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Development of Optical Vortex Doppler Spectroscopy: Azimuthal Doppler Shift and Phase Gradient

Mitsutoshi Aramaki
Nihon University
e-mail: aramaki.mitsutoshi@nihon-u.ac.jp

Recently the topological light sources have been developed by controlling the spatial structure of phase and polarization of the laser beam. By utilizing the spatial structure of light, the topological lasers can potentially add new functions to the traditional laser applications. In this study, we apply the optical vortex, which is one of the topological laser light, to the Doppler spectroscopy. Since the optical vortex beam has twisted wave front, the motion in the light field induces the Doppler shift in all the three-dimensional directions. We are developing the spectroscopic method sensitive to the flow perpendicular to the propagating direction of light, which is not detectable by the conventional Doppler spectroscopy.

Since the Doppler shift is caused by the additional phase shift by the movement, the Doppler shift in the plane wave occurs only in the light propagating direction. On the other side, since the optical vortex has twisted wave front, the motion in the light field causes the Doppler shift in all the three-dimensional directions [1]. The Doppler shift of the optical vortex is described as follows:

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

,where V_Z, V_R, and V_ϕ are the axial, radial and azimuthal velocity components of the atom, l is the topological charge, r is the distance from the beam center (phase singularity). In this study, we ignore the small terms in Eq. (1), and adopt Eq. (2) as the Doppler shift in the optical vortex.

$$\delta_{LG} = -kV_Z - \left(\frac{l}{r}\right)V_\phi \quad (2)$$

As a proof-of-principle experiment, the optical vortex Doppler absorption spectroscopy was performed in an inductively coupled plasma. In addition to the absorption spectroscopy, the phase distribution of the optical vortex was observed and the expected Doppler shift was evaluated using the results. Inductively coupled plasma is generated using a spiral antenna with applied RF power at 13.56 MHz. Argon gas is introduced through a thin tube along the discharge tube. The typical gas flow velocity was 200 m/s. An external cavity diode laser (ECDL) was tuned at 697nm for the excitation of the argon metastable generated in the plasma. Gaussian beam is converted to the optical vortex beam (l = ±1) or the plane wave (l = 0) using the computer generated hologram displayed on the spatial light modulator (SLM). The generated probe beams are introduced to the plasma from the direction perpendicular to the gas flow and are used for the Doppler absorption spectroscopy. The images of the probe laser were recorded by the sCMOS camera (Andor Zyla5.5) while scanning the wavelength of the ECDL. The Doppler absorption spectra are obtained by collecting the beam intensity at each pixel of the images, and the azimuthal Doppler shift induced by the beam crossing gas flow is derived as the shift from the Doppler spectrum observed with the plane wave.

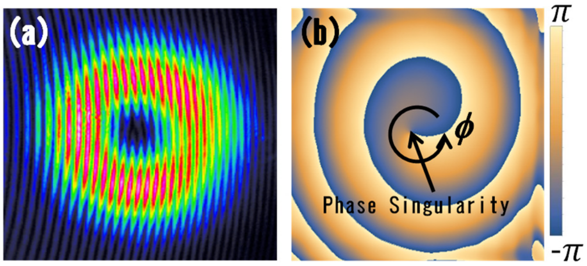

Fig.1 (a) Interference pattern of optical vortex and tilted quasi-plane wave, (b) phase profile of optical vortex.

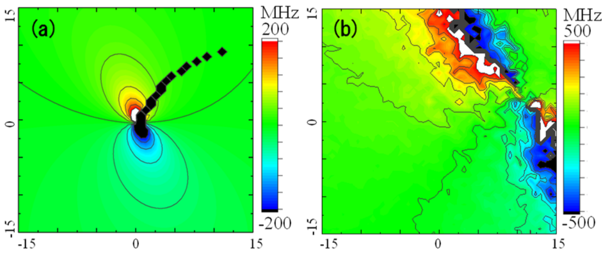

Fig.2 (a) Doppler shift distribution calculated from phase gradient, (b) Doppler Shift distribution obtained by the optical vortex Doppler absorption spectroscopy.

Figure 1(a) shows the interference pattern of the optical vortex and a tilted quasi-plane wave. By performing two-dimensional Fourier transformation on Fig. 1(a) and calculating phase at each pixel, the phase profile is obtained (Fig.1(b)). Since the optical vortex of l=1 is used for the experiment, the phase varies 2π around the phase singular point. Since the probe laser was introduced from the perpendicular direction to the gas flow, the distribution of the azimuthal Doppler shift is calculated from the phase gradient and gas flow velocity in the beam crossing direction. Figure 2(a) shows the expected azimuthal Doppler shift in the 200 m/s gas flow in the horizontal direction. The phase singularity is in the center of Fig. 2(a), and the sign of the azimuthal Doppler shift is inverted above and below it. Figure 2(b) shows the distribution of the azimuthal Doppler shift obtained from the shift of the Doppler spectra observed at each of the pixels. The experimental results qualitatively agree with the calculated shift distribution. The detail of the consistency among the experimentally obtained azimuthal Doppler shift, the expected value from phase gradient, and the theoretical value will be discussed.

References

[1] L. Allen, et al.: Opt. Comm. 112 (1994) 141-144.