Strong Field Effects on SPP Propagation in Nanostructures

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Abstract- It is shown that nonlocal effects of strong external electric field applied in the path of a propagating SPP can be used to enhance and manipulate its propagation. A finite-difference time-domain numerical simulation based on the Debye model is used. Interesting observations are reported including the change in plasmon frequency spectrum and a decrease in power loss.

1. INTRODUCTION

There is currently a great interest in the propagation of Surface Plasmon Polaritons (SPPs) in nano-sized optical waveguides that overcome the natural diffraction of light. Nano-metallic structures have been used to excite SPPs by visible light. Theoretical and experimental studies are available in literature [1]-[3]. In general, the propagation length of SPPs is limited to a few hundreds of nanometers due to ohmic and dispersion losses in the metallic structures. It is of a great advantage to study methods and possibilities to enhance this propagation length. One such possibility is the application of strong static electric fields in the path of a propagating SPP. It has been shown that such fields have pronounced effects on the optical-response properties of metallic surfaces [4]. In particular, these induced nonlocal effects lead to a significant shift in the SPP propagation owing to the change in the electronic concentration and the related change in the dielectric properties of the metal [5]-[6].

In this paper, we investigate the effects of strong static electric fields on the propagation properties of SPPs in a simple Au-based waveguide. The dispersion relation of metals can be approximated by the Debye model and is generally given by

$$\varepsilon(\omega) = \varepsilon_\infty \varepsilon_\circ + \frac{\varepsilon_s \varepsilon_\circ - \varepsilon_\infty \varepsilon_\circ}{1 + j\omega\tau} - j\frac{\sigma}{\omega} \qquad (1)$$

where ε_∞ is optical permittivity, ε_s is the static permittivity, σ is conductivity and τ is the damping coefficient. The investigation links the changes in electronic distribution inside the metal, and hence in both conductivity and relaxation time, to changes in the material dispersion relation.

2. PROPAGATION MODEL AND FDTD SOLUTION

To incorporate the frequency dependent dispersion relation in the time-domain field equations, we write the electric flux density, D, as

$$D(\omega) = \varepsilon_0 \varepsilon_r(\omega) E(\omega) \qquad (2)$$

Substituting the dispersion relation, we get

$$D(\omega) = \varepsilon_0 \varepsilon_\infty E(\omega) + \frac{\varepsilon_0(\varepsilon_s - \varepsilon_\infty)}{1 + j\omega\tau} E(\omega) + \frac{\sigma}{j\omega} E(\omega) \tag{3}$$

which can be written as,

$$D(\omega) = \varepsilon_0 \varepsilon_\infty E(\omega) + P_1(\omega) + P_2(\omega) \tag{4}$$

where

$$P_1(\omega) = \frac{\varepsilon_0(\varepsilon_s - \varepsilon_\infty)}{1 + j\omega\tau} E(\omega) \tag{5}$$

and

$$P_2(\omega) = \frac{\sigma}{j\omega} E(\omega) \tag{6}$$

P_1 and P_2 can be transformed to the time domain as follows. Re-writing equation 5 as

$$P_1(\omega) + j\omega\tau P_1(\omega) = \varepsilon_0(\varepsilon_s - \varepsilon_\infty) E(\omega) \tag{7}$$

and taking the Fourier Transform, we get

$$P_1(t) + \tau \frac{d}{dt} P_1(t) = \varepsilon_0(\varepsilon_s - \varepsilon_\infty) E(t) \tag{8}$$

The FDTD approximation to equation 8 is given by

$$P_1^n = -\frac{2\Delta t}{\tau} P^{n-1} + P_1^{n-2} + \frac{2\Delta t \varepsilon_0(\varepsilon_s - \varepsilon_\infty)}{\tau} E^{n-1} \tag{9}$$

Following the same procedure, the second pole is given by

$$P_2^n = P_2^{n-2} + 2\Delta t \sigma E^{n-1} \tag{10}$$

Now, the FDTD update algorithm becomes

$$E^n = (D^n - P_1^n - P_2^n) / \varepsilon_0 \varepsilon_\infty \tag{11}$$

$$P_1^n = C_{11} P^{n-1} + C_{12} P_1^{n-2} + C_{13} E^{n-1} \tag{12}$$

$$P_2^n = C_{21} P_2^{n-1} + C_{22} P_2^{n-2} + C_{23} E^{n-1} \tag{13}$$

where the C coefficients are obtained from the model parameters.

3. NUMERICAL RESULTS

Before studying the effect of applied static field, the SPP propagation in an Au nanowire of width 40 nm is illustrated. The optical pulse excitation with central wavelength of 600 nm is introduced at one end of the wire. Figures 1 and 2 show a snapshot of the propagating SPP mode and its spatial profile.

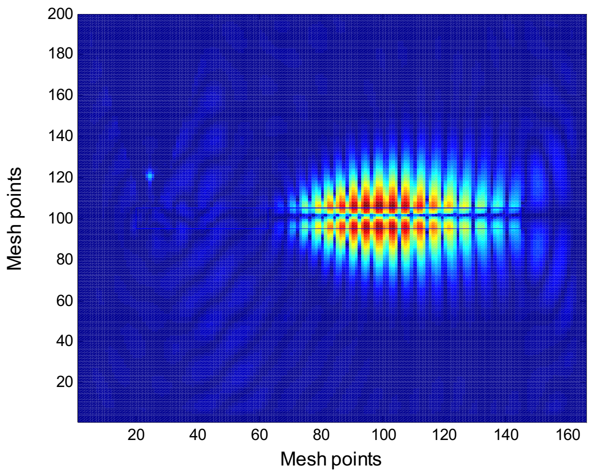

Figure 1. A snapshot of the propagating SPP along the nanowire.

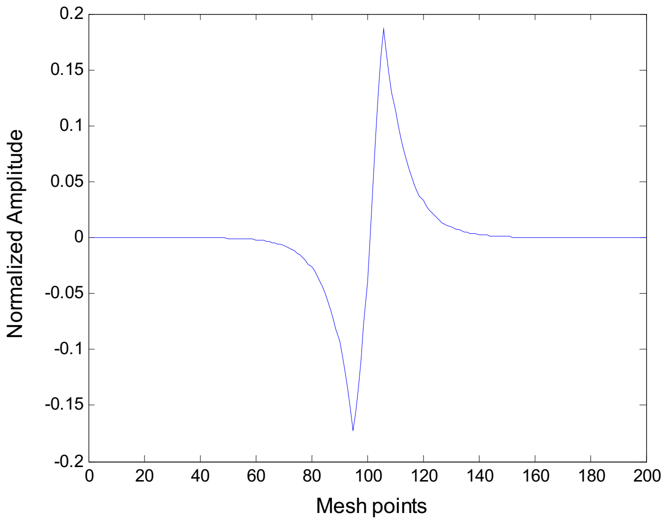

Figure 2. The spatial profile of the propagating SPP mode.

Next, a portion of the nanowire is subjected to a strong static electric field. Figure 3 shows the time and frequency profiles at three observation points along the direction of propagation. The observation points are taken just before, in the middle and outside the strong field region. The results for the opposite field polarity is shown in figure 4. It is interesting to observe the resultant blue shift with positive applied field and red shift with negative applied field, which agree with the findings in [6].

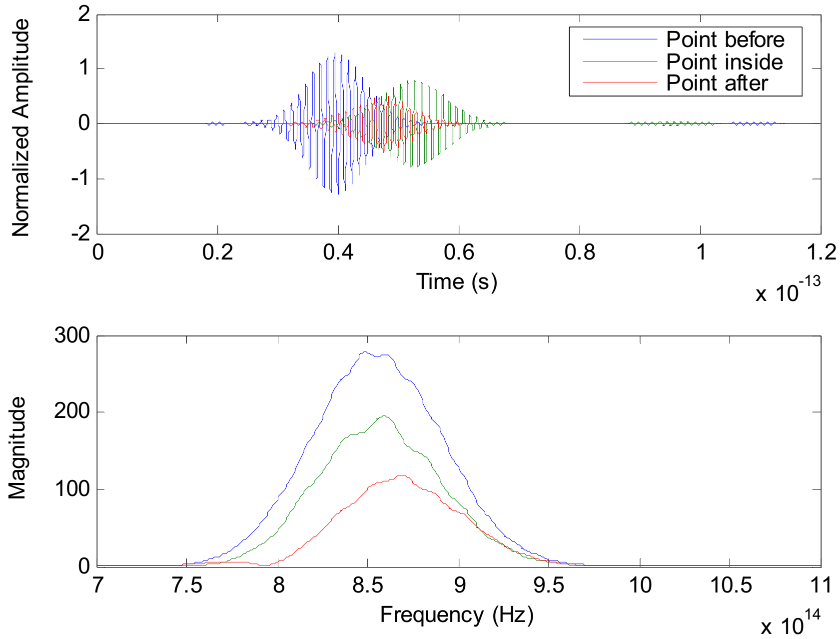

Figure 3. Time and frequency profiles of SPP at three observation points with applied positive field.

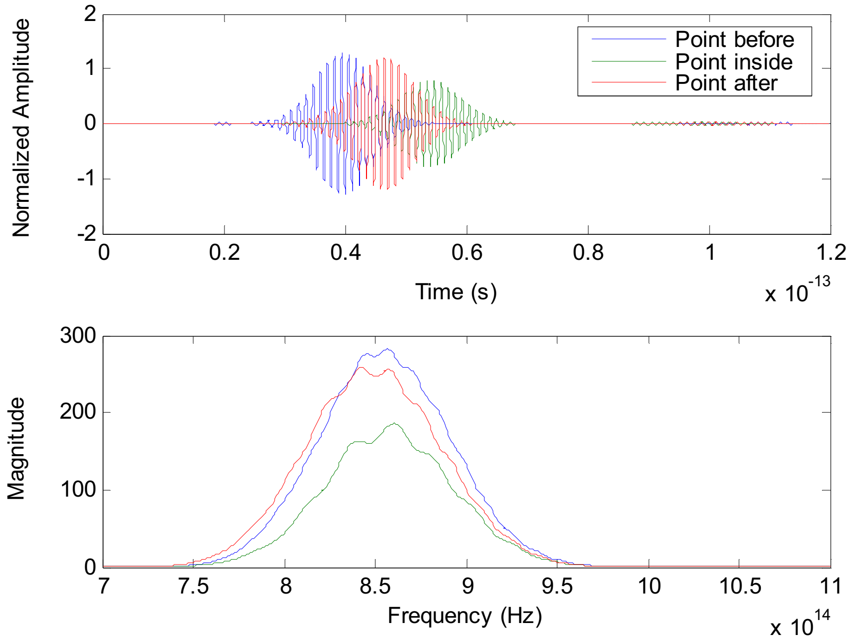

Figure 4. Time and frequency profiles of SPP at three observation points with negative applied field.

Finally, the region of applied field is extended to cover a larger portion of the nanowire. In this case the SPP power loss is calculated along the nanowire. We have assumed a simple step change in electron density and relaxation time such that both τ and σ are oppositely varied by an increasing percentage. Figure 5 shows the SPP power curves for different field strengths. It is interesting to notice that nearly zero power loss is achieved with a field strength that produces a 4% change in τ and σ.

5. CONCLUSIONS

A time-domain model for the analysis of nonlocal effects of strong external electric field applied in the path of a propagating SPP is presented. A FDTD numerical simulation based on the Debye model is used. The field effects were modeled as changes in both conductivity and relaxation time of the metallic structure. Numerical simulations confirm previous analytical findings concerning the change in plasmon frequency spectrum. They also show that lower SPP power loss can be achieved with specific values of applied field strength.

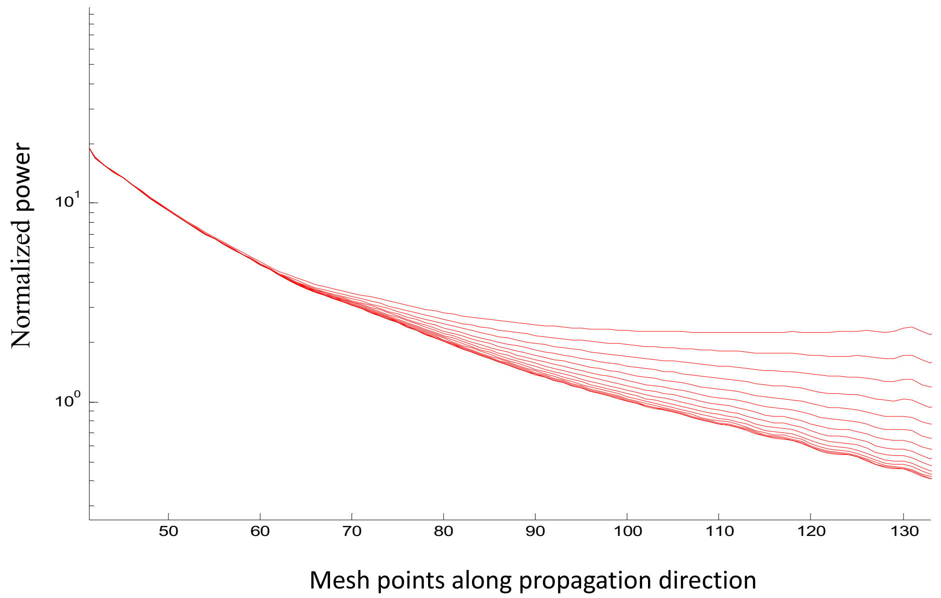

Figure 5. SPP power loss along the nanowire for different strengths of static field.

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