Far-field optical response of localized near-field enhancements induced by nano scatters in AgO$_x$ super-resolution near-field structure

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Abstract

The super-resolution near-field structure (super-RENS) is an ultrahigh-density near-field optical disk data storage medium which can achieve superior spatial resolution. Our previous studies found that enhanced local optical intensity occurred at the near field of the super-RENS disk, and the nonlinear near-field optical enhancement is related to the localized surface plasmons of silver clusters dissociated from the AgO$_x$ layer of the super-RENS disk. In this paper, we report the near-field and far-field properties of AgO$_x$-type super-RENS with different embedded silver nanoparticles using two-dimensional finite-difference time-domain (FDTD) calculations. Highly localized enhancements are found between adjacent silver nanoparticles in the near fields. The far-field signals of different types silver nano scatters confirm the super-resolution capability of AgO$_x$-type Super-RENS disks. The behaviors of far-field signals indicate the correlation between the enhanced localized surface plasmons and the super-resolution capabilities of AgO$_x$-type super-RENS.

Keywords: localized surface plasmon, super-resolution near-field structure, near-field optical storage, optical disks, finite-difference time-domain method, metallic nanoparticles.

1. Introduction

As the demand of data storage capacity grows up, data storage technologies are driven to ultrahigh recording densities. Near-field optical data storage technique was first demonstrated by Betzig and Trautman$^{1,2}$ on multilayered Pt/Co magneto-optical thin films using a near-field scanning optical microscope (NSOM). High spatial resolution recording was accomplished by using a sub-wavelength aperture at the tapered tip of an optical fiber operated in the near-field region. Although the diffraction limit was successfully overcome, it is quite difficult to precisely control the distance between probe and medium less than a wavelength and simultaneously maintain a high scanning rate. Terris et al. used solid immersion lens (SIL) to reduce the mechanical damage which comes from the near-field optical fiber...
probe and achieved higher recording speed\textsuperscript{3}. Results showed the focused spot size was decreased to 317 nm; however, the control of near-field distance between SIL recording head and the recording medium remains a major hurdle for commercial applications.

In 1998, a multilayer structure, polycarbonate / SiN(170 nm) / Sb(15 nm) / SiN(20 nm) / GeSbTe(15 nm) / SiN(20 nm), was used to demonstrate the overcome of diffraction limits and subsequently was named as “super-RENS”-super-resolution near-field structure\textsuperscript{4}. Results showed carrier-to-noise ratio (CNR) is more than 10dB for 90 nm recording marks. The thin Sb film above the phase-change medium, GeSbTe, in the super-RENS effectively replaces the fiber probe of the near-field optical recording system. An AgO\textsubscript{x}-type super-RENS\textsuperscript{5} was reported after the Sb-type super-RENS in 2001. The CNR can be 15dB for 90nm recording marks. To understand the optical properties of the AgO\textsubscript{x}-type super-RENS, we have used a tapping-mode tuning-fork near-field scanning optical microscope in transmission mode to measure the near-field optical images\textsuperscript{7}, and found enhanced local optical intensity at the near field and nonlinear optical effect related to the localized surface plasmon of silver clusters dissociated from AgO\textsubscript{x}\textsuperscript{7-16}. To study the relationship between random silver nanoparticles and nonlinear localized enhancements, the near-field optical fields of AgO\textsubscript{x}-type super-RENS with silver nanoparticles embedded in AgO\textsubscript{x} layer were calculated by two-dimensional finite-difference time-domain (FDTD) simulations\textsuperscript{18}. The silver nanoparticles and the localized evanescent waves around silver nanoparticles act as virtual near-field optical probes, and the disadvantage of the conventional NSOM method were also overcome by the super-RENS.

Metallic nanoparticles of nanometer size exhibit plenty of interesting optical phenomena related to geometry-dependent surface plasmon resonance. The enhanced electric fields are confined within a few nanometers near the surface of nanoparticles. The resonances are due to dipolar or high-polar collective oscillations of conduction electrons in particles\textsuperscript{6,17}. In previous studies, we found that the super-resolution efficiency of the AgO\textsubscript{x}-type super-RENS is related to the localized surface plasmon of silver clusters dissociated from the AgO\textsubscript{x} layer and the complicated interactions between the nonlinear near-field optical enhancements and the subwavelength recording marks\textsuperscript{7-16}. The highly enhanced localized surface plasmons improve the reading efficiency, but the relation between the nonlinear near-field optical effects and the measured far-field signals is still not clear. To further understand the unusual optical effect of the AgO\textsubscript{x}-type super-RENS, we used 2D finite-difference time-domain (FDTD) numerical calculation method to study the near-field properties of the AgO\textsubscript{x}-type super-RENS disks with different configurations of silver nano scatters. Because the detectable optical signals for disk drive system are the far-field signals, the near-to-far field transformation\textsuperscript{18} is used to find out the far-field performance of the AgO\textsubscript{x}-type super-RENS disks with different configurations of embedded silver nanoparticles.
2. Simulation model

The numerical calculation used in this paper is a two-dimensional FDTD method with periodic boundary condition and perfect matched layers. The advantages are effective reduce of memory requirement in computation and simplicity of calculating process in complex structure. The calculated structure of super-RENS is cover glass /ZnS-SiO$_2$ (20 nm) /AgO$_x$ (15 nm) /ZnS-SiO$_2$ (20 nm) /GeSbTe (16 nm), as shown in Fig. 1. The incident laser light is Gaussian distributed with wavelength of 650 nm, and the numerical aperture of the objective lens is 0.85. The refractive index of silver is 0.055 + 4.44i, and the dispersive behavior of silver is calculated by Lorentz model$^{19}$. The refractive index of ZnS-SiO$_2$ and AgO$_x$ layer is 2.07 and 2.7, respectively. Recording marks are created by the laser beam focused on the phase changed recording medium Ge$_2$Sb$_2$Te$_5$ (GST), and the refractive indices of amorphous GST and crystalline recording mark are 3.38 + 4.07i and 3.855 + 4.80i, respectively$^{14}$. The marks spread periodically in a 4000 nm regime, while the period of marks was double of the mark length. In order to correlate the calculated results with experimental CNR, we computed the far-field intensity differences between the on-mark and the off-mark cases of the super-RENS shown in the Fig. 1 for different mark sizes. The on-mark situation means that the incident light focuses on the recording mark, and off-mark situation means that the incident light focuses between two marks. The mark length is tuned from 20 nm to 400 nm, and the thickness of mark is 16 nm.

![Fig. 1. Structures of the super-RENS with four different configurations of nano scatters.](image)

Four different configurations of optical scatters shown in the Fig. 1 are used in our calculation for comparison. For the simplified model, the thickness of silver nano disk is 15nm and the diameter is set to be 7 nm, 15 nm and 25 nm, respectively. In the silver cluster case, five silver nanoparticles with 4 nm diameter are randomly positioned in an asymmetry situation within the 15 nm AgO$_x$ thin film layer as shown in Fig.1. However, the distribution of dissociated silver nanoparticles is more complex and very difficult to be observed directly. Based on the experimental results, we found two possible distributions of the nanoparticles or clusters at the AgO$_x$ layer of the super-RENS$^9$. The focused laser beam of reading or recording may drive the dissociated silver nanoparticles to form an aggregated silver clusters or bull’s eye ring type structures. Experiments also showed that the density and distribution of dissociated silver nanoparticles can be influenced by the intensity of focused laser spot. The density of silver nanoparticles or clusters is assumed to increase with the intensity of incident light in the calculation of this paper. For the aggregated case shown
in Fig. 1(c), the distribution of nanoparticles is set to be a random Gaussian distribution. For the case of Fig. 1(d), the silver particles are driven by incident laser pulse to form a ring structure, and we assumed that silver particles formed two Gaussian distributions at the edges of the incident laser beam. The number of silver nanoparticles is either 100 or 200 for the cases shown in Fig. 1 (c) and (d), and we calculate a 4000 nm (x 15 nm) spread regime. In this paper, we would like to find out the effects of the configuration of nanoparticles distribution, the size variation of silver particles is neglected. The diameter of silver nanoparticles is set to be 4 nm.

3. Results and discussions

Figure 2 shows the near-field intensity distributions of the Fig. 1(a) silver nano disk cases with diameter of 25 nm, 15 nm and 7 nm, respectively. The localized enhancements are induced around the edges of silver nano disks. The strongest enhancements are induced at the corners of the rectangular cross-section, especially two corners of the front edge which is directly illuminated by incident light. Results showed no distinct near-field optical enhancement in the center of the silver nano disk of 7 nm diameter, but not for the nano disk with larger diameter, such as the 25 nm one. The largest enhancement is induced in the case of 25 nm diameter, and the localized field is enhanced not only around the edge of the silver nano disk but also through the center of the disk. When the size of nano disk became larger, the localized enhancement highly increased. Fig. 3 shows the near-field intensity distribution of the silver cluster case, as shown in Fig. 1(b). The localized enhancements are generated between adjacent silver nanoparticles of the silver cluster. It is quite different from the cases of silver nano disk, the enhancement fields are distributed over the whole silver nanoparticle cluster. In the nano disk case of 7 nm diameter, the area of silver is similar to that of cluster-scatter shown in the Fig. 3, but the near-field peak intensity of the cluster-scatter case is twenty times stronger than that of the nano disk case. The strong near-field enhancement of the nanoparticle cluster may be resulted from the large edge to area ratio. For the cases of randomly distributed silver nanoparticles, as shown in Fig. 4, highly localized enhancements...
are produced between adjacent silver nanoparticles in near field. The localized enhancements induced by the silver nanoparticles of random Gaussian distribution are similar to that of ring distribution. These near-field optical signals of the AgOx thin film corresponded to the nonlinear near-field optical properties which were previously found in experiments.

Figure 3 displays the near-field intensity distribution of FDTD simulation for a silver cluster consists of five nanoparticles. Each curve is normalized against the case without marks. The curve of no silver nanoparticle existence is computed for comparison, and its far-field signals dropped around 200 nm of the mark size because of the diffraction limit. The far-field intensity differences decreased with mark size, and there is a bump in each curve of Fig. 3(a). For the silver nano disk of 25 nm diameter, the peak appeared at the mark length of 200 nm, but the peak of the nano disk of 15 nm diameter appeared at the mark length of 100 nm. The curve of 7 nm diameter is similar to that of 15 nm diameter. For the mark size smaller than 100 nm, the far-field signals of the nano disk of 15 nm diameter are higher than that of 25 nm and 7 nm diameters. The reason is that scatters with larger size may have worse resolution and the localized enhancement is too weak for the nano disk case of 7 nm diameter, which reduced the far-field signals significantly. For the silver cluster case shown in Fig. 1 (b), the far-field signals are similar to the nano disk cases, but there is a bump in the far-field signal around the mark length of 150 nm. Based on the 2D-FDTD simulation results, both the silver cluster and the silver nano disk cases demonstrated the super-resolution capability; however, the far-field signals of the nano disk cases are apparently higher than those of the silver cluster case.
Fig. 5 The calculated far-field difference signals for various recording remark lengths with different configurations of embedded silver nano-scatters: (a) a nano cluster which consists of five silver nanoparticles and a nano disk with diameter of 25 nm, 15 nm and 7 nm, respectively; (b) the dissociated silver nanoparticles of random Gaussian distribution (Fig. 1(c)) with 0, 100 and 200 silver particles, respectively; (c) a ring distribution with 0, 100 and 200 silver nanoparticles, respectively.

Figure 5(b) displays the far-field intensity differences for the dissociated silver nanoparticles of random Gaussian distribution as shown in Fig. 1(c). In comparison to the results of no silver nanoparticles, the cases with random silver nanoparticles embedded in the AgOx layer confirm the super-resolution capability and the far-field signals of mark size smaller than 100nm are distinguishable. Similar results have been observed in our previous CNR measurements of the AgOx-type super-RENS disks\textsuperscript{11,12}. The signal enhancement beyond diffraction limit is evident.

For the silver nanoparticles of ring distribution, the far-field difference signals are shown in Fig. 5(c). The near-field enhancements depend on the amount of embedded silver nanoparticles. The amount of embedded silver nanoparticles is related to the far-field difference signals of different mark lengths as well. The far-field signals of the recording marks beyond the diffraction limit seems to be saturated when the number of the silver nanoparticles above a threshold amount. A distinct nonlinear response of the AgOx thin film is shown in the results of our simulation, which
agreed with previous near-field and far-field measurements. In the cases of nanoparticles which are randomly Gaussian distributed and ring distributed, the curves of far-field difference signals are more complex than the cases of single nano disk and cluster. Because the far-field difference signals is affected by the near-field enhancements of localized surface plasmon resonances. These plasmon resonances are the interaction between incident electromagnetic waves and induced charges in metallic particles. With a p-polarized (TM polarization) illuminated wave, polarized charges are induced in the coupled system by the external field and interacted with the illuminated waves. No plasmon resonance can be excited for the s-polarization case. The coupling resonances between nanoparticles are influenced by induced charge distribution of clusters. The distribution of polarized charges plays an important role in this case.

4. Conclusions

Near-field and far-field optical properties of the AgOx-type super-RENS resulted from the complicated interactions between the nano recording marks and different configurations of silver nanoparticles are studied by FDTD calculations. The far-field intensity difference are distinguishable with recording mark size smaller than the diffraction limit, and the results of far-field difference signals are quite different for the configurations of simplified nano scatter and randomly distributed nanoparticles. The results of randomly distributed silver nanoparticles are quite similar to the experimental results of previous reports.

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