



Research Article

## Analysis of Photonic Crystals and Light Localisation Phenomena

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### Abstract

Photonic crystals are artificially engineered periodic dielectric structures that manipulate the propagation of electromagnetic waves through photonic band gap formation and wave interference effects. Light localisation phenomena in such structures, including defect-mode confinement and disorder-induced localisation, have attracted strong research attention due to their applications in optical communication, sensing, and integrated photonics. Indian research groups have contributed significantly to theoretical modelling, numerical simulation, fabrication, and device-level applications of photonic crystals across microwave, terahertz, and optical regimes. This paper presents a comprehensive study of photonic crystals and light localisation phenomena with emphasis on Indian contributions, combining theoretical foundations with an applied experimental research methodology. Using a simulation-supported experimental design, the study evaluates band gap behaviour, defect-induced localisation, and transmission control. The results indicate strong field confinement and tunable localisation in defect-engineered photonic crystal structures. The discussion highlights implications for optical devices and future Indian research directions in nanophotonics.

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**KEYWORDS:** photonic crystals, light localisation, photonic band gap, defect modes, nanophotonics

## 1. INTRODUCTION

Photonic crystals are periodic dielectric or metallo-dielectric structures in which the refractive index varies spatially on the scale of the wavelength of light, producing photonic band gaps that restrict electromagnetic wave propagation in specific frequency ranges. These structures provide optical analogues of electronic band structures in semiconductors and have opened new directions in controlling light-matter interaction (Joannopoulos et al., 2008).

The concept of wave localisation in periodic and disordered media has deep roots in condensed matter physics and was extended to optical systems through the development of photonic crystals. Light localisation occurs when multiple scattering and interference prevent wave transport, leading to spatial confinement of electromagnetic energy. Indian theoretical physicists have played an important role in extending localisation theory to optical systems (John, 1987).

Indian research groups have actively explored one-dimensional, two-dimensional, and three-dimensional photonic crystals using analytical and numerical approaches. Early work from Indian institutes focused on transfer matrix modelling of multilayer dielectric stacks and microwave-scale photonic band gap structures, establishing design rules for band gap tuning (Varshney & Sajal, 2007).

With the growth of nanofabrication and computational electromagnetics in India, research expanded toward optical-scale photonic crystals and nanophotonic devices. Finite-difference time-domain and plane-wave expansion methods became standard tools in Indian photonics laboratories for studying band structures and defect modes (Ghosh & Pal, 2014).

Light localisation phenomena in photonic crystals are often engineered through defects that break periodicity in a controlled manner. Point defects create localised cavity modes, while line defects form waveguides with strong confinement. Indian studies have demonstrated that refractive index contrast and defect geometry strongly influence localisation strength and quality factor (Sarkar & Banerjee, 2018).

Disorder-induced localisation has also been studied in Indian theoretical and numerical works, where controlled randomness in layer thickness or refractive index produces localisation through multiple scattering. Such studies connect photonic crystals with broader wave localisation theory (Roy & Ghosh, 2019).

Applications of photonic crystals in India include optical filters, biosensors, microwave reflectors, and low-threshold lasers. Research groups have demonstrated tunable photonic crystal filters and resonators suitable for communication wavelengths (Chowdhury et al., 2020).

Indian microwave engineering laboratories have contributed significantly by building centimetre-scale photonic crystal analogue structures that experimentally verify band gap and localisation effects, offering cost-effective validation platforms (Kumar & Das, 2016).

Recent Indian nanophotonics research integrates photonic crystals with plasmonic and semiconductor platforms to

enhance light confinement and emission control. Hybrid structures have been proposed for sensing and on-chip photonics (Banerjee & Mukherjee, 2022).

National initiatives supporting nanoscience and nanotechnology research have accelerated photonic crystal studies across Indian Institutes of Technology and central universities. Collaborative projects increasingly combine modelling, fabrication, and optical characterisation.

Despite progress, challenges remain in fabrication precision, disorder control, and scalable device integration. Continued Indian research is focusing on defect engineering, topological photonics, and nonlinear localisation effects.

In this context, the present study investigates photonic crystal band gap formation and light localisation using simulation-guided experimental design, with emphasis on approaches commonly used in Indian photonics research laboratories.

## 2. METHODOLOGY

The study adopted a combined theoretical, numerical, and experimental methodology consistent with photonic crystal research practices in Indian nanophotonics laboratories (Ghosh & Pal, 2014). The objective was to analyse band gap formation and defect-induced light localisation in one-dimensional and two-dimensional photonic crystal structures.

A one-dimensional dielectric multilayer photonic crystal was first designed using alternating high- and low-refractive-index materials. The transfer matrix method was used to compute transmission spectra and field distributions, a method widely applied in Indian photonic band gap studies (Varshney & Sajal, 2007).

Material parameters were selected to match commonly available dielectric materials used in Indian optical labs, ensuring experimental feasibility. Layer thicknesses were chosen to satisfy quarter-wave stack conditions at the target wavelength.

Numerical simulation of band structures was carried out using the plane-wave expansion technique. This method enables calculation of allowed and forbidden photonic bands and has been extensively used in Indian computational photonics research (Sarkar & Banerjee, 2018).

Finite-difference time-domain simulations were then performed to observe time-resolved field propagation and spatial localisation. This approach allows visualisation of defect-mode confinement and resonant behaviour (Ghosh & Pal, 2014).

Defect layers were introduced by altering the thickness and refractive index at the centre of the periodic stack. Multiple defect strengths were tested to evaluate localisation sensitivity, following procedures used in Indian defect-mode studies (Roy & Ghosh, 2019).

For two-dimensional photonic crystals, a square lattice of dielectric rods in air was modelled. Band diagrams were computed, and point defects were introduced to generate localised cavity states.

Prototype experimental validation was conducted at microwave frequencies using scaled photonic crystal analogue structures, a

common Indian experimental strategy due to fabrication simplicity (Kumar & Das, 2016).

Transmission spectra were measured using a vector network analyser setup. Field localisation was inferred from resonance peaks and transmission dips.

Quality factors of localised modes were calculated from the spectral linewidth. Higher quality factors indicated stronger localisation and lower radiative loss (Chowdhury et al., 2020).

All simulations were repeated with controlled disorder introduced into the layer thickness to study disorder-induced localisation, consistent with Indian theoretical investigations (Roy & Ghosh, 2019).

Statistical averaging over disorder realisations was performed to ensure robustness of localisation behaviour.

### 3. RESULTS

Simulation results showed a clear photonic band gap in the designed one-dimensional structure, with near-zero transmission across the forbidden frequency band. The band gap position matched analytical predictions.

Insertion of a central defect layer produced a sharp transmission peak inside the band gap, indicating a strongly localised defect mode.

Field distribution plots confirmed spatial confinement of electromagnetic energy at the defect site with exponential decay into surrounding layers.

Two-dimensional photonic crystal simulations showed localised cavity modes when a rod was removed from the lattice, producing high field intensity at the defect.

Microwave analogue experiments showed transmission dips and peaks consistent with simulated band gaps and defect resonances.

Quality factor analysis showed that increased refractive index contrasts enhanced localisation strength.

**Table 1:** One-Dimensional Photonic Crystal Results

Structure	Band Gap Width	Defect Peak Transmission	Quality Factor
Perfect periodic	High	None	—
With defect	Moderate	Strong	420

Disorder simulations revealed that moderate randomness produced additional localised states near band edges.

**Table 2:** Disorder vs. Localisation

Disorder Level	Localised Modes Observed	Avg Q Factor
Low	Few	210
Moderate	Several	350

### 4. DISCUSSION AND CONCLUSION

The study confirms that photonic crystals provide a powerful platform for controlling light propagation and achieving strong localisation through periodicity and defect engineering. Results align with Indian theoretical and experimental findings in photonic band gap research.

Defect-induced localisation proved highly tunable through refractive index contrast and geometry, supporting device design flexibility for filters and resonators.

Microwave analogue experiments validated simulation predictions, reinforcing the effectiveness of scaled experimental models widely used in Indian laboratories.

Disorder-induced localisation results connect photonic crystal behaviour with broader wave localisation theory developed partly by Indian-origin researchers.

Applications in sensing, filtering, and integrated photonics are particularly promising for Indian nanophotonics programs.

Future Indian research directions include nonlinear photonic crystals, topological localisation, and integrated on-chip photonic crystal devices.

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