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Mechanical tuning of two-dimensional photonic crystal cavity by micro Electro mechanical flexures

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Abstract

A nano-displacement sensing method for micro-opto-electro-mechanical-systems (MOEMS) is proposed. The method is based on a square lattice photonic crystal (PC) made of dielectric silicon posts, mounted on a micro mechanical flexure. The flexure is fixed at one end and is free to move at the other, to enable elastic deformations that, by being transferred to the photonic crystal array, modify its periodicity and the pertinent transmission characteristics. A missing-post defect is deliberately introduced in the photonic crystal, opening a narrow pass band within the band gap. The pass band wavelength is sensitive to dilatation of the micro mechanical flexure. The flexure Poisson ratio (PR) can be designed according to specific requirements to gain desired sensitivity. Simulations show high sensitivity of 12.3 nm band pass shift for every 1% flexure strain for flexure of a material with a Poisson ratio of −1. An inverted honeycomb based micro-electro-mechanical-systems (MEMS) flexure, with a Poisson ratio of −1, was fabricated in silicon and characterized.

Keywords: Photonic crystal; Tuning; Band gap; Band pass; MEMS; Honeycomb

1. Introduction

Micro-electro-mechanical-systems (MEMS) sensors occasionally rely upon precise measurement of micro-displacements of a sub-millimeter flexible component. Commonly employed methods include measurements of the charge on a variable capacitor, the resistance of piezoresistor and even tunneling of current through an air gap. Optical sensing technologies exhibit several inherent advantages such as environmental ruggedness, passivity, resistance to electromagnetic interference, lightweight, small size, low power consumption, wide bandwidth and high sensitivity (up to 1/90 μm^{-1}) [1].

Minimization and integration of large-scale optical sensors with micro-opto-electro-mechanical-systems (MOEMS) devices represents a challenge. Recently integration in waveguides and optical fibers for various pressure [2–5] and acceleration [1] detectors was studied. The use of a photonic crystal (PC) for microdisplacement measurements has been proposed—this would make use of two PC waveguides where one is mounted on a moving part and the other fixed to a stationary substrate [6,7].

The band gap of a PC has already been manipulated by changing its refraction index by varying its temperature [8], and by applying an electric [9,10] or magnetic field [11]. The PC band gap is also very sensitive to mechanical deformations [12–15]. Sensitivity can be further increased by adding a micro-cavity, by deliberately introducing a local defect in the center of the PC lattice, in the form of a missing post, which creates a narrow band pass in the PC band gap. The band pass frequency largely depends on the micro-cavity dimensions and is extremely sensitive to changes in the cavity size and shape [16].

Flexures, based on honeycomb structures, can be designed for a specific Poisson ratio (PR) with positive or negative values. The nature of positive PR materials is that the material shrinks in a direction perpendicular to an externally exerted tension, creating a highly distorted unit cell, whereas negative Poisson ratio (NPR) materials expand in the direction perpendicular to externally exerted tension, thus increasing the unit cell area and volume. An NPR flexure based on an inverted honeycomb structure with unit cell dimensions of $a \times b$ is illustrated in Fig. 1. A material with PR of −1 shows the same expansion in the tensioned and perpendicular directions, maintaining an undistorted unit cell.

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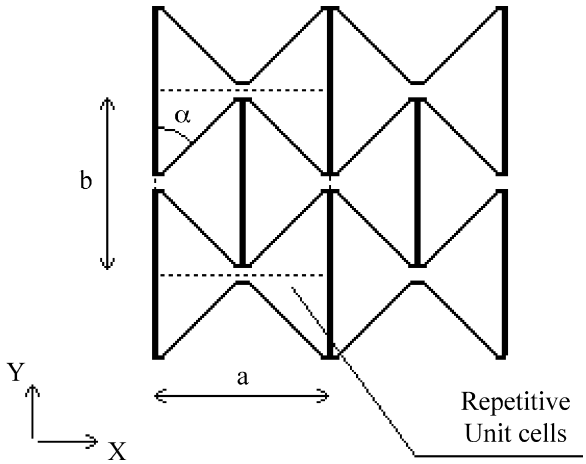

Fig. 1. A unit cell geometry of an NPR flexure based on an inverted honeycomb structure.

These types of flexures are suitable for MEMS since they can be fabricated using standard MEMS micro machining techniques [17] and can be deflected by relatively small forces.

Designing the flexure to a specific PR for small deflections involve only geometrical considerations and the PR is given by the expression:

$$\nu = -\frac{1}{\mu \ \tan\alpha} \tag{1}$$

where $\mu = b/a$ is the aspect ratio of the unit cell and α is the angle between the inclined beams and the vertical links [18,19] (see Fig. 1). Structures implemented in micro devices can undergo large deflections without damage. Under these conditions the small linear deflection description of the honeycomb structure is no longer sufficient to describe the changes in the PR value and large nonlinear deflection models should be used [20].

Mechanical tuning of a lattice parameter of a two-dimensional PC using MEMS flexure has never been introduced. The objective of this article is to present a method for mechanical tuning of lattice parameter of a two-dimensional PC using MEMS flexure. We also determine the effect of the flexure's PR on the device sensitivity, present design considerations for MEMS flexures under large deflections and show the fabrication and mechanical characterization of an NPR flexure with a PR of −1.

2. Model and simulations

The proposed sensing method is based on a square PC lattice mounted onto a MEMS flexure that is based on a honeycomb structure. The PC posts are mounted on platforms attached to the flexure and mimic its repetitive unit cell dimensions as illustrated in Fig. 2a. The MEMS flexure is fixed at one end and free to move at the other. Applying an external force in *X* direction at the free end causes mechanical deflections of the MEMS flexure that are being transferred to the PC unit cell as shown in Fig. 2b.

The deflections of the PC unit cell are highly dependent on the PR of the MEMS flexure. In the case of a large positive PR MEMS flexure, the PC unit cell will undergo large distortions, expanding in the direction of exerted tension and rapidly shrinking in the perpendicular direction, reducing its area. In a MEMS flexure with PR of −1, the PC unit cell will similarly expand in both directions, thus maintaining a rectangular shape. In the case where the PR is smaller then −1, the tensed PC unit cell will experience distortions that will increase its area.

The PC in our example is made of 8 × 8-unit cells with periodicity of 0.6 μm. The lattice is built of circular silicon posts (dielectric constant $\varepsilon/\varepsilon_0 = 11.7$), 0.228 μm in diameter surrounded by air. Removing one post at the center of the lattice creates a micro-cavity with a resonant frequency that opens a band pass in the original band gap as illustrated in Fig. 3.

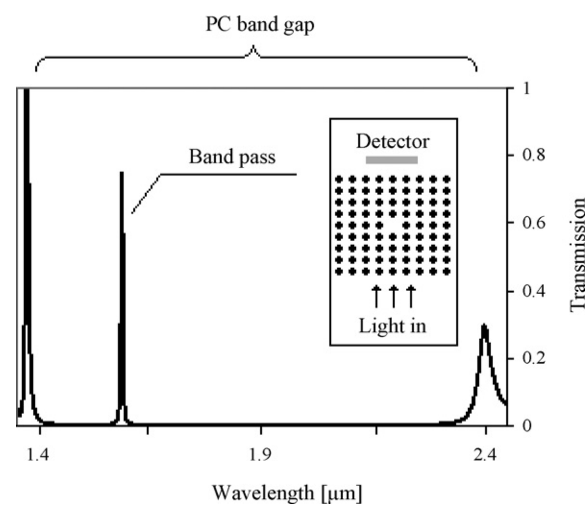

Fig. 3. Schematic drawing of the proposed photonic crystal cavity and its band pass.

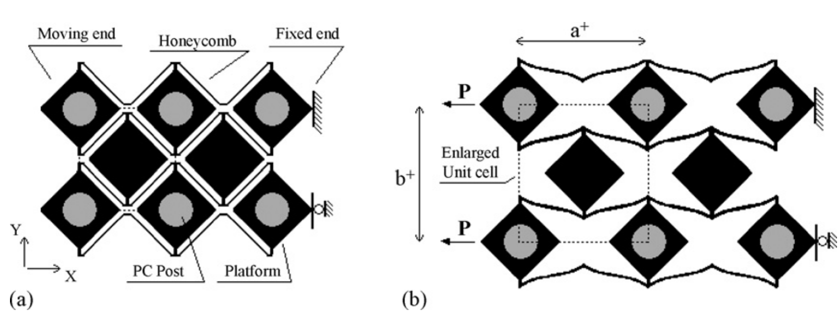

Fig. 2. NPR flexure with Poisson ratio of $\nu = -1$ carrying a rectangular PC lattice (a) before deflection and (b) after deflection.

The PC is illuminated by broadband light from one end, reaching a photodetector with spectral resolution at the other end. Most of the incident spectrum is reflected back by the PC band gap' only the pass band wavelength reaches the detector. The sensitivity can be defined as the ratio between the change in pass band frequency and the corresponding deformation (strain) of the MEMS flexure along the tensioned direction.

We now present numerical simulation results, where the pass band frequency is analyzed as a function of the flexure strains in the *X* direction. Simulations were performed for a PC mounted on various PR flexures. We used a 2D numerical code based on the Multifilament Current model [21] to compute the full solution of the propagation/scattering problem, and then to find the energy distribution and light intensity exiting the PC for different wavelengths. The Multifilament Current model is suited for numerical simulation of problems associated with resonating elements under time-harmonic excitation with high accuracy and simplicity.

3. Optical simulations results

Before any deflection occurs, simulations show that the band gap of the PC is situated between 1.39 and 2.4 μm wavelength and the micro-cavity creates an extremely narrow band pass at its resonant wavelength of 1.57 μm. Expansion of the PC unit cell increases the band pass wavelength up to 1.78 μm at a unit cell size of 0.70 μm × 0.70 μm, which corresponds to a mechanical strain of 0.1667.

Devices with different PRs were simulated, and were found to have different sensitivities (Fig. 4), where the sensitivity, as defined previously, is the curve slope of the graphs. A linear relation is shown between the PC micro-cavity pass band wavelength and the strains of the MEMS flexure for each PR. As can be deduced from the graphs, almost no sensitivity is shown with flexure with PR equals to 0.7. High sensitivity is achieved by using MEMS flexures with large positive and negative PR values. Large NPR values show positive shift in the pass band wavelength with flexure dilatation whereas large positive PR flexures show a negative shift. For example, a device with NPR of −2 shows high sensitivity of 1.82 μm where the pass band wavelength shifts to 1.755 μm for mechanical strains of 0.1. A device with PR of 2 shows sensitivity of 0.83 μm with the pass band wavelength decreased with the flexure strain (which can be defined as a negative sensitivity). In this case the pass band wavelength decreases to 1.49 μm for mechanical strains of 0.1.

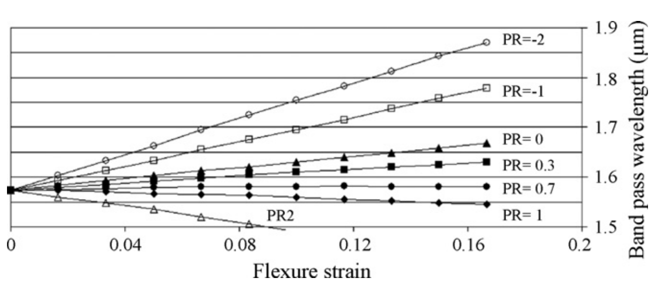

Fig. 4. Band pass wavelength dependence on the unit cell deformations for different MEMS flexure PR.

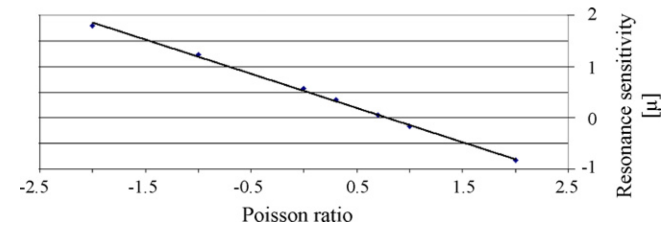

Fig. 5. Sensitivities of the band pass wavelength for different PR flexures.

Fig. 5 shows the linear dependence of the sensitivity as a function of the different flexure's PR.

4. Mechanical flexure simulation results

In cases where there are large deflections of the structure, the geometric nonlinearity of the beams plays an important role in the structural behavior. In contrast to the linear model for small deflections, the PR becomes strain dependent. As shown in the optical simulations, changes in the flexure's PR cause changes in the device sensitivity, thus controlling the PR is important. When the extensibility of the beam's axis is considered, it was found that, when tensed in *X* direction (see Fig. 1), the strain PR-dependence is not monotonic and has a minimum as shown in Fig. 6. Around this minimum point, the PR is practically insensitive to strains and working around this point will maintain constant optical sensitivity of the PC structure. This minimum point occurs due to influence of the beam's axis extensibility on the PR, which is opposite to the influence of the beam bending. At small deflections, the beam bending is dominant while decreasing the PR whereas the extensibility of the beam axis manifests itself mainly at large deflections, increasing the flexure's PR.

We divide the PR graph in Fig. 6 into three main zones corresponding to the three stages of deformation. In the initial stage of deformation the deflections are small and the PR can be calculated with a satisfactory accuracy using the linear model. In the second stage, as the deflections grow, the bending

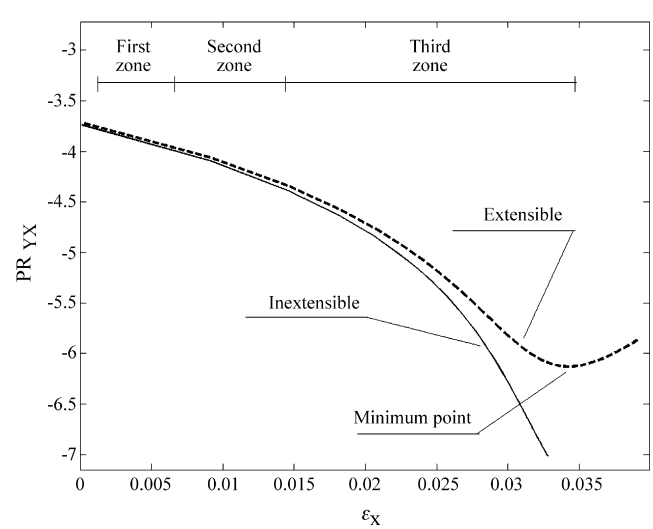

Fig. 6. The PR of the structure ($\alpha = 75°$, $\tilde{r} = 0.012$) described by the inextensible and extensible elastica models. The structure subject to the tension in *X* direction.

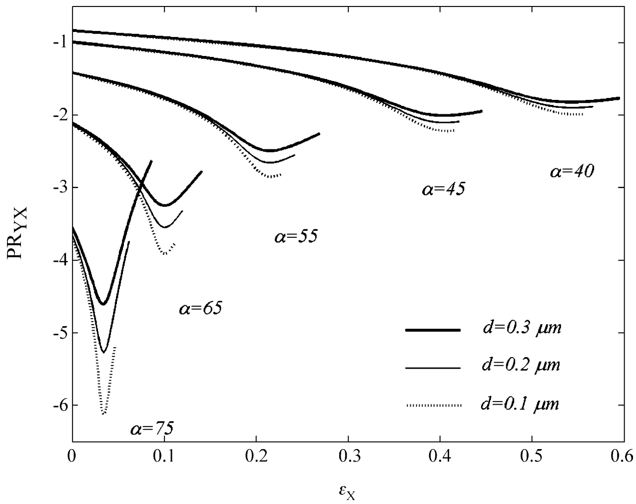

Fig. 7. The PR of a square unit cell $C_H = C_V = 10\ \mu m$ for different inclined beam angles α and beam width d.

of the inclined beam leads to a decrease in the PR. This can be explained by considering the linearized honeycomb structure in an actual deformed state using the small deformation model, which cause decreasing in the PR with the reduction of the angle α. At large deformations, as was already mentioned, the bending of the beam has minor contribution to the cell deformation, which the structure's PR increases mainly due to the extension of the beam axis. The reason is that at this stage the small increment in deflection in the *Y* direction requires a large increment in the loading since the force applied in *X* direction produces vanishing bending moment in the almost straightened beam. On the other hand, the increasing loading leads to the extension of the beam axis and consequently elongation of the cell in the *X* direction. It may be therefore concluded that at this stage the extensibility of the beam axis results in increased PR with loading.

Designing a honeycomb based structure under large deflections, where the PR is strain dependent, to a desired PR at a desired deflection, can be done by changing the inclination angle (α) and beams width (d). The inclination angle defines the strain that the minimum PR appears and the beams width define the PR of this minimum point as shown in Fig. 7.

5. Fabrication of an NPR structure

We now present the fabrication and characterization of an NPR structure with PR of −1 under small deflections. A large-scale silicon NPR MEMS structure was fabricated on an SOI wafer. The structure unit cell dimensions are 200 μm × 200 μm. The beam cross-section dimensions are 3 μm width and 30 μm height. The fabrication process used two masks, one for the front side defining the flexure geometry and the other for backside releasing.

A micrograph image of an example structure prior to any deformation is presented in Fig. 8a. Fig. 8b shows the same structure after small deformation with an illustration of the unit cell before and after the deformation. Fig. 9 shows a zoom micrograph image of a unit cell of the inverted honeycomb structure of Fig. 8 to better illustrate the details.

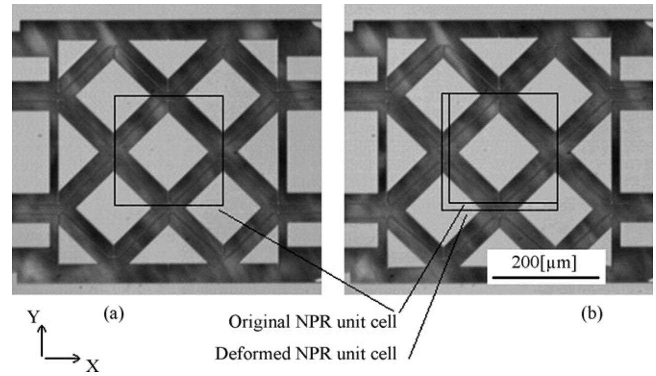

Fig. 8. An example NPR structure with PR of −1. The rectangular represents the unit cell dimension (a) before deflection and (b) after deflection.

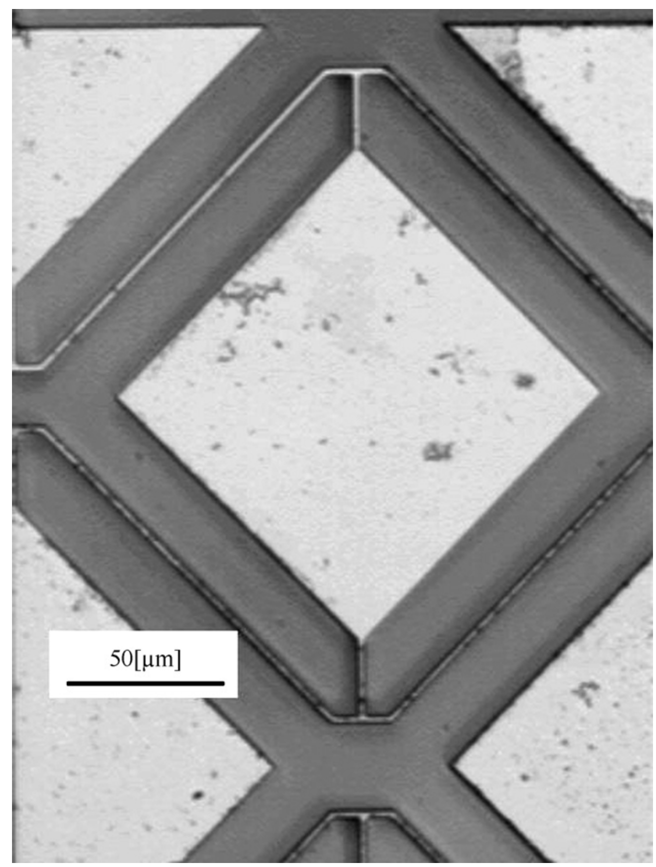

Fig. 9. Zoom image of one unit cell of Fig. 8.

The structure is deformed with a comb-drive actuator providing tension in the '*X*' direction. As one can see in Fig. 8b, the unit cell expands similarly in both directions, maintaining an un-deformed rectangular shape during deflection.

6. Discussion

The results presented can be effectively used for designing a PC nano-displacement sensor with desired properties. For devices for inertial measurements that require high sensitivity, a MEMS flexure with NPR smaller then −2 can be used. Devices with no sensitivity might also be required for implementations where mechanical deflections should not affect the PC optical properties. In such cases one should use a MEMS flexure with PR = 0.7. A linear relation between the MEMS flexure PR and the sensitivity of the device was demonstrated. This relation allow for easy design and adjustment for specific device requirements.

Combining the band pass wavelength from two PCs mounted on two different honeycomb flexures each with different PR can perform a differential measurement. This measurement results in intensity beats with frequency that equals to $f_b = \text{abs}\{f_f(\lambda_f - \lambda_d)/(\lambda_f)\}$ where f_b is the beats frequency arising, f_f is the band pass frequency from one of the deflected PCs and λ_d and λ_f are the band pass wavelengths from the two deflected PCs. Using such differential measurement may even increase the sensitivity of the device.

7. Conclusions

The optical characteristics of a PC can be tuned mechanically for integration with MOEMS sensors by mounting it on a micro mechanical flexure. The elastic deformations of the flexure are being transferred to the PC modifying its periodicity and the pertinent transmission characteristics. The sensitivity of the PC band pass wavelength to mechanical dilatation is dependent on the flexure's PR. Simulations show sensitivity of 18.2 nm band pass shift for every 1% flexure strain for flexure of a material with a Poisson ratio of −2 and sensitivity of 8.3 nm band pass shift for every 1% flexure strain for flexure of a material with a Poisson ratio of 2.

This method can be used for integrating PC with MOEMS devices for optical sensing. The sensor is extremely small, its sensitivity can be easily designed by the MEMS flexure PR and it can be monolithically integrated into a MOEMS sensor. A MEMS flexure with PR of −1, for small deflections, was fabricated and maintenance of its un-deformed shape during deflection was demonstrated.

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Biographies

Oren Levy has received his BSc degree in mechanical engineering in 1990 and his MSc degree in industrial engineering and management in 1995, both from the Ben-Gurion University in Israel. From 1990 to 2003, he worked in several high tech companies and startups in Israel and since 2003 he is a PhD student at the Department of Solid Mechanics, Materials and Systems at the Tel Aviv University in Israel. His research subject is "Study of micro-displacement optical sensing methods for integrated MOEMS", supervised by prof. Menachem Nathan from the Department of Physical Electronics, School of Electrical Engineering and Dr Ilan Gorldfarb from the Department of Solid Mechanics, Materials and Systems, School of Mechanical Engineering, both at the Tel Aviv University in Israel.

Mr. Levy's research interests are in MEMS and MOEMS devices as well as photonic crystals devices including design, fabrication and characterization.

Ben Zion Steinberg received the BSc, MSc (Summa Cum Laude) and PhD degrees in electrical engineering from the Faculty of Engineering in Tel Aviv University in 1982, 1984 and 1989. From 1989 to 1991, he has been a post-doctoral research associate at the Catholic University of America in Washington DC, working on underwater propagation. In 1991, he joined the department of Interdisciplinary Studies in the School of Electrical Engineering in Tel Aviv University, where he is now a professor of electrical engineering. Prof. Steinberg's research interests are in electromagnetic theory, and wave propagation and scattering, with application in rf and optics.

Amir Boag received the BSc degree in electrical engineering and the BA degree in physics in 1983, both Summa Cum Laude, the MSc degree in electrical engineering in 1985, and the PhD degree in electrical engineering in 1991, all from Technion—Israel Institute of Technology, Haifa, Israel.

From 1991 to 1992, he was on the Faculty of the Department of Electrical Engineering at the Technion. From 1992 to 1994, he has been a visiting assistant professor with the Electromagnetic Communication Laboratory of the Department of Electrical and Computer Engineering at the University of Illinois at Urbana-Champaign. In 1994, he joined Israel Aircraft Industries as a research engineer and became a manager of the Electromagnetics Department in 1997. Since 1999, he is with the Physical Electronics Department of the School of Electrical Engineering at Tel Aviv University, where he is currently an associate professor.

Dr. Boag's interests are in electromagnetic theory, wave scattering, imaging and design of antennas and optical devices. He has published over 60 journal articles and presented more than 100 conference papers on electromagnetics and acoustics.

Slava Krylov received the MSc degree in 1989 in structural mechanics and PhD degree in 1993 in applied mechanics, both from the State Marine Technical University of St. Petersburg, Russia. Since he moved to Israel in 1993, he was post-doctoral fellow at the Department of Solid Mechanics, Materials and Systems, Tel Aviv University, worked as a R&D engineer for Israel Aircraft Industries and as a principal scientist and co-founder of a start up company developing optical MEMS. He joined Department of Solid Mechanics, Materials and Systems, Tel Aviv University in 2002. His research interests include design and modeling of MEMS, especially optical MEMS, large displacement actuators and dynamics of micro- and nano-electromechanical devices.

Ilan Goldfarb received his BSc (1988) and MSc (1990) in materials engineering from Ben-Gurion University of the Negev in Beer-Sheva, and his DSc (1994) in materials science and engineering from the Technion—Israel Institute of Technology, Haifa, Israel.

Immediately on completion of his doctorate in 1994, he moved into Department of Materials in Oxford University (UK), where he stayed until 1999, first as a British Council Scholar and then as a research fellow. In 1999, he joined Faculty of Engineering in Tel Aviv University as a Senior Lecturer in the Department of Solid Mechanics, Materials & Systems. Soon after that, he was appointed to a Managing Committee of the Tel Aviv University Institute for Nanoscience and Nanotechnology.

Dr. Goldfarb's research interests include surface science, epitaxial and heteroepitaxial growth, self-assembly and self-organization of nanostructures and scanning tunneling microscopy. He has authored numerous journal articles and presented many invited and plenary talks at the international scientific conferences.