§9. Study of Atomic Excitation by Optical Vortex and its Application to a Novel Laser Spectroscopy

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The Doppler effect is induced by the phase change by the movement of an observer or source. The plane wave, which is commonly used for laser spectroscopy, has the flat wave front. Therefore, the induced Doppler shift is limited in the propagating direction of the laser beam. Recently electromagnetic waves which have twisted wave front are intensively studied in the field of high-resolution microscopy, optical tweezers, etc. The number of twists in one wavelength is called as the topological charge. The propagation mode is called as optical vortex (OV). The phase of OV changes linearly with the azimuthal angle around the beam center. Therefore the center of OV is a phase singularity, and its intensity is zero. Since OV has a three-dimensional phase structure, the motion in the light field causes the Doppler shift in all the three-dimensional directions[1]. It is described as follows:

$$\delta_{LG} = -\left[k + \frac{kr^2}{2(z^2+z_R^2)}\left(\frac{2z^2}{z^2+z_R^2} - 1\right) - \frac{(2p+|m|+1)z_R}{z^2+z_R^2}\right]V_z - \left(\frac{krz}{z^2+z_R^2}\right)V_R - \left(\frac{m}{r}\right)V_\phi \qquad (1)$$

,where V_z, V_R, and V_φ are the axial, radial and azimuthal velocity components of a moving atom, *m* is the topological charge, *r* is the radius from the singular point. The leading term of the V_z component is the usual Doppler shift $-kV_z$. We neglect the V_R component, since it is much smaller than the other components. Our current study aims to observe the azimuthal Doppler component. Since the V_z and V_φ components will be mixed into a single Doppler spectrum, development of a decomposition method is required. We performed a modified saturated absorption spectroscopy to separate the azimuthal Doppler shift from the other Doppler components. In the spectroscopy, a plane-wave pump laser and an OV probe laser are used. The excitation volume of the plane wave is perpendicular to V_z axis in the phase space, on the other side, the three-dimensional Doppler components of the OV define a tilted excitation volume. Although the plane-wave pump laser cancels the V_z–Doppler component, the azimuthal Doppler shift remains in the saturated dip. Therefore, the saturated dip is composed of the homogeneous broadening and the V_φ-Doppler broadening. Since the V_φ-Doppler effect depends on the radial position, the variation of the dip width gives the information of the azimuthal Doppler effect.

Figure 1 shows the experimental setup for the modified saturated absorption spectroscopy. An external cavity diode laser (ECDL) was tuned at 697nm for the excitation of an argon metastable atom. The laser beam is separated into the pump laser and the probe laser. The probe laser was converted to OV by a computer generated hologram displayed on the spatial light modulator (SLM). The images of the OV probe laser were recorded as the wavelength of the ECDL was scanned. The saturated absorption spectra are constructed using the variation of the beam intensity at each pixel.

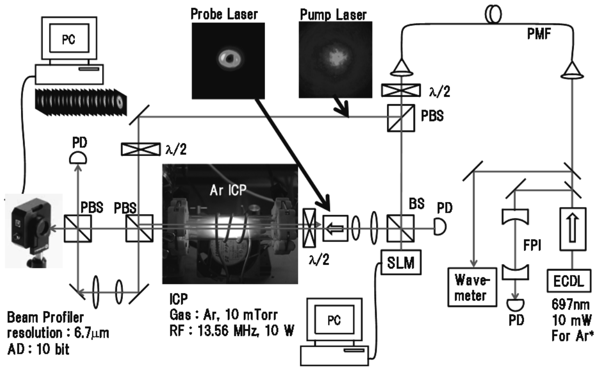

Fig. 1. Experimental setup for OV laser spectroscopy.

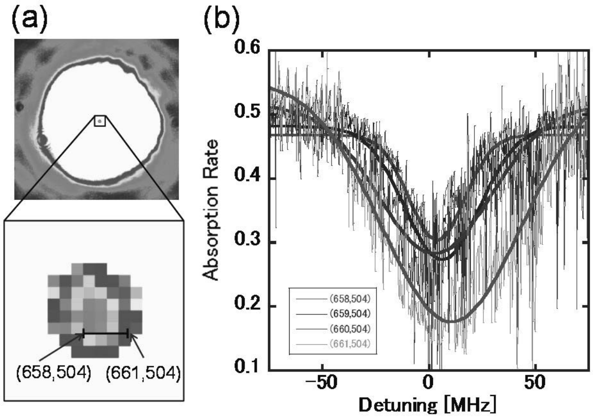

Fig. 2. (a) A picture of OV probe laser. The inset shows the singular point of the beam. (b) The dips of saturated absorption spectra constructed at the 4 pixels, respectively.

Figure 2(a) shows an intensity profile of the OV probe laser. Since the spectra obtained near the dark singularity are required, the images are recorded with long exposure time to increase the signal level. The 4 pixels (from (658, 504) to (661, 504)) located near the singular point are used to construct the saturated absorption spectra. Figure 2(b) shows the absorption dips of the saturated Doppler absorption spectra. Although the signal to noise ratio of the spectra is not good, the spatial variation of the dip width is still clear. The dip width consists of the azimuthal Doppler shift and the homogeneous broadening. In order to perform quantitative analysis of the azimuthal Doppler component, improvement of the spectroscopy system is planned in the next year.

1) L. Allen, et al.: Optics Communications 112 (1994) 141-144.