemes alternative to the electro-acoustic detetction. An exciting prospect would be to further increase the complexity of the system by engineering the phonon propagating path. Guiding surface acoustic waves however remains a challenge, even to date and at room-temperature. Phononic waveguiding is not mandatory, but it would be an extraordinary enabling element to further harness mechanical vibration in the proposed platform. We will therefore pursue this objective, either through phononic crystals or by resonator-to-resonator coupling. Managing waveguides capable of handling single-phonons would indeed constitute a most salient and significant achievement.

4.3 Expected Outcomes

The proposed research plan would obviously culminate in the demonstration of an all-electro-acousto-mechanical quantum platform. Such an achievement would made available on-chip devices where mesoscopic mechanical resonators will be strongly coupled by travelling surface acoustic waves. The level of integration of such a system associated with the intrinsically low propagation speed of phonons that has already made the use of acoustic wave based devices prevalent in modern radio-frequency communication systems, opens unexplored perspectives for the storage and delay of quantum information, or for the investigation of quantum effects at a chip scale. An exciting prospect lies in the possibility to achieve remote entanglement of quantum states hosted by distant qubits of different nature – including transmons, spin states or mechanical resonators – using surface acoustic waves in the single-phonon regime as information carriers. On a more fundamental level, the proposed research track will allow for the investigation of the coupling mechanisms between travelling and local mechanical resonances at a quantum level.

But a number of intermediate outcomes are fortunately to be expected. One of them lies in the ability to set up complex resonator architectures allowing to finely control the elastic displacement and hence the strain distribution at the substrate surface. Outside SAW localisation and waveguiding, this could be used to trigger and control strain-mediated coupling, a mechanisms that has proven its relevance in optomechanical or nano-mechanical systems. It is also now at the core of recent developments in nanomagnetism or spintronics, where the ability to generate highly localised coherent phonons to drive magnetisation precession or spin states in, e.g., neutral vacancy centers is decisive. The use of piezoelectric materials with high electromechanical coupling coefficients is an added-value with respect to the existing landscape of works tackling surface acoustic waves interfaced with other solid-state quantum systems, in particular with superconducting qubits. Accumulating - or balancing – effects linked to strain and electric-field-induced-coupling can lead to systems with higher SAW-qubit coupling strength, hence allowing to reach the strong coupling limit with lower quality factor mechanical resonators.

In the fields of information and communication technology, a demonstration of efficient electromechanically-driven resonator coupling can open the path to dense and integrated arrays of electro-acoustically coupled oscillators that could be used for synchronisation. Phononic resonators exhibiting dimensions well below the micrometer range are in addition low-mass structures that strongly confine gigahertz elastic vibrations. This particularity can be exploited for the design of highly sensitive mass or force sensors with a potential for an integrated interrogation involving interdigital transducers. Transposing our know-how in a cryogenic environment, and above all, to the quantum regime requires a significant leap forward, but it will allow to demonstrate a phononic platform with a remarkable degree of integrability, scalability and flexibility. We will hence reach an unmatched control of stress, strain and electric-field distribution at the sub-micron scale in both the classical and quantum regimes, and this very characteristic will allow coupling such a fully-fledged system to other quantum physical degrees of freedom, hence opening genuine perspectives for the implementation of hybrid quantum devices combining, in the long run, the storing properties of solid-state qubits, the fast transmission schemes brought by photons, the signal processing functionalities offered by phonons.

5
GENERAL CONCLUSION

Phononic crystals, or elastic metamaterials, to adopt a more general view, have now reached a certain level of maturity. In the low frequency regime, they are definitely being considered as serious alternatives to more conventional and well-established solutions for noise and vibration control. In the radio-frequency regime, however, they are still being considered as academic curiosities[2]. The initial expectations lied in the possibility to introduce complex phononic circuits in RF electronic circuitry, in order to outperform the current capabilities for RF signal processing with an unmatched level of miniaturization. The initial demonstrations were promising. Evidence of wave guiding or energy confinement in SAW and Lamb wave devices led to increased expectations. It however soon became manifest that the specifications that could be expected from RF phononic devices were far behind the stringent requirements imposed by RF communications systems, which are indeed pushing SAW or BAW devices to extremes. Waveguides suffered from large losses; reflectors, although compact, did not provide a better confinement than existing, easier-to-implement solutions; phononic anchors only proved relevant in rare applications were heat management was a genuine concern.

But, again, and to come back to what was already said in the introduction, Phononics has much more to offer than radio-frequency signal processing. Phononics allows reaching an unprecedented level of control of mechanical vibrations. And manipulation of mechanical vibrations at the micro- and nanoscale is a concern in many areas of science and technology.

We have therefore contributed to these fields by providing some insights on potential means of harnessing mechanical vibrations at this scale by combining surface acoustic waves and phononic crystals, associated or not with localised mechanical resonators. Our work on phononic crystals and waveguides has not only allowed us to set up proof-of-concepts experiments that demonstrated the feasibility of this approach for elastic energy distribution control, it has also lead us to gain a solid expertise in the related and rather demanding technological and instrumentation aspects inherent to operation at the micron-scale and in the radio-frequency regime. We are now implementing this know-how and the associated concepts to set up complex mechanical architectures, exploiting the the additional degree of freedom brought by traveling elastic waves, that can be used for both classical and quantum information processing. We have mentioned at length the scope of a recently granted ERC proposal dedicated to nanophononics in the quantum regime, where generation and manipulation of single-phonons will be sought after. But the pos-

[2] At the noteworthy exception of one-dimensional crystals (i.e. Bragg gratings) which are continuously re-discovered as a means to implement smart wave progataion control startegies, as in the case, for instance of the so-called *incredibly high performance* (I.H.P.) SAW [141].

sible control of the polarization states of the resonators by an electromechanical drive opens exciting perspectives for the realization and manipulation of mechanical states. This last point is of particular interest in the context of signal processing, even in the one of quantum computing. There have indeed been a number of recently reported works suggesting that Phononics could also be used as a tool to perform quantum-like operation at room temperature [142, 143]. The proposed idea is generally to exploit a number of quantum-like features, observable in classical objects or systems, such as non-reciprocity or $\mathcal{P}-\mathcal{T}$ symmetry, that could for example be observed in one-dimensional phononic chains exhibiting non-reciprocal propagation. A similar principle could be applied here, with the nonreciprocity being controlled by the conjunction of resonator-to-resonator and resonator-to-surface coupling. One could also work towards the implementation of circular polarization states with controlled handedness to obtain mechanical spin-like states that could be used as a basis for quantum computing. Again, one may find inspiration in Photonics, where it has been know and exploited for some time now that one could encode qubit states in different degrees of freedom, such as polarisation, frequency or transverse modal states.

Another aspect of this work, that we will definitely carry on exploiting in the coming years, lies in the ability to finely control the elastic displacement and hence the strain distribution at the substrate surface, that we tried to exploit to some extent in the context of acousto-optics and phoxonics. The control of strain-mediated coupling has proven its relevance in optomechanical or nano-mechanical systems, but also for charge transport in semi-conductors. It is now at the core of recent developments in nanomagnetism or spintronics, where the ability to generate highly localized coherent phonons to drive magnetization precession or spin states in, e.g., neutral vacancy centers is decisive. We will work with this objective in mind, targetting both room-temperature and cryogenic operation. Eventually, interaction with photonics could also be considred in the light of plasmonics provided a transposition of our structures to - technologically at hand - smaller scales.

This already well-filled list of potentialities is obviously not exhaustive. It illustrates, however, the still unexploited potential of radio-frequency Phononics in areas exceeding its initial outlines, that is mirrored by a growing interest from the optomechanics or solid-state physics communities. In addition to reviving the interest in higher-frequency phononics, this will unmistakebly shed a new light on the field.

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A
SCIENTIFIC MANAGEMENT

A.1 Research Projects

ERC Consolidator Grant uNIQUE (2020 - 2025) –
Principal investigator
The uNIQUE project aims at the development of an all-electro-acousto-mechanical quantum information platform exploiting the full potential offered by surface acoustic waves in the single-phonon regime, and by mechanical resonators beyond the standard quantum limit. It adopts a yet unexplored approach at the crossing of phononics, nanomechanics and quantum acoustics to yield a fully coherent mechanical playground that can be used at the interface with other solid-state or photon qubits or as an independent quantum signal processing system. It will exploit the substrate surface to prepare and transfer non-classical states of motion of surface-coupled phononic resonators with the utmost ambition to encode the state information in a travelling single-phonon, allowing remote entanglement. This platform will allow manipulating quantum states in exceedingly compact systems driven by a sheer radio-frequency signal.

ANR JCJC PhoRest (Dec. 2014 - Mar. 2019) –
Principal investigator
The PhoRest project aimed at the engineering of surface coupled nanophononic resonators allowing for a increased control of mechanical vibration propagation and localisation. It focused on the design, fabrication and characterization of deep sub-wavelength micron-scale resonators interacting with surface acoustic waves propagating on a piezoelectric substrate. The overall objective was to push forward a novel conceptual approach to design complex systems that could contribute to the development of disruptive Information and Communication Technologies based on advanced acoustic signal processing functionalites. The PhoRest project somehow contributed to bride the gap between Phononics and Micro- and Nanomechanics, allowing us to shed a different light on micron-scale Phononics. The obtained results indeed open excited prospects for the impleentation of versatile micro- nano-mechanical platforms where an increased control of mechanical vibrations could lead to hybrid, on-chip, signal processing devices merging electro-acoustics, mechanics, but also optics or plasmonics.

Projet Région de Franche-Comté (2013-2015) –
Spectroscopie spatio-temporelle des couplages photons-phonons-plasmons
Co-Principal Investigator
This project was aiming at launching an activity aiming at exploiting the similarities betaween surface-coupled resonators and plasmonic nanoparticles, first from a sheer acoustical point-of-view, then in the prospect of coupling plasmons to GHz-phonons. This project has laid the foundation of the ANR project PhoREst, described above. The phonon-plasmon interaction initially discussed remain topical and are discussed in the section *Perspectives* of this manuscript.

ANR P2N Project PhoxCry (2009-2013) –
Work Package Leader I have actively contributed to both the proposal writing and the scientific organization of the ANR Project PhoxCRy. This project involved FEMTO-ST, the IEMN in Lille, the LPMC in Nice and Thalès Research & Technology. I was particularly in charge of the technological aspects of the project and have been running a work package aiming at the experiental demonsration of simultaneous photonic and phononic band gaps in a lithium niobate phoxonic crystal.

Partenariat Hubert Curien - Appel PICASSO (2008-2009) –
Principal investigator on the French side
Scientific exchange programme between FEMTO-ST and the Institut de Ciencès Fotoniques (ICFO, Barcelona, Spain). This project was launched in the context of Didit Yudistira PhD's thesis, then a student at the Universitat Polytecnica de Catalunya under the supervision of Valerio Pruneri (ICFO).

A.2 Network Coordination

2018 - now: Head of the GdR CNRS *Métamatériaux acoustiques pour l'ingénierie* (GdR META, n°3759)
& 2016 - 2018: Co-founder and deputy head of the GdR CNRS *Métamatériaux acoustiques pour l'ingénierie*
I have taken part to the creation and the management of the groupement de recherche (GdR) *Métamatériaux acoustiques pour l'ingénierie* (META, GdR CNRS n°3759), initially launched at the incentive of Dr Anne-Christine Hladky-Hennion, CNRS Research Director at IEMN, Lille. The GdR META is a research network affiliated to the French National Center for Scientific Research (CNRS). Its aim is to contribute to the strengthening and enhancement of the scientific cooperation within the French community active in the fields of phononic crystals and acoustic & mechanical metamaterials. By bringing together students, engineers and researchers from academia and industry, the GdR META's ambition is to help sharing different perspectives on acoustic & mechanical metamaterials in order to produce scientific and technological knowledge, to identify potential industrial issues and to promote the development of acoustic & mechanical metamaterials as both a

fundamental and applied research field.
The GdR META was founded in 2016 with the idea to foster interaction between different areas in acoustics. It is built around four interest groups: underwater acoustics, radio-frequency communication systems, airborne acoustics, mechanics & vibro-acoustics. A fifth group is devoted to the identification of prospective applications of emerging directions in acoustic metamaterials, ranging for instance from seismic waves to heat management.

A.3 Institutional Activities within my host Institute

Executive board member of the FEMTO-ST technology center (2014-2018) –
Executive board in charge of the administrative and the operational management of the MIMENTO Technology Center of FEMTO-ST.

Member of the scientific steering committee of the MIMENTO technology center (Groupe de Réflexion Stratégique) (2008-2018) –
Advisory board in charge of the steering of the scientific and technological development of MIMENTO.

Technological advisor for the MN2S department (2008 - now) –
In charge of advising users on their clean room process flows.

A.4 Reviewing Activities and Participation to Scientific Commitees

A.4.1 Participation to scientific panels and advisory boards

2016 - 2018	Member of scientific evaluation committee of the French National Research funding agency (ANR), panel CE30 *Physics of condensed and diluted environments*
2017	Guest editor for Special Issue "Phononics" in *Crystals* (MDPI).
2012 - 2017	Expert at the *Observatoire des Micro- et Nano-technologies*, group Materials and Devices for Optics.
2015 - 2017	Member of the scientific advisory board for Phononics, the International Conference on Phononic Crystals and Acoustic Metamaterials.

A.4.2 Project reviewing, selection commitees and manuscript reviewing

- Evaluator for the French National Research funding agency (ANR) (until 2016).

- Evaluator for the Agencia Nacional de Evaluación y Prospectiva, Spain.
- Evaluator for the die Wissenschaftsfonds (FWF) Austrian Science Fund.
- Member of several selection committees for recruitment of research engineers or lecturers in various French institutions (2 research engineers at CNRS and ENSMM - 2008 & 2009, 1 lecturer at Univ. Paris XI - 2013, 1 at Univ. Lille - 2010, 2 lecturers at Univ. Franche-Comte - 2014, 2016.
- PhD jury member (CEA-LETI - 2011, 2 at Institut Langevin - 2016 & 2018, 2 at INSP - 2014 & 2018, 1 at C2N - 2018, 1 at IEMN 2017)
- Referee for the following journals: Nature Nanotechnology, Physical Review Letters, Physical Review Applied, Physical Review B, Optics Express, Optics Letters, Applied Physics Letters, Scientific Reports, Journal of micro-electromechanical systems, Journal of Optics, Journal of Physics D, IEEE TUFFC, AIP Advances, Ultrasonics, Journal of Sound and Vibration...

A.5 Organization of Scientific Meetings

2016-2019	Organization of a number of events organized within the frame of the GdR META (International Workshop on Microphononics and Applications, 2017 ; Industrials Day on Applications of Acoustic Metamaterials (2017 & 2020), National GdR kick-off meeting (2016).
2018	Member of the scientific and organizing committee of the European Workshop on Acoustic & Mechanical Metamaterials, London (UK) – To be repeated in 2020.
2017	Member of the scientific and organizing committee of the Summer School METAGENIERIE , Oleron (France).
2015	Member of the scientific and organizing committee of Phononics 2017, Paris (France).

B TEACHING AND SUPERVISION

B.1 Teaching Activities

- **Acoustical Microsystems**, 17h, 2^{nd}-year Master MIR (Microsystèmes, Instrumentation et Robotique), Université de Franche-Comté since 2017-2018.
- **Acousto-optics**, 17h, 2^{nd}-year Master PICS (Photonique, Information, Communication et Systèmes), from 2008 to 2017.
- Member of the *comité de perfectionnement du Cursus de Master en Ingénierie PICS (Photonique, Micro et Nanotechnologies, Temps-Fréquence, PICS)*, Université de Bourgogne Franche-Comté.
- **Technology for radio-frequency electro-acoustic devices**, Metagenierie Summer School, Oléron, juillet 2017, 4h.

B.2 Supervision of gradudate students and postoctoral fellows

B.2.1 Graduate Students

Didit Yudistira – PhD Student at ICFO, Spain.
Integrated acousto-optical filters using domain superlattices in lithium niobate
Thesis completed in June 2011, thesis director: Prof. Valerio Pruneri (ICFO).
I have contributed to the supervision of the thesis of Didit Yudistira, then PhD student at the Universitat Politecnica de Catalunya (UPC, Spain), while I was working as a post-doctoral fellow at ICFO, in the group of Prof. Valerio Pruneri. I had the opportunity to keep on supervising Didit and after leaving ICFO through the obtaining of a Partenariat Hubert Curien project (PHC *PICASSO*) and an additional funding from the UPC that allowed funding short as well as longer stays (up to 6 months) for Didit in Besançon. The thesis per se was dedicated to the simulation and fabrication of integrated acousto-optical devices based on surface acoustic waves and periodically-poled lithium niobate.

Said Sadat Saleh – Official Supervision Ratio: 40%
Bandes interdites photoniques et phononiques simultanées dans des cristaux phoxoniques en niobate de lithium - Simultaneous photonic and phononic band gaps in lithium niobate

phoxonic crystals.
Thesis completed in November 2011, thesis directors: Vincent Laude and Maria-Pilar Bernal, funding: Région de Franche-Comté.

Saïd Sadat-Saleh's thesis work was mostly devoted to attempts to demonstrate the existence of simultaneous photonic and phononic band gaps in lithium niobate phoxonic crystals, in collaboration with the Optics department of FEMTO-ST.

Younes Achaoui – Official Supervision Ratio: 30%
Bandes interdites de Bragg et résonances locales dans des cristaux phononiques microsoniques - Bragg and locally-resonant band gaps in micron-scale phononic crystals
Thesis completed in November 2011, thesis directors: Vincent Laude and Abdelkrim Khelif, funding: Ministère de la Recherche et de la Technologie.

Younes Achaoui's PhD thesis was mostly dedicated to the investigation of locally-resonant phononic crystals for surface acoustic waves. It particularly resulted in the experimental demonstration of phononic crystals supporting both Bragg and locally-resonant band gaps in the 100 MHz range.

Ludovic Socié – Official Supervision Ratio: 50%
Interaction acousto-optique dans les matériaux périodiquement structurés – Acousto-optical interactions in periodic structures
Thesis completed in June 2014, thesis director: Vincent Laude, funding: Ministère de la Recherche et de la Technologie.

Ludivoc Socié has mostly worked on the design and realization of high-aspect ratio transducers for surface acoustic waves, allowing for a lateral confinement of the elastic energy. These transducers were then used to implement acousto-optical modulators based on integrated Mach-Zehnder interferometers.

Laetitia Raguin – Official Supervision Ratio: 60%
Résonateurs phononiques couplés par la surface, Surface-coupled phononic resonators
Thesis completed in December, 2019, thesis director: Abdelkrim Khelif, funding: Ministère de la Recherche et de la Technologie.

Laetitia Raguin's thesis was directly related to the ANR project PhoRest and to our activities dedicated to surface-coupled resonators. The investigation of the coupling mechanisms occurring within pairs of mechanical resonators excited and coupled by surface acoustic waves constituted the core of her thesis work.

B.2.2 Post-doctoral fellows

Aurélie Lecestre – Research Engineer within the MIMENTO Technology Center from August 2010 to July 2011. Reserach topic: Lithium niobate dry etching.

Kim Ngoc Nguyen – Post-doctoral fellow, October 2014 - September 2015. Development of dual phononic-plasmonic devices. Collaboration with the Optics Department of FEMTO-ST, in the context of the LabEx ACTION.

Olivier Gaiffe – Post-doctoral Research Fellow. Development of optical instrumentation and protocols for the characterization of elastic displacement, in the context of the ANR projet PhoRest.

Benattou Sadani – Research Engineer, December 2017 - August 2018. Development of technological processes for silicon photonics. Collaboration Laboratoire Interdisciplinaire Carnot de Bourgogne, in the context of the LabEx ACTION.

Marie Gourier – Research Engineer, January 2018 - December 2018. Development of technological processes for micron-scale phononics, in the context of the ANR projet PhoRest.

B.3 Communication towards the general public

- Laboratory visits and meetings with high school students (Promotion of Science, equal gender opportunity in Science), on a regular basis.
- Supervision or participation to supervision of secondary school students (élèves de troisième) in the context of their job-shadowing programs.
- Science Festival 2014: setting-up and presentation of an experiment presenting a sonic crystal in the audible frequency range.

C
LIST OF PUBLICATIONS RELATED TO THE POST-DOCTORAL PERIOD

International peer-reviewed journal articles

P1. L. Raguin, O. Gaiffe, R. Salut, J.-M. Cote, V. Soumann, V. Laude, A. Khelif, and S. Benchabane, "Dipole states and coherent interaction in surface-acoustic-wave coupled phononic resonators," Nature Commun., **10**, 4583 (2019).

P2. V. Laude, A. Belkhir, A.F. Alabiad, M. Addouche, S. Benchabane, A. Khelif, and F.I. Baida, "Extraordinary nonlinear transmission modulation in a doubly resonant acousto-optical structure", Optica **4**, 1245 (2017).

P3. S. Benchabane, R. Salut, O. Gaiffe, V. Soumann, M. Addouche, V. Laude, and A. Khelif, "Surface-Wave Coupling to Single Phononic Subwavelength Resonators," Physical Review Applied **8**, 034016 (2017).

P4. M. Al Lethawe, M. Addouche, S. Benchabane, V. Laude, and A. Khelif, "Guidance of surface elastic waves along a linear chain of pillars," AIP Advances **6**, 121708 (2016).

P5. S. Benchabane, O. Gaiffe, R. Salut, G. Ulliac, V. Laude, and K. Kokkonen, "Guidance of surface waves in a micron-scale phononic crystal line-defect waveguide," Appl. Phys. Lett. **106**, 081903 (2015).

P6. R. P. Moiseyenko, J. Liu, S. Benchabane, N. F. Declercq, and V. Laude, "Excitation of surface waves on one-dimensional solid-fluid phononic crystals and the beam displacement effect," AIP Advances **4**, 124202 (2014).

P7. P. H. Otsuka, K. Nanri, O. Matsuda, M. Tomoda, D. M. Profunser, I. A. Veres, S. Danworaphong, A. Khelif, S. Benchabane, V. Laude, and O. B. Wright, "Broadband evolution of phononic-crystal-waveguide eigenstates in real- and k-spaces," Scientific Reports **3**, 3351 (2013).

P8. Y. Achaoui, V. Laude, S. Benchabane, and A. Khelif, "Local resonances in phononic crystals and in random arrangements of pillars on a surface", J. Appl. Phys. **114**, 104503 (2013).

P9. L. Socié, S. Benchabane, L. Robert, A. Khelif, and V. Laude, "Surface acoustic wave guiding in a diffractionless high aspect ratio transducer", Appl. Phys. Lett. **102**, 113508 (2013).

P10. A. Lecestre, S. Benchabane, L. Robert, R. Salut, G. Ulliac, and P. Blind, "Electroplated Ni mask for plasma etching of submicron-sized features in $LiNbO_3$", Microelectron. Eng. **105**, 95 (2013).

P11. E. Courjon, F. Bassignot, G. Ulliac, S. Benchabane, and S. Ballandras,"Acoustic wave filter based on periodically poled lithium niobate," IEEE Trans. Ultrason. Ferroelectr. Freq. Control **59**, 1942 (2012).

P12. V. Laude, R.P. Moiseyenko, S. Benchabane, and N.F. Declercq, "Bloch wave deafness and modal conversion at a phononic crystal boundary," AIP Advances **1**, 041402 (2011).

P13. Y. Pennec, B. Djafari Rouhani, C. Li, J.M. Escalante, A. Martinez, S. Benchabane, V. Laude, and N. Papanikolaou, "Band gaps and cavity modes in dual phononic and photonic strip waveguides," AIP Advances **1**, 041901 (2011).

P14. M. Gorisse, S. Benchabane, G. Teissier, C. Billard, A. Reinhardt, V. Laude, E. Defaÿ, and M. Aïd, "Observation of band gaps in the gigahertz range and deaf bands in a hypersonic aluminum nitride phononic crystal slab," Appl. Phys. Lett. **98**, 234103 (2011).

P15. D. Yudistira, S. Benchabane, D. Janner, and V. Pruneri, "Diffraction less and strongly confined surface acoustic waves in domain inverted $LiNbO_3$ superlattices," Appl. Phys. Lett. **98**, 233504 (2011).

P16. V. Laude, J.-C. Beugnot, S. Benchabane, Y. Pennec, B. Djafari-Rouhani, N. Papanikolaou, J.-M. Escalante, and A. Martinez, "Simultaneous guidance of slow photons and slow acoustic phonons in silicon phoxonic crystal slabs," Optics Exp. **19**, 9690 (2011).

P17. S. Benchabane, O. Gaiffe, G. Ulliac, R. Salut, Y. Achaoui, and V. Laude, "Observation of surface-guided waves in holey hypersonic phononic crystal," Appl. Phys. Lett. **98**, 171908 (2011).

P18. G. Ulliac, B. Guichardaz, JY. Rauch, S. Queste, S. Benchabane, and N. Courjal, "Ultra-smooth $LiNbO_3$ micro and nano structures for photonic applications," Microelectron. Eng. **88**, 2417 (2011).

P19. Y. Achaoui, A. Khelif, S. Benchabane, L. Robert, and V. Laude, "Experimental observation of locally-resonant and Bragg band gaps for surface guided waves in a phononic crystal of pillars," Phys. Rev. B **83**, 104201 (2011).

P20. V. Laude, K. Kokkonen, S. Benchabane, and M. Kaivola, "Material anisotropy unveiled by random scattering of surface acoustic waves," Appl. Phys. Lett. **98**, 063506 (2011).

P21. D. Yudistira, D. Janner, S. Benchabane, and V. Pruneri, "Low power consumption integrated acousto-optic filter in domain inverted $LiNbO_3$ superlattice," Optics Exp. **18**, 27181 (2010).

P22. A. Khelif, F.-L. Hsiao, A. Choujaa, S. Benchabane, and V. Laude, "Octave Omnidirectional Band Gap in a Three-Dimensional Phononic Crystal," IEEE Trans. on Ultrason. Ferr. Freq. Cont. **57**, 1621 (2010).

P23. Y. Pennec, B. Djafari Rouhani, E.H. El Boudouti, C. Li, Y. El Hassouani, J.O. Vasseur, N. Papanikolaou, S. Benchabane, V. Laude, and A. Martinez, "Simultaneous existence of phononic and photonic band gaps in periodic crystal slabs," Optics Express **18**, 14301 (2010).

P24. A. Khelif, Y. Achaoui, S. Benchabane, and V. Laude, "Locally resonant surface acoustic wave band gaps in a two-dimensional phononic crystal of pillars on a surface," Phys. Rev. B **81**, 214303 (2010).

P25. Y. Achaoui, A. Khelif, S. Benchabane, and V. Laude, "Polarization state and level repulsion in two-dimensional piezoelectric phononic crystals and waveguides," J. Phys. D: Appl. Phys. **43**, 185401 (2010).

P26. N. Courjal, S. Benchabane, J. Dadah, G. Ulliac, Y. Gruson, and V. Laude, "Acousto-optically tunable lithium niobate photonic crystal modulator," Appl. Phys. Lett. **96**, 131103 (2010).

P27. D. Yudistira, D. Janner, S. Benchabane, and V. Pruneri, "Integrated acousto-optic polarization converter in a ZX-cut $LiNbO_3$ waveguide superlattice," Opt. Lett. **34**, 3205 (2009).

P28. S. Sadat-Saleh, S. Benchabane, F. I. Baida, M.- P. Bernal, and V. Laude, "Tailoring simultaneous photonic and phononic band gaps," J. Appl. Phys. **106**, 074912 (2009).

P29. V. Laude, Y. Achaoui, S. Benchabane, and A. Khelif, "Evanescent Bloch waves and the complex band structure of phononic crystals," Phys. Rev. B **80**, 092301 (2009).

P30. D. Yudistira, S. Benchabane, D. Janner, V. Pruneri, "SAW generation in ZX-cut $LiNbO_3$ superlattices using coplanar electrodes," Appl. Phys. Lett. **95**, 052901 (2009).

P31. S. Benchabane, L. Robert, J.-Y. Rauch, A. Khelif, and V. Laude "Highly selective electroplated nickel mask for lithium niobate dry etching," J. Appl. Phys. **105**, 094109 (2009).

P32. S. Giurgola, A. Rodriguez, L. Martinez, P. Vergani, F. Lucchi, S. Benchabane, and V. Pruneri, "Ultra thin nickel transparent electrodes," J. Mater. Sci: Mater. Electron. **20**, S181 (2009).

P33. V. Laude, D. Gérard, N. Khelfaoui, C. F. Jerez-Hanckes, S. Benchabane, and A. Khelif, "Subwavelength focusing of surface acoustic waves generated by an annular interdigital transducer," Appl. Phys. Lett. **92**, 094104 (2008).

P34. D. Yudistira, D. Faccio, C. Corbari, P. G. Kazansky, S. Benchabane, and V.Pruneri, "Electric surface potential and frozen-in field direct measurements in thermally poled silica," Appl. Phys. Lett. **92**, 012912 (2008).

P35. K. Kokkonen, M. Kaivola, S. Benchabane, A. Khelif, and V. Laude, "Scattering of surface acoustic waves by a phononic crystal revealed by heterodyne interferometry," Appl. Phys. Lett. **91**, 083517 (2007).

P36. S. Benchabane, A. Khelif, J.-Y. Rauch, L. Robert, and V. Laude, "Evidence for complete surface wave band gap in a piezoelectric phononic crystal," Phys. Rev. E, **73**, 065601(R) (2006).

P37. Y. Pennec, B. Djafari-Rouhani, J.O. Vasseur, H. Larabi, A. Khelif, A. Choujaa, S. Benchabane, and V. Laude, "Acoustic channel drop tunneling in a phononic crystal," Appl. Phys. Lett. **87**, 261912 (2005).

P38. S. Benchabane, A. Khelif, A. Choujaa, B. Djafari-Rouhani, and V. Laude, "Interaction of waveguide and localized modes in a phononic crystal," Europhys. Lett. **71**, 570 (2005).

P39. V. Laude, M.Wilm, S. Benchabane, and A. Khelif, "Full band gap for surface acoustic waves in a piezoelectric phononic crystal," Phys. Rev. E **71**, 036607 (2005).

P40. V. Laude, A. Khelif, S. Benchabane, M. Wilm, Th. Sylvestre, B. Kibler, A. Mussot, J. M. Dudley, and H. Maillotte, "Phononic bandgap guidance of acoustic modes in photonic crystal fibers," Phys. Rev. B **71**, 045107 (2005). Selected by the Virtual Journal of Nanoscale Science & Technology **11** (2005).

P41. A. Khelif, A. Choujaa, S. Benchabane, B. Djafari-Rouhani, and V. Laude, "Experimental study of guiding and filtering of acoustic waves in a two dimensional ultrasonic crystal," Z. Kristallogr. **220**, 836 (2005).

P42. M. Schmid, S. Benchabane, F. Torabi-Goudarzi, R. Abram, A.I. Ferguson and E. Riis, "Optical in-well pumping of a vertical-external-cavity surface-emitting laser," Appl. Phys. Lett., **84**, 4860 (2004).

P43. A. Khelif, A. Choujaa, S. Benchabane, B. Djafari-Rouhani and V. Laude, "Guiding and bending of acoustic waves in highly confined phononic crystal waveguides," Appl. Phys. Lett. **84**, 4400 (2004).

Invited Papers

1. S. Benchabane, L. Raguin, O. Gaiffe, R. Salut, V. Soumann, J.-M. Cote, V. Laude, and A. Khelif, "Coherent control of mechanical states in surface-coupled phononic resonators", Metamaterials'19, The 13th International Congress on Artificial Materials for Novel Wave Phenomena (Rome, Italy).

2. S. Benchabane, L. Raguin, O. Gaiffe, R. Salut, V. Soumann, V. Laude, and A. Khelif, "Surface Coupled Phononic Resonators”, Phonons 2018 & PTES 2018 Joint Conference, (Nanjing, China).

3. S. Benchabane, L. Raguin, O. Gaiffe, R. Salut, V. Soumann, V. Laude, and A. Khelif, "Coupling of single mechanical resonators through surface elastic waves”, 2017 GdR MecaQ Annual Meeting (Paris, France).

4. S. Benchabane, L. Raguin, O. Gaiffe, R. Salut, V. Soumann, V. Laude, and A. Khelif, "Coupling of mechanical resonators under surface acoustic wave excitation”, 2017 IEEE International Ultrason. Symp. (Washington, USA).

5. S. Benchabane, L. Socié, A. Khelif and V. Laude, "Surface Elastic Wave Confinement in Defect-Based and Mass-Loaded Phononic Waveguides", Phononics 2013: 2nd International Conference on Phononic Crystals/Metamaterials, Phonon Transport and Optomechanics (Sharm-El-Sheikh, Egypt).

6. V. Laude, R.P. Moiseyenko, S. Benchabane, J. Liu, N.F. Declercq, “Phononic Crystal Diffraction Gratings for Surface and Bulk Acoustic Waves”, Phononics 2013: 2nd International Conference on Phononic Crystals/Metamaterials, Phonon Transport and Optomechanics (Sharm-El-Sheikh, Egypt).

7. S. Benchabane, L. Robert, A. Lecestre, G. Ulliac, R. Salut, V. Laude, "Structuring Lithium Niobate: Collective Etching and FIB Milling for Photonics and Phononics", 5th International Photonics and OptoElectronics Meeting (Wuhan, China, 2012)

8. O. Stepanenko 1, E. Quillier, H. Tronche, P. Baldi, P. Aschiéri, S. Benchabane, and M. P. De Micheli, "Towards Nonlinear Photonic Wires in Z-cut$LiNbO_3$", Laser Optics 2012 (Saint-Petersburg, Russia).

9. S. Benchabane, S. Sadat-Saleh, M.-P. Bernal, F. I. Baida, and V. Laude,"Cristaux phoxoniques intégrés : vers une nouvelle génération de composants opto-acoustiques", GDR Ondes (Nice, France, 2011).

10. V. Laude, S. Benchabane, Y. Achaoui, and A. Khelif, "Propagation and Trapping of Surface Acoustic Waves in Phononic Crystals", ASME 2012 International Mechanical Engineering Congres (IMECE, Houston, USA).

11. S. Benchabane, S. Sadat-Saleh, M.-P. Bernal, J.-C. Beugnot, V. Laude,Y. Pennec, B. Djafari-Rouhani, N. Papanikolaou and A. Martinez, "Phoxonic Crystals: A review", Proceedings of Phononics 2011, Paper Phononics-2011-0109, p. 84, (Santa Fe, USA, 2011).

12. S. Benchabane, A. Khelif and V. Laude, "Is there really a sound line limit for surface waves in phononic crystals?" Proceedings of the SPIE, 7946, 794618 (San Francisco, USA, 2011).

13. S. Benchabane, S. Sadat-Saleh, M.-P. Bernal, F. I. Baida, and V. Laude, "Towards phoXonic crystals," META'10 Second International conference on metamaterials, photonic crystals and plasmonics (Cairo, Egypt, 2010).

14. S. Benchabane, J.-C. Beugnot, S. Sadat Saleh, M.-P. Bernal, T. Sylvestre, H. Maillotte and V. Laude, "Les matériaux à bandes interdites phoxoniques," Journées Nationales d'Optique Guidée (Lille, France, 2009).

15. S. Benchabane, L. Robert, A. Khelif and V. Laude, "Piezoelectric Phononic Crystals for Surface Acoustic Waves," International Workshop on Phononic Crystals (Nice, France, 2009).

16. V. Laude, Y. Achaoui, S. Benchabane, A. Khelif, "Plane wave expansion method for phononic crystals: review and prospects," International Workshop on Phononic Crystals (Nice, France, 2009).

17. A. Khelif, A. Choujaa., S. Benchabane, V. Laude, "Omnidirectional band gap mirror for Surface Acoustic Wave", IUTAM Symposium on Recent Advances of Acoustic Waves in Solids (Taipei, Taiwan, 2009).

18. V. Laude, Y. Achaoui, S. Benchabane, A. Khelif, "Complex band structure of phononic crystals and the diffraction problem", IUTAM Symposium on Recent Advances of Acoustic Waves in Solids (Taipei, Taiwan, 2009).

19. V. Laude, B. Aoubiza, Y. Achaoui, S. Benchabane, A. Khelif, "Evanescent Bloch waves in phononic crystals", Proceedings of the SPIE 7223, 72230E (San Jose, USA, 2009).

20. N. Courjal, M.-P. Bernal, G. Ulliac, S. Benchabane, "$LiNbO_3$ acousto-optical and electro-optical micromodulators", EOS Annual Meeting, (Paris, France, 2008).

21. A. Khelif, F.-L. Hsiao, S. Benchabane, A. Choujaa, B. Aoubiza, V. Laude, "Ultrasonic and hypersonic phononic crystals", in Proc. SPIE - Photonic Crystal Materials and Devices VII, (San Jose, USA, 2008).

22. N. Courjal, M.-P. Bernal, M. Spajer, G. Ulliac, R. Salut, J. Dahdah, S. Benchabane, "FIB milling for lithium niobate photonic crystals", First international workshop on FIB for photonics (Eindhoven, The Netherlands, 2008).

23. S. Benchabane, A. Khelif, L. Robert, J. Y. Rauch, Th. Pastureaud, and V. Laude, "Elastic band gaps for surface modes in an ultrasonic lithium niobate phononic crystal," in Photonic Crystal Materials and Devices III, Proc. Soc. Photo.-Opt. Instrum. Eng. 6182, 618216 (Strasbourg, France, 2006).

International conferences with proceedings

1. L. Socié, S. Benchabane, L. Robert, and V. Laude,"SAW waveguiding in high aspect ratio interdigital transducers", 2012 IEEE International Ultrason. Symp., poster P4H-7 (Dresden, Germany).

2. M. P. De Micheli, O. Stepanenko, E. Quillier, H. Tronche, P. Baldi, P. Aschiéri, and S. Benchabane, "Towards Proton Exchanged Photonic Wires in $LiNbO_3$", Advances in Optical Materials, paper IF1A.6 (San Diego, USA).

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