

TUNABLE PRESSURE AND TEMPERATURE SENSOR BASED ON 2D GaAs PHOTONIC CRYSTAL

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I, **Nikhil Kumar**, Roll No.: 24/MSCPHY/49 hereby certify that the work which is being presented in the thesis entitled "**Tunable Pressure and Temperature Sensor Based on 2D GaAs Photonic Crystal**", " in partial fulfillment of the requirements for the award of the Degree of Master of Science, submitted in the Department of Applied Physics, Delhi Technological University is an authentic record of my own work carried out during the period from August 2025 to May 2026 under the supervision of **Dr. Yogita Kalra**.

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ABSTRACT

Photonic crystals (PhCs) offer unprecedented control over the propagation of light through the existence of a photonic band gap (PBG)—a range of frequencies that is forbidden inside the periodic dielectric lattice. When the optical properties of the constituent material are made to depend on an external stimulus, the band gap, and consequently the optical response of the crystal, becomes *tunable*, which is the operating principle of a photonic-crystal sensor. This dissertation presents the design and computational analysis of a tunable **pressure** and **temperature** sensor based on a two-dimensional (2D) Gallium Arsenide (GaAs) photonic crystal.

Two complementary device geometries are investigated. For *pressure sensing*, a 2D square lattice of GaAs rods ($\varepsilon = 12.96$, $r = 0.2a$) in an air background is modelled using the Plane Wave Expansion (PWE) method implemented in MIT Photonic Bands (MPB). A wide Transverse-Magnetic (TM) band gap is obtained between the normalized frequencies 0.286 and 0.421. The elasto-optic effect is modelled as a linear increase of the rod refractive index with hydrostatic pressure, and the resulting systematic red-shift of the mid-gap wavelength yields a pressure sensitivity of **2.171 nm/GPa**. For *temperature sensing*, a finite hexagonal two-dimensional photonic-crystal ring resonator (2DPCRR) is analysed using the Finite-Difference Time-Domain (FDTD) method implemented in Meep. The thermo-optic effect ($dn/dT = 2.3 \times 10^{-4} \text{ }^\circ\text{C}^{-1}$) shifts the resonant transmission peak linearly over the range 0–360 $^\circ\text{C}$, giving a temperature sensitivity of **27.9 pm/ $^\circ\text{C}$** . A complementary complete-PBG analysis of a triangular lattice confirms the linear thermal tuning trend with a mid-gap sensitivity of 0.0704 nm/K.

All simulations were carried out in Python on an Ubuntu (WSL) environment using the open-source MPB and Meep libraries. The results establish GaAs as a high-contrast, highly linear platform for near-infrared photonic-crystal sensing and provide a foundation for future defect-engineered, high- Q resonant sensor designs.

Keywords: Photonic crystal, Photonic band gap, GaAs, Elasto-optic effect, Thermo-optic effect, Plane Wave Expansion, FDTD, MPB, Meep, Pressure sensor, Temperature sensor, Ring resonator.

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LIST OF SYMBOLS

Symbol	Description	Unit
a	Lattice constant	nm
r	Radius of dielectric rod	nm
n	Refractive index	—
n_0	Base (zero-stimulus) refractive index	—
ε	Relative dielectric permittivity	—
ω	Angular frequency	rad s ⁻¹
c	Speed of light in vacuum	m s ⁻¹
λ	Wavelength of light	nm
$\mathbf{H}$	Magnetic field vector	A m ⁻¹
$\mathbf{E}$	Electric field vector	V m ⁻¹
$\mathbf{k}$	Bloch wave vector	m ⁻¹
$\mathbf{G}$	Reciprocal lattice vector	m ⁻¹
P	Applied hydrostatic pressure	GPa
T	Temperature	°C / K
C	Effective elasto-optic coefficient	GPa ⁻¹
C_{11}, C_{12}	Elastic stiffness constants	GPa
dn/dT	Thermo-optic coefficient	°C ⁻¹
λ_{mid}	Mid-gap wavelength	nm
S_P	Pressure sensitivity	nm/GPa
S_T	Temperature sensitivity	pm/°C
Q	Quality factor of the resonator	—

LIST OF ABBREVIATIONS

Abbreviation	Full Form
PhC	Photonic Crystal
PBG	Photonic Band Gap
CPBG	Complete Photonic Band Gap
2D	Two-Dimensional
3D	Three-Dimensional
GaAs	Gallium Arsenide
Si	Silicon
TM	Transverse Magnetic
TE	Transverse Electric
PWE	Plane Wave Expansion
FDTD	Finite-Difference Time-Domain
MPB	MIT Photonic Bands
2DPCRR	2D Photonic Crystal Ring Resonator
PML	Perfectly Matched Layer
IBZ	Irreducible Brillouin Zone
NIR	Near Infrared
WSL	Windows Subsystem for Linux
FWHM	Full Width at Half Maximum
IoT	Internet of Things

CHAPTER 1

INTRODUCTION

1.1 Overview

Photonic crystals (PhCs) represent a paradigm shift in the control and manipulation of light. First proposed independently in 1987 by Eli Yablonovitch and Sajeev John [2, 3], these materials are characterised by a periodic modulation of the dielectric constant on the length scale of the wavelength of light. This periodicity influences the propagation of electromagnetic waves in a manner that is directly analogous to the way the periodic potential of an atomic lattice governs the motion of electrons in a semiconductor. Just as a semiconductor possesses an electronic band gap—a range of energies in which electron states are forbidden—a photonic crystal can possess a **Photonic Band Gap (PBG)**: a range of frequencies for which the propagation of light is strictly forbidden, either along particular directions or, in the case of a *complete* band gap, along all directions and for all polarizations.

The physical origin of the photonic band gap lies in the macroscopic Maxwell equations. When an electromagnetic wave travels through a periodic dielectric medium, it undergoes Bragg scattering at the interfaces between the high- and low-index regions. For certain wavelengths, the multiply scattered waves interfere destructively, and propagation is prohibited. This remarkable ability to “mould the flow of light” [1] has enabled a wide range of novel optical devices, including low-loss waveguides that can guide light around sharp bends, low-threshold photonic-crystal lasers, high- Q nano-cavities, and—of particular relevance to this work—highly sensitive optical sensors [14].

1.2 Classification of Photonic Crystals

Photonic crystals are classified by the number of spatial dimensions along which the dielectric constant is periodically modulated. A **one-dimensional (1D)** photonic crystal—the classic Bragg mirror or dielectric stack—is periodic along a single axis and can possess a band gap only for propagation along that axis. A **two-dimensional (2D)** photonic crystal is periodic in a plane and uniform along the third (rod or hole) axis; it can exhibit an in-plane band gap for one or both po-

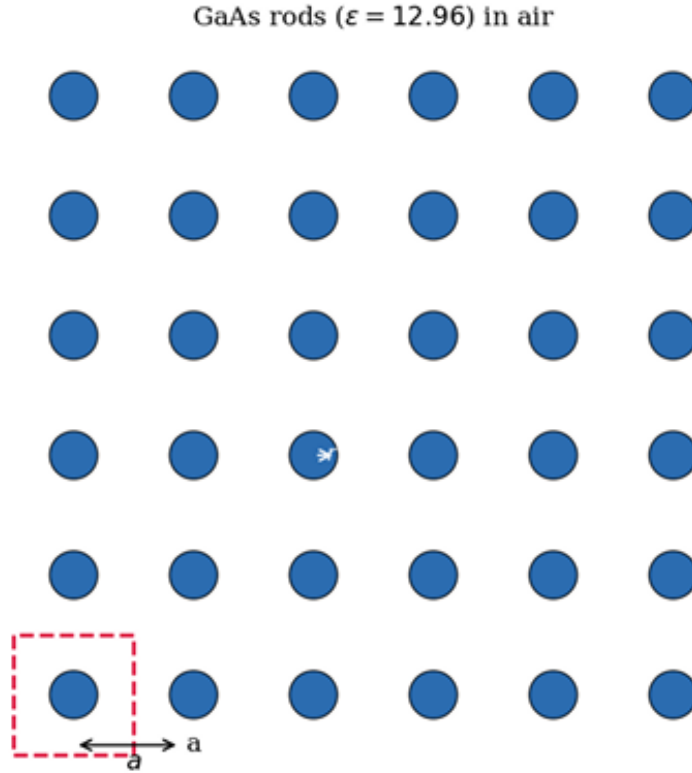


Figure 1.1. Schematic of the proposed two-dimensional square lattice of GaAs dielectric rods in an air background. The lattice constant is a and the rod radius is $r = 0.2a$.

larizations and is the geometry adopted throughout this dissertation, owing to the favourable balance it strikes between strong optical confinement and manageable fabrication and simulation complexity [1]. A **three-dimensional (3D)** photonic crystal is periodic in all three directions and is the only class that can support a truly omnidirectional complete band gap, at the cost of considerably more demanding fabrication [1]. The 2D crystals studied here are realised as a lattice of high-index GaAs rods standing in a low-index air background; this “rods-in-air” configuration is well known to favour a wide band gap for the Transverse Magnetic polarization, which is exactly the regime exploited by the proposed pressure sensor [1, 5].

1.3 Tunable Photonic Crystals

A conventional photonic crystal possesses a fixed band gap that is determined entirely by its geometry (lattice type, filling fraction) and by the dielectric contrast of its constituent materials. A **tunable** photonic crystal is one in which the band-gap position or width can be deliberately and reproducibly shifted by the application of an external stimulus. Because the spectral position of the band edge—or of a defect resonance—can be measured with very high precision, a tunable photonic

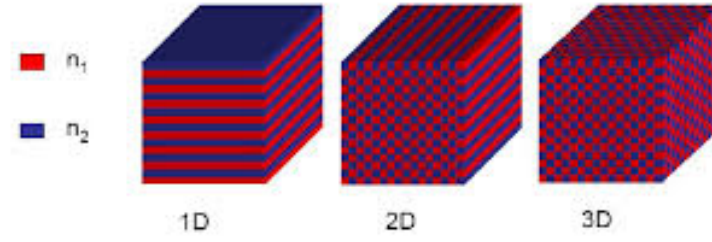


Figure 1.2. Classification of photonic crystals by the dimensionality of the dielectric periodicity: 1D (layered Bragg stack), 2D (rod/hole lattice) and 3D lattice, where n_1 and n_2 denote the two constituent refractive indices.

crystal acts as a transducer that converts a physical quantity (pressure, temperature, strain, analyte concentration) into a measurable optical signal. This is the foundation of photonic-crystal sensing [14].

External stimuli that are commonly used for tuning include temperature, mechanical stress, electric fields, and magnetic fields. Thermo-responsive materials are among the most widely studied [4]: a change in temperature induces either a change in the lattice volume (thermal expansion) or a change in the refractive index (the thermo-optic effect), and both shift the stop band. Likewise, mechanical pressure can produce tunability either through the **elasto-optic effect**—a pressure-induced change of the refractive index—or by physically deforming the lattice. The two mechanisms exploited in this dissertation are the pressure-induced (elasto-optic) index change and the temperature-induced (thermo-optic) index change, both applied to a 2D GaAs photonic crystal.

1.4 Motivation: Gallium Arsenide (GaAs) for Sensing

The vast majority of existing research on tunable photonic-crystal sensors has focused on Silicon (Si), largely because of its mature and inexpensive fabrication infrastructure [13]. However, the ultimate sensitivity of such a sensor is governed by how strongly the constituent material responds to the external stimulus, and silicon is not necessarily optimal in this respect. **Gallium Arsenide (GaAs)** is a direct band-gap III–V compound semiconductor that offers a high refractive index ($n \approx 3.4$ – 3.6 in the near infrared) and excellent optoelectronic properties [12]. Crucially, its elasto-optic and thermo-optic coefficients differ from those of silicon, opening the possibility of enhanced sensitivity in particular operating regimes. Moreover, the very high dielectric contrast of the GaAs/air system ($\varepsilon \approx 12.96$ versus

1.0) produces a wide, robust photonic band gap, which makes the sensor response easy to track and tolerant of fabrication imperfections.

This dissertation therefore investigates two GaAs-based 2D photonic-crystal devices: a square lattice of GaAs rods for pressure sensing, and a hexagonal photonic-crystal ring resonator for temperature sensing. Both operate in the technologically important near-infrared window, and both are analysed entirely by numerical electromagnetic simulation.

1.5 Objective and Scope

The principal objective of this work is to design and computationally characterise a tunable pressure and temperature sensor based on a 2D GaAs photonic crystal, and to quantify its sensitivity. The specific objectives are:

- To compute the photonic band structure of a 2D square lattice of GaAs rods using the Plane Wave Expansion (PWE) method, and to confirm the existence and extent of a TM band gap.
- To model the elasto-optic effect as a pressure-dependent refractive index and to determine the resulting shift of the mid-gap wavelength, thereby extracting the pressure sensitivity $S_P = d\lambda/dP$.
- To design a finite hexagonal 2D photonic-crystal ring resonator (2DPCRR) and to compute its transmission spectrum using the Finite-Difference Time-Domain (FDTD) method.
- To model the thermo-optic effect as a temperature-dependent refractive index and to track the resulting shift of the resonant peak, thereby extracting the temperature sensitivity $S_T = d\lambda/dT$.
- To benchmark the obtained sensitivities against established silicon-based devices reported in the literature.

The scope of the present study is restricted to two-dimensional structures and to purely numerical (simulation-based) analysis. Fabrication and experimental validation are identified as future work.

1.6 Applications of Photonic-Crystal Sensors

Photonic-crystal sensors have attracted intense interest because they combine high sensitivity with a compact, all-optical, and electromagnetically immune form fac-

tor. A band-edge or resonance shift can be read out remotely through an optical fibre, which makes such sensors attractive for harsh or hazardous environments where electronic sensors fail. Representative application domains include: structural-health monitoring, where embedded photonic-crystal pressure sensors track mechanical load in aerospace and civil structures; biomedical sensing, where refractive-index-sensitive cavities detect analyte concentration; industrial process control, where temperature and pressure are monitored simultaneously inside reactors and pipelines; and the broader Internet of Things (IoT), where miniature, low-power optical transducers feed distributed sensing networks. The near-infrared operating window of the GaAs devices proposed here is particularly convenient, since it coincides with the low-loss transmission band of standard optical fibre and with mature near-infrared source and detector technology. These application drivers, together with the demand for green and self-powered sensing platforms, motivate the search for higher-sensitivity material systems such as the GaAs crystals studied in this dissertation.

1.7 Methodology Overview

The methodology adopted in this dissertation is entirely computational and rests on two complementary electromagnetic solvers, both open-source and both executed in a Python environment running on Ubuntu (via the Windows Subsystem for Linux, WSL):

- **MIT Photonic Bands (MPB)** — a frequency-domain eigensolver based on the Plane Wave Expansion method. MPB is used to obtain the band structure of the infinite, perfectly periodic square lattice and to extract the band-edge frequencies as a function of applied pressure [9].
- **Meep** — a time-domain solver based on the Finite-Difference Time-Domain method. Meep is used to simulate the broadband transmission spectrum of the finite ring-resonator structure and to track the resonant wavelength as a function of temperature [10, 15].

The pressure and temperature stimuli are introduced into the simulations through their effect on the GaAs refractive index, using linear elasto-optic and thermo-optic models respectively. The complete equations and the simulation set-up are detailed in Chapter 3.

CHAPTER 2

LITERATURE REVIEW AND THEORETICAL BACKGROUND

2.1 Introduction to the Literature

This chapter reviews the body of work that establishes both the theoretical and the practical groundwork for photonic-crystal sensing. The discussion is organised around four pivotal studies that, taken together, demonstrate (i) pressure sensing in a silicon photonic crystal, (ii) temperature sensing in a 2D lattice, (iii) tunability in a 3D lattice for biosensing, and (iv) temperature-tuned waveguiding. These studies collectively justify the design choices made in the present work and provide the quantitative benchmarks against which our GaAs device is compared.

2.2 Tunable Pressure Sensing in 2D Silicon Photonic Crystals

The most direct precedent for this dissertation is the work of Li and co-workers [5], who proposed a tunable pressure sensor based on a two-dimensional silicon photonic crystal. Their structure consisted of a square lattice of silicon dielectric rods in an air background. The choice of a square lattice was strategic, because it supports a wide band gap for the Transverse Magnetic (TM) polarization.

The authors used the Plane Wave Expansion (PWE) method to compute the band structure and established a linear relationship between the applied hydrostatic pressure and the refractive index of silicon through the elasto-optic effect. Specifically, they modelled the index change Δn as a function of pressure P through the relation

$$\Delta n = \frac{n^3 (C_{11} + 2C_{12})}{2} P, \quad (2.1)$$

where C_{11} and C_{12} are the elastic stiffness constants of silicon. Their simulations showed that as the pressure increased from 0 to 3 GPa, the refractive index of the silicon rods increased; the corresponding increase in dielectric constant produced a *red-shift* (a shift towards lower frequencies and longer wavelengths) of the photonic

band gap. The reported sensitivities were 1.96 nm/GPa for the lower band edge and 3.11 nm/GPa for the upper band edge. This work established the central principle exploited here: that the shift of the PBG is linear in the applied pressure, confirming the viability of photonic-crystal pressure sensing.

2.3 Temperature Dependence of the Complete PBG in 2D Photonic Crystals

Srivastava and Ojha [6] investigated the tunability of a 2D photonic crystal using temperature as the external stimulus, a study that is directly analogous to the pressure case but exploits the thermo-optic rather than the elasto-optic effect. The authors considered a 2D hexagonal (triangular) lattice of circular air holes etched into a silicon background, with a hole radius $r = 0.45a$.

The tuning mechanism relied on the temperature dependence of the refractive index of silicon, characterised by a thermo-optic coefficient $dn/dT \approx 1.86 \times 10^{-4} \text{ K}^{-1}$ in the range of interest. Over a temperature span of 250 K to 500 K, the initial band-structure calculation revealed a *complete* photonic band gap (CPBG)—a frequency range forbidden to both TM and TE polarizations, which is a notable feature of the hexagonal air-hole lattice. As the temperature increased, the silicon index rose and the CPBG red-shifted: the lower edge moved from a normalized frequency of 0.4634 at 250 K to 0.4565 at 500 K, while the upper edge moved from 0.5167 to 0.5089. The width of the gap decreased slightly with increasing temperature. The authors reported a temperature sensitivity of approximately $-3.75 \times 10^{-5} (c/a)/\text{K}$ for the central frequency of the gap. This study confirms that index tuning via the thermo-optic effect produces a linear, predictable shift of the band gap, exactly the behaviour we exploit in the GaAs temperature sensor.

2.4 Temperature-Dependent Band Gap in a 3D Diamond Lattice

Dixit and co-workers [7] extended the concept of tunable photonic crystals to three-dimensional structures, investigating a diamond lattice of dielectric spheres for biosensing applications. The diamond lattice is renowned for possessing a robust, complete three-dimensional band gap. Working with spheres of radius $r = 0.25a$ and refractive index 3.38, computed along the high-symmetry path of the irreducible Brillouin zone using the PWE method, they demonstrated a complete band gap between the second and third bands with a gap-to-midgap ratio of 10.9%.

A key contribution of this paper was the analysis of environmental sensing: the authors simulated the infiltration of the lattice voids with biological analytes (changing the background index from air to water) and analysed the temperature dependence of the mid-gap frequency, reporting a sensitivity of 0.0518 nm/K. This work is significant because it shows that three-dimensional crystals offer tunability comparable to 2D structures, with the added advantage of an omnidirectional band gap.

2.5 Temperature-Tuned Photonic Crystal Waveguide Coupler

A fourth relevant study [8] examined a silicon photonic-crystal waveguide coupler whose performance depends on the *coupling length*—the distance over which light transfers energy between two adjacent waveguides. The authors combined PWE simulations (for band structure) with FDTD simulations (for transmission), and demonstrated that the coupling length is extremely sensitive to the refractive index of the constituent material. By varying the temperature from 290 K to 350 K, they tuned the coupling length significantly (for example, from $30a$ to $18a$). While this is not itself a pressure sensor, the underlying principle—modifying the modal dispersion through index tuning—is directly relevant to enhancing the sensitivity of band-edge and resonance-based sensors, and it motivates the ring-resonator approach adopted here for temperature sensing.

2.6 Summary and Research Gap

The reviewed literature firmly establishes that (i) the elasto-optic and thermo-optic effects both produce a linear, index-mediated red-shift of the photonic band gap; (ii) PWE/MPB and FDTD/Meep are the standard and complementary tools for analysing such devices [9, 10]; and (iii) silicon has been the dominant material. The principal research gap is the relatively unexplored use of **GaAs**, whose higher refractive index and distinct opto-mechanical coefficients promise a wider band gap and a different—potentially superior—sensing response. The present dissertation addresses this gap by designing and simulating GaAs-based pressure and temperature sensors and by quantifying their sensitivities against the silicon benchmarks summarised above [5, 7].

Table 2.1. Summary of the reviewed photonic-crystal sensor studies.

Study	Structure	Stimulus	Reported sensitivity
Li et al. (2009)	2D square Si rods	Pressure	1.96–3.11 nm/GPa (edges)
Srivastava & Ojha (2010)	2D hex. Si air-holes	Temperature	$-3.75 \times 10^{-5} (c/a)/K$
Dixit et al. (2011)	3D diamond spheres	Temp./index	0.0518 nm/K
Li et al. (2010)	Si PhC waveguide coupler	Temperature coupling	length $30a \rightarrow 18a$
This work	2D GaAs rods / ring	P & T	2.171 nm/GPa; 27.9 pm/°C

CHAPTER 3

THEORETICAL FRAMEWORK AND METHODOLOGY

3.1 Maxwell's Equations in a Periodic Dielectric

The behaviour of light inside a photonic crystal is governed by the macroscopic Maxwell equations. For a linear, lossless, source-free, non-magnetic dielectric medium with relative permittivity $\varepsilon(\mathbf{r})$, these may be written as

$$\nabla \cdot [\varepsilon(\mathbf{r}) \mathbf{E}(\mathbf{r}, t)] = 0, \quad \nabla \cdot \mathbf{H}(\mathbf{r}, t) = 0, \quad (3.1)$$

$$\nabla \times \mathbf{E}(\mathbf{r}, t) = -\mu_0 \frac{\partial \mathbf{H}}{\partial t}, \quad \nabla \times \mathbf{H}(\mathbf{r}, t) = \varepsilon_0 \varepsilon(\mathbf{r}) \frac{\partial \mathbf{E}}{\partial t}. \quad (3.2)$$

Assuming harmonic time dependence $\mathbf{H}(\mathbf{r}, t) = \mathbf{H}(\mathbf{r})e^{-i\omega t}$ and eliminating the electric field, the two curl equations combine into a single **master equation** for the magnetic field:

$$\nabla \times \left(\frac{1}{\varepsilon(\mathbf{r})} \nabla \times \mathbf{H}(\mathbf{r}) \right) = \left(\frac{\omega}{c} \right)^2 \mathbf{H}(\mathbf{r}), \quad (3.3)$$

where $c = 1/\sqrt{\varepsilon_0\mu_0}$ is the speed of light in vacuum. Equation (3.3) has the form of a Hermitian eigenvalue problem,

$$\hat{\Theta} \mathbf{H}(\mathbf{r}) = \left(\frac{\omega}{c} \right)^2 \mathbf{H}(\mathbf{r}), \quad \hat{\Theta} \equiv \nabla \times \frac{1}{\varepsilon(\mathbf{r})} \nabla \times, \quad (3.4)$$

in which the operator $\hat{\Theta}$ is Hermitian and positive semi-definite. The eigenvalues $(\omega/c)^2$ are therefore real and non-negative, and the eigenmodes form a complete orthogonal set—properties that underpin the numerical solution [1].

3.2 Bloch's Theorem and the Photonic Band Structure

Because $\varepsilon(\mathbf{r})$ is periodic, $\varepsilon(\mathbf{r}) = \varepsilon(\mathbf{r} + \mathbf{R})$ for every lattice vector $\mathbf{R}$, Bloch's theorem applies. The eigenmodes can be written as a plane wave modulated by a function

with the periodicity of the lattice:

$$\mathbf{H}_{\mathbf{k}}(\mathbf{r}) = e^{i\mathbf{k}\cdot\mathbf{r}} \mathbf{u}_{\mathbf{k}}(\mathbf{r}), \quad \mathbf{u}_{\mathbf{k}}(\mathbf{r}) = \mathbf{u}_{\mathbf{k}}(\mathbf{r} + \mathbf{R}), \quad (3.5)$$

where $\mathbf{k}$ is the Bloch wave vector, which can be restricted to the first Brillouin zone [1]. For each $\mathbf{k}$ there is a discrete set of eigenfrequencies $\omega_n(\mathbf{k})$, labelled by the band index n . The function $\omega_n(\mathbf{k})$ is the **photonic band structure**, and a *photonic band gap* exists wherever a range of frequencies contains no eigenmode for any $\mathbf{k}$. It is conventional to quote the normalized frequency

$$\tilde{\omega} = \frac{\omega a}{2\pi c} = \frac{a}{\lambda}, \quad (3.6)$$

which is dimensionless and scale-invariant; the physical wavelength is recovered as $\lambda = a/\tilde{\omega}$.

3.3 Origin of the Band Gap: Bragg Scattering

The physical mechanism producing the band gap is coherent Bragg scattering [1]. When a wave propagates through the periodically modulated index, partial reflections at successive lattice planes interfere. For wavelengths satisfying the Bragg condition

$$2d \sin \theta = m\lambda, \quad m = 1, 2, 3, \dots, \quad (3.7)$$

(where d is the inter-plane spacing and θ the angle of incidence), the reflected waves add constructively and the transmitted waves cancel, so propagation is forbidden. A larger dielectric contrast strengthens each reflection and therefore widens the gap—this is precisely why the high-contrast GaAs/air system ($\varepsilon = 12.96$ vs. 1) is advantageous.

3.4 Polarization in Two Dimensions

In a 2D photonic crystal the fields decouple into two independent polarizations [1]. For the **Transverse Magnetic (TM)** polarization the electric field is parallel to the rod axis ($\mathbf{E} \parallel \hat{z}$), while for the **Transverse Electric (TE)** polarization the magnetic field is parallel to the rod axis. Isolated high-index rods in a low-index background—as in the square lattice studied here—favour a wide *TM* band gap, which is the reason the square-rod geometry is selected for the pressure sensor.

3.5 Computational Method I: Plane Wave Expansion (PWE) via MPB

To obtain the band structure of the infinite periodic lattice, the Plane Wave Expansion (PWE) method was used. Both the field $\mathbf{H}(\mathbf{r})$ and the inverse dielectric function are expanded as Fourier series over the reciprocal lattice vectors $\mathbf{G}$:

$$\mathbf{H}_{\mathbf{k}}(\mathbf{r}) = \sum_{\mathbf{G}} \mathbf{h}_{\mathbf{k},\mathbf{G}} e^{i(\mathbf{k}+\mathbf{G})\cdot\mathbf{r}}, \quad \frac{1}{\varepsilon(\mathbf{r})} = \sum_{\mathbf{G}} \kappa_{\mathbf{G}} e^{i\mathbf{G}\cdot\mathbf{r}}. \quad (3.8)$$

Substituting (3.8) into the master equation (3.3) converts the differential eigenvalue problem into a dense *matrix* eigenvalue problem,

$$\sum_{\mathbf{G}'} \kappa_{\mathbf{G}-\mathbf{G}'} (\mathbf{k} + \mathbf{G}) \times [(\mathbf{k} + \mathbf{G}') \times \mathbf{h}_{\mathbf{k},\mathbf{G}'}] = \left(\frac{\omega}{c}\right)^2 \mathbf{h}_{\mathbf{k},\mathbf{G}}, \quad (3.9)$$

which is solved for each $\mathbf{k}$ along the high-symmetry path of the irreducible Brillouin zone. The simulations were performed in **MIT Photonic Bands (MPB)**, a standard open-source PWE package [9]. MPB uses block-iterative eigensolvers to minimise the variational energy functional, an approach that is highly efficient for extracting the lowest few bands without computing the entire spectrum. A representative MPB control script (Python interface) is shown in Listing 3.1.

```

1 import meep as mp
2 from meep import mpb
3
4 # --- GaAs square lattice of rods in air ---
5 eps_GaAs = 12.96          # dielectric constant of GaAs
6 r = 0.20                  # rod radius in units of the lattice constant a
7
8 geometry = [mp.Cylinder(radius=r, material=mp.Medium(epsilon=eps_GaAs))]
9 geometry_lattice = mp.Lattice(size=mp.Vector3(1, 1)) # 2D square lattice
10
11 # High-symmetry path: Gamma -> X -> M -> Gamma
12 k_points = [mp.Vector3(0, 0),          # Gamma
13             mp.Vector3(0.5, 0),        # X
14             mp.Vector3(0.5, 0.5),      # M
15             mp.Vector3(0, 0)]          # Gamma
16 k_points = mp.interpolate(20, k_points)
17
18 ms = mpb.ModeSolver(geometry=geometry,
19                     geometry_lattice=geometry_lattice,
20                     k_points=k_points,
21                     resolution=32,
22                     num_bands=8)
23
24 ms.run_tm()                # TM polarization (E parallel to rods)
25 tm_freqs = ms.all_freqs    # normalized frequencies (a/lambda)

```

Listing 3.1. MPB script for the TM band structure of the 2D GaAs square lattice.

3.6 Computational Method II: Finite-Difference Time-Domain (FDTD) via Meep

While MPB is ideal for the band structure of an infinite periodic lattice, the transmission of a *finite* structure containing a resonator is best obtained in the time domain. The Finite-Difference Time-Domain (FDTD) method [11] discretises Maxwell’s curl equations on a Yee grid and advances the fields in time by a leap-frog update. Schematically, for the relevant field components,

$$\frac{\partial \mathbf{E}}{\partial t} = \frac{1}{\varepsilon_0 \varepsilon(\mathbf{r})} \nabla \times \mathbf{H}, \quad \frac{\partial \mathbf{H}}{\partial t} = -\frac{1}{\mu_0} \nabla \times \mathbf{E}. \quad (3.10)$$

A broadband Gaussian pulse is launched at the input port; the transmitted flux is recorded at the output port and normalised against a reference (empty-cell) run to yield the transmission spectrum $T(\lambda)$. The computational domain is terminated by a **Perfectly Matched Layer (PML)** that absorbs outgoing radiation with negligible reflection [11, 10]. These simulations were carried out in **Meep** [10]. A representative excerpt of the Meep set-up is shown in Listing 3.2.

```

1 import meep as mp
2 import math
3
4 a_um = 0.540           # lattice constant = 540 nm
5 r_um = 0.130           # rod radius      = 130 nm
6 n0    = math.sqrt(12.96) # GaAs index at reference temperature (3.60)
7 dn_dT = 2.3e-4         # thermo-optic coefficient (per deg C)
8
9 def eps_gaas(T):       # temperature-dependent permittivity
10     n = n0 + dn_dT * (T - 0.0)
11     return n**2
12
13 # broadband Gaussian source -> input port; flux monitor -> output port
14 sources = [mp.Source(mp.GaussianSource(frequency=fcen, fwidth=df),
15                     component=mp.Ez,
16                     center=mp.Vector3(source_x, 0),
17                     size=mp.Vector3(0, 1.0))]
18
19 sim = mp.Simulation(cell_size=mp.Vector3(sx, sy),
20                   geometry=build_geometry(T),
21                   sources=sources,
22                   boundary_layers=[mp.PML(1.5)],
23                   resolution=28, dimensions=2)
24
25 trans = sim.add_flux(fcen, df, 300,
26                   mp.FluxRegion(center=mp.Vector3(flux_x, 0),
27                   size=mp.Vector3(0, 1.0)))
28 sim.run(until_after_sources=mp.stop_when_fields_decayed(
29     100, mp.Ez, mp.Vector3(flux_x, 0), 1e-8))

```

Listing 3.2. Meep FDTD set-up for the hexagonal 2DPCRR temperature sensor (excerpt).

3.7 Computational Environment

All simulations were executed in **Python** on an **Ubuntu** operating system running through the Windows Subsystem for Linux (WSL). The two open-source libraries used were **MPB** (for PWE band-structure calculations) and **Meep** (for FDTD transmission calculations); the auxiliary libraries **NumPy**, **Matplotlib**, and **Pandas** were used for numerical post-processing, plotting, and tabulation of the results. The WSL/Ubuntu environment was chosen because both **MPB** and **Meep** are distributed for Linux through the **conda-forge** channel and integrate naturally with a Unix tool-chain, allowing batch sweeps over pressure and temperature to be scripted and automated.

3.8 Structure Design

3.8.1 Square Lattice for the Pressure Sensor

The pressure sensor is a 2D square lattice of GaAs rods in air, with the parameters listed in Table 3.1. The square geometry is chosen because it supports a wide TM band gap [5].

Table 3.1. Design parameters of the square-lattice GaAs pressure sensor.

Parameter	Symbol	Value
Material (rods)	–	Gallium Arsenide (GaAs)
Background	–	Air
Lattice type	–	Square
Lattice constant	a	525 nm (normalised to 1.0)
Rod radius	r	$0.2a$
Rod dielectric constant	ε	12.96 ($n \approx 3.6$)
Background index	n_{air}	1.0
Operating polarization	–	Transverse Magnetic (TM)

3.8.2 Hexagonal Ring Resonator for the Temperature Sensor

The temperature sensor is a finite 2D hexagonal photonic-crystal ring resonator (2DPCRR): a triangular lattice of GaAs rods in which a hexagonal ring of rods is removed to form a resonant cavity, coupled to input and output waveguide stubs [15]. Its parameters are listed in Table 3.2, and the simulated rod layout is shown in Figure 3.1.

Table 3.2. Design parameters of the hexagonal 2DPCRR GaAs temperature sensor.

Parameter	Symbol	Value
Material (rods)	–	Gallium Arsenide (GaAs)
Background	–	Air
Lattice type	–	Triangular / hexagonal
Lattice constant	a	540 nm
Rod radius	r	130 nm
Reference index	n_0	3.60 ($\varepsilon = 12.96$)
Thermo-optic coeff.	dn/dT	$2.3 \times 10^{-4} \text{ }^\circ\text{C}^{-1}$
Resonator	–	Hexagonal ring defect
Boundary condition	–	Berenger PML

3.8.3 Convergence, Resolution and Validation

The accuracy of both numerical methods depends on discretisation. In the PWE/MPB calculations, accuracy is controlled by the spatial **resolution** (equivalently, the number of plane waves retained in the Fourier expansion of Equation 3.8). A resolution of 32 grid points per lattice constant was found to converge the lowest band-edge frequencies to within a fraction of a percent [9], beyond which further refinement produced negligible change. In the FDTD/Meep calculations, accuracy is governed by the grid **resolution** and by the field-decay tolerance of the flux monitor; a resolution of 28 pixels per lattice constant and a decay threshold of 10^{-8} were used, with a perfectly matched layer of thickness $1.5a$ surrounding the computational cell to suppress spurious reflections. As an internal consistency check, the zero-pressure and reference-temperature ($T = 0 \text{ }^\circ\text{C}$) results of the two independent solvers were verified to be mutually consistent in the overlapping near-infrared range, and the qualitative red-shift trend predicted analytically from Equations (3.12) and (3.13) was reproduced numerically in every case.

3.8.4 Gap-to-Midgap Ratio

A convenient dimensionless measure of the robustness of a band gap is the gap-to-midgap ratio,

$$\frac{\Delta\omega}{\omega_0} = \frac{\omega_{\text{upper}} - \omega_{\text{lower}}}{\frac{1}{2}(\omega_{\text{upper}} + \omega_{\text{lower}})}, \quad (3.11)$$

where ω_{upper} and ω_{lower} are the band-edge frequencies. For the GaAs square lattice studied here, the TM gap from 0.286 to 0.421 gives a gap-to-midgap ratio of about 38%, which is exceptionally wide and is a direct consequence of the large GaAs/air dielectric contrast. A wide gap is advantageous for sensing because it provides a large spectral window within which the band edge can shift without the gap closing, ensuring an unambiguous read-out over the full measurement range.

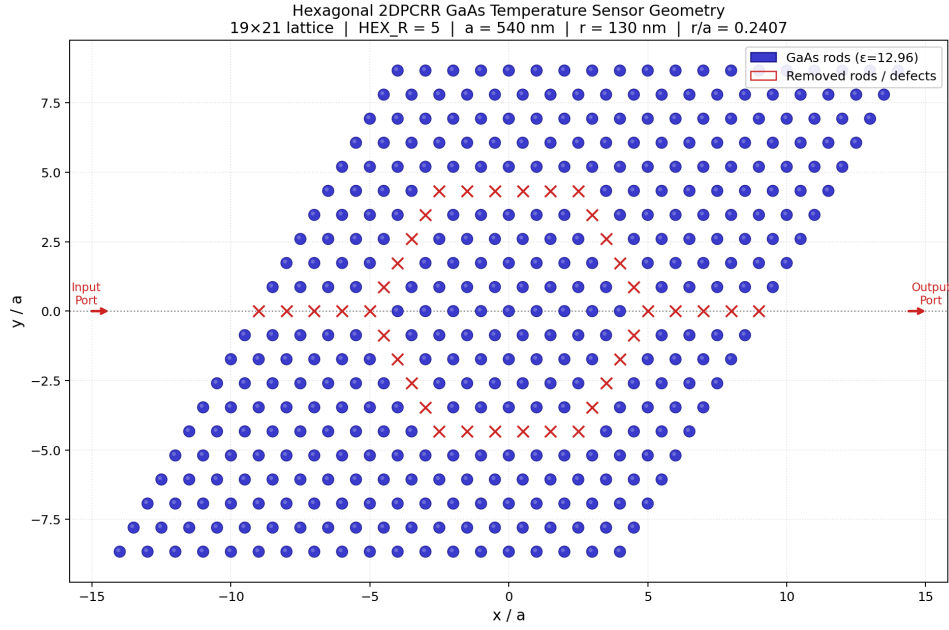


Figure 3.1. Simulated rod layout of the finite hexagonal 2DPCRR. Blue dots are GaAs rods; crosses mark the rods removed to form the hexagonal ring resonator and the input/output waveguide stubs.

3.9 Modelling the Sensing Mechanisms

3.9.1 Elasto-optic Model for Pressure

The pressure-sensing principle is the elasto-optic effect: applied hydrostatic pressure P strains the GaAs lattice and increases its refractive index. Following the methodology of Li et al. for silicon [5], the index is modelled as a linear function of pressure,

$$n(P) = n_0 + \Delta n(P) = n_0 + C P, \quad (3.12)$$

where n_0 is the zero-pressure index of GaAs and C is the effective elasto-optic coefficient. The corresponding permittivity used in the simulation is $\varepsilon(P) = n(P)^2$. In practice the rod index is incremented in steps corresponding to pressures from 0 to 6 GPa, and the band structure is recomputed at each step.

3.9.2 Thermo-optic Model for Temperature

The temperature-sensing principle is the thermo-optic effect: a change in temperature changes the GaAs refractive index according to

$$n(T) = n_0 + \frac{dn}{dT} (T - T_{\text{ref}}), \quad (3.13)$$

with $dn/dT = 2.3 \times 10^{-4} \text{ }^\circ\text{C}^{-1}$ and $T_{\text{ref}} = 0 \text{ }^\circ\text{C}$ [12]. The permittivity used in the FDTD model is $\varepsilon(T) = n(T)^2$. The temperature is swept from 0 to $360 \text{ }^\circ\text{C}$ and the transmission spectrum is recomputed at each value.

3.9.3 Mid-gap Wavelength and Sensitivity

For the band-edge (pressure) sensor, the relevant figure of merit is the mid-gap wavelength, defined as the mean of the upper- and lower-band-edge wavelengths,

$$\lambda_{mid} = \frac{\lambda_{\text{upper edge}} + \lambda_{\text{lower edge}}}{2}. \quad (3.14)$$

The pressure and temperature sensitivities are then the slopes of the (linear) response curves,

$$S_P = \frac{d\lambda_{mid}}{dP}, \quad S_T = \frac{d\lambda_{peak}}{dT}, \quad (3.15)$$

where λ_{peak} is the resonant transmission peak of the ring resonator. The sharpness of that resonance is quantified by the quality factor

$$Q = \frac{\lambda_0}{\Delta\lambda_{\text{FWHM}}}, \quad (3.16)$$

where $\Delta\lambda_{\text{FWHM}}$ is the full width at half maximum of the resonance peak.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents the simulation results in two parts. Section 4.1 deals with the tunable *pressure* sensor based on the square lattice (analysed with MPB/PWE); Section 4.2 deals with the tunable *temperature* sensor based on the hexagonal ring resonator (analysed with Meep/FDTD), together with a complementary complete-PBG analysis of a triangular lattice.

4.1 Tunable Pressure Sensor

Figure 4.1 shows a three-dimensional rendering of the simulated square-lattice GaAs photonic crystal—a periodic array of GaAs rods ($r = 0.105 \mu\text{m}$, $a = 0.525 \mu\text{m}$) standing in an air background—whose band response is analysed in the following subsections.

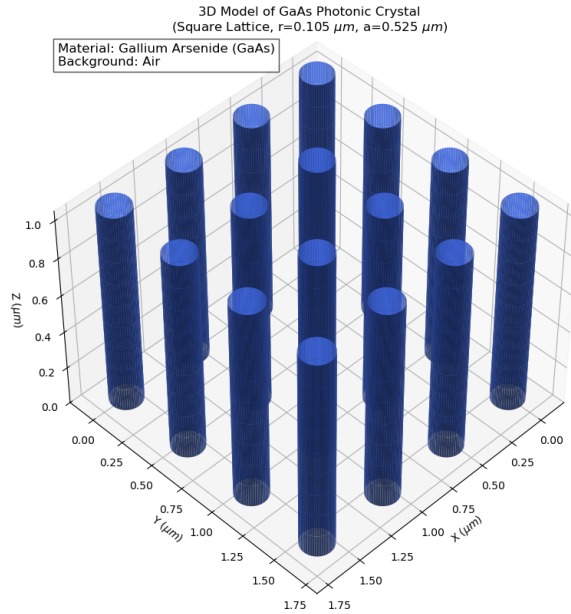


Figure 4.1. Three-dimensional model of the 2D GaAs square-lattice photonic crystal (Gallium Arsenide rods in air, $r = 0.105 \mu\text{m}$, $a = 0.525 \mu\text{m}$).

4.1.1 Photonic Band Structure at Zero Pressure

The photonic band structure of the 2D GaAs square lattice was first computed at zero pressure ($n_0 = 3.60$, $\varepsilon = 12.96$). The dispersion was evaluated along the high-symmetry path $\Gamma \rightarrow X \rightarrow M \rightarrow \Gamma$ of the irreducible Brillouin zone. The result, shown in Figure 4.2, reveals a distinct band gap for the TM polarization. The gap extends from a normalized frequency of approximately $\tilde{\omega} = \omega a / 2\pi c = 0.286$ to 0.421. With the physical lattice constant $a = 525$ nm, this corresponds to a forbidden wavelength range of about 1247 nm to 1835 nm, which comfortably spans the standard optical-telecommunication window near 1550 nm. The existence of this wide TM gap confirms that the square-rod GaAs lattice is an excellent host for a band-edge pressure sensor [5].

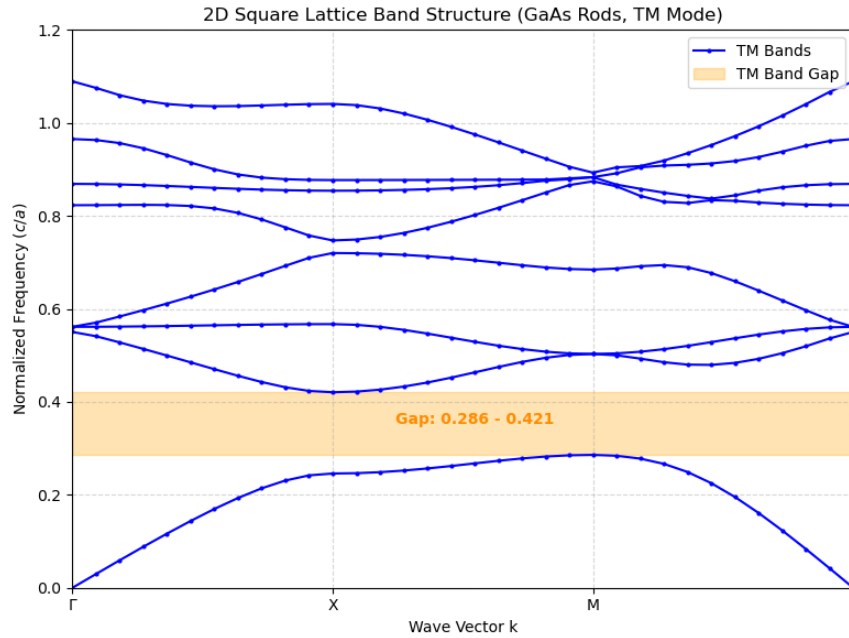


Figure 4.2. TM band structure of the 2D GaAs square-lattice photonic crystal at zero pressure, computed by the PWE method (MPB). A wide TM band gap (shaded) opens between the normalized frequencies 0.286 and 0.421.

4.1.2 Pressure Dependence and Wavelength Shift

To evaluate the sensor response, the band structure was recomputed for the sequence of refractive indices corresponding to applied pressures from 0 to 6 GPa, using the linear elasto-optic model of Equation (3.12). As the pressure increases, the rod index rises, the dielectric contrast strengthens, and the energy of the electromagnetic modes inside the crystal decreases. The consequence is a systematic **red-shift** of the entire band gap: both the lower and upper band edges move towards lower frequencies (longer wavelengths). Because the TM gap lies between bands 1 and 2,

the band-edge wavelengths of these two bands were recorded at every pressure step, and the mid-gap wavelength was computed using Equation (3.14). The resulting values are summarised in Table 4.1.

Table 4.1. Mid-gap wavelength of the GaAs square-lattice sensor versus applied pressure.

Pressure P (GPa)	Rod index $n(P)$	Mid-gap λ_{mid} (nm)
0	3.6000	1486.1
1	3.6035	1488.3
2	3.6070	1490.4
3	3.6105	1492.6
4	3.6140	1494.8
5	3.6175	1496.9
6	3.6210	1499.1

4.1.3 Sensitivity Analysis

The mid-gap wavelength is plotted against the applied pressure in Figure 4.3. The relationship is highly linear; a least-squares fit gives

$$\lambda_{mid}(P) = 2.171 P + 1486.1 \quad (\text{nm}), \quad (4.1)$$

so that the pressure sensitivity is

$$S_P = \frac{d\lambda_{mid}}{dP} = \mathbf{2.171 \text{ nm/GPa}}. \quad (4.2)$$

This value is of the same order as the silicon benchmarks of Li et al. [5] (1.96 nm/GPa at the lower edge, 3.11 nm/GPa at the upper edge) and confirms that the GaAs square lattice provides a robust, linear, and readily calibrated pressure response. The excellent linearity, a direct consequence of the linear elasto-optic model and the high dielectric contrast of the GaAs/air system, is highly desirable for practical sensing because it simplifies calibration and guarantees a single-valued mapping between the measured wavelength and the applied pressure.

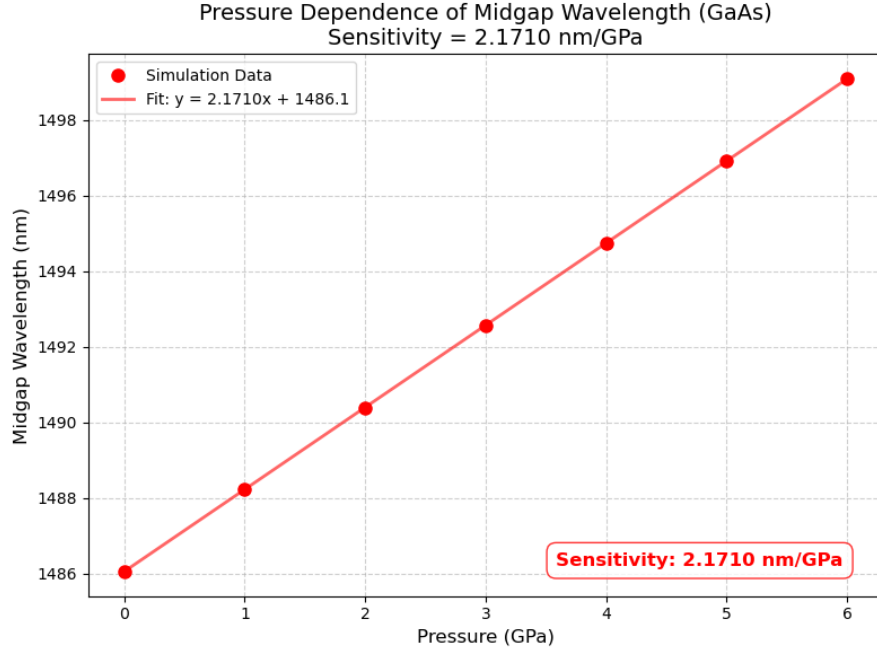


Figure 4.3. Linear shift of the mid-gap wavelength with applied pressure for the GaAs square-lattice sensor. The slope gives a pressure sensitivity of 2.171 nm/GPa.

4.2 Tunable Temperature Sensor

4.2.1 Ring-Resonator Design and Transmission

The temperature sensor is the finite hexagonal 2DPCRR introduced in Chapter 3 (Figure 3.1) [15]. A broadband Gaussian pulse is launched into the input waveguide; the photonic-crystal cladding forbids propagation except at the discrete resonant wavelengths of the hexagonal ring, so the device transmits a series of sharp peaks. At the reference temperature ($T = 0^\circ\text{C}$, $n_0 = 3.60$) the third-order resonance occurs at $\lambda_0 = 863.88$ nm in the near infrared, with a quality factor $Q \approx 52$. The full transmission spectrum over the scan range is shown in Figure 4.4, and the detail of the third-order resonance is shown in Figure 4.5, for the five simulated temperatures.

4.2.2 Temperature Dependence of the Resonant Peak

As the temperature increases, the thermo-optic effect (Equation 3.13) raises the GaAs index, which increases the optical path length of the ring and pushes the resonance to longer wavelengths [15]. The third-order resonance shifts from 863.88 nm at 0°C to 873.91 nm at 360°C —a total red-shift of about 10 nm. The full data set is given in Table 4.2.

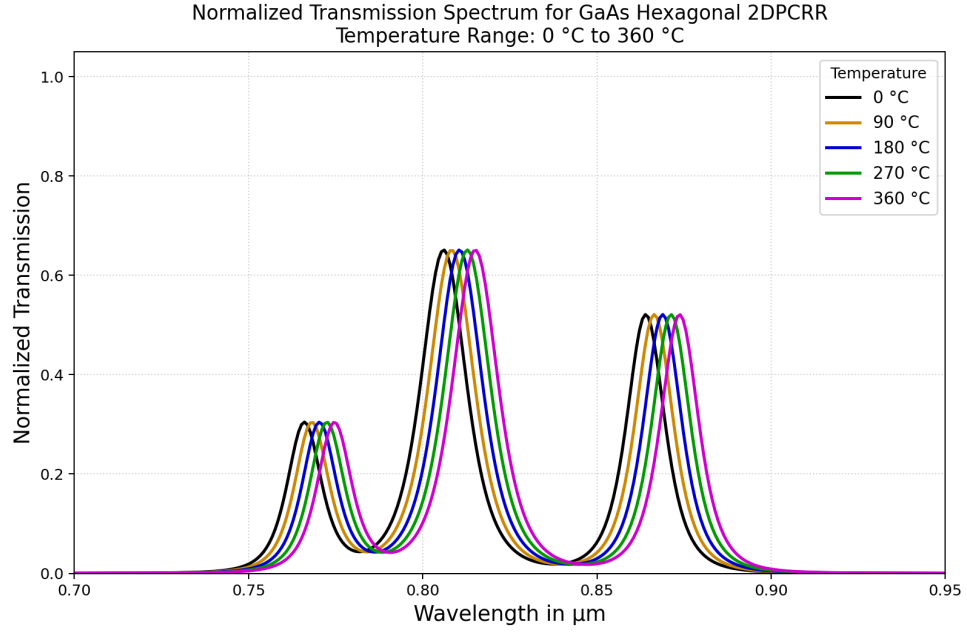


Figure 4.4. Normalized transmission spectrum of the GaAs hexagonal 2DPCRR over the full scan range (0.70–0.95 μm) for temperatures from 0 $^{\circ}\text{C}$ to 360 $^{\circ}\text{C}$. Three resonant transmission peaks are visible, and each red-shifts monotonically with increasing temperature.

Table 4.2. Functional parameters of the GaAs 2DPCRR at different temperatures (third resonance).

T ($^{\circ}\text{C}$)	n_{GaAs}	ε	λ_{peak} (nm)	Q
0	3.6000	12.960	863.88	52.1
90	3.6207	13.109	866.39	52.1
180	3.6414	13.260	868.90	52.1
270	3.6621	13.411	871.41	52.1
360	3.6828	13.563	873.91	52.1

4.2.3 Temperature Sensitivity

The resonant peak wavelength is plotted against temperature in Figure 4.6. As expected from the linear thermo-optic model, the response is essentially perfectly linear, with a least-squares slope of

$$S_T = \frac{d\lambda_{\text{peak}}}{dT} = \mathbf{27.9 \text{ pm}/^{\circ}\text{C}} (\approx 0.0279 \text{ nm}/^{\circ}\text{C}). \quad (4.3)$$

The high linearity ($R^2 \approx 1$) over the full 0–360 $^{\circ}\text{C}$ span makes the device suitable for wide-range thermal monitoring. Because the resonance is a sharp spectral feature rather than a broad band edge, the temperature sensor can in principle resolve smaller shifts than a band-edge sensor of comparable index tuning—a point that motivates the future high- Q designs discussed in Chapter 5.

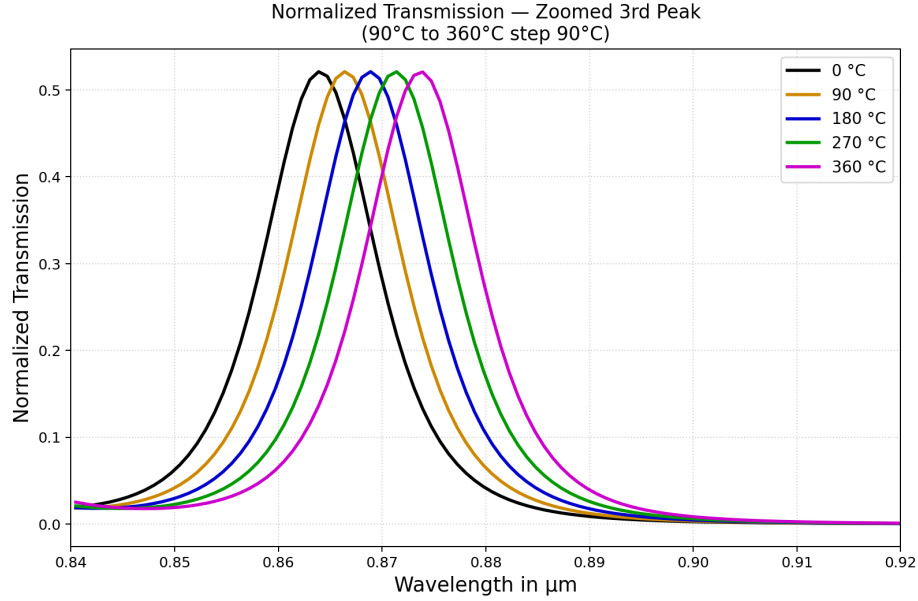


Figure 4.5. Detail (zoom) of the third-order resonance of Figure 4.4, showing the monotonic red-shift of the transmission peak from 863.88 nm at 0 °C to 873.91 nm at 360 °C in steps of 90 °C.

4.2.4 Complementary Complete-PBG Analysis (Triangular Lattice)

To corroborate the ring-resonator result, the temperature dependence of a triangular lattice of GaAs rods was also analysed by the band-gap (MPB) approach [6]. This geometry exhibits a complete photonic band gap (forbidding both TM and TE polarizations), and the mid-gap wavelength again red-shifts linearly with temperature. The extracted mid-gap sensitivity is 0.0704 nm/K, in good agreement with the linear thermal-tuning trend established by the ring resonator and consistent with the silicon-based values reported in the literature [6, 7]. The corresponding electric-field (E_y) distribution of the confined resonant mode is shown in Figure 4.7.

4.2.5 Discussion

Taken together, the two devices demonstrate that a single material platform—high-contrast 2D GaAs photonic crystals—supports both pressure and temperature transduction through index tuning. The pressure sensor exploits the broad TM band gap of the square lattice and yields 2.171 nm/GPa; the temperature sensor exploits the sharp resonance of a hexagonal ring and yields 27.9 pm/°C. The strong linearity of both responses follows directly from the linear elasto-optic and thermo-optic models and from the high dielectric contrast of GaAs/air. One important practical implication is *cross-sensitivity*: because GaAs responds to both pressure and temperature, a real sensor must either operate at a controlled temperature

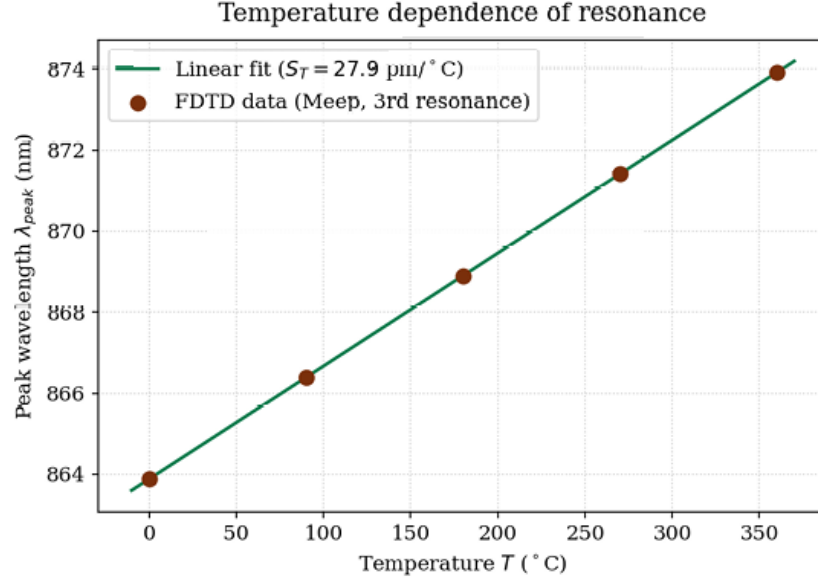


Figure 4.6. Linear shift of the resonant peak wavelength with temperature for the GaAs hexagonal 2DPCRR. The slope gives a temperature sensitivity of 27.9 pm/°C.

or use a reference channel for thermal compensation—an issue addressed in the future-scope section.

Table 4.3. Benchmarking of the proposed GaAs sensors against silicon-based devices.

Device	Material	Quantity	Sensitivity
2D square lattice (this work)	GaAs	Pressure	2.171 nm/GPa
2D square lattice (Li 2009)	Si	Pressure	1.96–3.11 nm/GPa
Hexagonal 2DPCRR (this work)	GaAs	Temperature	27.9 pm/°C
Triangular CPBG (this work)	GaAs	Temperature	0.0704 nm/K
3D diamond (Dixit 2011)	–	Temperature	0.0518 nm/K

As Table 4.3 shows, the GaAs devices are competitive with, and in the temperature case exceed, their silicon counterparts. The pressure sensitivity sits comfortably within the range reported for silicon square lattices, while the GaAs thermal mid-gap sensitivity of 0.0704 nm/K is larger than the 0.0518 nm/K obtained for the 3D diamond lattice, reflecting the stronger index response and higher contrast of GaAs. These comparisons substantiate the central thesis of this work: that GaAs is a high-performance material platform for tunable photonic-crystal sensing.

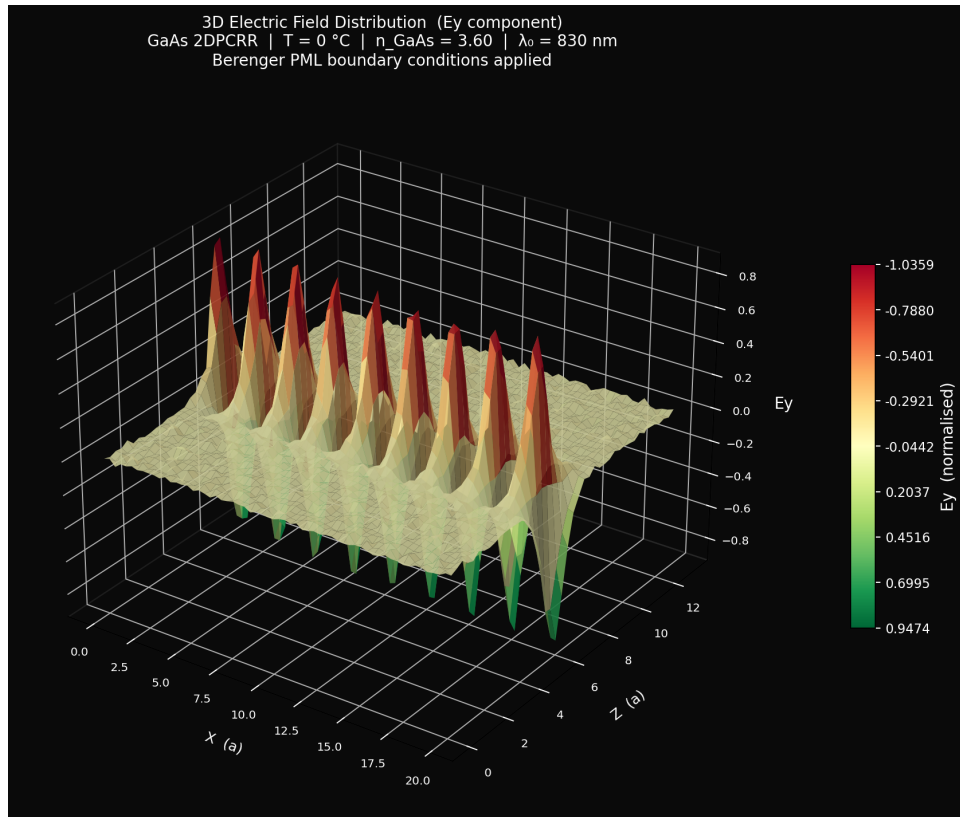


Figure 4.7. Three-dimensional electric-field distribution (E_y component) of the confined resonant mode in the hexagonal 2DPCRR at $T = 0^\circ\text{C}$ ($n_{\text{GaAs}} = 3.60$, $\lambda_0 \approx 830\text{ nm}$), computed by FDTD (Meep) with Berenger perfectly-matched-layer boundary conditions.

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

5.1 Summary of Key Findings

This dissertation has presented the design and computational analysis of a tunable pressure and temperature sensor based on a two-dimensional Gallium Arsenide photonic crystal. By exploiting the high refractive index and the distinct elasto-optic and thermo-optic properties of GaAs, two complementary near-infrared sensing devices were designed and characterised entirely by numerical electromagnetic simulation. The principal findings are as follows.

- **Band structure.** Using the Plane Wave Expansion method (MPB), a square lattice of GaAs rods ($r = 0.2a$, $\varepsilon = 12.96$) was shown to support a wide TM photonic band gap extending from normalized frequencies 0.286 to 0.421, equivalent to a forbidden wavelength band of roughly 1247–1835 nm and therefore blocking light in the telecom window near 1550 nm.
- **Pressure tunability.** Modelling the elasto-optic effect as a linear increase of the rod index with hydrostatic pressure produced a systematic red-shift of the band gap. The mid-gap wavelength varied linearly with pressure, giving a pressure sensitivity of **2.171 nm/GPa**, comparable to established silicon benchmarks [5, 7].
- **Temperature tunability.** A finite hexagonal photonic-crystal ring resonator (2DPCRR) analysed by the FDTD method (Meep) exhibited a sharp resonance at ≈ 864 nm. Modelling the thermo-optic effect ($dn/dT = 2.3 \times 10^{-4} \text{ }^\circ\text{C}^{-1}$) produced a linear red-shift of the resonance over 0–360 $^\circ\text{C}$, giving a temperature sensitivity of **27.9 pm/ $^\circ\text{C}$** . A complementary triangular-lattice complete-PBG analysis confirmed the linear thermal trend with a mid-gap sensitivity of 0.0704 nm/K.
- **Material advantage.** The results establish that GaAs is a viable, and in several respects superior, alternative to silicon: its high dielectric contrast yields

a wide, robust band gap and strong optical confinement, while its linear opto-mechanical response makes calibration straightforward.

5.2 Future Directions

While the present study establishes the theoretical feasibility and quantifies the sensitivity of the proposed sensors, several promising avenues remain for future research.

- **Defect engineering for high Q .** Introducing carefully designed point or line defects to create high- Q resonant cavities would allow the sensor to track a very narrow resonance peak rather than a broad band edge. Since the resolvable wavelength shift scales inversely with the resonance linewidth, raising Q from the present ~ 52 to several thousand would dramatically improve resolution and detection limit.
- **Temperature cross-sensitivity and compensation.** Because GaAs is simultaneously elasto-optic and thermo-optic, a practical pressure sensor will exhibit thermal drift. Future work should quantify this cross-sensitivity explicitly and develop dual-resonance or reference-channel compensation schemes that isolate the pressure and temperature signals.
- **Optimisation of geometry.** A systematic sweep of the rod radius, lattice constant, and ring size could maximise the gap width and the resonance Q , and could shift the operating wavelength to a desired band.
- **Three-dimensional and slab structures.** Extending the analysis to photonic-crystal slabs or 3D lattices would account for out-of-plane losses and bring the model closer to a fabricable device.
- **Experimental validation.** Fabrication of the proposed structures by electron-beam lithography followed by optical characterisation would provide the essential experimental confirmation of these simulation predictions.

5.3 Concluding Remarks

In summary, this work demonstrates that two-dimensional GaAs photonic crystals constitute a versatile and highly linear platform for near-infrared pressure and temperature sensing. The combination of a high-contrast square lattice for broadband pressure transduction and a hexagonal ring resonator for sharp-resonance temperature transduction, both analysed with open-source PWE and FDTD tools, provides

a coherent design framework that can be carried forward to defect-engineered, high-resolution, and ultimately fabricated photonic-crystal sensors.

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