MIDDLE TENNESSEE STATE UNIVERSITY

Finite Element Simulation of Surface Plasmon Resonance

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Abstract

A surface Plasmon(SP) is an electromagnetic surface mode resulting from the collective oscillation of charge at the interface between a metal and an insulator. Surface Plasmon Resonance(SPR) can be used to detect molecular absorption on surfaces and consequently the phenomenon is of significance for technologies ranging from gene arrays, biomolecules and DNA sensing, and surface electromagnetic field enhancement. SPR sensors can be based on either attenuated total reflection(ATR) prism coupling or metallic/dielectric grating coupling. However, the prism-based systems are widely used in practice because their sensitivity is 2-3 times higher than that of the grating-based sensors. We have been conducting numerical simulations on both types of structures to achieve higher sensitivity and electromagnetic field enhancement. Moreover, specially designed multilayer structures with alternating high and low refractive index layers have been studied because they support surface electromagnetic waves similar to surface plasmons but with potentially higher sensitivity and field enhancement.

Kretschmann Configuration: Prism - Metal Film - Air

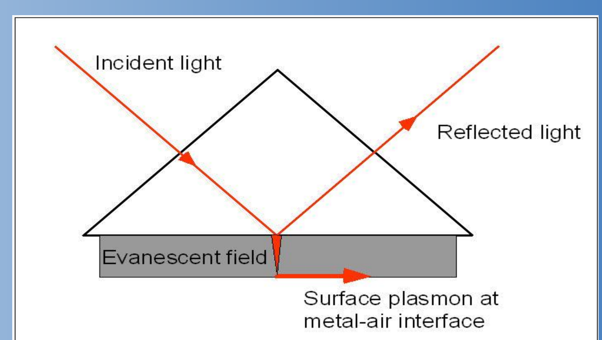

Figure 1. A schematic diagram of Kretschmann configuration for SP generation.

Surface Plasmons are non-radiative electromagnetic waves. So, they cannot be directly generated by light incident on a metal surface. This is due to the fact that although SP's exist on a metal surface with oscillation frequencies in the optical range, the SP wavelength is always smaller that that of light with the corresponding frequency. The most common way to circumvent this problem is to use a prism to couple light with SP, as shown in figure 1.

The wavelength of an incident light inside the prism is reduced by a factor of the refractive index of the prism. When the light is incident at an appropriate angle, greater than the critical angle, it creates an evanescent electromagnetic field in the vicinity of the metal-glass interface. This field, which has a wavelength equal to that of SP, couples with SP and converts the incident light into SP's. This phenomenon is known as Surface Plasmon Resonance (SPR).

When SPR occurs, the total amount of reflected light is greatly reduced which can be observed in their reflectivity curve as a function of angle of incidence of light.

Finite Element Simulation of Kretschmann Configuration

Electromagnetic wave(transverse magnetic) propagation in the kretschmann configuaration is governed by:

$$\nabla \times \left(\frac{1}{\epsilon(\boldsymbol{r})}\nabla \times \boldsymbol{H}(\boldsymbol{r})\right) = \left(\frac{\omega}{c}\right)^2 \boldsymbol{H}(\boldsymbol{r})$$

This equation was solved numerically for the 1D case with appropriate boundary condition(Floquet) and initial field(sinosoidal) in COMSOL, which uses Finite Element Method(FEM).

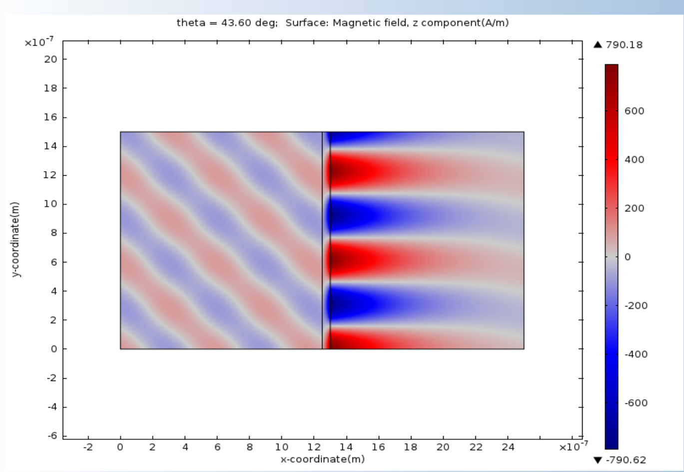

Figure 2. Top-view fo the magnetic field, z-component (A/m) distribution for the Kretschmann configuration at the resonance angle($\theta = 43.60^0$). A high intensity field is seen at the interface which decays rapidly away from the interface.

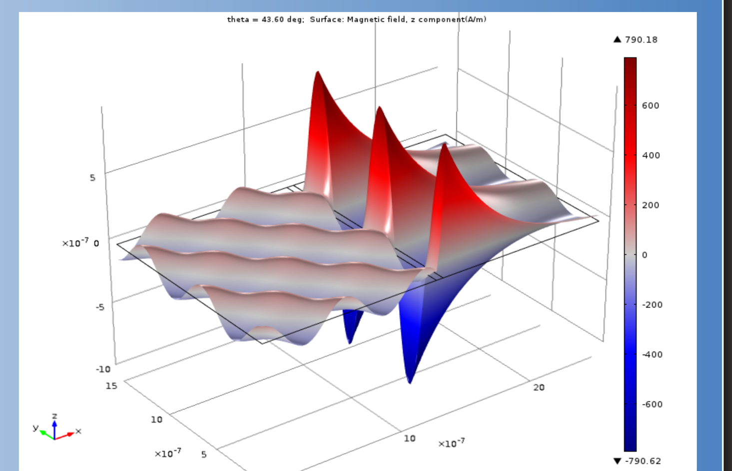

Figure 3. Magnetic field distribution for the Kretschmann configuration at the resonance angle($\theta = 43.60^0$). A sharp field enhancement at the interface between silver and air can be clearly observed, which is about 8 times greater than the input field.

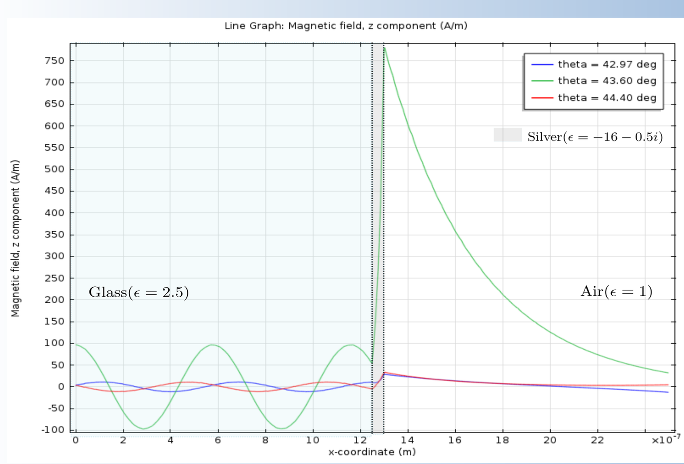

Figure 4. Magnetic field distribution across the media below($\theta = 42.97^0$), above($\theta = 44.40^0$), and at the resonance angle($\theta = 43.60^0$). Below and above the resonance angle, the SP's are not excited. The wavelength of incident light in free-space was taken to be 632nm.

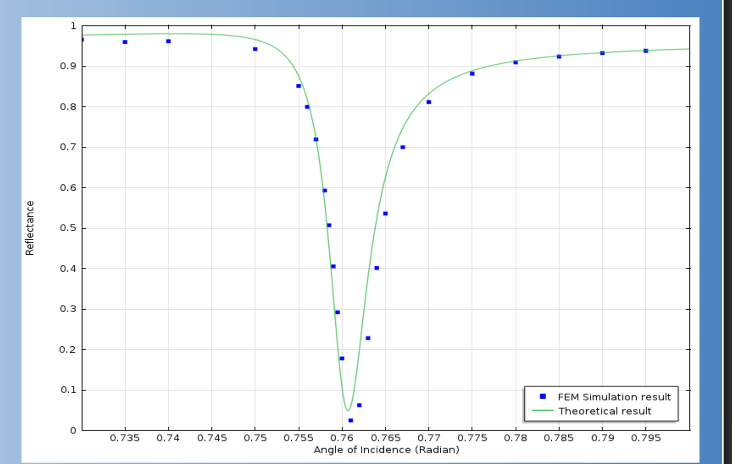

Figure 5. A sharp reduction in the reflected light is seen at the resonance angle($\theta = 43.60^0$). This acute reflectivity dip as a function of angle of incidence is the basis for the biosensors.The full width at high maximum (FWHM) is approximately 0.31^0.

SiO_2-TiO_2 Multilayer

A multilayer(1D) is a photonic crystal designed of dielectric material with alternating relative permittivity. These materials support SP-like waves, when a defect is introduced in their design. However, the sensitivity and field enhancement is much higher compared to that from the SP's in metal-air interface.

A 12-layered multilayer with alternating SiO_2 and TiO_2 was designed with a defect(in the form of extra thickness) in the topmost TiO_2 layer.

SiO_2-TiO_2 Multilayer Simulation Results

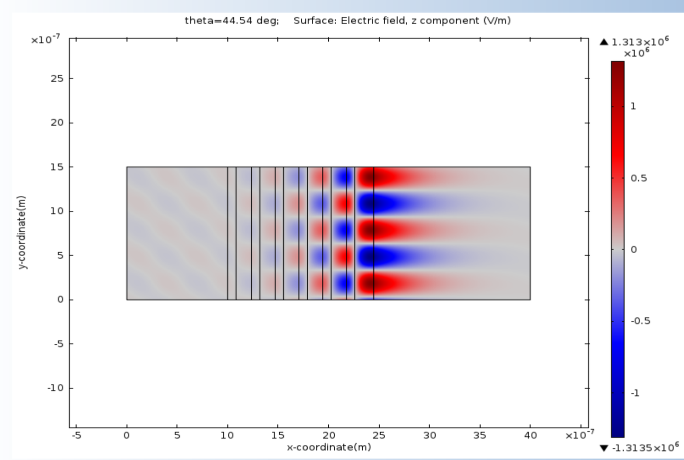

Figure 6. Top-view fo the electric field, z-component (V/m) distribution for the TiO_2-SiO_2 multilayer at the resonance angle($\theta = 44.54^0$). A high intensity field is seen in the last layer of SiO_2 which decays rapidly away from the interface.

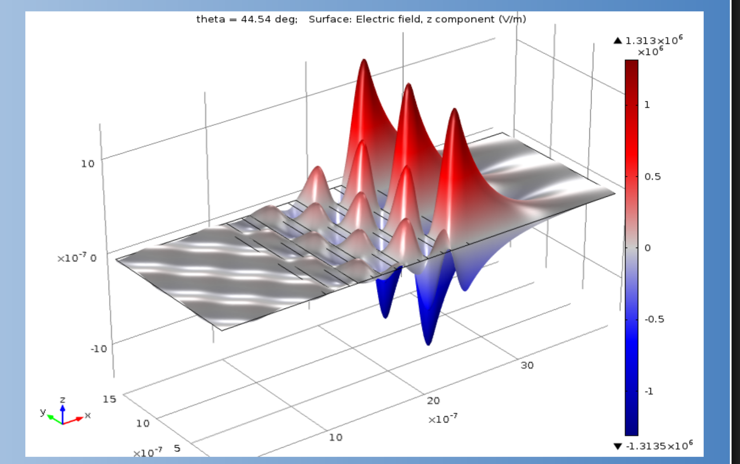

Figure 7. Electric field distribution for the TiO_2-SiO_2 multilayer at the resonance angle($\theta = 44.54^0$). A sharp field enhancement which is about 48 times greater than the input field is obtained in the last layer of the multilayer.

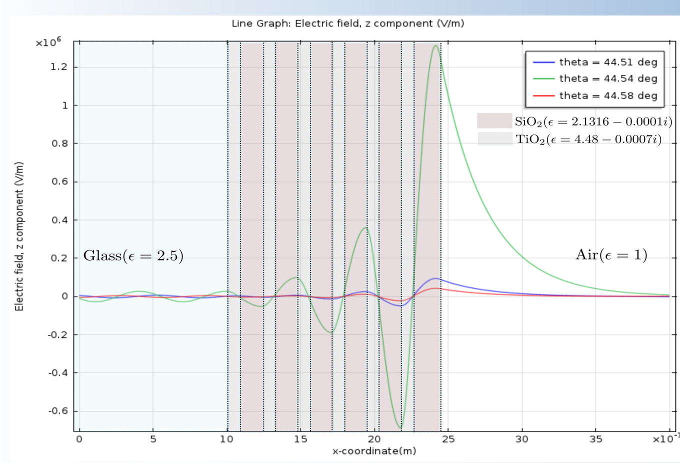

Figure 8. Electric field distribution across the media below($\theta = 44.51^0$), above($\theta = 44.58^0$), and at the resonance angle($\theta = 44.54^0$). Below and above the resonance angle, the SP-like wave are not excited. The wavelength of incident light in free-space was taken to be 632nm.

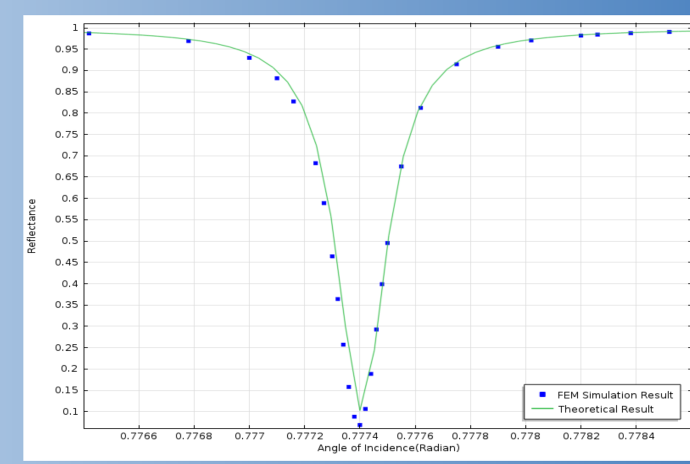

Figure 9. A sharp reduction in the reflected light is seen at the resonance angle($\theta = 44.54^0$). The FWHM is approximately 0.01^0, which is much smaller than that for the Kretschmann configuration. This property makes it a better choice for biosensors.

Future Directions

- Study of EM field enhancement in multilayer stuctures with grating surfaces.
- Design of optimized multilayer for strong localization of EM waves which will also give higher sensitivity as a biosensor.
- Finite Difference Time Domain(FDTD) simulation for EM wave propagation in these structures, which will enable us to see how they behave as time progresses.

References

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