# §1. Study of Atomic Excitation by Optical Vortex and Its Application to a Novel Laser Spectroscopy

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Recently electromagnetic waves which have twisted wave front are intensively studied in the field of high-resolution microscopy, optical tweezers, etc. The propagation mode is called as Laguerre-Gaussian mode, or so-called optical vortex (OV). The phase of OV changes linearly with the azimuthal angle around the beam centre. Therefore, the centre of OV is a phase singularity, and light intensity is zero at the phase singularity. 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]. Therefore, the OV Doppler spectroscopy is expected to be able to detect the multidimensional dynamics simultaneously. OV's Doppler shift is described as follows:

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

,where $V_z$, $V_R$, and $V_\phi$ are the axial, radial and azimuthal velocity of a moving atom, $l$ is the topological charge, $r$ is the distance from the singular point. The leading term is the usual Doppler shift $-kV_z$. Our current study aims to observe the azimuthal Doppler component. We performed a modified saturated absorption spectroscopy to separate the azimuthal Doppler component from the other components. In the spectroscopy, a plane-wave pump beam and an OV probe beam are used. The excitation volume of the plane wave is perpendicular to $V_z$ axis in the velocity space, on the other side, the OV Doppler components define a tilted excitation volume. By using the difference of the excitation volume configuration, the information of the azimuthal Doppler shift is obtained.

Figure 1 shows the experimental setup for the optical vortex saturated absorption spectroscopy. An external cavity diode laser (ECDL) was tuned at 697 nm for the excitation of an argon metastable atom. The laser beam is separated into the

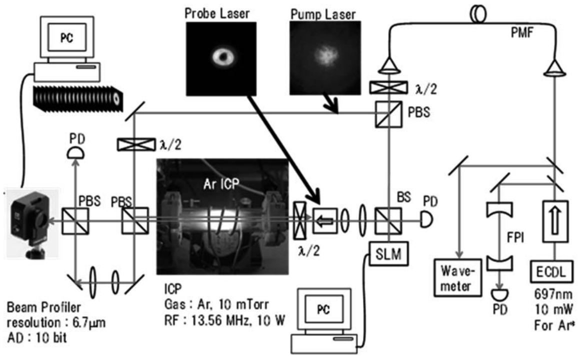


Fig. 1. Experimental setup for OV laser spectroscopy.

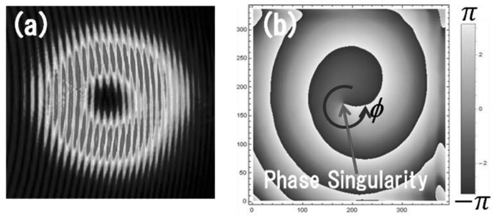


Fig. 2. (a) Interference pattern of the OV beam and the quasi-plane wave. (b) The phase profile of the OV beam in the beam cross-section.

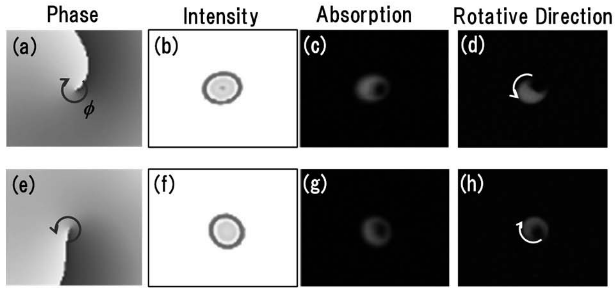


Fig. 3. The figures show the profiles of phase, intensity, absorption, and rotation direction of absorption dip of $l = +1$ beam ((a) – (d)) and $l = -1$ beam ((e) – (h)), respectively.

pump beam and the probe beam. The probe beam was converted to OV beam by a computer generated hologram displayed on the spatial light modulator (SLM). The intensity profiles of the OV probe beam were recorded with and without discharge as the wavelength of the ECDL was being scanned. The dependence of absorption profile on the laser wavelength is animated using the OV probe beam images. The interference patterns of the OV beam and the quasi-plane wave were also observed for the derivation of the phase structure of the OV probe beam.

Figure 2(a) shows an interference pattern of the OV beam and the quasi-plane wave. The two-dimensional Fourier transformation of the interference pattern was performed, and then the grid component was filtered. Figure 2(b) shows the phase profile obtained by the inverse Fourier transformation of the filtered Fourier component. From the phase profile, the location of the phase singularity and the topological charge were obtained[2].

The panels in Fig. 3 show the profiles of phase, intensity, absorption, and rotation direction of absorption dip of $l = +1$ beam ((a) – (d)) and $l = -1$ beam ((e) – (h)), respectively. Since the effect of azimuthal Doppler shift increases near the dark phase singularity, the intensity profiles were recorded with long exposure time to increase the signal level around the phase singularity. The local reduction of the absorption ratio was found as a dark spot near the phase singularity. The location of the dark spot rotates around the phase singularity as shown in Fig. 3(d) and (h). Since the rotation direction depends on the sign of the topological charge, it should be generated by the azimuthal Doppler shift. Further improvement of the imaging quality is required for the quantitative evaluation of the azimuthal Doppler shift.

1) L. Allen, et al., Optics Commun. 112 (1994) 141-144.
2) K. Yamane, et al., New J. Phys. 16, 053020 (2014).