Design and fabrication of multilayer-driven optomechanical device for force and vibration sensing

Sayginer, Osman, Chiasera, Alessandro, Varas, Stefano, Lukowiak, Anna, Ferrari, Maurizio, et al.

Osman Sayginer, Alessandro Chiasera, Stefano Varas, Anna Lukowiak, Maurizio Ferrari, Oreste S. Bursi, "Design and fabrication of multilayer-driven optomechanical device for force and vibration sensing," Proc. SPIE 11357, Fiber Lasers and Glass Photonics: Materials through Applications II, 113571S (1 April 2020); doi: 10.1117/12.2555347
Design and Fabrication of Multilayer-Driven Optomechanical Device for Force and Vibration Sensing

Osman Sayginer*\textsuperscript{a,b}, Alessandro Chiasera\textsuperscript{b}, Stefano Varas\textsuperscript{b}, Anna Lukowiak\textsuperscript{c}, Maurizio Ferrari\textsuperscript{b}, Oreste S. Bursi\textsuperscript{a,b}

\textsuperscript{a}Department of Civil, Environmental and Mechanical Engineering, University of Trento, Mesiano-Trento, Italy
\textsuperscript{b}IFN-CNR CSMFO Lab. and FBK Photonics Unit, Via alla Cascata 56/C Povo 38100 Trento, Italy
\textsuperscript{c}Institute of Low Temperature and Structure Research, PAS, Okolna 2, 50-422 Wroclaw, Poland

ABSTRACT

Multilayer structures are commonly used components in optics and photonics due to their unique properties to manipulate the spectral response of light. Multilayer-driven components for sensing purposes can bring some advantages such as high sensitivity, fast signal response, electromagnetic interference immunity, and low power consumption. Thus, a mechanically coupled optical system can be the right candidate for force and vibration detection. In this work, we propose and demonstrate an optomechanical sensing system for pressure and vibration detection using two multilayer structures, a circular membrane, a light source, and a photodiode. The design of this proposed system consists of two parts, which are optical design and mechanical design. In the optical design, we modeled the optical response of the multilayer structures in the visible spectra using the Transfer Matrix Method. The mechanical response, on the other hand, is calculated using finite element simulations via the COMSOL Multiphysics software. The multilayer structures are fabricated by RF-Sputtering technique and then integrated through a 3D printed mechanical housing. The sensor characteristics (sensitivity and resonance frequency) are experimentally investigated by a static loading test and a transient response analysis. Results are shown that the sensor frequency around 510 Hz and the sensitivity of the sensor about 50 Pa.

Keywords: Sensor design, Optomechanical Sensor, Vibration sensor, Pressure sensor, Multilayer structures

1. INTRODUCTION

Optics driven sensing technologies bring several advantages over the traditional pressure and vibration sensing approaches, which are mostly relying on piezoelectricity, capacity, and resistivity\textsuperscript{1}. The nature of the optical sensing systems offers some superior capabilities over the current sensing technologies, such as immunity to electromagnetic interference, high signal-to-noise ratio per unit area, and geometric miniaturization\textsuperscript{2,3}. For this reason, the development of optical sensing systems for pressure and vibration detection can extend the sensing limits in particular in structural health monitoring, optoacoustic medical imaging, and non-contact measurements\textsuperscript{3}.

Mechanical vibrations propagate as elastic waves through a solid medium, fluid, and gaseous media, the attenuation rate depending on the frequency\textsuperscript{4}. Refraction, interference, and polarization can be employed for the optical detection of mechanical vibrations. The refraction approach relies on the change in optical response due to the change in the local density of the material. On the other hand, the interference approach relies on the change of spectral behavior of the light due to the optical interference\textsuperscript{5}. The polarization strongly depends on the structure of the material. It is well known that all of these sensing conditions can contribute at the same time on the sensor response\textsuperscript{6}.

A thin-film multilayer (TFM) is an optical structure that is consisting of thin-film material layers on top of a rigid substrate with varying refractive indices and thicknesses.

* osman.sayginer@unitn.it;
Designing of the thin film layers, by tailoring material properties, the number of layers and thicknesses, enables us to create a unique optical structure with superior optical features. Thus, TFMs based on structures can be good candidates for sensing applications. There are several fabrication techniques for TFMs such as ion implantation, sol-gel deposition, radio frequency (RF) sputtering, and electron-beam evaporation. The concern of all fabrication techniques relies on thickness control and material homogeneity to have reproducibility. Among all of these fabrication techniques, RF sputtering offers thermal treatment-free direct deposition through the materials with a reliable thickness control.

In this paper, we propose an optomechanical sensing framework using the tunable spectral behavior of two TFMs in contact with a mechanical membrane. We present here the design, fabrication, and assessment of an optomechanical sensor (OMS) prototype as proof of the concept demonstration. The proposed sensing framework combines the design versatilities of the TFMs with a novel deposition protocol on polymeric flexible substrates using the RF sputtering technique. Optical characterization has been performed for TFMs. Measurement results were compared to the simulations obtained by Transfer Matrix Method. After that, the sensor characteristics of the OMS are tested using two types of experiments. In the first experiment, we have investigated the sensitivity of the sensor under static loadings. This experiment has also revealed the sensor’s potential for pressure sensing. In the second experiment, we have investigated the dynamical response of the sensor, in particular, the sensor resonance frequency.

For this reason, we performed an impact test on the OMS membrane. After that, the time response of the signal was converted into the frequency domain by Fast Fourier Transform Analysis (FFT). Experimental results were compared to the simulation models that are computed using the COMSOL Multiphysics software. Results have shown that the proposed OMS can be a good candidate for pressure and vibration detection. Moreover, with the use of flexible substrates, OMS offers a wide design degree of freedom for various pressure and vibrations sensing applications.

2. MODELING AND DESIGN

2.1 Working Principle

The sensing principle of the OMS relies on the change in the spectral behavior of the reflected light due to the change in the reflection angle of the reflector, which is in contact with a circular membrane. The light source and the filter are positioned to the reflection plane at an angle \( \alpha = 45^\circ \). Angles regarding the incident and the reflected light can be defined as by the angle of \( \beta \). Thus, the reflected light through the reflector enters the filter with the incident angle of 90-2\( \beta \). Deflections on the membrane about \( \theta \) due to the static or dynamic loadings change the angle of the incident light entering the filter about 20. Thus, the change in angle is observed as the shifts in the spectra. Changes in the spectral response will change the intersected region of the two optical components. The spectral intersection of two optical components defines the intensity of the light that is received by a photodiode. More in detail, the working principle of OMS is illustrated in Figure 1.

Figure 1. a. Illustration of the working principle of the OMS. Incident light (full spectra light) is reflected (b.) through the reflector that is attached to a circular membrane. The reflected light is filtered by the filter (c.) and received by a photodiode. The area of spectral intersection (orange) of the reflected (yellow color) and filtered (green color) is measured by a photodiode.
The OMS device is consisting of four fundamental components which are a reflector, a filter, a circular membrane, a light source, and a photodiode. Moreover, all components are assembled into a 3D printed housing. Depending on the sensor deflection, the sensitivity of the sensor can be defined while the working frequency of the sensor is defined by the resonance frequency of the circular membrane. Thus, the design of the membrane plays an important role in sensor response and sensitivity. The purpose of using a circular membrane is to have a simple single degree of freedom system with the ease of implementation. Another factor that influences the sensor sensitivity is the characteristics of the optical components. In other words, change in the wavelength range of the intersected area between the reflector and filter affects the amount of light received by the photodiode. For this reason, spectral reflection and transmission patterns of both the reflector and the filter is required to be designed accordingly. Thus, both OMSs designs and membrane design play an important role in OMS response.

2.2 Membrane Modeling

The OMS membrane is fabricated using Mylar polyester film with the material properties are given in Table 1. The reflector is attached to the half side of the membrane in order to achieve one-directional reflectivity from the light source into the filter. Reflector size is also a factor that influences the sensor sensitivity since it can affect the amount of reflected light per unit area. However, the reflector size is kept as 2 mm by 10 mm rectangle, and its effect on the membrane is neglected. The OMS membrane is illustrated in Fig 2. Membrane deflection \( h \) under static loading can be calculated\(^{14} \) using the formula in (1).

Table 1. Material Properties of the OMS Membrane

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>0.07 mm</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>98 MPa</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.38</td>
</tr>
<tr>
<td>Density</td>
<td>1390 kg/m(^3)</td>
</tr>
</tbody>
</table>

\[
h(r) = \frac{Pa^2}{4T_b}\left(1 - \frac{r^2}{a^2}\right)\]  

(1)

Figure 2. Illustration of the OMS membrane deflection. The reflector (shown in yellow) is attached to half part of the beam.
where, \( P \) is the uniform pressure acting on the membrane, \( a \) is the membrane radius, \( r \) is the radial position, and \( T_0 \) is the pretension force acting on the membrane.

Natural frequency \( (f_n) \) of the membrane can be analytically calculated\(^{15}\), as given in (2) where \( T_0 \) is the pretension of the membrane and \( \rho \) is the density of the membrane. Here the \( k_n \) is mode factor which is from the roots of the Bessel functions. For the first mode of the membrane (1,0 mode), the mode factor is taken as 2.4048.

\[
f_n = \frac{k_n \sqrt{T_0}}{2\pi a \sqrt{1\rho}}
\]

(2)

### 2.3 Modeling of Optical Components

The multilayer structures are designed using SiO\(_2\) and TiO\(_2\) alternating material layers in the spectra range from 400 nm to 800 nm. Thicknesses of SiO\(_2\) and TiO\(_2\) layers were chosen as 105 nm and 65 nm, respectively. The Transfer Matrix Method\(^{12,13}\) (TMM) is an effective route to calculate the propagation of electromagnetic waves in different dielectric media. TFM responses are calculated based on a simulation model that was created by considering the wavelength-dependent refractive indices where the material properties are taken from the literature\(^ {16,17}\).

![Refractive Index Distribution](image)

Figure 3. Refractive index distribution of the multilayer design at 800 nm. 1st and 16th layers correspond to air and silica substrate, respectively. Black and grey layers correspond to are TiO\(_2\) and SiO\(_2\), respectively.

### 3. RESULTS

We fabricated multilayer structures on silica (for the filter) and a polyester flexible substrate (for the reflector) where each substrate is consisting of seven couples of SiO\(_2\) and TiO\(_2\) layers, using multitarget RF sputtering technique by following the fabrication protocol in\(^ {18,19}\). The flexible substrate was placed on the OMS membrane. Optical components were assembled into a 3D printed housing. A white-colored LED light source was used to excite the optical system by connecting to a controller in order to tune the brightness. A photodiode was used to determine the system response by connecting to an oscilloscope. Details of the OMS and experimental setup is given in Fig 4.
3.1 Optical Response

The optical characterization of the multilayer components was performed using Varian Cary mod.5000 double-beam spectrophotometer in the visible range from 400 nm to 800 nm with a resolution of 2 nm. Transmission spectra measurement results of the multilayer on a silica substrate are shown in Fig 5. TMM simulated spectrum is also reported.

The same multilayer design is also deposited on a 3M PP2500 polyester substrate with 0.1 mm thickness. The reflectance spectra of the silica and flexible substrate are given in Fig 6.
Figure 6. Reflectance spectra of the multilayer on silica and the flexible substrate.

3.2 Static Response

The OMS response due to the membrane deflection was investigated. Thus, the membrane was deflected simply by placing weights that are 1.5 g, 3 g, and 4.5 g, respectively. Weights were contacted to the membrane using a circular container to have equally distributed forces through the membrane. Applied forces were converted into the unit of pressure. The OMS response due to applied pressure is shown in Fig 7.

Figure 7. The OMS response under loadings.
The deflection level of the OMS membrane was calculated analytically by using equation (1). Moreover, a finite element model was also computed using COMSOL Multiphysics. The OMS membrane pretension was assumed 250 kPa through the membrane edges for both calculations. Membrane deflection under 200 Pa loading is shown in Fig 8.

![Figure 8](image1.png)

**Figure 8.** Calculation of the membrane deflection under 200 Pa loading.

### 3.3 Dynamic Response Analysis: Impact test

In order to investigate the OMS characteristics under dynamic loadings, an impact test analysis is performed. Thus, the OMS membrane was hit with a metal stick for a short period of time\(^3\). The OMS response due to impact test recorded using an oscilloscope and signal measurements are given in Fig 9.

![Figure 9](image2.png)

**Figure 9.** The OMS response due to the impact tests. Signals that are labeled as Noise 1, 2, and 3 are measured without any excitation, while impact 1, 2, and 3 correspond to impact excitations with varying amplitudes.
Impact test signals are converted into the frequency domain by using the FFT. The spectral response of the OMS shows the resonance frequency of the sensor about 510 Hz. However, there is also another resonance detected at 1 kHz due to the background noise. According to equation (2), the resonance frequency is calculated considering 250 kPa membrane pretension. The OMS natural frequency for the first mode is calculated 513 Hz.

![FFT analysis of the impact test signals. The first three signals from bottom to top are showing background noise. Three signals from top to bottom are showing signals result from different impact forces.](image1)

In addition to analytical calculation and impact analysis, a finite element analysis was employed to investigate membrane mode shape. Using the COMSOL Multiphysics software, the first-order mode shape of the OMS membrane computed. The mode shape of the OMS membrane at 513 Hz is illustrated in Fig 11.

![Eigenfrequency analysis of the OMS membrane using COMSOL Multiphysics software shows the first-order mode shape at 513 Hz. Given the color bar reflects the level of displacement through the membrane body, however, does not reflect real values.](image2)

**4. CONCLUSIONS**

In this paper, we have presented an innovative optical sensing method for pressure and vibration detection by demonstrating an optomechanical sensor prototype (OMS). This proposed sensing scheme uses thin-film multilayer (TFM) structures relying on tunable spectral filters (TSF). The TFMs were fabricated using the RF-sputtering technique.
by depositing SiO$_2$ and TiO$_2$ material layers on top of a silica and flexible-polyester substrates. Thus, we introduced a novel flexible TFM structure for a sensing application. Spectra response of the TFMwas investigated by transmission and reflection measurements. In addition, spectra responses were simulated using the Transfer Matrix Method. Mechanical response of OMS, in particular membrane deflection and resonance frequency, was analyzed using both analytical and finite element method. Finally, sensor performance evaluation tests were performed by a static loading test and an impulse test. Static loading tests reveal the sensor sensitivity varying from 50 Pa to 200 Pa values. On the other hand, the impulse test results have shown the resonance frequency of the sensor about 510 Hz. Thus, with this work, we have demonstrated a new type of sensing methodology for both pressure and vibration sensing using flexible optical components. This sensing approach enables a wide range of design degrees of freedom for different sensing applications.

Acknowledgement

This research is performed in the framework of the CNR-PAS “Flexible Photonics” (2020-2021)

REFERENCES


