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TMM-Based One-Dimensional Photonic Crystal Biosensors for Refractive-Index Sensing: A Review of Structural and Material Engineering

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Abstract

One-dimensional photonic crystal (1D PhC) has emerged as promising platforms for label-free refractive-index sensing owing to their ability to control light propagation through periodic multilayer structure and localized defect mode. This review focus on theoretically proposed 1D PhC biosensors analysed using the transfer matrix method (TMM), with particular emphasis on defect-mode-based refractive-index sensing through resonance-wavelength shifts. The fundamental optical response of 1D PhC including photonic band-gap formation, defect-mode generation, and the sensing mechanism is first discussed. The review then traces the evolution of structural and material engineering approaches, from conventional binary dielectric structures to metal-assisted and ternary configurations, followed by geometrical and defect engineering and dual- or multiple-defect architectures. A comparative analysis of representative TMM-based designs highlights the trade-offs between sensing performance, resonance characteristics, and structural complexity. The review also identifies key limitations in the existing literature, including differences in evaluation conditions, limited experimental validation, fabrication tolerance, stability, and the absence of standardized performance comparisons. The review also highlights key research gaps related to experimental validation, fabrication tolerance, stability, standardized performance evaluation, and the trade-offs among sensitivity, spectral resolution, and structural complexity.

Keywords: One-dimensional photonic crystal, transfer matrix method, refractive-index sensing, structural engineering, biosensor

1.INTRODUCTION

Photonic crystals (PhCs) are periodic optical structures in which the refractive index varies spatially, enabling controlled propagation of electromagnetic waves and giving rise to a characteristic photonic band gap (PBG), a wavelength range where light propagation is strongly suppressed. The optical response of PhCs can be tailored by varying the refractive indices, layer thicknesses, periodicity, and structural arrangement, making them useful in applications such as optical filters, resonators, waveguides, switches, and sensors. Among them 1D PhCs consist of two or more materials with different refractive indices arranged periodically along a single direction. Their simple multilayer geometry offers advantages for theoretical analysis using well-established methods such as the transfer matrix method (TMM), while their planar structure also provides flexibility for practical optical implementation. The ability to control the layer composition, thickness, and number of periods enables systematic tuning of the optical response. These characteristics make 1D PhCs attractive platforms for investigating and designing optical and biosensing structures.

Biosensors play an important role in the detection and analysis of biological substances for applications such as medical diagnosis, environmental monitoring, and food safety. Among various approaches, optical biosensors are particularly attractive because biological interactions can be monitored through changes in optical properties such as wavelength, intensity, phase, or polarization. Photonic-crystal-based biosensors offer an additional advantage due to their strong sensitivity to small

changes in the refractive index of the sensing medium, enabling label-free detection of biological samples. In 1D PhC biosensors, a defect layer is commonly introduced into the periodic structure, breaking its periodicity and generating a localized optical mode within the photonic band gap. Since the resonance wavelength of this defect mode depends on the optical properties of the defect region, a change in the refractive index of the sample occupying the defect produces a measurable shift in the resonance wavelength, which can be used to evaluate the sensing performance. Consequently, defect-based 1D PhCs have been investigated for the detection of blood components, cancer-related samples, infectious diseases, and other biological analytes [1-4]

Although binary defect-based 1D PhCs provide a simple platform for label-free sensing, their performance is governed by several interrelated optical and structural parameters, including sensitivity, resonance linewidth, quality factor, figure of merit, detection limit, transmission intensity, and structural stability. Optimization of a single parameter does not necessarily result in an overall improvement in sensing performance, motivating the development of modified 1D PhC architectures with greater control over their optical response. This has led to a progressive evolution from conventional binary dielectric structures toward metal-assisted and ternary or multilayer configurations, where additional materials and interfaces provide increased freedom for controlling the photonic band structure, electromagnetic-field distribution, and defect resonance [5-9]. Geometrical and defect engineering, through optimization of layer thickness, defect dimensions and multiple-defect configurations, further enables control of resonance characteristics and the generation of multiple localized modes. However, increasing structural and functional complexity can introduce challenges such as optical loss, resonance splitting, fabrication tolerances, parameter optimization, and limited experimental validation. In addition, the predominance of single-resonance sensing restricts the amount of independent spectral information obtainable from a single measurement.

In this context, the present review traces the development of 1D PhC biosensors from conventional defect-based structures to material and structurally engineered structures with particular emphasis on how these developments influence sensing performance. The optical response and sensing mechanism of defect-based 1D PhCs are first discussed, followed by the evolution of structural engineering approaches including metal-assisted, ternary, geometrical, and defect-engineered structures. Finally, the reported approaches are comparatively assessed in terms of sensing performance, structural complexity, and practical limitations, and key research gaps and future directions are identified.

2. OPTICAL RESPONSE AND SENSING MECHANISM OF 1D PhC

Fig. 1 illustrates the basic optical response and sensing principle of a 1D PhC. A conventional 1D PhC consists of periodically arranged layers A and B with different refractive indices n_A and n_B, and thicknesses d_A and d_B, respectively [Fig. 1(a)]. At each interface, the incident electromagnetic wave is partially reflected and transmitted. Multiple reflections from successive interfaces interfere constructively and destructively, producing wavelength-selective reflection and transmission and resulting in a photonic band gap (PBG), within which light transmission is strongly suppressed [Fig. 1(b)]. The spectral position and width of the PBG depend primarily on the refractive-index contrast, optical thicknesses, and number of periods. The optical response is also influenced by the angle of incidence and polarization, since oblique incidence modifies the propagation conditions within the layers and can shift or alter the PBG. These characteristics provide several parameters for controlling the spectral response of 1D PhCs.

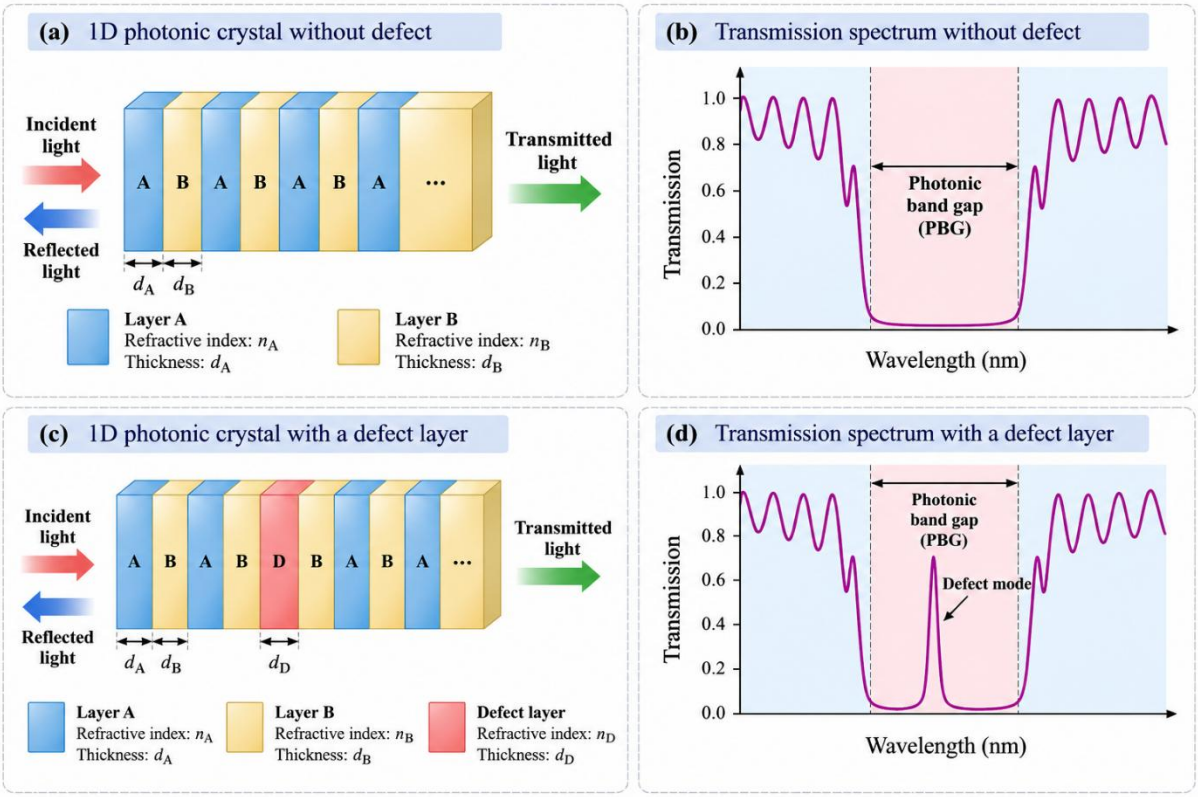


Fig. 1 Schematic representation of a 1D PhC and its optical response: (a) Defect-free 1D PhC (b) Transmission spectrum showing PBG (c) Defect-based 1D PhC (d) Transmission spectrum showing defect mode

The TMM provides a convenient analytical framework for describing this propagation. In TMM, the electromagnetic field at one side of an optical layer is related to the field at the other side through a characteristic matrix. The matrices corresponding to successive layers are then multiplied to obtain a single matrix representing the complete multilayer structure. Thus, a complex multilayer system can be treated as a sequence of simple optical layers. For a homogeneous layer j, the characteristic matrix can be written in the general form [10]

$$M_j = \begin{bmatrix} cos\delta_j & \frac{isin\delta_j}{\eta_j} \\ i\eta_j sin\delta_j & cos\delta_j \end{bmatrix}$$

where δ_j represents the phase accumulated by the electromagnetic wave during propagation through the layer and η_j is the optical admittance. The phase thickness is determined by the refractive index, layer thickness, wavelength, incidence angle, and polarization. For a multilayer photonic crystal, the characteristic matrices of all constituent layers are combined according to their spatial sequence to obtain the total transfer matrix. The transmission and reflection characteristics of the structure can then be calculated from the elements of this matrix. By scanning the wavelength, the transmission spectrum of the photonic crystal can be obtained, allowing the photonic band gap and localized defect resonances to be identified.

Introducing a defect layer into the periodic structure breaks its translational periodicity and generates a localized optical mode within the PBG [Fig. 1(c)]. As shown in Fig. 1(d), this defect mode appears as a narrow transmission peak within

the low-transmission PBG region. Its resonance wavelength depends on the refractive index and thickness of the defect layer, as well as on the properties of the surrounding PC. When the defect region acts as the sensing cavity and is filled with a biological sample, a change in the sample refractive index modifies the optical path length of the defect region, resulting in a measurable shift in the defect-mode resonance wavelength. This wavelength shift forms the fundamental sensing mechanism of defect-based 1D PhC biosensors. The sensing performance is commonly evaluated using parameters such as sensitivity, full width at half maximum (FWHM), quality factor (Q), figure of merit (FOM), and detection limit (DL), which provide complementary measures of wavelength response and spectral resolution.

Fig. 2 illustrates the resonance-wavelength shift produced by a change in the refractive index of the sensing medium. As the refractive index of the sensing medium changes from $n_1$to n_2, the defect-mode resonance shifts from λ_1 to λ_2 with the corresponding wavelength shift $\Delta\lambda_d$ forming the basis for refractive-index sensitivity. The figure also illustrates the FWHM and the related parameters used to characterize the spectral resolution of the sensor.

The performance is generally evaluated using several parameters, including sensitivity, resonance linewidth, quality factor, figure of merit, and detection limit. Sensitivity represents the change in resonance wavelength per unit change in the refractive index of the sensing medium and is expressed as

$$Sensitivity(s)=\frac{\Delta\lambda_{res}}{\Delta n}$$

Where $\Delta\lambda_{res}$ is is the resonance-wavelength shift corresponding to a refractive-index change Δn [9]. The Q-factor describes the spectral sharpness of the resonance and is given by

$$Q = \frac{\lambda_{res}}{\text{FWHM}}$$

Where λ_{res} is the defect peak resonance wavelength and FWHM is full width at half maximum [9]. A higher Q generally corresponds to a narrower resonance.

The figure of merit (FOM) combines sensitivity with resonance linewidth and can be expressed as [9]

$$FOM = \frac{s}{\text{FWHM}}$$

The detection limit (DL) represents the minimum refractive-index change that can be resolved by the sensor and depends on the wavelength shift and the spectral characteristics of the resonance [9]. Evaluating several parameters together provides a more complete assessment of sensing performance.

These sensing parameters provide the basis for comparing different 1D PhC architectures. Since the resonance characteristics depend strongly on the materials and geometrical configuration of the photonic crystal, various structural and material engineering strategies have been explored to improve the sensing response, as discussed in the following section.

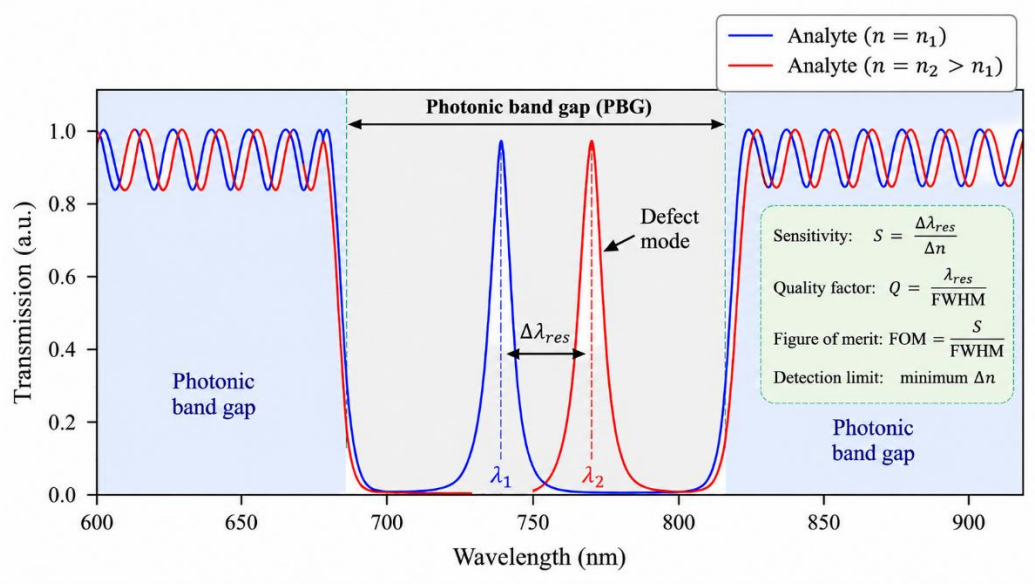


Fig. 2. Refractive-index sensing mechanism based on defect-mode resonance shift.

3. STRUCTURAL/MATERIAL ENGINEERING OF 1D PhC BIOSENSORS

The sensing performance of 1D PhC biosensors depends strongly on the structural and material configuration of the photonic crystal. Parameters such as the refractive-index contrast, constituent materials, layer thicknesses, number of periods, defect dimensions and position, incidence angle, and polarization influence the position and characteristics of the sensing resonance. Consequently, structural and material engineering has been widely investigated to obtain improved sensitivity, sharper resonances, enhanced field confinement, and greater control over the optical response. Conventional binary dielectric structures provide a simple platform for defect-mode sensing, while subsequent developments have introduced metallic layers, additional dielectric materials, geometrical modifications, and multiple defects to overcome the limitations of simple binary configurations.

Conventional binary 1D PhCs consist of periodically arranged layers of two dielectric materials with different refractive indices, with a defect introduced to generate a localized resonance within the PBG. Such structures have been investigated for the detection of biological analytes including blood components, cancer cells, and malaria infection. Their relatively simple geometry provides low optical loss and allows the resonance characteristics to be controlled through the layer thicknesses, number of periods, and defect parameters. However, the number of independently adjustable structural parameters is relatively limited, which restricts the simultaneous optimization of sensitivity, resonance linewidth, transmission, and mode stability. Experimental studies have also demonstrated the feasibility of implementing 1D PhC structures in microfluidic systems, including photonic-crystal resonators and refractive-index sensors, indicating that multilayer PC concepts can be integrated with practical fluidic sensing platforms [11-12].

One approach to increasing the design freedom is the incorporation of metallic layers into the photonic-crystal structure. Metal–dielectric interfaces can introduce additional light–matter interactions and modify the electromagnetic-field

distribution near the sensing region. However, metallic absorption can also reduce transmission, making the choice of metal, layer thickness, and position important design considerations. Early theoretical studies demonstrated the use of metal/defect configurations in 1D photonic-crystal biosensors for malaria detection, showing the potential of metallic layers to modify the optical response and enhance sensing performance. In particular, the incorporation of metal layers into defect-based structures provided additional control over the resonance characteristics and sensing response [13-14]. A subsequent metal-assisted 1D PhC biosensor for malaria detection systematically investigated the effects of metal type, metal-layer thickness, defect refractive index, incidence angle, and polarization. The optimized silver-based configuration achieved a sensitivity of 265.2 nm/RIU with a transmission intensity of 63% [9]. These studies demonstrate the additional optical control provided by metal incorporation, while also highlighting the trade-off between enhanced optical interaction and absorption loss.

A further development is the introduction of a third material into the periodic unit, forming a ternary photonic crystal. Compared with binary structures, ternary configurations provide additional interfaces and material parameters for controlling the photonic band structure and defect resonance. Ternary 1D PhCs have been investigated for malaria sensing, with studies demonstrating the potential of additional material layers to modify resonance characteristics and sensing performance [15-16]. Shibina et al studied a TiO_2/PMMA/SiO_2 ternary structure for malaria detection, where the additional PMMA layer provided greater control over defect-mode confinement and spectral characteristics. The optimized structure exhibited a sensitivity of 756.67 nm/RIU, a quality factor of 1.156×10^5, a figure of merit of 8.407×10^4 RIU−1, and a detection limit of 1.407×10^{-6} RIU [17]. These studies indicate that the introduction of an additional material can improve spectral characteristics beyond what can be achieved by simply increasing refractive-index sensitivity. At the same time, the increased number of material and geometrical parameters makes optimization more complex.

In addition to material modification, geometrical and defect engineering provide further ways of controlling the sensing response. Variations in layer thickness, number of periods, defect-layer thickness, defect position, incidence angle, and polarization can alter the resonance wavelength, linewidth, field confinement, and transmission characteristics. In particular, increasing the defect thickness can modify the optical path length and resonance position, but excessive structural modification may lead to resonance splitting or changes in mode stability. Thus, improving one sensing parameter does not necessarily improve the overall sensor performance, and structural optimization should consider sensitivity together with linewidth, transmission, and resonance stability.

An extension of defect engineering is the introduction of two or more defects to generate multiple localized resonances. Dual- and multiple-defect 1D PhCs have been investigated for blood-component detection, simultaneous refractive-index measurements, and biomedical sensing [18-19]. Multiple resonances can provide additional spectral information and may enable multiparameter or reference-assisted sensing. However, coupling between adjacent defect modes and the increased number of structural parameters can complicate spectral interpretation and optimization. Overall, the progression from binary dielectric structures to metal-assisted, ternary, geometrically engineered, and multiple-defect configurations has provided progressively greater control over the optical response of 1D PhC biosensors, but this increased design flexibility is accompanied by challenges related to optical loss, mode splitting, parameter optimization, fabrication tolerance, and practical implementation.

4. COMPARATIVE ANALYSIS AND RESEARCH GAPS

Table 1: Comparison of representative TMM-based 1D PhC biosensors for refractive-index sensing

Ref	1D PhC configuration	Application	Sensitivity (nm/RIU)	Q	FOM (RIU^{-1})	DL/Resolution
[20]	Binary PC + defect	Hemoglobin	167	NR	0.63	Resolution: 257 nm
[15]	Binary PC + defect	Malaria/RBCs	327.7	69,389	32,770	NR
[9]	Metal-assisted binary PC +defect	Malaria	265.2	135	49	DL: 3.771×10^{-4} RIU
[16]	Ternary PC + defect	Malaria	680	27,434	79,823	DL: 8.6×10^{-7} RIU
[19]	Binary dual-defect PC+ defect	Malaria/blood	401.57	NR	NR	NR
[18]	Binary dual-defect/coupled resonators+ defect	HIV/RI sensing	2300	6123	7419.3	NR
[21]	Binary dual-defect PC+ defect	Platelet	231	10680	4485	NR
[17]	Ternary PC+ defect	Malaria	756.67	1.156×10^{5}	8.407×10^{4}	DL: 1.407×10^{-6} RIU

The evolution of 1D PhC biosensors has progressed from conventional binary defect structures to metal-assisted, ternary, geometrically engineered, and multiple-defect configurations. Table 1 summarizes representative reported sensing performances. The comparison indicates that structural and material modifications can improve sensitivity, spectral resolution, Q-factor, or FOM, but improvements in one parameter may involve trade-offs in transmission, structural complexity, or fabrication requirements.

Despite these advances, several research gaps remain. Most reported studies are numerical, with limited experimental validation, fabrication-tolerance analysis, and long-term stability assessment. Moreover, performance metrics are often reported under different materials, wavelengths, incidence angles, and analyte conditions, making direct comparison difficult. Another important issue is the trade-off among sensing parameters, since improvements in sensitivity may be accompanied by reduced transmission, broader resonance linewidth, increased optical loss, or greater structural complexity. In addition, ternary and multiple-defect configurations can introduce mode splitting and coupled resonances, which increase the complexity of spectral interpretation and structural optimization. Future studies should therefore emphasize experimentally realizable designs, standardized performance evaluation, fabrication robustness, and multi-parameter or multi-resonance sensing strategies.

5. CONCLUSION

One-dimensional photonic crystals provide a flexible platform for label-free biosensing, with their optical response tunable through material selection, structural parameters, and defect engineering. Defect-mode configurations are particularly useful because changes in the refractive index of the sensing region can be detected through shifts in localized resonances. The review highlights the evolution of 1D PhC biosensors from conventional binary structures toward metal-assisted, ternary, geometrically engineered, and multiple-defect configurations, offering greater control over resonance characteristics and sensing performance. These approaches, however, can introduce challenges such as optical loss, structural complexity, mode coupling, and increased parameter-optimization requirements. Multiple- and dual-defect structures provide opportunities for multiple resonances and additional sensing information. Overall, 1D PhC biosensors are progressing toward structurally engineered, multiple-resonance, and potentially active sensing platforms. Future developments should focus not only on improving optical performance but also on fabrication tolerance, experimental validation, stability, reproducibility, and practical integration.

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