Localized Field Enhancements in Fractal Shaped Periodic Metal Nanostructures

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Fractal shaped structures (extending over ~ 100 × 100 μm^2) formed with a 100-nm-period square lattice of gold nanoparticles (height ~ 50 nm, diameter ~ 60 nm) placed on a 50-nm-thick gold film are characterized using far-field nonlinear scanning optical microscopy, in which two-photon photoluminescence (TPL) excited with a strongly focused laser beam (in the wavelength range of 730 - 790 nm) is detected. Spatial locations of nanoparticles within the fractal structures are calculated using part of the Mandelbrot fractal geometry and defined with electron-beam lithography, resulting thereby in reproducible nanoparticle clusters of practically all possible shapes within the available spatial range (i.e., from 100 nm to 100 μm).

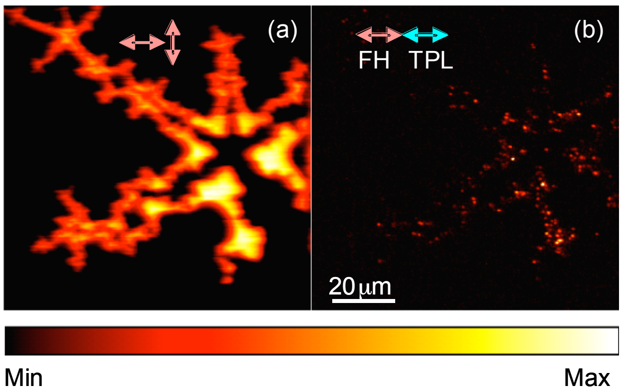

Fig. 1. Pseudo-color optical (a) FH and (b) TPL images of the fabricated fractal shaped structure of 60-nm-diameter gold particles. The used excitation wavelength (FH) was 730 nm and the polarization configurations are indicated by a pair (incident FH, detection) of colored arrows on the optical images. The maximum TPL signal in (b) was ~12k counts/s obtained at 1.2 mW incident power.

TPL images obtained for all wavelengths in the laser range exhibit diffraction-limited (~ 0.6 μm) bright spots corresponding to intensity enhancements of up to ~170, whose positions are dictated by the incident light wavelength and polarization. We relate these field enhancements to the occurrence of constructive interference of surface plasmon polaritons (SPPs) excited by the incident radiation (due to scattering by nanoparticles) and partially reflected by fractal shaped boundaries due to a difference in the SPP effective refractive index at a flat and periodically corrugated gold surface. This conjecture on SPP refractive index difference has been verified with observations (using leakage radiation microscopy) of SPP focusing by circular and waveguiding by rectangular areas filled with periodically arranged nanoparticles. Furthermore, these findings are supported by considering the polarization dependent SPP propagation in TPL images obtained near round and apparently SPP defocusing fractal boundaries. In addition, TPL bright spots where also found at the fractal boundaries, especially in less dense outer branches of the fractal shape and related to multiple scattering between individual nanoparticles.

We supplement the characterization of these areas with relevant numerical simulations using the total Green dyadic, including excitation of SPPs. Comparing TPL intensities from the fractal structure to that of an individual particle, the used simulation provide a qualitative prediction of the intensity enhancement levels (~220) obtainable from also less ordered metal nanostructures. Finally, we have obtained experimental TPL images of a large specially shaped defect leading to strong intensity enhancements of up to ~210 at a rather broad resonance

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