Cross-Sensitivity of an Optomechanical MEMS Transducer †

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Abstract: This work presents the investigation on a MEMS based optomechanical transducer for displacements or vibration regarding its cross-sensitivities to multidirectional input excitations. The principle of the optomechanical transducer is based on the modulation of the light flux passing through one static and one movable micromechanical aperture. This kind of transducer is of increasing interest for MEMS sensors since it has inherent benefits and can compete with state-of-the-art readout concepts regarding its resolution. We have experimentally proven that the sensitivities of the device is $3.3 \times 10^7$ V/m in $x$-direction, $8.23 \times 10^6$ V/m in $y$-direction, while it is negligible in $z$-direction.

Keywords: optomechanical; MEMS; cross-sensitivity; transducer

1. Introduction

Micro-electro-mechanical systems (MEMS) have become a common part of everyday life and they are subject to a constant development [1,2]. A critical part of all MEMS based sensors is the readout method, where the most prominent is the capacitive readout [3,4]. Recently, an optomechanical readout was published, which has significant impact on MEMS-based sensors due to its benefits, like galvanic separation, no reaction forces, no restrictions regarding displacement bandwidth, and easy fabrication. It was used to measure the low-frequency Earth tides in a micromechanical seismometer [5]. It was also demonstrated that such a concept can reach displacement resolutions down to 0.86 pm/√Hz [6] and, hence, compete with state-of-the-art transducers like capacitive readouts. Furthermore, the influence of the readout on the damping behavior was investigated [7]. In this work, we focus on the cross-sensitivities of the optomechanical MEMS readout to deflections in various directions. This is crucial for clearer understanding and further improvements of the transducer.

2. Materials and Methods

The optomechanical transducer’s output signal is proportional to the light flux modulated by two overlapping aperture arrays. One of the arrays is vapor deposited (chromium) on a fixed glass cover while the other one is etched into a movable seismic mass of a Si MEMS chip. The seismic mass (size $A = 4 \times 3 \text{ mm}^2$) is spring suspended for a preferred deflection direction (Figure 1). The device is micro-fabricated in a silicon-on-insulator wafer, where the thickness of the device layer is $d = 45 \mu$m.
The glass wafer, holding the stationary apertures, is bonded to the device layer with SU-8 as bonding promoter (Figure 2). The modulated light flux depends on the change of the open area of the aperture which consists of \( n \approx 2500 \) rectangular openings (\( A_0 = 10 \times 100 \mu m^2 \)).

![Figure 1](image1.png)

**Figure 1.** Schematic of the MOEMS device. A Si spring suspended seismic mass comprises rectangular aperture arrays. A glass cover on top of the structures contains the corresponding stationary chromium array (inlay, optical micrograph).

![Figure 2](image2.png)

**Figure 2.** Fabrication process. (a) Structuring of the device layer. (b) Backside DRIE to remove the substrate beneath the structures. (c) HF etching of the sacrificial SiO\(_2\) layer. (d) Bonding of the glass wafer with SU-8.

The mechanical vibration modes of the MEMS structure are determined prior to the measurements by means of finite element method (FEM) simulations. The device’s eigenmodes are simulated with Comsol Multiphysics in a 3D solid mechanics model. Figure 3 depicts the first eigenmodes where the lowest one \( f_1 = 296 \text{ Hz} \) is the vibrational mode in \( x \)-direction, followed by the basic vibrational mode in \( z \)-direction (\( f_2 = 1559 \text{ Hz} \)). At \( f_4 = 2496 \text{ Hz} \) is the vibrational mode in \( y \)-direction. The modes \( f_3, f_5, \) and \( f_6 \) are torsional modes around the \( x \)-, \( y \)-, and \( z \)-axis, respectively.

The fabricated MEMS structures are characterized with the help of a digital holographic microscope (DHM; LynceeTec, Lausanne, Switzerland) and a piezo-electric shaker unit. The device is mounted on the shaker with its preferred displacement direction facing in the \( x \)-direction. A frequency sweep between 100 Hz and 5 kHz is carried out by applying a sinusoidal voltage at the piezo shaker with an Agilent waveform generator (Agilent, 33220A). The digital holographic microscope is used to quantify the excitation amplitudes of the seismic mass, while a fiber-optic sensor (Philtec D6, Maryland, USA.) is used to measure the input excitation amplitudes, applied by the shaker unit. The measurement procedure is repeated with the device’s preferred displacement direction facing \( y \)- and \( z \)-direction regarding the shaker’s primary excitation direction. In this way, the basic vibration modes of the structure in \( x \)-, \( y \)-, and \( z \)- direction and the transfer characteristic of the seismic mass for different input excitation directions is calculated. Afterwards, the response of the optical readout out is characterized. An LED and a photodetector are put on the top and bottom side of the MEMS structure, respectively. The resulting photocurrent is converted and pre-amplified by a
transimpedance amplifier. Again, a frequency sweep was carried out and the corresponding signals from the readout circuit are measured with a lock-in amplifier (Stanford Research, SR830) (Figure 4). With the recorded signals, the transfer characteristic and sensitivities of the optomechanical transducer were calculated.

Figure 3. FEM simulated basic vibration modes of the structure with color coded total deflections.

Figure 4. A piezo-electric shaker is used to introduce excitations in different spatial directions at a set of frequencies. The deflections of the mass and the applied excitation amplitudes are evaluated with a digital holographic microscope and a fiber-optic sensor, respectively. The output from the readout circuit is recorded with a lock-in amplifier.

3. Results

The device was excited at a set of frequencies to obtain the transfer characteristic for input excitations in $x$-, $y$-, and $z$-direction, respectively. The simulated resonance frequencies of the seismic mass match the measured results very well. The response of the optomechanical transducer is depicted in Figure 5. The in-plane vibration modes $f_1$ ($x$-direction), $f_4$ ($y$-direction) can be clearly observed both in the amplitude and phase signal of the readout. The out-of-plane modes $f_2$ ($z$-direction), $f_3$ and $f_5$ (out-of-plane rotational modes) of the seismic mass were observable with the DHM, but not in the output of the optomechanical transducer. Also the in-plane-rotational mode $f_6$ could not be observed.
4. Conclusions

A micromechanical optomechanical transducer was characterized regarding its response to multidirectional input excitations based on the example of a vibration sensor. While the basic vibration modes of the seismic mass could be observed with a digital holographic microscope, the optomechanical transducer is only sensitive to in-plane excitations of the mass in $x$- and $y$-directions.

Figure 5. The transfer characteristic of the optomechanical transducer reveals that the in-plane vibration modes ($f_1, f_4, f_6$) are in very good agreement with the simulated ones. No out-of-plane modes ($f_2, f_3, f_5$) are observable in the transducer’s output signals. This indicates that the readout has a negligible cross-sensitivity regarding such out-of-plane deflections.

The basic vibration modes in $x$- and $y$-directions can be observed for all three input directions. This effect results from a non-ideal positioning of the device on the mechanical shaker and, hence, an at least partly transfer of the input excitation power into the $x$- and $y$-vibrational mode. Nevertheless, we have experimentally proven that the sensitivities of the chosen device and aperture design is $3.3\times10^7$ V/m in $x$-direction, $8.23\times10^6$ V/m in $y$-direction, and negligible in $z$-direction. This information is of use for the future development of tailor-made innovative optomechanical MEMS sensors.

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References


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