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Polarization State of Scattered Light in Apertureless Reflection-mode Scanning Near-Field Optical Microscopy

Yongfu Cai[1], Mitsuharu Aoyagi[1], Akira Emoto[2], Tatsutoshi Shioda[3], and Takayuki Ishibashi[1]*

[1]Department of Materials Science and Technology, Nagaoka University of Technology, Niigta 940-2188, Japan
[2]National Institute of Advanced Industrial Science and Technology (AIST), Ibaraki 305-8565, Japan
[3]Department of Electrical Engineering, Nagaoka University of Technology, Niigta 940-2188, Japan

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We studied the polarization state in an apertureless scanning near-field microscopy (a-SNOM) operating in reflection mode by using three-dimensional Finite-difference Time-domain (FDTD) method. As a result, the electric field around tip apex in the near-field region enhanced four times stronger than the incident light for p-polarization when the tip-sample separation was 10 nm. We find that the p- and s-polarization state is maintained for the scattered light when the probe is perpendicular to the sample. When the probe is not perpendicular to the sample, the polarization state of scattered light will rotate an angle that equals to the inclination angle of probe with p-polarization illumination. On the other hand, the polarization state will not rotate with s-polarization illumination.

Keywords : scanning near-field optical microscopy, FDTD, magneto-optical, near-field optical, polarization state

1. Introduction

Magneto-optical scanning near-field optical microscopy (MO-SNOM), based on scanning near-field optical microscopy (SNOM), has become a powerful tool for observing the magnetic domains with a high spatial resolution exceeding the diffraction limit of the visible light. In order to obtain magneto-optical (MO) signal, the polarization state of the light scattered from the sample should be preserved. Many groups have reported MO-SNOM with transmission-mode by using a tapered fiber-probe coated metal with an aperture [1-3]. Considering that most of magnetic materials are opaque, however, an apertureless reflection-mode MO-SNOM is the most suitable technique for the MO imaging. Recently, many groups are interested in the aptertureless reflection-mode SNOM (a-SNOM), and reported a spatial resolution of 10 nm [4]. However, there was no report on the polarization properties of the scattered light in a-SNOM as far as we know, although there are reports on the extinction ratio of light emitted from the aperture of the fiber-probe. More recently, we have reported that the extinction ratio larger than 100 in a-SNOM [5]. It seems that the polarization state is preserved. On the other hand, we found that the phase difference of scattered light with p- and s-polarization light illuminated is deviated from 90 degrees, which is approximately 80 degrees. In this paper, we report a simulation of the polarization property of scattered light by using the three-dimensional Finite-difference Time-domain (FDTD) method, in addition to experimental results on SNOM measurements.

2. FDTD Simulation in Ideal Case

The FDTD method is a straightforward calculation of Maxwell's equations in both time and space. In our simulation, we used a commercial soft named FullWAVE (RSoft Design Group, Inc.).

Fig. 1 shows a schematic drawing of a simulation model used in this study. A conical probe made of silicon ($n = 5.476 + i0.310$ at the wavelength of 408 nm) with an extremity's radius of 7 nm and a solid angle of 15 degrees is located above the Cr ($n = 1.80 + i3.61$ at the wavelength of 408 nm) film. A distance between the probe and the Cr is 10 nm. A pulse plane wave with a wavelength of 408

*Corresponding author: Tel: +81-25-847-9311
Fax: +81-258-47-9311, e-mail: t_bashi@mst.nagaokaut.ac.jp

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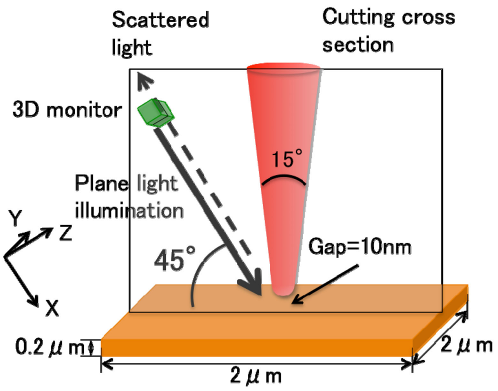

Fig. 1. (Color online) Schematic diagram of the simulation model.

nm and a pulse width of 2.1 fs impinges on the tip and the sample with an incident angle of 45 degrees. 3D monitors are located in front of light source to record the electric field of incident light and in the behind of light source to record the electric field of scattered light. The size of our model is 3 × 3 × 3 μm^3, using 3 × 3 × 3 nm^3 cell. The probe is set with normal to the Cr surface to study fundamental polarization properties of a-SNOM, although there is an inclination of approximately 10 degrees in the actual experiment.

Fig. 2 shows a cross section of a distribution of an

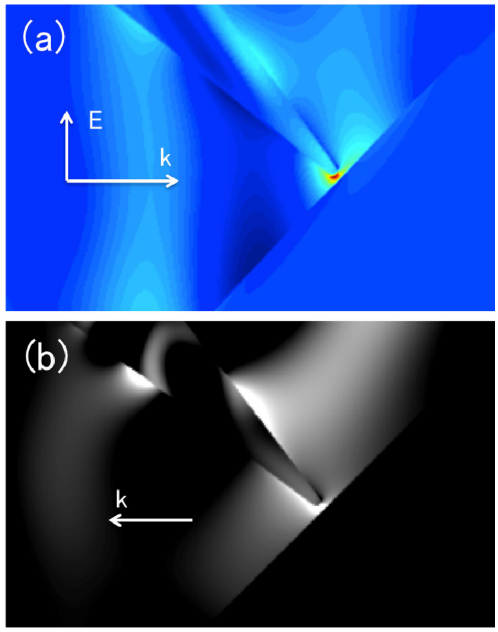

Fig. 2. (Color online) Sectional field distribution including the probe and the sample with p-polarization illumination, (a) evanescent field and (b) scattered light.

electrical field *Ez* for the p-polarization illumination. Fig. 2(a) and 2(b) show images when the incident light is impinging the top of the tip and the scattered light is com-

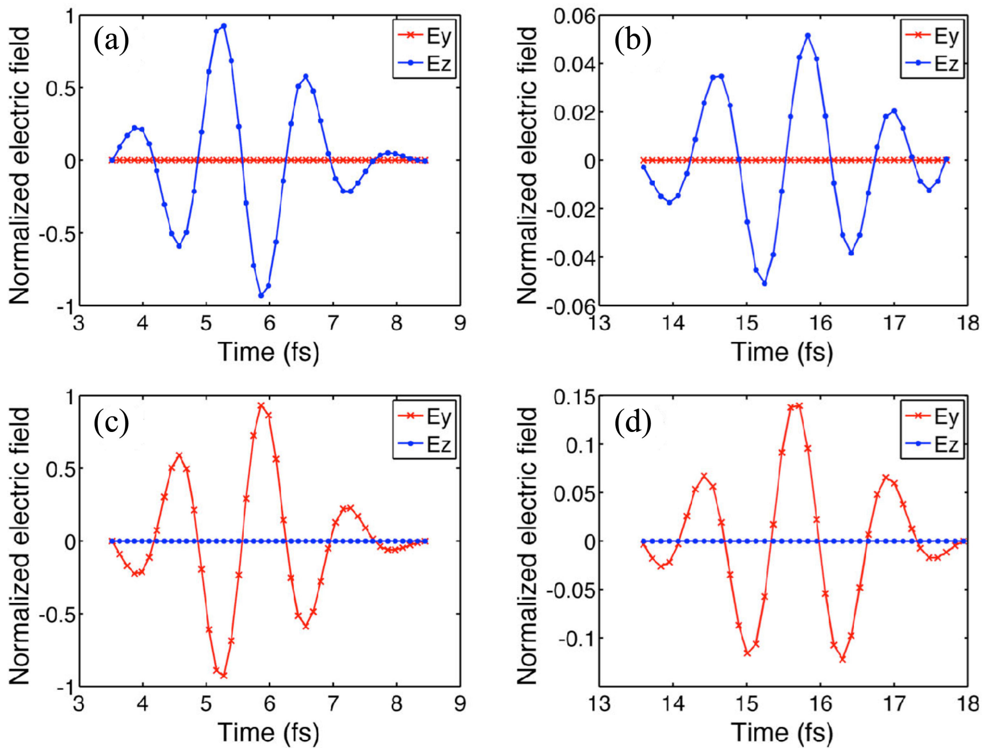

Fig. 3. (Color online) Electric field recorded by monitor vs. time. Electric field of (a) incident light and (b) scattered light with p-polarization illumination, (c) incident light and (d) scattered light with s-polarization illumination.

ing back, respectively. The enhancement of the electric field around the top of the probe is clearly observed in Fig. 2(a), which is 4.5 times stronger than that of the incident light. The scattered light from the evanescent field propagating to the left is also clearly observed in Fig. 2(b). When the tip and the sample are illuminated by s-polarization, an enhancement of the electric field at the top of the probe is not clearly observed. However, we could observe the scattered light from the gap between the tip and the sample.

Fig. 3(a) and 3(b) show the electric fields *Ey* and *Ez* of incident light and those of the scattered light for p-polarization illumination. Fig. 3(c) and 3(d) show the electric fields *Ey* and *Ez* of the incident light and those of the scattered light for s-polarization illumination. It is clearly observed that the incident light with p-polarization, polarized along z-direction and *Ey* = 0, propagates and the scattered light polarized along z-direction comes back in the same way as the incident, which is indicating the p-polarization is preserved. In the case of s-polarization, we also found that the s-polarization is preserved. As a result, we conclude that the polarization state of the linearly polarized light could be preserved in a-SNOM in the ideal cases.

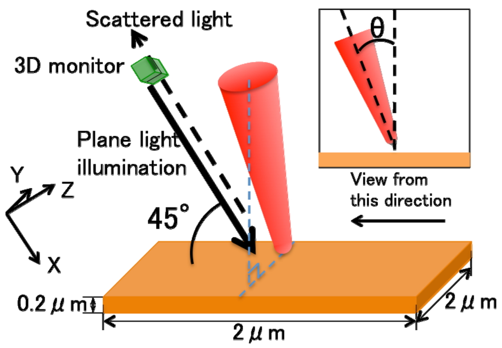

Fig. 4. (Color online) Schematic diagram of the simulation model with an oblique probe.

3. Polarization State Dependence on the Inclination of Probe

Regarding the phase difference observed in the experiment, we consider that it is due to the inclination of the probe at the present situation. For further understandings, we have investigated the polarization depending on the

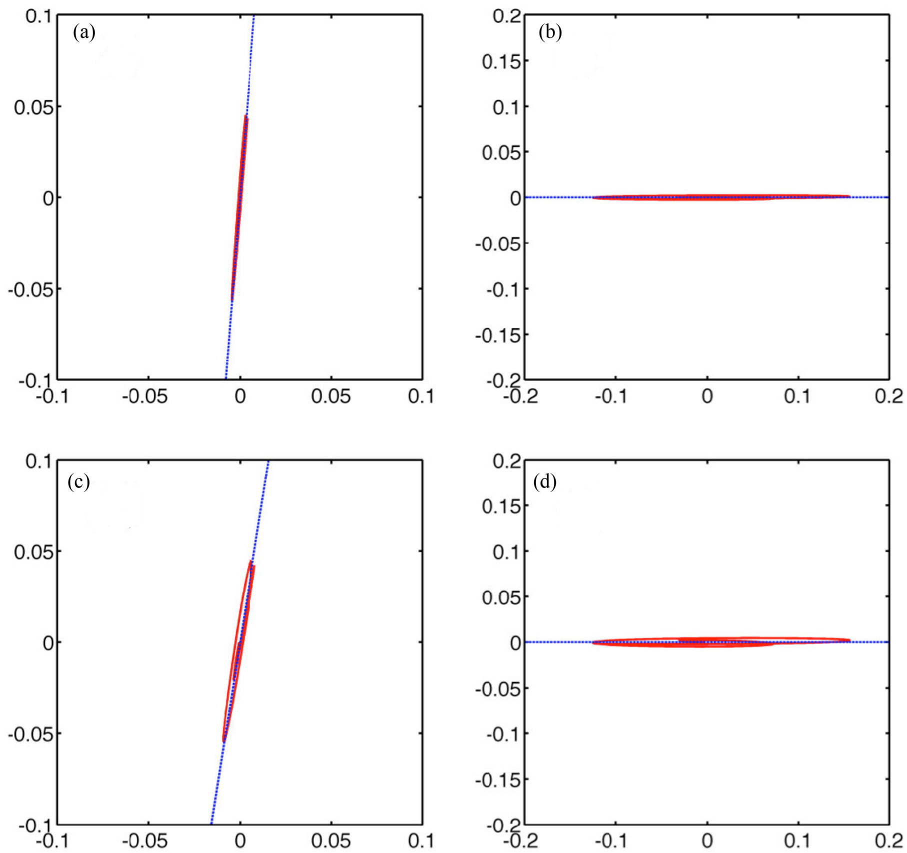

Fig. 5. (Color online) Polarization state of scattered light with (a) p-polarization and (b) s-polarization illumination when inclination angle is 5 degrees, (c) p-polarization and (d) s-polarization illumination when inclination angle is 10 degrees.

inclination of the probe, since the scattered light is generated by an interaction between a light and a system including a sample and a probe.

Fig. 4 shows a schematic drawing of a simulation model with an oblique probe. Viewing from the right side of the model, we can see the probe has an inclination of θ degrees with the normal line of the sample. The other parameters are same to the model used in section 2.

The solid lines in Fig. 5(a) and 5(b) show the polarization state of the scattered light with p- and s- polarization light illumination when θ is 5 degrees. The solid lines in Fig. 5(c) and 5(d) show the polarization state of the scattered light with p- and s- polarization light illumination when θ is 10 degrees. It is shown that the polarization state of the scattered light is linear polarization when the inclination angle is 5 degrees; on the other hand, the polarization state of the scattered light is elliptical (nearly linear) polarization when the inclination angle is 10 degrees. The dotted lines in Fig. 5(a) and 5(b) show the slope of the linear polarization, and we can see the phase difference of Fig. 5(a) and 5(b) is 85 degrees. The dotted lines in Fig. 5(c) and 5(d) show the long axes of the elliptical polarization, and we found that the angle between two long axes (i.e. the phase difference of Fig. 5(c) and 5(d)) is about 80 degrees that agrees with the experimental result.

However, basing on the simulation results, the extinction ratio of the scattered light will not be higher than 100 when the inclination angle is 10 degrees. Perhaps, the high extinction ratio observed in the experiment should be due to the vibration of the probe. Because, the inclination angle is changing when the probe is vibrating. On the basis of Fig. 5, we know that when the inclination angle becomes smaller (5 degrees), the extinction ratio will be higher.

In conclusion, it is important to consider the influence of the inclination of the probe when investigating the polarization state of scattered light. For MO measurement, we need to investigate for the circularly polarized light because MO effect originates in the difference in responses for right- and left-circularly polarized lights.

4. Conclusion

In order to make an explanation to the high extinction ratio (lager than 100) of scattered light from the a-SNOM [5], we have performed a 3-dimension FDTD simulation to calculate the polarization state of the scattered light. The results of the simulation showed that the polarization state is preserved in the scattered light for both p- and s-polarization incident light illumination when the probe is perpendicular to the sample. When the probe is not perpendicular to the sample, the polarization state is relevant to the inclination angle of the probe. When the inclination angle is small, the extinction ratio is larger; otherwise, the extinction ratio is smaller. Consequently, the a-SNOM setup we used has the potential to be developed into an MO-SNOM, and it is essential to consider the influence of the inclination of the probe when investigating the polarization state of the apertureless SNOM.

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