

Original Research

Label-Free Sensing of Thiamine, Pantothenic Acid and Pyridoxine Hydrosoluble Vitamins Using a Symmetric Photonic Heterostructure Resonator

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Abstract:

This study presents a label-free biosensor based on a symmetric one-dimensional photonic heterostructure resonator for the refractometric detection of three water-soluble B-complex vitamins. By filling the defect cavity with vitamin solutions, the sensor generated distinct resonance shifts proportional to refractive-index changes, enabling precise molecular discrimination. Optimal performance was achieved at a 60° incidence angle under transverse-electric polarization, yielding ultra-high sensitivity (nearly 280 nm/RIU), a sharp resonance quality factor exceeding 2000, and a detection limit as low as 1.21×10^{-3} RIU, accompanied by a figure of merit greater than 800 surpassing conventional 1D photonic crystal biosensors. A strong polarization-dependent response was observed, with transverse-magnetic (TM) mode performance degrading at high angles due to Brewster's effect, confirming TE polarization as the superior sensing configuration.

Keywords: Hydrosoluble vitamins; Label-free detection; Photonic crystals; Refractometric sensing; Resonators

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1. Introduction

Photonic crystals and plasmonic structures enable precise nanoscale light manipulation, allowing for the highly sensitive detection of biological and chemical substances. Recent advances have introduced platforms that strongly confine and precisely tune light. For example, combining a metal film with a photonic crystal has boosted certain optical signals by nearly a thousandfold [1]. Optical Tamm states at material interfaces can also create intense light concentration, which is highly valuable for sensing applications [2]. Other innovations include metasurfaces designed to perfectly absorb specific infrared light, matching human absorption for potential sensing uses [3]. Platforms that enhance molecular fingerprint signals have also been developed, allowing flexible spectral tuning [4]. Furthermore, new metasurfaces with indepen-

dently tunable resonances across infrared wavelengths enable sensitive biosensing and real-time monitoring of proteins, offering a powerful tool for integrated medical devices [5]. At the same time, photonic crystal fiber (PCF) sensors combined with surface plasmon resonance (SPR) are becoming powerful tools. A Kagome-lattice PCF-SPR sensor has shown excellent performance for detecting blood components [6], and reviews such as Ramola et al. [7] explain how different PCF-SPR designs can sense glucose, DNA, proteins, and even cancer cells. With the help of artificial intelligence, these sensors can be optimized for faster and more accurate detection [8, 9]. Together with other environmental sensing methods [10], these technologies are shaping a new generation of highly sensitive tools for medicine, food safety, and environmental monitoring. For non-invasive health mon-

itoring, two dual-polarized sensors have been developed: a triple-layered sensor designed for glucose monitoring in urine to prevent diabetes [11], and a comparable “PregBiosensor” for early pregnancy detection via urine analysis to lower miscarriage risk [12].

With these developments in photonic and plasmonic technologies, researchers are now extending such sensitive detection methods to water-soluble vitamins, which require precise and label-free analysis. Many new methods use plasmonic structures such as Metal-Insulator-Metal (MIM) waveguides; for example, Shangbo et al. [13] used Fano resonance for highly sensitive vitamin detection, while Sun et al. [14] designed an S-shaped plasmonic waveguide. At terahertz frequencies, Wang et al. [15] developed a metasurface sensor that can detect vitamins C and B₉ with very high accuracy, and electrochemical sensors improved with nanomaterials are widely used for vitamins like B₆ [16, 17]. In addition, recent studies on various nanomaterials show how tuning their optical and chemical properties can further improve detection. Examples include band-gap-tuned Ni-Co sulfide nanoparticles [18], optimized DNA-assisted CNT dispersions [19], and nanocomposites with enhanced photocatalytic activity [20]. Other works such as Ag-Cu alloy nanoparticles that reduce bacterial activity [21] and new pyrazole derivatives with selective antibacterial effects [22] also highlight how engineered nanoscale materials can support more effective biochemical analysis.

Photonic sensing has grown rapidly, but the detection of water-soluble vitamins using photonic crystal resonators is still limited. To help fill this gap, we designed a symmetric photonic heterostructure for label-free detection of three B-complex vitamins: thiamine (B₁), pantothenic acid (B₅), and pyridoxine (B₆). The symmetric structure creates sharp resonances and strong confinement. When vitamin solutions are placed in the cavity, even small changes in refractive index lead to clear shifts in the resonance peak. The sensor works best for TE polarization at incident angle $\theta = 60^\circ$, offering high sensitivity, a large quality factor, and a very low detection limit. It also shows a strong figure of merit and confirms that TM polarization weakens at higher angles due to Brewster’s effect, making the TE mode the preferred choice for sensing.

2. Materials and methods

In this work, a one-dimensional (1D) symmetric heterostructure biosensor a defect layer of water-soluble vitamin solution is considered as an optical microcavity for refractometric sensing. The structure is designed as $(AB)^N/D/(BA)^N$, where A = TiO₂ and B = SiO₂, with a defect (D) and N period. The 1D photonic crystal biosensor is superior to 2D/3D counterparts due to three key advantages: simpler optical analysis using straightforward methods like transfer matrix method versus complex finite element method simulations; easier and cheaper fabrication via standard deposition techniques compared to advanced and costly methods like electron beam lithography.

The proposed sensor model can significantly simplify the vitamin analysis process compared to conventional methods like high-performance liquid chromatography (HPLC) or enzyme-linked immunosorbent assay (ELISA). It eliminates the need for time-consuming and costly labeling steps such as fluorescent tagging, enzyme-antibody conjugation, or chemical derivatization. Also, the sample typically requires only simple dilution, whereas methods like HPLC demand extensive extraction and purification.

The refractive index of SiO₂ and TiO₂ layers were calculated by using the Sellmeier equation. The wavelength-dependent permittivity coefficients of SiO₂ and TiO₂ are assumed as follows [23, 24].

$$\begin{aligned} \varepsilon_A &= 5.913 + \frac{0.2441}{\lambda^2 - 0.0803}, \\ \varepsilon_B &= 1 + \frac{0.6961663\lambda^2}{\lambda^2 - (0.0684043 \times 10^{-6})^2} + \\ &\quad \frac{0.4079426\lambda^2}{\lambda^2 - (0.1162414 \times 10^{-6})^2} + \\ &\quad \frac{0.8974794\lambda^2}{\lambda^2 - (9.806161 \times 10^{-6})^2}. \end{aligned} \quad (1)$$

It should be noted that all supposed materials are non-magnetic. The performance of a biosensor is mainly determined by their quality factor as

$$Q = \frac{\lambda_0}{\Delta\lambda_{FWHM}} \quad (2)$$

where λ_0 is the resonant wavelength and $\Delta\lambda_{FWHM}$ represents the spectral width of the resonance peak at half maximum. Another biosensor parameter is sensitivity (S) which can be considered as

$$S = \frac{\Delta\lambda}{\Delta n} \quad (3)$$

where $\Delta\lambda$ denotes the resonant wavelength shift and Δn represents the corresponding refractive index change. This relation demonstrates that the sensor’s detection capability is directly proportional to the spectral displacement per refractive index variation. The third parameter is the detection limit (DL)

$$DL = \frac{\Delta\lambda_{\min}}{S} = \frac{\lambda_0}{S \cdot Q} \quad (4)$$

where λ_0 is the resonant wavelength, S is the sensitivity, Q is the quality factor and $\Delta\lambda_{\min}$ is the minimum detectable wavelength shift. The expression links the sensor’s fundamental optical characteristics (Q , S) with its practical detection capability. Finally, the fourth parameter is the figure of merit (FOM)

$$FOM = \frac{S \cdot Q}{\lambda_0} \quad (5)$$

The FOM comprehensively evaluates sensor performance by combining both S and Q [25].

The optical response of the proposed structure was numerically analyzed using the transfer matrix method

(TMM). The TMM is an analytical, layer-based approach. Unlike FDTD or COMSOL-type numerical solvers, The TMM does not require any spatial meshing, nodes, cells, or meshing-resolution parameters. In this method, each layer of structure is represented by a characteristic 2×2 transfer matrix that relates the forward- and backward-propagating electric fields at the input and output interfaces. The total transfer matrix of the entire stack is obtained by multiplying the individual matrices of all layers in sequence. The electric field in two adjacent layers is expressed as:

$$\begin{cases} E_1(z, \omega) = A_1 e^{ik_1 z} + B_1 e^{-ik_1 z}, & 0 < z \leq d_1 \\ E_2(z, \omega) = A_2 e^{ik_2(z-d_1)} + B_2 e^{-ik_2(z-d_1)}, & d_1 < z \leq d_2 \end{cases} \quad (6)$$

In these relations, k_1 and k_2 represent the wave numbers in the two layers. The coefficients A_1, B_1, A_2 and B_2 are determined by enforcing the boundary conditions at the interface between layers. After performing the necessary mathematical calculations, the transfer matrix is given by [26]:

$$M_j(\Delta z, \omega) = \begin{pmatrix} \cos(k_z^j \Delta z) & \frac{j}{q_j} \sin(k_z^j \Delta z) \\ j q_j \sin(k_z^j \Delta z) & \cos(k_z^j \Delta z) \end{pmatrix} \quad (7)$$

where $k_z^j = (\frac{\omega}{c}) \sqrt{\epsilon_j} \sqrt{\mu_j} \sqrt{1 - \sin^2 / \epsilon_j \mu_j}$ is the component of the wave vector along the z axis, c indicates the speed of light $q_j = \sqrt{\epsilon_j} / \sqrt{\mu_j} \sqrt{1 - \sin^2 / \epsilon_j \mu_j}$ for TE mode. The transmission coefficient is

$$t(\omega, \theta) = \frac{2 \cos \theta}{(m_{11} + m_{22}) \cos \theta + i(m_{12} \cos^2 \theta - m_{21})} \quad (8)$$

3. Results and discussion

Here, a 1D heterostructure was designed as $(AB)^N/D/(BA)^N$. The structure consists of alternating

layers of titanium dioxide ($A = \text{TiO}_2, n_A = 2.5$) and silicon dioxide ($B = \text{SiO}_2, n_B = 1.46$), arranged according to the quarter-wave thickness rule ($d = \lambda_0/4n$) at the design wavelength $\lambda_0 = 800$ nm. It should be noticed that because both sides of the defect layer are the same, the wave stays trapped more effectively. The corresponding physical thicknesses are $d_A = 80$ nm and $d_B = 137$ nm. The periodic number was set to $N = 7$ on each side of the structure. At the center of the structure, a defect layer (D) is introduced, filled with a water-soluble vitamin solution. To ensure strong resonance within the photonic bandgap, the defect thickness is set to half-wave optical thickness, calculated as $dD = \lambda_0/(2n_{\text{defect}})$, where $n_D = n_{\text{defect}}$ is the refractive index of the vitamin solution (see Table 1). The defect thickness was chosen approximately 300 nm for $\lambda_0 = 800$ nm and $n_D = 1.33$.

Table 1. Selected water soluble vitamins with concentration of 1 g/50 mL.

Vitamin	Refractive index	Reference
Vitamin B ₅ (pantothenic acid)	1.3360	[18]
Vitamin B ₁ (Thiamine)	1.3366	[18]
Vitamin B ₆ (Pyridoxine)	1.3371	[18]

Figure 1 presents the transmission spectra for the structure with defect filled with pure water ($n = 1.333$) and aqueous solutions of the three vitamins (B₁, B₅, and B₆) at a concentration of 1 g/50 mL. The spectra are calculated at normal incidence. There is no distinction is observed between TE and TM polarizations. The spectrum for water reveals a well-defined PBG in the near-infrared region, with a sharp resonant peak located

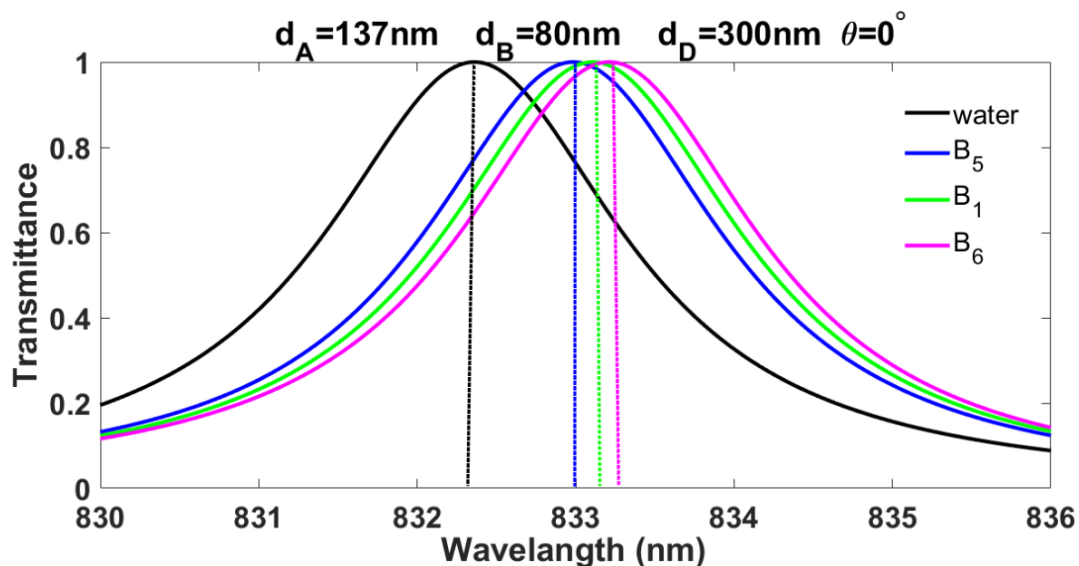


Figure 1. Transmission spectra as a function of wavelength at normal incidence angle $\theta = 0^\circ$ for water and selected water soluble vitamins with concentration of 1 g/50 mL.

at approximately 830 nm. The introduction of vitamin solutions into the cavity induces a red-shift for B₅ (833.47 nm) (Fig. 2 (b)), B₁ (833.59 nm) (Fig. 2 (c)), and B₆ (833.69 nm) (Fig. 2 (d)). This shift is proportional to the refractive index of the analyte (see Table 2). The biosensor performance results summarized in Table 3,

derived from the parameters in Table 2.

Figures 3 and 4 present the resonance behavior of the proposed photonic crystal at an incident angle of 30° for TE polarization. According to Fig. 4, the resonance wavelengths for water and vitamins B₅, B₁, and B₆ are about 793.58 nm (Fig. 4 (a)), 794.28 nm (Fig. 4 (b)),

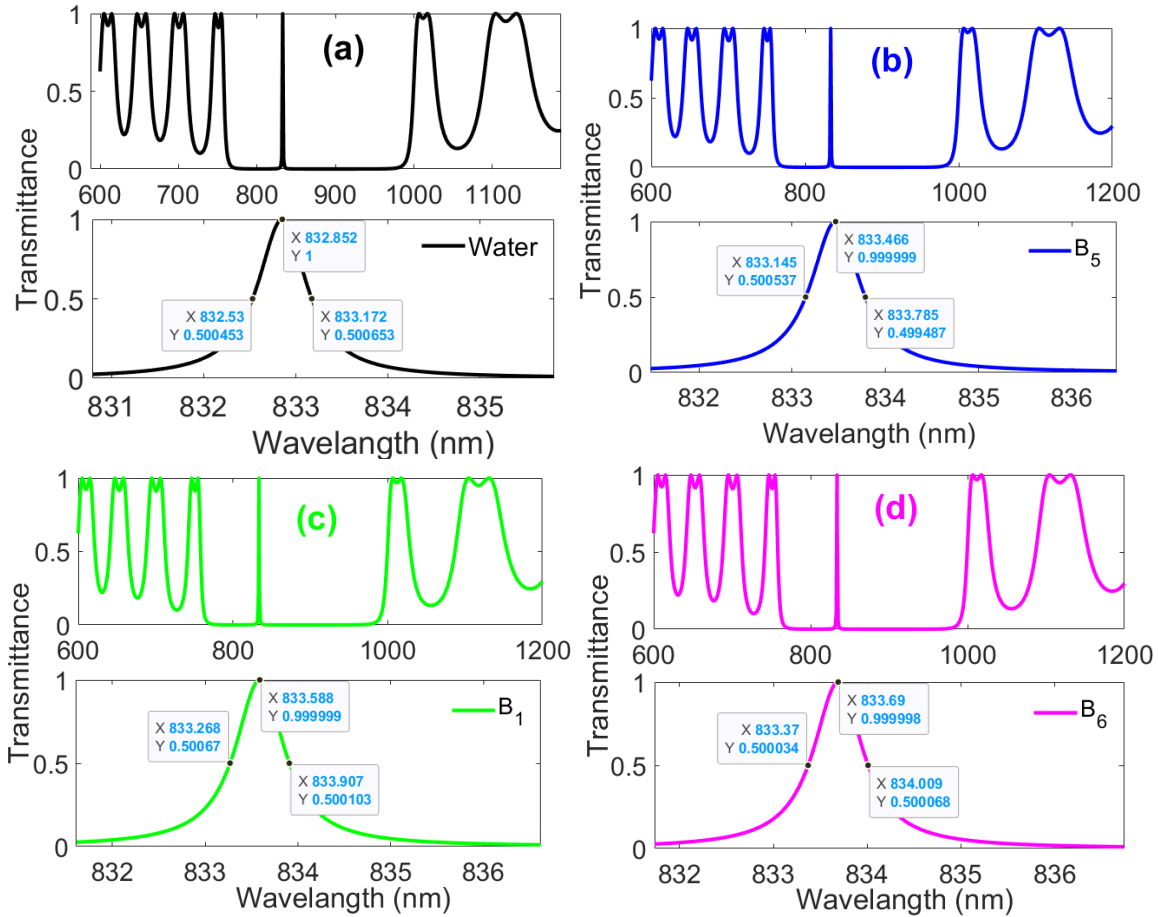


Figure 2. Detailed performance analysis of each vitamin based on Fig. 1 at normal incidence angle $\theta = 0^\circ$. (a) water, (b) B₅, (c) B₁, (d) B₆.

Table 2. Resonant wavelength (λ_0), resonance shift ($\Delta\lambda_0$) and full width at half maximum ($\Delta\lambda_{FWHM}$) at normal incident angle ($\theta = 0^\circ$).

Defect	Refractive Index	Resonant Wavelength λ_0 (nm)	$\Delta n = n - n_0$	$\Delta\lambda_0 = [\lambda_0(n) - \lambda_0(n_0)]$ (nm)	$\Delta\lambda_{FWHM}$ (nm)
Water	$1.333 = n_{\text{solvent}}$	832.852	0	0	0.642
Vitamin B ₅	~ 1.3360	833.466	0.003	0.614	0.640
Vitamin B ₁	~ 1.3366	833.588	0.0036	0.736	0.639
Vitamin B ₆	~ 1.3371	833.69	0.0041	0.838	0.639

Table 3. Quality factor (Q), sensitivity (S), detection limit (DL), and figure of merit (FOM) obtained from Table 2 at normal incident angle ($\theta = 0^\circ$).

Water Soluble Vitamin	Quality Factor ($Q = \lambda_0 / \Delta\lambda_{FWHM}$)	Sensitivity ($S = \Delta\lambda_0 / \Delta n$)	Detection Limit ($(\lambda_0 / S \cdot Q) \times 10^{-3}$)	Figure of Merit ($S \cdot Q / \lambda_0$)
Vitamin B ₅	1302.29	204.66	3.12	319.78
Vitamin B ₁	1304.51	204.44	3.12	319.93
Vitamin B ₆	1304.67	204.39	3.12	319.85

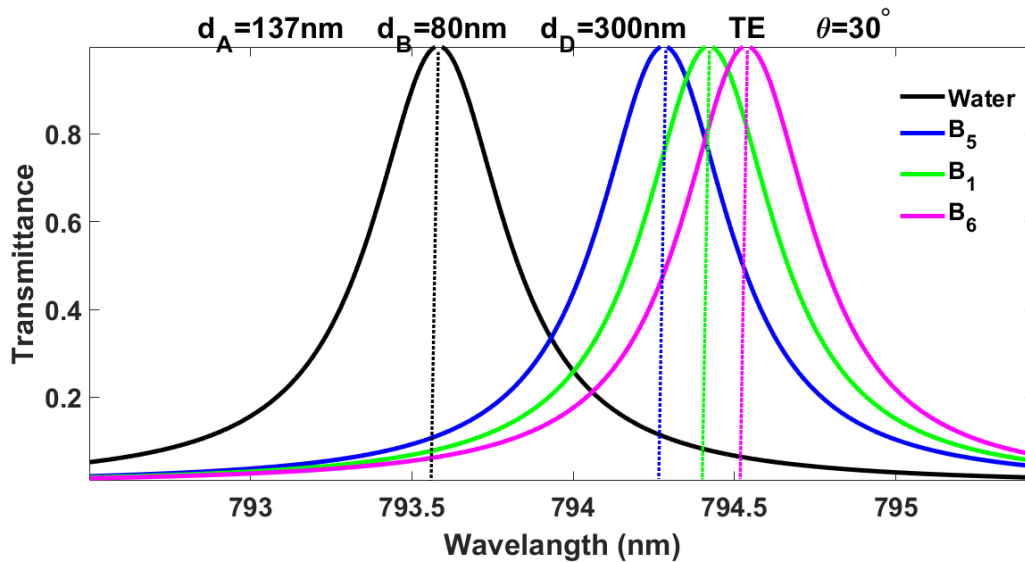


Figure 3. Resonance modes at incident angle $\theta = 30^\circ$ and for TE polarization wave.

794.42 nm (Fig. 4 (c)), and 794.53 nm (Fig. 4 (d)) respectively (see Table 4). As summarized in Table 4, the resonance wavelength shifts progressively from 793.58 nm for pure water (Fig. 4 (a)) to 794.53 nm for vitamin B₆ (Fig. 4 (d)). The device exhibits resonance linewidths ($\Delta\lambda_{FWHM} = 0.49 - 0.50$ nm), resulting high quality

factors ($Q = 1600$, Table 5). The sensitivity is above 230 nm/RIU, with detection limits near 2.1×10^{-3} RIU and FOM exceeding 470.

Figures 5 and 6 present the resonance spectra of the proposed photonic crystal resonator at an incident angle of 30° under TM polarization for water-soluble vitamin

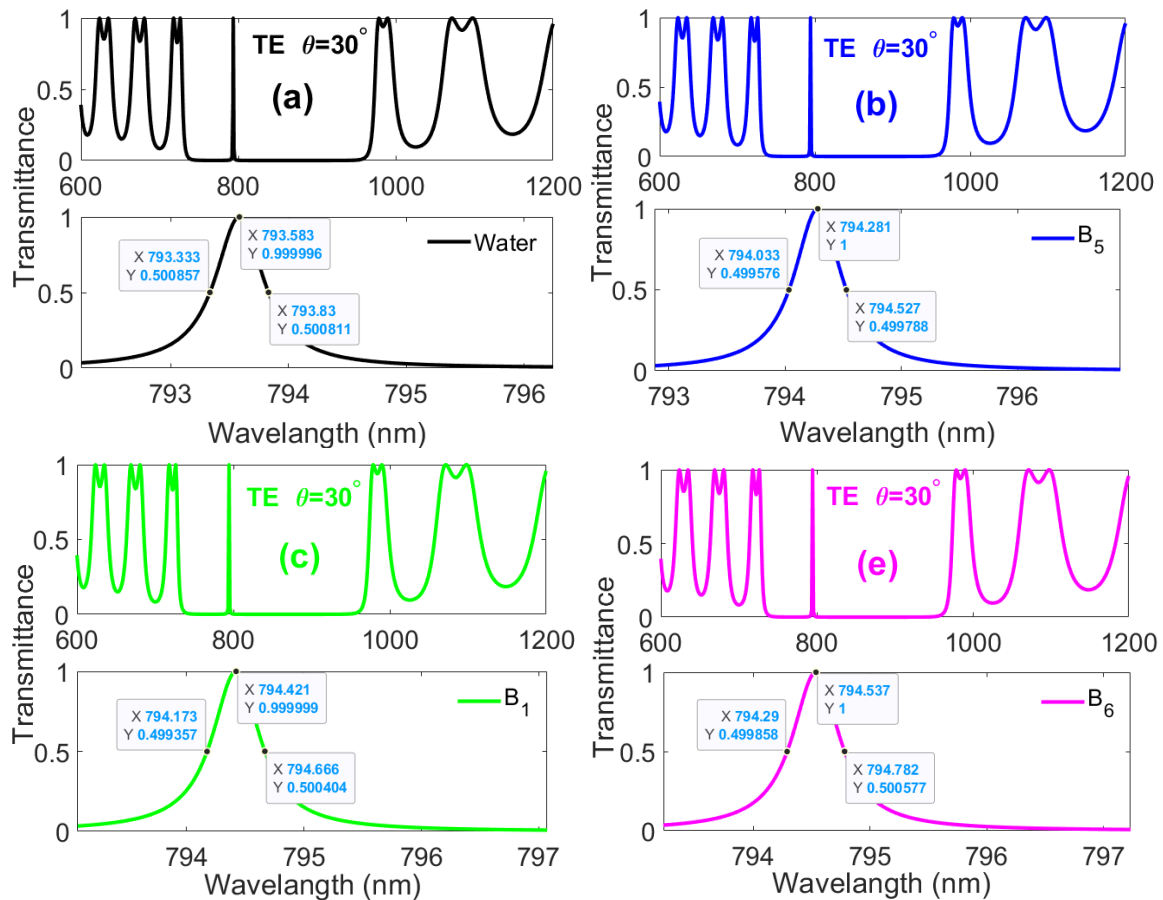


Figure 4. Detailed resonance analysis of each water soluble vitamin based on Fig. 3 different at incident angle $\theta = 30^\circ$ and for TE polarization wave. (a) water, (b) B₅, (c) B₁, (d) B₆.

Table 4. TE resonant wavelength (λ_0), resonance shift ($\Delta\lambda_0$) and full width at half maximum ($\Delta\lambda_{FWHM}$) at incident angle ($\theta = 30^\circ$).

Defect	Refractive Index	Resonant Wavelength λ_0 (nm)	$\Delta n = n - n_0$	$\Delta\lambda_0 = [\lambda_0(n) - \lambda_0(n_0)]$ (nm)	$\Delta\lambda_{FWHM}$ (nm)
Water	$1.333 = n_{\text{solvent}}$	793.583	0	0	0.497
Vitamin B ₅	~ 1.3360	794.281	0.003	0.698	0.494
Vitamin B ₁	~ 1.3366	794.421	0.0036	0.838	0.493
Vitamin B ₆	~ 1.3371	794.537	0.0041	0.954	0.492

Table 5. TE Quality factor (Q), sensitivity (S), detection limit (DL), and figure of merit (FOM) obtained from Table 4 at normal incident angle ($\theta = 30^\circ$).

Water Soluble Vitamin	Quality Factor ($Q = \lambda_0/\Delta\lambda_{FWHM}$)	Sensitivity ($S = \Delta\lambda_0/\Delta n$)	Detection Limit ($(\lambda_0/S \cdot Q) \times 10^{-3}$)	Figure of Merit ($S \cdot Q/\lambda_0$)
Vitamin B ₅	1607.856	232.666	2.123	470.983
Vitamin B ₁	1611.401	232.777	2.117	472.164
Vitamin B ₆	1614.912	232.682	2.114	472.93

defect layers. Figure 5 illustrates the overall transmission response, while figure 6 provides a detailed view of the resonance peaks for each vitamin. According to Fig. 6, the resonance wavelengths for water and vitamins B₅, B₁, and B₆ are about 798.38 nm (Fig. 6 (a)), 798.97 nm (Fig. 6 (b)), 799.1 (Fig. 6 (c)), and 799.2 nm (Fig. 6 (d)) respectively (see Table 6). Compared to the TE polarization at the same angle, the TM mode exhibits broader linewidths and lower Q -factors ($Q \sim 860$) and reduced FOM (~ 215), whereas TE mode reached $Q > 1600$ and $FOM > 470$ (see Tables 5, 7).

Figures 7 and 8 and corresponding performance analysis in Tables 8, 9 show the sensor's response at incidence angle of $\theta = 60^\circ$ for TE waves. The results demonstrate a significant improvement in nearly all performance

metrics compared to $\theta = 0^\circ$ and $\theta = 30^\circ$. According to Fig. 8, the resonance wavelengths for water and vitamins B₅, B₁, and B₆ are about 704 nm (Fig. 8 (a)), 704.83 nm (Fig. 8 (b)), 705 nm (Fig. 8 (c)), and 705.14 nm (Fig. 8 (d)) respectively. The striking improvement is in the quality factor, which exceeds 2000 for all selected vitamins. This high Q -factor is a direct result of the narrowed resonance linewidth ($\Delta\lambda_{FWHM} = 0.34$ nm). Consequently, the DL is significantly enhanced to 1.23×10^{-3} RIU, which is 2.5 times lower (i.e., better) than the DL at normal incidence (3.12×10^{-3} RIU). Furthermore, the sensitivity increases from 205 to 280 nm/RIU. Also, the FOM exceeds 800, which is more than 2.5 times greater than the FOM at normal incidence (320).

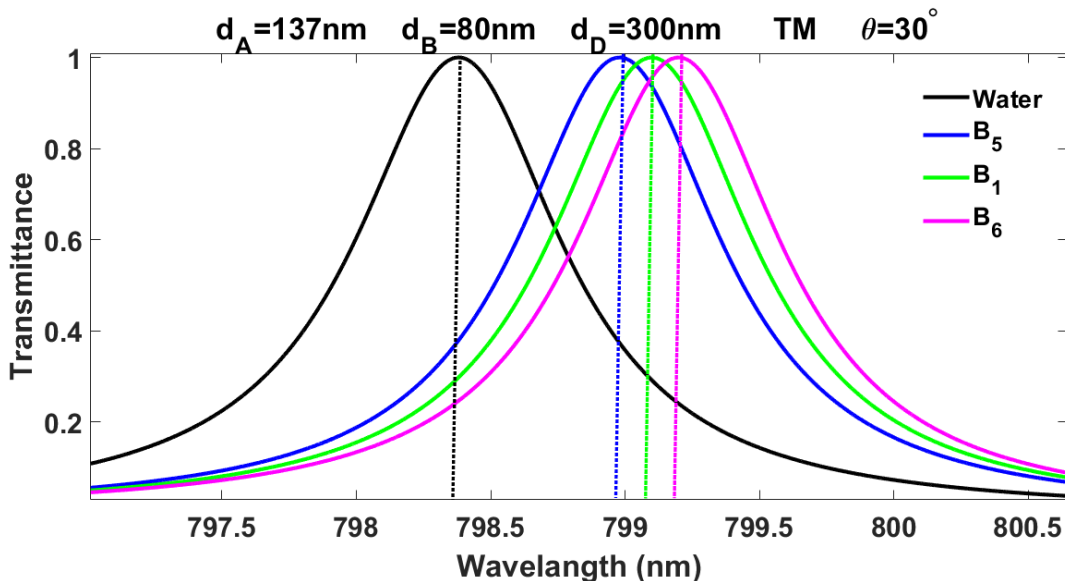


Figure 5. Resonance modes at incident angle $\theta = 30^\circ$ and for TM polarization wave.

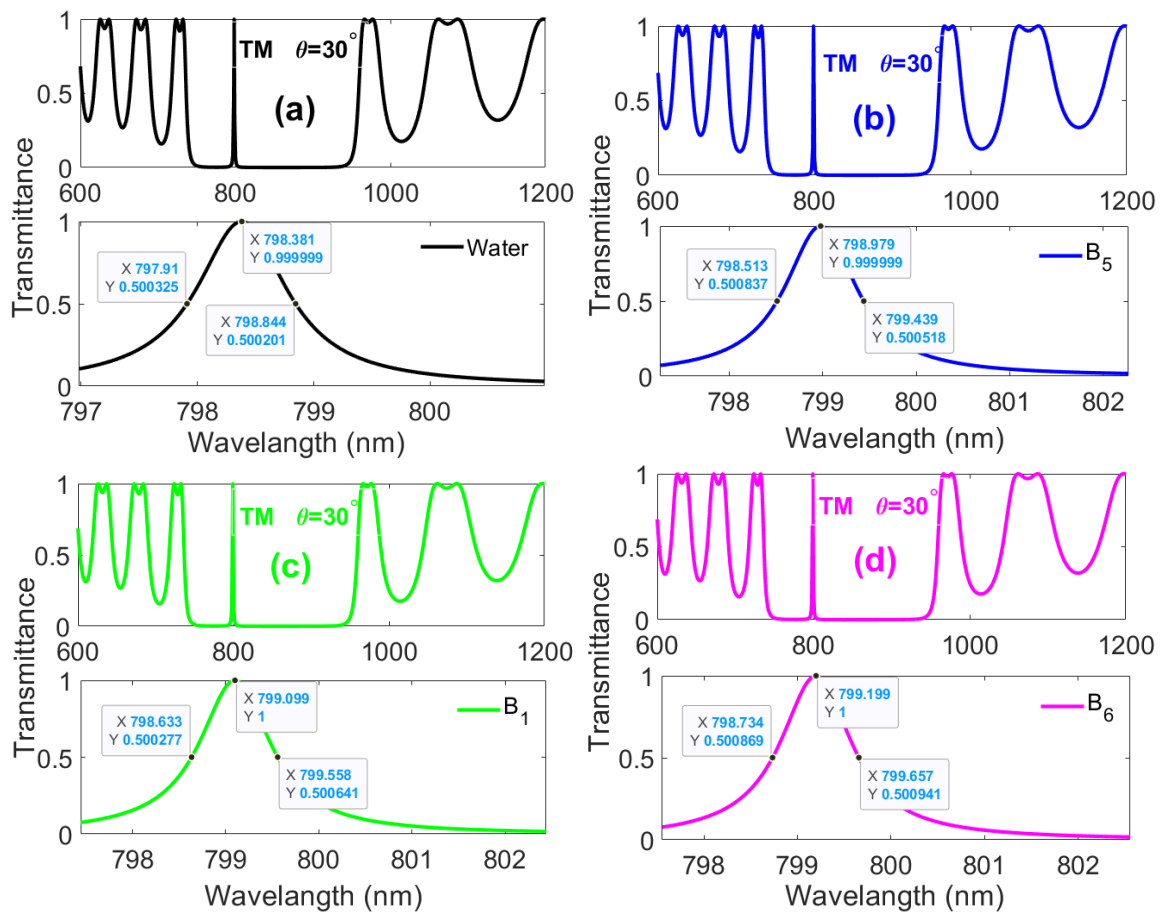


Figure 6. Detailed resonance analysis of each water soluble vitamin based on Fig. 5 different at incident angle $\theta = 30^\circ$ and for TM polarization wave. (a) water, (b) B₅, (c) B₁, (d) B₆.

A sensitivity of 280 nm/RIU is high for refractometric sensors and, combined with the measured narrow linewidth (high Q), yields a low detection limit (1.2×10^{-3} RIU in our TE/ 60° case). In this case,

for $\Delta n = 0.001$, a sensitivity of 280 nm/RIU yields $\Delta\lambda = 0.28$ nm. Our sensor's resonance linewidth in this configuration is less than 0.35 nm, this 0.28 nm shift is easily detectable and resolvable by a standard optical

Table 6. TM resonant wavelength (λ_0), resonance shift ($\Delta\lambda_0$) and full width at half maximum ($\Delta\lambda_{FWHM}$) at incident angle ($\theta = 30^\circ$).

Defect	Refractive Index	Resonant Wavelength λ_0 (nm)	$\Delta n = n - n_0$	$\Delta\lambda_0 = [\lambda_0(n) - \lambda_0(n_0)]$ (nm)	$\Delta\lambda_{FWHM}$ (nm)
Water	$1.333 = n_{\text{solvent}}$	798.381	0	0	1.001
Vitamin B ₅	~ 1.3360	798.979	0.003	0.598	0.926
Vitamin B ₁	~ 1.3366	799.099	0.0036	0.718	0.925
Vitamin B ₆	~ 1.3371	799.199	0.0041	0.818	0.92

Table 7. TM Quality factor (Q), sensitivity (S), detection limit (DL), and figure of merit (FOM) obtained from Table 6 at normal incident angle ($\theta = 30^\circ$).

Water Soluble Vitamin	Quality Factor ($Q = \lambda_0/\Delta\lambda_{FWHM}$)	Sensitivity ($S = \Delta\lambda_0/\Delta n$)	Detection Limit ($(\lambda_0/S \cdot Q) \times 10^{-3}$)	Figure of Merit ($S \cdot Q/\lambda_0$)
Vitamin B ₅	862.828	199.333	4.645	215.262
Vitamin B ₁	863.89	199.444	4.637	215.614
Vitamin B ₆	860.694	199.512	4.654	214.863

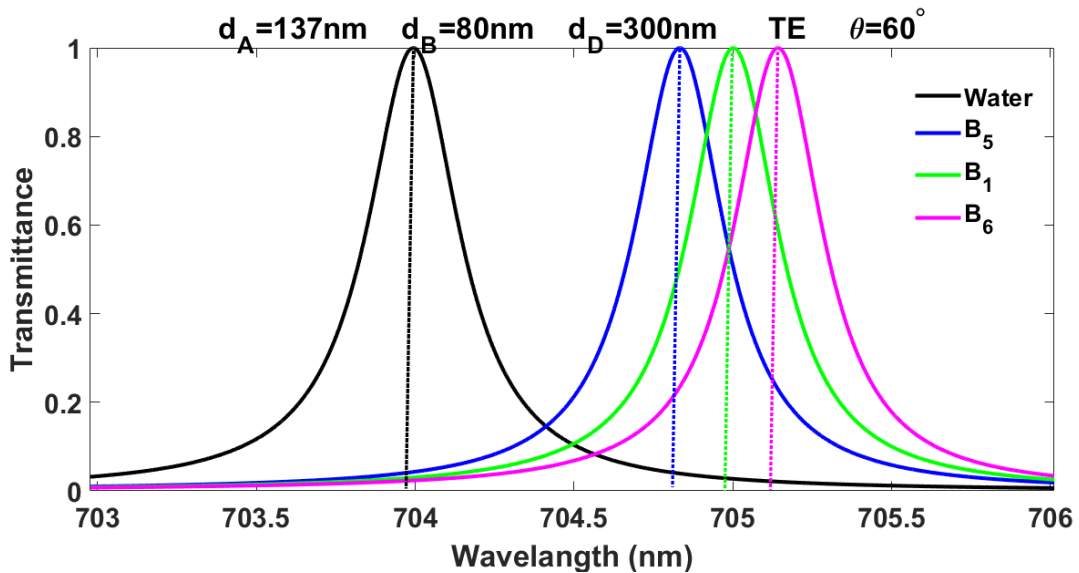


Figure 7. Resonance modes at incident angle $\theta = 60^\circ$ and for TE polarization wave.

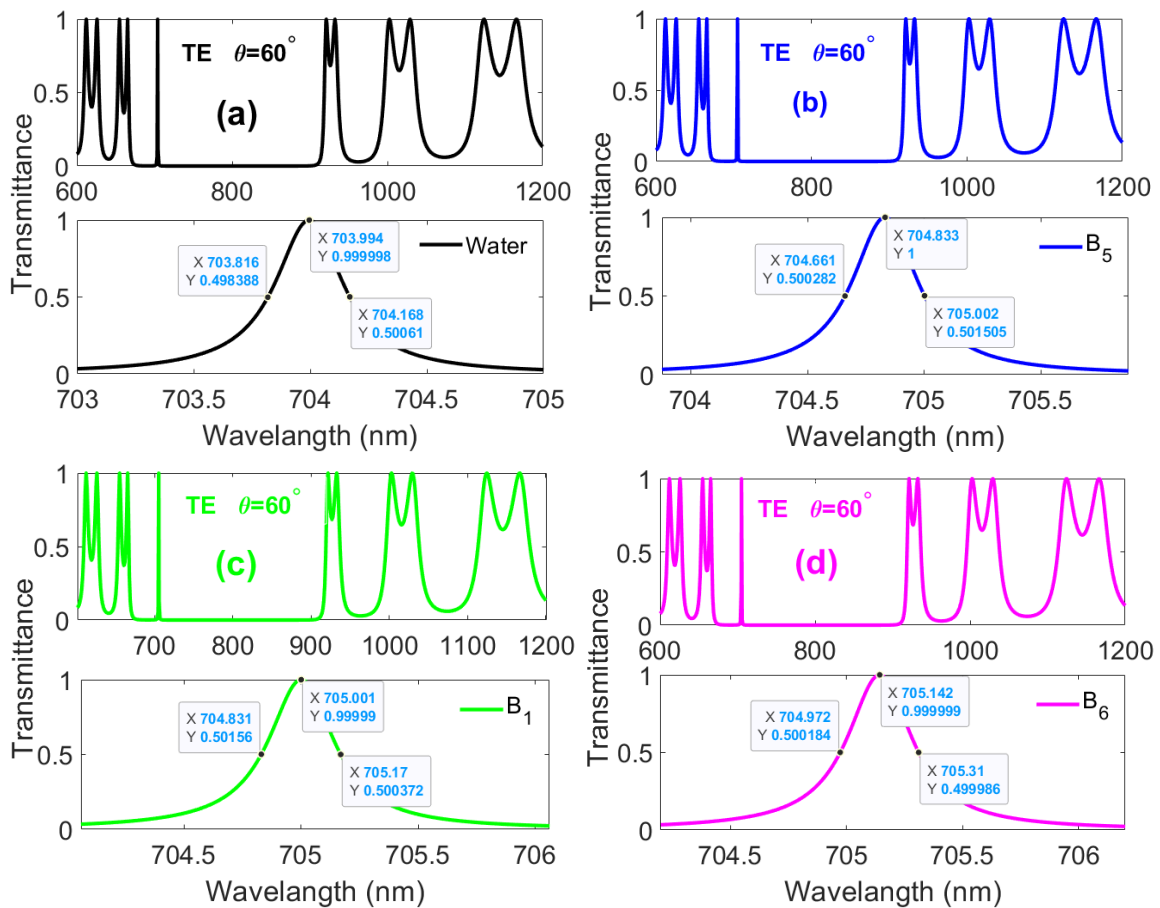


Figure 8. Detailed resonance analysis of each water soluble vitamin based on Fig. 5 different at incident angle $\theta = 60^\circ$ and for TE polarization wave. (a) water, (b) B₅, (c) B₁, (d) B₆.

spectrometer. Therefore, this level of sensitivity is useful and meaningful for the quantitative detection of target vitamins in the concentration range of interest. Thus $S = 280 \text{ nm/RIU}$ is a suitable baseline for label-free refractometric detection for many vitamin concentrations.

Figure 9 presents the transmission spectra for TM waves at an incident angle of 60° , while figure 10 provides

a detailed analysis of the sensor performance. The results demonstrate a significant degradation in performance compared to those in the TE polarization (see Tables 10, 11). According to Fig. 10, the resonance wavelengths for water and vitamins B₅, B₁, and B₆ are about 730.96 nm (Fig. 10 (a)), 731.18 nm (Fig. 10 (b)), 731.28 nm (Fig. 10 (c)), and 731.36 nm (Fig. 10 (d)) respectively.

Table 8. TE resonant wavelength (λ_0), resonance shift ($\Delta\lambda_0$) and full width at half maximum ($\Delta\lambda_{FWHM}$) at incident angle ($\theta = 60^\circ$).

Defect	Refractive Index	Resonant Wavelength λ_0 (nm)	$\Delta n = n - n_0$	$\Delta\lambda_0 = [\lambda_0(n) - \lambda_0(n_0)]$ (nm)	$\Delta\lambda_{FWHM}$ (nm)
Water	$1.333 = n_{\text{solvent}}$	703.994	0	0	0.352
Vitamin B ₅	~ 1.3360	704.833	0.003	0.839	0.344
Vitamin B ₁	~ 1.3366	705.001	0.0036	1.007	0.339
Vitamin B ₆	~ 1.3371	705.142	0.0041	1.148	0.338

Table 9. TE Quality factor (Q), sensitivity (S), detection limit (DL), and figure of merit (FOM) obtained from Table 6 at normal incident angle ($\theta = 60^\circ$).

Water Soluble Vitamin	Quality Factor ($Q = \lambda_0/\Delta\lambda_{FWHM}$)	Sensitivity ($S = \Delta\lambda_0/\Delta n$)	Detection Limit ($(\lambda_0/S \cdot Q) \times 10^{-3}$)	Figure of Merit ($S \cdot Q/\lambda_0$)
Vitamin B ₅	2048.933	279.666	1.23	812.982
Vitamin B ₁	2079.648	279.722	1.211	825.138
Vitamin B ₆	2086.218	280	1.207	828.401

The resonant peaks for TM polarization are broad, with a $\Delta\lambda_{FWHM}$ exceeding 2.1 nm, which is more than 6 times wider than the peaks for TE polarization at 60° (0.34 nm). This result leads to low quality factor of only 345, which is nearly 6 times lower than the Q -factor for TE polarization at the same angle (2080). Furthermore, the sensitivity and FOM are reduced to a very low value compared to the TE polarization. The reason for the significant reduction in performance is Brewster angle. At the $\text{SiO}_2/\text{TiO}_2$ interfaces used in our stack, the Brewster angle condition occurs near the oblique angle ($\theta_B = 59.7^\circ$). For TM polarization the Fresnel reflection coefficient goes to zero at this angle, so TM reflectivity collapses near θ_B and the photonic

bandgap weakens, and the cavity defect cannot form a narrow high- Q resonance. But, TE polarization does not have a zero-reflection condition at that angle, so TE retains reflectivity.

Finally, Table 12 provides a final summary of the biosensor's key results from the study. It shows a comparison of how the sensor's performance is affected by changing the incident angle and polarization.

About optimum angle 60° , we can say that at this angle the effective optical path inside each layer increases. This result causes a large phase shift per layer, which directly strengthens the Bragg condition, expressed as $2(n_A d_A \cos \theta_{iA} + n_B d_B \cos \theta_{iB}) = m\lambda$. When $\cos \theta_i$ becomes small at 60° , the terms $n \cdot d \cdot \cos \theta_i$ grows,

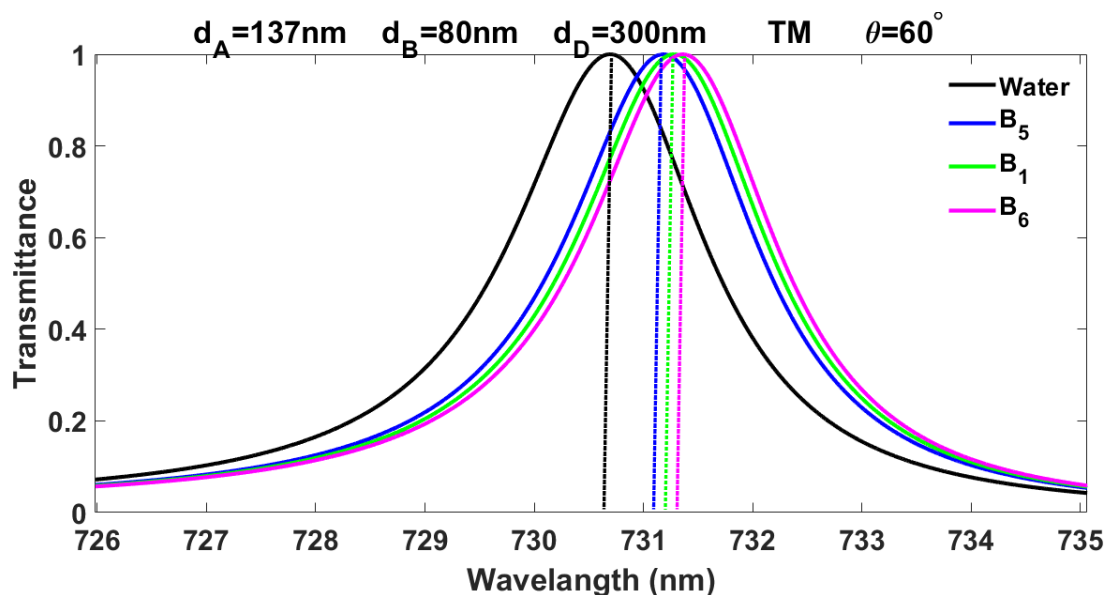


Figure 9. Resonance modes at incident angle $\theta = 60^\circ$ and for TM polarization wave.

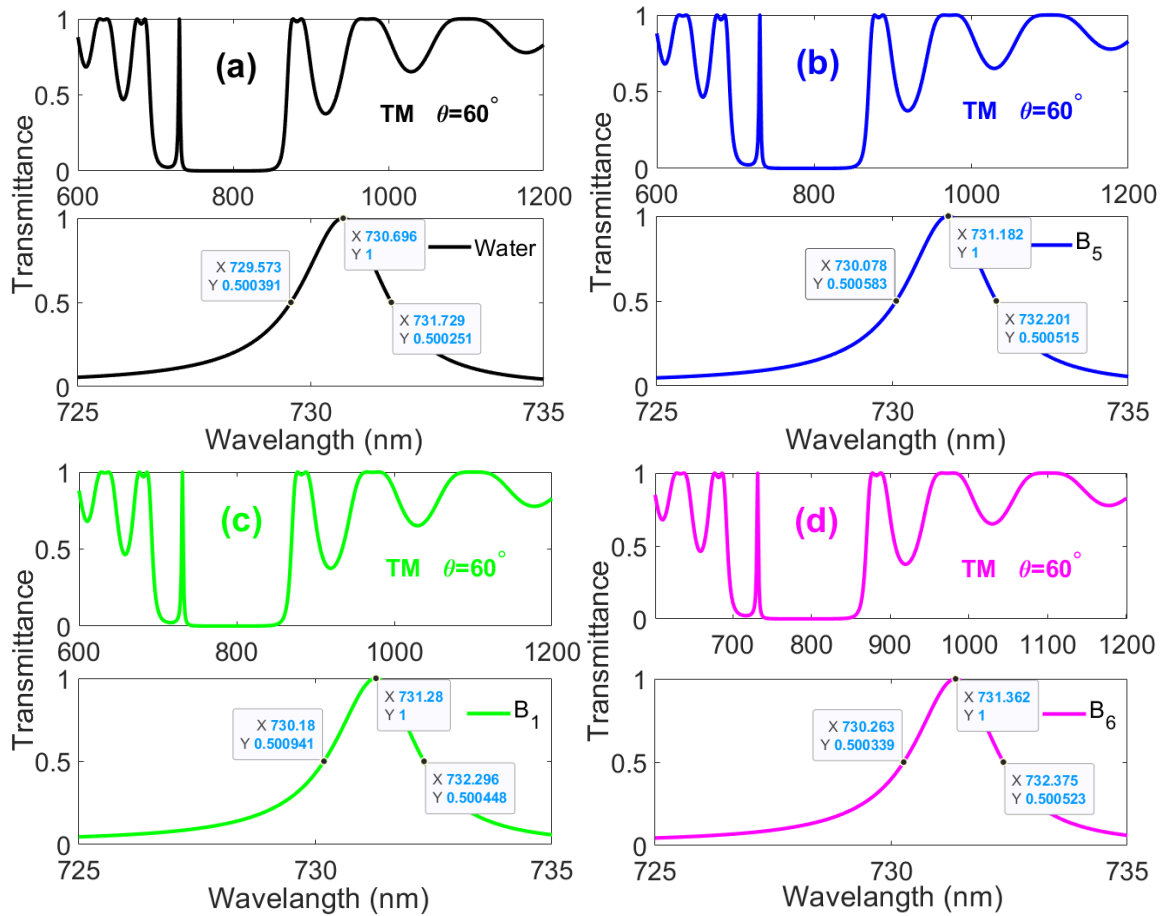


Figure 10. Detailed resonance analysis of each water soluble vitamin based on Fig. 5 different at incident angle $\theta = 60^\circ$ and for TM polarization wave. (a)water, (b) B₅, (c) B₁, (d) B₆.

yielding stronger constructive interference and higher reflectivity (higher Q). Because sensitivity is proportional to $\Delta\lambda/\Delta n$, a higher Q produces a pronounced

wavelength shift. Therefore, the increased optical path and strengthened Bragg reflection at 60° directly enhance the biosensor performance.

Table 10. TM resonant wavelength (λ_0), resonance shift ($\Delta\lambda_0$) and full width at half maximum ($\Delta\lambda_{FWHM}$) at incident angle ($\theta = 60^\circ$).

Defect	Refractive Index	Resonant Wavelength λ_0 (nm)	$\Delta n = n - n_0$	$\Delta\lambda_0 = [\lambda_0(n) - \lambda_0(n_0)]$ (nm)	$\Delta\lambda_{FWHM}$ (nm)
Water	$1.333 = n_{\text{solvent}}$	730.969	0	0	2.156
Vitamin B ₅	~ 1.3360	731.182	0.003	0.213	2.123
Vitamin B ₁	~ 1.3366	731.28	0.0036	0.311	2.116
Vitamin B ₆	~ 1.3371	731.362	0.0041	0.392	2.112

Table 11. TM Quality factor (Q), sensitivity (S), detection limit (DL), and figure of merit (FOM) obtained from Table 6 at normal incident angle ($\theta = 60^\circ$).

Water Soluble Vitamin	Quality Factor ($Q = \lambda_0/\Delta\lambda_{FWHM}$)	Sensitivity ($S = \Delta\lambda_0/\Delta n$)	Detection Limit ($(\lambda_0/S \cdot Q) \times 10^{-3}$)	Figure of Merit ($S \cdot Q/\lambda_0$)
Vitamin B ₅	344.409	71	29.901	33.443
Vitamin B ₁	345.595	86.388	24.494	40.826
Vitamin B ₆	346.2887 95.853	22.033	45.384	

Table 12. Summary table (performance comparison).

Angle	Polarization	Sensitivity	Q -Factor	FOM	DL [$\times 10^{-3}$]
0°	TE/TM	204.7	1303	320	3.12
30°	TE	232.7	1610	472	2.12
30°	TM	199.5	862	215	4.64
60°	TE	280	2080	825	1.21
60°	TM	43-96	345	20-45	22-49

4. Conclusion

We designed an optical sensor that can detect three water-soluble vitamins without using any labels and only by measuring small changes in refractive index. Our simulations showed that both the angle of the incident and polarization strongly affect the sensor's performance. The best results were obtained when the light entered the structure at a 60° angle with TE polarization, where the sensor achieved high sensitivity (about 280 nm/RIU), a very sharp resonance peak (Q greater than 2000), and a low detection limit (about 1.21×10^{-3}). In contrast, using TM polarization at high angles reduced the sensor's effectiveness because of Brewster's angle, which decreases reflected light for TM waves. Overall, these findings give a clear guideline for designing this type of sensor and show that the proposed structure can detect multiple vitamins at the same time. To become a practical device, this sensor must solve several real-world challenges. Its performance depends on extremely precise manufacturing to avoid tiny errors that degrade the signal. The design is sensitive to specific angles and light polarization, which are hard to maintain. Temperature changes and unwanted substances in samples can affect the results.

Availability of data and materials

The authors declare that the data supporting the findings of this study are available within the paper.

Conflict of interests

The authors assert that they do not have any identifiable conflicting financial interests or personal relationships that might be perceived to influence the work presented in this paper.

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