Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 120 (2015) 1095 – 1098

Procedia Engineering

www.elsevier.com/locate/procedia

EUROSENSORS 2015

Rapid prototyping of 3D phononic crystals using high-resolution stereolithography fabrication

F. Lucklum* and M. J. Vellekoop

Institute for Microsensors, -actuators and -systems (IMSAS), University of Bremen, Otto-Hahn-Allee NW1, D-28359 Bremen, Germany
Microsystems Center Bremen (MCB), Otto-Hahn-Allee NW1, D-28359 Bremen, Germany

Abstract

We present proof-of-concept devices to validate the suitability of high-resolution stereolithography fabrication, polymer material properties, and increased design freedom for realizing 3D phononic crystals. The maskless, single-step technology enables the fabrication of freeform 3D microstructures with high accuracy, which allows rapid prototyping of novel designs and leads to fast optimization cycles. Experimental results for devices with feature sizes down to 100 µm successfully indicate phononic band gap behavior, which is required for applications as sensor and microsystem structures.

Peer-review under responsibility of the organizing committee of EUROSENSORS 2015

Keywords:

1. Introduction

The advent of crystalline micro- and nanostructures has led to the discovery of unique properties, such as photonic behavior for electromagnetic wave propagation. Phononic crystals are the acoustic equivalent to photonic crystals featuring a unique spectral bandgap for wavelengths on the order of the crystal lattice constant [1, 2]. These metamaterials may exhibit characteristics not found in any conventional material. With sub-wavelength dimensions new physical behavior is possible. Besides growing crystalline structures, such complex geometries can also be artificially constructed.

* Corresponding author. Tel.: +49 421 218 62645; Fax: +49 421 218 62570.
E-mail address: flucklum@imsas.uni-bremen.de

Peer-review under responsibility of the organizing committee of EUROSENSORS 2015
doi:10.1016/j.proeng.2015.08.783

Planar microtechnology allows the fabrication of 2D crystals in a variety of materials for applications as, e.g., metamaterials [3], sensor material [4], filters, or insulators [5]. Extending this technology to 3D designs is challenging. However, with current advances in additive manufacturing an alternative technology exists. The field of additive manufacturing has undergone rapid progress in recent years thanks to ongoing developments in instrumentation and suitable materials [6]. Stereolithography printing has evolved to become the technology featuring highest resolution and best defined surfaces. With high-resolution stereolithography [7] arbitrary 3D geometries can be realized on the microscale in a variety of polymer materials. Due to the rapid production cycle of this technology, new design concepts can be quickly implemented and experimentally validated, overcoming challenges in modeling and simulation of phononic crystals.

2. Design and fabrication

As first proof-of-concept 3D design we extended the established 2D array of holes in a solid matrix to all three Cartesian directions. For a 15x15x15 cubic crystal with 1 mm lattice constant we utilize 800 µm holes yielding a minimum structure width of 100 µm at the edges (Fig. 1). The designs were fabricated with a high-resolution stereolithograpy printer (*Perfactory Micro HiRes*, EnvisionTEC Inc., USA), using a high-temperature acrylic polymer (*HTM140 M*, EnvisionTEC Inc.). We fabricated structures with 2 mm and 1 mm lattice constant, with excellent reproducibility even down to the smallest features (Fig. 2). To compare different designs and for optimal printing conditions, the experimental structures were encased in a container with 500 µm wall thickness. Two round mesa structures were added to the sides for similar boundary conditions when connecting acoustic transducers. Reference behavior is supplied by solid plastic blocks of the same dimensions and empty containers. The container designs also allows well defined filling with liquids for future measurements.

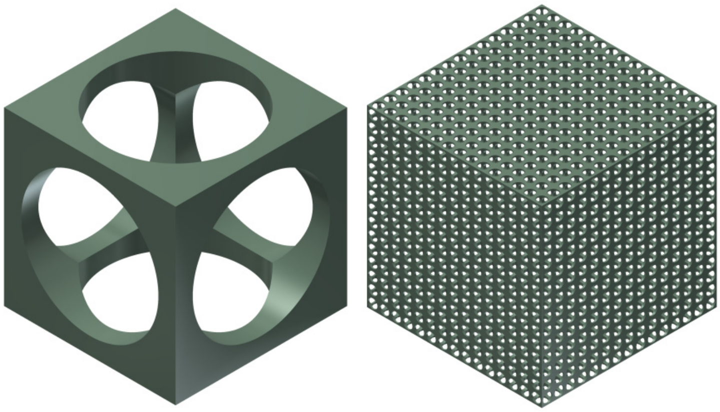

Fig. 1. Design of 3D phononic crystal: unit cell (left) and 15x15x15 lattice (right) using 800 µm holes in all three Cartesian directions with 1 mm lattice constant and minimum structure width of 100 µm.

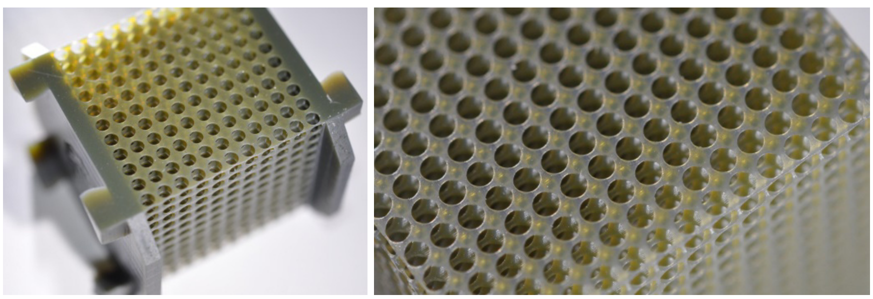

Fig. 2. Photographs of stereolithograpically fabricated 3D phononic crystals with 2 mm lattice constant (left) and 1 mm lattice constant (right).

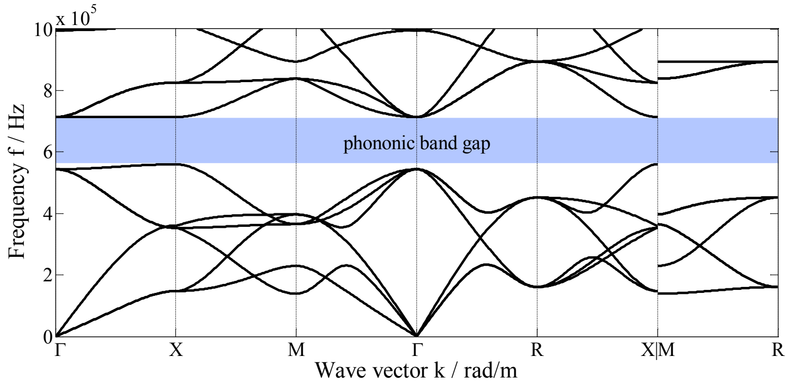

Fig. 3. Band structure of acoustic modes within first cubic Brillouin zone, validating band gap around 600 kHz, calculated for 1 mm unit cell of acrylic plastic corresponding to Fig. 1.

Using finite element eigenmode analysis of the unit cell with infinite periodicity we simulated the possible acoustic modes within the first cubic Brillouin zone. The calculated acoustic band structure of our 3D crystal design confirms a band gap around 600 kHz (Fig. 3). The simulation results are strongly dependent on the material. The acoustic velocity of acrylic plastic is around 2000 and 1000 m/s for longitudinal and shear vibrations, respectively, leading to an estimated band gap starting in the high hundred kHz range. Although the exact material properties (density, elastic coefficients) of the printed plastic are unknown, with rapid prototyping we can easily achieve experimental result and correlate those with the model.

3. Results and discussion

The transmission between two acoustic transducers (*PIC255*, Ø10x0.2 mm, PI Ceramic GmbH, Germany) at opposite sides of the samples was measured using a vector network analyzer (*ZVRE*, Rhode&Schwarz, Germany). The spectral characteristic of the piezo transducers shows shear mode resonances at 200 and 500 kHz, which are damped and shifted when attached to a sample, and a thickness mode around 10 MHz (Fig. 4). As reference we measured transmission through a solid plastic block with the same outer dimensions. The results indicate a uniform decrease in transmission and a suppression of acoustic shear modes above 300 kHz, with up to -60 dB damping compared to a solid block (Fig. 5). Especially the modes evident at 500 and 800 kHz for the solid block are not transmitted through the phononic crystal at all, with an additional decrease above 1 MHz.

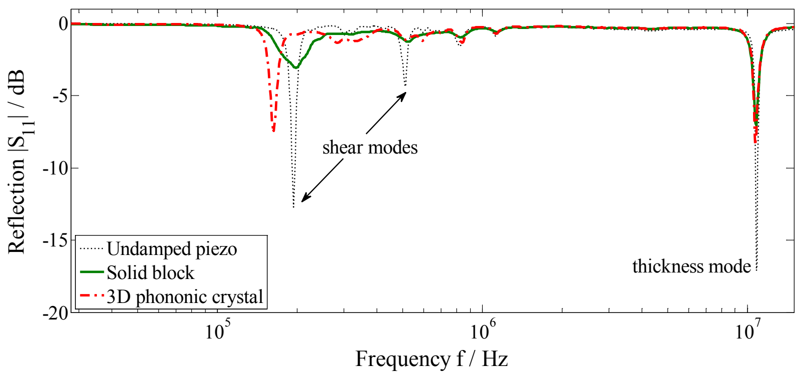

Fig. 4. Reflection spectrum of piezo, with characteristic shear resonances at 200 and 500 kHz and thickness mode around 10 MHz.

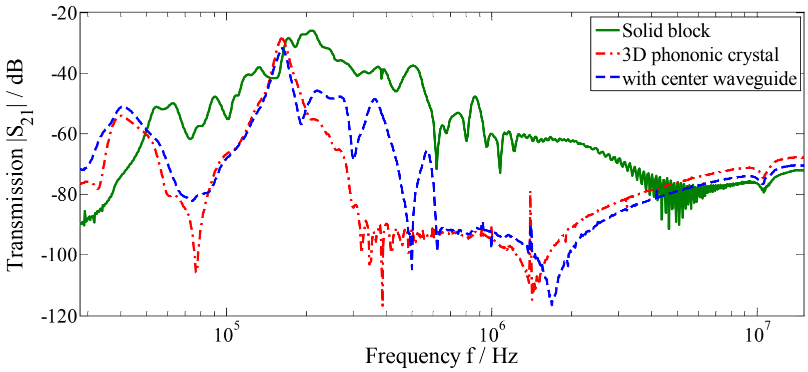

Fig. 5. Transmission spectrum between two piezos across 17 mm distance for a solid polymer block (solid green), a 15x15x15 phononic crystal with 1 mm lattice constant (dash-dotted red), and a similar phononic crystal with embedded solid waveguide in the center line of the 15x15x15 matrix (dashed blue).

On the other hand, a crystal with a solid waveguide in the center line of the 15x15x15 matrix shows acoustic transmission at unique frequencies within this bandgap. The longitudinal vibration mode around 10 MHz is transmitted in a similar fashion in all three samples as it is outside the bandgap region.

4. Conclusions

We have demonstrated the feasibility of using stereolithography printing to fabricate periodic 3D structures with high precision to achieve phononic crystal behavior. These devices exhibit a band gap, where acoustic wave transmission is strongly damped compared to solid or non-periodic elements. Theoretically calculated band gap behavior has been verified by experimental results for shear wave transmission. These results validate the concept of rapid prototyping of 3D phononic crystals, addressing complex challenges such as polymer material properties uncertainty and 3D short range and long range accuracy. This allows quick verification of novel designs without requiring extensive modeling and simulation.

In ongoing work we are validating phononic behavior for different designs in a wider frequency range for both longitudinal and shear wave transmission. Additionally, the influence of a filling medium is being investigated, leading to applications as fluidic sensor systems for possible integration in microfluidic devices.

References

[1] M.M. Sigalas and E.N. Economou, Elastic and acoustic wave band structure, *J. Sound and Vibrations* 158 (1992) 377–382.
[2] M.S. Kushwaha, P. Halevi, G. Martinez, L. Dobrzynski, and B. Djafai-Rouhani, Theory of acoustic band structure of periodic composites, *Phys. Rev. B* 49 (1994) 2313–2322.
[3] X. Zhang and Z. Liu, Negative refraction of acoustic waves in two-dimensional phononic crystals, *Appl. Phys. Letters* 85 (2004) 341–343.
[4] R. Lucklum and J. Li, Phononic crystals for liquid sensor applications, *Meas. Sci. Technol.* 20 (2009) 124014.
[5] P.E. Hopkins, C.M. Reinke, M.F. Su, R.H. Olsson, III, E.A. Shaner, Z.C. Leseman, J.R. Serrano, L.M. Phinney, and I. El-Kady, Reduction in the thermal conductivity of single crystalline silicon by phononic crystal patterning, *Nano Letters* 11 (2011) 107–112.
[6] M. Vaezi, H. Seitz, and S. Yang, A review on 3D micro-additive manufacturing technologies, *Int. J. Adv. Manuf. Technol.* 67 (2013) 1721–1754.
[7] C. Sun, N. Fang, D.M. Wu, and X. Zhang, Projection micro-stereolithography using digital micro-mirror dynamic mask, *Sens. Actuators A* 121 (2005) 113–120.