A Python-Flask Application for Modelling Surface Plasmon Resonance in Biosensors for Educational and Research use

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Abstract. We present an open-source, browser-based simulation tool for modelling Surface Plasmon Resonance (SPR) in biosensing applications, developed using Python and the Flask web framework. This application, termed the Surface Plasmon Resonance App (SPRA), enables users to visualize reflectance curves in real time, based on configurable parameters including incident wavelength, metal film thickness, and refractive indices of media such as gold, glass, plasma, and whole blood. The tool incorporates Drude-based optical models for metals and experimentally validated refractive index equations for biological materials. Designed with accessibility and scalability in mind, the SPRA is lightweight, installation-free, and suitable for low-resource settings, making it particularly valuable for undergraduate optics education, remote learning environments, and early-stage prototyping of SPR-based biosensors. Reflectance profiles can be exported for further analysis, and the app includes embedded demonstrations aligned with recent literature. By bridging theoretical modelling with an intuitive web interface, this platform addresses key barriers to SPR engagement in under-resourced contexts, while promoting a deeper conceptual understanding of plasmonic phenomena.

1 Introduction

Surface Plasmon Resonance (SPR) is a powerful optical sensing technique that enables real-time, label-free detection of molecular interactions at the nanoscale [1]. It is extensively used in pharmaceutical development, biomedical diagnostics, food safety, and environmental monitoring [2, 3, 4]. In its most common implementation, the Kretschmann configuration (Fig. 1), SPR occurs when TM-polarized light passes through a high-index prism and reflects off a thin metallic film, typically gold. At a specific incident angle, resonance between the incoming photons and surface plasmons is established, leading to a sharp dip in reflected light intensity. This resonance angle is exquisitely sensitive to changes in the refractive index of the medium adjacent to the metal surface, making SPR ideal for biosensing applications. However, despite its widespread use and scientific importance, access to SPR technology remains limited in many developing countries and educational institutions [5, 6, 7]. Commercial SPR instruments are expensive, involve complex optical alignments, and require specialized training. These barriers hinder student engagement, early-stage prototyping, and open-ended experimentation in optics and biosensor development.

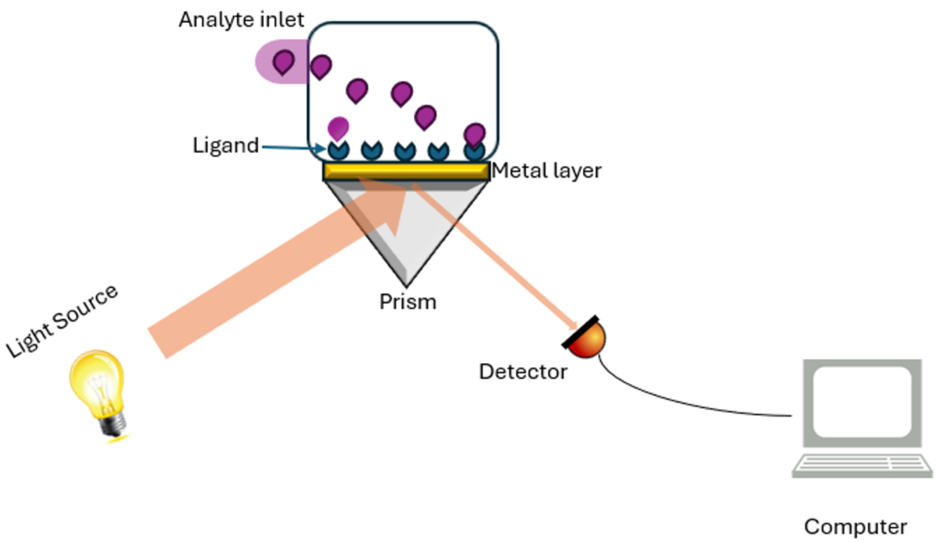

Figure 1: Schematic illustration of a SPR sensing setup in the Kretschmann configuration. TM-polarized light from a source passes through a prism and reflects off a thin metal film (typically gold), exciting surface plasmons at the metal–dielectric interface. Binding events between analytes and ligands at the sensor surface cause a refractive index change, shifting the SPR angle. The reflected light intensity is detected and processed in real time by a connected computer.

Numerous simulation tools have been developed to bridge this gap. Examples include MATLAB-based Fresnel simulators, Mathematica notebooks for multilayer stack analysis, and proprietary platforms like COMSOL Multiphysics or LabVIEW-controlled interfaces. While powerful, these tools are often encumbered by license fees, large installation footprints, or steep learning curves. This has created a noticeable gap for open, lightweight, and educational SPR modelling tools, especially in resource-constrained environments where browser-based tools are more viable than desktop applications. They tend to also be very convoluted and difficult to use.

To address this challenge, we developed a lightweight, browser-based Surface Plasmon Resonance simulator, named the Surface Plasmon Resonance App (SPRA), built using Python and Flask (Fig's. 2 and 3). The app allows users to model reflectance profiles of SPR systems in the Kretschmann configuration, with inputs for wavelength, metal layer thickness, and refractive indices of various media including BK7 glass, gold, water, and biological fluids. It computes angle-dependent reflectance using electromagnetic theory and visualizes the characteristic SPR dip interactively. Importantly, users can export simulation data for further analysis in Excel or CSV format. The SPRA is designed for accessibility: it runs on low-resource devices, requires no installation, and can be deployed on local or online servers. Its modular structure supports future upgrades including quantum light integration and multilayer stack modelling.

A live demonstration video of the SPRA is available at: hhttps://www.youtube.com/watch?v=insm7uRZ884, showcasing its interactive features and educational potential. In this paper, we detail the theoretical foundation, implementation, and utility of SPRA as a practical and pedagogical platform. To the best of our knowledge, this is the first Flask-based open-source SPR simulator tailored for biosensing education and prototyping within under-resourced contexts. By integrating fundamental SPR theory with modern web technologies, this tool bridges the gap between theoretical understanding and practical experimentation. It serves as both an educational aid and a prototyping platform for researchers, students, and engineers engaged in plasmonic sensor development. Validation was done with comparable Mathematica code.

2 Methodology

This section describes the design architecture, optical computation framework, and input parameter handling of the SPRA. The tool was engineered to balance computational precision with front-end responsiveness, ensuring

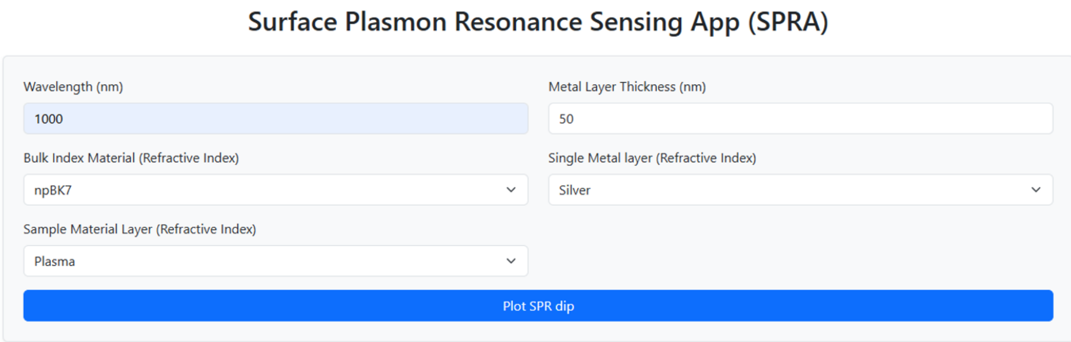

Figure 2: User interface of the Surface Plasmon Resonance Sensing App (SPRA), enabling users to simulate reflectance curves based on configurable inputs such as incident wavelength, metal layer thickness, and refractive indices of the prism, metal, and sample layers. The dropdown menus support common materials like BK7 glass and plasma, making the tool suitable for both educational use and biosensing prototyping.

real-time interactivity for educational and research users.

2.1 System Architecture

SPRA was developed using the Python Flask microframework, interfacing with front-end technologies such as HTML5 and JavaScript (Plotly.js) for dynamic user interaction. Numerical back-end calculations leverage NumPy and SciPy for matrix operations, complex refractive index calculations, and electromagnetic modelling. The application is fully browser-based and deployable on local servers or cloud platforms without installation requirements.

2.2 Optical Model and Reflectance Calculation

Reflectance $R(\theta)$ as a function of incidence angle θ is calculated using Fresnel's equations for a three-layer system (glass-metal-analyte). A discrete angular sweep (40° to 80°, 0.1° resolution) is performed to capture the characteristic SPR dip with high fidelity. The equation used is:

$$R(\theta) = \left| \frac{r_{01} + r_{12} e^{2ik_{z1}d}}{1 + r_{01} r_{12} e^{2ik_{z1}d}} \right|^2,$$

where r_{ij} are the complex Fresnel reflection coefficients, k_{z1} is the z-component of the wavevector in the metal, and d is the metal thickness.

2.3 Material Models

The optical response of gold is modelled using the Drude dispersion relation:

$$\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\gamma\omega}.$$

Refractive indices for analyte layers (e.g., water, blood, plasma) are derived either from user input or from literature-sourced empirical equations. BK7 glass and standard biological fluids are pre-loaded for convenience.

2.4 User Interface and Data Handling

The user interface allows dynamic entry of system parameters and generates interactive plots using Plotly.js. Simulated data can be exported in CSV or Excel format for further analysis or incorporation into experimental design. The modular design permits future upgrades, including quantum light modelling or multilayer stack extensions.

3 Results and Use Case

3.1 Simulated Reflectance Curve

An example simulation for a gold film on BK7 glass with blood as the analyte layer is shown in Figure 3. The sharp dip indicates the resonance angle, which shifts with refractive index changes due to binding events. In this simulation, the Surface Plasmon Resonance Sensing App (SPRA) was configured with an incident light wavelength of 1000nm, a silver metal layer of 50nm thickness, a BK7 glass prism (denoted as npBK7) as the bulk index material, and plasma as the sample analyte medium.

3.2 Educational and Research Value

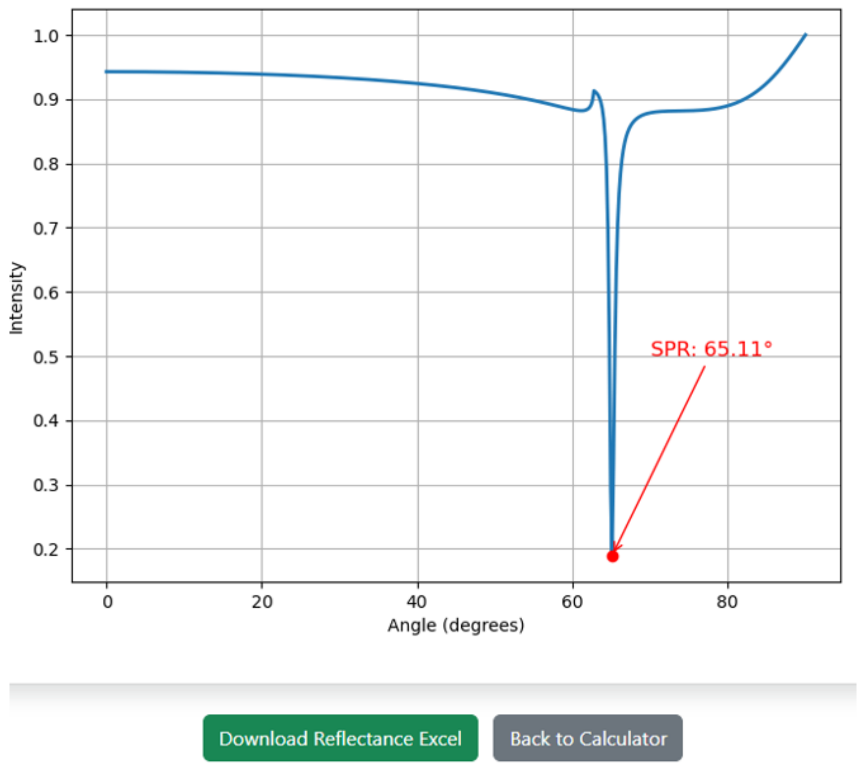

Figure 3: Simulated reflectance curve displaying the characteristic dip associated with surface plasmon resonance (SPR). This dip occurs at a specific angle of incidence where resonance conditions are met, indicating strong coupling between incident photons and surface plasmons at the metal–dielectric interface.

The SPRA application has the potential to be valuable in both educational and research contexts, particularly within undergraduate optics curricula and in the early-stage development of SPR-based biosensing systems. By simulating reflectance behavior and visualizing the angular SPR dip (Figure 3), the tool enables users to intuitively explore the impact of various system parameters, such as wavelength, metal thickness, and refractive index, on resonance behavior. Key advantages of the application include:

- **Real-time parameter adjustment:** Users receive immediate visual feedback when modifying system parameters, facilitating rapid experimentation and conceptual understanding.
- **Data export capability:** Simulated reflectance curves can be exported in a standardized format for further analysis in external software, supporting deeper investigation and integration into experimental workflows.
- **Platform independence:** As a browser-based application, it requires no local installation or specialized hardware, making it highly accessible for remote learning, classroom demonstrations, and field prototyping.

4 Conclusion

The Surface Plasmon Resonance App (SPRA) offers a powerful, accessible platform for simulating SPR-based biosensing phenomena, with direct relevance to both education and early-stage research. By integrating core optical theory with interactive visualization and a flexible Python-Flask backend, the tool allows users to explore how key system parameters, such as wavelength, film thickness, and analyte refractive index, modulate reflectance and shift the SPR angle. The application's lightweight, browser-based architecture removes traditional barriers of cost, installation, and hardware dependency, enabling broader participation in photonics and biosensing fields. Beyond simulation, its export functionality facilitates data-driven analysis and integration into broader workflows. As a next step, future iterations will incorporate multilayer stack models, support for broadband illumination and wavelength scanning, and quantum-enhanced source modelling. Taken together, the SPRA represents a significant step toward democratizing access to SPR education and prototyping tools, fostering skills development in optics, photonics, and biomedical engineering across diverse learning environments.

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