

Article

Enhancement of the Shift in the Photonic Spin Hall Effect and Its Application for Cancer Cell Detection

Alka Verma ^{1,*}, Devanshi Katiyar ¹, Vimal Mishra ², Rajeev Gupta ³ and Yogendra Kumar Prajapati ^{4,*} 

¹ Department of Electronics Engineering, Institute of Engineering and Rural Technology, Prayagraj 211004, India; devanshikatiyar2004@gmail.com

² Department of Computer Science Engineering, Institute of Engineering and Rural Technology, Prayagraj 211004, India; vimalmishra@iert.ac.in

³ Department of Electronics and Communication Engineering, Graphic Era Hill University, Dehradun 248002, India; rgupta@gehu.ac.in

⁴ Department of Electronics and Communication Engineering, Motilal Nehru National Institute of Technology Allahabad, Prayagraj 211004, India

* Correspondence: alkapra25@iert.ac.in (A.V.); yogendrapra@mnnit.ac.in (Y.K.P.)

Abstract

The photonic spin Hall effect (PSHE) originates from the spin–orbit interaction (SOI) of light. The literature indicates that the transverse spin-dependent shift, δ_H^- (SDS), from the PSHE is weak (in the nanometer range) and difficult to measure directly. This study utilizes a plasmonic structure to improve the δ_H^- in the PSHE. The obtained results of this study demonstrate that the inclusion of silicon nitride (Si_3N_4) significantly enhances the δ_H^- relative to its absence; however, plasmonic material is present in both cases. The enhanced shifts exhibit a significant dependence on the resonance angle (θ_r) and the thickness of layers of the PSHE structure to attain the maximum increase in δ_H^- of 350.82 μm at the plasmonic resonance condition. A systematic analysis of the centroid positions of the reflected beam indicates a distinct and constant separation of opposing spin components. Further, the improved δ_H^- is utilized in cancer cell detection, as changes in the refractive index (RI) of cells facilitate the identification of cancer cells from healthy to cancerous. All examined cell types demonstrate that cancerous cells had a greater δ_H^- than normal cells, owing to their elevated effective RI. These results illustrate that the proposed plasmonic-assisted PSHE structure offers significant enhancement and a high sensitivity of 439.30 $\mu\text{m}/\text{RIU}$ for label-free detection of cancer cells.

Keywords: spin–orbit interaction; transverse spin-dependent shift; photonic spin Hall effect; cancer cells detection



Academic Editors: Chao Zheng and Jim Freericks

Received: 7 January 2026

Revised: 6 February 2026

Accepted: 12 February 2026

Published: 17 February 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Recently, the quantum science-based photonic spin Hall effect (PSHE) [1–4] has emerged as a powerful tool in the advancement of photonic devices for assessing the optical thickness of nanostructures [5] and determining the layer count of thin 2D materials [6], chiral metamaterials [7], and nano-metal films [8]. PSHE results from the spin–orbit interaction (SOI) of light, generating nanoscale transverse beam shifts. When linearly polarized light passes through an interface with a refractive index (RI) gradient, light splitting occurs into right-handed circular polarization (RCP) and left-handed circular polarization (LCP) [4–6]. This separation arises from the mutual interplay and interaction between the polarization and trajectory of the light beam. Onoda et al. first introduced this concept in

2004, illustrating that linearly polarized light experiences spin-dependent splitting, δ_H^- (SDS) into LCP and RCP components, which propagate perpendicular to the RI gradient during interaction with a multilayer structure with different RIs [9]. In 2006, Bliokh et al. provided a description of the transverse displacement of the PSHE based on electromagnetic field theory, incorporating the principle of the conservation of the total angular momentum of all photons. This provided the foundational theory for later investigations into the PSHE [10]. This theory fundamentally comprises two distinct geometric phases: the spin-redirection Ryto–Vladimirskii–Berry (RVB) phase, associated with changes in wave vector direction, and the Pancharatnam–Berry (PB) phase, related to changes in the polarization state of light. Hosten and Kwiat conducted the initial experimental demonstration of spin-dependent beam splitting at an air-glass interface in 2008 [11]. Researchers are presently utilizing the phenomenon of the PHSE to design different types of sensors. The various sensing applications have been documented in the scientific literature, including gas sensing [12,13], RI sensing [14], hemoglobin sensing [15], cancer cell detection [14], magnetic field detection [16], and air quality index (AQI) sensors [17]. It has been observed that the sensitivity of these sensors correlates with the δ_H^- present in the PHSE. This indicates that a larger δ_H^- results in greater sensor sensitivity.

The PSHE refers to a spin-dependent shift, δ_H^- (SDS), of light caused by SOI. This phenomenon can be utilized to detect minute changes in the RI [12,15] and to identify cancer cells without the use of labels. A key aspect of this process involves the separation of LCP and RCP light waves in different directions. This separation is highly sensitive to various physical factors [2]. However, the intrinsic PSHE is typically weak, resulting in δ_H^- values that range from the nanometer to several micrometers [2,7,9,13,18]. To enhance the δ_H^- , researchers utilize various techniques and materials, including weak measurement methods, the Brewster angle [19], surface plasmon resonance (SPR) [3], guided wave-based SPR [1,20], metamaterials [21], chiral materials [22], optical Tamm states (OTS) [23], and others [18] to advance extremely sensitive sensors and tunable photonic devices such as RI sensors [14], gas sensors [12], biosensors [14,15,20], magnetic field detection [16], image edge detection [24], etc. The optical vortex pair can also manipulate the amplitude and polarity of the PSHE, facilitating improved and tunable transverse δ_H^- without necessitating alterations to the material interface [25]. A 2024 study revisited the longitudinal δ_H^- process and elucidates the physical relationship between longitudinal δ_H^- and the Goos–Hänchen effect, resolving prior interpretative uncertainties [26]. These studies enhance the tunability of spatially varying δ_H^- by integrating both transverse and longitudinal δ_H^- into a cohesive framework based on the principles of angular momentum conservation. Despite these efforts, this δ_H^- still requires further enhancements for applications such as sensing and precision metrology.

The growing global burden of cancer underlines the urgent need for extremely sensitive and early-stage diagnostic methods. In contemporary times, lifestyle choices significantly influence the impact of cancer on human life. It is estimated that all types of cancer, including breast, blood, skin, adrenal gland, and cervical cancers, claimed the lives of 9.74 million people worldwide in 2022. The annual toll is expected to rise to 16.9 million by 2045 due to aging populations and environmental carcinogens. According to the latest global cancer death report, approximately 10.4 million individuals worldwide died from cancer in 2023, with 18.5 million new cases reported [27]. Breast and blood cancers remain the primary causes of cancer-related deaths globally (2022–2023), accounting for a substantial share of all cancer fatalities, while skin, adrenal gland, and cervical cancers account for relatively fewer occurrences. Breast cancer is one of the top five causes of cancer deaths around the world, accounting for about 6.9% of all cancer deaths [28]. Blood cancers, which include leukemia, lymphoma, and myeloma, account for about 6–7% of

cancer deaths globally [29]. Cervical cancer is responsible for approximately 3.4% of all cancer-related deaths, with low- and middle-income countries bearing the majority of these cases [30]. Adrenal gland cancer is still very rare, making up less than 0.2% of all cancer deaths around the world. On the other hand, skin cancers, especially melanoma, make up more than 1% of all cancer deaths [31]. The literature indicates that the combined global impact of breast and blood cancers is significantly greater than that of other malignancies. Their detection is accomplished at an early stage through the usage of screening methods such as mammography, Pap tests, colonoscopy, and low-dose CT scans, which lead to satisfactory treatment results. However, these screening methods have the limitation that they can provide false positive or false negative results [32]. Therefore, it is necessary to use techniques that offer fast, accurate, non-invasive, and reliable cancer cell detection. In this direction, researchers proposed cancer cell detection using optical methods such as PSHE- and SPR-based sensing methods [14,20,33,34].

Based on the preceding discussion, it can be concluded that optical sensors are highly suitable for this challenge due to their capability for real-time detection, high sensitivity, compact design, and cost-effective operation without requiring elaborate sample preparation. Additionally, it has been observed that in optical SPR sensors utilized for cancer cell detection, cancer cells demonstrate a higher refractive index (RI) compared to normal cells, owing to the increased chromatin content within their larger nuclei. Therefore, the RI can be regarded as a vital parameter for differentiating between cancerous and normal cells [34].

The proposed PSHE structure in this work includes an SF10 glass prism, gold (Au), silicon nitride (Si_3N_4), molybdenum disulfide (MoS_2), and an analyte. This study represents the first attempt to enhance the SDS amplitude using MoS_2 and Si_3N_4 . Additionally, we investigate a PSHE structure for the detection of cancer cells. To our knowledge, there are only a few works regarding the detection of cancer utilizing the PSHE. In this study, we propose an optical RI sensor based on the photonic SHE and explore new applications for the detection of cancer. The proposed sensor is capable of not only differentiating between normal human cells (including skin, cervical, breast, adrenal gland, and blood cells) and cancer cells but also distinguishing various concentrations of cancer cells. The results illustrate the enhanced sensing capabilities of this proposed PSHE structure, with a sensitivity of $439.30 \mu\text{m}/\text{RIU}$, enabling effective discrimination between normal skin cells and cancerous cells.

2. Concept and PSHE Structure Design

2.1. PSHE Structure Design

To illustrate spin-dependent splitting (SDS) in a PSHE-based multilayer structure incorporating the Kretschmann configuration, a thin gold (Au) layer with optimized thickness (d_2) is deposited onto an SF10 glass prism. Subsequently, a layer of silicon nitride (Si_3N_4) with an optimized thickness (d_3) is deposited atop the gold, followed by molybdenum disulfide (MoS_2) positioned on the Si_3N_4 with a thickness of $d_4 = 0.65 \text{ nm}$. The sensing medium is situated above the MoS_2 , as depicted in Figure 1a. In this figure, the PSHE of reflected light is represented. Here, θ_i is the angle of incidence, d_2 is the thickness of gold (Au), d_3 is the thickness of Si_3N_4 , and δ_H^- and δ_H^+ are the transverse shifts of the RCP and LCP of reflected light. The incidence plane is xz , and the transverse shift is alongside the y -axis. The refractive indices (RIs) and thicknesses of all layers that make up the PSHE structure are shown in Table 1. The biomolecule solutions designed for both healthy and cancerous cells serve as a sensing medium to differentiate cancerous cells from healthy cells. The RI values for various cancer cell types and status are listed in Table 2. Gold serves as a plasmonic material that excites surface plasmons (SPs), which localize electromagnetic (EM) waves at the Au-dielectric interface. The excited SPs augment the

spin–orbit interaction (SOI) of light, thereby amplifying the magnitude of the PSHE [1,4]. The SF10 prism is chosen for its high RI, which aids in effective momentum matching and enhances δ_H^- . Si_3N_4 is a high-RI material employed to reduce radiative losses and enhance the confinement of the evanescent field at the metal–dielectric interface [35]. Furthermore, the use of MoS_2 is advantageous due to its direct bandgap, significant spin–orbit coupling, and larger light absorption [1,36]. Therefore, it interacts with light more strongly than conventional materials. This strong interaction modifies the refractive index variation gradient, which can effectively enhance the PSHE [1]. The Supplementary Materials (SM-1 and SM-2) [11,18,37–51] depict the potential experimental setup as well as possible deposition and characterization techniques for the proposed work.

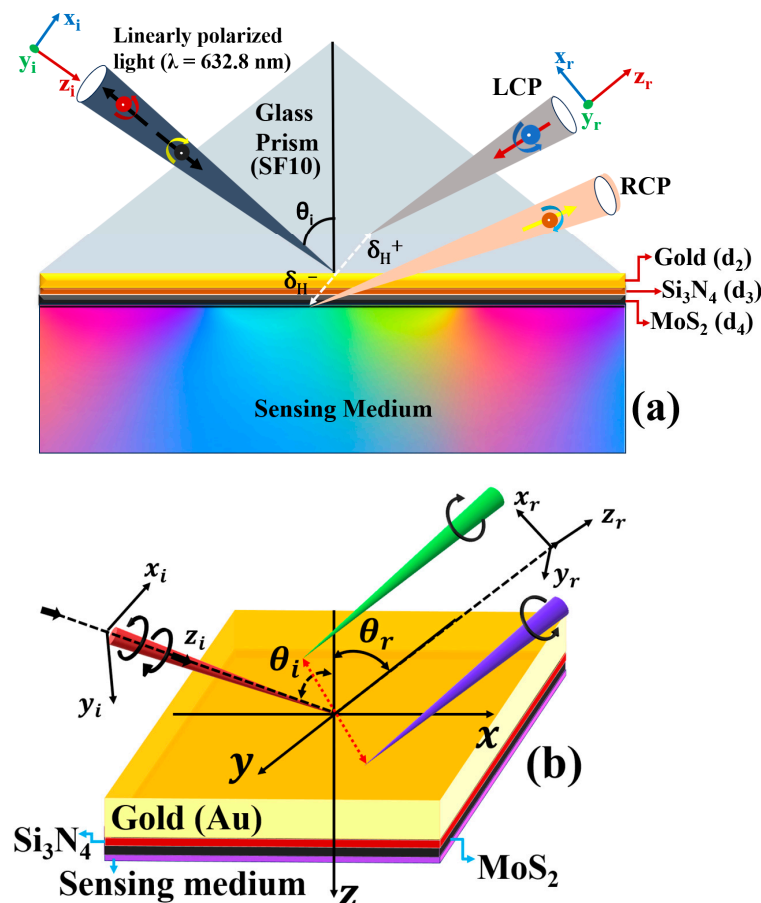


Figure 1. (a) Systematic representation of the proposed PSHE multilayer structure when a beam is reflected from an interface. (b) Frontal aspect.

Table 1. RIs used in the proposed PSHE structure at a wavelength of 632.8 nm.

Layers Used	RI ($n + ik$)	Thickness (nm)	Ref.
Glass prism SF10	$1.72314 + i \times 0$	--	[4]
Gold (Au)	$0.1378 + i \times 3.6196$	d_2 [Optimized]	[36]
Si_3N_4	$2.0394 + i \times 0$	d_3 [Optimized]	[35]
MoS_2	$5.08 + i \times 1.1723$	$d_4 = 0.65$ nm [Monolayer MoS_2 considered]	[36]
Sensing medium	$1.360\text{--}1.401$ Depending on the types of cancer as listed in Table 2	--	[34]

Table 2. RI data on cells in both healthy and cancerous states [34].

Cancer (Cell) Types	Status	RI
Skin (Basal)	Healthy	1.360
	Cancerous	1.380
Cervical (HeLa)	Healthy	1.368
	Cancerous	1.392
Blood (Jurkat)	Healthy	1.376
	Cancerous	1.390
Adrenal gland (PC12)	Healthy	1.381
	Cancerous	1.395
Breast (MDA-MB-231)	Healthy	1.385
	Cancerous	1.399
Breast (MCF-7)	Healthy	1.387
	Cancerous	1.401

2.2. Concept and Working of PSHE Structure

When linearly polarized Gaussian light passes through an inhomogeneous optical interface with a RI gradient, the PSHE occurs due to the interplay between the light's polarization and trajectory. This phenomenon arises from the spin-orbit interaction (SOI) of light, which causes the linearly polarized light to be separated into RCP and LCP light upon interacting with the interface. The photons of opposite spin states, which correspond to right- and left-circular polarization components, experience minute transverse spatial shifts. As illustrated in Figure 1, a monochromatic Gaussian light beam operating at a wavelength of 632.8 nm is incident on the proposed PSHE structure with a variation in the angle of incidence (θ_i). As illustrated in Figure 1b, the coordinate frames (x_i, y_i, z_i) and (x_r, y_r, z_r) represent the incident and reflected coordinates, respectively. For the purposes of this discussion, we will assume that the beam, which exhibits a linear polarization state, is reflected from a planar interface. A laboratory coordinate system is defined such that the reflecting interface lies in the xy -plane, and the plane of incidence is the xz -plane. This means the y -axis is perpendicular to the plane in which the light beam is incident. Because the proposed structure has an RI gradient in the xz -plane, the LCP and RCP components of light experience slightly different optical paths when the beam interacts with the interface. This difference causes the two spin components to shift in opposite directions along the z -axis, i.e., out of the plane of incidence. This opposite displacement of spins is known as the PSHE. So, when linearly polarized light is incident on the prism–Au interface, whether by reflection or refraction, it can be decomposed into LCP and RCP components. Each experiences a different geometric phase due to the RI gradient, causing spin-dependent shifts (SDSs) perpendicular to the incident plane (i.e., along y). These shifts are the observable signature of the PSHE in the device. It is generally agreed upon that the PSHE is the result of an effective SOI that describes the mutually beneficial effect of the trajectory and polarization of the light beam [1]. In studies by T. Tang et al. [52] and T. Srivastava et al. [53], the transverse SDS was determined utilizing a beam propagation model that incorporates angular spectrum theory. The transverse SDS (δ_H^-) can be written as follows:

$$\delta_H^- = \frac{1}{k_0} \left\{ 1 + \frac{|r_s|}{|r_p|} \cos(\varphi_s - \varphi_p) \right\} \cot\theta_i \quad (1)$$

where k_0 is the free space wave vector, and $r_p(r_s)$ and $\varphi_p(\varphi_s)$ are the Fresnel reflection coefficients and the phase difference between the incident and reflected lights of p-polarized (s-polarized) light, respectively. Equation (1) presents the formula for calculating the

mathematical amplification of the shift induced by the Fresnel reflection coefficients. It is crucial to understand that this shift is distinct from the physically measurable spatial displacement. The amplified shift outlined in Equation (1) arises from the rapid phase variation of the Fresnel coefficients at the resonance angle, which enhances the computed beam shift; however, it does not, by itself, indicate a spatial displacement. A measurable displacement occurs only after the convolution of the finite beam profile with the detector's response [9,11].

2.3. Sensing Performance of PSHE Structure for Cancer Detection

The sensing performance of the PSHE structure is assessed through sensitivity (S_{PSHE}) and a limit of detection (LoD_{PSHE}). The sensitivity can be defined to assess the performance of the PSHE structure in detecting cancer cells as follows:

$$S_{PSHE} = \frac{\Delta\delta_H^-}{\Delta n_s} \quad (2)$$

where $\Delta\delta_H^-$ represents the difference in SDS between healthy and cancerous cells, while Δn_s denotes the RI difference between these two types of cells. If the RI changes due to the attachment of cancerous molecules in the sensing medium, the change in Δn_s is altered, resulting in a corresponding change in $\Delta\delta_H^-$. The unit of S_{PSHE} is $\mu\text{m}/\text{RIU}$.

The LoD_{PSHE} is inversely proportional to the S_{PSHE} and proportional to the smallest detectable δ_H^- shift during the actual experimental measurements [4]. It is defined as follows:

$$LoD_{PSHE} = \frac{0.001^\circ}{S_{PSHE}} \quad (3)$$

The unit of LoD_{sd} is degrees $\text{RIU}/\mu\text{m}$. Furthermore, for sensing applications, it is essential that the sensor's S_{PSHE} be maximized, and that the magnitude of the LoD_{PSHE} be minimized.

3. Results

3.1. Optimization of Layers Thickness in the PSHE Structure

To improve the SDS (δ_H^-), it is crucial to optimize the thickness of both Au (designated as d_2) and Si_3N_4 (designated as d_3) inside the PSHE structure. Figure 2a,b illustrate the ratio of $\left|\frac{r_s}{r_p}\right|$ alongside the maximum δ_H^- in relation to the thicknesses of Au and Si_3N_4 . It is important to note that δ_H^- is proportional to the $\left|\frac{r_s}{r_p}\right|$ as indicated in Equation (1). This correlation is also illustrated in Figure 2, where both parameters demonstrate comparable tendencies, either increasing or decreasing concurrently as the thicknesses of Au and Si_3N_4 change. The peak δ_H^- value of $350.82 \mu\text{m}$ is achieved, corresponding to a maximum $\left|\frac{r_s}{r_p}\right|$ of approximately 3.2×10^7 at a resonance angle (θ_r) of 57.524 degrees, with d_2 measured at 44 nm and d_3 at 1 nm . These maximum values are indicated by the green circle in Figure 2. Furthermore, this study utilized the optimized thicknesses of Au (d_2) and Si_3N_4 (d_3) to assess sensitivity.

To investigate the effect of Si_3N_4 thickness on the peak of δ_H^- , we varied the thicknesses of Si_3N_4 , as shown in Figure 3a,b. In both figures, it is observed that the maximum δ_H^- is achieved at d_3 of 1 nm because at this thickness of Si_3N_4 , the ratio of $\left|\frac{r_s}{r_p}\right|$ is at its maximum due to r_p being at its minimum, and the phase gradient of r_p (φ_p) is maximized. From Figure 3, it is also indicated that without the use of Si_3N_4 , i.e., $d_3 = 0 \text{ nm}$, the maximum value of δ_H^- is only $9.10 \mu\text{m}$. The enhancement of the δ_H^- induced by the introduction of the Si_3N_4 layer is not attributed to its crystal structure, as Si_3N_4 is optically isotropic

and non-chiral in the wavelength range considered. Instead, the enhancement originates from interface-mediated SOI of light. The Si_3N_4 layer modifies the RI contrast and phase accumulation at the interface, leading to an increased gradient of the Fresnel reflection coefficients and an enhanced spin-dependent geometric (Pancharatnam–Berry) phase. These interfacial effects strengthen the transverse spin splitting characteristic of the PSHE. Prior research has extensively reported comparable enhancing mechanisms resulting from dielectric multilayers and interface engineering [2,8].

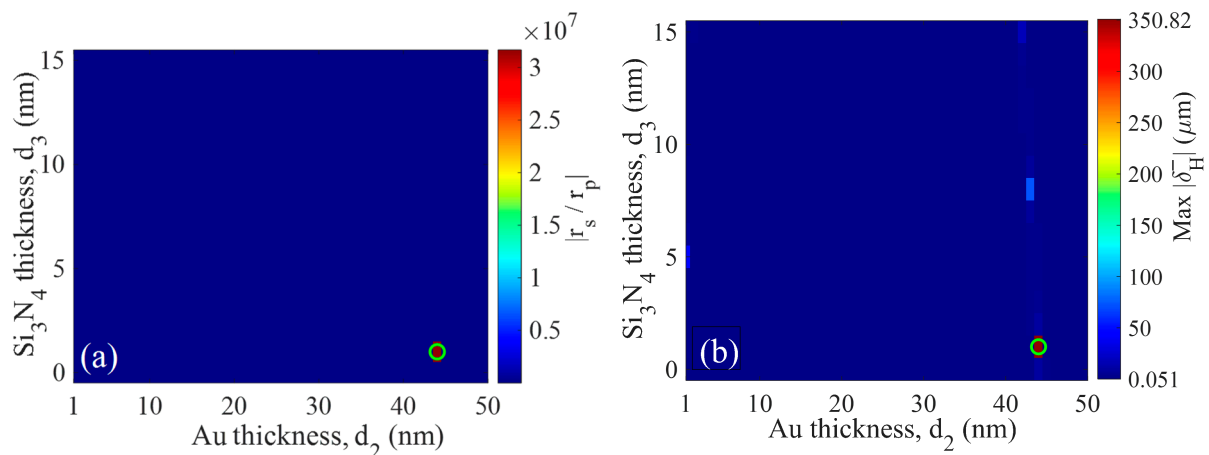


Figure 2. Optimization of (a) $\frac{|r_s|}{|r_p|}$ and (b) δ_H^- with the thicknesses of Au and Si_3N_4 .

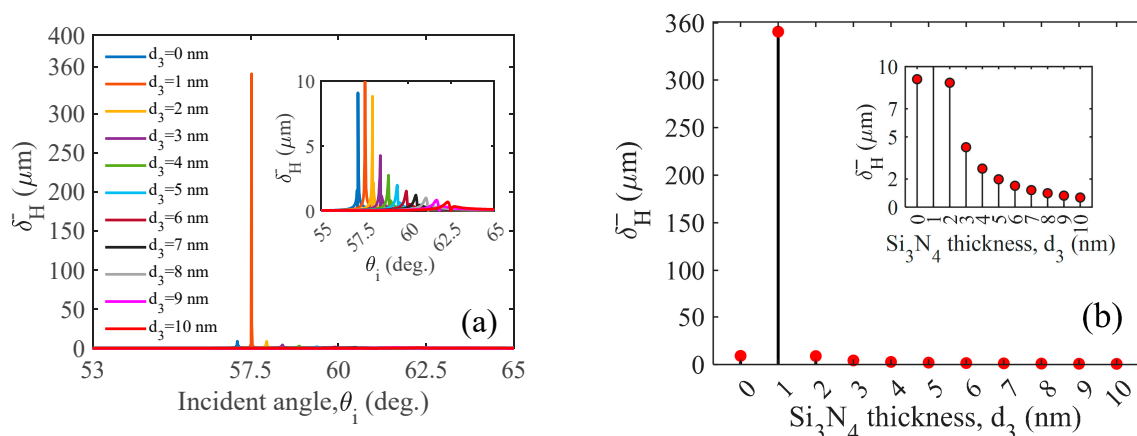


Figure 3. Impact of thicknesses of Si_3N_4 on δ_H^- (a) θ_i vs. δ_H^- (b) d_3 vs. δ_H^- .

Further, as the thickness increases, the δ_H^- is reduced because of the higher ohmic losses.

Figure 4 illustrates the out-of-plane spatial shift (Δ_y) as a function of the θ_i to determine the beam centroid position. This spatial shift is calculated using the expression $\Delta_y = \frac{\iint y_r |E_r^H|^2 dx_r dy_r}{\iint |E_r^H|^2 dx_r dy_r}$ [24,37]. It is observed that the maximum centroid of 6.12×10^{-5} nm occurs at the θ_r , attributed to the maximum phase gradient with low intensity, and $|E_r^H|^2$ values for the RCP and LCP components are identical. At angles other than the θ_r , the phase gradient changes, and $|E_r^H|^2$ values for the RCP and LCP components are not identical, so the result is a lower value of Δ_y in comparison to Δ_y at $\theta_r = 57.524$ degrees.

Finally, a comparison is made with the prism-based research on the PSHE to illustrate the enhancement in δ_H^- for the proposed PSHE structure. Table 3 provides a comparative analysis of the δ_H^- values achieved by different plasmonic PSHE structures. The obtained re-

sults indicate that the proposed PSHE structure attains a substantially higher δ_H^- compared to the current state of the art.

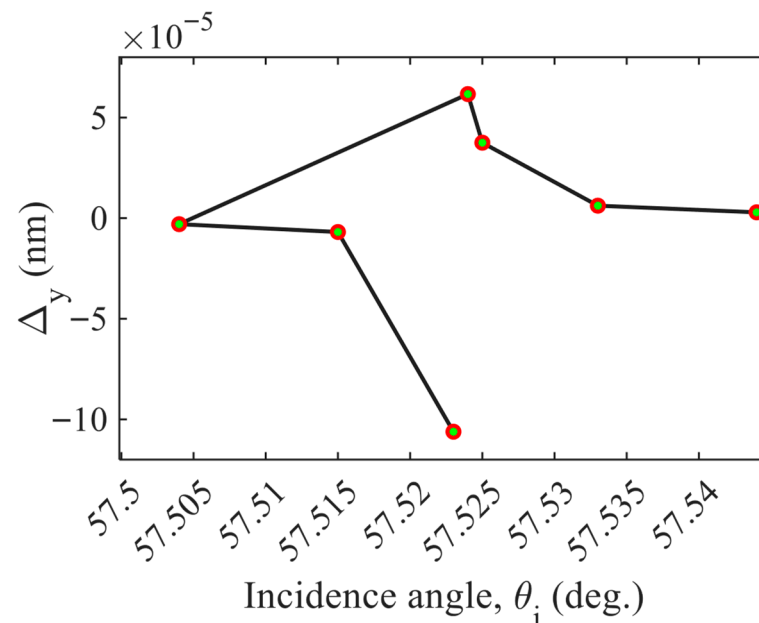


Figure 4. Beam centroid position shift with the θ_i .

Table 3. Comparative study of PSHE with prism-based work.

Structure	SDS, δ_H^- (μm)	Ref.
Prism/Au/Air	3.00	[54]
Prism/Au/BlueP/MoS ₂ /graphene/Biomolecule	11.26	[55]
Prism/Ag/Si/Air	11.50	[1]
Prism/PhC/Au/Biomolecule	18.00	[53]
Prism/Au/TDBC/Air	60.00	[56]
Prism/Au/Si ₃ N ₄ /MoS ₂ /DI water (proposed)	350.82	In this work

The proposed PSHE structure is further analyzed in relation to its application as a refractive index (RI) sensor for cancer cell detection.

3.2. Sensing Performance of the PSHE Structure for Cancer Cell Detection

From Figure 5, it is evident that the peak of the δ_H^- is distinguishable across all types of cancer cells, showing a significant shift between healthy and cancerous cells. The RIs of biomolecule solutions for healthy and cancerous basal cells in skin cancer are 1.36 and 1.38, respectively. As illustrated in Figure 5a, the PSHE structure clearly shows the resonance angle shift and δ_H^- resulting from the presence of cancerous basal cells. The S_{PSHE} and LoD_{PSHE} are determined to be 439.30 $\mu\text{m}/\text{RIU}$ and 2.28×10^{-6} deg. RIU/ μm , respectively. Normal HeLa cells become cancerous after infection with human papillomavirus 18 (HPV18). In Figure 5b, the RIs of normal and cancerous HeLa cells are measured at 1.368 and 1.392, respectively. The sensing performance of the PSHE structure for cancerous HeLa cells yields an S_{PSHE} of 322.02 $\mu\text{m}/\text{RIU}$ and a LoD_{PSHE} of 3.10×10^{-6} deg. RIU/ μm . In Figure 5c, the δ_H^- response as a function of the incident light angle is examined for normal and Jurkat cell recognition using the PSHE structure. The S_{PSHE} and LoD_{PSHE} for this configuration are found to be 149.78 $\mu\text{m}/\text{RIU}$ and 6.68×10^{-6} deg. RIU/ μm , respectively. For adrenal gland cancer, breast (MDA-MB-231) cancer, and breast (MCF-7) cancer, the S_{PSHE} values are 118.68 $\mu\text{m}/\text{RIU}$, 102.82 $\mu\text{m}/\text{RIU}$, and 91.49 $\mu\text{m}/\text{RIU}$, with LoD_{PSHE} values of 8.43×10^{-6} deg. RIU/ μm , 9.73×10^{-6} deg. RIU/ μm , and 10.90×10^{-6} deg. RIU/ μm , re-

spectively. These results indicate that the proposed biosensor has a high capability to detect subtle refractive index changes between normal and cancerous basal cells, demonstrating significant sensitivity. Additionally, a comparative analysis of all proposed configurations is presented in Table 4.

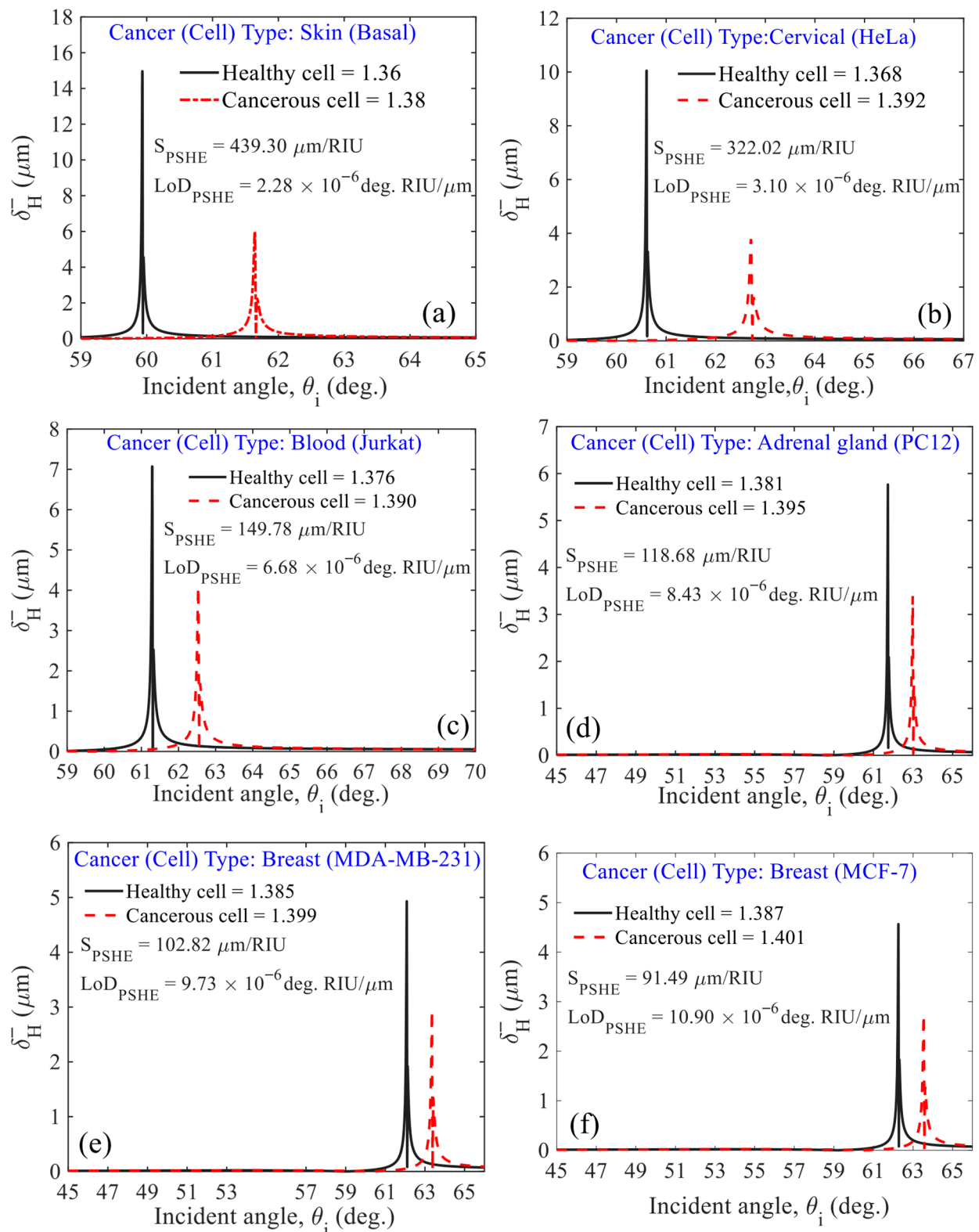


Figure 5. The δ_H^- response curves for six cancer cells to be used to examine S_{PSHE} and LoD_{PSHE} for (a) skin, (b) cervical, (c) blood, (d) adrenal gland (PC-12), (e) breast (MDA-MB-231), and (f) breast (MCF-7) cancer.

Table 4. The sensing performance of the proposed PSHE structure for cancerous cells with respect to normal cells.

Cancer Type	Cell Type	RI	$\Delta\delta_H^-$ (μm)	Sensitivity ($\mu\text{m}/\text{RIU}$)	LoD_{PSHE} (Deg. RIU/ μm)
Skin	Normal cell	1.360	8.78	439.30	2.28×10^{-6}
	Cancerous cell	1.380			
Cervical	Normal cell	1.368	6.44	322.02	3.10×10^{-6}
	Cancerous cell	1.392			
Blood	Normal cell	1.376	2.99	149.78	6.68×10^{-6}
	Cancerous cell	1.390			
Adrenal gland	Normal cell	1.381	2.37	118.68	8.43×10^{-6}
	Cancerous cell	1.395			
Breast (MDA-MB-231)	Normal cell	1.388	2.05	102.82	9.73×10^{-6}
	Cancerous cell	1.399			
Breast (MCF-7)	Normal cell	1.387	1.82	91.49	10.90×10^{-6}
	Cancerous cell	1.401			

Finally, Table 5 provides a comparative study of the proposed work with previously reported results. This analysis emphasizes the superiority of the present research due to its substantially enhanced sensitivity.

Table 5. Comparative analysis of sensitivity for the proposed PSHE structures with reported PSHE-based cancer cell detection.

Structure	Sensing Mechanism	Sensitivity	LoD_{PSHE}	Applications	Ref.
Multilayer structure	PSHE	Sensor 1(H): 1029.0 nm/RIU	--	Cancer Cells	[20]
		Sensor 2(V): 750.0 nm/RIU			
Multilayer structure (Present study)	PSHE	439.30 $\mu\text{m}/\text{RIU}$	2.28×10^{-6} deg. RIU/ μm	Cancer Cells	This work

4. Conclusions

In this work, first, the enhancement of the spin-dependent shift (δ_H^-) using a multilayer structure is proposed. The multilayer structure is optimized in such a way as to achieve the resonance condition to improve the PSHE. The maximized δ_H^- of 350.82 μm is achieved due to the combined SPR waveguiding effect, which is much higher than reported in the literature. In the second part of the study, the enhanced δ_H^- is utilized to detect cancerous cells. This sensitivity is achieved with minimal RI variations between healthy and cancerous cells. The PSHE structure showed a substantial incident angle shift in the PSHE resonance between healthy and cancerous blood cells. The maximum sensitivity of 439.30 $\mu\text{m}/\text{RIU}$ is attained for the skin cell. These findings collectively underscore the significant potential of PSHE-based sensing for biomedical applications, especially in accurately differentiating between diverse healthy and cancerous blood cells. This capability may facilitate the creation of sophisticated diagnostic photonics devices specifically designed for cancer detection and monitoring. Further, the authors believe that the proposed work also has potential future applications, such as secure encoding and encryption [57], and hardware-level security systems [58]. The proposed work can be further enhanced by integrating it

with compact on-chip photonic platforms. This integration would allow for its application within the wider framework of ongoing developments in PSHE-based sensing, security, and information processing, ultimately strengthening the overall impact and future prospects of the study.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/quantum8010017/s1>, Figure S1: The schematic representation illustrates the experimental setup for measuring PSHE.

Author Contributions: Conceptualization, A.V. and Y.K.P.; methodology, A.V. and Y.K.P.; software, A.V., D.K. and Y.K.P.; validation, A.V., D.K. and Y.K.P.; formal analysis, A.V. and Y.K.P.; investigation, A.V. and Y.K.P.; resources, A.V., Y.K.P. and V.M.; data curation, A.V.; writing—original draft preparation, A.V., D.K. and Y.K.P.; writing—review and editing, A.V., Y.K.P., V.M. and R.G.; supervision, A.V. and Y.K.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Xiang, Y.; Jiang, X.; You, Q.; Guo, J.; Dai, X. Enhanced spin Hall effect of reflected light with guided-wave surface plasmon resonance. *Photonics Res.* **2017**, *5*, 467–472.
2. Li, H.; Jia, Q.; Shi, B.; Zhou, Y.; Cao, Y.; Luan, K.; Wang, D.; Zhu, T.; Shi, Y.; Tang, D.; et al. Large Optical Lateral Force with a Phase-Engineered Photonic Spin Hall Effect. *ACS Photonics* **2025**, *12*, 3337–3343. [[CrossRef](#)]
3. Zeng, Z.; Liang, J.; Guo, L.; Deng, D.; Wang, G.; Zhang, L.; Liang, C. Manipulating photonic spin Hall split based on nonlinear effect and surface plasmon resonance. *Opt. Commun.* **2024**, *572*, 130949. [[CrossRef](#)]
4. Kumar, V.; Maurya, J.B.; Prajapati, Y.K. Piezoplasmonic System for Enhanced Photonic Spin Hall Effect for Applications in Optical Refractive Index Sensing. *IEEE J. Sel. Top. Quantum Electron.* **2025**, *31*, 1–9. [[CrossRef](#)]
5. Ling, X.; Zhou, X.; Luo, H.; Wen, S. Steering far-field spin dependent splitting of light by inhomogeneous anisotropic media. *Phys. Rev. A* **2012**, *86*, 053821. [[CrossRef](#)]
6. Zhou, X.; Ling, X.; Luo, H.; Wen, S. Identifying graphene layers via spin Hall effect of light. *Appl. Phys. Lett.* **2012**, *101*, 251602. [[CrossRef](#)]
7. Wang, H.; Zhang, X. Unusual spin Hall effect of a light beam in chiral metamaterials. *Phys. Rev. A* **2011**, *83*, 053820. [[CrossRef](#)]
8. Olaya, C.M.; Hayazawa, N.; Balgos, M.H.; Tanaka, T. Enhancing angular photonic spin Hall effect at surface plasmon resonance. *Nanophotonics* **2025**, *14*, 3115–3124. [[CrossRef](#)]
9. Onoda, M.; Murakami, S.; Nagaosa, N. Hall effect of light. *Phys. Rev. Lett.* **2004**, *93*, 083901. [[CrossRef](#)]
10. Bliokh, K.Y.; Bliokh, Y.P. Conservation of angular momentum, transverse shift, and spin Hall effect in reflection and refraction of an electromagnetic wave packet. *Phys. Rev. Lett.* **2006**, *96*, 073903. [[CrossRef](#)]
11. Hosten, O.; Kwiat, P. Observation of the spin Hall effect of light via weak measurements. *Science* **2008**, *319*, 787–790. [[CrossRef](#)] [[PubMed](#)]
12. Kumar, V.; Srivastava, R.; Prajapati, Y.K. Improved Photonic Spin Hall Effect by an Induced Polarization Gradient in Anisotropy-Black Phosphorous and Its Application to NO₂ Gas Detection. *IEEE Sens. J.* **2023**, *23*, 20976–20983. [[CrossRef](#)]
13. Yang, W.; Ang, L.K.; Zhang, W.; Han, J.; Xu, Y. High sensitivity gas sensor based on surface exciton polariton enhanced photonic spin Hall effect. *Opt. Express* **2023**, *31*, 27041–27053. [[CrossRef](#)] [[PubMed](#)]
14. Cheng, J.; Xiang, Y.; Xu, J.; Liu, S.; Dong, P. Highly sensitive refractive index sensing based on photonic spin Hall effect and its application on cancer detection. *IEEE Sens. J.* **2022**, *22*, 12754–12760. [[CrossRef](#)]
15. Ahlawat, L.; Kishor, K.; Sinha, R.K. Photonic spin Hall effect-based ultra-sensitive refractive index sensor for haemoglobin sensing applications. *Opt. Laser Technol.* **2024**, *170*, 110183. [[CrossRef](#)]
16. Pandey, S.; Shukla, H.; Mishra, V.; Pal, S.; Prajapati, Y.K.; Verma, A. Highly Sensitive Magneto-Optical SPR Sensor Based on the Photonic Spin Hall Effect with CeYIG and Graphene. *IEEE Trans. Magn.* **2026**, *62*, 4000409. [[CrossRef](#)]
17. Ahlawat, L.; Kishor, K.; Baitha, M.N.; Sinha, R.K. Photonic Spin Hall Effect-Based AQI Sensor: Effect of Concentration of PM_{2.5}. *IEEE Sens. J.* **2025**, *25*, 14589–14597. [[CrossRef](#)]

18. Liu, S.; Chen, S.; Wen, S.; Luo, H. Photonic spin Hall effect: Fundamentals and emergent applications. *Opto-Electron. Sci.* **2022**, *1*, 220007. [\[CrossRef\]](#)
19. Ma, Z.; Lai, Z.; Lin, S.; Hong, J.; Chen, Y.; Zhou, X. Generalized Brewster angle enhanced photonic spin Hall effect in an all-dielectric metasurface. *Opt. Lett.* **2023**, *48*, 3003–3006. [\[CrossRef\]](#)
20. Kim, Y.; Baitha, M.N.; Chun, H.-J.; Kim, K. High-sensitivity cancer cell detection with dual-polarization photonic spin Hall effect. *Opt. Laser Technol.* **2025**, *189*, 113174. [\[CrossRef\]](#)
21. Ling, X.; Zhou, X.; Yi, X.; Shu, W.; Liu, Y.; Chen, S.; Luo, H.; Wen, S.; Fan, D. Giant photonic spin Hall effect in momentum space in a structured metamaterial with spatially varying birefringence. *Light. Sci. Appl.* **2015**, *4*, e290. [\[CrossRef\]](#)
22. Zhou, Q.; Tan, Y.; Sheng, L.; Cao, Y.; Wang, Z.; Ling, X. Chirality-induced tunable quasi-Brewster angle and anomalous photonic spin-Hall effect. *Opt. Laser Technol.* **2025**, *187*, 112811. [\[CrossRef\]](#)
23. Tang, J.; Zhang, Y.; Yuan, H.; Long, X.; Jiang, J.; Tian, H.; Jiang, L. Enhanced and tunable photonic spin Hall effect with optical Tamm states. *J. Appl. Phys.* **2023**, *134*, 233102. [\[CrossRef\]](#)
24. Zhu, T.; Lou, Y.; Zhou, Y.; Zhang, J.; Huang, J.; Li, Y.; Luo, H.; Wen, S.; Zhu, S.; Gong, Q.; et al. Generalized spatial differentiation from the spin hall effect of light and its application in image processing of edge detection. *Phys. Rev. Appl.* **2019**, *11*, 034043. [\[CrossRef\]](#)
25. Zhen, W.; Wang, X.-L.; Ding, J.; Wang, H.-T. Controlling the symmetry of the photonic spin Hall effect by an optical vortex pair. *Phys. Rev. A* **2023**, *108*, 023514. [\[CrossRef\]](#)
26. Zhen, W.; Wang, X.L.; Ding, J.; Wang, H.T. Revisiting physical mechanism of longitudinal photonic spin splitting and Goos-Hänchen shift. *New J. Phys.* **2024**, *26*, 013045. [\[CrossRef\]](#)
27. Filho, A.M.; Laversanne, M.; Ferlay, J.; Colombet, M.; Piñeros, M.; Znaor, A.; Parkin, D.M.; Soerjomataram, I.; Bray, F. The GLOBOCAN 2022 cancer estimates: Data sources, methods, and a snapshot of the cancer burden worldwide. *Int. J. Cancer* **2025**, *156*, 1336–1346. [\[CrossRef\]](#)
28. Al-Hajj, M.; Wicha, M.S.; Benito-Hernandez, A.; Morrison, S.J.; Clarke, M.F. Prospective identification of tumorigenic breast cancer cells. *Proc. Natl. Acad. Sci. USA* **2003**, *100*, 3983–3988. [\[CrossRef\]](#)
29. Jang, S.J.; Gardner, J.M.; Ro, J.Y. Diagnostic approach and prognostic factors of cancers. *Adv. Anat. Pathol.* **2011**, *18*, 165–172. [\[CrossRef\]](#)
30. Hakim, R.U.; Amin, T.; Islam, S.M.B.U. Advances and challenges in cervical cancer: From molecular mechanisms and global epidemiology to innovative therapies and prevention strategies. *Cancer Control.* **2025**, *32*, 10732748251336415. [\[CrossRef\]](#)
31. Nissan, N.; Albiztegui, R.E.O.; Fruchtmann-Brot, H.; Gluskin, J.; Arita, Y.; Amir, T.; Reiner, J.S.; Feigin, K.; Mango, V.L.; Jochelson, M.S.; et al. Extremely dense breasts: A comprehensive review of increased cancer risk and supplementary screening methods. *Eur. J. Radiol.* **2025**, *182*, 111837. [\[CrossRef\]](#)
32. Macios, A.; Nowakowski, A. False negative results in cervical cancer screening—Risks, reasons and implications for clinical practice and public health. *Diagnostics* **2022**, *12*, 1508. [\[CrossRef\]](#)
33. Alsaad, A.M.; Al-Hmoud, M.; Marashdeh, M.W.; Aljaafreh, M.J.; Rababah, T.M. Design and modeling of a novel highly sensitive surface plasmon resonance sensor applying tin selenide and graphene for cancer detection. *Plasmonics* **2024**, *19*, 2061–2069. [\[CrossRef\]](#)
34. Mostufa, S.; Akib, T.B.A.; Rana, M.; Islam, R. Islam, highly sensitive TiO₂/Au/graphene layer-based surface plasmon resonance biosensor for cancer detection. *Biosensors* **2022**, *12*, 603. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Yesudasu, V.; Srivastava, R.; Pal, S.; Verma, A.; Prajapati, Y.K. Numerical analysis of an advanced surface plasmon resonance biosensor utilizing nitride material-tungsten ditelluride-black phosphorus. *Phys. B Condens. Matter* **2023**, *675*, 415619. [\[CrossRef\]](#)
36. Wang, Q.; Jiang, X.; Wang, X.; Dai, X.; Xiang, Y. Enhancing photonic spin Hall effect in the surface plasmon resonance structure covered by the graphene-MoS₂ heterostructure. *IEEE Photonics J.* **2017**, *9*, 1–10. [\[CrossRef\]](#)
37. Luo, H.; Zhou, X.; Shu, W.; Wen, S.; Fan, D. Enhanced and switchable spin Hall effect of light near the Brewster angle on reflection. *Phys. Rev. A* **2011**, *84*, 043806. [\[CrossRef\]](#)
38. Bliokh, K.Y.; Alonso, M.A.; Ostrovskaya, E.A.; Aiello, A. Angular momenta and spin-orbit interaction of nonparaxial light in free space. *Phys. Rev. A* **2010**, *82*, 063825. [\[CrossRef\]](#)
39. Lin, S.; Hong, J.; Chen, Z.; Chen, Y.; Zhou, X. Optimal weak measurement in the photonic spin Hall effect for arbitrary linear polarization incidence. *Optics Express* **2022**, *30*, 4096–4105. [\[CrossRef\]](#)
40. Homola, J. *Surface Plasmon Resonance Sensors*; Springer: Berlin/Heidelberg, Germany, 2006.
41. Chopra, K.L. *Thin Film Phenomena*; McGraw-Hill: New York, NY, USA, 1969.
42. Smith, D.L. *Thin-Film Deposition: Principles and Practice*; McGraw-Hill: New York, NY, USA, 1995.
43. George, S.M. Atomic Layer Deposition: An Overview. *Chem. Rev.* **2010**, *110*, 111–131. [\[CrossRef\]](#)
44. Elam, J.W.; Zinovev, A.V.V.; Pellin, M.J.; Comstock, D.J.; Hersam, M.C. Nucleation and growth of ALD films on noble metals. *J. Vac. Sci. Technol. A* **2003**, *21*, 1099–1107.

45. Meng, X.; Byun, Y.C.; Kim, H.S.; Lee, J.S.; Lucero, A.T.; Cheng, L.; Kim, J. Atomic layer deposition of silicon nitride thin films: A review of recent progress, challenges, and outlooks. *Materials* **2016**, *9*, 1007.
46. Powell, C.J.; Jablonski, A. Surface sensitivity of X-ray photoelectron spectroscopy. *J. Electron. Spectrosc. Relat. Phenom.* **2010**, *178–179*, 331–346. [[CrossRef](#)]
47. Wang, Q.H.; Kalantar-Zadeh, K.; Kis, A.; Coleman, J.N.; Strano, M.S. Electronics and optoelectronics of two-dimensional transition metal dichalcogenides. *Chem. Soc. Rev.* **2015**, *44*, 2664–2680. [[CrossRef](#)]
48. Najmaei, S.; Liu, Z.; Zhou, W.; Zou, X.; Shi, G.; Lei, S.; Yakobson, B.I.; Idrobo, J.-C.; Ajayan, P.M.; Lou, J. Vapour phase growth and grain boundary structure of MoS₂ atomic layers. *Nature Mater.* **2013**, *12*, 754–759. [[CrossRef](#)]
49. Garcia, R.; Perez, R. Dynamic atomic force microscopy methods. *Surf. Sci. Rep.* **2002**, *47*, 197–301. [[CrossRef](#)]
50. Tompkins, H.G.; Irene, E.A. *Handbook of Ellipsometry*; William Andrew Publishing: Norwich, NY, USA, 2005.
51. Moulder, J.F.; Stickle, W.F.; Sobol, P.E.; Bomben, K.D. *Handbook of X-Ray Photoelectron Spectroscopy*; Perkin-Elmer: Shelton, CT, USA, 1992.
52. Tang, T.; Li, C.; Luo, L. Enhanced spin Hall effect of tunneling light in hyperbolic metamaterial waveguide. *Sci. Rep.* **2016**, *6*, 30762. [[CrossRef](#)]
53. Srivastava, T.; Chitriv, S.; Sahu, S.; Gorai, P.; Jha, R. Photonic spin Hall effect using hybrid Tamm plasmon polariton. *J. Appl. Phys.* **2022**, *132*, 203103. [[CrossRef](#)]
54. Zhou, X.; Ling, X. Enhanced Photonic Spin Hall Effect Due to Surface Plasmon Resonance. *IEEE Photonics J.* **2016**, *8*, 1–8. [[CrossRef](#)]
55. Srivastava, A.; Sharma, A.K.; Prajapati, Y.K. On the sensitivity-enhancement in plasmonic biosensor with photonic Spin Hall effect at visible wavelength. *Chem. Phys. Lett.* **2021**, *774*, 138613. [[CrossRef](#)]
56. Sahu, S.; Srivastava, T.; Jha, R. Plexcitonic system for high photonic spin Hall effect. *Appl. Phys. Lett.* **2023**, *123*, 203302. [[CrossRef](#)]
57. Pei, N.; Zheng, Y.; Tang, Y.-Q.; Tang, X.-Z.; Zhang, H.-F. Theoretical investigation of photonic spin Hall effect based on layered metastructure with graphene regulation by WOA for encoding and encryption. *Mater. Des.* **2025**, *255*, 114218. [[CrossRef](#)]
58. Divyanshu, D.; Goyal, A.K.; Massoud, Y. Physical unclonable function using photonic spin Hall effect. *Sci. Rep.* **2024**, *14*, 14393. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.