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Stimulated emission depletion phenomenon in luminescence of Ce: LSO excited by soft X-rays

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A stimulated emission depletion (STED) phenomenon occurred in the luminescence of a Ce-doped Lu_2SiO_5 crystal (Ce:LSO) excited by soft X-rays using BL-11D beamline, when the scintillator was simultaneously irradiated with azimuthally polarized laser light. The observed spot size of the luminescence was reduced by the STED phenomenon. Application of this STED scintillator emission to a two-dimensional sensor is one promising method to reduce the pixel size of SX cameras.

1 Introduction

The spatial resolution of a stimulated emission depletion (STED) microscope is represented by the modified Abbe diffraction limit [1]. When the spatial resolution δd_N of an ordinary objective lens at a wavelength λ is given by the Abbe diffraction limit, $\delta d_N = \lambda/2\mathrm{NA}$, where NA is the numerical aperture of the objective lens. The spot diameter δd_{STED} of the luminescence spot limited by the STED is given by the modified Abbe diffraction limit is

$$\frac{\delta d_{\mathrm{STED}}}{\delta d_N} = \frac{1}{\sqrt{1+I_{\mathrm{STED}}/I_{\mathrm{sat}}}}, \qquad (1)$$

where I_{sat} is the fluorescent saturation intensity of the phosphor, I_{STED} is the light intensity of the stimulated emission light at the focal plane, and $I_{\mathrm{STED}}/I_{\mathrm{sat}}$ is referred to as the normalized laser intensity [1].

Some scintillators have demonstrated the STED phenomenon under UV light excitation, such as Tb:LSO scintillators, and the possibility of realising a super-resolving microscope using a scintillator has been proposed [2]. If this STED phenomenon can be applied to detection of the luminescence image of the scintillator plate, the spatial resolution of the luminescence image will decrease and exceed the Abbe diffraction limit [1].

One scintillator, Lu_2SiO_5 crystal doped with cerium atoms (Ce:LSO), shows that the luminescence intensity has a maximum value at a wavelength, 400 nm and shows a tail structure on the long-wavelength side from the peak [3]. Because the Lu atoms in the LSO crystal are located at two different sites and the Ce atoms that are introduced randomly displace Lu atoms, the Ce atoms are thus also coordinated to the two different sites. The dominant transitions of the luminescence are from the lowest unoccupied Ce 5d state to the two occupied Ce 4f states: the $2F_{5/2}$ and $2F_{7/2}$ orbitals. Therefore, the Ce:LSO luminescence spectrum shows four different luminescence peaks. In this paper, we demonstrate the STED phenomenon in the luminescence of Ce:LSO that has been excited by SX light and the area limits of the luminescence region using vector light at the weak luminescent wavelength of Ce:LSO.

2 Experimental

A laser diode (L520P50, Thorlabs Inc.) having a wavelength of 520 nm with the power of 50 mW in maximum used as a STED light source. The light emitted from the laser was introduced into the vector light optical system, which is composed of a light-vortex optical system and a vector-vortex optical system, and the vortex phase can be canceled by adding the vortex phases having $e^{+i\theta}$ and $e^{-i\theta}$, respectively (Fig. 1) [4]. The sample Ce: LSO was optically polished to a thickness of 0.2 mm and had a size of 5 × 5 mm^2.

Beamline BL-11D was used as an SX light source for the SX excited STED experiment. Since the facility operated in "Top-Up Mode" at the time of the measurement, no normalization was performed by the incident SX light intensity in the STED experiment. The wavelength resolution of the incident SX light was $\lambda / d\lambda = 1000$. For the reduction of a STED light spot and the enlargement of a scintillator image, a self-made microscope system was used (Fig. 1). The reflection light of STED light and the luminescence light of the scintillator were separated from the light from a sample by a dichroic mirror with an optical filter which was inserted between an infinity-corrected objective lens (NA = 0.2, 10X) and an imaging lens.

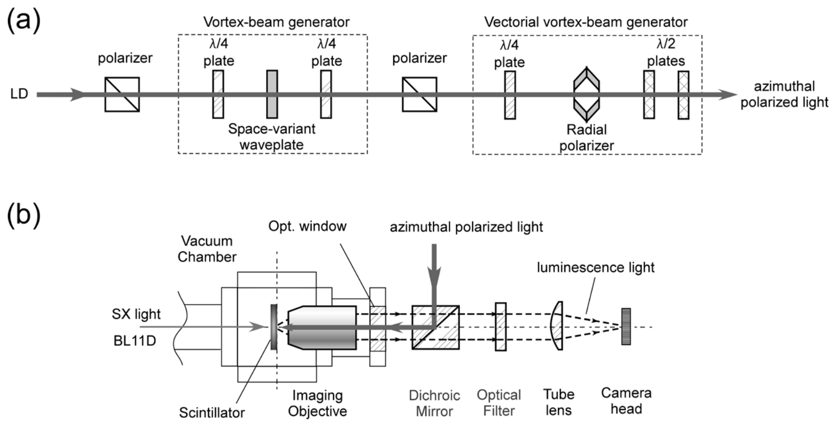

Fig. 1: Layout of optics, (a), vector generation optical system, (b), microscope unit for SX excitation.

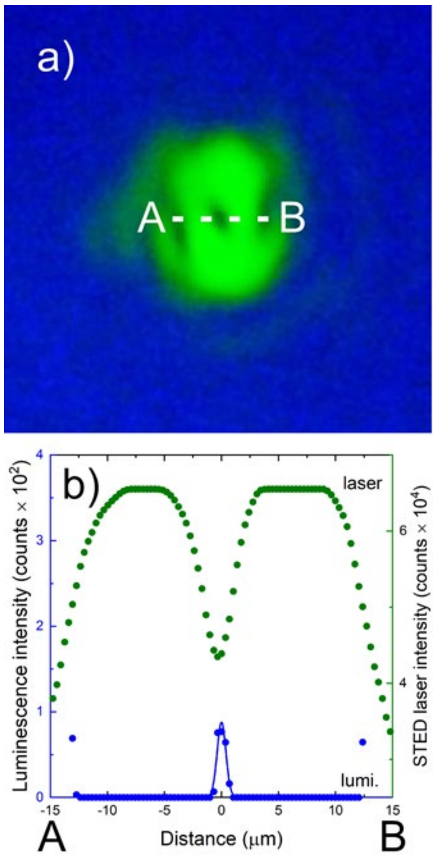

Fig. 2 : Luminescence of the Ce:LSO,(a), and intensity profile at line A-B,(b).

A camera head for detecting images has 2560 × 1920 pixels, and color filters deposited on it operates in the wavelength range of B (390 to 510 nm), G (480 to 600 nm), and R (580 to 680 nm). Thus, the camera head can separate the color of an image, therefore the excitation light and the luminescence light if the colors of the lights are different. The obtained light intensities of the STED light and the scintillator's luminescence were normalized by the measurement time and the number of pixels. The effective NA values of the objective lens was 0.044 at the SX excitation measurements.

3 Results & Discussion

Figure 2(a) shows the emission point excited at the wavelength 403 nm with the STED beam spot irradiated. The light intensity profile between the points A and B is also plotted in Fig. 2(b). In this case, the diameter of the emission point was 1/16 of the STED beam diameter. The STED phenomenon of the scintillator excited by an SX light of the photon energy, 800 eV, was also confirmed [4].

4 Summary

A phenomenon of STED occurred in the luminescence of a Ce doped Lu_2SiO_5 crystal (Ce: LSO) excited by UV or SX light when the scintillator was irradiated with azimuthally polarized laser light with the wavelength 520 nm. The size of the luminescence reduced by the STED phenomenon and decreased also as the increase of the light intensity of the STED laser.

Acknowledgments

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