JOURNAL OF APPLIED PHYSICS **123**, 094901 (2018)

Hybridization bandgap induced by an electrical resonance in piezoelectric metamaterial plates

N. Kherraz,[1,2,3] L. Haumesser,[2] F. Levassort,[2] P. Benard,[1] and B. Morvan[1]
[1]*University of Normandie, UNIHAVRE, Laboratoire Ondes et Milieux Complexes, UMR CNRS 6294, 75 Rue Bellot, 76600 Le Havre, France*
[2]*University of Tours, GREMAN, UMR CNRS 7347, 03 Rue de la Chocolaterie, 41000 Blois, France*
[3]*Department of Physics, University of Torino, Via Pietro Giuria 1, 10125 Torino, Italy*

(Received 20 November 2017; accepted 20 February 2018; published online 5 March 2018)

We demonstrate numerically and experimentally the opening of a locally resonant bandgap in an active phononic crystal (PC) made of a homogeneous piezoelectric plate covered by a 1D periodic array of thin electrodes connected to inductive shunts. The application of periodic electrical boundary conditions (EBCs) enables an at will tailoring of the dispersion properties of the PC plate, thus leading to a control of the dispersion of the propagating guided elastic waves in the plate. Depending on the nature of the EBCs, several bandgaps open up, the most important being a Hybridization Bandgap (HBG) in the subwavelength regime. The PC behaves as a locally resonant metamaterial. The HBG originates from the interaction of propagating elastic waves (Lamb modes) with an electrical resonant mode whose dispersion can be effectively described through an equivalent transmission line model. *Published by AIP Publishing.*
https://doi.org/10.1063/1.5016496

I. INTRODUCTION

During the last few years, phononic crystals (PCs) have demonstrated their great ability to manipulate elastic waves. Selective filtering,[1] beamforming,[2] super resolution imaging,[3] and acoustic resonators[4] are, among many others, different applications that have emerged. Phononic crystals derive their properties from the periodic arrangement of their constitutive materials. This periodicity has to be of the order of the wavelength of the propagating waves, which explains why most of the experiments and practical applications have been developed for ultrasonic waves for which the wavelength remains small. Recently, the willingness to reduce the size and weight of devices, for instance, for the audible sound mitigation purpose or for electronic applications where miniaturization is needed, has led to a strong interest in locally resonant metamaterials (MMs) that enable the control of wave propagation at deep sub-wavelength scale. One way to achieve a locally resonant material is to use the high sound velocity contrast between the host matrix material and embedded inclusions. Using metallic spheres coated with silicone in an epoxy matrix, Liu *et al.* developed a sonic MM with bandgap caused by negative effective elastic constants with a lattice constant 300 times smaller than the wavelength in epoxy.[5] Brunet *et al.*[6] exploited Mie resonances of soft porous silicone rubber particles together with their surrounding fluid matrix to obtain a metafluid, exhibiting simultaneously negative effective mass density and bulk modulus. However, this MM is difficult to use in practice for the realization of a super-resolution lens due to strong absorption inside the porous inclusions.

The use of active materials such as piezoelectric materials is another way to obtain local resonances within a MM. Such mechanisms that couple mechanical vibrations to electrical passive or active circuits have been extensively studied in the low frequency range for their ability in vibration damping and energy harvesting.[7–13] In addition, the insertion of piezoelectric materials in PCs offers a frequency agility which can be easily controlled electrically and does not require any geometry modification nor phase transition of constitutive materials.[8–10,13–15] For instance, a Bragg gap can be shifted by switching from the open to the short circuit the electrical boundary condition (EBC) of piezoelectric inclusions in a PC.[16] Electrical resonances can be easily induced in a piezoelectric element by connecting an inductive shunt. Several studies aim at the attenuation of structure vibrations by sticking piezoelectric elements linked to an independent inductive circuit. It was demonstrated theoretically and experimentally that these structures exhibit hybridization bandgaps (HBGs) at the electrical resonance frequencies.[17–21] This technique gives the opportunity to tune the stiffness of the substrate as reported by Bergamini *et al.*[22] and to modify the wave dispersion in the medium by tailoring the external electrical circuit. In their work, piezoelectric discs are inserted between an aluminium substrate, where guided waves propagate, and cylindrical stubs arranged periodically on the surface. The implementation of this kind of EBC is simple and can also be efficient at high frequencies by implementing active circuits. However, these resonators are isolated between each other and have inherently narrow frequency band behavior, thus limiting the coupling with the mechanical modes supported by the waveguide. To overcome this limitation, some authors have proposed a hybrid electric/mechanical medium:[23–27] the spatial periodicity of the mechanical part is settled by the arrangement of the piezoelectric elements, whereas the electrical part is composed of the lumped transmission line achieved by combining inductive circuits with resistors and the piezoelectric elements. This enables the propagation of