Localized surface plasmon waveguide integrated on dielectric waveguide

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Abstract—**We first study theoretically the behavior of metallic nanoparticles chains in vacuum excited by a plane wave, with a coupled-dipole approximation method and with a 3D FDTD software. Then we consider the integration of nanoparticule chains on a dielectric waveguide, and their excitation by evanescent coupling, in the telecom range.**

Keywords- guided optics; plasmons; nanoparticule; simulation

I. INTRODUCTION

Scale reduction of optical components can be realized by manipulating light at the subwavelength scale. Especially metallic nanoparticle (MNP) chains supporting localized surface plasmons (LSP) can propagate light at the subwavelength scale [1] and realize specific function like very compact coupler [2]. However insertion of such waveguide in integrated circuit or devices requires optical coupling optimisation between dielectric waveguide and plasmonic waveguide. This paper is organized as follows. In the section II we theoretically study the behaviour of a finite MNP chain in vacuum excited with a plane wave, and the influence of NP spacing. Simulations are performed with a coupled-dipole approximation (CDA) analytical method and with a commercial FDTD 3D method (Finite Difference Time Domain Lumerical Solutions). Then the section III is dedicated to the evaluation of transmission in these MNP chains excited by evanescent coupling from a dielectric waveguide. Integration of such LSP waveguide on dielectric waveguide is discussed.

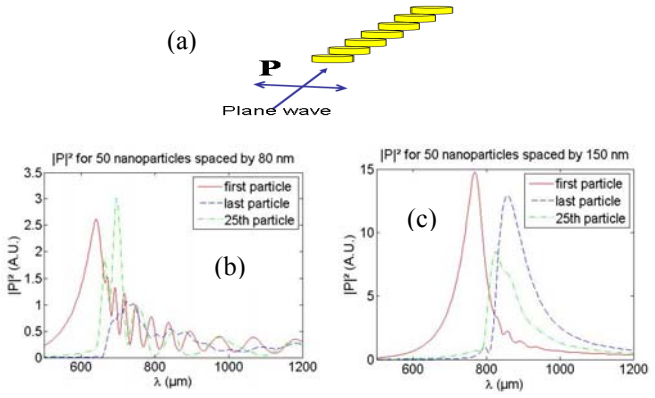

Figure 1. (a) Excitation by a plane wave along the NP chain for 50 gold nanorods spaced by a distance center to center d. The ohmic dissipated power is plotted for the first (solid red curve), the 25th (green dashed point) and the last (bleu dashed) rod as a function of the wavelength. The rods are spaced by 80 nm (b) or 150 nm (c).

II. MNP WAVEGUIDE IN VACUUM

The coupled-dipole approximation method considers each nanoparticle (NP) as a point. The response of this point to an external electric field is dipolar. In this approximation a single dipole has a polarization $\mathbf{p}e^{-i\omega t}$ oscillating with frequency ω which results from the multiplication of the local electric field by the NP polarisability. For a finite linear chain of N point dipoles the induced dipole moment on the nth NP results from the external applied field $\mathbf{E}^{(ext)}e^{-i\omega t}$ and the electric fields generated by each NP:

$$\mathbf{p}_n = \alpha(\omega)\left\{\mathbf{E}_n^{(ext)} + \frac{1}{4\pi\varepsilon_0}\sum_{m\neq n}^{N}\left[\left(1-\frac{i\omega|n-m|d}{c}\right)\frac{3(\hat{\mathbf{r}}\cdot\mathbf{p}_m)-\mathbf{p}_m}{|n-m|^3 d^3} + \frac{\omega^2}{c^2}\frac{\mathbf{p}_m-(\hat{\mathbf{r}}\cdot\mathbf{p}_m)}{|n-m|d^3}e^{i\omega|n-m|d/c}\right]\right\}, \quad (1)$$

with $\alpha(\omega)$ is the polarisability and $\hat{\mathbf{r}}$ is the unit vector pointing from the dipole to the field point. The electric field and the polarisability fully take into account retardation effects [3, 4, 5]. The NP chain supports a transverse mode of propagation (**P** perpendicular to the chain) and a longitudinal mode (**P** parallel to the chain). Our structure is composed by 50 gold nanorods spaced by a distance d (center to center distance Fig. 1(a)). Dimensions of the rods are 240 nm × 60 nm × 25 nm, and they are positioned parallel to their longer dimension. We consider only a transverse excitation (the electric field is parallel to the longer rods dimension). We use the "Drude" model for the dielectric function of gold where the plasma frequency is $\omega_p = 1.29\cdot10^{16}$ rad/s and the electron scattering rate is $\gamma = 1.14\cdot10^{14}$ s^{-1} [6].

Considering a continuous transverse excitation by a plane wave at an extremity of the chain (defined as the "first" NP), we plot the ohmic dissipated powers spectra in the range 500-1200 nm for different value of d and for different positions in the chain (the first, the 25th and the last NP) (Fig. 1). The dissipated power is proportional to $|\mathbf{P}_n|^2$. It is concentrated differently on the first, the 25th and the last particle depending on the wavelength. Its repartition is also strongly dependent on the spacing d.

The same structures are simulated with FDTD 3D commercial software (Fig. 2). Chain resonance 150 nm shift is attributed to different refractive index models used in both

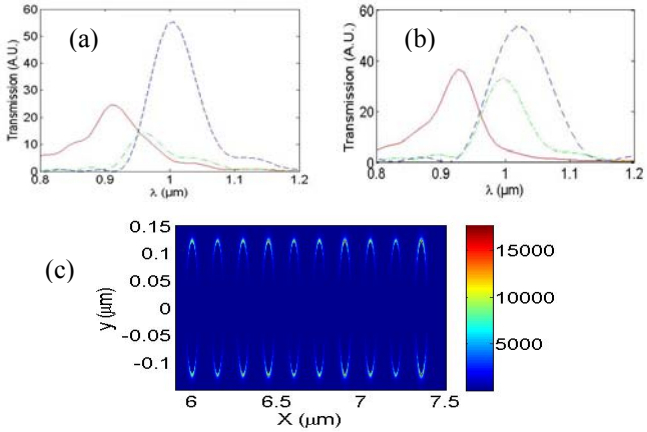

Figure 2. Excitation by a plane wave along the NP chain for 50 gold nanorods the Transmission power is plotted for the first (solid red curve), the 25th (green dashed point) and the last (bleu dashed) rod in function of the wavelength. (a) The rods are spaced by 80 nm (a) or 150 nm (b). (c) Intensity mapping for the last ten nanorods with a150 nm spacing at λ=1.04μm.

softwares, respectively "Palik" model in FDTD [6] and "Drude" model in CDA. Fig. 2(c) shows the intensity mapping along the 150 nm spacing chain. The nanorod LSP response to the excitation appears as a dipole that validates the approximation in CAD. But for a spacing of 80 nm (Figs. 1(b) and 2(a)) the results for both models are different. One hypothesis is that the point dipole approximation is no more valid: taking into account of the nanorod shape through only the polarisability is no more sufficient. More generally, the comparison between the models shows that the CDA is a good approximation for a chain with nanorods spacing higher than 120 nm. In the case of a 150 nm spacing (Figs. 1(c) and 2(b)) both models give the same global behavior, despite a higher difference between the power of the first and the last NP with FDTD.

In the figs. 2(a) and 2(b) the first and the last NP are preferentially excited by respectively short and long wavelength waves. This phenomenon is explained by the phase of the excitation plane wave respect to the LSP response of each particle, the phase matching being function of wavelength and propagation distance. We can see for intermediate wavelengths about 950 nm that all the NP of the chain are excited.

III. COUPLING OF LSP AND DIELECTRIC WAVEGUIDES

Such LSP waveguides could be integrated in photonic circuits in order to generate specific functions. Integration of LSP waveguide requires optical coupling with circuits waveguides. Taking into account the geometry of such structure, we use 3D FDTD for simulation of nanorods chain deposited on a monomode Si_3N_4 waveguide (Figs. 3). Nanoparticles are the same as in the section II. Due to the interaction with the dielectric medium, the resonance of LSP shifts up to λ = 1410 nm. We inject a 1410 nm transverse electric (TE) guided mode at the entrance of the Si_3N_4 waveguide, and we calculate the evolution of the light

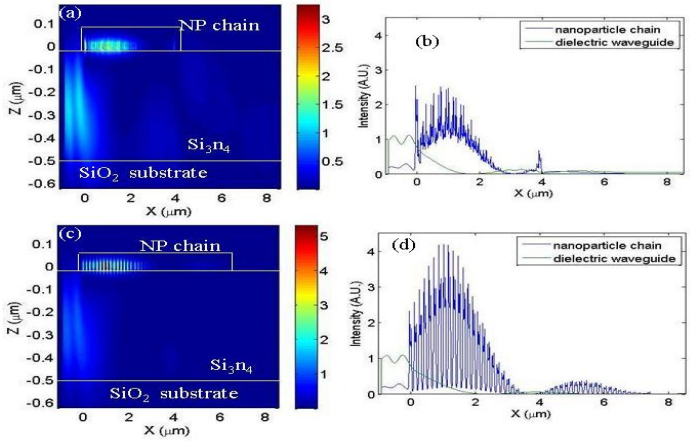

Figure 3. Intensity mapping of a coupling of a LSP waveguide a dielectric waveguide for λ = 1410 nm and for 80 nm (a) and 150 nm (c) NP spacing. Intensity as a function of the propagation direction, inside the dielectric waveguide (green curve) and the nanoparticles chain (blue curve) for 80 nm (b) and 150 nm (d)spacing at λ = 1410 nm.

along the structure. At this wavelength, the 150 nm spacing chain seems more uniformly excited than the 80 nm spacing one (Fig.3). Moreover the injected power is almost totally transferred in the NP chain before to re-couple in the dielectric waveguide. Decrease of the power in the NP chains after 1 μm propagation is attributed to both the ohmic losses in the metal and the re-coupling in the dielectric waveguide. Interestingly, the two waveguides (dielectric and LSP) behave as almost balanced coupled waveguides with a characteristic distance of around 3μm similar for the two considered NP spacing. Such behavior could be used to define a complex effective index for the LSP waveguide, thanks the coupled mode theory.

In this paper, we compare the CDA and FDTD methods to study metallic nanoparticle periodic chains in vacuum. We also show by FDTD the possibility to excite LSP waveguide by evanescent coupling from a dielectric waveguide in the telecom range.

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