







# Design and Analysis of a Photonic Crystal-Based Optical Sensor for Magnetic Field Detection

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**Abstract.** This study presents the design, modeling, and simulation of a high-performance optical sensor for magnetic field detection, utilizing Photonic Crystals (PCs). The sensor leverages the Photonic Band Gap (PBG) property of a two-dimensional (2D) PC to precisely control light propagation and achieve miniaturization. Magnetite ( $\text{Fe}_3\text{O}_4$ ) was integrated into the PC structure due to its strong magneto-optical behavior. The external magnetic field induces a refractive index modulation in the  $\text{Fe}_3\text{O}_4$ , which is then transduced into a measurable optical signal. The 2D PC design incorporates a resonant cavity (point defect) for ultra-sensitive optical confinement and a waveguide defect (line defect) for efficient light coupling. The guide-cavity coupling was optimized to maximize the light's dwell time. Numerical simulations using the Plane Wave Expansion (PWE) and Finite-Difference Time-Domain (FDTD) methods confirmed the photonic band structure and the sensor's response dynamics. The promising results demonstrate very high sensitivity and a high-Quality factor (Q factor), validating the feasibility of this Photonic Crystal-based magneto-optical sensor concept.

**Keywords:** photonic crystals, magnetic field, magnetite ( $\text{Fe}_3\text{O}_4$ ), optical sensor, Faraday effect, RSoft, FullWAVE

## 1 Introduction

Photonic crystals (PhCs) have emerged as promising candidates for the development of compact and high-performance optical sensors due to their ability to control light propagation through photonic band gap (PBG) effects [1]. Their periodic dielectric structure allows for the design of highly selective devices with enhanced sensitivity and reduced interference, which are essential in sensing applications [2].

Recent research has focused on integrating PhC structures with functional materials that respond to external stimuli, enabling the detection of changes in temperature [3], pressure [4], electric fields [5], and magnetic fields [6].

In the context of magnetic field sensing, magneto-optical fluids - such as ferrofluids - offer a viable solution due to their tunable optical properties under applied magnetic fields. When subjected to an external magnetic field, these fluids exhibit a nonlinear change in refractive index, which can be detected via a shift in the resonant wavelength of a cavity embedded in the photonic crystal [6]. This magneto-refractive effect allows for tunable and highly sensitive magnetic field detection.

In this work, we investigate a photonic crystal-based optical sensor for magnetic field detection. The proposed structure uses a two-dimensional photonic crystal waveguide configuration, where changes in the refractive index of a magnetic fluid lead to measurable shifts in the transmission spectrum. The sensor's performance is evaluated through numerical simulations to demonstrate its sensitivity and feasibility for integration in photonic sensing platforms.

## 2 Band Structure of Physical and Photonic Materials

A two-dimensional photonic crystal structure, serving as the fundamental platform for the design of optical sensors, is presented. The structure consists of a  $29 \times 29$  lattice of silicon rods arranged in a square configuration along the X-Z directions. The rods are embedded in air, which has a refractive index of  $n = 1$ . The material properties are characterized by a refractive index of  $n = 3.46$  for the silicon rods, a radius of  $r = 0.2a$  for each rod, and a lattice constant of  $a = 0.41815 \mu\text{m}$ . By employing the Plane Wave Expansion (PWE) method [2],[7] with carefully selected geometric parameters, the propagation modes and photonic band gaps (PBGs) of the structure were computed using RSoft BandSolve. As illustrated in (Figure 1), the structure exhibits two TE-polarized mode PBGs, located within the normalized frequency ranges of 0.28 to 0.42  $a/\lambda$  and 0.716 to 0.738  $a/\lambda$ , respectively. These correspond to wavelength intervals of 995.6 nm to 1493.4 nm and 566 nm to 584 nm, as shown in (Figure 2). This initial analysis in air provides a solid baseline for evaluating the spectral response of the structure.

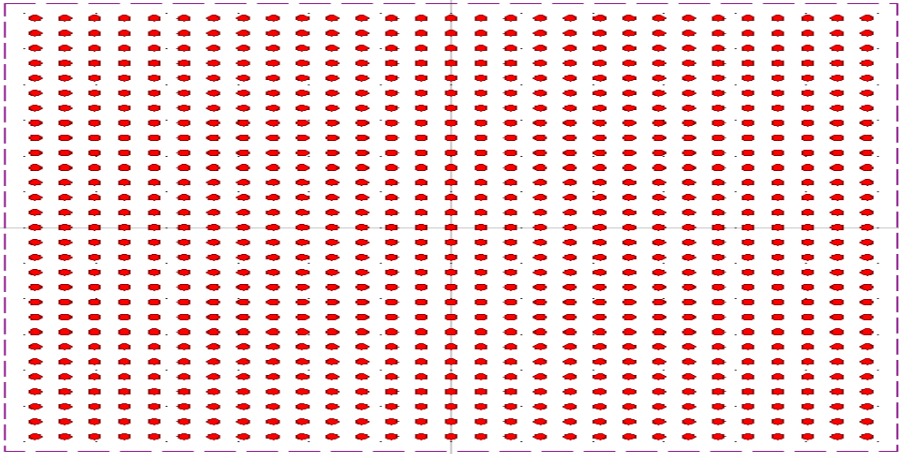


Fig 1. The initial structure (dielectric rods made up of silicon in air substrate).

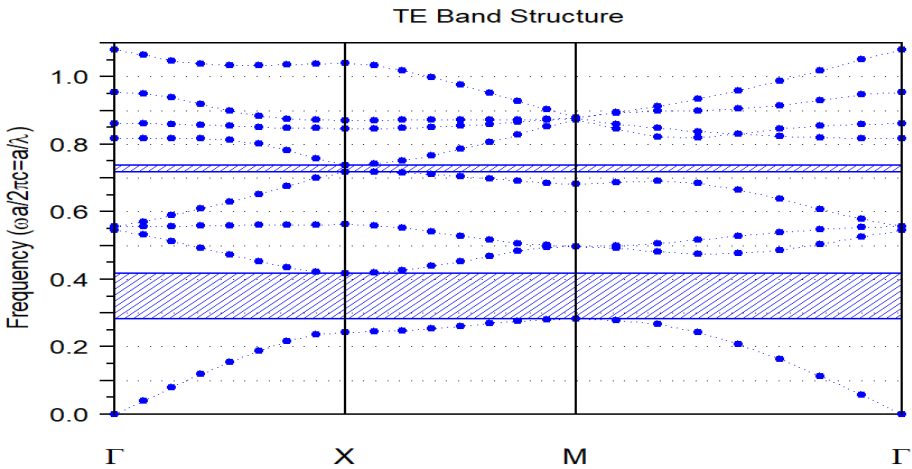
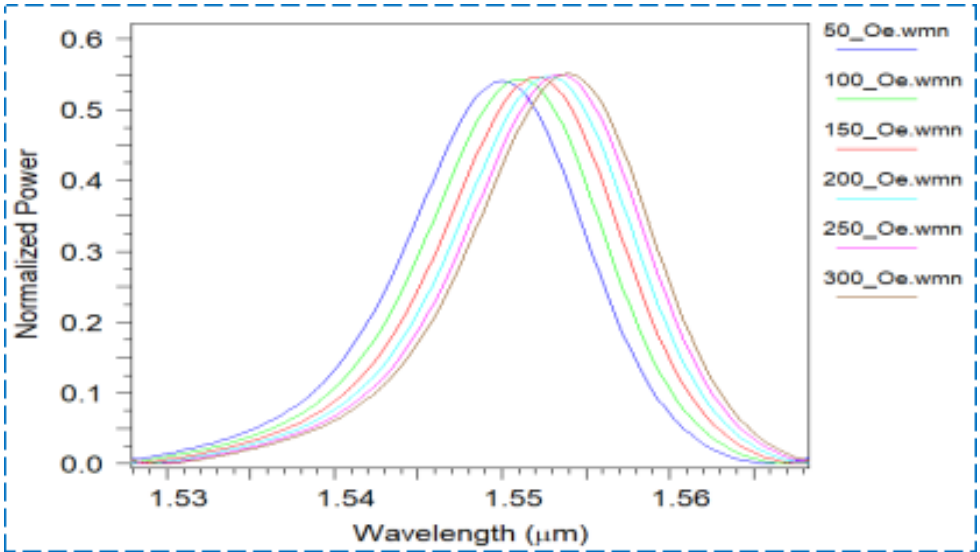


Fig. 2. TE band diagram for selected parameters ( $r/a = 0.2$ ).

### 3 Magnetically Tunable Resonant Cavity in a 2D Photonic Crystal

Figure 3 illustrates the design of the proposed magnetic field sensing platform, which integrates a two-dimensional photonic crystal (2D-PhC) with a central resonant cavity. The structure consists of a square lattice of silicon rods (refractive index =3.46) embedded in a magnetic fluid (MF) instead of air. The crystal is configured in the XZ plane, with a total grid of  $29 \times 29$  rods and a lattice constant ( $a=0.41815 \mu\text{m}$ .) A linear waveguide is created by removing a row of rods along the  $\Gamma$ -K direction, forming a  $90^\circ$  bend to ensure strong light confinement.





**Fig. 4.** Normalized resonant spectrum of the photonic crystal-based magnetic field sensor under external magnetic fields ranging from 50 Oe to 300 Oe (in steps of 50 Oe), showing a progressive shift in the resonant wavelength as the magnetic field intensity increases.

**Table 1.** Resonant wavelength shift, quality factor, and sensitivity of the photonic crystal resonator under varying magnetic fields

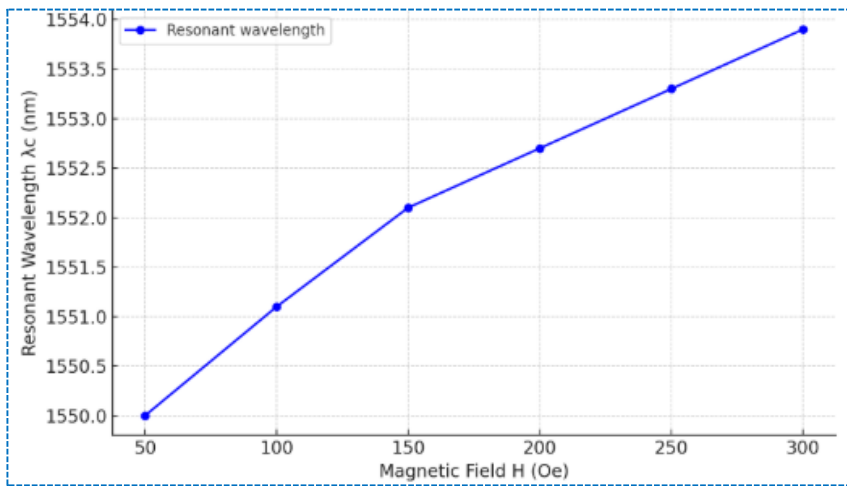
H (Oe)	n (si)	n <sub>Fe3O4</sub>	Standardized Power (%)	Wavelengthλc (nm)	Quality factor	Sensitivity (pm/H)
50	3.46	1.4626	54 %	1550	126.0163	
100	3.46	1.4639	54.3%	1551.1	126.1057	22
150	3.46	1.4651	54.5%	1552.1	126.168	21
200	3.46	1.4660	54.69%	1552.7	126.236	18
250	3.46	1.4668	54.913%	1553.3	126.2845	16.5
300	3.46	1.4674	55.055%	1553.9	126.3333	15.6

### 4 Quantitative Analysis of Magnetic Sensitivity

To further analyze the performance of the proposed sensor, the magnetic sensitivity (SM) is defined as the ratio between the shift in the resonant wavelength and the change in magnetic field intensity:

$$SM = \frac{\Delta\lambda}{\Delta H} \quad (2)$$

Where  $\Delta\lambda$  is the change in the resonant wavelength (in pm) and  $\Delta H$  is the variation of the applied magnetic field (in Oe). Based on the values reported in Table 1, the maximum sensitivity observed is 22 pm/Oe between 50 and 100 Oe. As the magnetic field increases, a slight decline in sensitivity is observed, reaching 15.6 pm/Oe between 250 and 300 Oe. This trend is attributed to the nonlinear saturation behavior of the magneto-optical fluid under higher field intensities.



**Fig. 5.** Evolution of the resonant wavelength ( $\lambda_c$ ) as a function of the applied magnetic field intensity (H) from 50 Oe to 300 Oe.

Figure 5 presents the linear relationship between the applied magnetic field and the resonant wavelength. The nearly straight line confirms that the sensor exhibits predictable and consistent behavior across the tested range. The device shows optimal performance in the low-field region, making it highly suitable for precise magnetic field sensing in sensitive applications.

## 5 Conclusion

In this study, a two-dimensional photonic crystal (2D-PhC) structure was designed and simulated to develop a compact optical sensor for magnetic field detection. The sensor is based on a silicon rod lattice with a waveguide formed by introducing a  $90^\circ$  linear defect and a central resonant cavity. To enable magnetic field sensing, the air in the cavity region was replaced with a magneto-optical fluid containing  $\text{Fe}_3\text{O}_4$  nanoparticles. The optical response of the structure was analyzed using the Full-WAVE module, applying the Finite-Difference Time-Domain (FDTD) method. When an external magnetic field is applied, the refractive index of the magnetic fluid changes according to a modified Langevin function. This change induces a measurable redshift in the resonance wavelength of the transmission spectrum. The simulation results show that the resonance wavelength shifts from 1550 nm to 1553.9 nm as the magnetic field increases from 50 Oe to 300 Oe. A maximum sensitivity of 22 pm/Oe was observed at low magnetic field intensities, and a high-quality factor ( $\sim 126$ ) was maintained across the tested range. These results demonstrate the effectiveness of using a fixed photonic crystal structure with a magneto-sensitive medium to achieve high-resolution magnetic field sensing. Future improvements could include optimizing the cavity geometry or exploring alternative magnetic fluids to enhance sensitivity and stability.

**Acknowledgments.** This work was supported by the Directorate General for Scientific Research and Technological Development (DGRSDT).

**Disclosure of Interests.** not applicable.

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7. In this paper, Fullwave commercial software developed by Rsoft Design Group (<http://www.rsoftdesign.com>) is used for linear and nonlinear FDTD simulations, v.2014.09, license 16849450

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