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# Realization of high-performance bandpass filter by impedance-mirroring

Il Kyu Lee, Hong Min Seung, Yoon Young Kim*

*School of Mechanical and Aerospace Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 151-742, South Korea*

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ABSTRACT

Ideal bandpass filters must have sharp roll-off and high transmission over a target pass band simultaneoulsy, but it is still difficult to make such filters of a reasnoable size. To achieve such performance, we propose a novel finite phononic crystal filter made of impedance-mirrored elements each of which constists of two layers having different impedances. For broad bandpass filtering, one of the two layers is selected to be one eighth wavelength long at the center frequency of the passband and the other layer, one quarter wavelength long with a matched impedance. For narrow bandpass filtering, the broad bandpass filter is slightly modified in such a way that the concept of the impedance-mirroring is applied globally over the finite periodic structure filter, not within each unit cell. To check the performance of the proposed filters, experiments using torsional elastic waves in a rod were conducted.



## 1. Introduction

The realization of ideal or quasi-ideal filters [1–4] has been an important issue in various applications. Among these efforts, the technique to insert a cavity [5–10] or a defect [11–13] inside a finite phononic crystal (PC) is known to be effective for narrow bandpass filtering, but not so useful for broad bandpass filtering. On the other hand, a more classical method of impedance matching may be used to make bandpass filters (see, e.g. [14]), but its direct use makes it difficult to achieve sharp roll-off and high transmission in a target passband simultaneously.

As an alternative method to overcome the above-mentioned limitations of PC-based or direct impedance matching based filtering, Lee and Kim [15] suggested a method to combine the stopping mechanism of PC structures and the high-transmission capability of impedance matched structures. They showed that if the impedance-mirroring approach is incorporated in forming a finite-sized PC, the resulting PC functions as a high-performance bandpass filter. Although the potential of the impedance-mirroring concept was demonstrated by simulations, actual realization of such a filter was not made because the suggested unit cell was made of a number of thin layers of incrementally-varying impedances, which makes its fabrication difficult. Therefore, in this study, we propose a new impedance-based mirroring method to design finite PC-type bandpass filters and perform filtering experiments. The main aspect in the proposed PC-type filter is that the PC unit cell is made of two simple impedance-mirrored elements and each element is formed only by two distinct layers of tuned lengths and impedances. After the filter design method based on the impedance mirroring concept is presented, simulation and experimental results are presented where torsional waves propagating in an elastic rod are used.

* Corresponding author. Tel.: +82 2 880 7154; fax: +82 2 872 1513.
*E-mail address:* yykim@snu.ac.kr (Y.Y. Kim).

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## 2. Method

To give an idea of the proposed filtering method, Fig. 1 shows a schematic diagram of a proposed broad bandpass filter made of $N_c$ unit cells that is realized in an elastic rod of diameter $D$. A torsional wave generated at the left side of the inserted filter is filtered as it propagates through the filter. While the physics behind the proposed unit cell configuration will be given below, an attention is paid first to the unique unit cell configuration in Fig. 1. To explain the configuration, the filter is assumed to be inserted in a uniform elastic rod of mechanical impedance $Z_A$ and wave speed $c_A$ although the present filter can be directly extended to connect two rods of difference impedances. The symbols $\boldsymbol{M}$ and $\tilde{\boldsymbol{M}}$ denote elements forming the unit cell but more detailed accounts of $\boldsymbol{M}$ and $\tilde{\boldsymbol{M}}$ will be given shortly. Throughout this study, the center frequency ($f_c$) of bandpass filters to be designed is set at 100 kHz but there is no problem to choose different center frequencies.

The design of a broad bandpass filter is considered first. In this case, we propose to form a unit cell $\boldsymbol{C}$ by using two elements, $\boldsymbol{M}$ of length $d_{\boldsymbol{M}}$ and $\tilde{\boldsymbol{M}}$ of length $d_{\tilde{\boldsymbol{M}}}$. The resulting unit cell will be denoted by $\boldsymbol{C}=\left[M\tilde{\boldsymbol{M}}\right]$. The key aspect in forming $\boldsymbol{C}$ is that the impedance distribution of $\tilde{\boldsymbol{M}}$ is exactly the mirror distribution of $\boldsymbol{M}$. Furthermore, element $\boldsymbol{M}$ is made only of two distinct layers: an arbitrary-impedance layer $l_B$ of an adjusted length $d_B$ ($Z_B \neq Z_A$) and a well-known quarter-wave impedance matching layer $l_m$ of length $d_m$. For instance, we can choose $Z_B = 4Z_A$.

About the layer lengths $d_B$ and $d_m$, Fig. 1 suggests that the phase changes in the two layers must be $\pi/2$ (corresponding to a quarter-wave layer $l_m$) and $\pi/4$ (corresponding to a one-eighth-wave layer of an arbitrary impedance $Z_B$), respectively at $f_c$. As explained before, the unit cell structure should be configured by using the impedance-mirroring concept. In what follows, we will explain the rationale to propose the configuration in Fig. 1 and also the physics behind the extraordinary filter performance of broad bandwidth, high transmission and sharp roll-off. Then, we will demonstrate how one can modify the proposed configuration to make a narrow bandpass filter with high transmission.

Note that the proposed filter is to be built upon finite phononic crystals (PC's). Therefore, some of the well-known characteristics of stop and pass bands of PC's will be naturally utilized. Among others, we recall an obvious fact that the resonance phenomena occurring in a finite PC deteriorate wave transmission performance. Therefore, the resulting oscillatory transmission behavior in the passband frequency must be suppressed to make a high-performance bandpass filter.

Let us now present how to make bandpass filters using the unique unit cells designed by the impedance-mirroring concept. Because a periodic PC structure will be used as a hosting structure to make a bandpass filter, the formation of stop/pass bands will be naturally utilized. To realize a bandpass filter of broad bandwidth, one may locate the center frequency $f_c$ of a desired frequency within the passband frequencies of a PC made of $\boldsymbol{C}=[\boldsymbol{E}]$, resulting in the total phase change of $3\pi/4$ through $\boldsymbol{C}$. The symbol $\boldsymbol{E}$ denotes a bi-layer element made of two layers, $E=\{l_A l_B\}$ such that the phase changes in $l_A$ and $l_B$ are $\pi/2$ and $\pi/4$, respectively at $f_c$. Obviously, finite-sized PC's exhibit oscillatory behavior in the passband.

To flatten the oscillations in the passband by $\boldsymbol{C}=[\boldsymbol{E}]$ and achieve sharp roll-off characteristics, we can use the impedance-mirroring concept [15] but should come up with a filter configuration that can be practically fabricated for actual engineering applications. To this end, we replace $l_A$ in $E=\{l_A l_B\}$ by $l_m$, a matching layer to suppress the undesirable oscillations. The resulting element will be denoted by $\boldsymbol{M}=\{l_m l_B\}$. To ensure good transmission at $f_c$, we select the matching layer $l_m$ having the impedance of $Z_m=\sqrt{Z_A Z_B}$ where the impedance of the base rod is $Z_A$. In this case, the phase change through $l_m$ becomes $\pi/2$. Equivalently, $k_m d_m=\pi/2$ where $k$ stands for wavenumber. This layer is the well-known quarter-wave matching layer.

When the resulting PC made of the unit cell $\boldsymbol{C}=[\boldsymbol{M}]$ is inserted in a base rod of impedance $Z_A$, impedance mismatch occurs between the right side of the finite PC and the base rod. So, we introduce the impedance-mirroring concept to avoid the mismatch. Specifically, the following unit cell $\boldsymbol{C}$ constructed:

$$\boldsymbol{C}=\left[M\tilde{\boldsymbol{M}}\right], \tag{1a}$$

where

$$M=\{l_m l_B\} \text{ and } \tilde{\boldsymbol{M}}=\{l_B l_m\} \tag{1b}$$

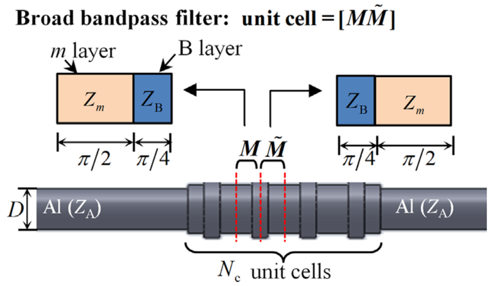


**Fig. 1.** An illustration of the proposed broad bandpass filter inserted in a rod.