On the proposal of an standard design for piezoelectric resonators with in-phase mechanical displacement: 2-d Photonic Transducers

Silvia Ronda, Francisco Montero de Espinosa José Luis Aragón

Abstract— In the searching of a standard method to get piezoelectric transducer resonators with piston-like vibration pattern, good results have been obtained by drilling square phononic lattices along the length direction. To increase the number of holes maintaining the hole filling ratio, modified lattices have been successfully tested. A cross parametric study using the lattice parameter and the hole diameter has been made to study a standard 200 kHz piezoelectric sandwich transducer with a “forbidden” length-to-radial ratio of 0.2. Finite Element modelling (COMSOL Multyphysics 5.2a) has been used. It has been concluded that for a filling ratio of 14% and 4.2 mm hole diameter, the phononic resonator behaves like a piston.

Keywords— phononic crystals, piezoelectric transducers, mechanical resonators, actuators

I. INTRODUCTION

Ultrasonic piezoelectric resonators are usually made of two sections: an active piezoelectric plate and a bonded or fixed metallic part. From these, the Langevin type [1] is the most common design, where the transducer length is usually half the wavelength (λ) at the resonance frequency. Piezoceramics and metals with low mechanical losses are used to optimize energy delivery at the working frequency.

When designing a piezoelectric resonator to be used to emit ultrasound or to transmitting vibrations to a medium, the transducer vibration pattern is the key designing parameter. For instance, Langevin type transducer design has a length-to-radial aspect ratio higher than 2 to get a piston-like mechanical displacement at the emitting transducer surface, avoiding the interference of the lateral modes with the main length resonance. If the piezoelectric plate and/or the metallic part have lateral dimensions on the order or bigger that the thickness, the transducer vibration surface will not be in phase and the amplitude distribution of the emitting face will not be homogeneous and, so, the transducer will not be useful for any application [1].

In this work, we are interested in find a design framework to get piston-like piezoelectric transducer resonators regardless their lateral geometry and dimensions.

As an alternative to optimize the geometry of the transducer in order to stop or minimize lateral modes, we recently proposed the use of diffracting networks (phononic crystals) to stop the propagation of lateral elastic waves, and tested this proposal in piezoceramics and in metals [2] [3][4]. A typical design of these phononic crystals is the drilling of holes in a plate following a square pattern [5]. If the holes are drilled with the adequate pitch and radius, the propagation of the waves travelling in the directions perpendicular to the thickness of the plate can be stopped. The reason is that if the lattice parameter agrees with half a wavelength of the wave frequency, the existence of a band gap centred at this frequency prevents the propagation of these waves [6][7][8][9][10]. It was shown that even known that with this procedure the transmitting transducer effective surface is reduced, the overall efficiency remains unchanged because the surface amplitude vibration increases [4]. The main design drawback is that if the lateral dimensions of the require transducer is small, as the lattice parameter of the square array of holes is fixed, it may happen that only two or at most three copies of the unit cell can be drilled. This considerably reduces the effectivity of the phononic lattice. Here we propose a new way to overcome this last drawback making

Silvia Ronda, Francisco Montero de Espinosa is with ITEFI-CSIC, Serrano 144, 28006 Madrid, Spain silvia.ronda@csic.es , francisco.montero@csic.es

José Luis Aragón is with
Centro de Física Aplicada y Tecnología Avanzada, Universidad Nacional Autónoma de México, Apartado Postal 1-1010, Querétaro 76230, Mexico aragon@fata.unam.mx

this “phononic transducers” suitable for industrial applications.

II. TRANSDUCER GEOMETRY AND DESIGN

When the industrial needs requires that the radial dimension of the piezoelectric resonator is so small that only a few holes of a square array with lattice parameter *a* fit , the proposed idea is to use a double lattice composed with the standard square lattice superimposed with another square lattice displaced by $a/\sqrt{2}$*2 along the crystallographic direction [1-1] [11] . In this way, two displaced square lattices are obtained that viewed along the crystallographic direction [1-1] form a square lattice with lattice parameter $a/\sqrt{2}$ *2 with twice holes that a single layer. Notice that *a* is the optimal for the piezoelectric resonator material with a given lateral wave propagation velocity, in the sense that it is calculated to stop the radial modes. A lattice with a small lattice parameter (in this case $a/\sqrt{2}$ *2) may not work efficiently and simulations must be made around this value to get the best figure. Figure 1 shows the concept, being Figure 1a and 1b the standard lattice and Figure 1c the proposed double lattice. The hole diameter, d, of the double lattice is smaller to get the same filling factor.

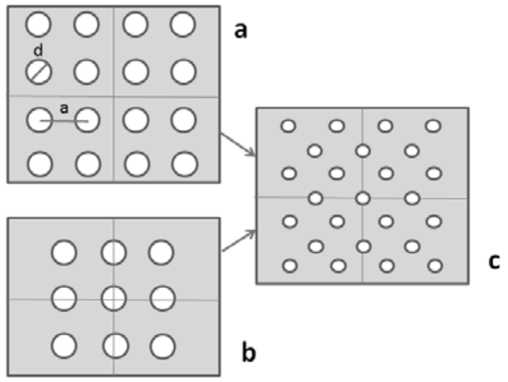


Fig 1. a) and b) standard diffraction lattice, c) proposed double lattice

III. CALCULATION METHOD

To get the optimum figures of the sandwich piezoelectric resonator with e double diffraction lattice- Figure 3b- , a cross parametric study was made computing a number of models were the lattice parameter and the hole diameter were varied. *Piezoelectric Device Module* of Finite Element Software (*COMSOL Multyphysics 5.2a* ®) was used. Based on the theory prediction of an optimum lattice efficiency [3], the hole diameter were varied between 2.8 and 4.2 mm, using three different lattice parameter 10mm,12mm and 14 mm. First, the module of the electrical impedance was calculated and the vibration pattern of the resonator is studied at this resonance frequency. The frequency range studied covers 20 calculated points between 140 kHz and 240 kHz (one every 50 kHz).

The resonator has four parts: two inner discs of piezoceramic material with the polarization in opposition and two steel discs at the top and the bottom forming a “sandwich transducer”. The steel discs are excited with a potential of 2V and the piezoceramic faces in contact are grounded, like is represented in Figure 2. The materials employed for the simulations are the common materials used in power ultrasonic transducers, which properties are included in COMSOL`s Material Library: *PZT-4* for the piezoceramic and *Steel AISI 4340*. In the case of the piezoceramic, a mechanical isotropic damping of η=1+2 10e-2i was introduced. The heights of the piezoelectric and metal discs are 3 mm and 2 mm respectively and have a diameter of 50 mm.

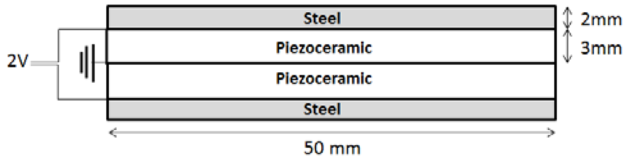


Fig 2. Transducer representation. Parts, materials and dimensions

First of all, a standard resonator without any diffraction lattice made of holes is computed to localize the thickness resonance and to observe the interference of the lateral modes (standard model) – Figure 3a-. The cylindrical symmetry of the problem allows us to work with a quarter of the disc applying symmetry conditions. Then, nine models were made with the lattice parameter and diameter as shown in the two first columns of Table 2. A general representation of the drilled models is shown in Figure 3b.

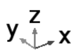
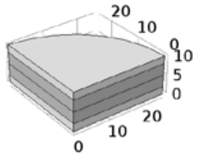
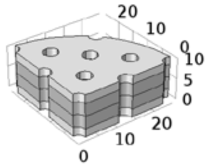
Axes	Standard Model	Drilled Model
	 a	 b

Fig 3. Orientation axes and geometic representation of computerized models. Scale is in mm. a) Standard model and b) drilled model

For a wave propagation problem, separation between calculated points should be, at least, $\lambda/5$. Considering that the minimum propagation velocity in our case is about 3000 m/s and the main frequency is 200 kHz, we have to use a maximum mesh of 4 mm. Extra fine mesh COMSOL’s configuration is employed, which have a maximum element size of elements of 0.875 mm.

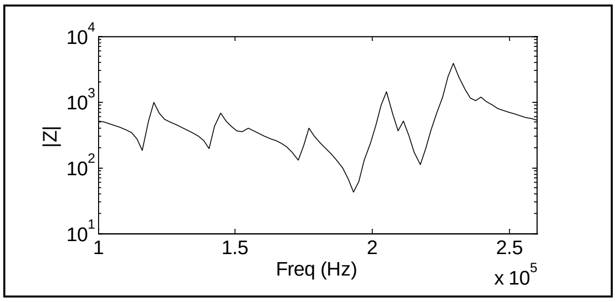


Fig 4. Module of the electrical impedance for the experimental model of the “sandwich” transudcer without drilling

IV. Results

Figure 5 shows the module of the electrical impedance for the case of the three models having holes of d=2.8 mm with lattice parameter a= 10mm, 12mm and 14 mm. Comparing this figure with the case for the standard model -Figure 4- it is clear that the lattices stop in some degree the propagation of the lateral modes. The minimum of each case, 9 in total,- Table I- are the frequencies of the modes that are then studied to qualify their piston-like vibration behavior.

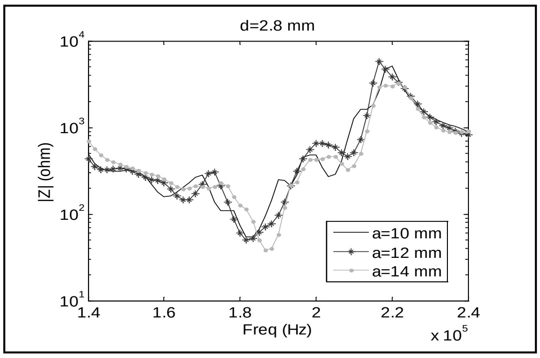


Fig 5. Module of the electrical impedance for the simulated model of the “sandwich” transudcer with holes of d= 2.8 mm of diameter for a lattice parameter of a= 10, 12 and 14 mm.

TABLE I. RESONANCE FREQUENCY

Minimum of the electrical impedance		
d [mm]	***a [mm]***	***f [kHz]***
2.8	10	183
	12	182
	14	187
3.5	10	182
	12	178
	14	182
4.2	10	178
	12	177
	14	177

We defined a figure of merit σ to qualify the piston-like behavior at the mechanical resonance of the nine models. This figure of merit based on the amplitude vibration, *A*, and phase, *θ*, of each calculated point of the resonator upper face -equation 1-, gives an idea the in-phase vibration behavior. In the case of a piston, σ=1. So, for each model, the amplitude, *A*, and phase, *θ*, of the vibration is calculated. Data are exported to MATLAB and the qualifying factor is calculated like:

$$\sigma = \frac{\sum_{i=1}^{n} A_i \cos(\theta_i)}{\bar{A} \cdot n} \qquad (1)$$

Were n are the number of calculated points. The results are shown in Table II

TABLE II. FIGURE OF MERIT

Figure of merit based on the Amplitude and Phase of the vibration in the longitudinal direction for the resonant frequency				
d [mm]	***a [mm]***	***A [nm]***	***Acos(θ) [nm]***	***σ***
2.8	10	4.21	1.02	0.242
	12	4.33	1.63	0.376
	14	4.88	3.14	0.064
3.5	10	4.22	1.80	0.426
	12	2.92	2.38	**0.815**
	14	3.90	2.58	0.661
4.2	10	4.70	1.88	0.401
	12	5.11	1.28	0.250
	14	3.22	2.65	**0.823**

In the cases in which the vibration is close to the piston-like situation, the phase doesn’t influence the average vibration amplitude A. This is the case of the models with d=3.5 mm and a=12 mm and d=4.2 mm and a=14 mm which figure of merit are bigger than 0.8 -see Table II- . The vibration amplitude and phase of the two models are shown in figures 6 and 7 respectively. The filling factor in both cases is close to 14% (13.36% in the first case and 14.14% in the second).

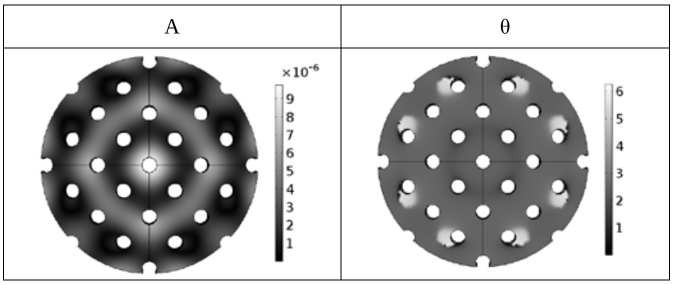


Fig 6. Calculated vibration amplitude in the longitudinal direction (A) and phase (θ) for a phononic sandwich transducer with holes of 3.5 mm and a lattice parameter of 12 mm.

A	θ

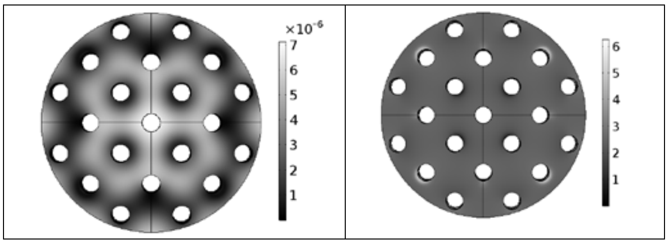


Fig 7. Calculated vibration amplitude in the longitudinal direction (A) and phase (θ) for a phononic sandwich transducer with holes of 4.2 mm and a lattice parameter of 14 mm.

V. CONCLUSIONS

The parametric study made with sandwich phononic piezoelectric resonators by using Finite Element modelling, shows that with a filling ratio of 14% and 4.2 mm hole diameter, the phononic resonator behaves very close to a piston. The lateral resonance modes coming from the cylindrical contour and the holes walls are confined and do not interacts with the length movement at the resonance frequency.

This design opens a new ultrasonic transducer generation free of lateral coupling, facilitating the solution of a number of industrial applications because disappears the dimensional constraints of the standard Langevin transducers.

We believe that our numerical results are encouraging to pursuing along this direction, which has been promising in other fields, such as graphene, were it has been shown that the stacking rotation between two layers of graphene modifies the electronic transport properties. Finally, it is worth to mention that our proposal involves concepts of three realms: piezoelectric transducers, phononic crystals and coincidence site lattices.

Acknowledgment

J.L.A. thanks DGAPA-UNAM-PAPIIT for financial support through grant IN110817. F.M. thanks DPI2016-80254-R support. Finally, F.M. and J.L.A. thank the “Programa de Movilidad Académica de la Coordinación de la Investigación Científica-UNAM”.

References

[1] Neppiras, E.A. “The Pre-Stressed Piezoelectric Sandwich Transducer” Ultrasonic International: London, UK, 1973, pp. 295–302.

[2] Iglesias, E.; Chinchurtreta, F.; De Frutos, J.; Montero de Espinosa, F. “Tailoring the efficiency of ultrasonic transducers for physiotherapy” Ferroelectrics 2016, 499, pp. 83–89.

[3] Aragón, J.L.; Quintero-Torres, R.; Domínguez-Juárez, J.L.; Iglesias, E.; Ronda, S.; Montero de Espinosa, F. “Planar modes free piezoelectric resonators using a phononic crystal with holes” Ultrasonics 2016, 71, pp. 177–182.

[4] Ronda S., Aragón JL., Iglesias E., Montero de Espinosa F. “The use of phononic crystals to design piezoelectric power transducers” Sensors, 2017, 17(4), pp.729

[5] Laude, V.; Wilm, M.; Benchabane, S.; Khelif, A. “Full band gap for surface acoustic waves in a piezoelectric phononic crystal.” Phys. Rev. E 2005, 71, 036607

[6] Sigalas, M.N.; Economou, E.N. “Elastic and acoustic wave band structure” J. Sound. Vib. 1992, 158, pp. 377–382.

[7] Kushwaha, M.S.; Halevi, P.; Dobrzynski, L.; Djafari-Rouhani, B. “Acoustic band structure of periodic elastic composites” Phys. Rev. Lett. 1993, 71, pp. 2022.

[8] Montero de Espinosa, F.; Jiménez, E.; Torres, M. “Ultrasonic band-gap in a periodic two-dimensional composite.” Phys. Rev. Lett. 1998, 80, pp. 1208.

[9] Sánchez-Pérez, J.V ; Caballero, D.; Martínez-Sala, R.; Rubio, C.; Sánchez-Dehesa, J.; Meseguer, F.; Llinares, J.; Gálvez, F. “Sound attenuation by a two-dimensional array of rigid cylinder.” Phys. Rev. Lett. 1998, 80, pp. 5325.

[10] Vasseur, J.O.; Deymier, P.A.; Frantziskonis, G.; Hong, G.; Djafari-Rouhani, B.; Dobrzynski, L. “Experimental evidence for the existence of absolute band gaps in two-dimensional periodic composite media.” *J. Phys. Condens. Matter* 1998, *10*, pp. 6051–6064.

[11] MacDonald, A.H., Bistritzer, R. “Graphene moiré mystery solved?” Nature, 2011, 474 (7352), pp. 453-454