A PLANE-WAVE-EXPANSION MODEL TO SIMULATE PHONONIC BAND GAP DEVICES

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Abstract : Phononic band gap structures represent an attractive solution for future high compactness low loss passive devices. In this paper, different patterns are considered by analogy with optics and fabrication of corresponding acoustic devices is investigated. The modelling of such structures is also addressed by considering periodic boundary conditions applied on an elementary cell of the phononic band gap device. As a conclusion, applications of the studied structures are briefly discussed.

Keywords : Phononic bandgap, Plane-Wave-Expansion, periodic structures, electroforming

1. INTRODUCTION

Many research activities in optics have been devoted to the analysis and the development of structures capable to reflect waves whatever their incidence and polarization. Such a phenomenon requires the existence of a so-called full band gap spectral behaviour of the structure, which means that for any incidence of the wave, the structure will act as a quasi perfect mirror totally reflecting it. This can be achieved by using for instance periodic arrays mixing materials with large difference between their optical indexes together with a particular geometrical arrangement. The corresponding structures are usually called photonic band gap materials (Ref.1). They can be advantageously used as classical mirrors insensitive to alignment mismatch, but also to develop new kinds of wave guides offering the possibility to define an optical pass within the array. For instance, it was shown that using such wave guides, one can define optical passes exhibiting 90° angles (Ref. 2). Some typical pattern of band gap structure together with their specific properties are recalled in the first section of the paper.

Recent works have shown that these principles can be applied to acoustics in fluids but also in solids, although the wave polarization in the later case yields more difficulties in the analysis of the problem (Ref. 3). However, the possibility to design periodic arrays in solids exhibiting a full band gap spectrum in a given frequency range leads one to the notion of phononic band gap materials. In the proposed work, an analytical model is developed to address the problem of acoustic wave propagation in solids exhibiting periodic changes in their elastic properties in one, two or three space directions. This model is based on the Plane-Wave-Expansion (PWE) describing the material properties as well as the vibration field. Different kind of materials are considered in the analysis allowing one to mix isotropic, anisotropic and even piezoelectric bodies together taking their intrinsic acoustic and electric losses into account. The analysis also considers different boundary conditions such as infinite, semi-infinite or finite thickness materials, with surfaces metallized or not. The possibility to derive an harmonic admittance for electrically driven devices has been also addressed. Fundamentals of the method are briefly explained in the second section of the paper.

Simulation examples using the proposed analysis are then presented. Dispersion curves have been computed for different combinations of materials and the existence of full band gap phenomenon was investigated for accessible materials (i.e. Nickel and an epoxy-based photoresist). Simple structures for which experimental assessment can be achieved are particularly considered in this paper. Their fabrication is discussed and first examples of phononic band gap devices built using a combination of thick photoresist (SU-8®) and electroplated nickel are presented. As a conclusion, further developments of the presented study are evoked.

2. TYPICAL BAND GAP STRUCTURES

Band gap structures in Optics are generally built using in-plane biperiodic arrays of elementary pillars of dielectric materials (SiO_2, Si_3N_4, etc.). Strong localized variations of optical index can be obtained, inducing large frequency stop bands for photon propagating in the array at its Bragg condition. The existence of defects in the array can be advantageously used for instance to guide the wave. If the array exhibits what is called a full band gap spectrum, one can achieve very complicated optical path at the appropriate wavelengths. In that case, the wave cannot propagate within the array but at locations for which defects have been created. This is illustrated in fig.1 showing a square angle path within a biperiodic array. The wave is assumed to propagate in the path and exhibits an evanescent behavior when penetrating the array.

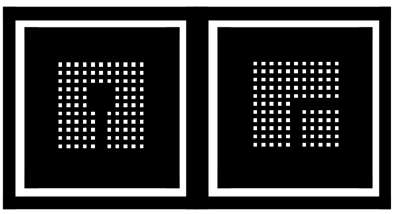


Fig.1 Square angle path within a band gap array and resonant cavity

Two other kind of configurations are also considered, i.e. the resonant cavity which consists in a dead end path, providing a structure able to trap incident energy without any losses, and also the longitudinal coupler. In this later case, two longitudinal paths exhibit a common border with a narrow separation composed of just one layer of obstacle. Both may exchange energy via the evanescent behavior of the wave within this separation layer. Both structures are roughly presented in fig.2. In the present work, we intend to transpose these basic concepts to acoustic devices for passive signal processing purposes.

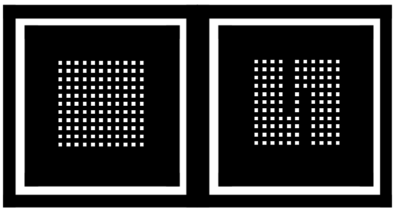


Fig.2 Simple periodic structure and longitudinal coupler built using full band gap structures

3. PLANE-WAVE-EXPANSION MODEL

Different approaches can be implemented for modeling periodic devices, such as finite difference or finite element analyses (Ref. 4) but also the so-called Plane-Wave-Expansion (PWE) method. In that later approach, one extensively uses the expansion of all the model parameters and fields as infinite series developed on a complex trigonometric base. The material properties of the elementary cell of the array is described via Fourier series of the material constants (mass density, elastic, piezoelectric and dielectric coefficients) whereas the electromechanical field (generalized displacements and stresses) are developed according to the Bloch-Floquet theorem as follows :

$$\alpha(\mathrm{r})=\sum_l \alpha_{G^l} e^{-jG^l \mathrm{r}}$$
$$h(\mathrm{r},t)=e^{j(\omega t-\mathrm{K}r)}\sum_l h_{\mathrm{K}+G^l} e^{-jG^l \mathrm{r}} \quad (1)$$

Note that in the present study, material losses are represented using complex material constants (particularly needed when computing electrical responses). These forms are then inserted in the propagation equation as well as in Poisson's condition for dielectric bodies. In order two avoid cumbersome developments, the Christoffel problem is expressed according to the Fahmy-Adler formulation (Ref. 5), considering the generalized displacements u_i and . stresses T_{3i} as the independent unknowns of the problem :

$$[A(\omega,K_1,K_2)]\begin{pmatrix} u_{\mathrm{K+G}^l} \\ \cdot \\ u_{\mathrm{K+G}^N} \\ jT_{3\mathrm{K+G}^l} \\ \cdot \\ jT_{3\mathrm{K+G}^N} \end{pmatrix} = K_3[B(K_1,K_2)]\begin{pmatrix} u_{\mathrm{K+G}^l} \\ \cdot \\ u_{\mathrm{K+G}^N} \\ jT_{3\mathrm{K+G}^l} \\ \cdot \\ jT_{3\mathrm{K+G}^N} \end{pmatrix} \quad (2)$$

Once the above eigensystem solved, one has access to the general solution of the problem as a combination of eigenvectors, computed for each harmonic of the Bloch-Floquet expansion, as follows :

$$\begin{pmatrix} u(r,t) \\ T_3(r,t) \end{pmatrix} = e^{j(\omega t-K_1x_1-K_2x_2)}\sum_l e^{-jG^l r}\sum_n A^{(n)} e^{-jK_3^{(n)}x_3}\begin{pmatrix} u^{(n)}_{K+G^l} \\ T^{(n)}_{3\,K+G^l} \end{pmatrix} \quad (3)$$

Different kind of boundary conditions can be applied to determine either the dispersion properties of the considered structure or the actual electromechanical field or derived parameters (harmonic electric admittance for instance). The case of in-plane 2D periodic devices has been particularly studied in this work. The simplest boundary condition consists in assuming the structure infinite along its thickness (x_3). In that case, only the eigensystem of eq.(2) has to be solved, directly yielding the dependence of the wave number K versus the angular frequency ω. Note that this approach can also be used to compute the dispersion properties of 3D periodic structures. If the structure occupies for instance the lower semi-space, one has to applied stress free boundary conditions at the surface of the device (see Ref.6) allowing then the identification of surface guided wave. In the case of a plate, we have shown (Ref.7) that applying stress free boundary conditions on both sides of the device yields the determination of the plate modes. For the electrical part of the problem, one can assume open or shorted surfaces. In all cases, a boundary condition algebraic system is built and the dispersion relation is obtained by searching a couple (K, ω) annulling the determinant of this system (yielding non trivial solutions to the problem). It was also shown in previous work (Ref. 7) that for piezoelectric devices, one can derive a so-called harmonic admittance which provide useful information about the coupling efficiency of piezoelectrically excited acoustic modes.

4. COMPUTATION RESULTS

In the present work, we have focused our interest on arrays built using materials easy to implement for low frequency validation tests. The combination of electroplated Nickel and epoxy-based thick photoresist (for instance the SU-8®) as used in LIGA-UV processes allows one to manufacture in-plane 2D periodic devices exhibiting various patterns with a high level of accuracy. The mass density of the Nickel was set to 8900 Kg/m3, with elastic constants C_{11}=280 GPa, C_{12}=125 GPa and C_{44}=77.5 GPa. the photoresist is assumed isotropic with a mass density equal to and Lame coefficients λ and μ respectively set to 4.71 GPa and 1.805 GPa.

We have considered first the case of square polymer bars in a Nickel matrix. The period was set to 1.1 mm and the side length of the bars to 450µm. Computations are performed according to the scheme of fig.3 in order to analyze all the possible incidence of the wave on the array. The corresponding dispersion curves are reported in fig. 4 showing the spectral distribution of bulk modes along the wave incidence.

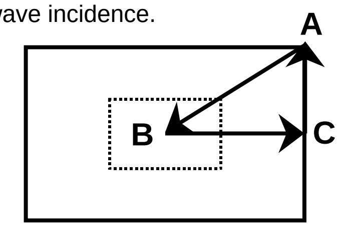


Fig.3 Definition of the wavenumber for a comprehensive computations of the wave incidences

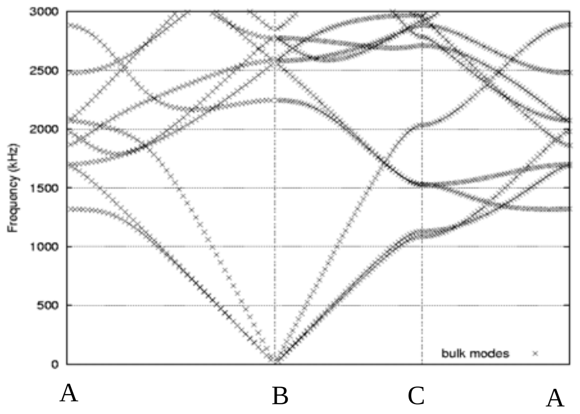


Fig.4 Dispersion curve for bulk modes in an array of polymer bars within a Nickel matrix

The classical shear and longitudinal modes can be identified on this graph which also shows that no full band gap can be found in such a configuration. As usual, higher order modes exhibiting complicated in plane polarization are found on the dispersion curve. The computation of the dispersion curve for a plate of finite thickness (90 µm) has been also performed assuming a propagation direction along the x1 axis. Superposition of bulk and plate dispersion curves shows that more modes arise in the plate but no major changes can be expected in regard with the bulk dispersion curve (see fig.5).

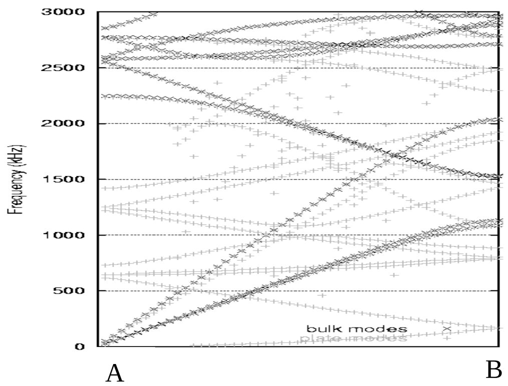


Fig.5 Dispersion curve for a plate (90µm), propagation along x_1

However, by simply inverting both material yielding Nickel bars surrounded by a polymer matrix, one can obtain a nice full band gap dispersion behavior as reported in fig.6

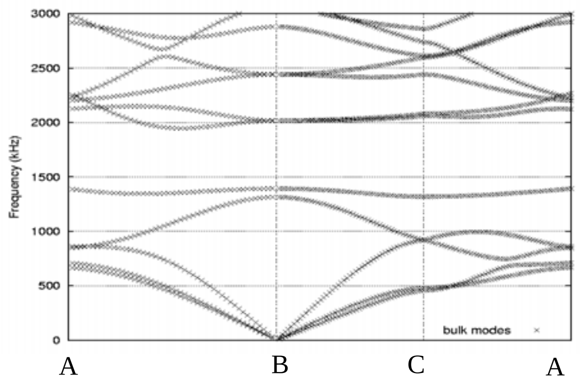


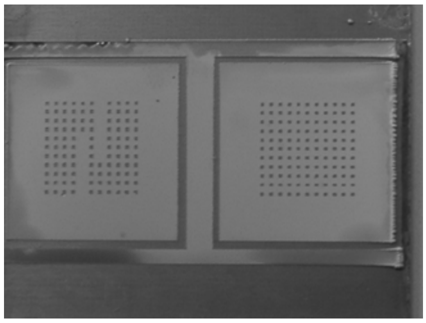
fig. 6 Full band gap dispersion behavior for Nickel bars in a polymer matrix

5. TECHNOLOGICAL IMPLEMENTATION

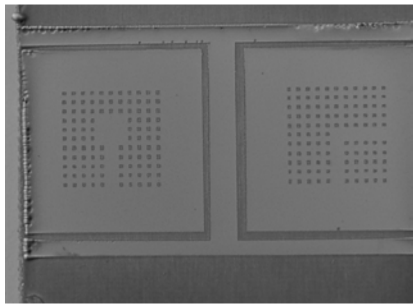
The structures of fig.1 and fig.2 have been manufactured to try and test the dispersion properties of the array. The technological process implemented to fabricate these devices is now described.

First, a thick resist process is applied on 2 inches copper substrates. A layer of negative high viscosity SU-8® photoresist is poured on the substrate and spin coated at 1700 rpm during 60 s. After an appropriate thermal treatment, the layer is insolated (165 mJ/cm^2) and developed using PGMEA developer. The obtained mold insert is then dived in a Nickel sulphamate bath for the electrofoming step. The characteristics of the electrolyte are as follows : 80g/l of metallic Nickel, a boric acid for a buffered pH equal to 4, a wet agent and a temperature set to 50°C. The current density is equal to 3 A/dm^2.

The resulting structures may be finally separated from the substrate by an isotropic wet etcher as classically used in microelectronics. Fig.7 a and b show the 4 devices exhibiting a thickness close to 90µm.



(a)



(b)

Fig.7 Electroformed band gap structures combining electroplated Nickel and SU-8® photoresist

These devices are expected to be tested by an external excitation source, for instance a PZT transducer operating on its fundamental piston mode. On the other hand, this kind of excitation does not exactly correspond to what expected, i.e. a very wide band transducer able to excite the structure over the frequency band of interest (corresponding to the full band gap). Such a transducer is still beyond reach.

6. CONCLUSION

A simulation tool based on the PWE approach has been implemented in order to study phononic band gap structures, corresponding to the transposition of photonic band gap devices to acoustics. The model has been particularly developed to address the case of in-plane 2D periodic devices with possibility to take piezoelectricity into account as well as material losses (needed when excitation taken into account).

Computations have been then performed for a simple combination of electroplated Nickel and the SU-8® photoresist, yielding the possibility to find structures exhibiting full band gap spectral behavior. Experimental devices have been then fabricated.

Our efforts must be now concentrated on testing the corresponding devices to access their dispersion properties. The possibility to use transducers with large frequency bandwidth in that matter is currently investigated. The insertion of a piezoelectric element within the band gap structure is also envisaged, with the restriction that only one incidence direction will accessible in those approaches. A fine control of the incidence of the wave may be achieved using a high precision X-Y-Z-θ table supporting the excitation transducer. The goal of such experiments is of course to check the existence of the predicted full band gap phenomenon but also to check the pertinence of the transposition from scalar optics to vectoring acoustics. The proposed low frequency experiments could be then transposed to higher frequencies to try and answer the requirements for RF passive signal processing.

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