Support Loss-free Micro/Nano-mechanical Resonators using Phononic Crystal Slab Waveguides

Saeed Mohammadi, Ali A. Eftekhar, and Ali Adibi

***Abstract*— Phononic crystals (PnCs) are inhomogeneous materials with periodic variations in their elastic (or acoustic) properties. PnCs, if properly designed, can show frequency ranges in which the propagation of elastic waves is completely prohibited. Within these frequency ranges, called complete phononic band gaps (CPnBGs), elastic energy can be confined and manipulated by the PnC structure. Micro-machined PnC structures with two-dimensional (2D) periodicities and finite thicknesses have been developed to possess large CPnBGs. Such structures have shown to be very effective in confining mechanical vibrations at very high frequencies. It is argued that by replacing the supporting structure of the suspended conventional high-Q micro/nano-mechanical (MM) resonators with PnC structures, the support loss in the resonators can be suppressed. However, a such resonators may give rise to spurious modes in the resonance profile of the resonance. Therefore, the development of more efficient PnC resonators with complete elimination of the supporting structures in all in-plane directions and with large spurious-fee spectral ranges is pending.**

In this paper we discuss different architectures and properties of support-loss-free PnC micro-mechanical resonators and compare their performance with the conventional MM bar resonators with supporting anchors. We have recently shown that in a thin-film piezoelectric on substrate (TPoS) MM resonator, the quality factor can be greatly improved by replacing the supporting structure with PnC structures. Qs of more than 6,000 are obtained at very high frequencies (~130 MHz) for the case of PnC resonators compared to Qs the order of about 1,000 for the structures with support. It is though observed that the PnC structure in such resonators may lead to undesirable spurious modes around the main resonant mode. In order to mitigate the spurious modes, in this paper PnC waveguides are engineered and designed to form more effective PnC resonators. Waveguide-based PnC resonators with Qs of more than 7,000 and with a large free spectral range around the resonant mode are hence developed.

***Index Terms*—Micro-electro-mechanical system, Phononic crystal, phononic band gap, waveguide, resonator**

I. Introduction

Phononic crystals (PnCs) [1], [2] are inhomogeneous materials with periodic variations in their elastic (or mechanical) properties. The dispersion characteristics of the PnCs can be engineered to achieve functionalities not obtainable by the conventional bulk materials. One of the most important properties obtainable in PnC structures is the possibility of achieving complete phononic band gaps (CPnBGs). CPnBGs are frequency ranges in which the propagation of any elastic waves is prohibited. CPnBGs can be the basis of realizing a variety of functionalities including, but not limited to: mirroring, guiding, entrapment, filtering, multiplexing, and demultiplexing of elastic (acoustic) waves. Such functionalities can be obtained by modifying portions of the PnC structure. The implementation of such functionalities using PnC structures can lead to integrated acoustic devices with superior performance over the conventional electromechanical devices used in wireless communication and sensing systems.

There has been a growing recent interest in PnC slabs (plates), which have two-dimensional (2D) periodicity and a finite thickness (of the order of a wavelength) in the third dimension [3]–[11]. In PnC slab structures the elastic waves can be manipulated in the plane of periodicity by the PnC structure while being confined within the finite thickness of the slab in the third dimension due to acoustic mismatch. The air (or vacuum) on top and bottom of the PnC slab (or membrane) decouples the elastic energy in the PnC slabs from leaking into the substrate. Thus, the loss of the elastic waves in the PnC slabs is considerably lower than the loss of the surface acoustic wave (SAW)-based 2D PnC structures.

On the other hand, high quality factor (Q) micro/nano-mechanical (MM) resonators at high frequencies are of great interest for realizing compact and efficient wireless communication and sensing devices. Among several material systems proposed for such resonators, silicon (Si)-based systems have many advantages due to low cost, the availability of complimentary-metal-oxide-semiconductor (CMOS) fabrication tools that allow accurate and economical fabrication of Si structures, proper elastic properties that are required for low-loss applications, and the possibility of integration with other functionalities. To obtain high Q resonators in Si-based systems, mechanical energy needs to be stored in a resonating structure with the lowest loss possible. The most common resonating structure in such systems is a slab of solid suspended in air or vacuum to eliminate the loss of elastic energy to the surroundings. However, supporting structures are required to keep the structure suspended and for providing a path to interrogate the resonator. Unfortunately, such supports are a source of loss (and therefore lowering the

This work was supported by the National Science Foundation, and the Office of Naval Research.

The authors are with the school of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA (saeedm@gatech.edu, eftekhar@ece.gatech.edu, adibi@ece.gatech.edu, correspondence: Saeed Mohammadi).

Q) in the desired resonators as mechanical energy can leak through them to the substrate.

We have recently proposed MM structures based on PnC slab structures that can provide mechanical support to the suspended structure while limiting the loss of the stored mechanical energy to the surroundings through the use of CPnBGs [9]. In the reported PnC resonator structures, spurious modes would arise in addition to the principal modes of the resonators. In this paper, we propose high-Q waveguide-based PnC slab structures which show spurious mode-free operation while suppressing the support loss through the use of PnC structures. Such PnC resonators can serve as a basis for more complex functionalities with adiabatic manipulation of elastic energy.

II. An Efficient Phononic Crystal Waveguide

To eliminate the problem of spurious modes in the previously proposed PnC structures [9], we propose to implement a PnC waveguide with limited number of supported modes. The PnC waveguide then can be confined by the PnC structure on its input and output so that it can confine forward and backward (and hence standing) waves within the waveguide region.

The PnC structure is composed a hexagonal (honeycomb) lattice of void holes in a free-standing Si slab. If the thickness of the slab is represented by *a,* the lattice constant and the radius of the holes are *a* and 0.43*a*, respectively. As previously reported, the extent of the CPnBG for such a geometry is 1750 m/s < $f \times a$ < 2265 m/s . Although we have previously shown the possibility of waveguiding in the PnC structures [10], the waveguides reported so far support many modes within the CPnBG. Such multi-mode nature of the developed waveguides limits their application and the usable bandwidth. Therefore, a PnC waveguide with reduced number of modes is introduced. In order to obtain such a waveguide, instead of removing lines of holes completely, PnC holes in two rows are reduced in size to form a waveguide. A schematic of such PnC waveguide is shown in **Fig. 1**.

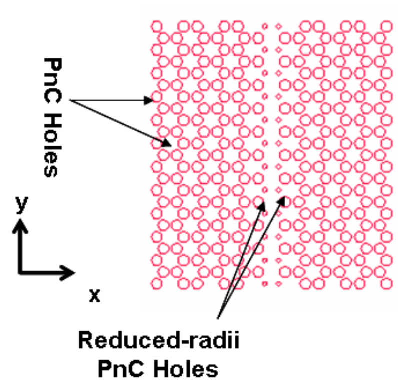

Fig. 1. Layout of the designed phononic crystal waveguide. Two rows of holes in the PnC structure are reduced in size to allow for a limited number of guided modes in the formed PnC waveguide.

The dispersion profile of the waveguide shown in Fig. 1 for the reduced PnC holes of with radius of 0.2*a* is given in Fig. 2. By considering the profiles of each mode in the wave vector domain (e.g., at Γ and K points), the size of the holes is chosen based on the dispersion curve characteristics and the profile of the propagating modes in the formed waveguide.

III. Waveguide-based PnC Resonator

In order to form the PnC resonator based on the PnC waveguide, the input and output ports of the waveguide are blocked by the PnC structure. The length of the confined waveguide is ten periods. This leads to the formation of an efficient waveguide-based PnC resonator. In order to interrogate the resonator, a 100 nm gold layer is deposited on top of the resonator to form as a common excitation/detection electrode. A 1 µm layer of piezoelectric zinc-oxide is sputtered on top of the gold layer to serve as the transduction medium. A 100 nm aluminum (Al) layer is then patterned on top of the structure to form the second excitation/detection electrode to interrogate the appropriate resonant modes.

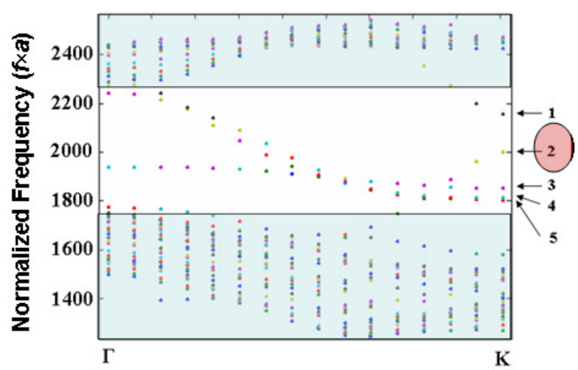

Fig. 2. The dispersion characteristics of the PnC waveguide shown in Fig. 1. As indicated in this figure, five modes appear in the dispersion profile of the waveguide within the CPnBG of the PnC

A Schematic of the layout, and a scanning electron microscope (SEM) image of the fabricated structure are shown in Fig. 3 and Fig. 4, respectively.

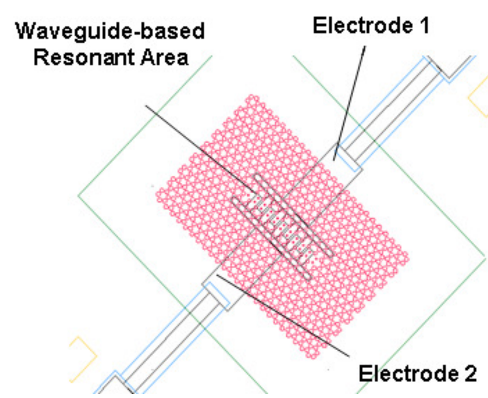

Fig. 3. Schematic of the layout of a waveguide-based PnC slab resonator structure.

The Al electrodes are placed on top of the resonant region to effectively excite the mode of interest, which is an extensional mode indicated by number 2 in Fig. 2.

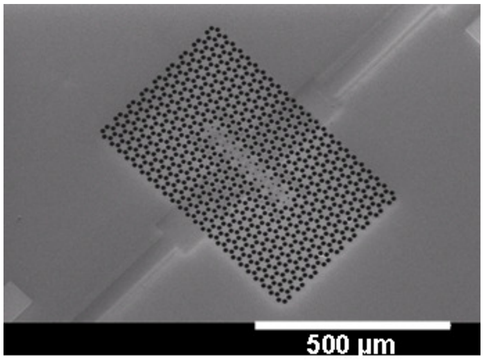

Fig. 4. SEM image of the fabricated waveguide-based MM PnC resonator.

In order to accurately evaluate the resonance properties of the excited mode, we fit a Butterworth Van Dyke model [11] to the resonant profile of the structure measured through a vector network analyzer. The resonance profile of the fabricated waveguide-based MM PnC resonator in the form of admittance is shown in Fig. 5. The resonance parameters extracted from fitting a BVD model are also given in the figure, where f, Q, R_m, C_p, and R_p represent the frequency of resonance, the quality factor, the motional impedance, the parallel capacitance, and the parallel resistance, respectively.

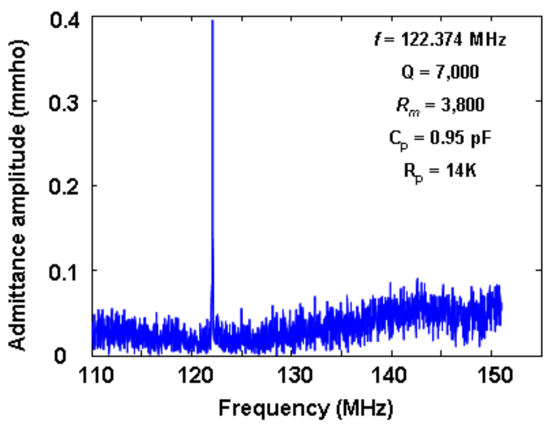

Fig. 5. Admittance profile of the waveguide-based PnC resonator.

As can be seen in this figure, the Q of the resonance is 7,000 which is slightly higher than the previously reported PnC resonators fabricated on the same chip and went through an exact same fabrication process [9] confirming the suppression of the support loss. The frequency of resonance of the MM resonator is 122.374 MHz, which is about % 9 lower than what predicted through the simulations. The reason can be clearly attributed to the transducer stack placed on top of the Si slab, which reduces the propagation phase velocity of the waves. The effect of this stack is not included in the simulations. It is worth noting that the resonance profile is free of any spurious modes, which offers a very large spurious-free spectral range. This shows that obtaining support-loss free MM resonators is possible through the use of PnC structures. Although the mechanism of excitation is based on piezoelectric transducers in this paper (which limits the achievable Q due to the transducer material loss), this method of obtaining support loss-free resonators can be extended to MM resonators with other means of excitation.

IV. Conclusion

In this paper we showed that by using phononic crystal waveguides, support loss-free mirco/nano-mechanical resonators with large spurious free spectral ranges can be obtained. This solves the problem of the presence of spurious modes in the previously reported micro/nano-mechanical resonators with support-loss suppression. Although the reported waveguide-based resonator is applied to piezoelectrically-excited resonators, the use of phononic crystal structures to obtain support loss-free resonators can be applied to other resonators with different mechanisms of interrogation.

Acknowledgment

The authors wish to thank the staff at Georgia Tech Microelectronics Research Center for their support in fabrication, Prof. W. D. Hunt for the lab equipment, and the IEEE International Frequency Control Symposium Technical Program Committee for the travel support.

References

[1] M. M. Sigalas, and E. N. Economou, " Elastic and acoustic wave band-structure," J. Sound and Vibr., vol. 158, pp. 377–382, Oct. 1992.

[2] M. S. Kushwaha, P. Halevi, L. Dobrzynski, and B. Djafari-Rouhani, ," acoustic band-structure of periodic elastic composites," Phys. Rev. Lett., vol. 71, pp. 2022-2025 Sep. 1993.

[3] X. Zhang, T. Jackson, E. Lafond, P. Deymier, and J. Vasseur, "Evidence of surface acoustic wave band gaps in the phononic crystals created on thin plates," Appl. Phys. Lett., vol. 88, pp. 419111-419113, Jan. 2006.

[4] A. Khelif, B. Aoubiza, S. Mohammadi, A. Adibi, V. Laude, "Complete band gaps in two-dimensional phononic crystal slabs," Phys. Rev. E, vol. 74, pp. 0466101-0466105, Oct. 2006.

[5] J.H. Sun, T.T. Wu, "Propagation of acoustic waves in phononic-crystal plates and waveguides using a finite-difference time-domain method," Phys. Rev. B, vol. 76, pp. 1-8, Sep. (2007).

[6] F.L. Hsiao, A. Khelif, H. Moubchir, A. Choujaa, C.C. Chen, V. Laude, "Waveguiding inside the complete band gap of a phononic crystal slab", Phys. Rev. E, vol. 76, pp. 0566011-0566016, Nov. 2007.

[7] S. Mohammadi, A.A. Eftekhar, A. Khelif, H. Moubchir, R. Westafer, W.D. Hunt, A. Adibi, " Complete phononic bandgaps and bandgap maps in two-dimensional silicon phononic crystal plates," Electron. Lett., vol. 43, pp. 898-899, Aug. 2007.

[8] S. Mohammadi, A.A. Eftekhar, A. Khelif, W. D. Hunt, and A. Adibi, "Evid ence of large high-frequency complete phononic band gaps in silicon phononic crystal plates," Appl. Phys. Lett., vol. 92, pp. 2219051-2219053, Jun. 2008.

[9] S. Mohammadi, A. Eftekhar, A. Khelif, and A. Adibi, "Support loss suppression in micromechanical resonators by the use of phononic band gap structures," in Proc. of 2010 SPIE Photonics West, p. 76090W.

[10] S. Mohammadi, A. A. Eftekhar, W. D. Hunt, and A. Adibi, "Demonstration of large complete phononic band gaps and waveguiding in high-frequency silicon phononic crystal slabs," in Proc. of 2008 IEEE International Frequency Control Symposium, 19-21 May 2008, pp. 768-772.

[11] K. S. Van Dyke, "The piezo-electric resonator and its equivalent network," Proceedings of the Institute of Radio Engineers, vol. 16(6), pp. 742-764, 1928.