Nonlinear Near-Field Optical Effects of the AgO_x -Type Super-Resolution Near-Field Structure

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AgO_x -type super-resolution near-field structure (Super-RENS) exhibits nonlinear near-field optical behavior in the near field, which is closely related to the subwavelength resolution capability of the Super-RENS disk. Finite-difference time-domain (FDTD) numerical simulations were used to demonstrate that these nonlinear effects may result from collective localized surface plasmons of silver nanoparticles. [DOI: 10.1143/JJAP.42.1031]

KEYWORDS: near-field optical recording, super-resolution near-field structure, evanescent field, localized surface plasmon, finite-difference time-domain simulation

The super-resolution near-field structure (Super-RENS) was introduced by Tominaga *et al.*^{1–5)} to perform the task of near-field recording in a more feasible way. Up to now, there have been two major types of Super-RENS: Sb-type [SiN (170 nm)/Sb (15 nm)/ SiN (20 nm)] and AgO_x -type [ZnS-SiO_2 (20 nm)/ AgO_x (15 nm)/ ZnS-SiO_2 (20 nm)]. The 15 nm Sb and AgO_x thin films were considered as the nonlinear optical layers which control the near-field optical aperture. Super-RENS has the advantages of simpler recording head design, less mechanical damage, and higher recording speed. Our previous research has shown that the collective effects of the localized surface plasmon and the heterogeneous material structure are responsible for the unusual optical property of the Super-RENS.^{6–8)} To further explore this nonlinear near-field optical property, we study near-field optical images using two-dimensional finite-difference time-domain (FDTD) simulations of the AgO_x -type Super-RENS. Our results indicate a close connection between the surface plasmon effects of silver nanoparticles and the nonlinear near-field optical property observed in experiments.

In our previous study on the direct near-field measurements of the Super-RENS sample, cover glass/ ZnS (20 nm)/ AgO_x (15 nm)/ ZnS (20 nm), was fabricated by the rf reactive-magnetron sputtering method. The dielectric layer, ZnS-SiO_2 , has an index of refraction of about $2.25 + 0.01i$, and the AgO_x has a refractive index of about $2.70 + 0.08i$ at the wavelength of 650 nm. A tapping-mode tuning-fork near-field scanning optical microscope^{9,10)} was used in the direct measurements of the transmission near-field intensity profiles at different incident laser powers for the clean cover glass slip and the AgO_x -type Super-RENS.⁷⁾ There was clearly an enhancement of the near-field intensity profile for the Super-RENS sample, and the enhancement at the center of the focused spot was stronger. The magnitude of this enhancement agreed with that of the enhancement of the surface plasmon effect.⁶⁾ With increasing input power, the peak profile intensities of the cover glass sample were linearly increased. Surprisingly, the peak intensities of the Super-RENS exhibit nonlinear behavior with increasing input laser power.

It is likely that there are nano-size silver nanoparticles embedded in the AgO_x layer either by the fabrication process or by the photodissociation process with incident light. With increasing incident laser power, more silver particles could be photodissociated and the density of silver nanoparticles

Fig. 1. Scheme of randomly distributed silver nanoparticles in a dielectric thin film. The wavelength of the incident light is 650 nm and the index of refraction of the AgO_x is $2.70 + 0.08i$. The diameter of the silver nanoparticles is 4 nm and their index of refraction is $0.055 + 4.44i$.

increases. We designed a simplified two-dimensional model, and used FDTD simulations to study the relation between the density of the silver nanoparticles and the nonlinear near-field optical response of the AgO_x -type Super-RENS. Figure 1 shows the simulations in which a normally incident light of 650 nm wavelength is illuminated on a AgO_x (15 nm) thin film embedded with silver nanoparticles of 4 nm diameter. We assume that the silver nanoparticles are of the same size, and are randomly distributed in the AgO_x thin film. Figures 2(a) and 2(b) show the near-field distributions of silver nanoparticles at different densities. In the low-density case of Fig. 2(a), each embedded silver nanoparticle behaves like a dipole and a very strong scattering center, but there is less interaction between silver nanoparticles. If the density of the silver nanoparticles is increased tenfold, as shown in the high-density case of Fig. 2(b), the local fields from adjacent nanoparticles are coupled together and produce highly enhanced evanescent fields. The local fields are evanescent and decay very rapidly away from the thin film. This is caused by the collective localized surface plasmons of the clusters of silver nanoparticles.

For the near-field distributions either crossing the center of the AgO_x film or on the surface of the AgO_x film, our results shown in Fig. 3 indicate that the average intensities of the local fields exhibit nonlinear optical response with increasing nanoparticle density. Since increasing the incident laser power will increase the density of the silver

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Fig. 2. Near-field distributions of (a) low-density silver nanoparticles and (b) high-density silver nanoparticles.

nanoparticles by the photodissociation process, the results of Figs. 3(a) and 3(b) qualitatively agree with the nonlinear behaviors of near-field optical scanning profiles. The collective effects of localized surface plasmon of silver nanoparticles resulted in a nonlinear near-field optical response. Our results also demonstrated the relation of the complicated material structure to the enhancement of the surface plasmon effects. However, the sizes of the silver nanoparticles should be different, and the distribution of the nanoparticles may not be uniformly random in the realistic situation. Further research on the effects of size variations and different distribution patterns of the silver nanoparticles may yield a better understanding of the optical properties of the AgO_x -type Super-RENS.

In conclusion, the nonlinear near-field optical properties of the AgO_x -type Super-RENS have been studied by numerical FDTD simulations. Highly enhanced local evanescent fields and nonlinear optical behaviors were demonstrated in our simulations, which agree well with previous near-field scanning measurements. The surface plasmon excitation of the embedded silver nanoparticles in the AgO_x layer gives a satisfactory explanation for the nonlinear optical property and the high carrier-to-noise ratio (CNR) of the scattering-type near-field optical readout on the AgO_x -type Super-RENS.

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Fig. 3. Nonlinear behavior of (a) central field intensities and (b) surface field intensities of the AgO_x -type Super-RENS as a function of the density of silver nanoparticles. Both axes are in arbitrary units.

Corporation.

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