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Phononic crystal as a neutron detector

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ABSTRACT

A perfect phononic crystal model composed of concrete and epoxy, and another defect model of Aluminum/Concrete/Epoxy were proposed. The two models were analyzed computationally and theoretically based on the transfer matrix method. The proposed models were capable of detecting and sensing neutrons irradiations over a wide fluence range based on the effects of neutrons fluence on the Young's modulus of the concrete. The neutrons fluence significantly changed the transmission spectra of the phononic crystal models whether the neutrons-induced temperature was considered or not as the phononic band gaps and the local resonant peaks were shifted. Also, neutrons irradiations made a strong dispersion in the conventional parameters of the proposed phononic crystal models. The results presented in this work might pave the way for designing an effective detector that works over a wide range of neutron fluence.

1. Introduction

Phononic Crystals (PnCs) are artificial periodic composites that could control propagation of elastic and acoustic waves [1–4]. The interesting feature of PnCs is the appearance of the so-called phononic band gap that through it all frequencies are effectively prohibited [5–9]. Most of the engineering applications for the PnCs have emerged based on their phononic band gaps [12–22]. Many structures could be considered PnC structures such as membranes, layered structures, and mass-spring systems [10,11]. However, the PnCs gained attention in sensing applications limited researches focused on the radioactivity sensing and nuclei detection [23,24]. Recently, the concept of ions detection (Helium-4) based on PnC structure was studied [25]. The main parameter in ions detection process by PnCs is the Debye frequency of the PnC constituent materials that can be changed under effect the energy of the incident particles regardless of the particle type [26]. Therefore, employing PnCs to distinguish and detect different radiations is considered a great challenge.

The respective correlation between Young's modulus and irradiation fluence could introduce a new solution in radiations detection techniques by PnCs. However, the main issue is how to apply such a correlation in a material of great application importance. Concrete can be considered as an excellent practical material for an extensive lasting shield against the risks of radiation. It likewise offers the benefits of being modest, simple to work with fundamentally self-supporting for all intents and purposes indestructible and without maintains costs[27]. Many nuclear reactors and radioactive materials are shielded by concrete. Employing concrete as an indicator or sensor for the radiation fluence and effects would be fruitful.

The most penetrating part of radiations in many accelerators is the neutrons of a wide energy range and are classified to different types according to their energies; Fast neutrons, epithermal neutrons and slow or thermal neutrons. Neutrons characterized by both high penetrating power and ionizing energy, so they can be utilized as a part of medicinal treatments, for example, radiation therapy.

Here, we extended the last studies of radiation detection employing PnC as a neutron detector. The band gaps and transmission spectra of the proposed models are derived based on the transfer matrix method. Concrete/epoxy PnC model and defect model (aluminum/concrete/epoxy) were studied. In the numerical examples, in particular, the local resonance phenomenon that enables the strong coupling between irradiation fluence and the percentage of the local resonant peaks was analyzed. The effect of the induced temperature and the irradiation neutron fluence were considered in the simulation of the transmission spectra of the (Concrete/Epoxy) PnC structure.

2. Theoretical model and method of calculation

2.1. Concrete PnC model

Considering the 1D PnC $(A/B)^N$ structure shown in Fig. 1 as the structure consists of repeated unit cells. Each unit cell has two different materials, concrete and epoxy, with thicknesses a_1 and a_2 respectively. N represents number of periods and a is the lattice constant that is given by $a = a_1 + a_2$.

The propagation of the elastic waves in a 1D periodic structure is

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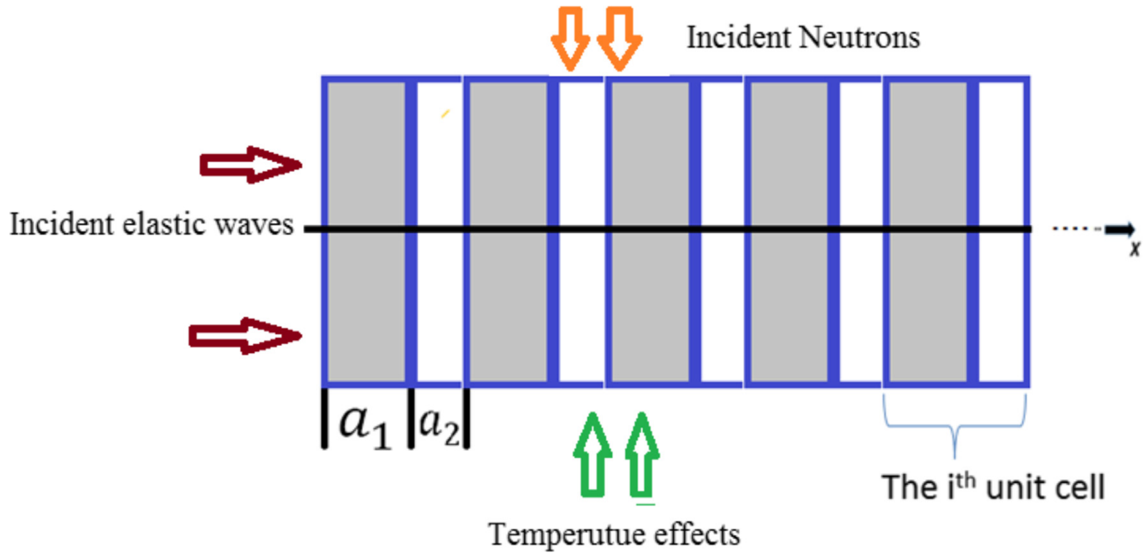

Fig. 1. The model of a 1D concrete PnC neutrons detector.

given by the following equation [28]:

$$\rho\ddot{u} = \frac{\partial}{\partial x}(\sigma) + f, \tag{1}$$

where $\rho = \rho(x)$, $u = u(x, t)$, $\sigma = \sigma(x, t)$ and $f = f(x, t)$ denote the density, displacement, stress and external force respectively. The solution of Eq. (1) is $u = u(x, t)$ that represents the wave propagation in the entire structure. At the interfaces between each two layers, there is a superposition between the incident and reflected waves. The solution of such traveling wave can be written as follow:

$$u = u(x, t) = [A_+^j e^{ik(j)x} + A_-^j e^{-ik(j)x}]\times e^{-i\omega t} \tag{2}$$

where $k(j) = \frac{\omega}{c_j}$ is the wave vector, ω is the angular frequency, c_j is the perspective velocity in each layer and the two layers are denoted by the subscript $j = 1, 2$.

When elastic waves propagate through a PnC structure, it suffers multi scatterings at the interface between each two layers. Due to the continuity of the wave form at these interfaces, boundary conditions at every interface relate coming waves to the reflected ones. Our objective is to compute the transmission spectrum that characterizes the frequencies corresponding to neutrons irradiation on the concrete encompassed in constructing of a PnC. The transfer matrix method utilized here to simulate the transmission properties of the 1D PnCs is discussed extensively in literatures [2–4].

The transmission coefficient of an elastic wave incident normal to the face of PnC structure subjected between two semi-infinite solids is given by,

$$\frac{U_e}{U_0} = \frac{2E_0(T_{11}T_{22} - T_{12}T_{21})}{E_0(T_{11} - E_eT_{21}) - (T_{12} - E_eT_{22})}, \tag{3}$$

where E_0 andE_e are Young's moduli of the two semi-infinite solids at the left and right of the PnC structure, U_e and U_0 are the transmitted and incident amplitudes respectively. $T_{ij} = T(i, j)$ represent the elements of the total transfer matrix T; $T = T_nT_{n-1}. .T_i. .T_1$ with $T_i = T_2'T_1'$, and T_j' can be written in the following form [4,8]

$$T_j'(1, 1) = T_j'(2, 2) = \frac{[\exp(-i\,q_{Tj}\zeta_j) + \exp(iq_{Tj}\zeta_j)]}{2},$$
$$T_j'(1, 2) = \frac{iq_{Tj}\mu_j.[\exp(i\,q_{Tj}\zeta_j) - \exp(-iq_{Tj}\zeta_j)]}{2},$$
$$T_j'(2, 1) = \frac{i[\exp(-i\,q_{Tj}\zeta_j) - \exp(iq_{Tj}\zeta_j)]}{2q_{Tj}\mu_j}. \tag{4}$$

where $q_{Tj} = \frac{\omega a_j}{c_{Tj}}$, c_{Tj} is the transverse wave velocity in each layer, and ζ_j are the dimensionless thickness of each layer.

Young's modulus of the concrete varies from 14 to 41 GPa and the average value of 27.5 GPa was considered in our calculations, which corresponds to hardened concrete [27,29]. Also, we considered the suitable epoxy material at high temperatures from the epoxy adhesive composites.

3. Results and discussions

3.1. The relation between concrete Young's modulus and neutrons fluence

Effect of the neutron fluence on the concrete has been studied to investigate the feasibility of employing the concrete as a detector. The ratio of moduli of elasticity for irradiated and unirradiated concrete, $(\frac{E_c}{E_{co}})$, was given versus the neutrons fluence in Fig. 2.

As shown in Fig. 2, once the incident neutrons fluence on the concrete reached 1×10^{19}n cm^{-2} the Young's modulus of the concrete significantly decreased. The Young's modulus of the concrete considerably declined over the neutron fluence with various rates depending on the neutron flux range. On contrary, the Young's modulus of the organic and soft composites such epoxies is almost constant at different neutrons irradiations [30]. Based on this direct variation in the

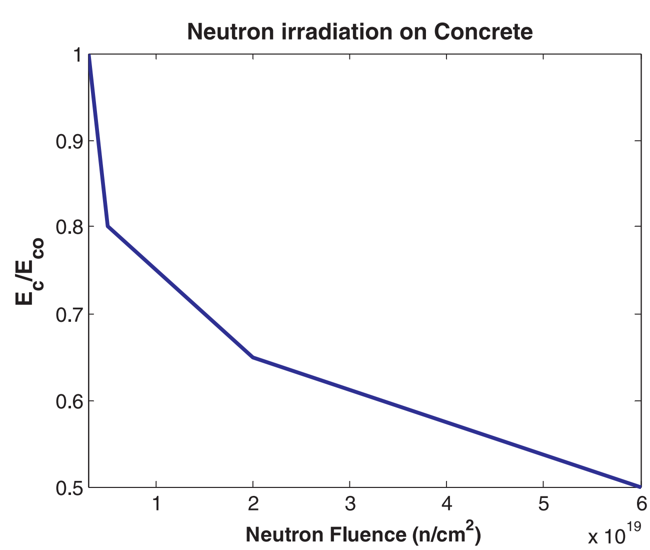

Fig. 2. Young's modulus of concrete after neutron irradiation E_c related to Young's modulus of unirradiated Concrete E_{co} [27].

Table 1
Material constants used in calculations.

Material	Density ($\frac{kg}{m^3}$)	Poisson's ratio	Young's modulus ($\frac{N}{m^2}$)	Transverse speed of sound ($\frac{m}{s}$)
Concrete	2320	0.20	27.5×10^9	2222
Epoxy	1018	0.368	4.35×10^9	1160
Aluminum	2699	0.355	6.752×10^{10}	3043

Young's modulus value of the concrete, the sound velocity in the concrete changes. Since the transverse component of the sound velocity can be written in the form; $c_T = \sqrt{\frac{\mu}{\rho}}$, $\mu = E/2(1+\sigma)$ where μ, E and σ are shearing modulus, Young's modulus and Poisson's ratio of the concrete respectively. The concrete constants are displayed in Table 1. Therefore, employment the concrete as a built unit in the construction of PnCs would be beneficial for neutrons detection. Where exposing the concrete to the neutrons leads to modify the phononic band gap and the transmission properties of the PnCs.

3.2. Neutrons detection by 1D concrete phononic crystals

A 1D-PnC model composed of concrete and epoxy forming five unit cells PnCs $(Concrete/Epoxy)^5$ was analyzed. The thickness of the concrete and epoxy layers were

a_1 and a_2, and were considered 1×10^{-2}m and 0.5×10^{-2}m respectively, so the thickness of the concrete to the epoxy was 2:1. It is well-known the thickness ratio between the constituent materials has the major efficacy in the form and magnitude of the band gap range. The characteristics of the utilized materials are listed in Table 1 [18,29]. In Fig. 3 the transmission is plotted as a function of the normalized or dimensionless frequency ($\omega a/2\pi c_T$). Where, ω is the angular frequency of the incident elastic wave, a is the lattice constant and c_T is the transverse velocity of elastic waves, here c_T is considered of the epoxy material in all calculations ($c_T = c_{T2}$). So we can calculate the frequency value of the incident wave easily form this normalized value. We intended to plot the transmission as a function of the normalized frequency instead the frequency f to choose any value of the lattice constant or incident velocity.

The transmission coefficient of the PnCs structure was calculated assuming E_c was equal to E_{co} (Fig. 3a). The PnC presented a wide band gap through which waves of certain frequency range couldn't propagate. Actually, the frequency value of such band gap can be calculated from the relation $\omega a/2\pi c_T$. For example, at the value $\omega a/2\pi c_T = 0.6$ in Fig. 3(a), the characteristic frequency = 7.7×10^4Hz.

Upon exposing the PnC to the neutron flux the Young's modulus of the concrete decreased [27]. As a result, the band gap width of the PnC decreased and the band gap shifted to a higher frequency range (Fig. 3d). For instance, when the incident neutron fluence was large enough to modify the Young's modulus of the irradiated concrete to become $E_c = 0.5E_{co}$, the band gap width of the PnC decreased to be half width of the unirradiated PnC system (Fig. 3a and d). Fig. 4 confirmed these results where the transmission distribution of the elastic waves (maximum value with the red shadow) decreased to the minimum in the unirradiation condition at $E_c = E_{co}$. Therefore, the phononic band gaps can be shifted and tuned by neutrons irradiation on PnC composed of the concrete. The concrete PnC can be used as a neutron detector over a wide neutron fluence range. The sensitivity of the concrete PnC to neutrons fluence was depicted in Fig. 5. Upon increasing neutrons fluence incident on the concrete PnC, phononic band gap shifted to higher frequency range.

3.3. Temperature dependence of the concrete PnC

Neutrons interactions in nuclear reactors cause temperature elevation of the surrounding environment. Therefore, in order to construct neutrons detector based on the concrete material, effect of the induced

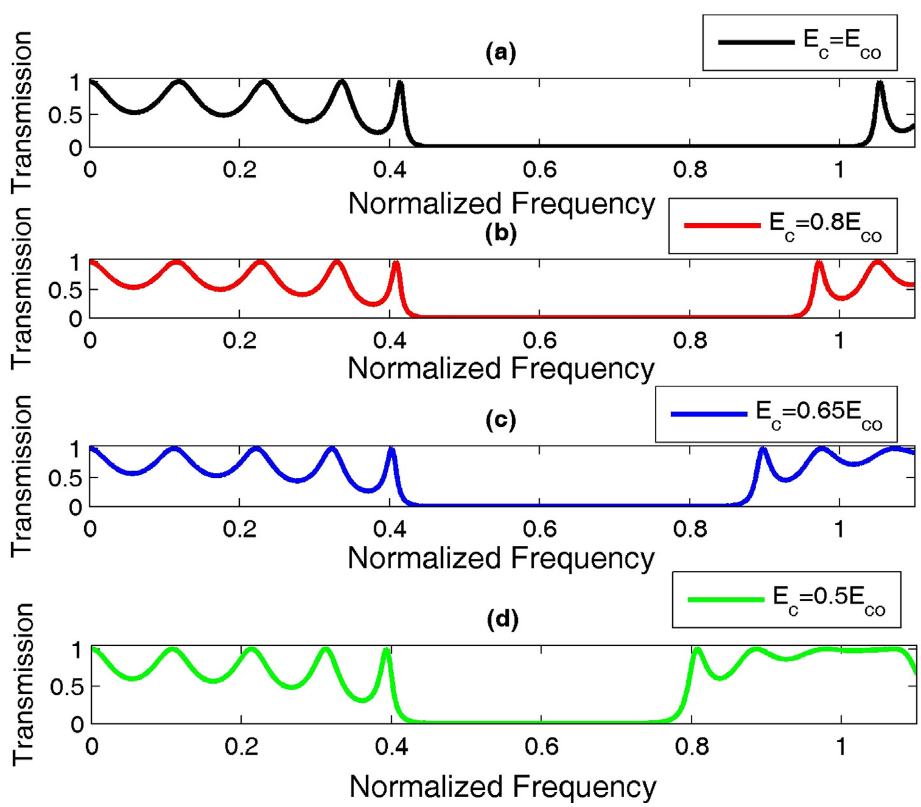

Fig. 3. A Plot of the transmission and the normalized frequency ($\omega a/2\pi c_T$) for normal incident elastic wave on a 1D PnC structure $(Concrete/Epoxy)^5$ at different neutrons fluences at room temperature: (a) $E_c = E_{co}$, (b) $E_c = 0.8E_{co}$, (c) $E_c = 0.65E_{co}$ and (d) $E_c = 0.5E_{co}$.

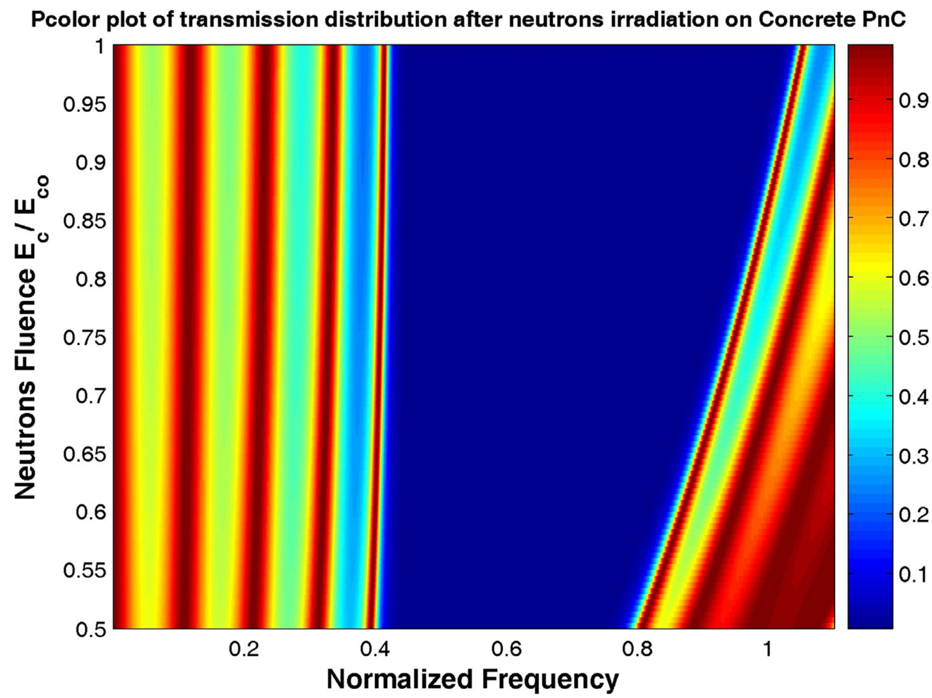

Fig. 4. Color map of the transmission distribution versus neutron irradiation on concrete PnC at room temperature.

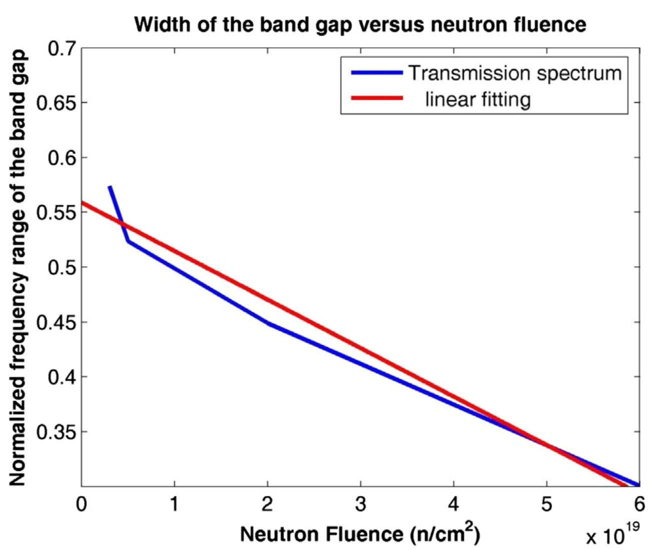

Fig. 5. The relation between band gap width and neutron fluence in the concrete PnC.

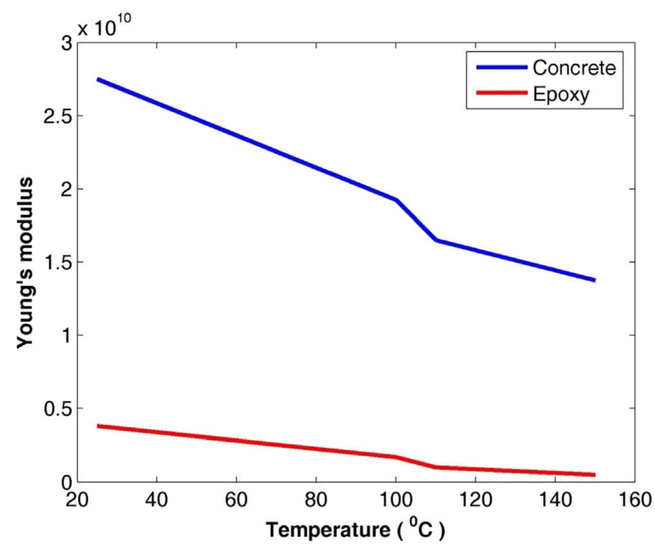

Fig. 6. The relation between Young's modulus of the concrete and epoxy versus temperature.

temperature has to be taken into account. High temperatures decrease the Young's modulus, softening the concrete [31]. The influence of the temperature on Young's modulus of the concrete and the epoxy is presented in Fig. 6 taken from the literatures [31,32].

The transmission spectra of the $(\text{Concrete/Epoxy})^5$ PnC were recalculated at neutrons fluence of 1×10^{19}n cm^{-2} but in these calculations the temperature effect was considered (Fig. 7). The temperature effect on the concrete PnC was opposite to the influence of neutron irradiation. The width of the phononic band gap increased with raising the temperature as at the high temperature of 150 °C the width of the band gap reached double the width of the band gap at a temperature of 25 °C. Raising the temperature modified Young's modulus of the two constituent materials; however, epoxy Young's modulus decreased much larger than of the concrete as depicted in Fig. 6. Consequently, the ratio of the Young's modulus values of the two materials increased widening the band gap. Therefore, temperature elevation considerably enhances the efficiency of the concrete PnC detector.

3.4. *Local resonance in a 1D concrete phononic crystal*

In this section, we tend to show the local resonance phenomenon inside the concrete PnC which has been appeared in many photonic crystals structures [4,15,33–35]. Such a feature emphasizes the flexibility and efficiency of usage the concrete PnC detector to sense and measure neutrons fluence based on different parameters of the PnCs. Inserting the concrete material as a defect layer inside the PnC structure can generate resonant peaks in the transmission spectrum. Here, we consider the PnC structure composed of $(\text{Al/Epoxy})^4$ with thicknesses 2, and 0.5×10^{-2} m respectively. The concrete material is inserted in the middle of the PnC structure with thickness 1×10^{-2} m.

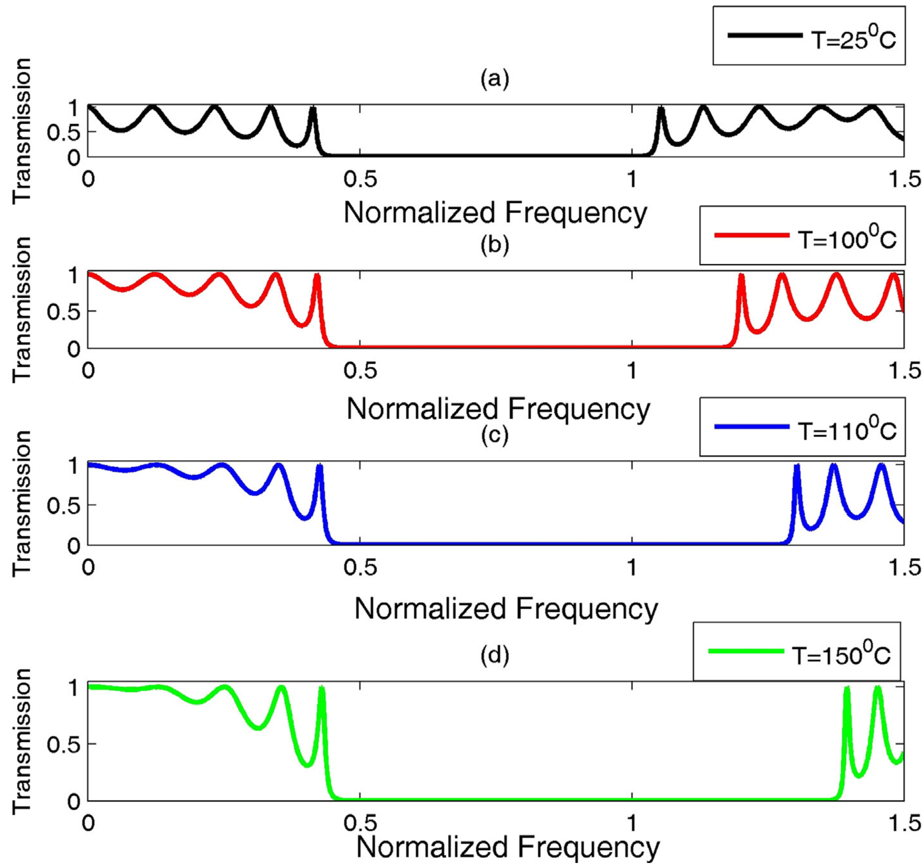

Fig. 7. The transmission spectrum of neutrons irradiation on the concrete PnC detector at temperature influences.

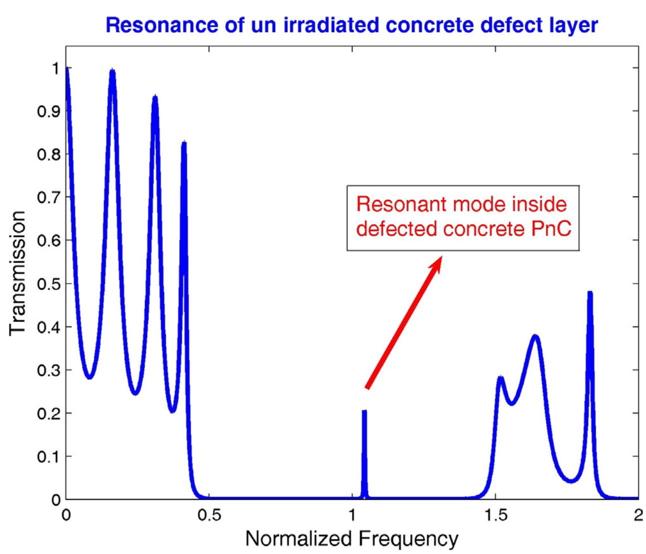

Fig. 8. The transmission spectrum of a PnC (Al/Epoxy)^4 contains the concrete as a defect layer.

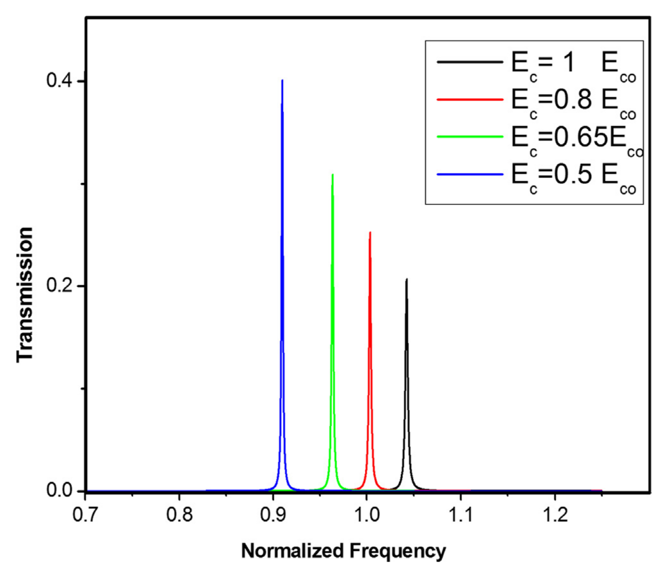

Fig. 9. The transmission spectrum of a PnC (Al/Epoxy)^4 contains the concrete as a defect layer.

As shown in Fig. 8 a resonant mode (peak) with an intensity of 20% appeared inside the band gap of the transmission spectrum. As a result of neutrons irradiation on the defected PnC, Young's modulus of the defect layer (concrete) decreased shifting the resonant peak toward lower frequencies and increased the peak intensity. These increment and the displacement of the resonant peak are due to the increment of the impedance mismatch between the concrete and (Al/Epoxy) unit cell. For a neutrons fluence $= 6 \times 10^{19} \frac{n}{cm^2}$ (Young's modulus of irradiated concrete $E_c = 0.5E_{co}$) the peak intensity doubled to be approximately 40% compared to the unirradiated concrete. Hence, the defected PnCs contained the concrete as a defect layer can be considered an effective neutron detector (see Fig. 9).

4. Conclusions

Employing the correlation between the elastic wave transmission and neutrons irradiation fluence in one- dimensional phononic crystal composed of the concrete was studied. The conclusions are drawn as follow:

(a) For neutrons irradiation on a 1D periodic array of (Concrete/Epoxy)^5, the phononic band gap decreased with increasing neutrons fluence.
(b) Increasing the temperatures of the concrete phononic crystal resulted in canceling the decrement in the band gap width caused by neutrons fluence by the same amount.
(c) The resonant peak transmitted through the defect layer (concrete) inside the (Al/epoxy) unit cell was significantly shifted with increasing the neutrons fluence.

Based on these findings, concrete phononic crystals can be considered as an effective tool for measuring, sensing and detecting the neutrons fluence inside reactors buildings and for many radioactive sources.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ultras.2018.10.012.

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