Near-Field Optical Recording on Phase-Change Nanoparticles and Reflective Reproduction from Nanoantenna using Plasmonic Resonance

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ABSTRACT

For high-density optical memory system, near-field recording on a medium with phase-change nanoparticles and dual metal layers was proposed. A finite difference time domain (FDTD) analysis demonstrated that a combination of a nanoantenna with such a medium so as to enhance plasmonic resonance would enable effective recording with larger (~10 times) working distance (WD) than for a conventional medium. A reproduction method of detecting the intensity of the reflected wave from the nanoantenna was also proposed in the same setup as the recording. We found that plasmonic resonance induced in the nanoantenna was enhanced and the intensity of reflected light was also increased when the phase state of the nanoparticle was crystalline. Since the sub-diffraction limited size of nanoantenna is larger than a nanoparticle, the detected signal intensity can be greatly improved. Calculated results showed that our proposed system and methods for recording and reproduction would have a potential to become effective solutions for terabyte-class optical memory system.

1. Introduction

In the field of optical storage, an optical memory system with phase-change optical disk is highly attractive as a reliable and recordable one. The recording density of the BDXL disk is 24 Gb/inch^2 and the minimum mark length is 112 nm. By using the SIL optical system with numerical aperture (NA) of 1.6, the minimum mark length in dual-layer phase-change optical disk was reported to be as small as 78 nm [1]. In these optical memory systems, however, the recording density is restricted by a diffraction limit determined by a wavelength of λ and an NA ($\propto \lambda$/NA).

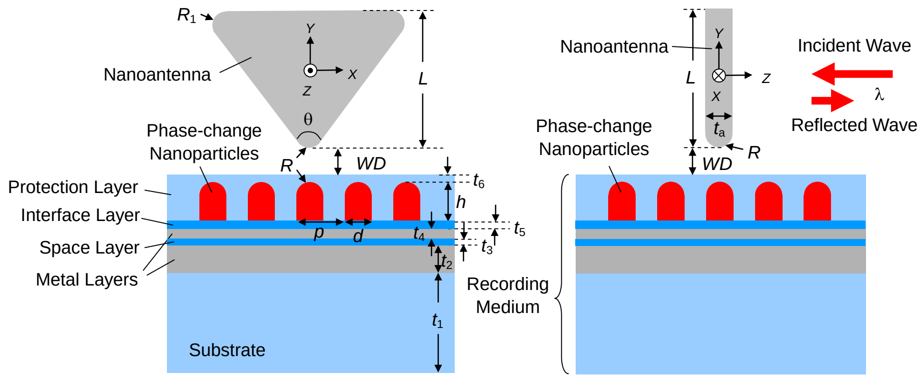
In recent years, the near-field optical recording technology has broken through the diffraction limit and the recording size of 40 nm was demonstrated in a phase-change thin film using a metallic nanoantenna [2]. However, for a medium with the phase-change thin film covered by a protection layer, the nanoantenna has to be nearly contact to the medium (WD= 3 nm in [2]) to achieve as small mark length as nearly an apex size of the nanoantenna.

We propose high-density optical memory system with larger WD using plasmonic resonance [3]. In this paper, the constructions of the optical memory system are described. Then, the performances of recording and reproduction are analyzed by using a FDTD method, and the theoretical results are discussed.

2. Construction and operation of high-density optical memory system

Figure 1 shows the construction of a nanoantenna and the recording medium with phase-change nanoparticles and dual metal layers in the proposed optical memory system. Both for recording and reproduction, the same setup can be used. A triangular metallic nanoantenna is placed longitudinally on a recording medium with working distance of WD. The nanoantenna has a length of L, and an apex angle of θ. The recording medium consists of a protection layer, an interface layer, and dual metal layers with a space layer on a substrate. The nanoparticles have vertically long and bell-shaped structure with a curvature radius of R and a height of h, where their period is p and the diameter is d. Illumination of an incident wave polarized in the Y direction to the nanoantenna induces surface plasmon resonance in the metallic nanoantenna and generates a near-field light at the apex of the nanoantenna. When a nanoparticle especially in a crystalline state is closely aligned with the nanoantenna in the polarization (Y) direction, the plasmonic resonance in the nanoantenna is intensified by the interaction with the nanoparticle. The dual metal layers under the nanoparticle further enhance the plasmonic resonance.

When the incident wave has power to record, the near-field light changes the phase state (crystalline phase transition in this case) of the nanoparticle and the information is recorded. For reproduction, the nanoantenna is irradiated with an incident light with less power than for recording, and the reflected light from the nanoantenna is detected. When a nanoparticle is crystalline phase of which the real part of the dielectric constant is negative like a metal, the plasmonic resonance in the nanoantenna is enhanced by the interaction with the nanoparticle, and the intensity of reflected light from the nanoantenna is increased correspondingly. For an amorphous nanoparticle, the reflected light doesn't become strong so much, because the real part of the dielectric constant of the amorphous phase has generally larger value like a dielectric than one of the crystalline phase. By using the intensity difference of the reflected light from the nanoantenna, it is possible to reproduce the information recorded in the nanoparticles of the optical medium.



(a) (b)

Fig. 1. Construction of a nanoantenna and a recording medium with phase-change nanoparticles and dual metal layers in the proposed optical memory system: cross-sectional views on (a) *XY* plane at z=0, and (b) *YZ* plane at x=0.

3. FDTD analysis of recording and reproduction performances

3.1 Analytical parameters

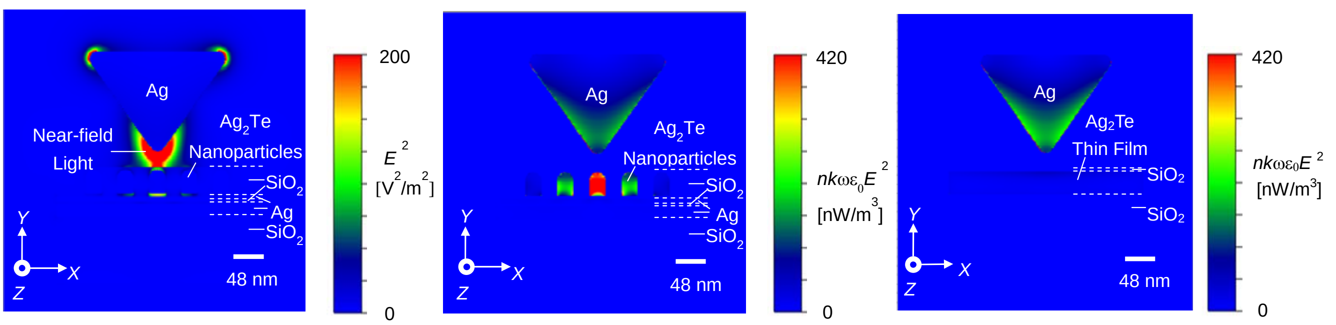
By an electromagnetic theory of a FDTD method in combination with commercial software and self-produced programs, recording and reproduction performances were analyzed when a *Y*-polarized plane wave illuminated a nanoantenna in the – *Z* direction. The computational domain was set as 3.0 μm x 3.0 μm x 2.0 μm with a non-uniform cell size. The domain has total field / scattered field (TFSF) formulation for the plane wave source, and perfectly matched layer (PML) as an absorbing boundary condition. The cell was designed to have the smallest size of 1.0 nm at a central area along all axes.

Ag_2Te was used as an analytical example of phase-change material, of which the crystalline state shows large metallic property at λ=780 nm in addition to the difference in dielectric constant between phase states. The real parts of the complex relative dielectric constants were measured to be Re[ε*] = -14.9 (crystalline phase) and -5.8 (amorphous phase) in Ag_2Te thin film. A dielectric of SiO_2 was applied as a material of a protection layer, an interface layer, a space layer and a substrate. Ag thin films were used as metal layers.

The period of p of the nanoparticles is an important parameter to determine the recording density. The square array with p=48 nm and d=24 nm gives a recording density of 0.28 Tb/inch^2 (capacity of 0.40 TB as a 12-cm diameter disk). The standard values were determined by optimization as follows: L=152 nm, θ=70°, R=R_1=12 nm and t_a=24 nm in the nanoantenna, and h=36 nm (1.5d), t_1=100 nm, t_2=20 nm, t_3=4 nm, t_4=8 nm, t_5=4 nm and t_6=4 nm in the medium.

3.2 Analytical results of recording characteristics

At first, the recording performances are described for a medium with 5 x 5 squarely-arranged nanoparticles that are all in a crystalline state. Figure 2 (a) and (b) show the calculated distributions of E^2 (square of amplitude of electric field), and $nk\omega\varepsilon_0E^2$ (absorption per unit volume) by on *XY* plane at z=0, respectively when *Y*-polarized plane wave with λ=780 nm and E^2=1 V^2/m^2 illuminated, where n is the refractive index, k is the extinction coefficient, ω is the angular frequency, and ε_0 is dielectric constant in vacuum. The degree of absorption in the nanoparticle is a measure of the



(a) (b) (c)

Fig. 2. Distributions of (a) E^2, (b) $nk\omega\varepsilon_0E^2$ (absorption per unit volume) on *XY* plane at z=0 for a medium with phase-change nanoparticles, and (c) $nk\omega\varepsilon_0E^2$ on *XY* plane at z=0 for a medium with phase-change thin film when WD=24 nm.

recording sensitivity. It is seen that the near-field light generated from the apex of the nanoantenna was effectively focused on a central nanoparticle. It is considered that the dielectric polarization at the curved surface of the nanoparticle that was induced by the interaction of the nanoantenna would collect the electric field. The almost uniform absorption in the nanoparticle in Fig. 2 (b) demonstrated the effective irradiation of the near-field light.

Figure 2 (b) also shows cross-write by absorption that causes some absorption inside neighbor nanoparticles. Cross-write is defined by the absorption ratio to an averaged one of the adjacent four nanoparticles. It was calculated to be 0.35.

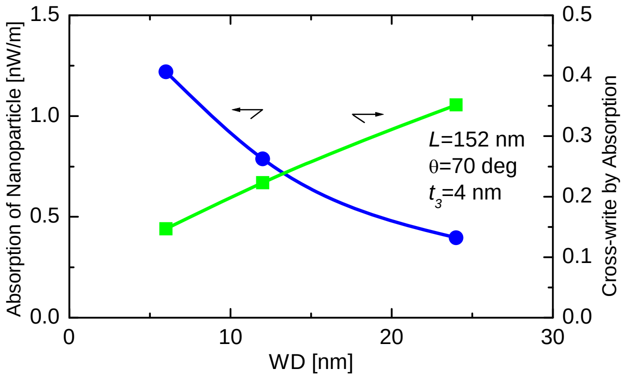


Fig. 3. Absorption of the central nanoparticle and cross-write by absorption calculated as a function of WD.

Recording property for a conventional medium with Ag_2Te phase-change thin film (thickness 36 nm) and a SiO_2 protection layer (thickness 4 nm) was analyzed as shown in Fig. 2 (c). At WD=24 nm, the absorption was much smaller and the full width at half maximum (FWHM) of E^2 was much larger (170 nm) in Ag_2Te thin-film. When WD decreased to be as small as 2 nm, the FWHM of E^2 was reduced to be 20 nm in Ag_2Te thin film. This means that effective recording with larger (~10 times) WD would be enabled in the proposed system than for the medium with phase-change thin film.

Figure 3 shows absorption per unit length (sum of absorption per unit volume on *XY* plane at z=0) of the central nanoparticle and cross-write by absorption calculated as a function of WD. The reduction of WD increased the absorption sensitivity of the nanoparticle by the enhancement of the plasmonic resonance. In addition, the cross-write can be also greatly improved by the decrease of WD (0.15 at WD=6 nm, for example).

3.3 Analytical results of reproduction characteristics

Reproduction can be performed by detecting the intensity of reflected light from the nanoantenna depending on the phase state of a target nanoparticle. An incident wave was focused using a lens with NA to the nanoantenna, and the reflected wave from the nanoantenna was collected by the same lens with the same NA to a photo detector.

In order to evaluate the potential of our reproduction method, let us consider simple two cases of reproduction signals when the phase state of only the central nanoparticle was changed in a medium with all crystalline ones and all amorphous ones, respectively. Corresponding to the above two cases, calculations were performed on four kinds of media of which nanoparticles were all crystalline, center amorphous (central amorphous nanoparticle surrounded by all crystalline ones), center crystalline (central crystalline nanoparticle surrounded by all amorphous ones) and all amorphous. The reflectance difference between all crystalline and center amorphous was designated as ΔR_1, and one between center crystalline and all amorphous was ΔR_2.

Figure 4 shows ΔR_1 and ΔR_2 calculated as a function of NA of the lens for focus and detection. ΔR_1=0.27% and ΔR_2=0.30% at NA=0.71. It is noted that ΔR_1 and ΔR_2 increased drastically with NA. When NA rose from 0.71 to 0.84, for example, ΔR_1 and ΔR_2 increased to be 0.57% and 0.62% (2.1 times), respectively. These are actual values enough to detect. This means that the reproduction to resolve the nanoparticle with a diameter of d=24 nm was theoretically demonstrated.

Figure 5 exhibits ΔR_1 and ΔR_2 calculated as a function of WD when NA=0.71. The decrease of WD can improve the reproduction characteristics in the same way as for recording by the enhancement of the plasmonic resonance.

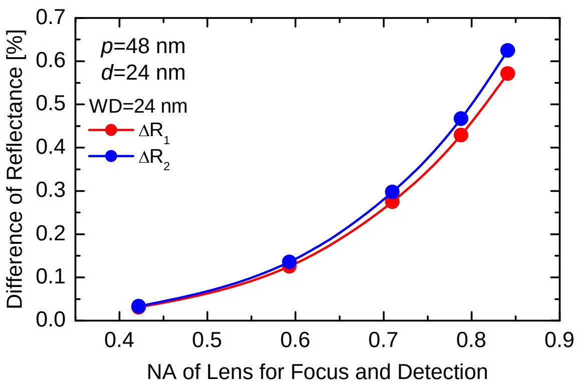


Fig. 4. ΔR_1 and ΔR_2 calculated as a function of NA of the lens for focus and detection.

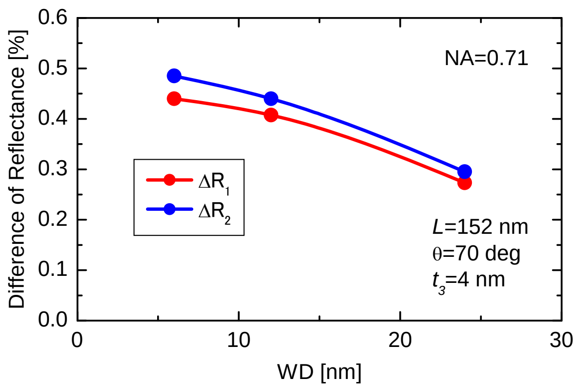


Fig. 5. ΔR_1 and ΔR_2 calculated as a function of WD when NA=0.71.

When WD was reduced to be 6 nm, for example, values of ΔR_1 and ΔR_2 increased to be 0.44% and 0.49% (1.6 times).

3.4 Further high-density examination

In order to evaluate the potential for high-density terabyte-class optical memory, two models of media were examined. One medium has a 5 x 5 square array of nanoparticles with p=24 nm and d=12 nm that provides the recording density of 1.12 Tb/inch^2 (capacity of 1.6 TB as a 12-cm diameter disk). The other one has a 7 x 7 hexagonal close-packed array with p=16 nm and d=12 nm that gives the recording density of 2.91 Tb/inch^2 (capacity of 4.1 TB). In these media, t_3, t_5 and t_6 were reduced to be 2 nm in addition to h=18 nm (1.5d) both for 1.12 Tb/inch^2 and 2.91 Tb/inch^2 media. The nanoantenna had a conical apex with R=6 nm. Other parameters were the same as for 0.28 Tb/inch^2 medium that was described in 3.1. In accordance with the thin-layer thickness t_3, t_5 and t_6 = 2 nm in these models, the smallest cell size of 0.5 nm was used in the Y direction for the FDTD analysis.

Figure 6 plotted the cross-write calculated as a function of recording density and recording capacity. At WD=12 nm, cross-write by absorption was as good as 0.43 in 1.12 Tb/inch^2 medium, while it degenerated to 0.58 in 2.91 Tb/inch^2 one. When WD=6 nm, for example, the cross-write values were improved to be 0.28 and 0.41, respectively.

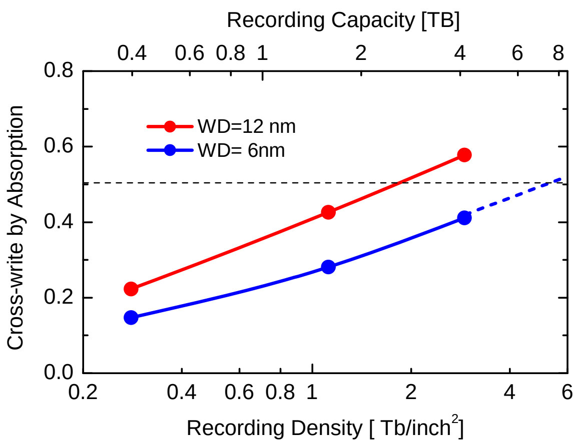


Fig. 6. Cross-write calculated as a function of recording density and recording capacity (ϕ 12 cm).

Thermal analysis is necessary to estimate the limit of the recording density. By an analysis to solve heat conduction equations based on the calculated absorption distributions, it was found that thermal cross-write was close to the cross-write by absorption. It is because the heat generated in phase-change nanoparticle tended to propagate to metal layers in the –Y direction.

In reproduction at WD=12 nm for 1.12 Tb/inch^2 medium, ΔR_1 and ΔR_2 were 0.12% and 0.15% for NA=0.71, and were improved to 0.26% and 0.30% for NA=0.84, respectively. In reproduction at WD=12 nm for 2.91 Tb/inch^2 medium, ΔR_1 and ΔR_2 were calculated to be 0.05% and 0.08% for NA=0.71 and were 0.11% and 0.16% for NA=0.84, respectively. By the decrease of WD and further optimization of parameters in high-density models, the values of ΔR_1 and ΔR_2 would be improved.

4. Conclusion

Performances of recording and reproduction were examined in the same setup by using FDTD method. It was demonstrated that a combination of a nanoantenna with such a medium so as to enhance plasmonic resonance enabled effective near-field recording with ~10 times larger WD than for a conventional medium with phase-change thin film. A reproduction method of detecting the intensity of the reflected light from the nanoantenna was also proposed. For a crystalline nanoparticle, plasmonic resonance induced in the nanoantenna was enhanced and the intensity of reflected light was also increased. Calculated results showed that our proposed system and methods for recording and reproduction would have a potential for terabyte-class optical memory system. The research on phase-change nanoparticles has started and their fabrication process and experimental crystallization properties were reported [4, 5]. As the next step, the experimental examination will be approached in the proposed optical memory.

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