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Band structures tunability of bulk 2D phononic crystals made of magneto-elastic materials

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The feasibility of contactless tunability of the band structure of two-dimensional phononic crystals is demonstrated by employing magnetostrictive materials and applying an external magnetic field. The influence of the amplitude and of the orientation with respect to the inclusion axis of the applied magnetic field are studied in details. Applications to tunable selective frequency filters with switching functionnality and to reconfigurable wave-guides and demultiplexing devices are then discussed. *Copyright 2011 Author(s). This article is distributed under a Creative Commons Attribution 3.0 Unported License*. [doi:10.1063/1.3676172]

I. INTRODUCTION

Phonic crystals may have potential applications in numerous technological domains.[1] Nevertheless, one of the major stumbling block to the application of phononic crystals is the lack of practical frequency tunability of their properties. Tunability could be achieved by changing the geometry of the inclusions[2,3] or by varying the elastic characteristics of the constitutive materials through application of external stimuli.[4] For instance, some authors have proposed the use of electrorheological materials in conjunction with application of external electric field.[5] Other authors have considered the effect of temperature on the elastic moduli.[6] In all cases, significant effect on the band structure of the phononic crystal can only be achieved by applying stimuli with very large magnitude. Recent theoretical[7] and experimental[8] works exploit the change of the structure of the phononic crystal due to an external stress to alter the band structure. However this approach requires physical contact with the phononic crystal. We have proposed a contactless way to tune the properties of phononic crystals using magneto-elastic components.[9] The elastic properties of a magneto-elastic material are very sensitive to its magnetic state and on the applied external magnetic field. For instance, in giant magnetostrictive material, such as Terfenol-D, this dependence can lead to more than 50% variation of some of the elastic constants, even at ultrasonic frequencies.[10] Moreover, for some directions of the applied external magnetic field, a spin reorientation transition (SRT) appears leading to even more variations of the elastic constants.[11] So, if one of the components of a phononic crystal is a magneto-elastic medium, then one can expect that the elastic contrast, and subsequently the phononic crystal properties could be controlled without any contact by a magnetic field.

The introduction of a magneto-elastic constituent opens the possibility of easy controllability of the properties of a phononic crystal without any contact. Using this controllability, one may imagine the design of devices with tunable functionalities such as frequency filters, superlens for acoustic imaging . . .

This paper is organized as follows. Section II presents briefly the theoretical model developed for calculating band structures of bulk (*i.e.* of infinite extent along the three spatial directions) magneto-elastic phononic crystals. Some theoretical results showing the tunability of the stop bands of these periodic structures are presented and discussed as functions of the magnitude and the orientation of the external applied magnetic field. Section III is devoted to the possible applications of magneto-elastic phononic crystals especially as reconfigurable wave-guides and as demultiplexing devices. Conclusions of this work are reported in section IV.

II. TUNABLE MAGNETO-ELASTIC PHONONIC CRYSTALS

To study the tuning of a magneto-elastic phononic crystal when an external static magnetic field is applied, we use the theoretical model we have previously developed,[9] that allows us to derive for an arbitrary direction and amplitude of the applied magnetic field, an equivalent piezomagnetic material of a polarized ferromagnet, with field dependent elastic moduli C_{ijkl}, piezomagnetic coefficients q_{lij} and magnetic permeability μ_{ij}. The equivalent piezomagnetic material formulation, leads to the following equations similar to those classically used for piezoelectric materials

$$\rho_0 \frac{\partial^2 u_i}{\partial t^2} = \frac{\partial \sigma_{ij}}{\partial x_j},$$
$$\frac{\partial b_i}{\partial x_i} = 0, \tag{1}$$

with

$$\sigma_{ij} = C_{ijkl}\left(H_{ext}\right) \frac{\partial u_k}{\partial x_l} + q_{lij}\left(H_{ext}\right) \frac{\partial \varphi_m}{\partial x_l}, \tag{2}$$

$$b_i = q_{ikl}\left(H_{ext}\right) \frac{\partial u_k}{\partial x_l} - \mu_{il}\left(H_{ext}\right) \frac{\partial \varphi_m}{\partial x_l}, \tag{3}$$

where ρ_0 is the mass density, u_i and b_i are the i^{th} component of the particle displacement and magnetic induction, x_i denotes the Eulerian coordinates, σ_{ij} are the stress tensor components, and φ_m is the magnetic potential.

Figure 1 presents the variations of the equivalent elastic moduli, piezomagnetic coefficients and magnetic permeabilities as a function of the applied magnetic field in the case of an infinite Terfenol-D rod and for a magnetic field parallel (left) or perpendicular (right) to the direction of the rod. Some of these constants strongly depend on the magnetic field amplitude. One notes also that when the applied external field $\boldsymbol{H_{ext}}$ is parallel to the Z direction, only the two shear components $C_{44} = C_{55}$ depend on the magnitude of the external field while $C_{55} = C_{66}$ depend on $|\boldsymbol{H_{ext}}|$ when $\boldsymbol{H_{ext}}$ is along X. The variations of these elastic moduli are of the order of 300% when $|\boldsymbol{H_{ext}}|$ is varying from 0 to 20 kOe.

Using the equivalent constants, we computed the band structures of two-dimensional arrays of Terfenol-D circular rods embedded in an epoxy matrix with the help of the well-known Plane Wave Expansion (PWE) method,[9] and particularly the one developed for piezoelectric media.[12] According to the Bloch-Floquet theorem, the displacement vector and the magnetic potential can be expanded in infinite Fourier series

$$u_i\left(\boldsymbol{r}, t\right) = \sum_{\boldsymbol{G}} u_{k+G}{}^{i} e^{j(\omega t - \boldsymbol{k}.\boldsymbol{r} - \boldsymbol{G}.\boldsymbol{r})},$$
$$\varphi_m\left(\boldsymbol{r}, t\right) = \sum_{\boldsymbol{G}} \varphi_{k+G} e^{j(\omega t - \boldsymbol{k}.\boldsymbol{r} - \boldsymbol{G}.\boldsymbol{r})}, \tag{4}$$

where $\boldsymbol{r} = (x,y,z)$ is the position vector, ω is the circular frequency, $\boldsymbol{G}$ are the reciprocal lattice vectors and $\boldsymbol{k}$ is the wave vector. Moreover, due to the periodicity of the material constants $\rho(\boldsymbol{r})$, $C_{ijkl}(\boldsymbol{r})$, $q_{lij}(\boldsymbol{r})$ and $\mu_{ij}(\boldsymbol{r})$ are also expanded as Fourier series

$$\alpha\left(\boldsymbol{r}\right) = \sum_{\boldsymbol{G}} \alpha_G e^{-j\boldsymbol{G}.\boldsymbol{r}}. \tag{5}$$

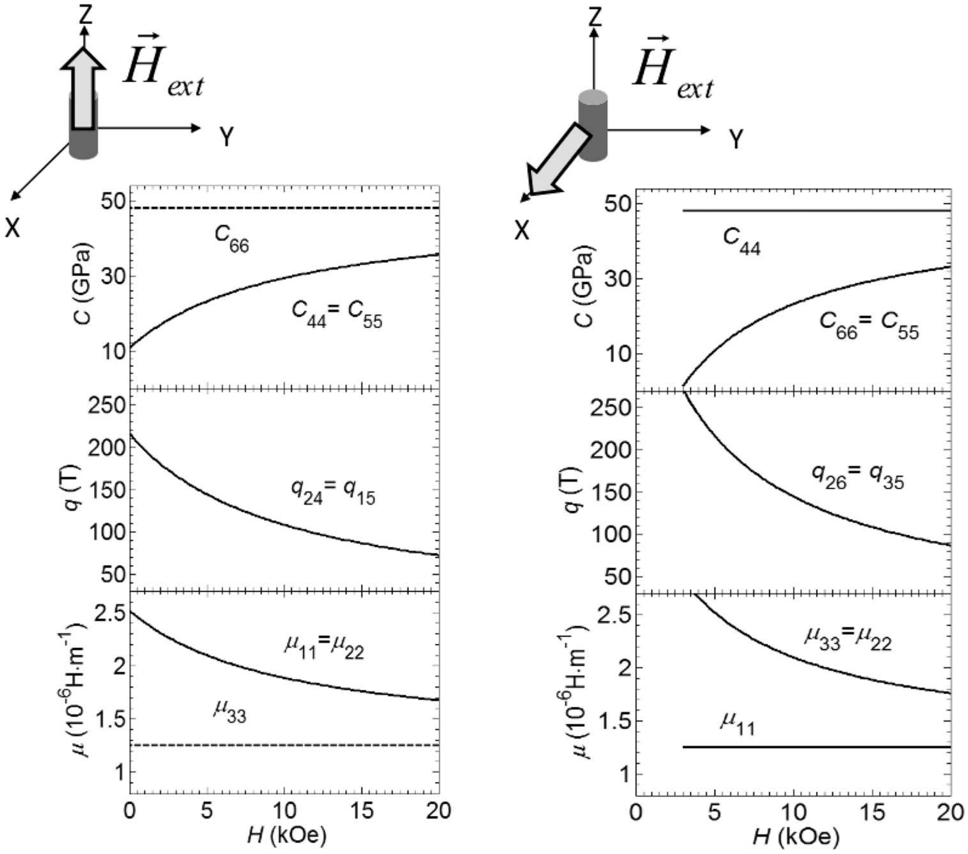

FIG. 1. Evolution of the effective elastic moduli, piezomagnetic constants, and magnetic permeabilities of a Terfenol-D rod as a function of the static external magnetic field applied along the rod axis (*Z*) (left) and along the *X* axis (right). The effective elastic and piezomagnetic constants are expressed in Voigt notations.

Inserting these expansions, Eqs. (4) and (5), in Eqs. (1)–(3), using orthogonality property of Fourier series components and collecting terms, yields the following generalized eigenvalue equation[12]

$$\omega^2 \tilde{\boldsymbol{R}}\tilde{\boldsymbol{U}} = \Gamma_i \tilde{A}_{il} \Gamma_l \tilde{\boldsymbol{U}}, \tag{6}$$

where $\tilde{\boldsymbol{U}}$ is a vector gathering the Fourier amplitudes of the generalized displacement $\tilde{\boldsymbol{U}} = (u_1, u_2, u_3, \varphi_m)$, $\tilde{\boldsymbol{R}}$, $\tilde{A}_{\text{il}}$ are $4N \times 4N$ matrix involving only material constants, and Γ_i are diagonal matrices involving the wave vector and the reciprocal lattice vectors. The detailed expressions of all these matrices are given in Ref. 12. By solving Eq. (6) for ω as a function of the wave vector $\boldsymbol{k}$ describing the periphery of the irreducible Brillouin zone of the considered lattice, the band structures can be calculated.

The band structures of Figs. 2(b) and 2(c) illustrate the effect of the external magnetic field when $\boldsymbol{H}_{ext}$ is along *Z* for a filling factor of inclusions $f = 0.6$. When the magnitude of $\boldsymbol{H}_{ext}$ increases from 1 to 20 kOe, the two pass bands around 1 Mhz in Fig. 2(b) are shifted to higher frequencies in Fig. 2(c). This leads to the enlargement of the first band gap of approximately 30%. These two pass bands around 1 Mhz in Fig. 2(b) correspond to out of plane transversely polarized modes for which the displacement field is parallel to the *Z* direction and perpendicular to the wave vector. These modes are the only ones to be affected by the variations of the shear elastic modulus C_{44} (see Fig. 1(a)). Around 1 MHz, this phononic crystal behaves like a tunable filter with switching functionality. This switching functionality is also illustrated on Fig. 3 where the width of the two first stop bands is reported as a function of the magnitude of the external magnetic field for two different filling factors namely $f = 0.35$ (Fig. 3(a)) and $f = 0.5$ (Fig. 3(b)). In Fig. 3(a), the phononic crystal behaves around

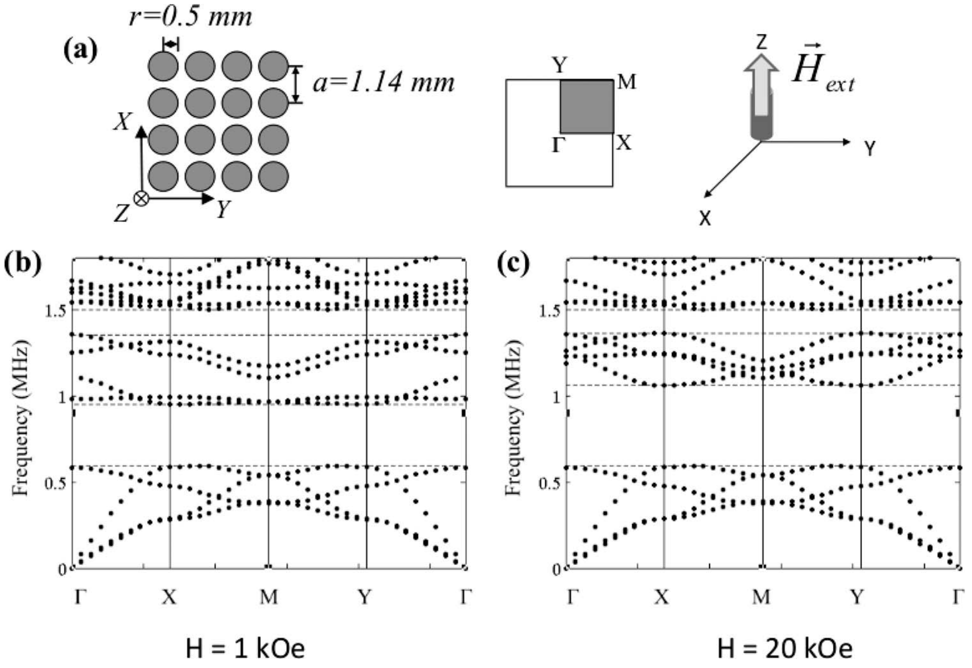

FIG. 2. (a) The square-lattice 2D phononic crystal consisting of magneto-elastic cylindrical rods of infinite length along the Z direction made of Terfenol-D and embedded in an epoxy matrix. Band structure of a square lattice of Terfenol-D cylindrical rods with a filling factor $f = 0.6$, embedded in an epoxy matrix for two applied static magnetic fields: (b) H_{ext}=1 kOe and (c) H_{ext}=20 kOe. The diagrams to the right of (a) show the irreducible Brillouin zone of the square array and the direction of the applied magnetic field.

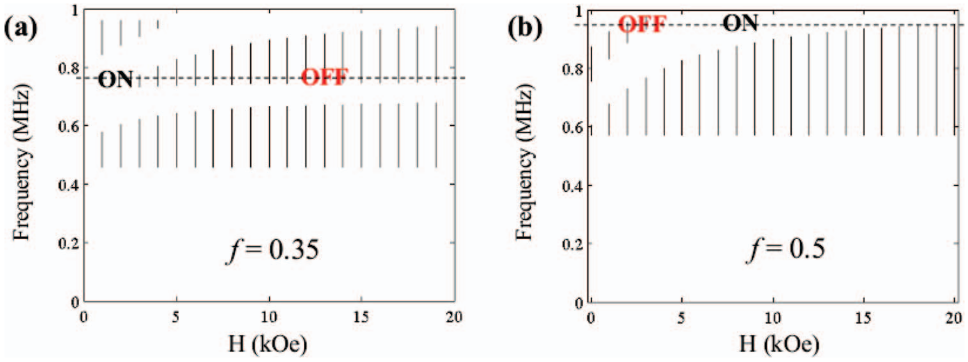

FIG. 3. Evolution of the absolute elastic band gaps of a square lattice of Terfenol D cylindrical rods embedded in an epoxy matrix as a function of the amplitude of the applied static external magnetic field along the rod axis Z, for a filling factor (a) f= 0.35 and (b) f= 0.5.

0.8 MHz as a passing filter for low magnitude of $\boldsymbol{H}_{ext}$ and as a stopping filter for $|\boldsymbol{H}_{ext}|$ larger than 4 kOe. Opposite situation is obtained around 0.9 MHz when f is increased to 0.5 (see Fig. 3(b)).

III. APPLICATION TO TUNABLE AND RECONFIGURABLE WAVE-GUIDES

We have seen in section II, how a sufficient, *i.e.* at least 30%, level of tunability can be introduced in the properties of 2-D phononic magneto-elastic crystals when an external magnetic field is applied. This tuning capability allows us to design and create phononic crystal devices with new or enhanced functionalities.

Among the potential applications of phononic crystals, the guiding with minimal losses,[13,14] even in guides with sharp bends, the filtering or the demultiplexing[15] of acoustic waves at the scale

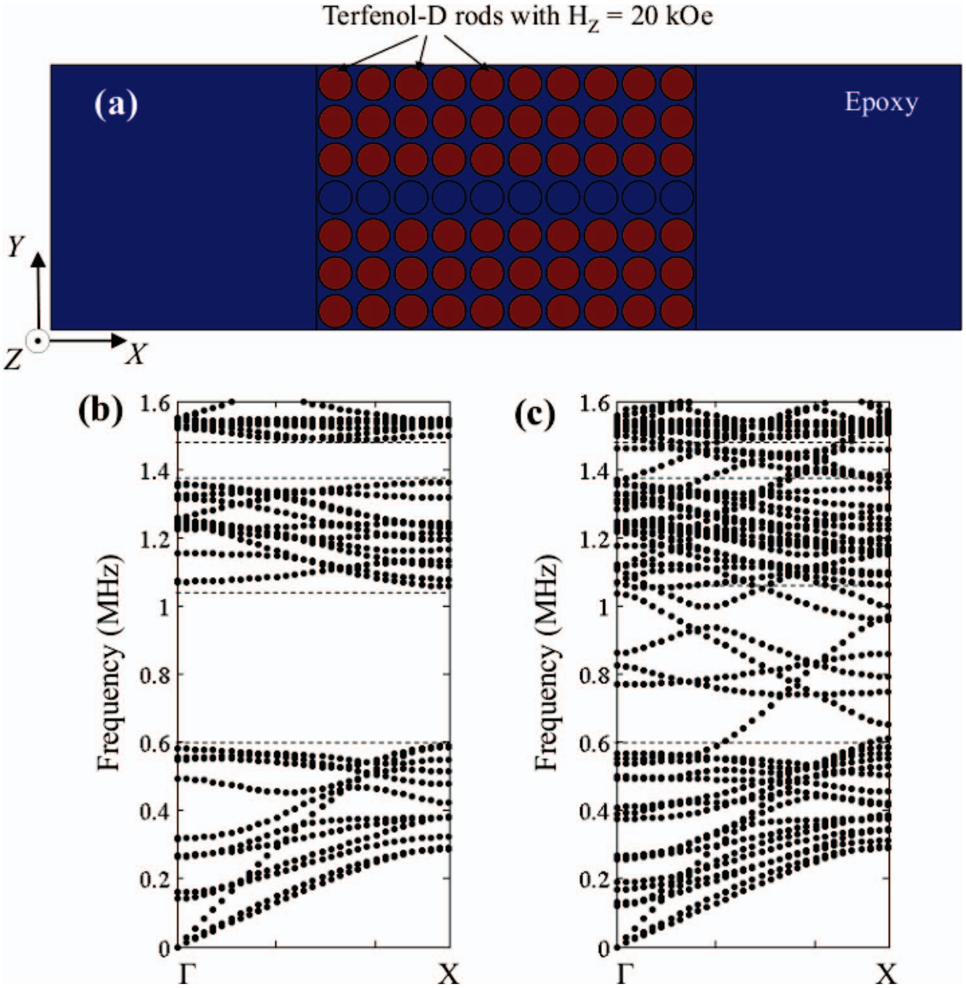

FIG. 4. (a) Structure of a linear wave-guide created, in a square-lattice 2D phononic crystal, by removing one row of cylindrical Terfenol-D inclusions along the X direction. The phononic crystal is constituted of cylindrical Terfenol-D rods of 0.5 mm radius embedded in an epoxy matrix with a filling factor f=0.6. The applied static magnetic field is 20 kOe along the Z axis. (b) Band structure of the perfect square-lattice 2D phononic crystal, performed by considering a supercell of 7 periods along the Y direction. (c) Band structure of a square-lattice 2D phononic crystal containing a linear wave-guide obtained by removing one row of cylindrical Terfenol-D inclusions along the X direction. The calculation is performed by considering a supercell of 7 periods along the Y direction.

of the wavelength have attracted numerous authors in the last years. We will consider here the use of a 2-D magneto-elastic tunable phononic crystal to design a completely reconfigurable waveguiding device.

All the simulations of the propagation of elastic waves in the designed phononic crystal devices, presented in this section, have been performed using Comsol Multiphysics, a commercial Finite Element (FE) software. Second-order Lagrange elements have been used in all the FE calculations.

A. Reconfigurable wave-guides

The building block of the considered reconfigurable wave-guide system is a 7 by 10 array of 0.5 mm radius Terfenol-D cylindrical rods embedded in an epoxy matrix, as shown in Fig. 5(a). A filling factor of 0.6 is chosen in order to obtain a large band gap around 1 MHz when an external static magnetic field of 20 kOe is applied along the rod axis, see Fig. 2(c). The 2-D phononic crystal is sandwiched between two homogeneous parts composed of epoxy. To simulate infinite media,

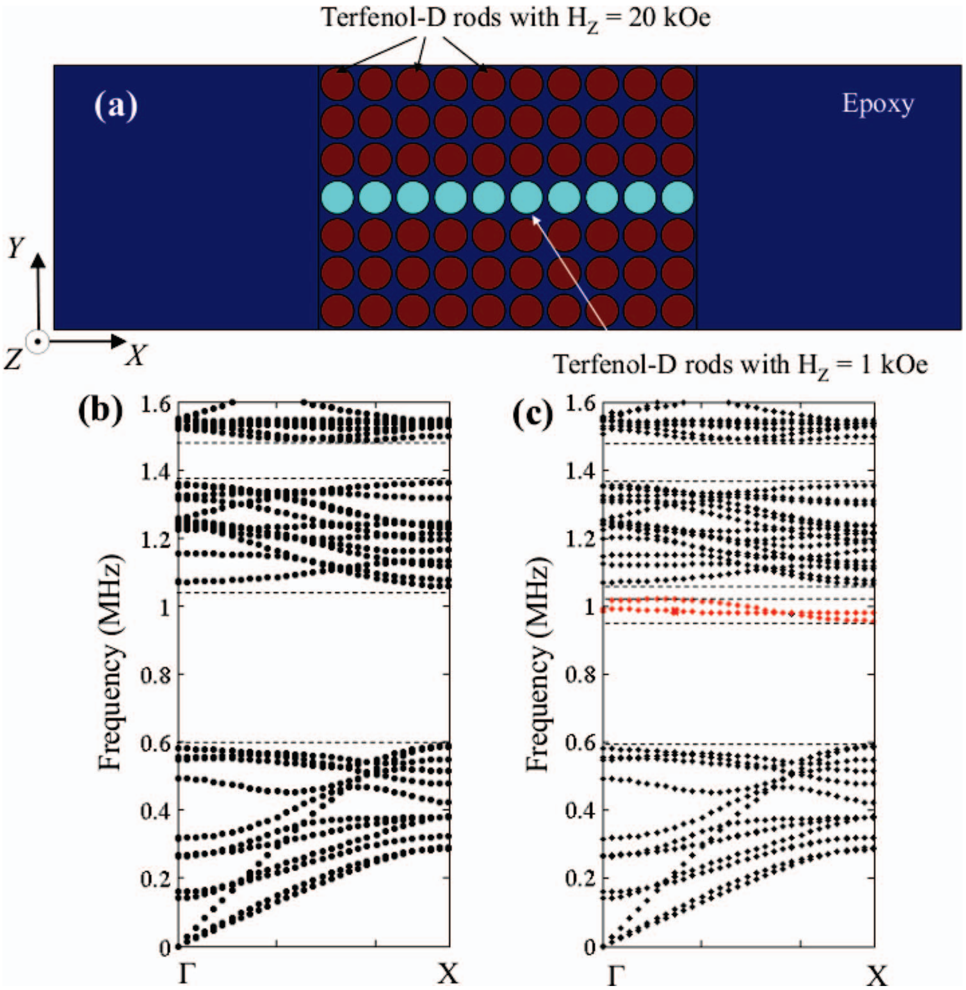

FIG. 5. (a) Structure of a linear wave-guide created, in a square-lattice 2D phononic crystal, by applying an external magnetic field of 1 kOe on one row of cylindrical Terfenol-D inclusions along the *X* direction. The phononic crystal is constituted of cylindrical Terfenol-D rods of 0.5 mm radius embedded in an epoxy matrix with a filling factor f=0.6. The applied static magnetic field is 20 kOe along the *Z* axis. (b) Band structure of the perfect square-lattice 2D phononic crystal, performed by considering a supercell of 7 periods along the *Y* direction. (c) Band structure of a square-lattice 2D phononic crystal, containing a linear wave-guide obtained by applying an external magnetic field of 1 kOe on one row of cylindrical Terfenol-D inclusions along the *X* direction, performed by considering a supercell of 7 periods along the *Y* direction.

Perfectly Matched Layers (PML) are implemented on the left and right sides of the calculation domain.[16] Moreover, periodic boundary conditions are used on the upper and lower sides.

Classically, wave-guides are created in a phononic crystal by removing one row of inclusions as shown in Fig. 4(a). Here, we consider a straight wave-guide created by applying locally a static magnetic field of 1 kOe (in place of 20 kOe) on one row of cylinders along the propagation direction (*X* axis), as shown in Fig. 5(a). The length of the obtained wave-guide is 10 periods and its width is one period. From an experimental point of view, the external magnetic field can be applied locally on each cylinder using a magnetic write head, as the ones used in Perpendicular Magnetic Recording (PMR) systems.[17] To understand the difference between these two kinds of wave-guide, the band structures for the wave-guide modes along Γ*X* are calculated in each configuration with the FE method, by defining a super-cell of seven periods in the *Y* direction. For a wave-guide realized by removing one row of rods the number of modes falling inside the band gap is quite high, as shown in Fig. 4(c). It is well known that to decrease this number of modes, the width of the wave-guide needs to be reduced. On the other hand, in the case of a wave-guide created by applying locally a

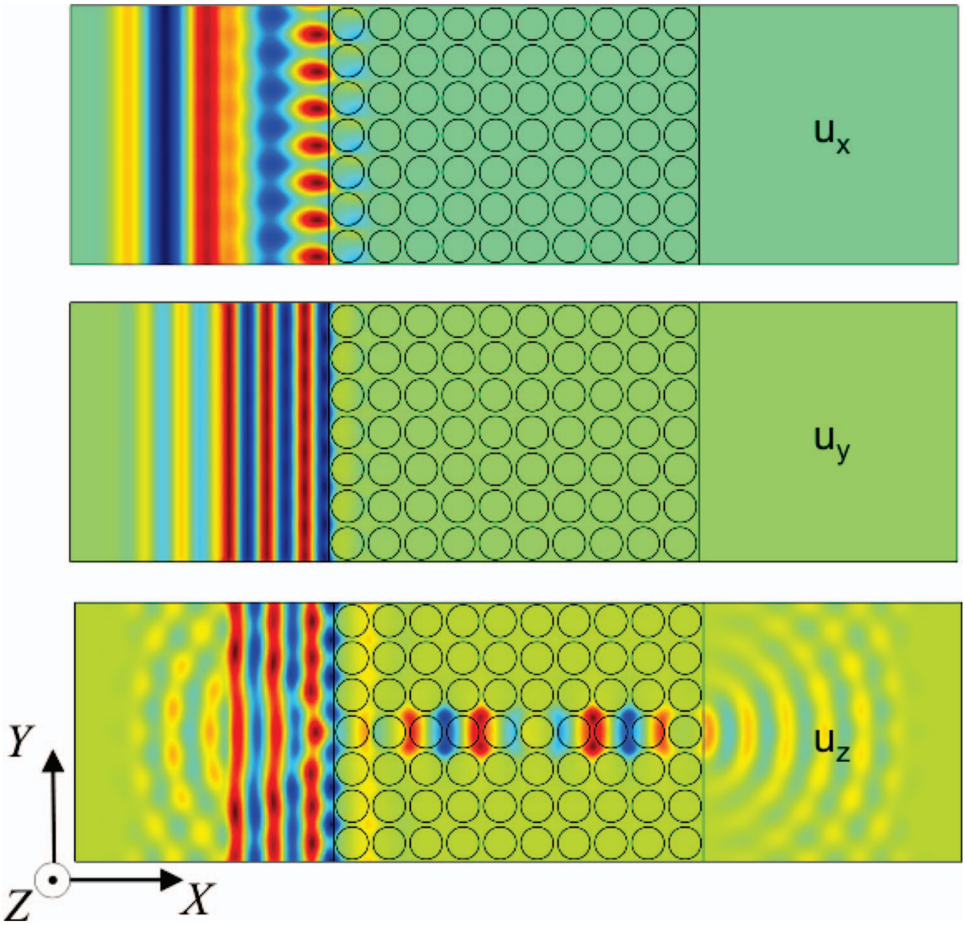

FIG. 6. Three components of the particle displacement of a plane wave with a frequency of 970 kHz impinging on a square-lattice 2D phononic crystal containing a linear wave-guide. Only the out of plane transversely polarized mode is transmitted through the wave-guide.

static magnetic field of 1 kOe, only two flat modes appears in the band gap of the phononic crystal (see Fig. 5(c)), leading to the apparition of a narrow passing band. As it will be shown latter on, such flat modes can be used for multiplexing or demultiplexing applications.[15] The difference between the two kinds of guide can be explained as follows. If a row of Terfenol-D rods is removed, then an incident wave with frequency inside the stop band of the perfect phononic crystal can propagate in the wave-guide, but not in the surrounding phononic crystal. The conditions on the frequencies and wavelengths for an incident wave to be injected inside the guide are, in this case, very similar to those for an epoxy guide with rigid wall. As the width of the created wave-guide is quite large, at least one wavelength, a large number of guided modes could exist. But, as shown, the band structure of the realized magneto-elastic phononic crystal can be tuned by changing the amplitude (or the direction) of the applied external magnetic field. In the present configuration, when the amplitude of the magnetic field applied along the rod axis, *i.e.* the Z axis, is reduced to 1 kOe, then a transmission band appears in the gap near 1 MHz, as displayed in Fig. 2(b). So, if one row of this periodic structure is inserted inside the previous wave-guide, in place of epoxy, then only these two modes could now propagate through the guide. It can be noted that the two modes which constitute this transmission band correspond to out-of plane transversely polarized modes.[9]

A plane wave, containing components in the three directions, with a frequency of 970 kHz, belonging to the pass band of the wave-guide, is launched from the left side of the 2-D phononic crystal. The obtained three components of the particle displacement u_x, u_y, and u_z are displayed in Fig. 6. As shown, only the out-of plane transversely polarized mode is transmitted through the

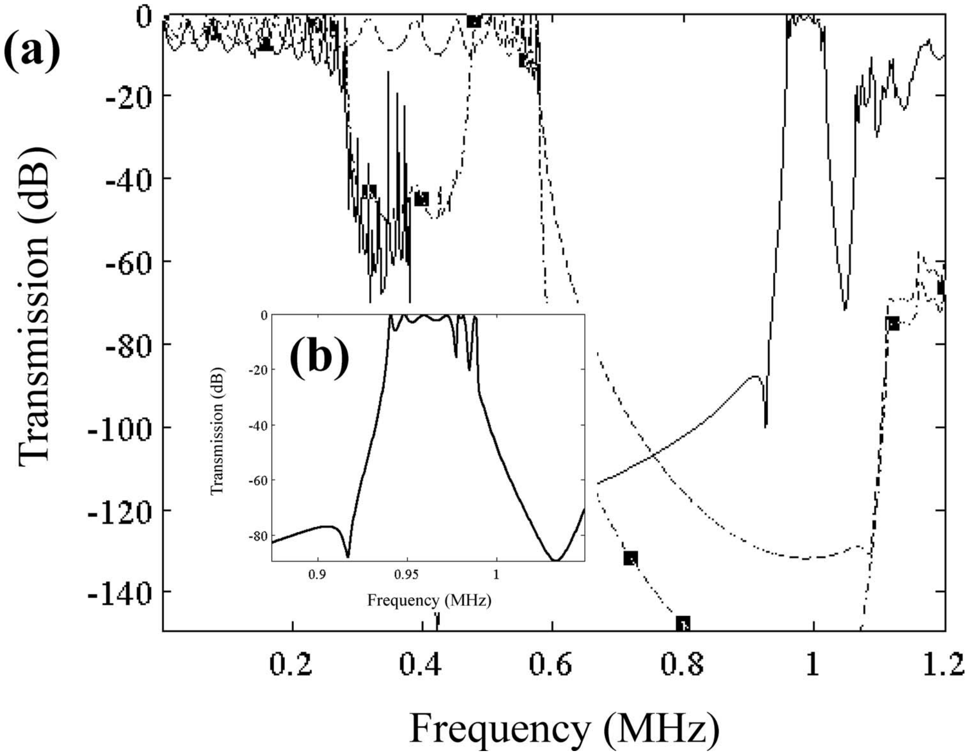

FIG. 7. (a) Transmission in dB through the wave-guide for an out of plane transversely polarized (solid line), an in plane transversely polarized (dash-dotted line) and an in plane longitudinal (dashed line) incident waves. Inset (b): Zoom of the transmission in dB around the passing band introduced by the linear guide for out of plane transversely polarized modes

wave-guide, which is consistent with the fact that when the magnetic field is applied along the rod axis only the propagation of the out of plane transverse waves are sensitive to the field.

The signal transmitted along the wave-guide is recorded at its end and integrated along its width. The transmission is then calculated by normalizing this signal with respect to the case where a homogeneous epoxy medium is considered. The calculated transmission is displayed as a function of frequency in Fig. 7(a). We can observe full transmission of out-of plane elastic waves for certain frequencies within the phononic crystal stop-band. Zooming on this passing band, as shown in Fig. 7(b), we can see oscillations on the transmission coefficient as a function of frequency typical of phononic wave-guide, induced by the roughness, with a periodicity a, of the guide walls.

As a matter of comparison, the transmission calculated in a similar manner is displayed in Fig. 8 for the same phononic crystal but without any waveguide, *i.e.* a defect-free phononic crystal. This clearly confirms that only the out of plane transversely polarized wave transmission is modified by the presence of the waveguide: not only a narrow passing band is created in the band gap of the phononic crystal, but also the transmission around 1.1 MHz is perturbed.

Very efficient simulations of linear pulse propagation in such phononic crystal wave-guide can be obtained with only a chosen number of frequency calculations. Frequency domain calculations, similar to those displayed in Fig. 6, for 1000 frequencies equally spaced between 0 and 1.2 MHz have been made. In Fig. 9, the snapshots of the amplitude of the displacement at eight instants equally spaced, reconstructed by inverse Fourier transform of the 1000 frequency responses multiplied by the Fourier transform of the time evolution of the source, are displayed. Here, an Hanning time evolution source, centred around a frequency $f_0 = 960$ kHz and with a length of $50/f_0$, has been used. The snapshots show that, even if a large part of the incident plane wave behind the wave-guide arrives to penetrate inside it, a reflection is noticeable, due to a not perfect matching between the wave-guide and the surrounding medium. It is to be noted that any kind of time evolution of the source can be very quickly calculated for the same frequency domain calculations.

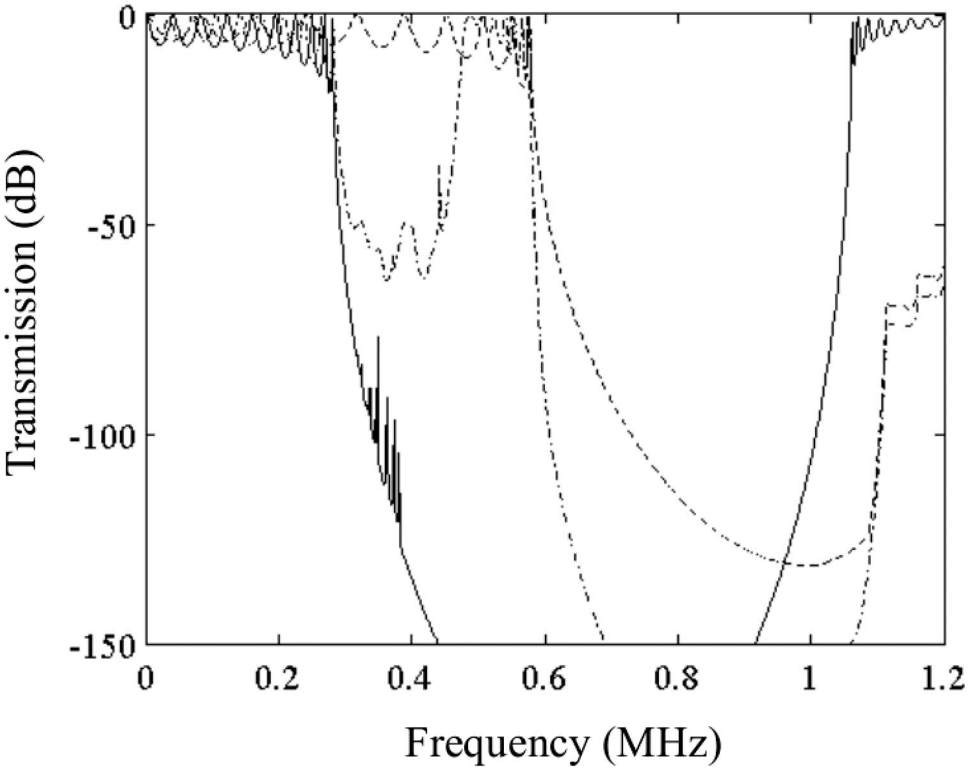

FIG. 8. Transmission in dB through a defect-free phononic crystal for an out of plane transversely polarized (solid line), an in plane transversely polarized (dash-dotted line) and an in plane longitudinal (dashed line) incident waves.

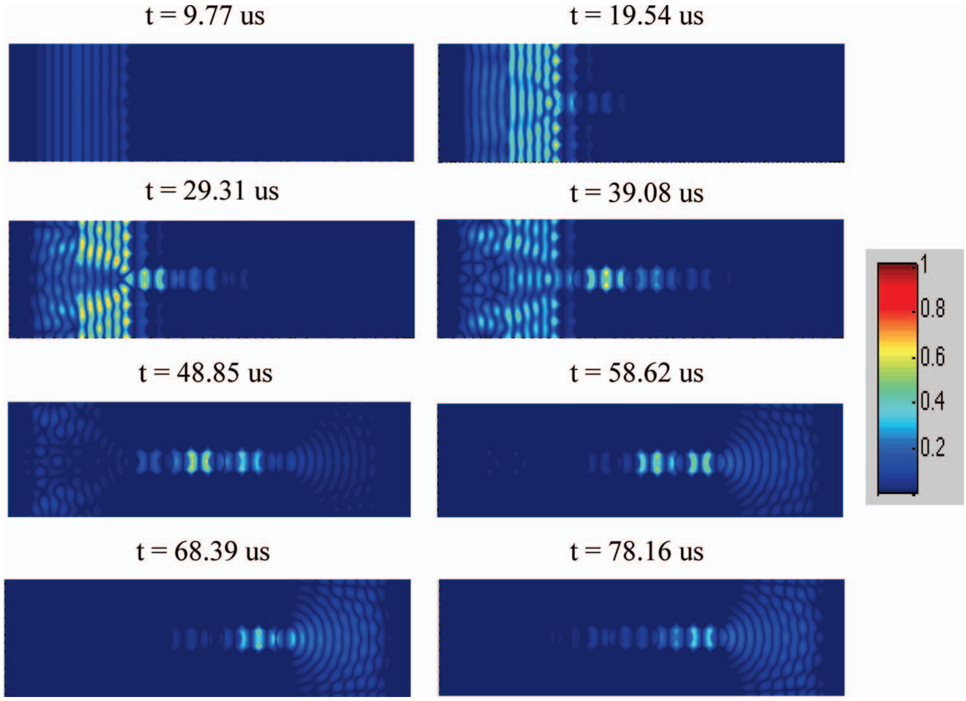

FIG. 9. Snapshots of the normalized amplitude of the particle displacement of an out of plane transversely polarized elastic wave at eight instants, showing the propagation of a pulse along the wave-guide.

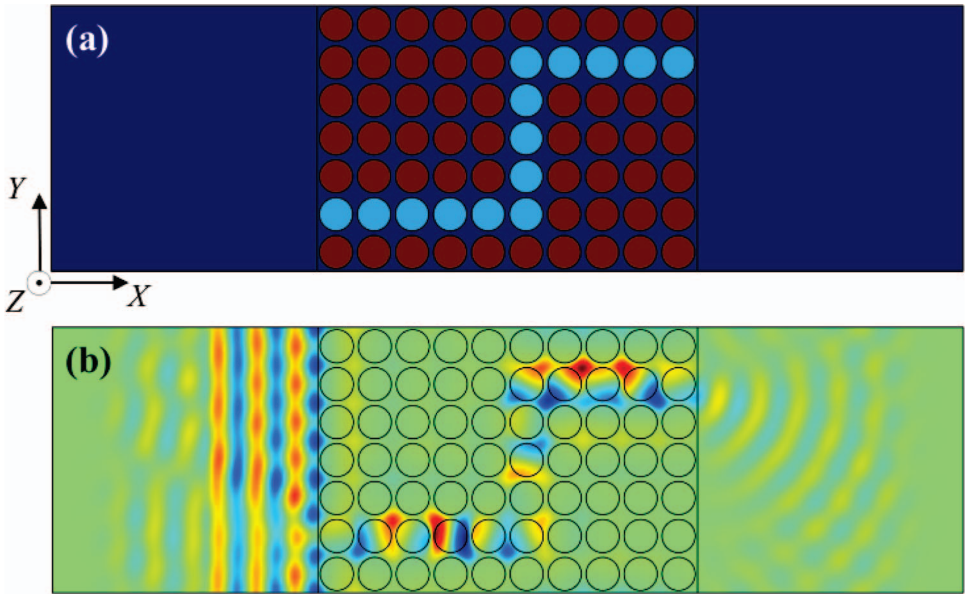

FIG. 10. (a) Structure of a square-lattice 2D phononic crystal, containing a bended wave-guide obtained by applying an external magnetic field of 1 kOe along the *Z* direction on cylindrical Terfenol-D inclusions. The phononic crystal is constituted of cylindrical Terfenol-D rods of 0.5 mm radius embedded in an epoxy matrix with a filling factor f=0.6. The applied static magnetic field is 20 kOe along the *Z* axis. (b) Out of plane component u_3 of the particle displacement of a plane wave with a frequency of 970 kHz impinging on the wave-guide.

Now, if we apply the localized 1 kOe static magnetic field on a succession of Terfenol-D rods forming a complex path, we can for example design a bended wave-guide, as shown in Fig. 10(a). Calculating, as in the case of a straight wave-guide, the particle displacement induced by an impinging plane wave at a frequency of 970 kHz, we can see that the wave follows the guide even in the sharp corner (90°). Similar study was conducted recently in 2D phononic crystals made of piezolectric inclusions. Active wave-guiding has been realized in the stop band frequency range by controlling electrically the physical properties of the piezolectric inclusions.[18]

B. De-multiplexer

With the same system of Terfenol-D rods embedded in an epoxy matrix, we can design an Y-shaped wave-guide,[15] as shown in Fig. 11(a). The left part of the wave-guide contains cylinders of Terfenol-D with two different applied magnetic fields along the *Z* direction: 1 kOe (blue rods) and 2 kOe (green rods). In the right part, each branch of the Y contains one type of cylinder. Applying a 2 kOe magnetic field moves the passing band of the 2D-phononic crystal to higher frequencies. As the passing band created in the band gap is sufficiently narrow we can find frequencies moving from the passing band to the band gap, or inversely, when the amplitude of the applied magnetic field is changed. The plot of the out of plane component of the displacement field for the Y-shaped wave-guide is represented in Fig. 11 for two different frequencies: 1023 kHz (b) and 960 kHz(c). These spectra show that the superposed waves supported by the mixed wave-guide are separated and directed toward the two branches of the Y junction. This system can be used as a demultiplexer or a multiplexer, if used in the reversed direction. The wave pattern observed behind the phononic crystal is linked to the interferences between the incident wave and the wave reflected by the phononic crystal and the waveguide. Indeed, in the designed system the "impedance" of waveguide is not perfectly matched to the surrounding epoxy, and moreover varies as a function of the frequency. Moreover, as we used periodic boundary conditions on the upper and lower sides along the *Y* direction, interfering wavefront coming from a "virtual" neighboring waveguide are visible at the

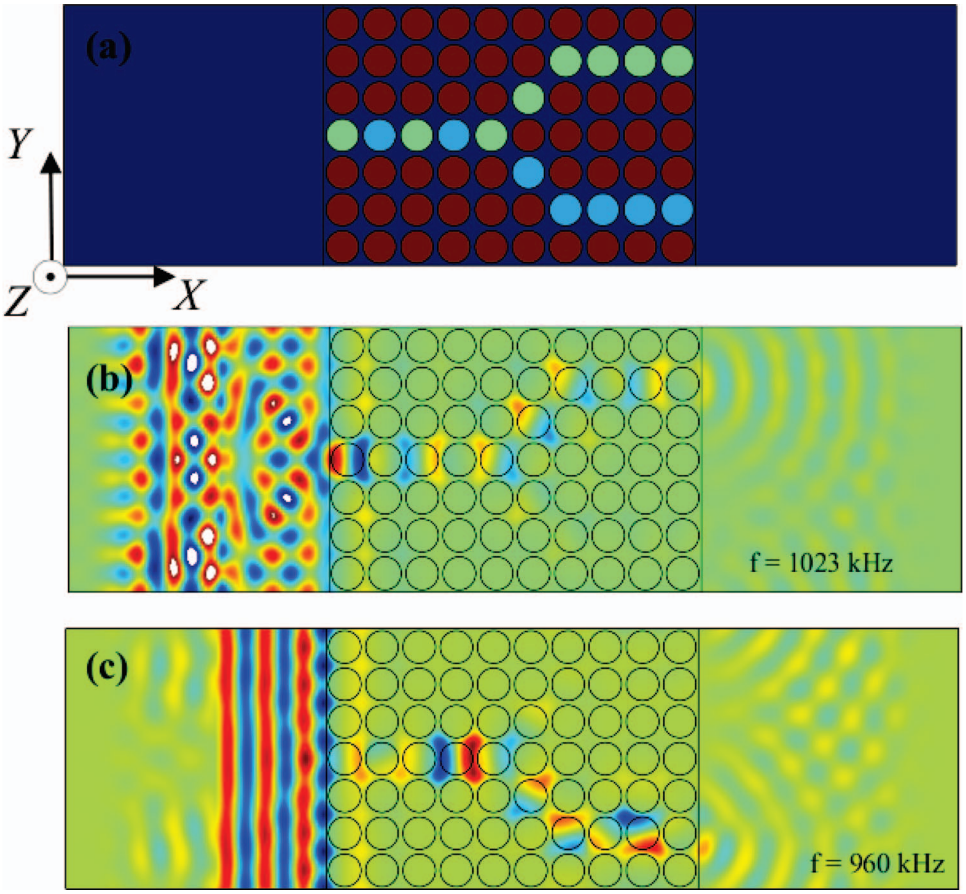

FIG. 11. (a) Schematic of the Y-shaped wave-guide. The left part of the wave-guide contains cylinders of Terfenol-D with two different applied magnetic fields along the *Z* direction: 1 kOe (blue rods) and 2 kOe (green rods). The phononic crystal is constituted of cylindrical Terfenol-D rods of 0.5 mm radius embedded in an epoxy matrix with a filling factor *f*=0.6. The applied static magnetic field is 20 kOe along the *Z* axis (red rods). Each branch of the Y contains one type of cylinder. Representation of the out of plane component of the displacement field for the Y-shaped wave-guide at two frequencies of (b) 1023 kHz, and (c) 960 kHz.

output of the waveguide. These artefacts may be alleviated by imposing PML on the same sides, at the cost of a huge computation time increase.

In conclusion, we have seen that an array of Terfenol-D arranged in a square lattice and embedded in an epoxy matrix can be used as a reconfigurable device for guiding, multiplexing or demultiplexing acoustic waves.

IV. CONCLUSION

We have shown that tunability of magneto-elastic phononic crystals could be achieved by varying the elastic characteristics of their constitutive materials through application of external magnetic field. Variation of the relative band gap width of more than 30% could be attained. The introduction of such an active material constituent opens the possibility of easy controllability of the properties of a phononic crystal without any physical contact. More specifically one can achieve additional functionalities such as the switching of transmission in a defined frequency range or the reconfiguration of wave-guides and multiplexers. Tunable phononic crystals with filtering functionnalities may have potential applications, especially for Radio-Frequency communication devices. Nevertheless magneto-elastic 2D phononic crystals based on arrays of Terfenol-D rods are probably not the best suited building blocks. For this kind of application, magneto-elastic phononic crystals fabricated with nano-structured thin films with giant magnetostriction, such as TbFe/FeCo films, could be envisaged. Indeed tunability of the physical properties of TbFe/FeCo films requires using lower external magnetic fields, of the order of 100 Oe or even less. Moreover, they are compatible with micro-electronic and nanotechnology processes.

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