ISSN 1392–1207. MECHANIKA. 2017 Volume 23(5): 769–773

Numerical Analysis of Microresonator Developed on the Basis of PZT Nanocomposite

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crossref http://dx.doi.org/10.5755/j01.mech.23.5.16308

1. Introduction

Microresonators have demonstrated great promise as fundamental building blocks for a variety of applications. Recent advances in nanofabrication technology offer the possibility of manufacturing microresonator devices with dimensions of the order of the optical wavelength in a variety of natural and artificial material systems. Integrated-circuit deposition, lithography and etching techniques are used in the fabrication process [1]. Microresonator is a device where a piezoelectric coating plays most important role in the design and operation of the element itself. Recent year's scientific researchers concentrated on fabrication and improvement of microresonators in different levels of components: design, electronic, mechanical and control levels. Up-to-date technologies allow reaching precise and sensitive design with good signal-to-noise ratio (SNR) [2], wide frequency range, simplified digital interface, etc. However, basic problem of these novel microresonators is the variation of its cross-section leading to a complicated assessment of the resonant frequency and its high sensitivity to surface processes (e.g. large surface area to mass ratio). Usage of piezoelectric materials in the design of microresonators requires low driving voltage and enables self sensing and self actuation. It may be designed in a compact structure and easily integrated in any electronic circuit.

Due to the ability of piezoelectric material to generate electrical signal it can be employed to measure natural frequency changes, where vibrometers and other indirect measurement methods are destructive and hardly can be used in-situ analysis. Moreover, piezoelectric layer allows to control parameters of microresonators, which could assure higher functionality and accuracy of micromechanical systems. Lead oxide based ferroelectrics, represented by lead zirconate titanate (Pb(Zr,TI)O3) or PZT [3,4], polyvinylidene fluoride (PVDF) films [5, 6] and zinc oxide (ZnO) films [7,8] are the three main materials used in most piezoelectric applications due to their high piezoelectric coefficients, very good flexibility and strong electromechanical coupling [9].

Microresonators can be implemented for such diverse applications as lasers, amplifiers, switches, mechanical filters, micromirror devices, optical add/drop (de)multiplexers (OADMs), switches, routers, logic gates, and artificial media [10]. Additionally, they can be adapted in a moulding process and biomedical applications.

Therefore, the aim of this paper is to create a novel microresonator with controllable parameters which could assure much higher functionality of microelectromechanical system. Design of the microresonator was developed taking into account the characteristics of created novel PZT nanocomposite [11] which would assure microresonators 'controllable parameters. It is planned that this microresonator will be able to work in different frequency range and will have a high quality factor *Q*.

2. Finite element model of microresonator

Copper disc of 15.94 mm diameter and 40 μm thickness was taken as the base of the microresonator (Fig. 1, element 1) and served as ground electrode for piezoelectric comb. The whole circumference of the disc was fixed. Piezoelectric comb structures of 2 mm width and thickness of 54 μm were created for the actuating (Fig. 1, element 3) and sensing purposes (Fig. 1, element 2). Meshed finite element model of microresonator in 3D Comsol Multiphysics environment is presented in Fig. 2.

Tetrahedral elements concluded the mesh for the structures' simulation. A mesh with 50172 degrees of freedom was constructed. All of the mesh parameter are presented in Table 1.

Table 1

Mesh parameters

Property	Value
Degrees of freedom	50172
Mesh points	2696
Elements	9062
Tetrahedral	9062
Boundary elements	5538
Triangular	5538
Edge elements	772
Vertex elements	71
Element quality	0.036
Element volume ratio	0.007

Simulation model consisted of copper and a novel PZT nanocomposite, which is able to work at low frequencies and to harvest energy or to cause deformations [11]. Compound of 20% polyvinyl butyral together with synthesised PZT powder, which has a high piezoelectric coefficient and permittivity, large dielectric constants and good conversion efficiency, was created. Polyvinylbutyral ables a strong binding and flexibility to the PZT material [11]. The base material, copper, was constrained from movement for better results depending only on the piezoelectric. The material properties could be found in Table 2.

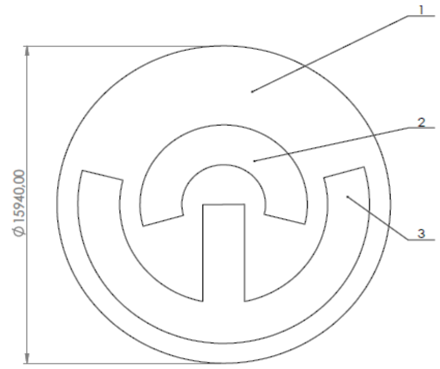


Fig. 1 Drawing of microresonator (measurements in micrometres)

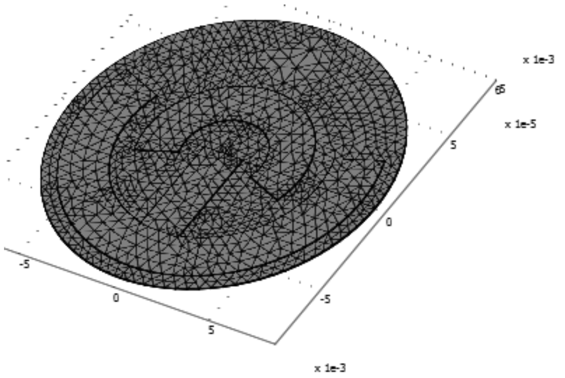


Fig. 2 Meshed finite element model of microresonator in 3D Comsol Multiphysics environment

Table 2

Material properties and boundary conditions

Properties	Copper	PZT nanocomposite
Young's modulus (*E*)	110 MPa	2 MPa
Density (ρ)	8700 kg/m^3	3900 kg/m^3
Poisson's ratio (v)	0.35	0.42

Eigen frequency solver in Comsol Multiphysics is based on finite elements to compute the closest values of Eigen frequencies to real world values. Finite element solver algorithm leads to generalized eigenvalue system:

$$(\lambda-\lambda_0)^2 EU-(\lambda-\lambda_0)DU+KU+N_F\Lambda=0, \qquad (1)$$

where E, D, K, N, N_F are the solution vector U_0, λ are the Eigenvalue, λ_0 is the linearization point.

3. Results and discussion

Eigen frequency analysis shows that 12 Eigen frequencies were ranged from 1105.49 to 11731.77 Hz. Therefore, the range of frequency from 1000 to 15000 Hz was selected for the frequency response analysis. Using the obtained Eigen frequencies, with the input voltage of 10 V the electrical response of the sensing electrode was simulated (Fig. 3). The highest electrical potentials were registered at 8150 and 13900 Hz. Fig. 4 represents the vibration form (left column) and distribution of electrical potential (right column) in the vibrating element.

From the received results it can be stated that the proposed microresonator works as a membrane, due to its small thickness. At 8150 Hz frequency the recorded electrical potential reached 2.2 V for the corresponding 10 V input. The electrode shows the same sign charge. The division of element into smaller segments is not needed as it produces maximum voltage. On the other hand, at 13900 Hz frequency it generates up to 3.2 V, but the sign of the generated electrical potential through all length of sensing electrode varies. Therefore, to fully maximize the generated voltage, the sensor has to be segmented further. As the highest results without segmentation were obtained at 8150 Hz frequency, this frequency was selected for further analysis. Increase of input voltage gives the result of linear increased output.

Also, presented microresonator could be updated by additional PZT nanocomposite element or whole layer of composite material. They allow controlling stiffness and resonant frequencies of microresonator what enables operation of the designed microresonator in different environments. In the future researches, it is planned for synthesis of lead free PZT to use calcium instead of plumbum. This material will be used for design of microresonator, which operates in biological environment.

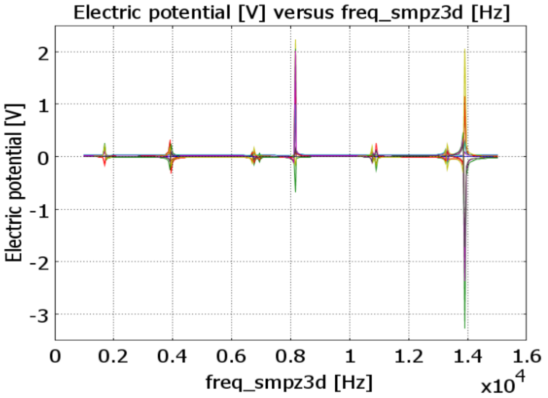
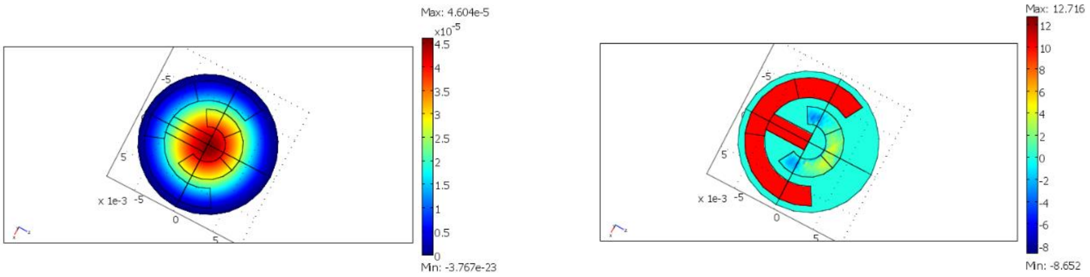
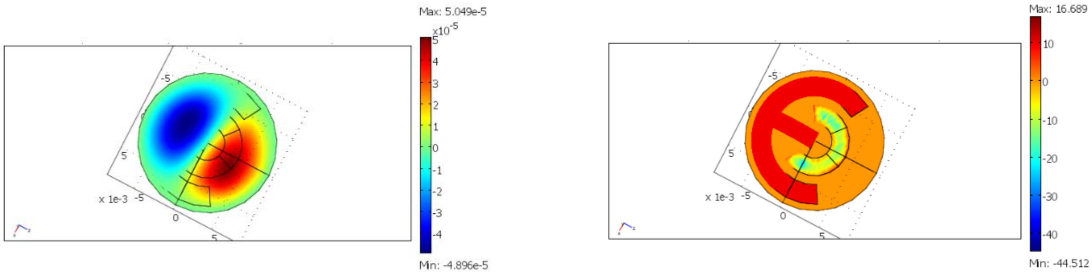


Fig. 3 Electrical potential generated by piezoelectric element at different points

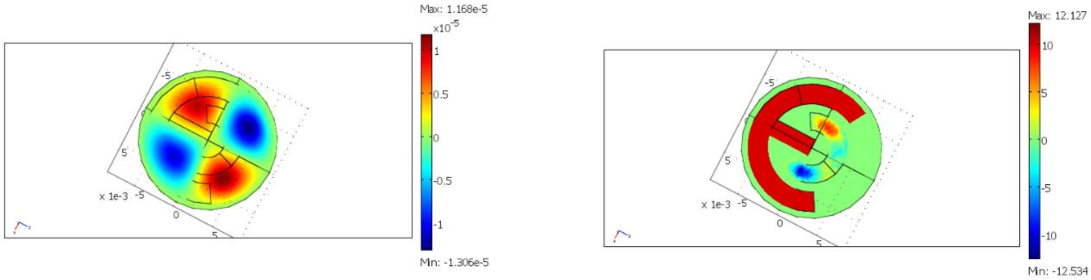
Another very important advantage of the developed microresonator is the possibility to form a periodical microstructure (Fig. 5) in PZT nanocomposite used for comb formation. Then system acquires the advantage of registration of electrical signal and diffraction efficiency changes simultaneously. Combination of electrical and optical measurement techniques increases accuracy of the sensing microresonator. Lamellar periodical microstructure (period – 4 μm and depth – 574 nm) was formed in PZT nanocomposite material using hot embossing technique at 100°C temperature, 5 atm pressure and 10 s of holding time.



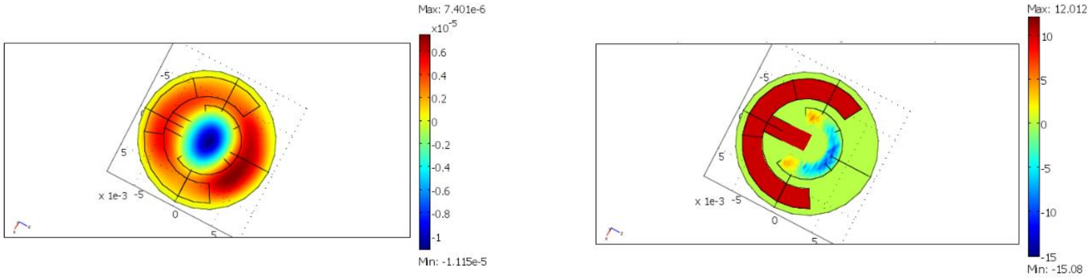
1710 Hz



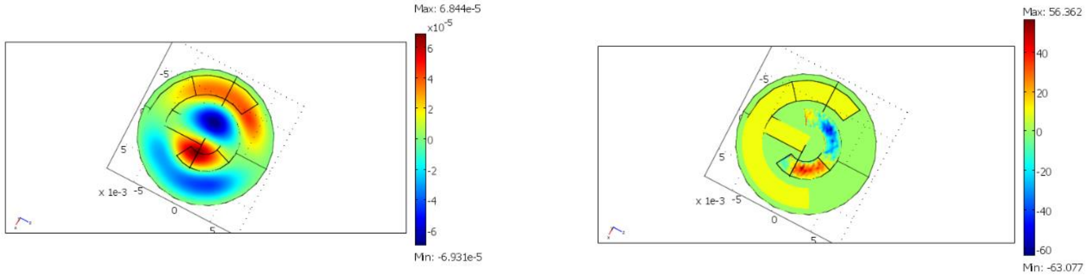
3924 Hz



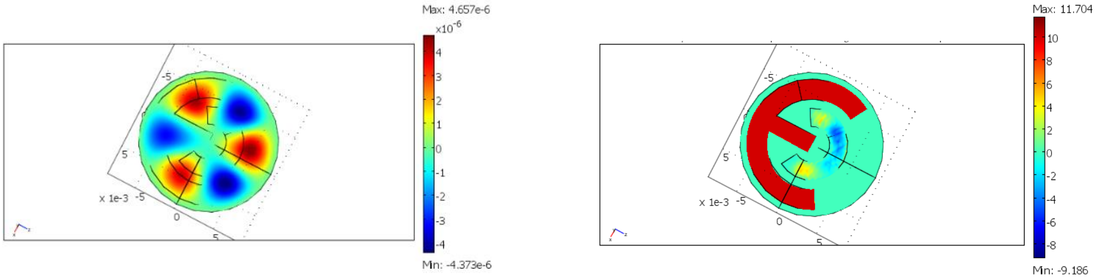
6730 Hz



8150 Hz



10770 Hz



13900 Hz

Fig. 4 Vibration form (left column) and distribution of electrical potential (right column) of microresonator at different excitation frequencies

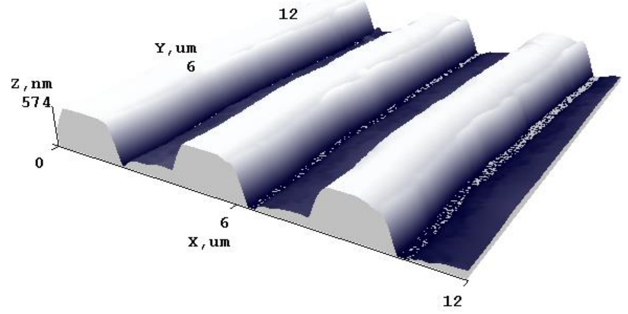


Fig. 5 Periodical microstructure formed in a PZT nanocomposite

PZT nanocomposite material, used for formation of periodical microstructure, allows controlling not only mechanical properties of microresonator but optical parameters too. Example of reflected diffraction efficiency of first order diffraction maxima and its diffraction angle dependence on period changes of microstructure caused by electrical signal is presented in Fig. 6. During this analysis the incident laser light (wavelength 632.8 nm) were cast at 40º angle to the top surface of nickel coated periodical microstructure integrated into PZT nanocomposite. Results have shown that the period changes by 10 nm leads to changes of diffraction efficiency to about 0.1% and diffraction angle about 0.15º.

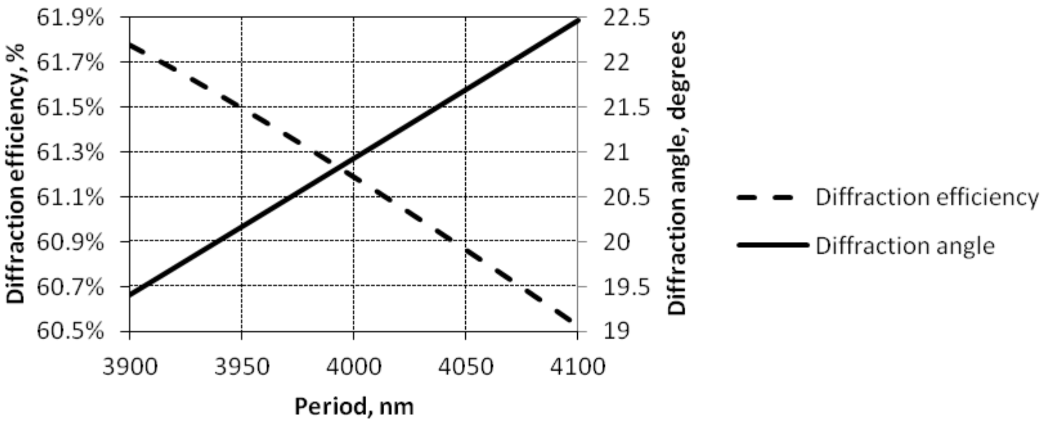


Fig. 6 Diffraction efficiency and diffraction angle versus period of periodical microstructure

Created microresonator with controllable mechanical and optical parameters assures much higher functionality of microelectromechanical systems.

4. Conclusions

New type microresonator with electro-optic feedback was proposed. Experimental approach of new type microresonator with multilayer element was carried out. Calculated Eigen frequencies of proposed microresonator have been registered in the range of 1105.49 to 11731.77 Hz. Frequency response have shown that the highest amplitude of electrical potential can be achieved at 8150 and 13900 Hz. The electrical potential value reaches 3.2 V.

Adding PZT nanocomposite layer with formed periodical microstructure to the proposed microresonator increases its accuracy due to the possibility to use both electrical and optical measurement techniques. Added nanocomposite allows to control not only mechanical properties of microresonator, but optical parameters too. Change of period by 10 nm followed 0.1% diffraction efficiency change and 0.15° shift of diffraction angle.

Created microresonator with controllable parameters will allow it to integrate in various MEMS systems: high stability electrical oscillation sources (generators); electric filters; in sensors for testing proteins, viruses, chemical species and etc.; in energy harvesting and etc.

Acknowledgments

This research was funded by a grant (No. MIP-081/2015) from the Research Council of Lithuania.

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NUMERICAL ANALYSIS OF MICRORESONATOR DEVELOPED ON THE BASIS OF PZT NANOCOMPOSITE

Summary

Microresonators are fundamental components integrated in hosts of MEMS applications: safety and stability systems, biometric sensors, switches, mechanical filters, micromirror devices, material characterization, gyroscopes, etc. Microresonator is a device where a piezoelectric coating plays most important role in the design and operation of the element itself. Also piezoelectric layer allows to create a novel microresonator with controllable parameters, which could assure much higher functionality of microelectromechanical systems. Forming periodical microstructure in the nanocomposite material allows to involve two measurement types for better accuracy: electrical and optical. Finite element model in Comsol Multiphysics environment was created. Numerical analysis of microresonator developed on the basis of PZT nanocomposite is presented. Electrical potential of 2.2 V for the corresponding 10 V input was recorded. Dependency of diffraction efficiency and diffraction angle to period changes were investigated.

Keywords: microresonator, piezoelectric material, periodical microstructure, diffraction efficiency.

Received February 28, 2016
Accepted October 13, 2017