Silver Nanowires Terminated by Metallic Nanoparticles as Effective Plasmonic Antennas

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ABSTRACT

Metallic nanowires constitute a distinctive class of nanostructures that are able to guide surface plasmons in sub-wavelength dimensions. The effective use of light in- and out-coupling in low dimensional systems, such as excitation of surface plasmon polaritons along metallic nanowires, have been proposed to reduce physical dimensions of opto-electronic and nano-optical components and for high-resolution microscopy applications. Our investigation of in- and out-light coupling on silver nanowire systems by scanning optical coupling microscopy (SOCM) performed in combination with atomic force microscopy (AFM) revealed that the maximum

coupling was obtained when the exciting laser light is projected at the end of the nanowire with a positioning accuracy of approximately 100 nm. Furthermore, it was found that a nanoparticle positioned at the end of a nanowire imparts an enhanced (by almost the factor of four) plasmon in- and out-coupling light efficiency as compared to a free nanowire under the same excitation conditions. These findings are supported by theoretical simulations, which in addition provide a correlation between the nanoparticle size and the out-coupling light efficiency. Our investigations demonstrate that a combination of SOCM and AFM methods provide reliable qualitative and quantitative evaluation of plasmon in- and out-coupling characteristics on metallic nanowire systems.

KEYWORDS: Surface plasmon resonance, plasmon waveguide, nano-antennas, nanowires, silver nanowires, remote excitation

Introduction

Surface plasmons hold the promise of becoming the next medium for future energy and information transport applications, which are expected to be very power efficient, while operating under significantly increased (at roughly four orders of magnitude) higher frequencies as compared to present day technology. In particular, surface plasmon polaritons (SPPs) that are electromagnetic waves of considerably shorter wavelength than the incident light, can deliver a greatly reduced effective wavelength and, thus a corresponding significant increase in spatial confinement and local field intensity.¹ SPPs are guided along metal-dielectric interfaces similar to light guided by an optical fiber.² SPPs propagations however, display unique characteristic of sub-wavelength-scale confinement normal to the interface plane. The bound transverse magnetic

mode oscillations propagate at a metal – dielectric interface by coupling to SPPs and therefore, this mode is used to direct SPPs in a given direction. As infra-red (IR) and visible frequency electromagnetic waves are localized (trapped at or guided along) on metal-dielectric interfaces, it affords miniaturization of integrated optical elements and photonic circuits, as the structure – property relationships of metallic nanostructure systems at a scales that are significantly smaller than the optical diffraction limit can now be explored.^{2a}

Naturally, coupling of far-field light to such nanometer-scale metal structures (*e.g.* gratings, nanowires, nanoparticles) is of interest for future waveguiding applications. At present, a number of geometrical arrangements have been derived for effective control of plasmon propagation. These include: planar and rectangular waveguide channels cut into the metal surface,³ metal nanowires,⁴ metal nano-ribbons,⁵ and nanoparticles chains.⁶ Among these plasmonic waveguide systems metal nanowires fabricated by wet-chemical synthesis methods are of particular interest due to their high degree of crystallinity and surface smoothness.⁷ These advantageous properties significantly improve light propagation in metal nanowires owing to reduced Ohmic losses and significantly reduced radiative decay.

Our earlier work demonstrated that by using the propagating SPPs along a silver nanowire it is possible to provide remote excitation (RE) of surface enhanced Raman scattering (SERS), RE-SERS.⁸ We showed that the RE-SERS spectra could be collected over 10 μm away from the laser light in-coupling position, and such phenomenon has not been reported previously. Application of the RE-SERS method requires efficient light coupling to SPPs. Although SERS spectra with excellent signal-to-noise ratio of over 100 have been obtained using this approach, nonetheless the low efficiency of light coupling to SPPs due to the dispersion relation mismatch remains a major obstacle for practical applications (*e.g.* tip-enhanced Raman scattering

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3 microscopy). Until now major research efforts have been concerned with the coupling of intense
4 laser light (typically, of few hundreds of kW/cm^2) at the end of metallic nanowires in order to
5 excite SPPs. This approach demands that the relative position of the incident light at in-coupling
6 position has to be known and, if possible, to be precisely controlled. Taking into account the
7 diffraction limited laser focus (~ 300 nm) and the diameter of metallic nanowire (~ 100 nm), it is
8 safe to assume that the localization of the laser light with precision of 100 nm is required.
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11 In order to improve the coupling efficiency, several approaches have been proposed. One of
12 efficient methods is to excite surface plasmons polaritons into silver nanowires by attaching
13 them on a dielectric waveguide, such as polymer waveguide, silicon oxide nano-ribbon, ZnO
14 nanowire, and optical fiber taper, with which 50 – 80% of coupling efficiency has been
15 demonstrated. Another fascinated approach is use of a metallic bowtie nano-structure at one end
16 of a nanowire as an efficient coupling antenna. Alternatively, as a simple ‘bottom-up’ approach,
17 nanoparticles adsorbed at the middle of a metallic nanowire have been used to be efficient
18 antennas for light coupling into SPPs along the nanowire. Knight *et al.* reported that
19 nanoparticles at the middle of a silver nanowire acted as defect sites ensuring effective SPPs
20 excitation and SPPs propagation along the nanowire.^{4c} Nanoparticle assemblies already showed
21 low absorption losses of strongly coupled surface plasmons upon irradiation⁹ and this principle
22 can be applied with a nanoparticle/nanowire combination. Further, it was demonstrated that the
23 intensity of far-field light emission at the end of the nanowire strongly depends on the incident
24 polarization orientation as much as on the relative adsorption position(s) of the nanoparticles.
25 These factors are non-negligible to ensure the most efficient light coupling into SPPs.
26 Furthermore, the influence of a single nanoparticle attached at the end of a nanowire for SPPs
27 excitation and enhancement has not been investigated yet and its effects are unknown.
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In this contribution we address this question and provide experimental evidence on the plasmon interactions between the nanowire and a (single) nanoparticle. We employ scanning optical coupling microscopy (SOCM)¹⁰ in combination with AFM technique to investigate the dependence of the laser light focus position on the in- and out-coupling characteristics of SPPs in a nanowire terminated by a metallic nanoparticle and, in a (single) free nanowire that was used as a reference sample. The work is supported by detailed theoretical analysis aimed at elucidating the SPPs interactions between the nanoparticle and the nanowire and, investigates the effect of the nanoparticle size on light in- and out-coupling characteristics in this type of plasmonic waveguide structure.

Experimental methods

a) Preparation of metal nano-structures

Silver nanowires are synthesized using the polyol synthesis process in the presence of poly vinyl pyrrolidone (PVP of Mw ~ 40.000, Sigma – Aldrich) yielding uniform 5 – fold twinned nanowire crystals with the growth direction of [110].⁷ Under typical synthesis conditions 3 mL ethylene glycol solution (anhydrous, Sigma-Aldrich) of silver nitrate (100 mM) (99.9999% purity, Sigma-Aldrich) and 3 mL ethylene glycol solution of polyvinylpyrrolidone (600 mM) were injected into 5 mL ethylene glycol, which was refluxed at 160 °C for more than 1 hour, at a rate of 50 - 200 μ L/minute. The distribution of nanowires diameter was found to be approximately 100 $\pm$ 50 nm. Silver nanoparticles are prepared using the citrate reduction process as described by P.C. Lee and D. Meisei.¹¹

Prior to deposition of nanowires on a glass cover slip, the surface of a cleaned cover slip was modified with 3-mercaptopopyltrimethoxy silane (MPTMS). A drop of a pure MPTMS is added into a small bottle and a cleaned cover slip is placed over the bottle to shield it. The bottle

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3 containing MPTMS at the bottom is heated up to 50 °C for 20 s and then cooled down to the
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5 room temperature. The cover slip is then lifted off the bottle and further heated to 50 °C in order
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7 to remove excess MPTMS and to accelerate the reaction with the glass surface; this step is
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9 followed with the rinse with Milli Q water and blow-drying in *Ar* gas. The nanowire solution is
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11 then spin-coated on the modified cover slip and the slip is rinsed thoroughly with Milli Q water
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13 and dried. Finally, on top of the cover slip, that contains deposited nanowires, a solution of silver
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15 nanoparticles is administered, spin-coated and dried.
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22 **b) Scanning optical coupling microscopy measurements combined with AFM**

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24 SOCM measurements were performed using an inverted microscope (IX71, Olympus)
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26 equipped with a cooled electron multiplying charge-coupled device (CCD) camera
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28 (Cascade512B, Roper Scientific, Inc.). A piezoelectric positioning stage of an Atomic Force
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30 Microscope (Combiscope, AIST-NT) positioned on top of the inverted microscope was used to
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32 scan the sample surface over the laser-focused point and to synchronize both the scanning and
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34 the optical detection measurements. Manipulations of the nanoparticles and nanowires by the
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36 AFM tip were used to prepare nanoscale systems consisting of a single nanowire terminated with
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38 a single nanoparticle; a purely mechanical approach was used for dislodging, moving and/or
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40 complete removal of silver nanoparticle(s) from silver nanowire(s). The diffraction limited
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42 focused light excitation was provided by a continuous wave 632.8 nm *He-Ne* laser (Model
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44 1145P, JDS Uniphase Co.). In order to obtain diffraction-limited focus collimated laser light was
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46 guided to an oil-immersed objective with numerical aperture (N.A.) of 1.3 (Plan Fluorite,
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48 Olympus). Excitation polarization was tuned using a half-wavelength ($\lambda/2$) and a quarter-
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wavelengths ($\lambda/4$) wave plates for circular polarization at the sample. Under typical experimental conditions the in-coupling far-field light excitation was used at or below 0.1 kW/cm^2 .

c) Numerical simulations

The effects of light in-coupling on plasmon excitation efficiency were numerically simulated for both a free nanowire system and, for a single nanoparticle attached to a nanowire system using the finite differential time-domain (FDTD) method (Lumerical Solution, Lumerical Solutions, Inc. Vancouver, Canada). The incident light focus was simulated using a Gaussian source. A far-field photon flux (*i.e.* out-coupling) function from the free end of the nanowire was monitored to evaluate the relative coupling efficiency. For simplification and in order to reduce the computational task all calculations were performed under vacuum (*i.e.* with refractive index of the media set at 1). Intensity of the far-field emission was calculated by integration of the power of the poynting vector at a monitor position using the plane wave relation between electric and magnetic fields,

$$I(\mathbf{r}) = \int \text{Re} \left(\frac{1}{\mu_0} \mathbf{E} \times \mathbf{B} \right) \sim \int \text{Re} \left(\frac{1}{2\mu_0 c} |\mathbf{E}|^2 \right), \quad (1)$$

where μ_0 is the vacuum permittivity, c is the speed of light, n is the refractive index, whereas $\mathbf{E}$ and $\mathbf{B}$ represent the electric field and the magnetic flux density detected by the monitor, respectively. Total intensity of the far-field photon flux was estimated by integrating $I(\mathbf{r})$ in space as following.

$$I_{total} = \int I(\mathbf{r}) d\mathbf{r} \quad (2)$$

Results and Discussion

i) Experimental results

The excitation of SPPs along the silver nanowire is provided by focusing laser light at an in-coupling position. Two in-coupling positions were investigated. One was located the end of the nanowire for a free nanowire system studied; this position is referred as the ‘nanowire end position’. The other in-coupling position was located at the adsorption point of the nanoparticle (*i.e.* attached to the nanowire) for the system consisting of a nanowire with a nanoparticle attached at one of its ends; the latter position is referred as the ‘nanoparticle-nanowire position’. As the coupling of laser light into SPPs mode is sensitive to the exact location of the laser spot with respect to metal nano-structure irradiated and, due to the sub-micrometer-sized dimensions of metal structures and the diffraction-limited laser focus (approximately half of excitation wavelength as noted earlier), the precise location of the laser focus spot has to be determined in order to achieve maximum light in-coupling efficiency. In order to locate the exact location of the most efficient in-coupling position that will provide for maximum SPPs excitations, a coupling position (at an end of NW or at position of adsorbed NPs) was scanned over the diffraction-limited focused excitation using the piezoelectric stage of the AFM (see Fig. 1a top). Simultaneously, the far-field photon emissions at the other nanowire end or at the other nanoparticle position were detected with the CCD camera at each scanning position (Fig. 1a bottom). The intensity trajectories of far-field emissions at each position were calculated from the image sequence as a function of the video frame sequence (Fig. 1b). The synchronization between the sample scanning and the image capturing enable to reconstruct a spatial mapping (SOCM image) of the far-filed emission intensity reconstructed as a function of the separation between the laser spot and the light in-coupling position as shown in Fig. 1c. Thus, the SOCM

image is essentially a representation of spatial mapping of light in- and out-coupling efficiencies at the nanowire.

It is now known that the end of a nanowire can act as a defect site providing the momentum paring between photons and plasmons, thereby the far-field light excitations can be directly coupled to plasmons.^{4, 8} Figure 1 illustrates this phenomenon of light in- and out- coupling to SPPs on a free nanowire with the diameter of approximately 100 nm and the length of ~5 μm . However, the most efficient position on the wire for exciting the SPPs is unknown. While it is logical to assume that the spot where the laser light is projected on the nanowire can be aligned within 100 nm accuracy normal to the center axis of the nanowire, the required accuracy for aligning the far-field light parallel to the center axis could not be estimated. Figure 1c displays an SOCM reconstructed intensity image of the free photons coupled out of the nanowire, This intensity was measured at the out-coupling position of the nanowire (*i.e.* non-illuminated end), generated by propagating SPs excited at the other end of the wire, and was found to be influenced by both the in- as the out-coupling position of the nanowire and by the shape of the focal spot. By fitting 2D – Gaussian function, the distribution was found to be asymmetric and slightly elliptical with its full width at half maxima (FWHM) of approximately 470 nm for transverse axis and 560 nm for longitudinal axis of the nanowire. These values were found to be larger than the beam diameter of the diffraction-limited spot from the in-coupling light (*i.e.* ~300 nm for 632.8 nm irradiation at N.A. of 1.3). This is likely due to non-perfect focus during the experiments. The diffraction limited laser spot size was estimated using an approximation

$$\omega_0 \sim \lambda / (\text{N.A.} \times n) \quad (2)$$

where ω_0 is the radius of the diffraction limited in-coupling spot size, N.A. is the numerical aperture, and n is the refractive index. Thus, in order to obtain maximum in- and out-coupling

light efficiency, the focus of the laser light has to be positioned at the very end of a nanowire with a precision of no less than 100 nm.

As noted earlier the SPPs of the nanowire are hardly excited by focusing the in-coupling light away from the local defect sites (such as the end of the nanowire) and/or at the middle of a nanowire owing to the inherent momentum mismatch between photons and plasmons. An introduction of an artificial scattering element, such a nanoparticle at the end of a nanowire, is known to provide an antenna-like function for in-coupling far-field light to SPPs in the nanowire, significantly increasing the in-coupling light efficiency overall.^{4c} A very recent work by Lu *et al.* confirmed this observation for nanowires intercalated into double- and triple-bonded bundle systems.¹² In the case for a nanowire terminated with a nanoparticle, the light coupling in such system must strongly dependent on the physical dimensions and the geometry of the nanoparticle relative to the size of the nanowire.

Figure 2a shows an AFM image with nanoparticles attached to the nanowire at three positions (*i.e.* positions 1, 2 and 3) along its long axis. The in-coupling of incident far-field light was performed by focusing at the adjoining gap position between the nanoparticle and the nanowire. Figures 2b and 2c illustrate the corresponding SOCM reconstructed images of the out-coupling light emission at position 3 when SPPs were excited at positions 1 and 2, respectively. Although FWHMs of these distributions were found to be similar (*i.e.* asymmetric, elliptical) to the one shown in Figure 1c. The SOCM images for the terminated nanowire systems clearly illustrate that the spatial distribution of light in- and out-coupling intensities is directly affected by the type of the nanostructure probed and, its coupling geometry. Our experimental findings revealed that the in- and out-coupling light efficiency was often found to be higher at an end of a free (uncoupled) nanowire as compared to a nanowire with a nanoparticle attached at the middle of it.

We found that overall the efficiency of far-field light coupling into a nanowire was relatively low. That is, in order to obtain a RE-SERS spectrum with a signal to noise ratio of over two orders of magnitude, the optical density of the excitation often had to be set above 100 kW/cm^2 .⁸ On the other hand, such high a optical excitation density is often detrimental as it incites strong Rayleigh scattering, which in turn, contributes to a greatly increased background noise, a melt down of metal nanowires, photo – toxicity of surrounding samples and other unfavorable effects. As a result, low light in-coupling efficiency under high optical excitation densities potentially is a limiting factor for these systems for light waveguiding applications. Nonetheless, light in-coupling at the nanowire could be improved with carefully positioned complimenting scatter elements, such as nanoparticles, that may act as antenna-like elements at the end of a nanowire. However, it is not currently known nor has been experimentally confirmed of whether a nanoparticle attached at an end of a nanowire will warrant an increase of far-field light in-coupling.

Figure 3a shows an AFM image of a nanowire terminated with a nanoparticle (the bottom half of the image is cropped due to the lack of AFM feedback). The size of the nanoparticle was found to be approximately 220 nm, that is more than the size of the diameter of the nanowire which is ~80 nm. Figure 3c displays an SOCM reconstructed image with far-field excitation light projected at the nanoparticle-nanowire position with maximum intensity of the out-coupling light emission measured at the other (uncoupled) end of the nanowire amounting to ~2200 counts/50 ms. The out-coupling light emission was found to be approximately 600 counts/50 ms for the bare nanowire with the nanoparticle removed by AFM tip manipulation (Fig. 3b). The out-coupling light intensity emission for free nanowire is shown in Figure 3d. These results indicate

that a nanoparticle attached at an end of a nanowire increases the out-coupling light efficiency under the same in-coupling light conditions almost by a factor of 4.

ii) Theoretical simulations

In order to gain further understanding of the effect of light in-coupling focus position at the end of a free nanowire and, at the nanoparticle-nanowire position, numerical simulations applying the FDTD method were performed. The input parameters for the simulation were as follows: the diameter and the length of a nanowire were set at 100 nm and 5 μm , respectively, whereas the diameter of the nanoparticle was set at 200 nm. The SPPs were launched at an end of the nanowire employing a 632.8 nm Gaussian source with the beam diameter of ~ 300 nm (for the estimation of the beam profile, see to Eq. 2). Linearly polarized excitation light along the long axis of the nanowire was used for the simulation. Figure 4 displays the results of these theoretical calculations with steady-state images of electromagnetic near-field distribution for the free silver nanowire (Fig. 4a) and for the nanowire terminated with a nanoparticle (Fig. 4b) with the excitation of SPPs by a Gaussian source from the left end. The propagation of plasmon standing wave along the nanowire is shown on both images with the SPPs wavelength found to be approximately $\lambda_{\text{SPPs}}/2$. The electromagnetic field is shown undulating along the nanowire axis resulting in an asymmetric SPPs leakage normal to the nanowire axis. Although, the simulation showed that by attaching a nanoparticle to a nanowire the undulating nature of the SPPs field is seemingly enhanced. Further, the strongest intensities can be found over longer distances away from the excitation position, proving the higher efficiency of exciting SPPs. In the simulation, the in-coupling light focus position was projected to scan at and along the axis (x axis) of the nanowire with zero point position set at the end of a nanowire (Fig. 5). As expected, maximum

for the in- and out-coupling light intensity was obtained at the very end of the nanowire (at $x = 0$ nm), see Figure 5b. On the other hand, for the nanowire terminated with a nanoparticle (Fig. 5c), the maximum for the out-coupling light intensity was obtained not at the adjoining gap between the nanowire and the nanoparticle but at the nanoparticle. It must duly that the particle is attached to the wire and the gap exists do the curvature of the particle

The second part of the FDTD numerical simulation was concerned with the effect of the size of a nanoparticle positioned at the end of the nanowire (*i.e.* at the excitation position) with respect to the out-coupling light efficiency. In this part of the simulation the diameter of the nanoparticle was gradually varied from 0 to 400 nm. Notably, the diameter of 0 nm is used for a free (*i.e.* without a nanoparticle) nanowire system. The excitation condition for the in-coupling far-field light was changed to plane wave confined in a region measuring $0.5 \times 0.5 \times 0.5 \mu\text{m}^3$ in order to excite both the nanoparticle and the end of the nanowire simultaneously. This excitation condition is comparable to the excitation when using lenses with a low numerical aperture. ($\text{N.A.} \leq 0.6$). Figure 6 displays the relative intensity of the far-field photon out-coupling emission from the opposite (uncapped) end of the nanowire as a function of the nanoparticle size. The results of the simulation show that as the diameter of a nanoparticle increases the intensity of the out-coupling far-field light emission also increases. This trend can be understood using the following arguments: first, as the physical cross-sectional area of the nanoparticle increases the optical cross-section of the in-coupling position also increases; secondly, it can be assumed that there is a size dependent momentum matching condition for the nanoparticle attached to the nanowire.

Conclusions

Our experimental investigations of in- and out- plasmon coupling on silver nanowire systems consisting of a free nanowire, a nanowire decorated with silver nanoparticles and, a nanowire terminated with a single nanoparticle using a combination of SOCM and AFM techniques revealed the following. The maximum for the in- and out-coupling light efficiency was obtained when the in-coupling laser focus was projected at the end of a nanowire with an accuracy of no less than 100 nm for a nanowire with the diameter of 100 nm. Under the same irradiation conditions, the efficiency of the out-coupling light was found to be higher at an end of a free (uncoupled) nanowire than compared to a nanowire with a nanoparticle affixed at the middle of it. However, a nanoparticle attached at the end of a nanowire is found to increase the in- and out-coupling light efficiency by almost the factor of four as compared to a free nanowire system.

The results of the theoretical simulations supported the experimental results confirming substantial enhancement of electromagnetic near-field and the increase of undulation of the SPPs field at the condition when a nanoparticle is attached at the end of a nanowire. The FDTD calculations also showed the importance of the focus position for the in-coupling light, which must be projected at the very end of a nanowire (for free nanowire system) or, at a nanoparticle (for a nanowire terminated with a nanoparticle) for maximum out-coupling light efficiency.

Our investigations demonstrate that the SOCM and AFM methods when used in combination provide highly visual and reliable means for the evaluation of plasmon in- and out-coupling characteristics on these promising metallic nanowire systems. Our work-in-progress will elucidate the effect of the aperture on the in- and out-coupling light efficiency, and will provide further details about the nanoparticle size dependence in the nanoparticle-nanowire systems for potential applications in time-resolved Raman spectroscopy and RE-SERS.

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Figure 1. (a) Schematic illustration of the principle of scanning optical coupling microscopy with the Z- scan movement of the probe tip in X-Y plane (top); light scattering intensity as function of image frame (bottom). (b) A CCD image of light in/out-coupling into/from SPPs on the silver nanowire. The in-coupling light excitation was focused at one end of the nanowire (bottom left corner); the intense light out-coupling was observed at the other end of the nanowire (top right corner marked by white square). (c) A reconstructed SCOM image measured at the out-coupling position (white square).

Figure 2. (a) An AFM image of the nanowire decorated with nanoparticles at positions 1, 2 and 3. (b) A SCOM reconstructed image of the out-coupling light emission at position 3 when excited at position 1. (c) The out-coupling light emission at position 2 when excited at position 1.

Figure 3. (a) An AFM image of the nanowire terminated with a nanoparticle (nanoparticle shown as a bright spot at the top right corner). (b) An AFM image of the nanowire with the nanoparticle dislodged by AFM manipulations. (c) An SCOM reconstructed image of the nanowire at the moment of far-field light in-coupling at the nanoparticle-nanowire position. (d) An SCOM image of the far end of the nanowire after the nanoparticle has been removed.

Figure 4. Steady-state simulation image of electromagnetic near-field along a nanowire. (a) An image of a free (uncapped) nanowire under the in-coupling light excitation focused on the left

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2
3 end of the nanowire. (b) An image of the nanowire terminated by a nanoparticle under the same
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5 excitation conditions.
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12 **Figure 5.** (a) Schematic representation of the simulations of the in-coupling light excitation at
13 the nanoparticle-nanowire position. The focus position of the far-field light was set at 0 nm (*i.e.*
14 at the end of a nanowire). The out-coupling photon-flux from the other (uncapped) end of the
15 nanowire was detected by the power monitor positioned 50 nm away from the emitting end of
16 the nanowire.
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25 (b) FDTD simulation of normalized far-field light emission as function of focus position for a
26 free (uncapped) nanowire. (c) Normalized far-field light emission for the nanowire terminated
27 with a nanoparticle. Graphical inserts represent the focus positions, which provide the maximum
28 out-coupling light intensity of the far-field light emissions.
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39 **Figure 6.** FDTD simulation of nanoparticle size dependence of the intensity of the out-coupling
40 light emission. Simulated in-coupling light excitation was carried out under the plane wave
41 conditions. Far-field out-coupling light intensity is shown normalized at 0 nm.
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Figure 1

Figure 3

figure 4

Figure 5

Figure 6

Table of Contents