Simulation of Surface Plasmons and Bloch Surface Waves Using COMSOL

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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. SP-like waves, known as Bloch waves, are supported in another type of materials made up of alternating high and low refractive index dieletrics. Such multilayer structures are much more sensitive than the traditional sensors based on metals. We have been conducting numerical simulations on both types of structures to achieve better sensitivity and electromagnetic field enhancement.

Another useful application of such multilayers is generation of slow light, or reducing the speed of light. Slow light can be used for applications like optical buffers, optical storage devices, enhancement of nonlinear effects in optical devices, strong matter-light interactions, etc.

Kretschmann Configuration:

Surface Plasmons are non-radiativeelectromagnetic 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 or Bloch waves, as shown in figure 1.

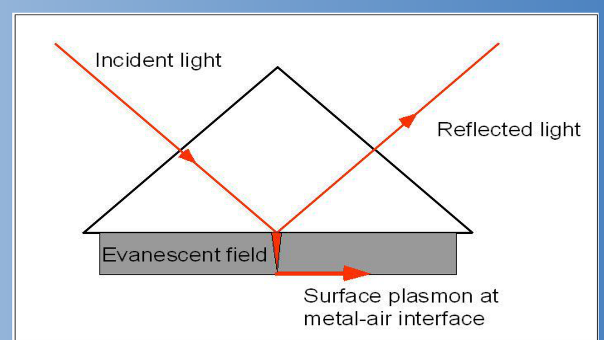

Figure 1. A schematic diagram of Kretschmann configuration for SP generation.

The dielectric multilayer, also known as band-gap structures have forbidden band gaps, where electromagnetic waves cannot propagate regardless of their wavelengths. Figure 2 illustrates such allowed (green) and forbidden (blue) bands of a typical multilayer structure. Propagating modes can be excited in the forbidden gaps by introducing some kind of defect in the structure. The green line in the forbidden gap in Figure 2 is a mode generated by a defect in the multilayer.

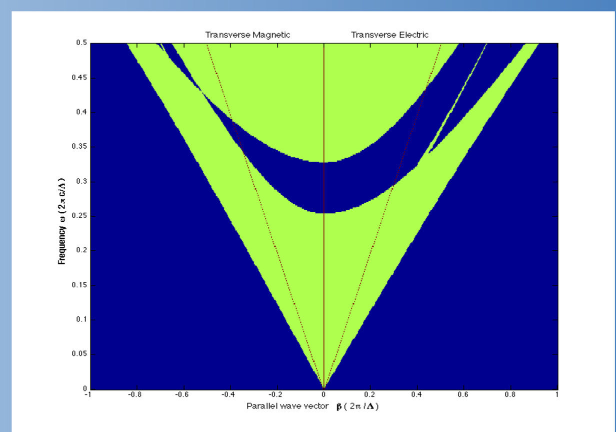

Figure 2. Allowed (gren) and forbidden (blue) regions of a multilayer such a defect layer at the top.

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 conditions and source fields in frequency domain using COMSOL, which uses Finite Element Method (FEM).

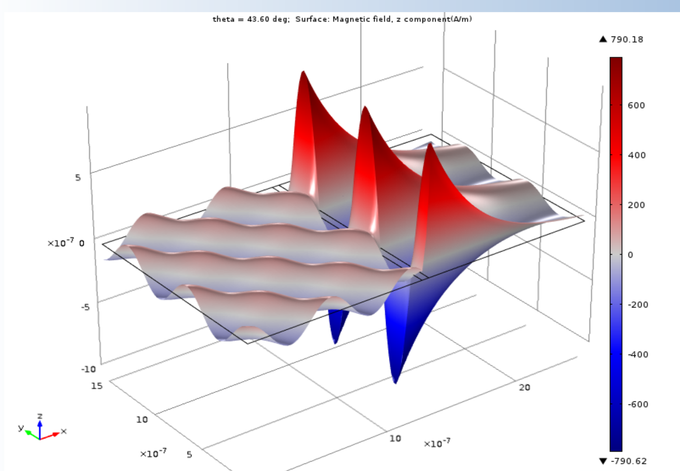

Figure 3. Magnetic field distribution for the Kretschmann configuration at the resonance angle($\theta = 43.60^0$). A sharp field enhancement at the interface between silver and air can be clearly observed, which is about 8 times greater than the input field.

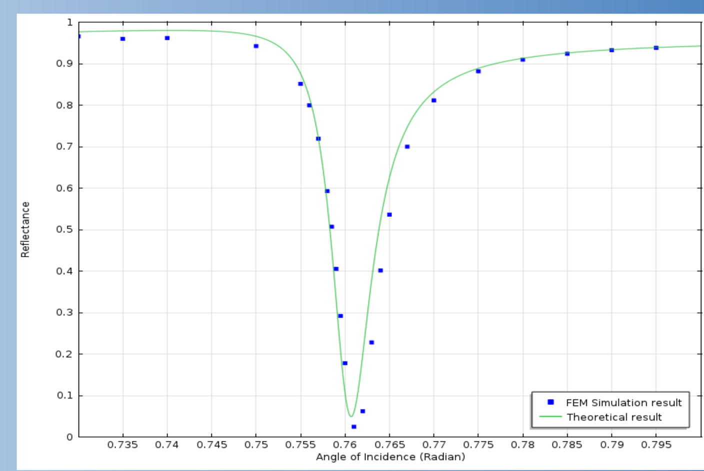

Figure 4. A sharp reduction in the reflected light is seen at the resonance angle($\theta = 43.60^0$). This acute reflectivity dip as a function of angle of incidence is the basis for the biosensors.The full width at high maximum (FWHM) is approximately 0.31^0.

SiO_2-TiO_2 Multilayer

A multilayer is a 1D-Photonic crystal designed of dielectric material with alternating relative permittivity. These materials support Bloch surface waves, similar to SPs in metal-dielectric interface, when a defect is introduced intheir design. One of the advantages of such dielectric multilayers is that 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.

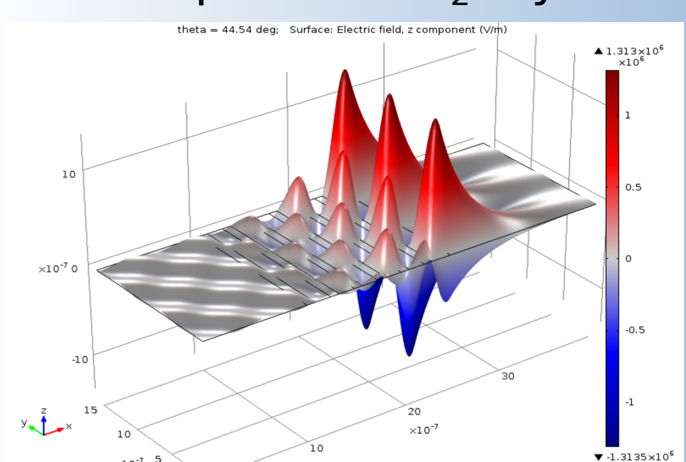

Figure 5. Electric field distribution for the TiO_2-SiO_2 multilayer at the resonance angle($\theta = 44.54^0$). A sharp field enhancement which is about 48 times greater than the input field is obtained in the last layer of the multilayer.

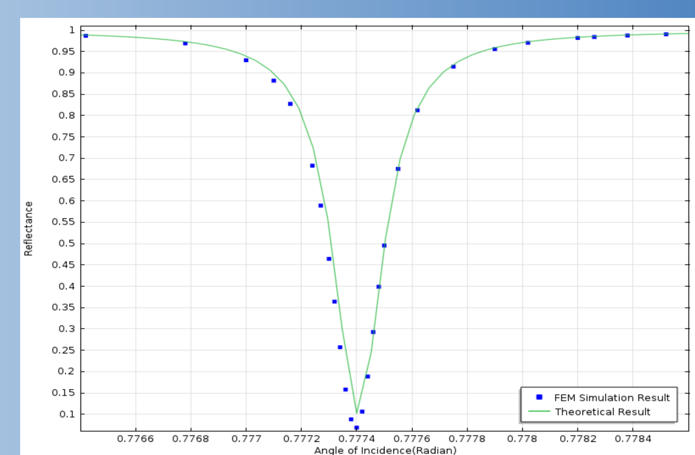

Figure 6. A sharp reduction in the reflected light is seen at the resonance angle($\theta = 44.54^0$). The FWHM is approximately 0.01^0, which is much smaller than that for the Kretschmann configuration. This property makes it a better choice for biosensors.

Slow Light Generation Using SiO_2-TiO_2 Multilayer

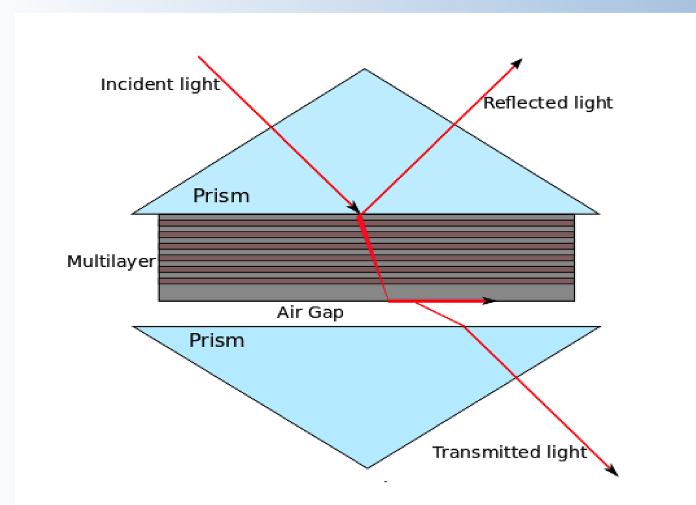

Figure 7. A Schematic diagram of a set-up for the genereation of slow light. The multilayer structure is sandwitched between two prisms with an air gap in between the multilayer and the second prism.

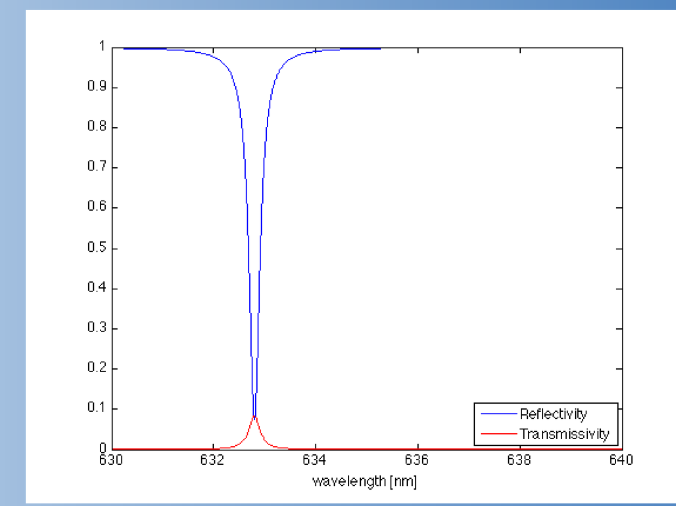

Figure 8. Reflectivity (blue) and Transmissivity (red) at the resonance agle of 43.395^0 for the slow light configuration. About 10% of the incident light (slowed down) is transmitted to the other side of the system.

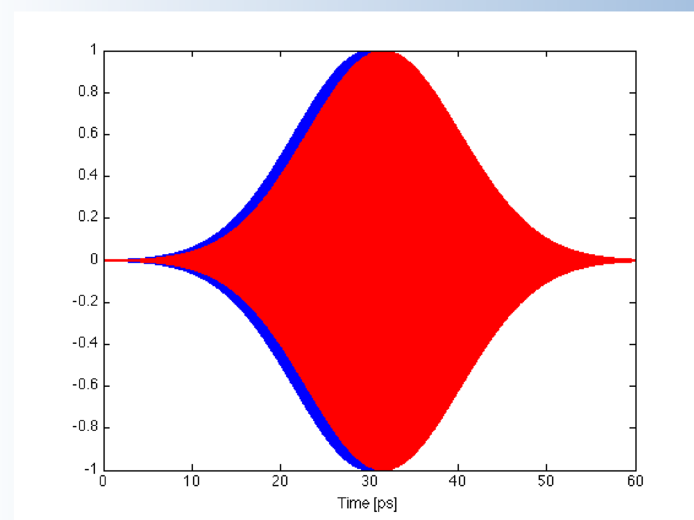

Figure 9. Slow Pulse (red) with delay time of about 1.65 pico-seconds. This delay time corresponds to reducing the speed of light by a factor of about 165 compared to the speed of light in vacuum.

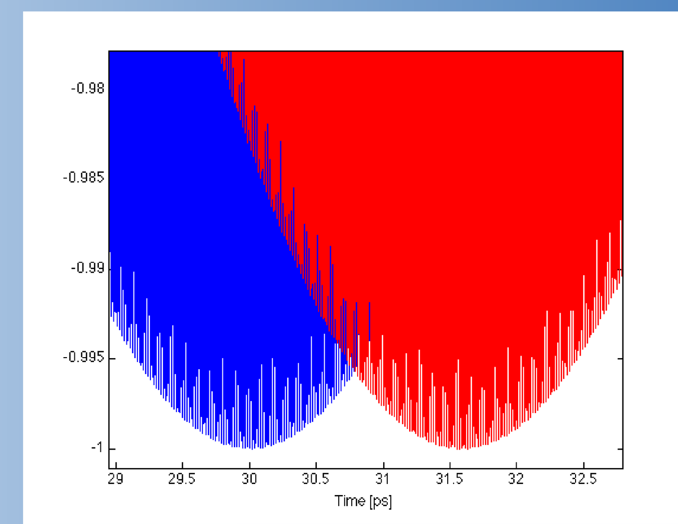

Figure 10. Zommed in version of the peaks of the normal (blue) and slowed (red) pulses. A delay time of about 1.65 ps obtained with an air gap of 1500nm. The delay time changes as a function of the width of the air gap.

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 and improved slow down factor.
- 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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