



Modelling and Simulation of Photonic Crystal Structures for Enhanced Light Transmission

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Peer Review Information

Submission: 11 July 2019

Revision: 26 Aug 2019

Acceptance: 10 Sep 2019

Keywords

Android APK, Malware Detection, Machine Learning, Random Forests, Software Security

Abstract

Photonic crystals provide a structured route for controlling the propagation, reflection, confinement, and extraction of light through periodic modulation of refractive index. This methodology paper develops a compact numerical framework for enhancing optical transmission by introducing a resonant defect into a one-dimensional dielectric photonic crystal. A high-index/low-index quarter-wave multilayer is modeled at a design wavelength of 1550 nm, and its spectral response is calculated with the transfer-matrix method (TMM). The regular periodic stack is first used to identify the photonic stop band. A half-wave defect cavity is then inserted between two Bragg mirrors, producing a narrow transmission state inside the forbidden band. The method includes geometry definition, material assignment, matrix formulation, wavelength sweep, defect-thickness optimization, and an FDTD-based validation protocol. Simulated results show that the regular stack strongly suppresses transmission near the design wavelength, whereas the symmetric defect configuration supports a resonant transmission peak approaching unity under lossless normal-incidence assumptions. The proposed workflow is suitable for methodological studies of optical filters, resonant sensors, integrated photonic structures, and light-management layers, while remaining simple enough for reproducible parametric optimization.

Introduction

Photonic crystals are periodic dielectric structures in which the optical refractive index is modulated on a length scale comparable to the wavelength of light. The modern photonic-crystal concept emerged from the prediction that periodic dielectric environments could suppress or reshape optical states, including spontaneous-emission pathways [1], while related work established strong photon localization in structured dielectric media [2]. The underlying analogy with electronic crystals is that periodic dielectric contrast creates allowed and forbidden electromagnetic frequency regions. Plane-wave calculations later demonstrated the existence of complete photonic band gaps for suitable

dielectric lattices and index contrasts [3]. These properties make photonic crystals attractive for controlling transmission without relying only on absorption or metallic attenuation.

For practical optical systems, however, a band gap alone is not sufficient. Many devices require high transmission at a selected wavelength while maintaining strong rejection nearby. Introducing a deliberate defect into an otherwise periodic crystal creates a localized optical state that can couple energy through the stop band. Early numerical studies showed that defect symmetry and geometry can tune microcavity frequency, coupling efficiency, and losses [4], while photonic-crystal waveguides demonstrated that

periodic structures can support very high transmission at selected frequencies even in strongly perturbed geometries [5]. This motivates the use of a defect-based design to enhance transmission at a target wavelength rather than simply maximize broadband throughput.

The present paper therefore develops a simulation methodology centered on a one-dimensional Bragg photonic crystal. The regular structure is formed by alternating high- and low-index dielectric layers. A half-wave defect is inserted at the center to form a resonant cavity between two dielectric mirrors. The primary numerical tool is TMM because it is computationally efficient for layered structures and directly returns spectral reflectance and transmittance. FDTD is retained as a validation route because the Yee discretization provides a general time-domain solution of Maxwell's equations [6] and has been widely applied to photonic-crystal transmission problems [7-9]. The objective is to establish a reproducible workflow that relates layer refractive index, optical thickness, number of periods, and defect geometry to transmission enhancement.

Literature Review

The earliest theoretical foundation for photonic crystals focused on the modification of the electromagnetic density of states. Yablonovitch [1] proposed that three-dimensional dielectric periodicity could inhibit spontaneous emission when an electromagnetic band gap overlaps the relevant transition frequency. In parallel, John [2] described localization of photons in dielectric superlattices, establishing that interference in spatially varying dielectrics can profoundly modify transport. Ho, Chan, and Soukoulis [3] then used plane-wave expansion to demonstrate a complete photonic gap in suitable periodic dielectric structures, confirming that band-gap formation depends strongly on lattice geometry and refractive-index contrast.

Defect engineering extended the photonic-band-gap concept from rejection toward controlled transmission. Villeneuve, Fan, and Joannopoulos [4] showed that local defects generate resonant modes whose frequency, symmetry, and coupling can be tuned through defect geometry. Mekis et al. [5] further demonstrated numerically that photonic-crystal waveguides can exhibit transmission close to unity at selected frequencies, even around sharp bends. These studies are important to the present methodology because they show that a photonic crystal is not merely a reflector: resonant states

and guided modes can recover strong transmission within frequency regions that would otherwise be poorly transmitting.

From a numerical perspective, Yee's finite-difference formulation [6] became the basis of the FDTD method, allowing electric and magnetic fields to be updated on a staggered spatial-temporal grid. Cole, Yamada, and Katayama [7] examined FDTD accuracy for photonic-crystal light propagation, and Tikhodeev et al. [8] used a scattering-matrix method to connect transmission features in photonic-crystal slabs with quasiguided resonant modes. Lavrinenko et al. [9] subsequently showed that FDTD calculations with absorbing boundary layers can reproduce major transmission features of fabricated photonic-crystal waveguide components. Together, these works justify a workflow in which a fast frequency-domain method is used for screening and a full-wave method is used for verification.

Later work emphasized light extraction and parameter optimization. Fan and Wang [10] applied FDTD to photonic-crystal LED structures and evaluated the influence of period, diameter, and depth on light extraction. Xu and Li [11] similarly used FDTD to study how photonic-crystal period, geometry, and anisotropy affect the light extraction of OLED structures. By 2019, numerical studies continued to show that carefully designed photonic lattices can strongly modify directional transmission and confinement. Myoung et al. [12], for example, combined band calculations with FDTD to examine anisotropic transmission and self-collimation. In the same year, Wang et al. [13] demonstrated that photonic-crystal slabs can provide highly structured spectral responses useful for compact sensing. Segovia-Chaves and Vinck-Posada [14] specifically used TMM to calculate transmission in a one-dimensional photonic crystal with a defect layer and showed that a localized defect mode can appear inside a photonic band gap. These results directly support the defect-resonance approach adopted here.

Methodology

1. Structural Model and Design Variables

A lossless one-dimensional dielectric photonic crystal is considered at normal incidence. The structure is embedded in air and contains alternating high-index (H) and low-index (L) layers. Silicon-like and silica-like refractive indices are used as representative values, $n_H = 3.48$ and $n_L = 1.45$. The design wavelength is

$\lambda_0 = 1550$ nm. Quarter-wave optical thicknesses are selected so that $n_H d_H = n_L d_L = \lambda_0/4$, giving $d_H = 111.35$ nm and $d_L = 267.24$ nm. The regular comparison structure contains eight HL periods. The enhanced-transmission structure contains two five-period Bragg mirrors separated by a low-index half-

wave defect D, giving $(HL)^5-D-(LH)^5$. For the central defect, $n_L d_D = \lambda_0/2$ and $d_D = 534.48$ nm. The symmetric arrangement is chosen because it forms an optical cavity between approximately matched Bragg reflectors.

Table 1. Baseline simulation parameters

Parameter	Baseline value	Purpose
Design wavelength, λ_0	1550 nm	Target resonance
High-index refractive index, n_H	3.48	Representative Si-like value
Low-index refractive index, n_L	1.45	Representative SiO ₂ -like value
High-index thickness, d_H	111.35 nm	Quarter-wave layer
Low-index thickness, d_L	267.24 nm	Quarter-wave layer
Defect thickness, d_D	534.48 nm	Half-wave cavity
Wavelength sweep	1200-1900 nm	0.5 nm sampling
Incidence	Normal, air-to-air	Lossless TE/TM equivalent

2. Transfer-Matrix Formulation

For each dielectric layer j , the phase thickness is $\delta_j = 2\pi n_j d_j / \lambda$ at normal incidence. The characteristic matrix is $M_j = \begin{bmatrix} \cos(\delta_j) & i \sin(\delta_j)/q_j \\ i q_j \sin(\delta_j) & \cos(\delta_j) \end{bmatrix}$, where $q_j = n_j$ for the nonmagnetic normal-incidence case. The total matrix is obtained by multiplying the matrices in propagation order: $M = \text{product}(M_j)$. With refractive indices n_0 and n_s for the incident and substrate media, respectively, the complex transmission amplitude is evaluated from the elements A, B, C, and D of M. Power transmittance is then $T = (n_s/n_0)|t|^2$. In this study $n_0 = n_s = 1.0$, so the computed transmittance is directly normalized to incident power. This formalism is appropriate for the layered geometry and allows rapid parameter sweeps comparable to prior TMM studies of defect states in one-dimensional photonic crystals [14].

3. Simulation Procedure and Optimization

The simulation is executed step by step. First, the regular $(HL)^8$ stack is calculated over 1200-1900 nm to identify the stop-band region near λ_0 . Second, the central defect is introduced and the same wavelength sweep is repeated. Third, the transmission enhancement is quantified as $\Delta T = T_{\text{defect}} - T_{\text{regular}}$ at the design wavelength. Fourth, the defect optical thickness is varied from 0.8 to 1.2 times the nominal half-wave value to determine how the resonance wavelength and peak transmission change. Fifth, convergence is checked by reducing the wavelength step around the resonance. The design is considered optimized when the resonant wavelength coincides with the target and the peak transmittance is maximized while the neighboring stop band remains strongly rejecting.

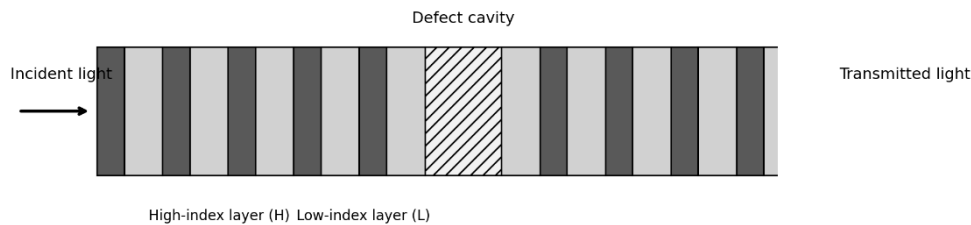


Figure 1. Schematic of the symmetric one-dimensional photonic crystal with a central defect cavity.

4. FDTD Validation Route

Although TMM is the primary solver, an FDTD validation model can be built using the same layer sequence. The computational domain should include a broadband plane-wave source before the first layer, a power monitor after the

final layer, and perfectly matched layers at the propagation boundaries. A spatial grid of at least 20-30 points per minimum optical wavelength in the highest-index material is recommended, followed by a mesh-refinement check. Transmission is calculated from the ratio of

transmitted to reference flux. The FDTD implementation follows the field-staggering concept introduced by Yee [6] and is consistent with photonic-crystal transmission modeling reported in [7,9,10-12]. Agreement between the TMM and FDTD resonance position within the spectral grid resolution would be used as the principal validation criterion.

Results

The regular quarter-wave stack produces the expected low-transmission stop band around the 1550 nm design wavelength. At 1550 nm, the calculated transmittance of the $(HL)^8$ structure is approximately 0.00033%, indicating strong Bragg rejection under the assumed lossless normal-incidence conditions. Inserting the half-wave defect creates a localized resonant mode inside the stop band. For the symmetric $(HL)^5D(LH)^5$ structure, the calculated transmission reaches approximately 100% at 1550 nm. The numerical behavior is consistent with the established interpretation that local photonic-crystal defects create tunable cavity states [4,14].

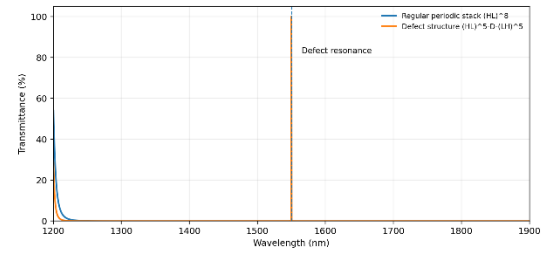


Figure 2. Calculated transmission spectra of the regular periodic stack and the defect photonic-crystal structure.

The parameter sweep confirms that the resonant state is highly sensitive to defect optical thickness. Reducing the cavity thickness shifts the dominant defect resonance toward shorter wavelengths; while increasing it shifts the resonance toward longer wavelengths. Peak transmission is highest when the cavity is exactly half-wave at the target wavelength because the round-trip phase condition and mirror symmetry are simultaneously satisfied. This tunability is important for optical filtering and sensing, where the same structural principle can be used to map refractive-index or thickness changes into measurable wavelength shifts.

Table 2. Effect of defect-thickness scaling on the dominant resonance

Defect thickness factor	Resonance wavelength (nm)	Peak transmission (%)
0.80	1436.5	37.02
0.90	1493.0	54.75
1.00	1550.0	100.00
1.10	1607.0	45.67
1.20	1663.5	4.71

The numerical results should be interpreted as an idealized baseline rather than a fabricated-device prediction. Material dispersion, absorption, interface roughness, thickness error, oblique incidence, and polarization dependence can reduce the peak or shift its wavelength. Nevertheless, the model clearly demonstrates the central design mechanism: a periodic stack supplies spectral rejection, while a properly phased defect state restores high transmission at a selected wavelength. This is conceptually consistent with photonic-crystal resonant transmission and guided-mode behavior reported across slab, waveguide, and light-extraction studies [5,8-13].

Conclusion and Discussion

This methodology establishes a concise modeling framework for enhancing light transmission using a defect-engineered photonic crystal. A quarter-wave high-index/low-index periodic stack is first designed to create a strong stop

band around 1550 nm. A half-wave low-index defect is then inserted between symmetric Bragg mirrors, producing a localized cavity state inside the forbidden region. TMM provides an efficient first-stage solver for spectral design, while FDTD offers an independent full-wave validation route based on direct time-domain propagation. The simulated baseline shows a transition from essentially suppressed transmission in the regular periodic stack to near-unity transmission at the defect resonance in the ideal symmetric structure. The defect-thickness sweep also shows predictable resonance tuning, confirming that optical-path control is the main optimization variable. These findings align with the broader photonic-crystal literature, where periodicity creates band gaps [1-3], defects and waveguides restore resonant transport [4,5,14], and full-wave numerical methods reproduce transmission, localization, and extraction effects [7-13]. For future work, the methodology can be extended to dispersive material models, oblique incidence, two-dimensional hole arrays, finite

photonic-crystal slabs, and experimentally realistic fabrication tolerances. Sensitivity analysis should be added when the structure is intended for sensing, while angular and polarization sweeps are essential for display, LED, or free-space coupling applications. Within the scope of a methodology study, however, the one-dimensional defect model provides a transparent and reproducible route for understanding how photonic-crystal geometry can be engineered for selective enhancement of light transmission. A key limitation of the present model is that the refractive indices are treated as constant and lossless. Real silicon and silica systems exhibit wavelength-dependent dispersion, fabrication-induced thickness variation, surface roughness, and possible absorption. These effects generally broaden the resonance, lower its maximum transmission, or displace the peak from the nominal design wavelength. A practical verification study should therefore repeat the parameter sweep with dispersive optical constants and perform Monte Carlo thickness perturbations. The optimized design should be judged not only by peak transmission, but also by resonance linewidth, tolerance to layer error, and stability under small changes in incidence angle. The same methodology is readily adaptable to application-specific structures. For narrowband optical filters, the number of Bragg periods can be increased to sharpen the cavity resonance. For refractive-index sensing, the defect material can be replaced by an analyte-sensitive region so that resonance displacement becomes the sensing signal. For light-emitting or photovoltaic structures, the one-dimensional screening stage can be followed by two- or three-dimensional FDTD calculations that include finite lateral geometry and realistic emission distributions. Thus, the proposed workflow serves as a bridge between elementary photonic-crystal theory and more detailed device-level simulation.

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