



Graphene-Integrated One-Dimensional Photonic Crystal for Enhanced Optical Biosensing: A Transfer-Matrix Study

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Abstract

Graphene-assisted one-dimensional photonic crystals provide a route for controlling electromagnetic confinement at a sensing interface while retaining the compact geometry of multilayer optical sensors. This manuscript develops a transfer-matrix-based description of a graphene-integrated 1D photonic-crystal biosensor consisting of a BK7 coupling prism, dielectric/graphene periodic layers, a thin plasmonic metal film, an interfacial binding layer, and an aqueous sensing medium. The supplied simulation study compares conventional SPR, photonic-crystal, PC-SPR, and glass-assisted PC-SPR arrangements for Au, Ag, and Cu. Calculations are performed for TM-polarized illumination at 633 nm. For the Au case, the model uses a 45 nm metal film, a 0.34 nm graphene layer, a 470 nm PMMA layer, a 3 nm binding layer, and nine periodic units. The reported angular spectra indicate that incorporation of the photonic-crystal/glass section narrows the resonance feature. The literature source used in the supplied report also describes a 14.8-fold sensitivity enhancement for a graphene-based 1D photonic-crystal sensor; this value is a literature result and is not presented here as a new experimental measurement. The study therefore provides a reproducible numerical framework for subsequent optimization and experimental validation.

Keywords

graphene; one-dimensional photonic crystal; optical biosensor; surface plasmon resonance; transfer matrix method; refractive-index sensing; resonance angle; FWHM; photonic band gap; plasmonic sensing.

1. Introduction

Optical biosensors translate an interaction at a sensing interface into a measurable optical change. Depending on the device architecture, the observable may be reflectance, transmittance, resonance angle, wavelength, phase, or polarization. Refractive-index-based detection is especially useful when the sensing surface is designed to respond to adsorption or binding of biological species.

A one-dimensional photonic crystal is formed by repeating layers with different optical refractive indices. Periodic modulation of the dielectric environment modifies wave propagation and can create forbidden frequency or wavelength intervals known as photonic band gaps [1–4]. Appropriate

structural design can also generate localized modes or sharpen resonant features, which is useful for optical sensing.

Graphene is attractive for photonic and plasmonic devices because an atomically thin layer can strongly modify the local optical response while adding very little physical thickness. Its high carrier mobility, optical properties, large specific surface area, and compatibility with surface functionalization make it relevant to sensing platforms [5,6].

The present work reorganizes the supplied project study into a research-paper format. The emphasis is on the physical architecture, transfer-matrix formulation, model parameters, reported reflectance behavior, and practical considerations for graphene-assisted PC-SPR sensing. Results explicitly identified as originating from the supplied report or published literature are kept distinct from the proposed interpretation.

2. Device Concept and Physical Principle

2.1 Surface-plasmon-resonance principle

In the Kretschmann geometry, TM-polarized radiation is coupled through a high-index prism toward a thin metal layer. At a suitable incidence condition, the tangential component of the incident optical wavevector can match the momentum of a surface plasmon mode. Energy transfer into this mode produces a reduction in the reflected intensity. A change in the refractive index close to the metal surface modifies the resonance condition, so the corresponding angular displacement can be used as a sensing observable.

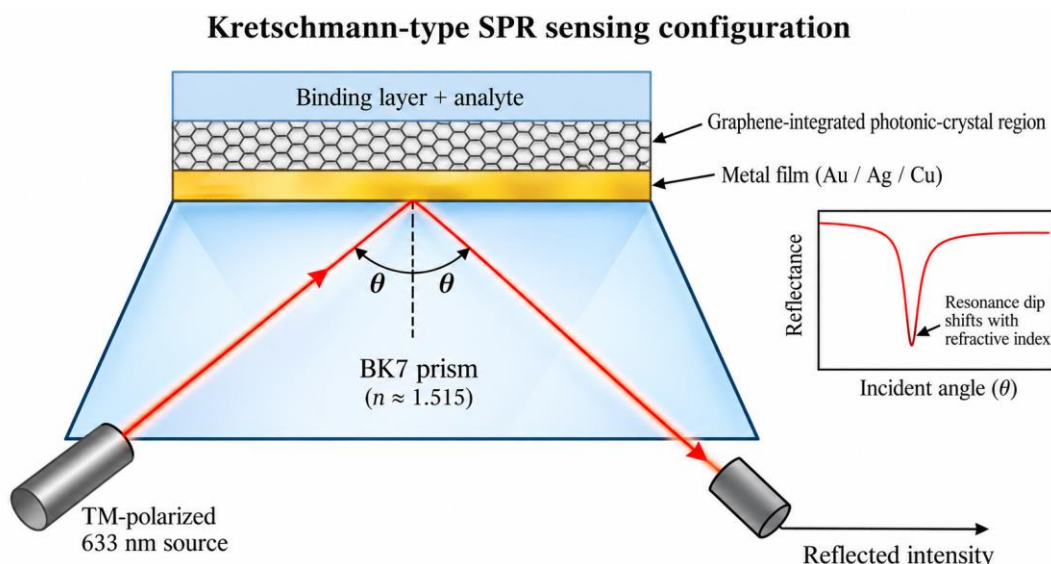


Fig. 1. Schematic representation of a Kretschmann-type SPR arrangement with a graphene-integrated photonic-crystal sensing region.

2.2 One-dimensional photonic-crystal concept

The proposed photonic-crystal section is represented by alternating optical layers A and B. The repeated unit cell is denoted by AB, and the refractive-index contrast between the two materials controls the formation of photonic stop bands. When the periodic structure is combined with a plasmonic interface, its optical modes can interact with the surface resonance and modify the angular linewidth and depth of the reflectance minimum.

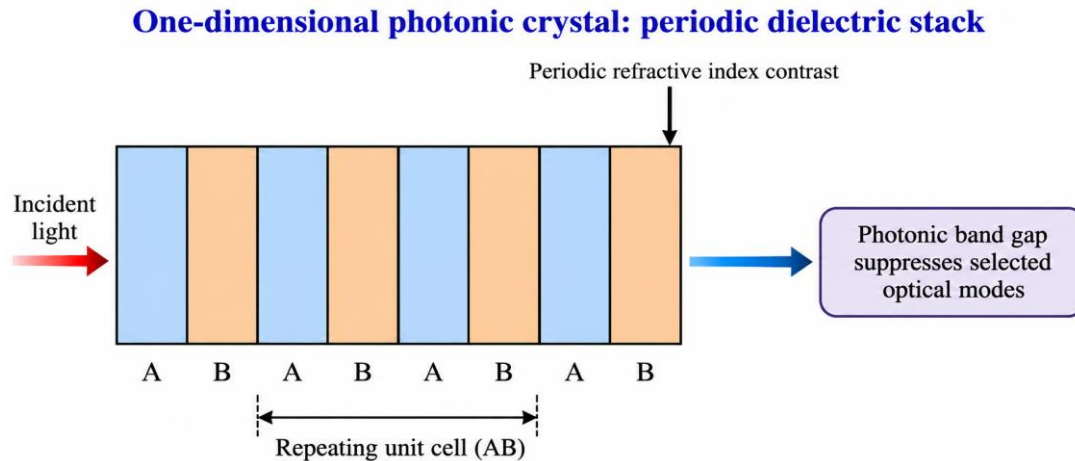


Fig. 2. Periodic AB dielectric stack used to illustrate the one-dimensional photonic-crystal band-gap concept.

2.3 Graphene-integrated sensing architecture

The proposed sensing stack combines a coupling prism and glass section with a periodic graphene-containing photonic-crystal region, a plasmon-supporting metal layer, an interfacial binding layer, and the analyte medium. In the conceptual design, analyte binding changes the local refractive index. The resulting modification of the optical field and resonance condition is monitored through the reflected or transmitted signal.

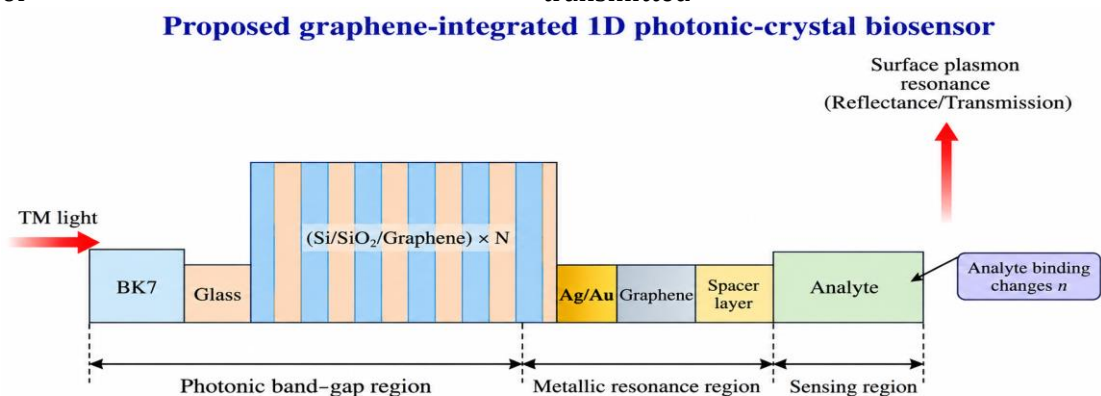


Fig. 3. Proposed graphene-integrated 1D photonic-crystal biosensor architecture.

3. Theoretical Model and Methodology

3.1 Transfer-matrix formulation

The multilayer optical response is evaluated with the transfer matrix method (TMM). For each boundary between adjacent media, an interface matrix connects the forward- and backward-propagating field amplitudes. A propagation matrix accounts for phase accumulation through a layer of finite thickness. Multiplication of the individual matrices in the physical order of the stack gives the global matrix M .

For a stack represented by successive interface and propagation matrices, the reflection and transmission amplitudes can be written in the form

$$M = I_{01} \cdot L_1 \cdot I_{12} \cdot L_2 \cdot \dots \cdot I_{(N-1),N}$$

$$r = M_{12} / M_{22}, \quad R = |r|^2$$

$$t = 1 / M_{22}, \quad T = |t|^2$$

$$S = \Delta\theta_{res} / \Delta n$$

Here R and T denote reflectance and transmittance, respectively; θ_{res} is the resonance angle; n is the refractive index of the sensing medium; and S is the angular sensitivity when resonance-angle tracking is used. The supplied computational procedure evaluates the TM response over 65.5° – 85° at a wavelength of 633 nm.

3.2 Model parameters

Parameter	Value	Function in model
BK7 refractive index	1.515	Coupling prism
Graphene refractive index	$3 + 1.149i$	Optically absorbing graphene
PMMA refractive index	1.49	Dielectric photonic-crystal layer
Binding-layer refractive index	1.462	Biorecognition/interface layer
Water/analyte refractive index	$1.33 + \Delta n$	Sensing medium
Graphene thickness	0.34 nm per layer	Monolayer model
PMMA thickness	470 nm	Photonic-crystal layer
Binding-layer thickness	3 nm	Sensing interface
Au thickness	45 nm	SPR metal
Periodic units	$N = 9$	1D photonic-crystal stack
Wavelength	633 nm	TM-polarized illumination

Transfer-matrix simulation workflow

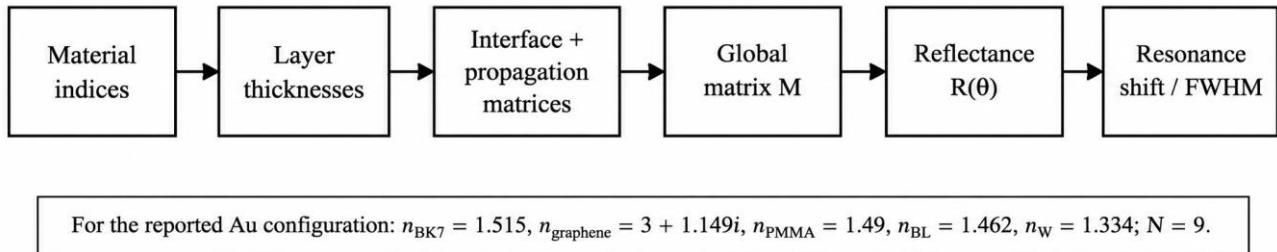
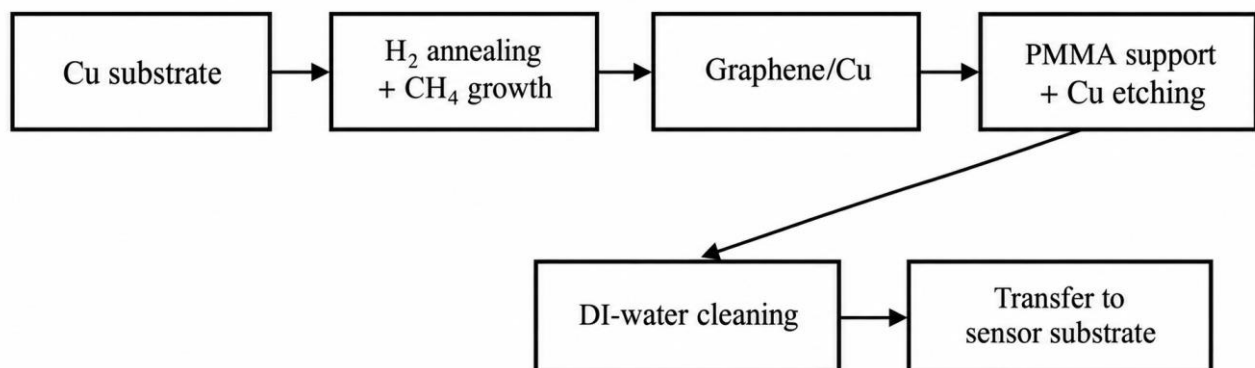


Fig. 4. Transfer-matrix workflow used to obtain the reflectance response and resonance characteristics.

3.3 Graphene growth and transfer

The supplied project describes graphene growth on copper by chemical-vapour deposition followed by a polymer-assisted transfer process. In the reported route, hydrogen annealing precedes methane-based growth. A PMMA support is then used while the copper is removed by etching. The supported graphene is rinsed with deionized water and subsequently transferred to the intended sensor substrate.

CVD growth and transfer route for graphene



The source report describes CVD growth on Cu followed by PMMA-assisted transfer and cleaning.

Fig. 5. Simplified CVD growth and PMMA-assisted transfer route for graphene.

4. Results and Discussion

Four structural arrangements were compared in the supplied numerical study: conventional SPR, a photonic-crystal sensing structure without a metal film, PC-SPR, and PC-SPR incorporating a glass section. For Au, the corresponding labels are BK7/Au/BL/W, BK7/PC/BL/W, BK7/PC/Au/BL/W, and BK7/glass/PC/Au/BL/W. Equivalent Ag and Cu structures were also considered.

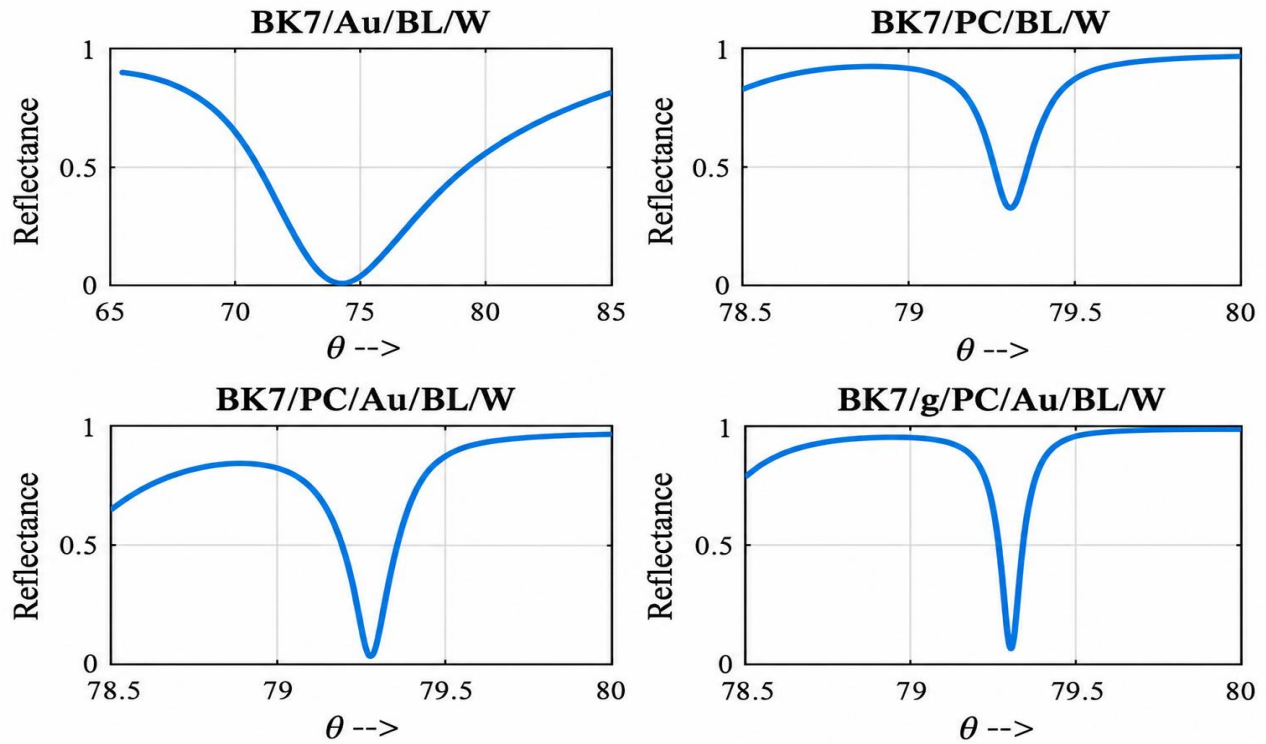


Fig. 6. Replotted illustration of the four Au-based angular reflectance responses. The curves are schematic reproductions for presentation; quantitative values should be taken from the original TMM data.

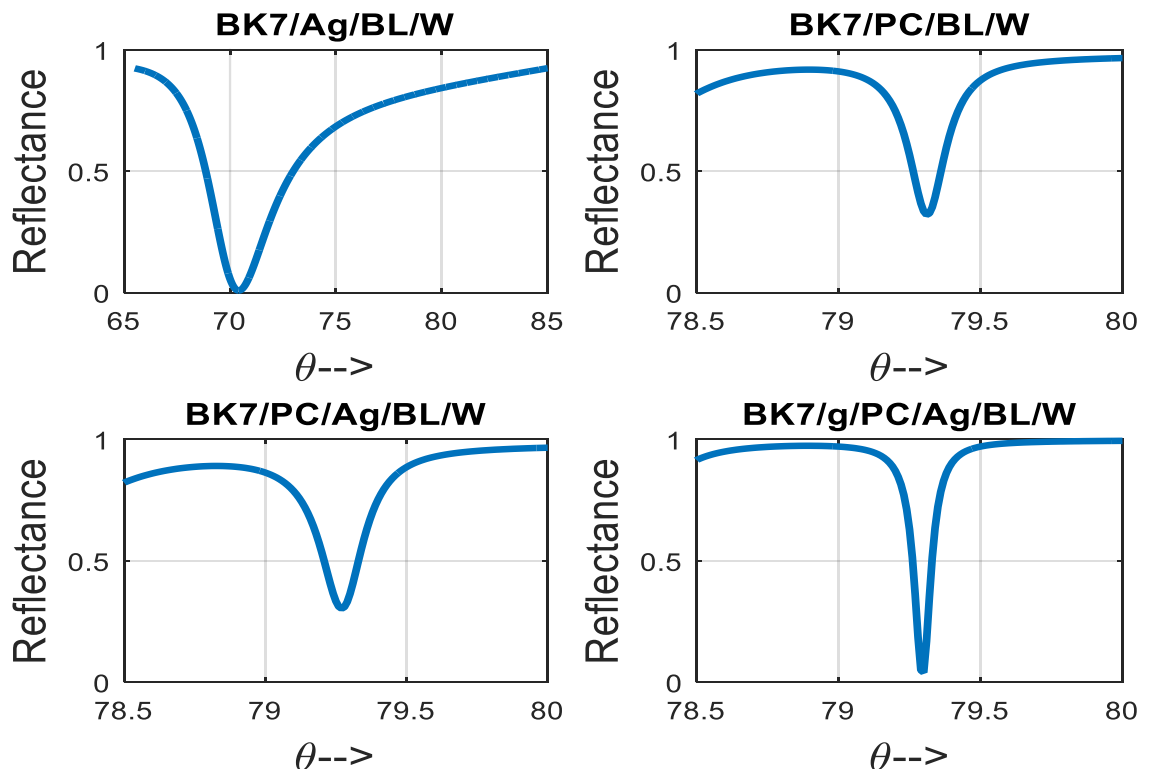


Fig. 7. Ag-based reflectance versus incident angle for the four compared configurations, reproduced from the supplied report.

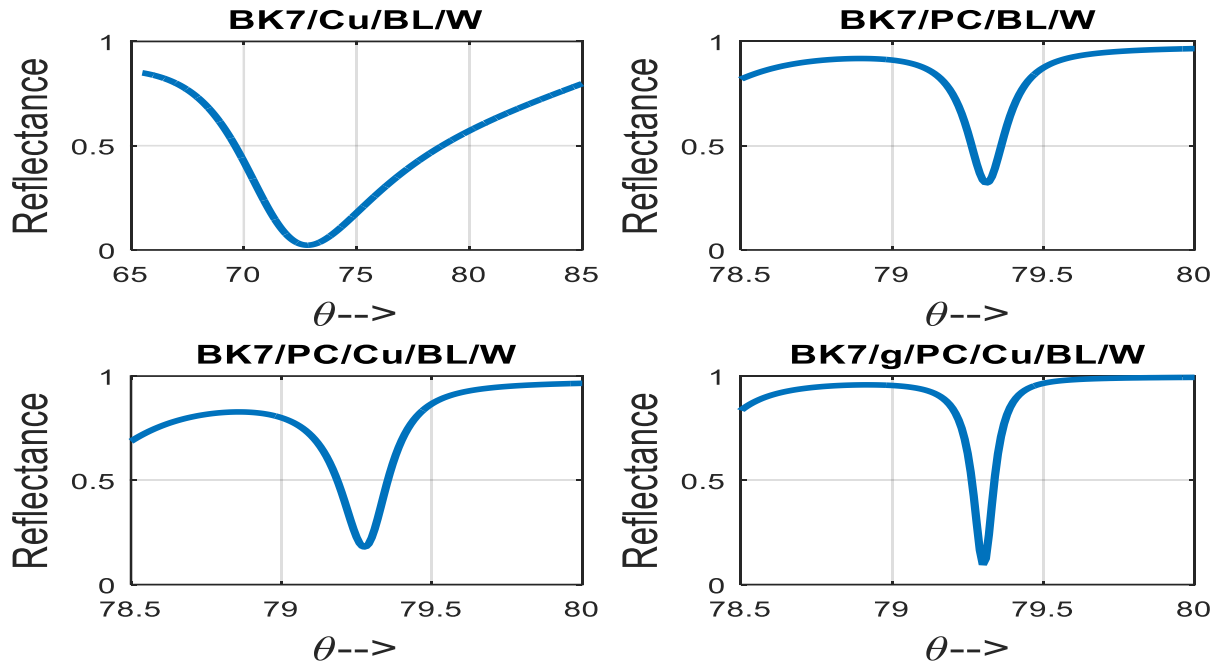


Fig. 8. Cu-based reflectance versus incident angle for the four compared configurations, reproduced from the supplied report.

Source attribution: Figures 7 and 8 are retained from the supplied project/report data and are reproduced here for comparison. They are not presented as newly generated experimental measurements.

The calculated response shows the qualitative effect of adding the photonic-crystal section: the broad conventional SPR feature becomes a more localized angular resonance. In the supplied analysis, inclusion of the glass-assisted photonic-crystal section produces the narrowest resonance among the compared structures. A narrow feature is useful because it permits the resonance position to be located more precisely, although sensitivity must ultimately be obtained from a calibration curve rather than from linewidth alone.

4.1 Resonance width and sensing response

Two useful characteristics of an angular SPR signal are the position of the reflectance minimum and the width of the resonance. A smaller full width at half maximum (FWHM) generally indicates a sharper spectral or angular feature and can improve the precision of resonance tracking. It should not, however, be interpreted by itself as proof of higher refractive-index sensitivity.

4.2 Comparison of plasmonic metals

Metal	Behavior reported in supplied analysis	Cost-related consideration
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Au	Strong and comparatively sharp SPR response with a low reflectance minimum	Highest material cost
Ag	Sharp PC-SPR response, particularly with the glass-assisted structure	Lower cost than Au
Cu	Broader response and higher reflectance minimum in the reported comparison	Lower material cost

The supplied analysis therefore treats Ag as a potentially useful compromise between optical response and material cost. Cu is less attractive when very narrow angular resonances are required. These statements describe the supplied comparison and should be validated for a specific fabrication process and operating environment.

4.3 Reported graphene-related sensitivity enhancement

The published graphene-based 1D photonic-crystal literature cited in the supplied report reports a sensitivity enhancement of 14.8 times relative to the reference SPR configuration [8]. This should be written as a 14.8-fold enhancement, not as a 14.8% increase. The present manuscript does not claim this value as a newly measured result.

Reference SPR = 1.0 (normalized); graphene/PC-enhanced response = 14.8 (normalized)

5. Practical Implementation and Optimization

- Operating wavelength: examine the response around the selected illumination wavelength; the supplied model uses 633 nm.
- Metal thickness: perform a controlled thickness sweep around the reported 45–50 nm range rather than assuming one thickness is universally optimal.
- Photonic-crystal design: vary the number of periods, dielectric thicknesses, and graphene-layer count to determine their effects on the resonance.
- Sensing calibration: vary the analyte refractive index systematically and calculate the resonance-angle or wavelength shift per refractive-index unit.
- Graphene characterization: use appropriate optical and structural techniques such as Raman spectroscopy, AFM, SEM, or TEM to establish layer number, morphology, and defect characteristics.
- Device validation: quantify reproducibility, selectivity, response time, detection limit, and long-term stability before presenting the structure as an experimentally validated biosensor.

6. Limitations and Scope for Further Work

The supplied material contains the TMM formulation, model parameters, reflectance plots, and computational basis, but it does not provide a complete numerical table of resonance angles, FWHM values, and calibration slopes for every configuration. Consequently, those quantities should be regenerated directly from the numerical code before being reported as precise new results.

The literature-derived 14.8-fold sensitivity enhancement is retained only as a cited benchmark. It should not be described as an independent experimental measurement from the present manuscript. Future work should perform automated parameter sweeps, independently verify the optimum structures using a second numerical method such as FDTD, include uncertainty analysis, and compare simulated results with fabricated devices.

7. Conclusion

A graphene-integrated one-dimensional photonic-crystal architecture offers a physically motivated platform for modifying local optical fields and sharpening plasmonic sensing resonances. The transfer-matrix framework provides a practical way to examine the effects of graphene, dielectric-layer thickness, metal thickness, periodicity, and analyte refractive index. The supplied comparison indicates that adding the photonic-crystal and glass sections produces substantially narrower angular features than the conventional arrangement. Au provides a strong optical response, while Ag offers a lower-cost alternative in the reported comparison. The key next step is to replace literature-derived or source-report-derived performance claims with independently reproduced numerical data and experimental measurements.

References

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