

A Highly Sensitive Optical Biosensor with Tunable Point Defect Cavity for Point-of-Care Testing

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Abstract— This paper introduces a surface stress-based BioMEMS sensor featuring an optomechanical detection system designed to measure the target bioparticles' concentration. The sensor incorporates a defective 2D photonic crystal along with a MEMS transducer. When the target bioparticles are absorbed by the bioreceptors immobilized on the sensing area, they induce deformation in the MEMS transducer, which alters the defect structure of the photonic crystal and changes its transmission spectrum. This modification facilitates the precise measurement of the target bioparticles' concentration. Both numerical and analytical analyses were conducted to evaluate the device's performance. The functional characteristics of the proposed device suggest its suitability for near-patient testing applications.

Keywords— BioMEMS, biosensor, microelectromechanical systems (MEMS), photonic crystal.

I. INTRODUCTION

In recent years, biosensors utilizing Micro-Electro-Mechanical Systems (MEMS) technology for label-free detection of bioparticles have attracted considerable attention. This interest is primarily attributed to their remarkable attributes, which encompass high sensitivity, cost-effectiveness, and compact footprint [1]. These sensors employ MEMS transducers to convert the absorption of the target bioparticles into mechanical displacement. The utilization of optical mechanisms to assess the deformation of MEMS transducers enhances the sensitivity of these devices [2]. MEMS-based biosensors can operate in either dynamic or static modes. In dynamic mode, the adsorption of target bioparticles results in a shift in the resonant frequency due to the increase in mass, allowing for detection and quantification based on frequency changes. To achieve high mass sensitivity in this mode, nanoscale structures with high quality factors (typically ranging from 10^3 to 10^5) are required, which can only be realized under vacuum conditions. However, in liquid environments—crucial for most biological applications—the quality factor decreases significantly (approximately $Q \approx 1 -$

10) due to viscous damping, thereby considerably limiting sensor performance.

Alternatively, in static mode, the detection of target bioparticles relies on the quantification of transducer deformation, which results from the surface stress generated by the interactions between the target bioparticles and their corresponding bioreceptors. This methodology demonstrates significant applicability in both gaseous and aqueous environments, thereby enhancing its versatility in various sensing applications [3].

Furthermore, the performance of the BioMEMS sensors can be further improved by incorporating innovative detection systems, making these platforms more reliable and sensitive for commercialization [4,5].

This paper presents a surface stress-based BioMEMS sensor utilizing a novel optical detection system based on a defective two-dimensional photonic crystal (2DPhC) for label-free detection of the target bioparticles in the sample. Although the proposed biosensing platform is compatible with a wide range of bio-recognition elements, it is particularly suitable for protein-based biomarkers whose binding interaction generates measurable surface stress on the MEMS transducer. Typical examples include C-reactive protein (CRP) [6], cardiac troponin (cTnI) [7], and prostate-specific antigen (PSA) [8]. These biomarkers play a key role in the early diagnosis of inflammatory diseases, cardiovascular disorders, and prostate cancer, respectively. Since such biomarkers are often present at very low concentrations in biological fluids, a highly sensitive label-free detection mechanism is required.

The proposed sensing platform is designed to operate in liquid-phase biological samples, which is essential for practical point-of-care diagnostics. Since the detection mechanism is based on surface-stress modulation rather than high-Q mechanical resonance, the device maintains stable performance even in viscous environments. Typical fluids that can be used with the sensor include serum and plasma, which are widely

utilized for quantifying protein biomarkers such as CRP and cardiac troponin. Additionally, the platform is compatible with urine and saliva samples, enabling non-invasive or minimally invasive testing for applications such as renal biomarkers, infectious disease screening, and cancer-related analytes. This compatibility with multiple biological fluids reinforces the suitability of the proposed device for PoC applications.

The rest of the paper is organized as follows: Section II presents the design and operational principles of the proposed device. Section III explains the mechanical and optical analysis and simulation results. Finally, Section IV compares the functional characteristics of the present BioMEMS sensor with other related contributions in this area.

II. DESIGN AND OPERATIONAL PRINCIPLES OF THE PROPOSED BIOMEMS SENSOR

As shown in Fig. 1, the proposed BioMEMS sensor consists of a SU-8-made biomechanical transducer with fixed ends, and a defective 2DPhC is created utilizing GaAr-made rods positioned on the SU-8 substrate. The deformation of the MEMS transducer due to the biochemical interactions results in the variation of the geometrical configuration of the 2DPhC rods. To functionalize the MEMS transducer, the bioreceptors are initially immobilized onto the outer surface of the beam. With the flow of the sample on the sensing area, the target bio molecules are captured by the bioreceptors, which introduces a mechanical stress on the surface of the beam, leading to deformation of the MEMS transducer as illustrated in Fig. 2. The curvature of the beam can be calculated as follows [9]:

$$\frac{1}{R} = \frac{6(1-\nu)}{Eh^2} \Delta\sigma \quad (1)$$

where L and h represent the length and height of the MEMS transducer, respectively. E and ν refer to Young's modulus and Poisson's ratio of SU-8, and $\Delta\sigma$ represents the variation in surface stress induced by the binding of target bioparticles to the immobilized bioreceptors on the surface of the MEMS transducer. The physical and geometrical parameters of the proposed device are presented in Table I.

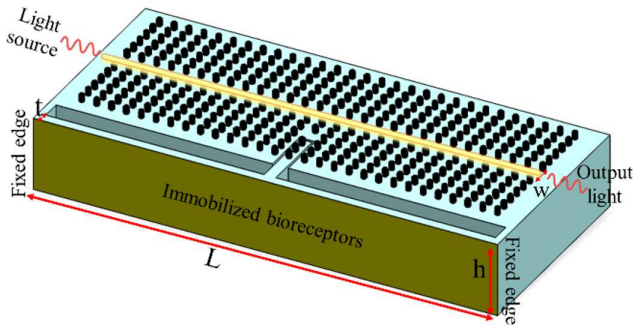


Fig. 1. Schematic of the proposed BioMEMS sensor.

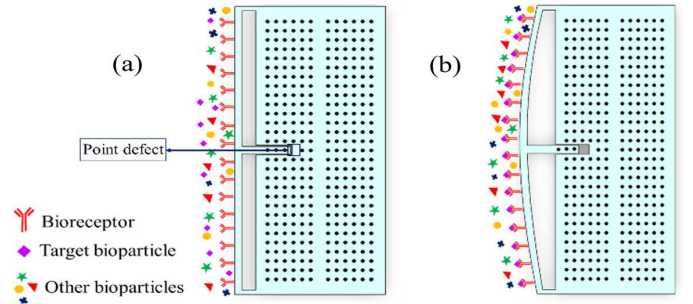


Fig. 2. The mechanical state of the MEMS transducer (a) before, (b) after the absorption of the target bioparticles.

TABLE I. PHYSICAL AND GEOMETRICAL PARAMETERS OF THE PROPOSED BIOSENSOR

Symbol	Description	Value
E	Young's modulus of SU-8	4.2 Gpa
ν	Poisson ratio of SU-8	0.22
L	Length of beam	100 μm
t	Thickness of the beam	0.9 μm
h	Height of the beam	10 μm
w	Width of waveguide	0.7 μm
r	Radius of rods	0.15 μm

In order to implement the optical detection system, a straight waveguide is created by removing a single row of rods to facilitate light propagation through the 2DPhC structure. Additionally, by introducing a point defect adjacent to the waveguide, a high-Q resonant cavity is formed.

As shown in Fig. 2, the deflection of the MEMS transducer changes the initial position of a few rods of the 2DPhC, which results in a red shift in the transmittance spectrum of the photonic crystal.

III. FUNCTIONAL ANALYSIS OF THE PROPOSED DEVICE

The functional characteristics of the proposed BioMEMS sensor are obtained by analytical and numerical analysis and the results are presented in the following subsections. All simulations are performed using COMSOL Multiphysics.

A. Mechanical Analysis

As the target biomolecules in the sample are captured by the bioreceptors immobilized on the surface of the transducer, their interaction induces a surface stress that results in the transducer's deformation. Fig. 3 illustrates the displacement of the center of the MEMS transducer as a function of beam length and thickness. It is evident that increasing the beam length and decreasing its thickness leads to greater displacement, and thus, enhanced mechanical sensitivity. However, such configurations may introduce challenges in the fabrication process. To balance sensitivity and manufacturability, the sensor's geometrical dimensions have been carefully selected, as summarized in Table I, ensuring both high performance and structural reliability. Therefore, the mechanical sensitivity (S_m) of the proposed sensor can be defined as follows:

$$S_m = \frac{\Delta d}{\Delta\sigma} = 1.1 \mu\text{m/Nm}^{-1} \quad (2)$$

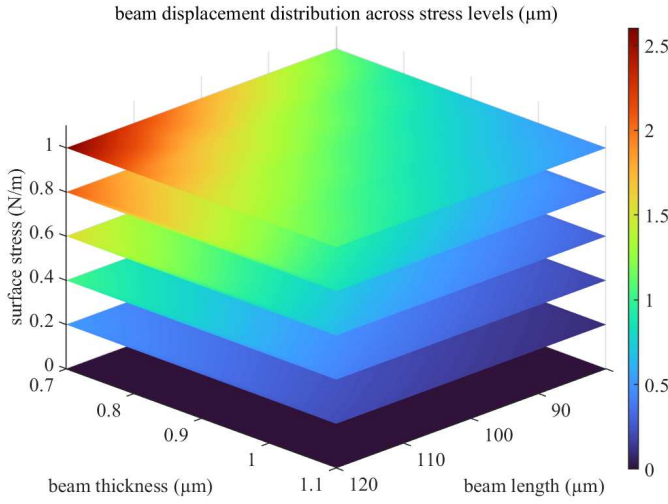


Fig. 3. The displacement of the MEMS transducer as a function of beam length and thickness under surface stress.

An essential mechanical parameter that governs the performance of MEMS-based biosensors is their resonance frequency, which defines the sensor's bandwidth and dynamic response characteristics. To determine this frequency, the sensor's dynamic behavior is modelled through the classical mass-spring model, the fundamental resonance frequency can be expressed as follows:

$$f_r = \frac{1}{2\pi} \sqrt{\frac{k}{m}}, \quad (3)$$

where k denotes the effective spring constant, and m corresponds to the mass of the MEMS transducer.

Fig. 4 presents the first six mechanical resonance modes of the proposed device, as obtained through numerical simulations. These results are in agreement with the outcomes predicted by analytical methods, thereby validating the theoretical analysis. The frequency response of the proposed sensor is depicted in Fig. 5 to evaluate its operational bandwidth. As illustrated, the response remains nearly constant across a wide frequency range up to the onset of the first resonance peak. Accordingly, the bandwidth of the biosensor is considered as 5 kHz.

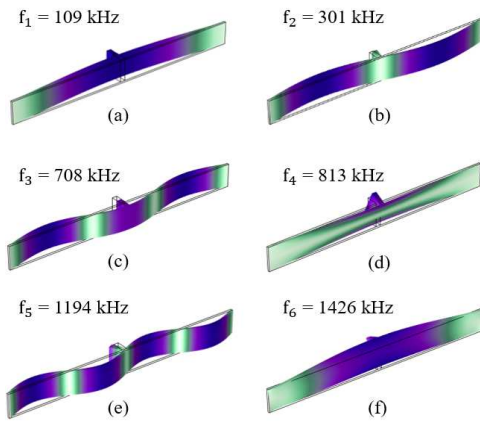


Fig. 4: The first six resonance modes.

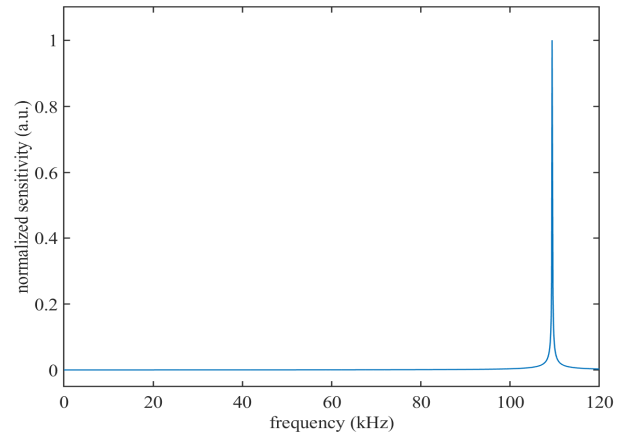


Fig. 5. The frequency response of the proposed device.

B. Optical Analysis

As shown in Fig. 1, a waveguide is created within the 2DPhC structure by removing a row of rods, enabling light transmission. By introducing a single point defect adjacent to the waveguide, a notch filter with a high-quality factor is formed, resulting in zero transmission at the resonant wavelength (λ).

The deformation of the MEMS transducer induces a displacement within a column of rods positioned in proximity to the point defect. This results in a shift in the transmission spectrum, which indicates the concentration of the target bioparticles present in the sample. The wavelength shift of the resonating trough is illustrated in Fig. 6, which determines the optical sensitivity (S_o) of the proposed device as follows:

$$S_o = \frac{\Delta\lambda}{\Delta d} = 0.315 \quad (4)$$

Finally, the sensitivity (S) of the proposed device can be defined as a function of the mechanical and optical sensitivity according to:

$$S = S_m \times S_o = \frac{\Delta\lambda}{\Delta\sigma} = 0.3465 \mu\text{m}/\text{Nm}^{-1} \quad (5)$$

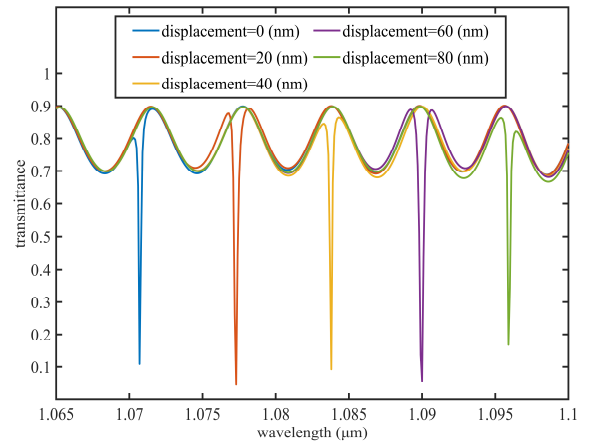


Fig. 6. Transmission spectrum of the proposed design with the deformation of the MEMS transducer.

Additionally, the proposed device exhibits exceptional optical characteristics, including:

$$\text{figure of merit: } FOM = \frac{S_o}{FWHM} = 1.575, \quad (6)$$

$$\text{quality-factor: } Q = \frac{\lambda}{FWHM} = 5353.5, \quad (7)$$

where $FWHM$ denotes the full width at half maximum of the resonating trough ($FWHM = 0.2$ nm).

IV. COMPARATIVE STUDY

The performance of the proposed MEMS-based biosensor has been compared with other optical and surface stress-based biosensors, as detailed in Tables II and III.

In Table II, the proposed design is evaluated against various optical biosensors that utilize mechanisms such as metamaterials [10], plasmonic [11], and 2D photonic crystals [12]. The proposed sensor demonstrates a superior Q-factor and a narrower $FWHM$, indicating enhanced optical performance.

Additionally, Table III offers a comparison of the current device with two surface stress-based designs. While the mechanical sensitivity remains comparable, the proposed sensor demonstrates superior optical sensitivity and overall sensitivity when compared to reference [13], although it does not reach the levels of reference [2]. However, it presents key advantages, including a simpler fabricate on process and a more compact design. Furthermore, it outperforms both of the other contributions in terms of Q-factor.

In conclusion, the exceptional sensitivity, compact design, and ease of fabrication make the proposed sensor particularly well-suited for point-of-care testing applications.

TABLE II. THE OPTICAL PROPERTIES OF THE PROPOSED SENSOR COMPARED TO THE RELATED CONTRIBUTIONS

Ref	Operation Mechanism	Q	$FWHM$ (nm)
[10]	Metamaterial	27	52
[11]	Plasmonic	< 60	>12
[12]	2D Photonic crystal	81.58	19.6
Proposed device	MEMS 2D Photonic crystal	5353.5	0.2

TABLE III. COMPARISON OF THE PROPOSED DEVICE WITH THE RELATED SURFACE STRESS-BASED BIOSENSORS

Ref	S_m ($\mu\text{m}/\text{Nm}^{-1}$)	S_o	S ($\mu\text{m}/\text{Nm}^{-1}$)	Q
[13]	1.05	0.2	0.2	3078
[2]	1.2	0.5	0.6	80
Proposed device	1.1	0.315	0.3465	5353.5

V. CONCLUSION

This paper presents a novel surface stress-based BioMEMS sensor, utilizing a MEMS mechanical transducer with a defective 2D photonic crystal for optical detection. The detection mechanism relies on bioparticle-induced surface stress, which deforms the MEMS transducer and modulates the photonic crystal's transmission characteristics. Both analytical modelling and numerical simulations confirmed the sensor's capability to detect changes in bioparticle concentration with high optical sensitivity.

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