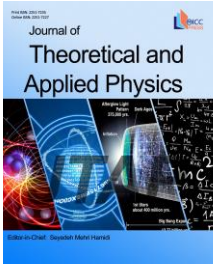

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Research Article

Ultra-Compact and Highly Sensitive Pressure Sensor Based on a 2D Photonic Crystal Square-Ring Resonator for High-Pressure Range (0 to 10 GPa)

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Abstract

This study presents an optical platform for pressure sensing based on a square-ring resonator. Numerical simulations reveal a shift in the resonant frequency towards lower frequencies, concomitantly with a shift in the resonant wavelength towards higher wavelengths, in response to an increase in applied pressure. Two simulation methodologies, the plane wave expansion (PWE) method and the finite-difference time-domain (FDTD) method, were employed to extract the guided mode and analyze the functional characteristics of the proposed sensor under varying pressure constraints. The envisioned structure is distinguished by a high-quality factor, a sensitivity of approximately 4.39 nm/GPa over a dynamic range from 0 to 10 GPa, and an ultra-compact footprint of 274 µm². These properties render this structure particularly suitable for integration into microscale photonic integrated circuits.

Keywords: Photonic Crystal, Pressure Sensor, Ring Resonator, FDTD, High-Pressure

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1. Introduction

In the realm of optical sensing, photonic crystal (PC) structures are recognized as an innovative and highly electromagnetic field, possess the unique ability to confine and manipulate light. This light confinement capability makes them exceptionally suitable for a broad spectrum of promising approach, primarily due to their superior performance capabilities. These periodic dielectric structures, characterized by a precisely tuned lattice parameter aligned with the wavelength of the propagating sensing applications, including chemical, biological, and physical sensing. [1-7]. Two-dimensional photonic crystals (2DPCs) offer a highly adaptable platform for the development of various optical integrated circuits, such as demultiplexers [8-10], logic gates [11-15], and filters [16]. Among these applications, sensors based on PC technology have received significant attention.

PC-based sensors can generally be classified based on their operating principle, including those using microcavities, waveguides, and ring resonators for the detection of physical parameters like electric field [17], temperature [18], and notably, pressure [19, 20]. Their function relies on the modification of the refractive index or structure induced by the parameter being measured.

Their functionality hinges on the modification of the refractive index triggered by the force exerted on the device's sensing surface.

This characteristic enables precise detection while requiring minimal sample volumes, positioning these sensors as valuable instruments for a wide array of applications.

In the present research, a pioneering pressure nanosensor based on a triangular two-dimensional photonic crystal (2DPC) structure, integrated with a ring resonator, is developed to detect pressure within a span of 0 to 10 GPa.

The device's sensing efficacy was evaluated and modeled through the application of two separate computational methods:

plane wave expansion (PWE) and finite-difference time-domain (FDTD).

An in-depth analysis was performed to assess the sensor's performance metrics, including its dynamic range, resonance wavelength, output power, quality factor (Q-factor), and sensitivity.

2. A comprehensive study of pressure sensing mechanisms in sensors

Pressure sensors operating on the photoelastic effect leverage the phenomenon of stress-induced birefringence to quantify applied pressure.

When subjected to mechanical stress, the refractive index of the optical material undergoes a modification that is directly proportional to the magnitude of the exerted force. This alteration in the refractive index induces a shift in both the photonic bandgap and the resonant wavelength of the structure.

The correlation between hydrostatic pressure (P) and refractive index (n) can be mathematically expressed through the following equation [21]:

$$n = n_0 - (c_1 + 2c_2)\sigma \tag{1}$$

Where c_1 and c_2 are defined as:

$$c_1 = \frac{n_0^3\ (p_{12} - 2Vp_{11})}{2E} \tag{2}$$

$$c_2 = \frac{n_0^3\ [(p_{12} - V(p_{11} + p_{12}))]}{2E} \tag{3}$$

In this context, n_0 represents the refractive index of silicon under zero pressure (0 GPa), σ denotes the applied hydrostatic pressure, c_1 and c_2 are the stress-optic constants, V signifies Poisson's ratio, E corresponds to Young's modulus, and p_{11} and p_{12} are the strain-optic coefficients.

A positive linear correlation is established between the refractive index of silicon within the sensor and the magnitude of the applied hydrostatic pressure. This relationship manifests as an incremental rise in the refractive index of silicon, quantified at 0.03985 per GPa increase in pressure.

3. Basic structure and analysis of photonic properties

The fundamental structure of the photonic circuit under investigation is a two-dimensional array of silicon (Si) rods suspended in air (refractive index n = 1). These rods are arranged in a square pattern, with a lattice of 29 rows and 29 columns.

The distance between two adjacent rods, denoted by "a", is the same in the X and Z directions and is 0.5635 µm.

The radius of the rods, "r", is equal to 0.2a. In order to analyze the behavior of light within the structure and its optical confinement properties, a numerical method based on plane wave expansion (PWE) was employed. This approach allowed for the study of the propagation modes and photonic bandgaps (PBGs) of the structure, using carefully selected structural parameters. The results obtained are presented in Figure 1.

The structure exhibits two TE (Transverse Electric) mode-specific Brillouin bandgaps (PBGs). These PBGs lie in distinct wavelength ranges, namely 1361.11 nm to 2102.61 nm for the first and 774 nm to 805 nm for the second, corresponding to filling factor a/λ of 0.268 to 0.414 and 0.7 to 0.728, respectively.

It is crucial to highlight the perfect match between the first TE mode PBG (1361.11 nm to 2102.61 nm) and the third optical window of silicon (Si), which is known for its low losses.

This remarkable coincidence makes the proposed structure exceptionally well-suited for the intended application, namely pressure sensors.

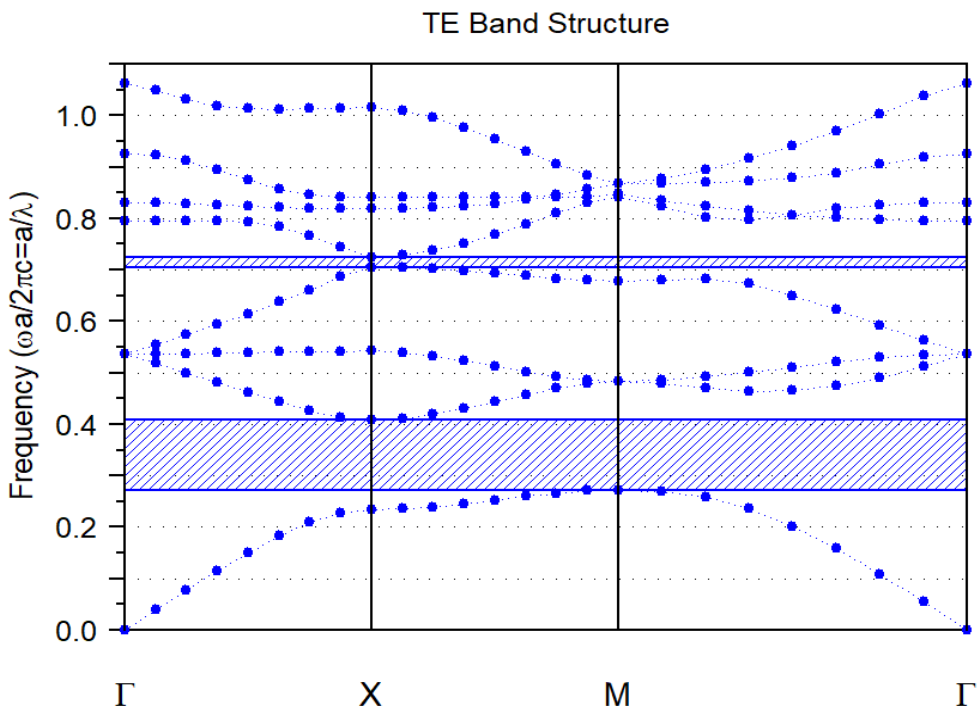

Figure 1. The fundamental PhC band structure

4. Optical pressure sensor design

A Gaussian optical signal with a central wavelength of 1550 nm is initially injected into the input port of an optimized ring resonator.

The device is designed to promote the exclusive transmission of this specific wavelength while attenuating others. The signal passes through the resonator in an air medium with a pressure of 0 GPa and is collected at the output port. The analysis of the output spectrum is performed by applying the Fast Fourier Transform (FFT) to the Gaussian signal recorded and stored by a sampling oscilloscope (represented in green) (Figure 2a and 2b). The Finite-Difference Time-Domain (FDTD) method is used to simulate the normalized transmission spectrum at the output of the resonator in the presence of pressures applied to the sensor surface.

This approach allows for the evaluation of the influence of these pressures on the transmission properties of the resonator and to characterize its sensitivity to pressure detection.

Evaluating the performance of pressure sensors is crucial to ensure their reliability and effectiveness in various industrial applications.

A key parameter in this evaluation is the quality factor Q, which reflects the sensor's ability to discriminate between different wavelengths of the light spectrum. This quality factor is defined as the ratio of the resonance wavelength (λ) to the full width at half maximum (FWHM) of the wavelength spectrum (Δλ).

The quality factor Q can be calculated using the following equation:

$$Q = \lambda / \Delta\lambda \qquad (4)$$

Where: λ represents the resonance wavelength of the sensor

Δλ corresponds to the full width at half maximum of the wavelength spectrum.

Measuring the quality factor (Q) is paramount for evaluating the sensitivity and accuracy of a pressure sensor.

A high Q-factor signifies superior spectral resolution, making it an invaluable metric for sensor performance assessment.

In the context of ring resonators, the Q-factor plays a pivotal role in quantifying energy storage and loss. A higher Q-value translates into a sharper peak at the resonant wavelength, highlighting the direct proportionality between Q and energy storage and the inverse proportionality between Q and energy loss. Consequently, determining the Q-factor of the proposed pressure sensor holds significant importance in this domain.

The findings of this investigation reveal a displacement of resonance wavelength values toward higher magnitudes with each increment of pressure, suggesting enhanced sensitivity across all tested conditions.

The efficacy of the microstructure-based optical sensor is quantitatively assessed through the sensitivity of the refractive index in response to varying pressure levels.

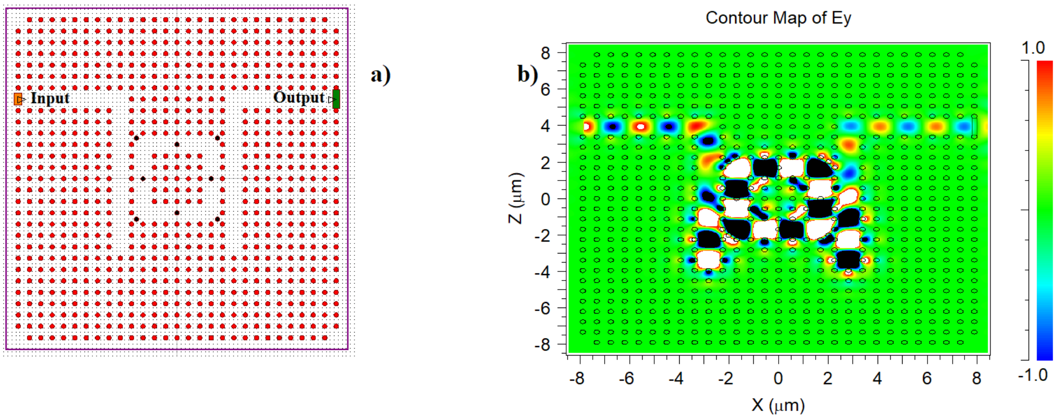

Figure 2. a) Proposed Pressure Sensor Layout. b) Behavior of the optical field inside the pressure sensor

Table 1. Simulated Performance Parameters (Pressure level, Wavelength, Transmission efficiency, Q-Factor, Sensitivity) of the Sensor under Hydrostatic Pressure

Pressure level (GPa)	Refractive Index of Refraction (RIU)	Resonance wavelength (nm)	Transmission efficiency (%)	Quality factor	Pressure sensitivity (nm/GPa)
0	3.42	1550	97.2	1550	Ref.
1	3.45985	1555.0	97.7	1727	5
2	3.4997	1559.4	97.9	1732	4.7
3	3.53955	1563.7	98.3	1954	4.56
4	3.5794	1568.0	98	2240	4.5
5	3.61925	1572.3	96.9	2620	4.46
6	3.65	1575.6	96.9	2626	4.2
7	3.69895	1580.9	97.3	2634	4.41
8	3.7388	1585.2	92.7	2642	4.4
9	3.77865	1589.5	96.7	2649	4.38
10	3.8185	1593.9	92.8	2656	4.39

This sensitivity is characterized as the ratio of the shift in resonance wavelength to the corresponding change in the refractive index induced by the applied pressure:

$$S_n = \frac{\Delta\lambda}{\Delta n} \quad (5)$$

Where $\Delta\lambda$ represents the resonance wavelength shift and Δn corresponds to the refractive index variation for each pressure. Generally, an elevation in refractive index sensitivity corresponding to each pressure level results in notable shifts in the resonance wavelength, contingent upon these refractive index changes. Within the framework of this research, the annular resonator micro-sensor demonstrates a remarkably high sensitivity to applied pressure, achieving approximately 4.39 nm/GPa. For each pressure condition examined, Figure 3 and Table 1 encapsulate the performance metrics of the optical pressure sensor, encompassing resonance wavelength, normalized transmission efficiency, quality factor, and sensitivity.

5. Results and discussion

The analysis of the data presented in Table 1 elucidates the material's optical properties across a pressure range of 0 to 10 GPa, with measurements taken at 1 GPa increments. The refractive index, an indicator of the material's optical density, rises steadily from 3.42 to 3.8185 as pressure escalates, reflecting a progressive reduction in the speed of light through the medium due to increased densification. Concurrently, the resonance wavelength, which denotes the wavelength of peak material resonance, shifts from 1550 nm to 1593.9 nm, underscoring pressure-induced modifications in the atomic structure of the silicon (Si) material that alter its optical behavior. Transmission efficiency, representing the proportion of light passing through the material, exhibits a marginal decline from 97.2% to 92.8% with rising pressure, suggesting the emergence of additional optical losses at elevated pressure levels. In contrast, the quality factor (Q), a metric of resonance efficiency tied to the narrowness of the resonance bandwidth, demonstrates a significant enhancement, increasing from 1550 to 2656, indicative of improved resonance performance under higher pressure. Lastly, the pressure sensitivity, defined as the change in resonance wavelength per unit of pressure, remains relatively stable, fluctuating between 4.2 and 4.7 nm/GPa, which points to a consistent and linear response of the Si material to applied pressure across the tested range.

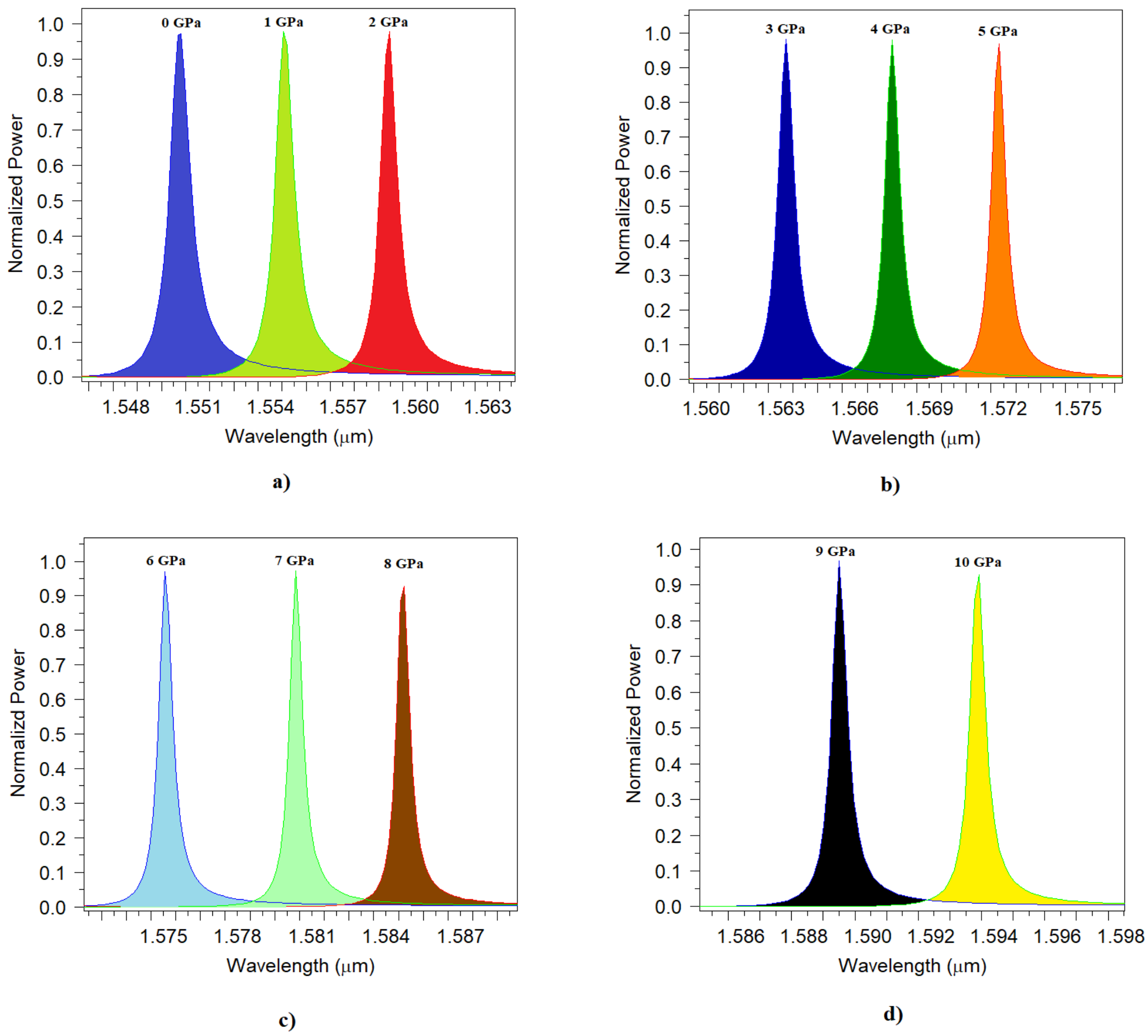

Figure 3. Normalized transmission spectra, acquired for each applied pressure within the range of 0 to 10 GPa, are presented near the resonance peaks in units of [GPa]

Table 2. Comparative analysis with state-of-the-art pressure sensors

Reference	Structure	Pressure Range	Sensitivity	Q-Factor	footprint
Our work	PC 2D Ring Resonator (Si)	0 – 10 GPa	4.39 nm/GPa	1550 – 2656	274 μm^2
[19]	polymer-(PC)	0 – 7 GPa	0.021 μm/GPa	29 363	-
[20]	PC Microcavity	0 - 3 GPa	18.2 nm/GPa	4296 - 8638.5	265.8 μm^2
[22]	PC Microcavity	0 – 4 GPa	3.5 nm/GPa	2200	-
[23]	PC Microcavity	0 – 2 GPa	13.9 nm/GPa	1500	300 μm^2

To effectively position the performance of our proposed design against recent work in the field of photonic crystal-based pressure sensors, Table 2 presents a comparison of key performance parameters.

Our sensor, based on a silicon square-ring resonator, is distinguished primarily by its impressive operational range of 0 to 10 GPa, which is significantly broader than that of most comparable devices focused on low or medium-pressure applications.

While the average sensitivity is reported as 4.39 nm/GPa, a figure typical for photoelastic sensors operating in this very high-pressure regime, the total resonance wavelength shift is substantial at 43.9 nm, ensuring excellent resolution across the entire measurement span.

Furthermore, the structure exhibits a high Quality Factor (Q), reaching 2656 at 10 GPa, which guarantees superior spectral resolution.

Crucially, with an ultra-compact footprint of only 274 μm^2, our design confirms its viability for seamless, large-scale integration into Photonic Integrated Circuits (PICs), establishing a new benchmark for miniaturization in high-pressure sensing.

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6. Conclusion

This research introduces and examines an innovative configuration for a photonic crystal pressure sensor (PCPS) characterized by enhanced sensitivity. The sensor's core architecture is predicated on a square array of silicon rods embedded within an air medium. The proposed design incorporates two quasi-linear waveguides interconnected via a ring resonator. The operational mechanism relies on the modulation of the silicon material's refractive index, which varies in response to pressure fluctuations spanning 0 to 10 GPa. This alteration precipitates a pronounced shift in the sensor's operational wavelength. The device demonstrates a remarkable sensitivity of approximately 4.39 nm/GPa, alongside an exceptionally rapid response time, a superior quality factor, and a notably compact form factor. The design is distinguished by its robustness and its seamless adaptability for integration into a diverse array of sensing applications.

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Authors Contribution
E. Kouddad designed the sensor and performed simulations; H. Dahbi and S. B. Chabani analyzed the data; I. Hassani and N. Kaddouri drafted the manuscript. All authors approved the final version.

Availability of data and materials
Data are available from the corresponding author upon reasonable request.

Conflict of interests
The authors declare no conflicts of interest regarding this article.

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