

High sensitivity pressure sensing via two-dimensional germanium photonic crystal

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This research focuses on enhancing the accuracy and properties of optical sensors, particularly those based on a two-dimensional (2D) photonic crystal (PhC) structure with a triangular lattice composed of germanium (Ge). The primary objective is to improve sensitivity (S) and the quality factor (Q) within the pressure range of 1 GPa to 1.7 GPa, a critical parameter in sensor design. To achieve this, adjustments were made to the cavity within the sensing structure, and the radius of designated slots along the linear waveguide was fine-tuned. Using computational techniques such as Plane Wave Expansion (PWE) and Finite Difference Time Domain (FDTD) simulations, the photonic band gap (PhC), and transmission characteristics were thoroughly analyzed. The results demonstrate a linear shift in sensor response toward lower wavelengths with increasing pressure levels, achieving maximum sensitivity of 456 nm/RIU equivalent to 19.1 nm/GPa, a quality factor of 2931.16, a transmission rate of 99.56%, and an impressive full width at half maximum (FWHM) of 0.6 nm. These findings confirm the feasibility of the design as a high-sensitivity and high-quality pressure sensor, suitable for practical applications in pressure detection. The validation, supported by RSoft simulations and graphical representations, highlights favorable outcomes in terms of transmission values, sensitivity, and quality factor in the optimized sensor design.

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1. Introduction

In late 1987 Eli Yablonovitch and Sagiv John introduced a concept for visualizing photonic crystals (PhCs) [1], which can manipulate the flow of light. A photonic crystal is essentially a structured material characterized by periodic variations in refractive index, typically on the scale of light wavelengths, occurring in one, two, or three dimensions.

In recent times, one of the emerging areas that has garnered considerable attention and occupies a prominent position in technological design is photonic crystal design. Consequently, any structure characterized by intermittent changes in refractive index (RI) is referred to as a PhC [2].

Researchers find the properties of photonic crystals particularly attractive, including features such as the photonic band gap (PBG), refractive effect, and the localization effect. Devices can be produced by incorporating localized or linear defects into this structure [3], such as waveguides [4,5], nanocavities [6,7], lasers [8,9], filters [10,11], optical fibers [12,13], and various types of optical sensors.

In PhC characterized by uniform periodicity, a notable attribute is the inhibition of wavelength dispersion within a band referred to as the PBG, to achieve the localization of light within the PBG range [38], a strategy that involves the creation of a localized defect within the crystal structure, forming a waveguide or an optical cavity [14]. In industries related to monitoring, including the industrial, environmental, and agricultural sectors, pressure sensors are highly demanded [15,16]. There has been significant interest in scientific research focused on these sensors due to their compact size, high sensitivity, responsiveness, and resistance to interference [17].

Due to the easy, speed, and high sensitivity of examining and detecting pressure ranges, optical devices are widely used and implemented today. An optical pressure sensor is a device that converts applied pressures into wavelengths that can be read and studied. Thus, it can be used for a variety of applications including weather monitoring, process control, military applications, and clinical analysis [37]. Transitioning from electronic sensors to optical sensors constructed from photonic

crystal fibers represents a significant advancement and substantial contribution to the realm of technology.

In recent years, there has been a growing interest in ultra-small optical sensors among researchers. These sensors are highly regarded within the optical community for their ability to meet modern demands due to their advantages, such as being lightweight, compact, low-power consuming, fast-responding, and high-resolution, as well as being adaptable to various applications [18]. Concurrently, photonic crystal structures have captured significant attention from researchers, often compared to optical analogs of semiconductors, for their capability to control and manipulate the propagation of light or photons [19]. Projects are currently focusing on the development of low-power, high-sensitivity, compact, and precise optical sensors utilizing the electromagnetic field for a variety of applications [20]. However, as device sizes decrease, optical losses tend to increase [21]. To tackle this issue, photonic crystal-based devices are being widely utilized to scale down devices to the nanoscale while minimizing optical loss and achieving robust photon confinement within the waveguide [22].

This study proposes and develops a novel pressure sensor based on a two-dimensional (2D) photonic crystal linear waveguide, incorporating a triangular grating with enhanced air holes. The design further integrates a localized cavity where the air hole radii are strategically varied to achieve high sensitivity in detecting subtle fluctuations in the refractive index.

The sensing mechanism works by monitoring changes in the transmission spectrum when the RI of the germanium photonic crystal undergoes modification due to hydrostatic pressure applied to the sensor surface. In photonic crystal sensors, the refractive index is used as the detection element [23]. This sensing principle is based on the phenomenon of resonant wavelength shift during the transmission process, which is caused by changes in the refractive index of the sensor. This study investigated a pressure sensing module consisting of a photonic crystal and linear waveguides with a scale ranging from 1 GPa to 1.7 GPa.

It is worth mentioning that previously, a sensitivity of 2 nm/GPa was achieved within the pressure range of 0 GPa to 7 GPa by K.V.Shanthi et al [24]. Furthermore, a sensitivity ratio of 15.8 nm/GPa was obtained within the range of 0 GPa to 10 GPa by T.Zouache et al [25]. Additionally, sensitivities of 13.9 nm/GPa within the range of 0 GPa to 2 GPa were achieved by S.TAO et al [26] and 18.2 nm/GPa within the range of 0 GPa to 3 GPa were reached by E.Kouddad et al (2023) [27]. E. Kouddad et al have recently (2026) achieved values of 4.39 nm/GPa [36].

2. Description of the structure

Photonic crystals (PhC) are periodic dielectric materials capable of governing the propagation and manipulation of light, in our research Fig. 1 (a) depicts the used 2D PhC (XZ) plane, which includes a 2D triangular

photonic lattice crystal of 21×21 , this crystal structure consists of numerous air holes arranged within a sheet of germanium slab (Ge) with a refractive index of $n_{\text{Ge}} = 4$, where the lattice constant is defined as $a = 0.44 \mu\text{m}$, the air holes have a radius $r = 0.38 \times a \mu\text{m}$, the basic feature of a PhC is the PBG, taking into account the structure with circular air holes and no defects, the calculation used the plane wave expansion (PWE) method to calculate the photonic band gap diagram of the structure, this analysis was performed along the Γ -M-K- Γ edge path within the Brillouin zone, analysis of the crystal shown in Fig. 1 (b) reveals a broad forbidden band centered around an average natural frequency of $a/\lambda = 0.27129$ operating in TM mode, this band extends between the standard frequencies of 0.20382 (a/λ) and 0.33876 (a/λ), corresponding to wavelengths from 1.298 μm to 2.158 μm .

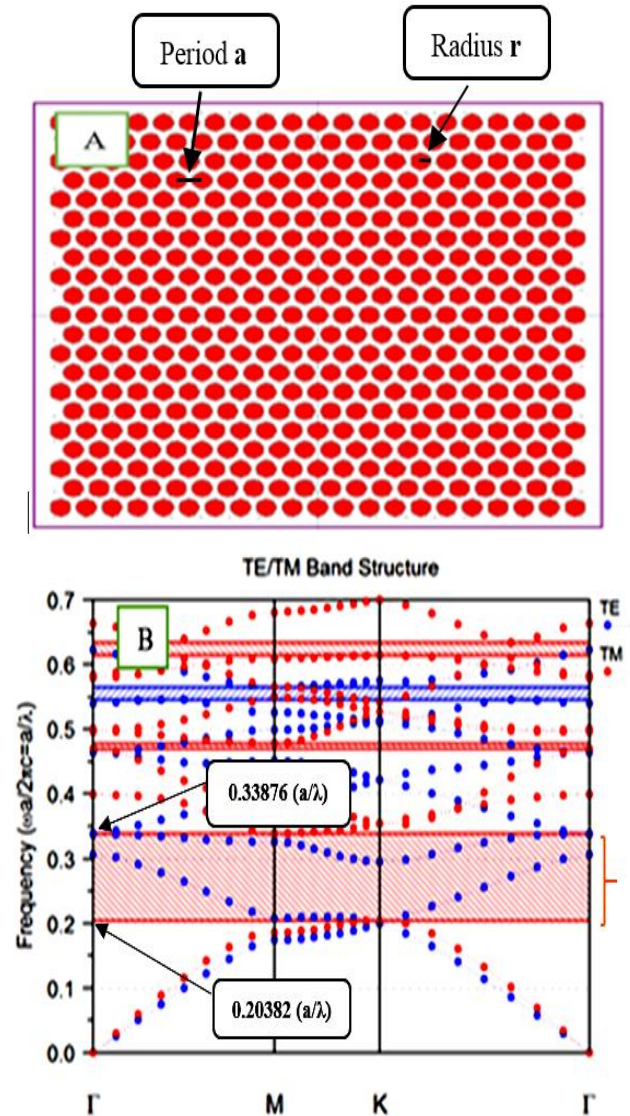


Fig. 1. (a) Basic photonic crystal configuration with a triangular lattice (21×21), characterized by parameters $a = 0.44 \mu\text{m}$ and $r = 0.1672 \mu\text{m}$, without defects; (b) Dispersion curves and PBG for TM polarizations observed in the fundamental structure (colour online)

3. Numerical simulation and analysis

The contour map presented illustrates Fig. 2 (a) the refractive index profile of both the hole and slab components along the xz axis, the color bar accompanying the map indicates the refractive index values, ranging from 1 to 4, providing a comprehensive visual representation of the refractive index distribution within the structure.

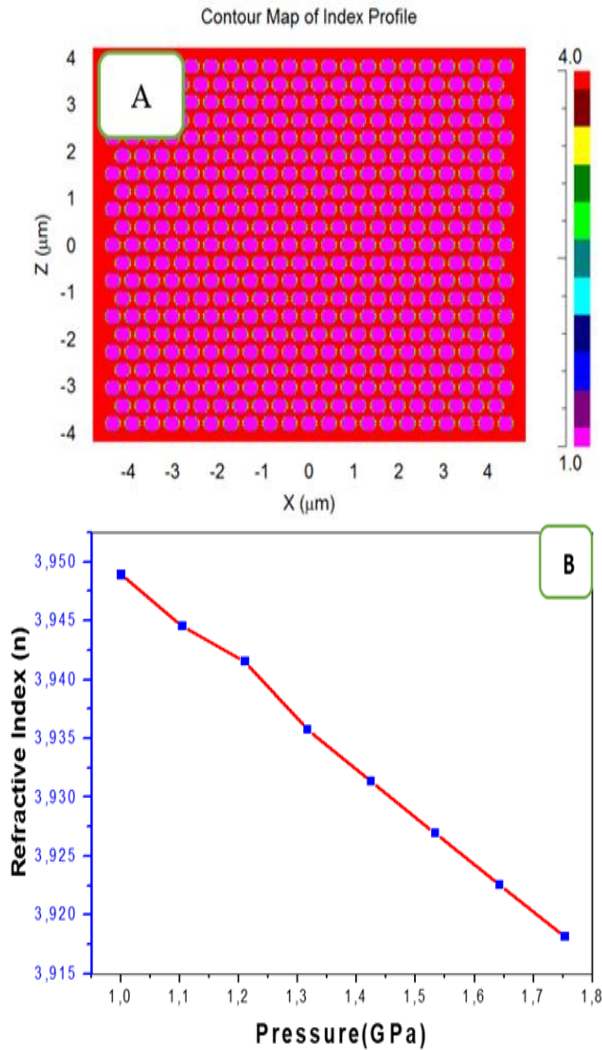


Fig. 2. (a) Shows the contour map of the refractive index profile of the hole and slab along the xz axis (the color bar indicates the RI ranging from 1 to 4); (b) a linear curve to depict the relationship between the refractive index of Germanium (Ge) values and the pressure applied in the design (colour online)

The correlation between the applied hydrostatic pressure P and the refractive index n_{Ge} of germanium is provided [25,28]:

$$n_{Ge} = \sqrt{15.94 - 0.36 \times P + 0.014 \times P^2} \quad (1)$$

Applying relation (1) we graphically represent the variation in the refractive index of germanium within our designated pressure range from 1 GPa to 1.7 GPa. The

results are depicted in Fig. 2 (b) This curve illustrates a line decline in the refractive index in response to the applied pressure. Hence, this pressure range can be effectively employed in simulating the sensor. Using finite-difference time-domain (FDTD) to investigate the properties of light in plasmonic guides coupled in cavities [31,32].

Moreover, within the context of the depicted linear waveguide, identified as w1 in the illustration, there is an ongoing investigation into the impact of functional line defects on transmission, dispersion, and light-directing properties.

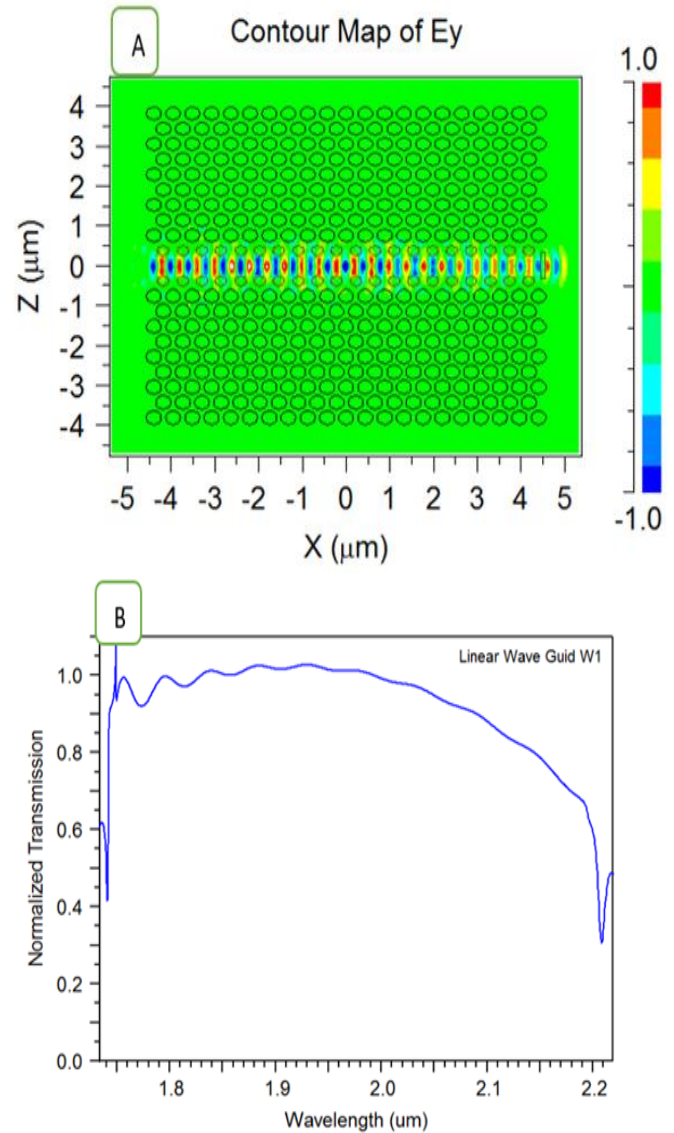


Fig. 3. (a) Illustrates the distribution of the electric field through the guide W1 in the XZ plane; (b) Transmittance of a linear wave guide varying with wavelength (colour online)

Specifically, modifications have been made to the holes positioned at the core of the design, with their radii adjusted along the two ends of the guide. Additionally, the electric field distribution of the waveguide is depicted for detailed analysis in Fig. 3 (a), the magnetic field

distribution shows how the magnetic field is spatially confined and propagated inside the photonic crystal structure, the magnetic field intensity is mainly concentrated in specific regions of the crystal, indicating strong localization of the electromagnetic wave. The field decreases rapidly outside these regions, which confirms the presence of a photonic band gap and efficient confinement of light. The distribution also reflects the effect of the periodic structure on controlling wave propagation and guiding the electromagnetic energy through the desired path.

Fig. 3 (b) depicts the exit ratio and excellent transmission values achieved by an optimized linear waveguide, notably, these results are obtained without any loss in transmission value, and no local defects are introduced into the design.

Fig. 4 (a) illustrates our sensor structure, which comprises a linear waveguide with a radius ratio of $R_v=0.29 \times a$, this configuration is achieved by selectively removing a single row of air holes in the ΓK direction, and the waveguide is seamlessly integrated with a centrally localized cavity characterized by the ratio of radius $R_b=0.5 \times a$ (which in turn is the element that contributes to improving the performance and characteristics of the sensor), and $R_j=0.25 \times a$ shown in blue and yellow respectively, aligned with the guide at the entrance of the waveguide a pulsed light source emitting Gaussian wavelengths of $1.55 \mu\text{m}$ is employed, adhering to the wavelength standard for communication devices. At the exit, a screen is positioned to meticulously capture the exit ratio at the terminus of the waveguide.

As illustrated in the typical transmission spectra of the sensor in Fig. 4 (b), the resonance wavelength at its resting state (where $P = 0$ GPa) was determined to be $\lambda_0 = 1.8028 \mu\text{m}$ pressure ranging from 1 to 1.7 GPa is gradually applied to verify the design performance, throughout the range studied, the sensor transmission rate remains consistently high, ranging from 98% to 99.56%, showing a homogeneous and linear behavior. The noticeable trend in the figure is that as the applied pressure increases, the wavelength decreases, this indicates a clear inverse relationship between the resonance wavelength and the applied hydrostatic pressure. To evaluate the sensor's performance and precisely gauge the hydrostatic pressures it sustains, we analyzed the data from Table I to characterize its sensitivity, as illustrated in Fig. 5. The design exhibits an exemplary and highly satisfactory sensitivity profile, peaking at 19.1 nm/GPa near 1.1 GPa and maintaining a consistent response of approximately 17 nm/GPa across the remaining pressure range. This sensitivity is fundamentally driven by the application of uniform hydrostatic pressure, which compresses the photonic crystal structure and reduces the lattice constant while simultaneously inducing shifts in the material's refractive index. These structural and optical perturbations modify the photonic band gap and light propagation characteristics, demonstrating that hydrostatic pressure serves as an effective mechanism for tuning and controlling the optical properties of the photonic crystal sensor.

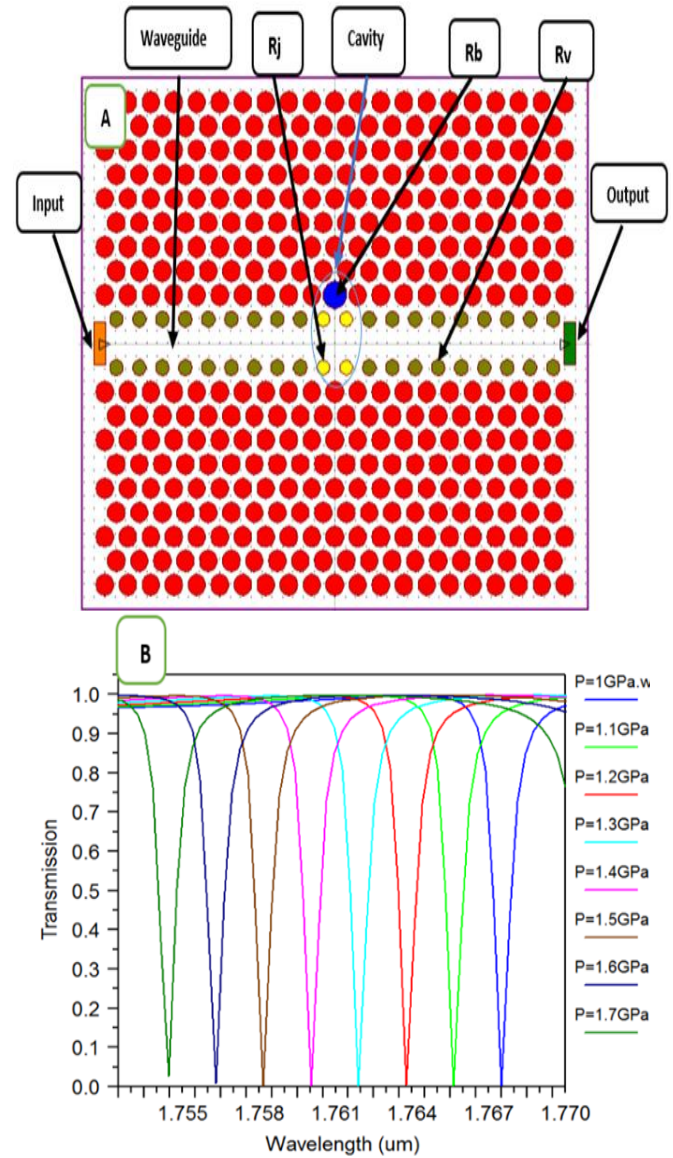


Fig. 4. (a) Schematic diagram of the 2D-PhC pressure sensor; (b) Illustrates the normalized transmission spectra of the sensor (colour online)

The sudden increase in sensitivity at 1.1 GPa is attributed to the nonlinear effect of hydrostatic pressure on the photonic crystal parameters, particularly the refractive index and lattice spacing. This behavior is not accidental and reflects an enhanced optical response near this pressure value. However, it does not indicate that is outside the sensing range; rather, it represents a region of higher sensitivity within the operating range of the sensor.

The shift in the transmission peak with increasing pressure is attributed to a decrease in the lattice constant and a change in the refractive index under hydrostatic pressure. As the density of the optical crystal structure increases, the resonant wavelength shifts towards shorter wavelengths, resulting in a change in the transmission spectrum.

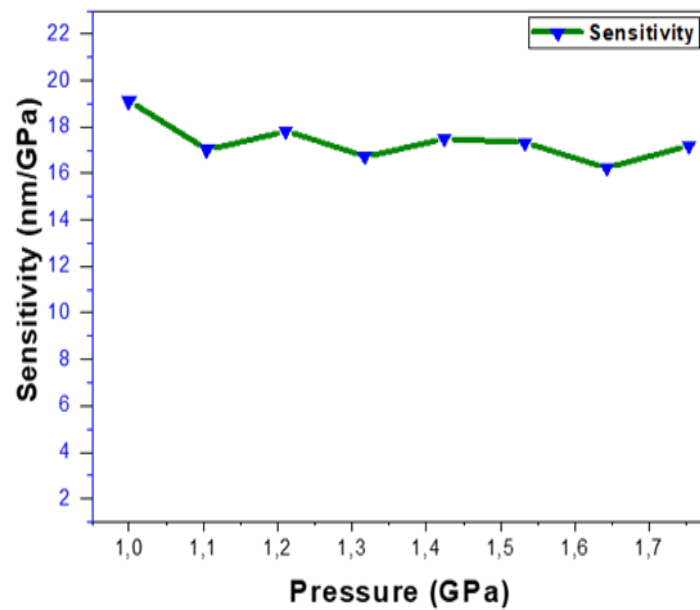


Fig. 5. Variation of sensitivity in the output of the sensor as a pressure (colour online)

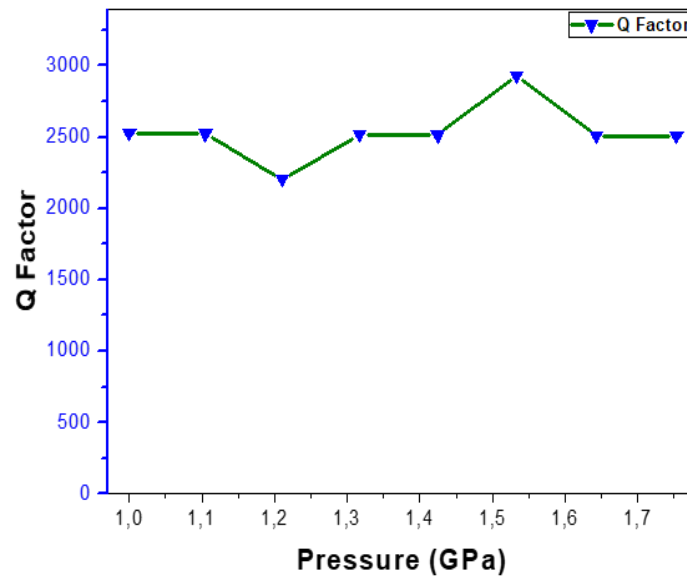


Fig. 6. Variation Q factor in the output of the sensor as a function of pressure (colour online)

Fig. 6 illustrates the quality factor in terms of pressure. The quality factor plays a crucial role in sensor design, aiding in minimizing the overlap of exit peaks and effectively distinguishing them from one another, a lower quality factor implies the presence of overlapping sensor pulses, based on our results, the quality factor ranges from a minimum value of 2205.375 to a maximum value of 2931.16, this indicates a favorable degree of peak separation and minimal pulse overlap, affirming the effectiveness of our design.

Table 1 below displays the simulation results, showing changes in resonance wavelengths corresponding to small changes in refractive indices. The sensor shows consistent and impressive sensitivity and quality factors.

Table 2 shows a comparative study of the optimal sensitivity obtained with other previous works we can observe that the sensitivity obtained 19.1 nm/GPa is very remarkable.

Table 1. Summarizes the results of the pressure analysis along with its corresponding refractive index, wavelength, *Q* factor, and sensitivity

Pressure (GPa)	Refractive index	Wavelength (nm)	Sensitivity (nm/RIU)	FWHM (nm)	Q factor	Sensitivity (nm/GPa)
1	3.94892390	1768.1	456	0.7	2525.85	19.1
1.1	3.94454053	1766.1	410	0.7	2523	17.04
1.2	3.94015228	1764.3	432	0.8	2205.375	17.82
1.3	3.93575913	1762.4	409	0.7	2517.71	16.73
1.4	3.93136108	1760.6	431.5	0.7	2515.14	17.49
1.5	3.92695811	1758.7	431	0.6	2931.16	17.32
1.6	3.92255019	1756.8	408	0.7	2509.71	16.25
1.7	3.91813731	1755.0	435	0.7	2507.14	17.18

Table 2. Comparison of the proposed pressure sensor with various similar PhC designs

References	Year	Material	Sensitivity (nm/GPa)
[24]	2016	Ge	13.7
[25]	2017	Ge	15.8
[39]	2025	Ge	12
[27]	2018	Ge	15.3
[33]	2023	Si	18.2
[35]	2023	Si	3
[36]	2026	Si	4.39
In this work	2025	Ge	19.1

Table 3. Comparison of the proposed pressure sensor with various similar PhC designs

Parameters	Values
Structure	Holes in Slab
Structure made of Lattice	Triangular
Plane	XZ
Lattice constant <i>a</i>	0.44 μm
Size	21 $\times$ 21
The radius of the Holes <i>r</i>	0.1672 μm
Refractive Index of the Slab Ge	4
Polarization	TM
The radius of the Holes in the cavity	0.22 μm
Refractive Index of Holes	1
Photonic Band Gap Range	1.298 μm – 2.158 μm

Table 3 shown above was compiled to document the parameters and their corresponding values used in the construction and design of the sensor for easy reference and accessibility.

4. Conclusion

This study investigates a high-sensitivity pressure sensor utilizing a Germanium-based 2D photonic crystal slab. The sensing mechanism relies on the hydrostatic pressure-induced deformation of air holes and refractive index modulation, which triggers a measurable shift in resonant wavelengths. By optimizing structural parameters and cavity configurations, the design achieves a

remarkable sensitivity of 19.1 nm/GPa and a quality factor of 2931.16. Simulation results confirm excellent transmission characteristics, demonstrating performance metrics that rival or exceed existing state-of-the-art designs. These advancements underscore the sensor's potential for high-precision, scalable applications in diverse industrial and scientific fields.

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