Integrated Localized Surface Plasmon Waveguides

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Abstract

Compact plasmonic structures made of gold nanoparticles chains are inserted on silicon optical waveguides. We show that silicon-on-insulator waveguide TE mode energy can be almost totally transferred in a 5 gold nanoparticles plasmonic chain and that this short chain can also behave as a waveguide.

Introduction

The excitation of plasmons in guided configuration remains a crucial step towards a true implementation of plasmonic functions in photonic circuitry. While silicon waveguides allow strong confinement of light and almost transparent propagation, lossy surface plasmon waveguides can exhibit small dimensions at the nanometer scale [1]. Within plasmonics world, localized surface plasmons (LSP) present a decisive advantage for energy concentration in specific spatial region. Electromagnetic wave can indeed be excited and hugely concentrated at the extremities of a non-spherical nanoparticle, or possibly inside a 3D nanogap between two metallic nanoparticle (MNP) [2]. Moreover, localized surface plasmons potentially offer a wide variety of configurations since metallic nanoparticles can be arranged on demand on a waveguide [3, 4].

Several applications could profit from MNP plasmonic waveguides integrated on photonic circuits. The use of long dielectric waveguides would allow positioning optical sources and detectors far from the plasmonic section, thus providing an independent access to this section for optical sensing and biodetection. In addition, the waveguide configuration allows using the entire optical energy available at the waveguide input for launching the plasmon in the coupled MNP chain. In all cases, short MNP chains should be used to avoid excess losses.

Recently we have theoretically and experimentally demonstrated that the transverse plasmonic mode of a 20 gold MNP chain can be efficiently excited by evanescent coupling [5] from a SOI waveguide TE mode, within telecoms wavelength range. Strong coupling between both waveguides occurs as soon as respective propagative mode k-vectors are matched. Coupling strength expresses itself in the very short coupling length, as low as ~560nm on a wide wavelength range. This is attributed both to the high optical confinement in SOI and to the plasmonic resonance.

In this work, we compare the impact of different chain lengths from 5 to 50 MNPs. Especially, we demonstrate that the optical energy carried by the TE silicon-on-insulator (SOI) waveguide mode can be efficiently transferred into the transverse plasmon mode of a coupled metal nanoparticle chain including the case of a very short chain, even if periodic coupling cannot be established.

Sample description and principle

LSP excitation is achieved by interaction between evanescent field of the TE Si waveguide mode and the gold nanoparticles deposited on top (Fig.1). Ellipsoidal shape, size and spacing of MNPs are accurately determined by using finite-difference time-domain (FDTD) simulations so that the transverse plasmonic T1 [6] chain mode can be excited in the transmission range of the SOI waveguide (λ>1.1 µm). Center-to-center distance between particles is equal to 150 nm for optimum dipolar coupling. Silicon ridge waveguides have a 500×220 nm^2 cross section. Gold MNP chains were fabricated using electron-beam lithography followed by a lift-off process. They are made of 1 nm thick titanium adhesion layer and 30 nm gold layer deposited by electron-beam evaporation. The as-cleaved Si waveguide supporting MNPs was 4 mm long and was ended by coupling tapers for an easy characterization.

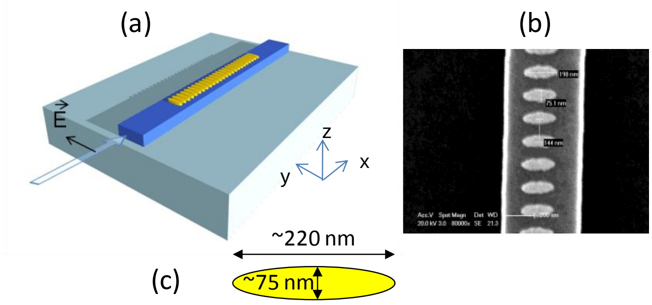

Figure 1: Sample: (a) schematic view of a gold nanoparticle chain on top of a SOI waveguide; (b) scanning electron micrograph of 7 gold nanorods of a 20-nanoparticles chain; (c) typical size of the ellipsoids.

Such structures were fabricated with chains of 5, 20 and 50 MNPs, with ellipsoids typical dimensions of respectively, $200 \times 80 \times 30$ nm^3, $220 \times 80 \times 30$ nm^{3}and $220 \times 75 \times 30$ nm^3.

Experiment

Samples were characterized by optical transmission through the structure. The waveguide transmission spectra were measured with the experimental setup shown in Fig. 2. The output beam of a tunable laser emitting in the wavelength range from 1260 to 1630 nm was injected into the sample using a lensed polarization maintaining fiber (PMF). The PMF was positioned in such a way that the polarization of the light injected into the waveguide was mainly TE. The light at the sample output was collected by an objective with x20 magnification and 0.35 numerical aperture, and was focused onto a power meter. A second polarizer was used to eliminate parasitic TM polarized light.
In each case, a reference waveguide without MNP was used on the same chip for transmission normalization.

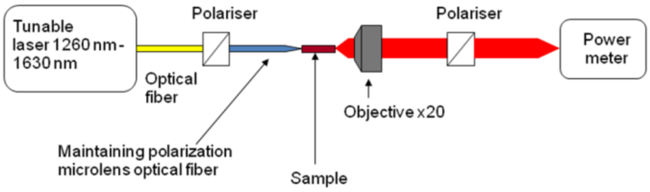

Figure 2: Schematic view of the transmission measurement setup.

Simulation

Numerical simulations were performed using a FDTD model incorporating measured parameters of the fabricated structures. Accurate dispersion data were introduced for home deposited gold after fitting a Drude model to ellipsometric measurements. The presence of a thin layer of native oxide between Si and Ti was also accounted for in FDTD calculations. The layer thickness was measured to be 3nm by scanning electron microscopy for our technological process.

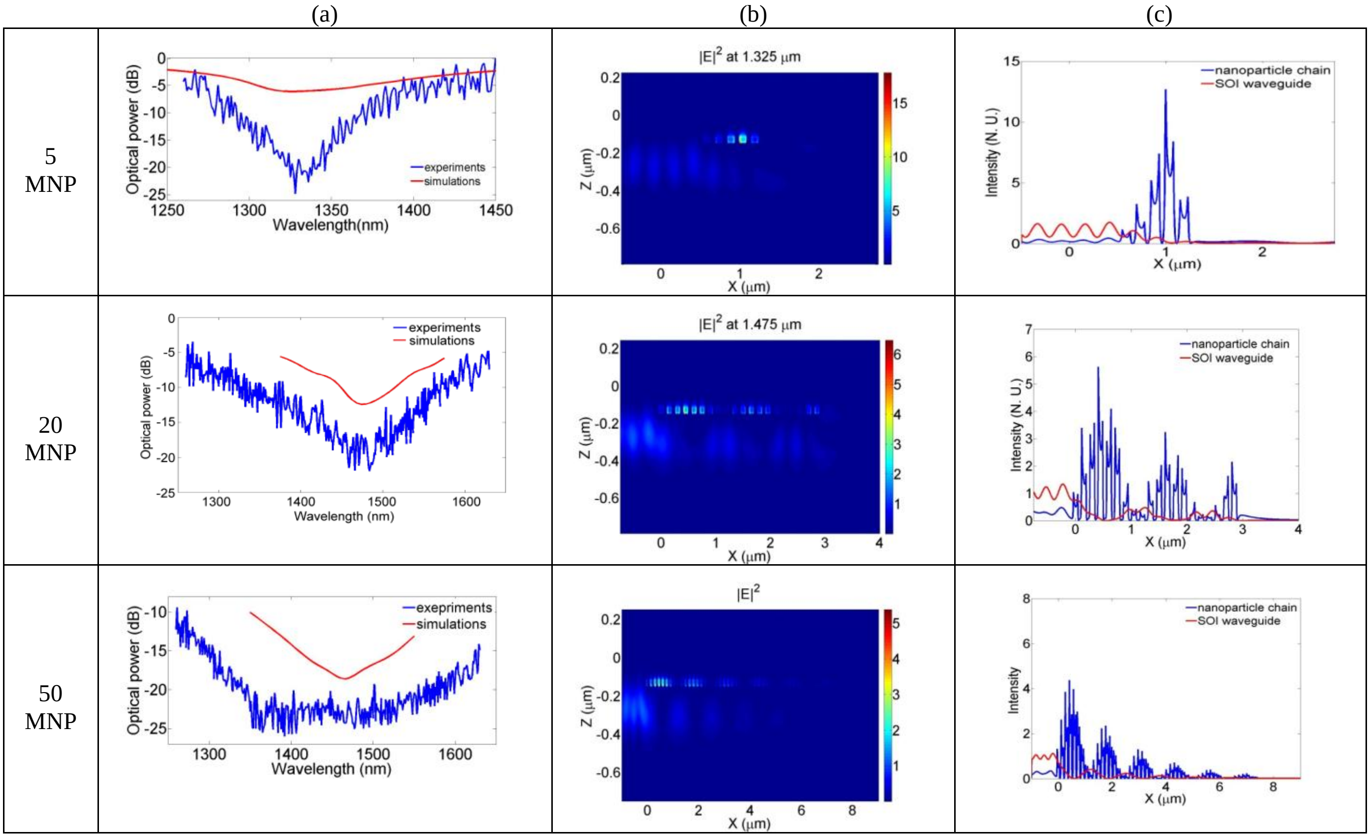

Figure 3: Excitation of LSP for 5 to 50 MNP chains integrated on SOI waveguide: (a) fiber-to-fiber transmission spectra (red: simulation, blue: experiment); electric field intensity evolution along propagation axis x at transmission minimum wavelength: (b) 2D cartographies at the middle of the structure and at minimum transmission wavelength, (c) intensity in the center of SOI waveguide and MNP chain.

The calculated transmission spectrum of Fig. 3(a) was obtained using these input data and 3D mesh with dimensions smaller than 3nm in the MNP region. As seen, there is an excellent agreement between calculations and measurements. The slightly broader resonance found in measurements is readily explained by the size distribution of MNPs.

Results and discussion

The interaction of the SOI and the LSP modes is studied from experimental and theoretical data for three different chain lengths. In Figure 3 are represented, for 5, 20 and 50 MNP chain lengths, respectively (a) the fiber-to-fiber transmission spectrum of the samples, (b) the calculated longitudinal side view of the middle cut structure field intensity cartography at the minimum transmission wavelength, and (c) the corresponding evolution along propagation direction of the intensity in the middle of the MNP chain (blue curves) and of the SOI waveguide (red curves).

LSP waveguide behavior within MNP chain is obtained thanks to energy transfer via dipolar interactions between closely spaced metal nanoparticles [3,6]. However this behavior occurs only if collective (or long distance) oscillation of the dipoles is realized, i.e. if a mode specific to the chain exists. LSP mode excitation is then obtained if the wave vectors of the SOI mode and the LSP mode are similar.

In the longer structures (20 and 50 MNPs), optical intensity oscillates between SOI waveguide and plasmonic chain: the full structures behave like coupled waveguides. We can deduce that MNP chains behave themselves like a waveguide at the considered wavelength.

We have shown previously that this behavior is obtained only in a restricted wavelength range [5]. Indeed, below the light line MNP chain dispersion curve has a maximum (as shown in [7]) near the individual MNP resonance frequency. For this reason, there is no solution for dispersion curve at higher frequency (or shorter wavelength) than this resonant frequency, and then the chain cannot collectively resonate and behave as a waveguide. On the transmission curve, this occurs at ~1440 nm for both 20 and 50 MNPs chains and this coincides with a slope change.

For both chain lengths, when collective excitation occurs, the oscillation period between coupled waveguides is lower than 600nm, which corresponds to a coupling constant as high as 2805 mm^{-1} according to coupled-mode theory [8]. This allows almost totally transferring the incident optical intensity in the fourth or fifth nanoparticle of the chain, during the first oscillation.

Interestingly this property is preserved also in the case of the 5 MNP chain. This very short chain can also behave as a waveguide, and the SOI mode can be then transferred in the fourth MNP as shown in Fig. 3(b) and (c). In that case, waveguide behavior of the 5MNP chain cannot be deduced from periodic oscillation between SOI and plasmonic chain since the latter is too short to allow recoupling in SOI. Let's examine top view of calculated y-component electrical field phase along the chain, at 1325 nm (Fig. 4). Phase is clearly distorted by MNPs. Excitation of collective mode in MNP chain is revealed by this phase distortion which shows independent propagation mode in the chain, similarly to results obtained with 20MNP chain [5]. These assumptions, sustained by dipoles electric field analysis, confirm the excitation of proper LSP modes in 5 MNP chains.

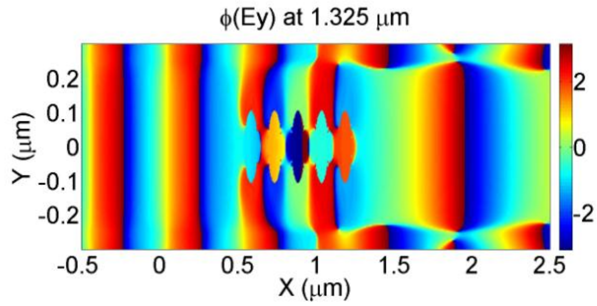

Figure 4: y-component of E-field phase in 5MNP chain at transmission minimum (λ=1325 nm). Cut-view at the middle of MNP chain. SOI waveguide position is at y=+/-0.25µm

Conclusions

As a consequence coupling between a dielectric waveguide and a coupled MNP chain allows not only for a highly efficient excitation of the chain plasmonic collective mode, but also for very short distance (<600 nm) excitation of this mode. We have demonstrated that this behavior can be obtained for long (20 to 50 MNP) or short (5 MNP) chains with similar coupling distance. Since propagation losses decrease with the interaction distance, short MNP chains represent an attractive way to implement LSP based integrated optical devices with nanometer sizes and moderate losses in photonic circuits.

Acknowledgements

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