



Article

The Effect of Grating Modulation Depth on Surface Plasmon Resonance

Nguyen H. Le * and Ribal Georges Sabat

Department of Physics and Space Science, Royal Military College of Canada, Kingston, ON K7K 7B4, Canada; georges.sabat@rmc.ca

* Correspondence: anthony.le@rmc-cmr.ca

Abstract

Periodic grating structures allow for the excitation of surface plasmon resonance (SPR) by matching the momentum of incident light to the plasmon mode. Herein, we investigate Au-coated sinusoidal gratings with depths from 50 nm to 280 nm using transmission and reflection spectroscopy. For gratings with an 806 nm period, increasing the modulation depths results in an SPR red shift of more than 125 nm, spectral broadening, and branch separation in the SPR dispersion. Rigorous coupled-wave analysis simulations using Gsolver (v5.2) reproduced the experimentally observed depth-dependent spectral trends. These results suggest that the grating modulation depth is a key structural parameter for tuning the SPR wavelength, bandwidth, and dispersion characteristics of a grating-coupled SPR system.

Keywords: grating-coupled surface plasmon resonance; laser interference lithography; grating modulation depth; sinusoidal surface relief grating; SPR dispersion; effective refractive index; Gsolver simulation; plasmon confinement

1. Introduction

Surface plasmon resonance (SPR) can be used for precise optical sensing since any changes to the refractive index near the metal–dielectric interface will be experimentally observed as a shift in the SPR wavelength [1–3]. This characteristic enables practical applications such as biomarker detection [4,5], drug development [6], environmental monitoring [7], and molecular binding analysis [4,8]. In localized plasmonic systems, periodic nanoparticle arrays can use the diffraction-mediated coupling of localized plasmon modes to produce narrow optical responses [9] and enhanced sensing performance [10]. For propagating SPR excitation, prism coupling has been used to provide the momentum [11,12], whereas periodic gratings offer a compact alternative that can be integrated in miniaturized optical devices.

Grating-coupled SPR structures can be fabricated with different grating geometries such as rectangular [13], chirped [14,15], and sinusoidal [13,16]. Among these geometries, sinusoidal surface relief gratings (SRGs) are attractive because they provide a smooth periodic modulation of the metal surface and can be fabricated using laser interference lithography. The optical response of grating-coupled SPR depends strongly on the grating geometry. In grating phase-matching theory, the SPR excitation wavelengths depend on the grating pitch, the light incidence angle, the refractive indices of the metal and the dielectric, and the light polarization [17]. However, the flat interface SPR theory does not explicitly account for the grating modulation depth, which can strongly influence the SPR peak depth,



Academic Editor: Raffaella Signorini

Received: 4 June 2026

Revised: 7 July 2026

Accepted: 3 August 2026

Published: 5 August 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.

spectral bandwidth, and the SPR dispersion [18–21]. As the grating modulation becomes deeper, the interaction between the optical field and the periodic metal structure increases, leading to a stronger grating-mediated plasmon coupling due to changes in the effective refractive index of the dielectric [18,20–23].

The role of the grating modulation depth has been recognized in both SPR sensor design and plasmonic theory. In grating-based SPR sensors, the modulation depth can be optimized to improve the reflectance amplitude, the full width at half maximum, and the bulk sensitivity of the sensor [18,19,21]. Previous works have shown that increasing the grating modulation depth enhanced the sensitivity, but also broadened the SPR spectrum, which is detrimental for sensors trying to achieve maximum bulk sensitivity. In plasmonic theory, increasing the modulation depth of a sinusoidal grating has been shown to theoretically shift the plasmon resonance wavelength, broaden the SPR bandwidth, and generate plasmonic bandgaps due to stronger Bragg scattering and changes in local effective refractive indices [20,22,23]. Although the grating modulation depth is an important design parameter for grating-coupled SPR sensors, few studies have experimentally tracked how the SPR response continuously evolves from shallow to deep gratings.

Herein, we experimentally and numerically investigate the role of grating modulation depth in controlling the optical response of grating-coupled SPR, including the resonance wavelength, spectral bandwidth, and the SPR dispersion, using transmission and reflection spectroscopy. By varying the modulation depth from a shallow-grating to a deep-grating regime, we characterize the changes in the SPR response and compare the experimental trends with rigorous coupled-wave analysis performed using Gsolver. This study provides insight into the relationship between grating geometry and plasmon coupling, enabling an improved design of grating-based plasmonic devices.

2. Materials and Methods

2.1. Fabrication and Characterization of Gold-Coated Azobenzene Surface Relief Gratings

Disperse Red-1 functionalized mexylaminotriazine molecular glass, or simply azobenzene molecular glass (gDR1), was synthesized following an established procedure [24]. The gDR1 powder was dissolved in dichloromethane (Sigma-Aldrich, Oakville, ON, Canada) at 3% (*w/v*). The solution was filtered and 70 μ L was spin-coated onto a cleaned 3.8 cm $\times$ 3.8 cm soda lime glass substrate (Ted Pella, Redding, CA, USA) at 1400 rpm for 35 s. The coated substrates were then baked at 65 $^{\circ}$ C for 10 min to remove residual solvent. The film thickness was measured using a DektakXT stylus profilometer (Bruker Corporation, San Jose, CA, USA).

Sinusoidal SRGs were inscribed in the gDR1 solid thin films by laser interference lithography using a Lloyd's mirror interferometer, as previously described [25]. A 532 nm Verdi V6 diode-pumped solid-state laser (Coherent Inc., Santa Clara, CA, USA) was expanded and collimated to produce a beam diameter of 25 mm with an irradiance of 286 mW/cm². The time for which the laser was exposed to the azobenzene substrates was varied from 100 to 500 s to control the grating modulation depth. When using the Lloyd's mirror interferometer, the grating pitch is directly related to the laser incidence angle θ and wavelength λ , according to the following equation: $\Lambda = \lambda / (2 \sin \theta)$. Two randomly chosen grating pitches ($\Lambda = 806$ nm and 705 nm) were selected for the fabrication of the gratings. The actual resulting grating pitches were measured using a red-laser diffraction angle method and further confirmed by atomic force microscopy.

The grating morphology was characterized using an atomic force microscope (Dimension Edge AFM, Bruker Corporation, San Jose, CA, USA). The azobenzene substrates with the inscribed gratings were secured on the AFM stage under vacuum and imaged using the tapping mode with a scan rate of 0.5–1 Hz and a resolution of 1152 points per line.

AFM images were analyzed using NanoScope Analysis software (version 2.0). Line profiles were extracted perpendicular to the grating grooves to determine the grating pitch and modulation depth, with the latter defined as the average difference between the peaks and valleys over the entire scanned area of the SRGs.

For SPR excitation, the fabricated gratings were coated with a 30 nm layer of gold (Au) using a sputtering coater (Q 150V ES Plus, Quorum, Laughton, East Sussex, UK). The deposition was performed at 30 mA with an estimated deposition rate of approximately 18 nm/min. Au sputtering was performed without intentional substrate heating, and the low-intensity optical measurements were not expected to induce thermal or photoinduced changes in the grating profile.

2.2. Surface Plasmon Resonance Optical Measurement

Surface plasmon resonance (SPR) measurements were performed using a free-space optical setup, as shown in Figure 1. The Au-coated gratings were mounted on a motorized rotation stage, allowing for changes in the light incidence angle. A SLS301 halogen white-light source (Thorlabs, Newton, NJ, USA) was collimated and passed through an iris to define a beam diameter of ~2 mm. Afterwards, the beam passed through a polarizer to polarize incident light along the grating vector, and it was then directed onto a beam splitter. The reflected light was collected by an optical fiber connected to a QE Pro and NIR spectrometer (Ocean Insight, Orlando, FL, USA). For transmission measurements, the transmitted light was collected on the opposite side of the sample using a lens to direct light towards the optical fiber of the spectrometer. The azobenzene sample was rotated from normal incidence to $\pm 10^\circ$, in increments of 1° , using the motorized stage controlled via LabVIEW (v2017) software (National Instruments, Austin, TX, USA). Spectra were normalized with respect to an area of the azobenzene sample that did not have a grating.

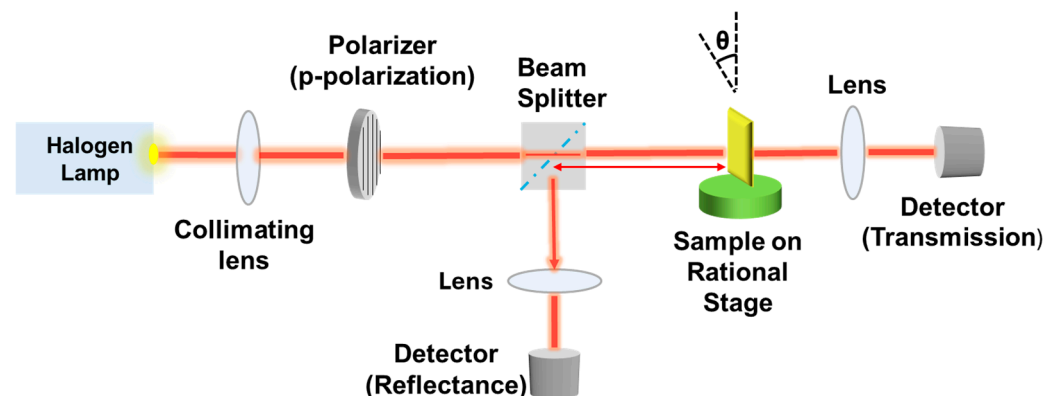


Figure 1. Schematic illustration of the optical setup used to measure angular SPR responses in transmission and reflection modes. A polarized white-light beam was directed onto the Au-coated grating substrate (yellow) mounted on a rotational stage (green), and the transmitted or reflected light was collected using a fiber-coupled spectrometer. The orange lines and red arrows indicate the optical beam paths and the directions of propagation, and the blue dotted diagonal line represents the beam-splitter interface.

2.3. Data Analysis and Numerical Simulation

Transmission spectra were analyzed using custom Python (v3.14) scripts. The SPR peaks were determined by selecting the maximum (transmission) or minimum (reflection) intensity within the selected wavelength range for each incident angle. The extracted peak

wavelengths were then used to construct the dispersion curve via the phase-matching condition by solving the following equations [17,26]:

$$k_{SPR} = k_0 n_d \sin \theta + m \left(\frac{2\pi}{\Lambda} \right) \quad (1)$$

where $k_0 = 2\pi/\lambda$, n_d is the refractive index of the dielectric medium, λ is the SPR wavelength, θ is the incident angle, Λ is the grating pitch, and m is the diffraction order. In this work, the first-order grating coupling was used with $m = \pm 1$. The corresponding angular frequency was calculated as

$$\omega = \frac{2\pi \times c}{\lambda} \quad (2)$$

The dispersion relation was obtained by plotting ω as a function of k_{SPR} , with the light line included as a reference.

Grating-coupling SPR spectra were simulated using the Gsolver software, a numerical electromagnetic simulation software based on rigorous coupled-wave analysis for periodic grating structures [27]. The simulations were performed at the interface of the metal-dielectric (air-gold). The simulated grating pitch was selected to match the experimentally measured value, and the grating modulation depth was theoretically varied to examine its effect on the simulated SPR response.

Because changing the depth of a curved GSolver profile also changed the number of layers used to discretize the curve, rectangular-layer models were used to vary the grating depth directly while keeping the lateral dimensions fixed. To match the experimental sinusoidal grating geometry, the simulated theoretical grating was represented using stacked rectangular layers of Au on a Au base layer. In the simplest one-layer model, the simulated grating was approximated using a single rectangular Au layer positioned on a Au base layer with a width of $0.5W_b$ and a height equal to the total grating depth, d , where W_b is the width of the Au base. More realistic geometries were also generated using three- and five-layer Au models. In the three-layer model, the lateral widths were fixed at $0.5W_b$, $0.4W_b$, and $0.3W_b$ from the bottom to the top layer, and each layer had a height of $d/3$. In the five-layer model, the lateral widths were fixed at $0.5W_b$, $0.4W_b$, $0.3W_b$, $0.2W_b$, and $0.1W_b$, from the bottom to the top layer. For each total grating depth, the individual layer heights (h_1 – h_5) were varied empirically while maintaining $d = h_1 + h_2 + h_3 + h_4 + h_5$. Different height combinations were simulated, and the geometry giving the closest agreement between the calculated and experimental normal-incidence resonance positions was retained. The final five-layer dimensions are provided in Table S2. The spectra were simulated using a light polarization along the grating vector, and the resulting simulated zeroth-order transmitted intensity allowed for the identification of the SPR wavelength. The extracted SPR wavelengths were then used to calculate the theoretically effective refractive index using the same phase-matching equation applied to the experimental spectra.

3. Results and Discussion

The goal of this work was to investigate how the grating modulation depth affects the optical response for grating-coupled SPR, with particular focus on the SPR dispersion curve and the effective refractive index at the metal-dielectric boundary. Figure 2a illustrates the fabrication of Au-coated grating substrates using laser interference lithography on an azobenzene molecular glass thin film. Under laser illumination, molecular azobenzene undergoes photoinduced mass transport, leading to sinusoidal SRGs. The deposition of a thin Au layer (~30 nm) produce the metal-dielectric interface required to support SPR. The grating modulation depth is controlled by the laser irradiance and exposure time, as well

as the azobenzene film thickness and the azobenzene solution concentration, as previously described [24,28]. In this work, all fabrication parameters were held constant, except for the laser exposure time, which was varied to modify the grating modulation depth as desired.

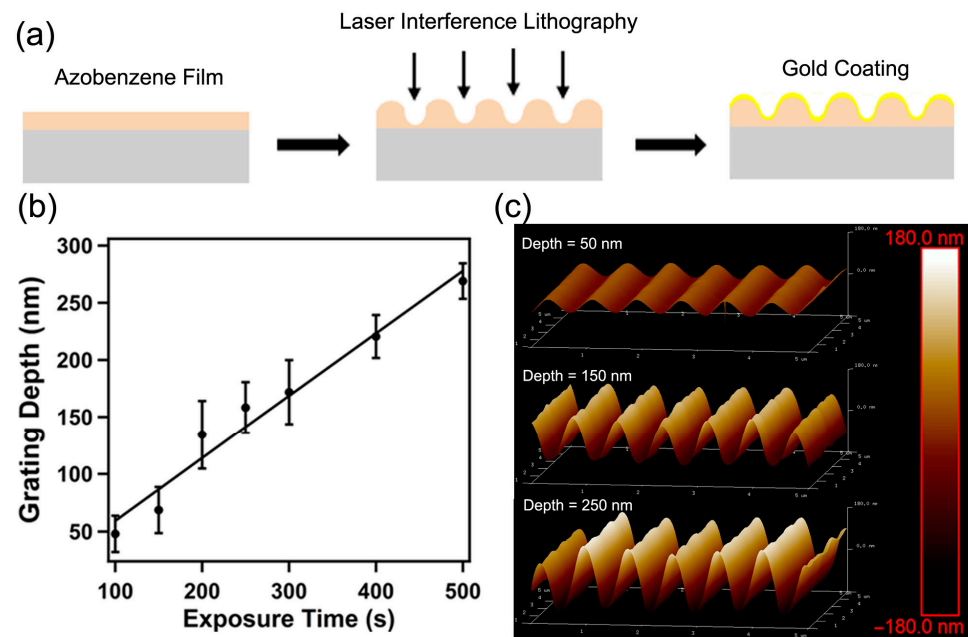


Figure 2. Fabrication and characterization of grating-coupled SPR structures with controlled grating modulation depth. (a) Schematic illustration of laser interference lithography used to generate periodic SRGs in azobenzene thin films (beige), followed by Au coating (yellow) to form grating-coupled SPR substrates. The downward black arrows indicate laser irradiation. (b) Plot of the grating modulation depth as a function of laser exposure time. Error bars represent mean $\pm$ S.D. of replicates ($n = 3$). (c) Representative AFM images of gratings with depths of 50 nm (top), 150 nm (middle), and 250 nm (bottom), respectively. The color scale represents height from -180 nm to 180 nm.

To evaluate the controllability of the fabrication process, the grating modulation depth was plotted as a function of the laser exposure time for a fixed laser irradiance. As shown in Figure 2b, the grating modulation depth linearly increased with an increase in the exposure time from 100 to 500 s, demonstrating that the laser exposure time provides a controllable approach to fabricating gratings with different modulation depths. For clarity, the gratings in this study were classified into three depth regimes: shallow gratings (~ 50 – 120 nm), intermediate gratings (~ 130 – 180 nm), and deep gratings (>200 nm). These regimes are not intended as universal boundaries, but provide a framework for comparing the depth-dependent SPR response observed in this work.

Figure 2c contains representative AFM images for these regimes, with representative grating modulation depths of 50 nm, 150 nm, and 250 nm. The AFM images confirm that increasing the laser exposure time results in deeper surface modulation while preserving the periodic grating geometry. AFM scans acquired at an additional location separated by approximate 1 mm of distance show a low modulation depth variation with differences of 1.9–5.4% (provided in Table S1 and Figure S1), confirming the good spatial uniformity of the grating profiles across the sample. AFM comparisons before and after Au sputtering indicated that the grating periodicity, modulation depth, and overall sinusoidal profile were preserved, without profile distortion, trough filling, cracking, or film breakup (Figure S2). This preserved morphology is consistent with a continuous Au coating rather than a discontinuous or percolated film [29]. These results confirm that the grating depth was controlled and remained stable after Au coating, enabling an examination of how the

grating modulation depth influences the SPR spectra, the dispersion curve, and the effective refractive index.

3.1. Depth-Dependent Optical Response of Grating-Coupled SPR

Next, we investigated how the grating modulation depth affects the optical response of grating-coupled SPR using the transmission and reflection setup shown in Figure 1. This configuration allowed the monitoring of the depth-dependent spectral response associated with the grating-coupled excitation of surface plasmon modes at the Au/air interface. Although the thin Au film supports two asymmetric resonance modes associated with the Au/air and Au/azobenzene interfaces, this study examines the Au/air mode because the Au/azobenzene mode is expected to lie outside the investigated spectral range. Previous studies have similarly shown that asymmetric structures containing ultra-thin film Au films can support distinct SPP modes predominantly associated with the two metal–dielectric interfaces [30,31].

First, we measured the transmission spectra of the 806 nm pitch gratings with different modulation depths. As shown in Figure 3, increasing the grating modulation depth progressively changed the transmission spectra in the three depth-dependent regimes. In the shallow regime, as the modulation depth increased from 50 to 90 nm, the transmission intensity increased, and the SPR feature became slightly broader and redshifted slightly by 0.7 nm, indicating that the shallow modulation depth only weakly perturbs the SPR response. In the intermediate depth regime, when the modulation depth increased from 165 to 180 nm, the SPR response began to change significantly. For the 165 nm depth grating, the SPR feature was already noticeably broader than those of the 50- and 90 nm depth gratings. Furthermore, relative to the 50 nm depth grating, the SPR redshifted by 7.3 nm for the 165 nm depth grating and by 41.9 nm for the 180 nm depth grating. This result suggests a transition from weak depth perturbation to stronger grating–plasmon coupling.

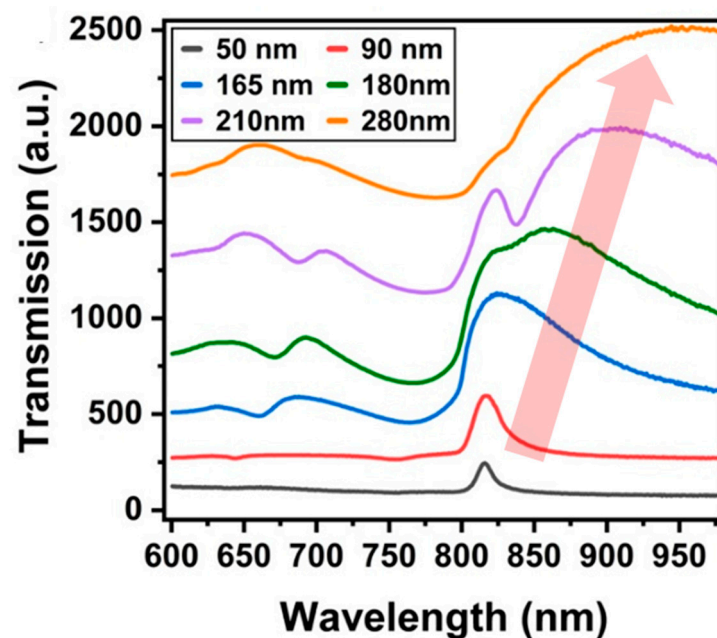


Figure 3. Effect of grating modulation depth on the optical spectra of grating-coupled SPR. Transmission spectra of grating-coupled SPR of the 806 nm pitch with various grating depths: 50 nm (black), 90 nm (red), 165 nm (blue), 180 nm (green), 210 nm (purple), and 280 nm (orange). The light pink arrow indicates the red shift in the SPR peak with increasing grating depth. The spectra are vertically offset by 0, 200, 400, 600, 1100, and 1600 counts, respectively, for clarity.

In the deep-grating regime, the spectral changes became more pronounced. The SPR feature continued to broaden and red-shift, relative to the 50 nm depth grating, with SPR wavelength shifts of 87.9 nm for the 210 nm depth grating and 125.5 nm for the 280 nm depth grating, as seen in Table 1. At these larger depths, a peak split appeared in the SPR response, indicating a bandgap-like separation in the SPR coupling mode. Overall, these results indicate that the SPR response is weakly affected by the grating modulation depth in the shallow-grating regime, but becomes more sensitive in the intermediate depth regime, and is strongly affected in the deep-grating regime. This observation is consistent with stronger grating-induced coupling to the plasmon mode and a stronger influence of the effective refractive indices of the metal and the dielectric on the SPR response, thus leading to a modification of the plasmon dispersion curve [20,22,23]. Furthermore, AFM analysis of the Au-coated grating surface roughness yielded Sq values of 4.9 ± 1.2 , 3.2 ± 0.4 , and 5.9 ± 1.8 nm for grating depths of 90, 165, and 235 nm, respectively, showing no systematic increase in surface roughness with increasing modulation depth. Therefore, the broadening is primarily attributed to enhanced grating-mediated radiative coupling associated with the increased surface modulation depth rather than progressive surface roughness-induced scattering. Nevertheless, a minor contribution from roughness-induced scattering cannot be excluded, as surface imperfections can scatter energy away from the coherent surface plasmon polaritons (SPPs) mode, thereby increasing damping and contributing to spectral broadening [32].

Table 1. SPR wavelength and wavelength shift as a function of grating modulation depth for the Au-coated 806 nm pitch gratings.

Grating Modulation Depth (nm)	λ_{SPR} (nm)	$\Delta\lambda_{\text{SPR}}$ Relative to 50 nm Grating Depth (nm)
50	818.3	-
90	819	0.7
165	825.6	7.3
180	860.2	41.9
210	906.2	87.9
280	943.8	125.5

To confirm that the effect of the grating modulation depth on the SPR response is not specific to one grating pitch, the complementary reflectance spectra of the 806 nm pitch grating are included in Figure S3. Furthermore, the transmission and reflectance spectra of the 705 nm pitch gratings are also included in the Supplementary Information in Figure S3. For each of these figures, it was also found that increasing the grating modulation depth led to the same qualitative spectral evolution observed in the transmission measurements of the 806 nm pitch grating (Figure 3).

3.2. The Effect of Grating Modulation Depth on SPR Dispersion Curve

Next, we examined the effect of the grating modulation depth on the plasmon dispersion curve using the transmission measurements in Figure 1. Figure 4a,b contain representative angular transmission spectra for the shallow and the deep-grating regimes. For the shallow grating with a modulation depth of 50 nm, the spectrum at normal incidence has a single narrow SPR peak. As the light incident angle increased, this resonance peak separated into two features that shifted in opposite directions (or two branches), corresponding to the +1 and −1 diffraction orders coupling to the plasmon mode. At normal incidence, the single peak is a result of a standing SPR wave since both the forward- and backward-diffraction orders couple with the plasmon mode at the same time. As the angle is varied from normal incidence, the forward-diffraction mode couples into the

SPR mode first (at a lower wavelength), then the backward-diffraction order couples with the plasmon mode at a higher wavelength. Both of these off-normal peaks correspond to propagating plasmon waves. In contrast, at the normal incidence, the deep grating with the modulation depth of 210 nm has a broader and redshifted SPR peak when compared to the 50 nm depth grating. Although there is still a split in that peak, this corresponds to the plasmonic bandgap, which is generated by the changes in the effective refractive indices as the modulation depth increases. For the 210 nm depth grating, as the incidence angle increases, the SPR peaks also split as the off-normal diffraction orders couple separately into the plasmon mode. In Figure 4b, when increasing the incidence angle, it seems that the SPR peaks move asymmetrically away from the band gap at the normal incidence angle. To visualize the SPR peak movement, the dispersion curves were constructed using the grating phase-matching condition given in Equations (1) and (2).

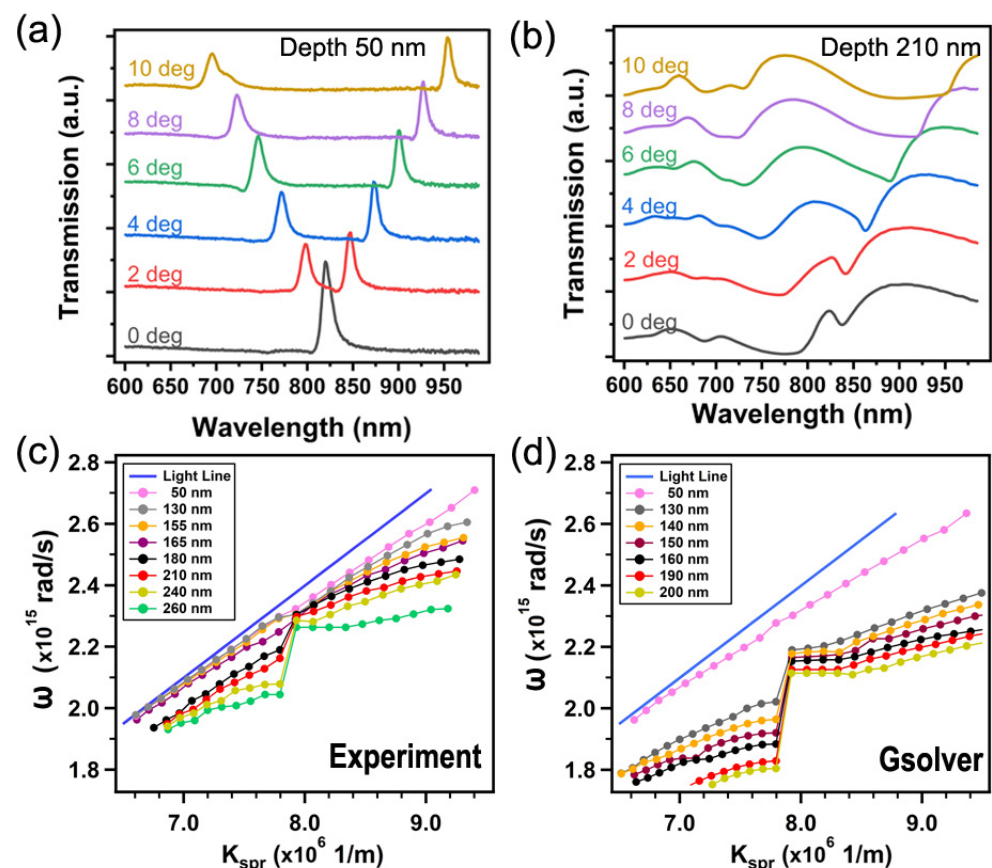


Figure 4. Effect of grating modulation depth on dispersion curve of grating-coupled SPR. (a,b) Plot of transmission spectrum measured from 0 degree to 10 degree of 806 nm pitch gratings with the depths of 50 nm (a) and 210 nm (b). The spectra are vertically offset for clarity. (c,d) Experimental (c) and Gsolver-simulated (d) dispersion curves for 806 nm pitch gratings with depths from 50 nm to 260 nm, and 50 nm to 200 nm, respectively. The blue line represents the light line.

Figure 4c contains the experimental SPR dispersion curves extracted from the positive angle transmission spectra for gratings with different modulation depths. For shallow gratings, the dispersion curve is nearly linear, indicating that shallow surface modulation only weakly couples into the SPR mode. As the grating depth increases into the intermediate regime, a split is seen in the dispersion curve, particularly for depths above ~150 nm. For deeper gratings, the split in the dispersion curve becomes more pronounced and increases further with increasing depth. This splitting is a result of the stronger Bragg back-scattering/coupling of SPPs due to the deeper periodic corrugation of the Au/air

interface [22]. At normal incidence, the periodic grating couples forward and backward SPP modes. Deeper grating depth increases this SPR coupling, lifting the degeneracy of the original SPP modes and forming two standing waves for the plasmon mode with different field distributions relative to the grating peaks and valleys. This is ultimately related to the changes in the effective refractive index at the interface between the metal and the dielectric. As a result, the two modes have different energies, which is shown in the measurement as plasmonic bandgap splitting. This interpretation is consistent with previous studies showing that periodic metal gratings couple oppositely propagating SPP modes and that the plasmonic bandgap width increases with grating groove depth [22,23].

To compare the experimental observation with the theoretical simulation of grating modulation depths on SPR, we simulated the dispersion curves using Gsolver, which uses rigorous coupled-wave analysis to solve Maxwell's equations for periodic grating structures [27]. By using a simplified one-layer grating model simulation, the simulated dispersion curves agree with the same qualitative trend observed experimentally (Figure 4d): shallow gratings show linear dispersion lines, whereas deeper gratings produce a larger bandgap. The same trend was also observed for the 705 nm pitch grating, as shown in Figure S4, where both the experimental and the simulated dispersion curves have increased split separation with increasing grating depth. These results suggest that grating modulation depth strongly affects the plasmonic bandgap in grating-coupled SPR structures.

3.3. Depth-Dependent Effective Refractive Index of Grating-Coupled SPR

The effective refractive index of the dielectric can be a useful parameter for describing how the grating modulation depth affects the grating-coupled plasmon response. The effective refractive index can be obtained from the SPR wavenumber as follows [26]:

$$n_{\text{eff}} = \frac{\beta}{k_0} \quad (3)$$

where β is the SPR propagation wavenumber and $k_0 = 2\pi/\lambda$ is the free-space light wave vector. For grating-coupled SPR ($\beta = k_{\text{SPP}}$), n_{eff} can be approximated using Equation (1) and written as

$$n_{\text{eff}} = n_d \sin \theta + m \left(\frac{\lambda_{\text{SPR}}}{\Lambda} \right) \quad (4)$$

where n_d is the refractive index of the incident medium, θ is the incident angle, λ_{SPR} is the SPR, Λ is the grating pitch, and m is the diffraction order.

To focus on the effect of the grating modulation depth and avoid ambiguity from the angle-dependent splitting of the SPR peak, the apparent effective refractive index n_{eff} was obtained from the normal incidence SPR peak wavelength. Thus, at $\theta = 0^\circ$ and for a positive first-order coupling ($m = 1$), Equation (4) simplifies to

$$n_{\text{eff}} = \left(\frac{\lambda_{\text{SPR}}}{\Lambda} \right) \quad (5)$$

This effective refractive index was then used for both the experimental and simulated SPR results to observe its change with the grating modulation depth.

To compare the experimental n_{eff} trend with simulations, the sinusoidal grating profile was approximated in Gsolver using one-, three-, and five-layer models, as illustrated in Figure 5a. The one-layer model represents the grating as a simple rectangular Au structure, whereas the three- and five-layer models provide progressively closer stepped approximations to the sinusoidal grating profile.

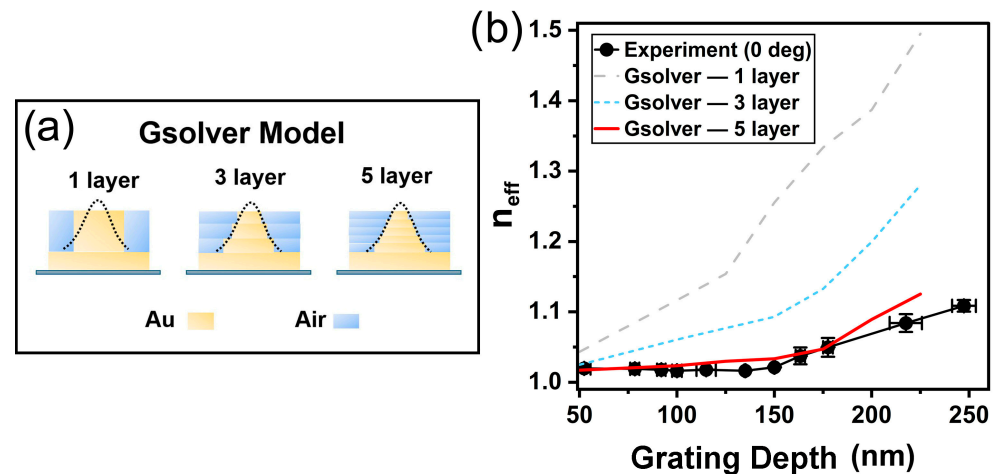


Figure 5. Effect of the grating modulation depth on the effective refractive index of grating-coupled SPR. (a) Schematic illustration of the one-, three-, and five-layer Gsolver models used to approximate the experimental grating geometry. Au and air regions are shown in yellow and blue, respectively. The black dotted line represents the sinusoidal grating profile approximated of the rectangular layers (b) Plot of effective refractive index as a function of grating modulation depth for experimental data (black) and Gsolver simulations using one-layer (dashed gray), three-layer (dotted blue), and five-layer (red) Au grating models. The multilayer approximation was used to better represent the sinusoidal Au-coated grating profile. The horizontal and vertical error bars represent the standard deviation of grating depths and effective refractive index, respectively ($n = 3$ data point per group).

Next, we compared the n_{eff} values from the experimental data to the simulated values obtained. Since the grating pitch was fixed, the calculated n_{eff} is directly proportional to the normal incidence SPR wavelength. Figure 5b has the calculated values of n_{eff} for both the experiments and the Gsolver simulations. Experimentally, n_{eff} changed only weakly for shallow gratings but increased more noticeably for grating depths above 150 nm. Interestingly, among the tested Gsolver models, the five-layer model gave the closest agreement with the experimental data, indicating that the simulated resonance wavelength is sensitive to how realistically the Au/air grating geometry is represented. This result suggests that Gsolver simulations not only align with the depth-dependent measurements, but they are also affected by the similarity between the real and simulated grating profiles. However, the five-layer model still does not completely reproduce the experimental values. This remaining difference likely arises from the simplified stepped approximation of the sinusoidal profile and uncertainty in the effective Au/air composition of the grating region. Consistent with this interpretation, additional simulations with different Au/air ratios indicate that the calculated n_{eff} also depends on the ratio of the simulated Au/air interface in the model (Figure S5).

3.4. Depth-Dependent Penetration Depth and Propagation Length of Grating-Coupled SPR

Since n_{eff} is related to the plasmon wavevector and affects how the surface plasmon field is distributed at the Au/air interface, we used the experimentally calculated n_{eff} to estimate how the grating modulation depth affects the SPR mode confinement, represented by the SPR penetration depth and the SPR propagation length. Figure 6a illustrates the penetration depth (δ_d) into the dielectric medium and the propagation length (L_x) along the Au/air interface, which are key SPR-excitation parameters related to the interface geometry, the field confinement, and the propagation loss. The SPR penetration depth and the SPR propagation length were calculated using the experimental n_{eff} values to compare the relative effect of grating depth on the plasmon mode.

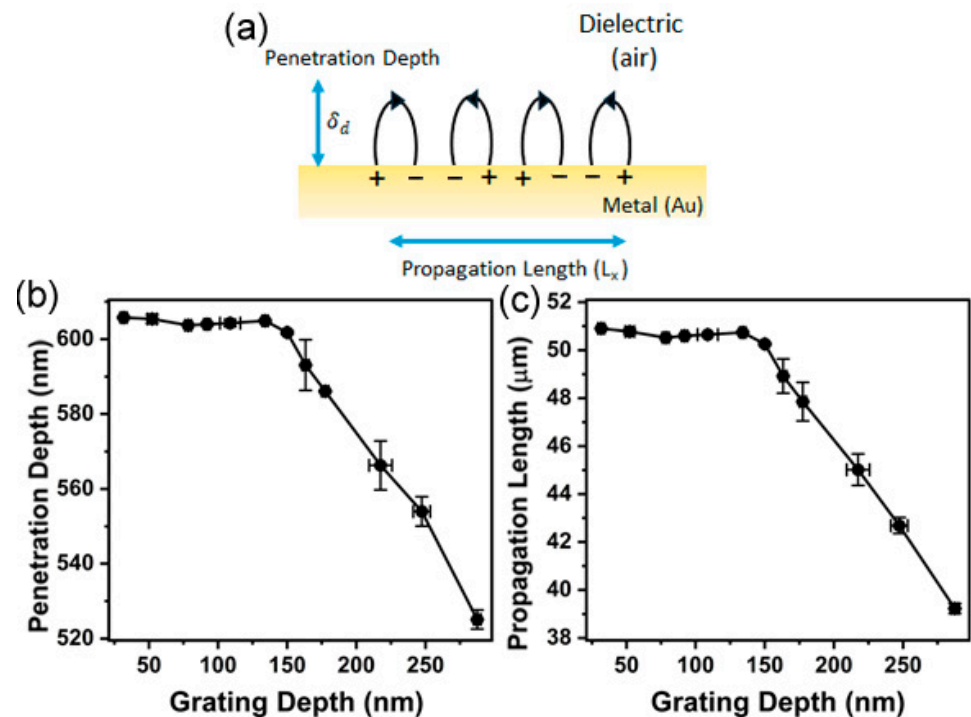


Figure 6. Effect of grating modulation depth on the penetration depth and propagation length of the SPR mode. (a) Schematic illustration of the penetration depth (δ_d) into the dielectric medium and the propagation length (L_x) along the Au/air interface. The black curved arrows depict the electric field lines extending from positive to negative surface charges at the interface (b,c) Plot of calculated penetration depth (b) and propagation length (c) of the SPR mode as a function of grating depth. The horizontal and vertical error bars represent the standard deviation of grating modulation depths ($n = 3$ data point per group).

The SPR penetration depth into the dielectric medium is calculated using the following equation [26]:

$$\delta_d = \frac{\lambda}{2\pi} \sqrt{\frac{\epsilon'_m + \epsilon_d}{\epsilon_d^2}} \quad (6)$$

The SPR propagation length along the Au/air interface is calculated using the following equations [26,33]:

$$L_x = \frac{1}{2k''_x} \quad (7)$$

$$k''_x \approx \frac{2\pi}{\lambda} \left(\frac{\epsilon'_m \epsilon_d}{\epsilon'_m + \epsilon_d} \right)^{3/2} \frac{\epsilon''_m}{2(\epsilon'_m)^2} \quad (8)$$

where λ is the SPR wavelength, ϵ'_m and ϵ''_m are the real and imaginary parts of the Au permittivity, respectively, and $\epsilon_d = n_{\text{eff}}^2$ was used as the effective dielectric permittivity. The optical constants of Au were taken from Johnson and Christy [34] at the wavelength used for the calculation. The calculated δ_d and L_x values were therefore used for comparing depth-dependent trends.

Because Equations (6)–(8) are derived for a planar metal–dielectric interface, the calculated penetration and propagation lengths are interpreted here as effective comparative quantities rather than direct measurements of the complete electromagnetic field distribution in the corrugated gratings. As shown in Figure 6b,c, both parameters change only slightly in the shallow-depth regime but decrease more rapidly when the grating depth > 150 nm, consistent with the increase in n_{eff} shown in Figure 5. The decrease in penetration depth suggests that deeper gratings confine the plasmon field more strongly

near the structured Au/air interface. At shallow depths, the weakly perturbed SPR mode extends farther into the dielectric region. As the grating becomes deeper, the increased effective plasmon momentum produces a more confined evanescent field, reducing the penetration depth. Similarly, the decrease in propagation length indicates that deeper gratings increase scattering and propagation loss, causing the plasmon to decay over a shorter distance along the interface. This increased loss is consistent with the spectral broadening observed in Figure 2, where deeper gratings exhibit broader SPR peaks than the shallow 50 nm depth grating. A shorter propagation length corresponds to stronger damping of plasmons; consequently, the resonance spreads over a wider wavelength range, leading to a broader SPR peak. Therefore, increasing grating modulation depth augments near-surface plasmon confinement, as shown by the reduced penetration depth into the dielectric medium, but also shortens the propagation length along the interface. Deeper gratings can localize the plasmonic field closer to the Au/air surface, which is advantageous for detecting refractive-index changes or molecular binding near the interface. However, the reduced propagation length leads to greater damping and SPR loss. Thus, grating modulation depth provides a practical design parameter for balancing field confinement, sensing volume, and propagation loss in grating-coupled SPR structures.

4. Conclusions

In this work, we investigated the effect of the grating modulation depth on the optical response of grating-coupled SPR. By controlling the laser exposure time during the interference lithography, we fabricated azobenzene-based sinusoidal gratings with different modulation depths while maintaining the same periodicity. Shallow gratings produced only small SPR wavelength shifts and small changes in the effective refractive index at the Au/air interface, whereas deeper gratings caused stronger SPR spectral broadening, larger wavelength shifts, plasmonic bandgap-like features, and an increase in the effective refractive index at the boundary. These changes suggest that the grating modulation depth influences the plasmonic mode supported by the corrugated Au/air interface, rather than simply changing the measured optical intensity. GSolver simulations further confirmed the experimental observation that increasing grating modulation depth modifies the SPR dispersion curve and increases the effective refractive index. Quantitative agreement depended on how the grating morphology was represented in the model, indicating that grating-coupled SPR simulations are sensitive to the simulated geometrical profile of the grating. Therefore, realistic grating morphology should be included when using simulations to design grating-coupled SPR structures. Overall, these results provide a practical framework for designing grating-based SPR structures in which grating depth and profile are used to tune resonance wavelength, coupling strength, and plasmonic mode properties.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/appliedphys2030008/s1>, Figure S1: AFM morphology and line-profile comparison of representative shallow-, intermediate-, and deep-modulation gratings; Figure S2: AFM morphology and line-profile comparison of shallow-, intermediate-, and deep-modulation gratings before and after Au sputtering; Figure S3: Reflectance spectra of grating-coupled SPR of the 806 nm pitch with various grating depths; Figure S4: Effect of grating modulation depth on optical responses of grating-coupled SPR for the 705 nm pitch gratings; Figure S5: SPR dispersion curves derived from transmission spectra of the Au-coated 705 nm pitch gratings; Figure S6: Effect of the Au:air ratio in the one-layer model of GSolver simulation on the effective refractive index of grating-coupled SPR; Table S1: Modulation-depth variation measured by AFM at two locations separated by approximately 1 mm; Table S2: Individual layer heights used in the five-layer GSolver model.

Author Contributions: Conceptualization, R.G.S.; methodology, N.H.L. and R.G.S.; software, N.H.L.; validation, N.H.L.; formal analysis, N.H.L.; investigation, N.H.L.; resources, R.G.S.; data curation, N.H.L.; writing—original draft preparation, N.H.L.; writing—review and editing, R.G.S.; visualization, N.H.L.; supervision, R.G.S.; project administration, R.G.S.; funding acquisition, R.G.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by Defence Research and Development Canada, and the Natural Sciences and Engineering Research Council of Canada (RGPIN-2026-05986).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting the findings of this study, including processed spectral data and analysis files, are available from the corresponding author upon request.

Acknowledgments: The authors thank Paul Rochon for helpful discussions and technical guidance during the preparation of this manuscript.

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

Abbreviations

The following abbreviations are used in this manuscript:

Au	Gold
SPR	Surface plasmon resonance
SRGs	Surface relief gratings

References

- Godi Tchére, M.; Robert, S.; Dutems, J.; Bruhier, H.; Bayard, B.; Jourlin, Y.; Jamon, D. Characterization of a Perfect Sinusoidal Grating Profile Using an Artificial Neural Network for Plasmonic-Based Sensors. *Appl. Opt.* **2024**, *63*, 3876. [\[CrossRef\]](#) [\[PubMed\]](#)
- Homola, J. Surface Plasmon Resonance Sensors for Detection of Chemical and Biological Species. *Chem. Rev.* **2008**, *108*, 462–493. [\[CrossRef\]](#) [\[PubMed\]](#)
- Barnes, W.L.; Dereux, A.; Ebbesen, T.W. Surface Plasmon Subwavelength Optics. *Nature* **2003**, *424*, 824–830. [\[CrossRef\]](#) [\[PubMed\]](#)
- Chirco, A.; Meacci, E.; Margheri, G. A Tutorial Review on Surface Plasmon Resonance Biosensors: Applications in Biomedicine. *ACS Bio Med Chem Au* **2025**, *5*, 922–946. [\[CrossRef\]](#) [\[PubMed\]](#)
- Hashemi, Z.; Ranjbari, F.; Ranc, V.; Fathi, F. Multiplexed Biosensing: A Review of Surface Plasmon Resonance Platforms for Biomarker Analysis. *Talanta* **2026**, *304*, 129564. [\[CrossRef\]](#) [\[PubMed\]](#)
- Acharya, B.; Behera, A.; Behera, S. Optimizing Drug Discovery: Surface Plasmon Resonance Techniques and Their Multifaceted Applications. *Chem. Phys. Impact* **2024**, *8*, 100414. [\[CrossRef\]](#)
- Dostálek, J.; Homola, J. SPR Biosensors for Environmental Monitoring. In *Surface Plasmon Resonance Based Sensors*; Springer: Berlin/Heidelberg, Germany, 2006; Volume 4, pp. 191–206.
- El Biyari, N. Surface Plasmon Resonance Biosensors: Advancements, Applications, and Future Directions in Molecular Detection. *Biotechnol. Notes* **2026**, *7*, 22–43. [\[CrossRef\]](#) [\[PubMed\]](#)
- Kravets, V.G.; Kabashin, A.V.; Barnes, W.L.; Grigorenko, A.N. Plasmonic Surface Lattice Resonances: A Review of Properties and Applications. *Chem. Rev.* **2018**, *118*, 5912–5951. [\[CrossRef\]](#) [\[PubMed\]](#)
- Danilov, A.; Tselikov, G.; Wu, F.; Kravets, V.G.; Ozerov, I.; Bedu, F.; Grigorenko, A.N.; Kabashin, A.V. Ultra-Narrow Surface Lattice Resonances in Plasmonic Metamaterial Arrays for Biosensing Applications. *Biosens. Bioelectron.* **2018**, *104*, 102–112. [\[CrossRef\]](#) [\[PubMed\]](#)
- Capelli, D.; Scognamiglio, V.; Montanari, R. Surface Plasmon Resonance Technology: Recent Advances, Applications and Experimental Cases. *TrAC-Trends Anal. Chem.* **2023**, *163*, 117079. [\[CrossRef\]](#)
- Ahamed, S.; Venkatesan, K.K.; Jalaludeen, S.A. A Review on Various Surface Plasmon Resonance-Based Sensors. *Plasmonics* **2025**, *20*, 6869–6885. [\[CrossRef\]](#)
- Long, S.; Cao, J.; Geng, S.; Xu, N.; Qian, W.; Gao, S. Optimization of Plasmonic Sensors Based on Sinusoidal and Rectangular Gratings. *Opt. Commun.* **2020**, *476*, 126310. [\[CrossRef\]](#)
- Bdour, Y.; Escobedo, C.; Sabat, R.G. Wavelength-Selective Plasmonic Sensor Based on Chirped-Pitch Crossed Surface Relief Gratings. *Opt. Express* **2019**, *27*, 8429. [\[CrossRef\]](#) [\[PubMed\]](#)

15. Yeh, W.H.; Kleingartner, J.; Hillier, A.C. Wavelength Tunable Surface Plasmon Resonance-Enhanced Optical Transmission through a Chirped Diffraction Grating. *Anal. Chem.* **2010**, *82*, 4988–4993. [[CrossRef](#)] [[PubMed](#)]
16. Bianco, M.; Sonato, A.; De Girolamo, A.; Pascale, M.; Romanato, F.; Rinaldi, R.; Arima, V. An Aptamer-Based SPR-Polarization Platform for High Sensitive OTA Detection. *Sens. Actuators B Chem.* **2017**, *241*, 314–320. [[CrossRef](#)]
17. Raether, H. Surface Plasmons on Smooth Surfaces. In *Surface Plasmons on Smooth and Rough Surfaces and on Gratings*; Springer: Berlin/Heidelberg, Germany, 1988.
18. Sukhotskiy, V.; Cady, N.C.; Chou, E.; Reddy, I.V.A.K.; Furlani, E.P. Numerical Modelling of a Sinusoidal Grating-Based Surface Plasmon Coupled Emission Biosensor. In *Proceedings of the TechConnect Briefs 2018—Advanced Materials*; Laudon, M., Case, F., Romanowicz, B., Eds.; TechConnect: Austin, TX, USA, 2018; Volume 4, pp. 205–208.
19. Su, W. Design of High Performance Surface Plasmon Resonance Biosensor Using Silver-Based Sinusoidal Diffraction Grating. *Optik* **2017**, *131*, 104–109. [[CrossRef](#)]
20. Raether, H. Surface Plasmons on Gratings. In *Surface Plasmons on Smooth and Rough Surfaces and on Gratings*; Springer: Berlin/Heidelberg, Germany, 1988.
21. Bijalwan, A.; Rastogi, V. Sensitivity Enhancement of a Conventional Gold Grating Assisted Surface Plasmon Resonance Sensor by Using a Bimetallic Configuration. *Appl. Opt.* **2017**, *56*, 9606. [[CrossRef](#)] [[PubMed](#)]
22. Barnes, W.L.; Preist, T.W.; Kitson, S.C.; Cotter, N.P.K.; Nash, D.J. Photonic Gaps in the Dispersion of Surface Plasmon on Gratings. *Phys. Rev. B* **1995**, *15*, 11164. [[CrossRef](#)] [[PubMed](#)]
23. Karademir, E.; Balci, S.; Kocabas, C.; Aydinli, A. Plasmonic Band Gap Engineering of Plasmon–Exciton Coupling. *Opt. Lett.* **2014**, *39*, 5697. [[CrossRef](#)] [[PubMed](#)]
24. Bennani, O.R.; Al-Hujran, T.A.; Nunzi, J.M.; Sabat, R.G.; Lebel, O. Surface Relief Grating Growth in Thin Films of Mexylaminotriazine-Functionalized Glass-Forming Azobenzene Derivatives. *New J. Chem.* **2015**, *39*, 9162–9170. [[CrossRef](#)]
25. Natansohn, A.; Rochon, P. Photoinduced Motions in Azo-Containing Polymers. *Chem. Rev.* **2002**, *102*, 4139–4175. [[CrossRef](#)] [[PubMed](#)]
26. Maier, S.A. *Plasmonics: Fundamentals and Applications*; Springer: Berlin/Heidelberg, Germany, 2007. ISBN 9780387378251.
27. Moharam, M.G.; Gaylord, T.K. Rigorous Coupled-Wave Analysis of Planar-Grating Diffraction. *J. Opt. Soc. Am.* **1981**, *71*, 811–818. [[CrossRef](#)]
28. Bdour, Y.; Rochon, P.; Sabat, R.G. Fabrication of Surface Relief Micro-Gratings in Azobenzene Films and Their Conversion to Gold Microwires. *Micro Nano Lett.* **2026**, *21*, e70017. [[CrossRef](#)]
29. Hövel, M.; Gompf, B.; Dressel, M. Dielectric Properties of Ultrathin Metal Films around the Percolation Threshold. *Phys. Rev. B* **2010**, *81*, 035402. [[CrossRef](#)]
30. Patskovsky, S.; Kabashin, A.V.; Meunier, M.; Luong, J.H.T. Silicon-Based Surface Plasmon Resonance Sensing with Two Surface Plasmon Polariton Modes. *Appl. Opt.* **2003**, *42*, 6905–6909. [[CrossRef](#)] [[PubMed](#)]
31. Luo, S.; Yang, H.; Yang, Y.; Zhao, D.; Chen, X.; Qiu, M.; Li, Q. Controlling Wave-Vector of Propagating Surface Plasmon Polaritons on Single-Crystalline Gold Nanoplates. *Sci. Rep.* **2015**, *5*, 13424. [[CrossRef](#)] [[PubMed](#)]
32. Raether, H. Surfaces of Enhanced Roughness. In *Surface Plasmons on Smooth and Rough Surfaces and on Gratings*; Springer: Berlin/Heidelberg, Germany, 1988.
33. Barnes, W.L. Surface Plasmon-Polariton Length Scales: A Route to Sub-Wavelength Optics. *J. Opt. A Pure Appl. Opt.* **2006**, *8*, 587–593. [[CrossRef](#)]
34. Johnson, P.B.; Christy, R.W. Optical Constants of the Noble Metals. *Phys. Rev. B* **1972**, *6*, 4370–4379. [[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.