DYNAMIC ANALYSIS OF PHOTONIC CRYSTAL-BASED MECHANOCHROMIC OPTICAL MODULATORS

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1 INTRODUCTION

Microresonators and oscillators based on MEMS (micro-electromechanical system) structures play an important role in microwave and optical communications [1], [2]. Among the main building blocks in the MEMS are bulk- or surface-micromachined microcantilevers, diaphragms and bridge structures (clamped-clamped beams), see Fig. 1. The operation of these components is typically based on their deflection/vibration, which is further used for tuning electrical, magnetical or optical signals.

Among the proposed deflection readout methods based on conversion to electrical signals the most often used are piezoresistive (readout elements are monolithically built into the structure, typically in the form of a Wheatstone bridge), capacitive (often met in communications) and inductive.

Among the optical readout methods the prior art includes free-space light beam methods like beam deflection by the moving part of the MEMS building block (e.g. cantilever tip, diaphragm or bridge middle) or interference readout. None of these methods utilizes solid-state integration with the building block.

The paper [3] describes a sensing structure for MEMS modulators based on photonic crystal optical waveguides. The use of photonic crystals for deflection sensing was first proposed in [4]. Photonic crystals (photonic bandgap materials, PBG) are very convenient for this purpose because of a marked mechanochromic effect (change of transmitted or reflected wavelength due to applied stress) which itself is a consequence of an extremely high dispersion of their optical coefficients. Generally, tunable PBG structures are one of the most intensively researched topics within the photonic crystal field because of its interest for telecommunications – where they can be utilized for many different active and passive all-optical components with a very high degree of integration [2], [5]. Various external variables are utilized to achieve tunability of PBG properties, among others electrical and magnetic fields, optical fields, mechanical force, etc.

The mechanochromic effect (tuning of photonic crystal spectral transmission or reflection by mechanical force) is especially convenient for the readout of MEMS building block deflection by photonic crystals. It makes use of the changes of photonic bandgap in a stressed/strained structures due to deformation of the unit cell, as well as of the photoelastic changes of its refractive index.

![Fig. 1. Main mechanical building blocks for MEMS optical modulators (denoted by dark red). a) micromachined diaphragm; b) bridge structure; c) microcantilever](image-url)
The chosen approach to perform the modal analysis of our MEMS was to use full 3D finite element modeling. The starting point were standard dimensions of the MEMS building blocks routinely produced in the IHTM and then variations were performed in order to assert the directions for possible optimization.

II METHODOLOGY

Vibration characteristics (natural frequency and mode shapes) were determined by FEM modal analysis. Transient analysis, spectrum and harmonic analysis were not performed.

The classical eigenvalue problem was solved

\[ K\phi_i = \omega_i^2 M\phi_i, \]

where \( K \) is the stiffness matrix, \( M \) is the mass matrix, \( \phi_i \) is the eigenvector of mode shape, and \( \omega_i \) the eigenvalue of the natural circular frequency.

The Block Lanczos method was used to solve eq. (1). Only linear and constant-temperature behavior was taken into account in modal analysis, and anisotropy of material properties (Si) was taken into account.

The modal analysis was performed using the finite element modeling software Ansys®. The block SOLID64 was used (8 nodes, 3 degrees of freedom). Anisotropy of silicon was taken into account, while damping effects of medium were neglected. The mesh had typically 50-100 divisions per individual axis (depending on the particular structure).

III NUMERICAL RESULTS

The first analyzed building block is diaphragm, i.e. a bulk-micromachined silicon structure whose width and length are much larger than its thickness. Typically these are produced in rectangular or circular shape, flat or with a boss in the middle, fixed along all sides or only at the corners. Our calculations were done for a square flat diaphragm fixed along all sides, the structure routinely fabricated at the IHTM by bulk-micromaching and used for sensor structures.

Fig. 2 shows the dependence of diaphragm resonant frequency on its thickness. The diaphragm side was 2 \( \mu \)m. A linear dependence was obtained and the values of the resonant frequency were relatively low, below 1 MHz, which was a consequence of relatively large diaphragm area. The reason we chose such dimensions is that they are standard for our micromachined diaphragms.

Further we calculated the resonant frequency of vibrating diaphragm in dependence on the side length. For the thickness we assumed 20 \( \mu \)m, again because this is the typical value for our micromachined diaphragms. Fig. 3 shows that large resonant frequencies are obtainable for thicker and smaller structures; however, very thin diaphragms are difficult to practically implement.

Our next calculation cycle was devoted to the analysis of the bridge structure (length much larger than either thickness or width, with larger than thickness, both ends clamped). A similar geometry in combination with photonic crystal readout was proposed in [5] for the use in telecommunication applications. Such structures are particularly convenient in combination with quasi-1D PBG "bridges" [3].

Fig. 2. Zeroth resonant frequency for a square Si diaphragm in dependence on its thickness

Fig. 3. Zeroth resonant frequency for a square Si diaphragm in dependence on the side length

Fig. 4. Zeroth resonant frequency for a bridge (clamped-clamped) structure in dependence on the beam thickness
Fig. 4 shows the dependence of the resonant frequency on the beam thickness for a microbridge structure 200 µm long and 50 µm wide. The zero resonant frequency in dependence on the microbridge length is shown in Fig. 5.

![Resonant frequency vs beam length](image1)

**Fig. 5.** Zeroth resonant frequency for a bridge (clamped-clamped) structure in dependence on the bridge length

Probably one of the most often used MEMS building blocks are microcantilevers. Variations of these structures include different shapes of the cantilever tip (pointed, flat, rounded), double or even multiple beams with various geometries, and use of different materials and material combinations (e.g. bimaterial or bimetal structures).

The FEM calculation results for the modal behavior of these structures are shown in Figs 6-8.

![Resonant frequency vs cantilever thickness](image2)

**Fig. 6.** Zeroth resonant frequency for a microcantilever in dependence on the beam thickness

Fig. 6 shows the resonant frequency in dependence on the cantilever thickness, and Fig. 7 depicts resonant frequency versus cantilever length. A comparison with bridge of similar dimensions shows that the frequencies are roughly twice lower, which is the consequence of the bridge being clamped at both its ends.

![Resonant frequency vs cantilever length](image3)

**Fig. 7.** Zeroth resonant frequency for a microcantilever in dependence on the microcantilever length

Fig. 8 shows the in-plane stress versus cantilever thickness in the point of maximum stress (near the attachment point). It is seen that the stress decreases with the cantilever thickness, contrary to the behavior of the resonant frequency. This is actually valid for all MEMS building blocks. Since it is usually necessary to have simultaneously larger stress and higher resonant frequencies, it is necessary to choose optimum dimensions for each particular application.

![In-plane stress vs cantilever thickness](image4)

**Fig. 8.** Dependence of the maximum in-plane stress (in proximal part of the structure) on microcantilever thickness for various cantilever lengths

IV CONCLUSIONS

A finite element analysis of three basic building blocks of MEMS-based microoscillators was performed (diaphragm, bridge, cantilever). The results show that larger resonant frequencies are obtained if the ratio between the length, the thickness and the width of a given building blocks is smaller (i.e. thicker diaphragms, shorter bridges and cantilevers, etc.)

The calculation results show that megahertz resonant frequencies are readily obtainable even with structures whose dimensions are of the order of hundreds of micrometers. Simple extrapolation of the presented results confirms the quotes from literature that NEMS (nanoelectromechanical) structures can reach mechanical frequencies of the order of GHz.

It can be seen e.g. by comparing Fig. 7 and Fig. 8 that the requirements for maximum operating frequency and maximum stress are contradictory, which calls for careful optimization in dependence on the particular application of the oscillator.
Acknowledgement: The authors wish to thank Dr. Aleksandar Vujanic from IFWT, Austria for the use of the FEM software package Ansys®. This work has been partially supported by the Serbian Ministry of Science, Technologies and Development within the framework of the project IT.1.04.0062.B.

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Abstract: We performed analysis of modal behavior of the main microsystem building blocks utilized in telecommunications as modulators. The analysis is dedicated to MEMS (microelectromechanical system) structures with 1D or 2D photonic crystal waveguides integrated with mechanical modulator element and utilizing mechanochromic effect to obtain amplitude or frequency modulation. Full 3D finite element modeling was used to calculate stress distribution and resonant frequencies. Three basic building blocks were analyzed, micromachined diaphragm, microbridge and microcantilever, while the basic material was silicon. The results show that for the structure dimensions of the order of tens of micrometers the achievable frequencies reach tens of megahertz.

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