Multi-dimensional Doppler Spectroscopy Using an Optical Vortex Laser

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The Doppler effect is caused by the additional phase change by the movement of an observer. As shown in Fig. 1 (a) and (b), the plane wave, which is commonly used for laser spectroscopy, has the flat wave front, and its phase is constant in a cross section. Therefore, the induced Doppler shift is limited in the propagating direction of the laser beam. Recently electromagnetic waves which have twisted wave front (see Fig.1 (d)) are intensively studied in the field of high-resolution microscopy, optical tweezers, etc. The number of twists in one wavelength is 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 (see Fig.1 (e)). Therefore the center of OV is a phase singularity, and the intensity is zero (see Fig. 1(f)). 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:

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

,where V_z, V_R, and V_φ are the axial, radial and azimuthal velocity components of the 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 obtain the information of the azimuthal Doppler shift from the V_φ component. Since the V_z and V_φ components will be mixed into the single Doppler spectrum, development of a decomposition method is required. We performed a modified saturated absorption spectroscopy to get the azimuthal Doppler signal.

Figure 2 shows the experimental setup for OV laser spectroscopy. An external cavity diode laser (ECDL) was tuned at 697nm for the excitation of an argon metastable atom. The laser beam is separated

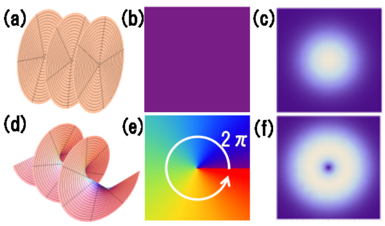

Fig. 1: (a) (d) *wave front,* (b) (e) *phase profile in cross section, and* (c) (e) *intensity profile of plane wave and optical vortex, respectively.*

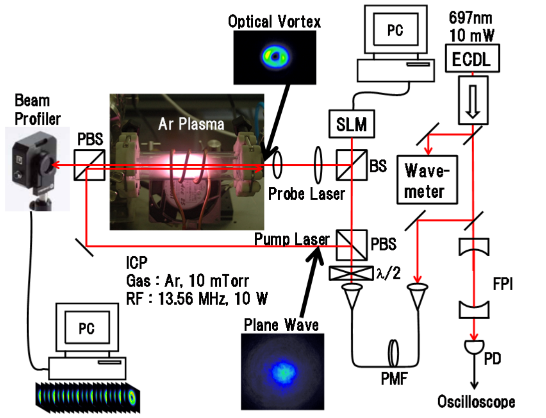

Fig. 2: *Experimental setup of OV laser spectroscopy*

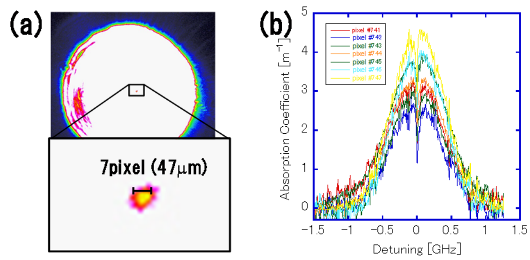

Fig. 3: (a) *A picture of OV probe laser. The inset is the singular point of the beam. (b) The saturated absorption spectra constructed at the 7 pixels.*

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 variation of the intensity at each pixel.

Figure 3(a) shows a picture of OV probe laser. The 7 pixels located near the singular point are used to construct the saturated absorption spectra shown in Fig. 3(b). 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. The concept of optical vortex spectroscopy, the development of the OV laser system, and some results of the proof-of-principle experiment will be presented.

References

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