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Development of Optical Vortex Laser System for Plasma Flow Measurement
プラズマ流計測のための光渦レーザーシステムの開発

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A cross-disciplinary collaboration research project has been initiated to develop a novel plasma diagnostics using a Laguerre-Gaussian-mode laser beam or an optical vortex. Atoms moving across the optical vortex experience an additional Doppler shift in their resonant wavelengths, which can be used to provide a new degree of freedom to conventional Doppler spectroscopy. For that purpose, a tunable optical vortex laser source has been developed, in which an optical vortex beam is obtained as a diffracted light from a spatial light modulator that displays a computer-generated hologram pattern.

1. Introduction

Laser spectroscopy is a powerful nonintrusive technique to measure various important quantities in plasmas. For instance, the laser Doppler spectroscopy is used to obtain absolute flow velocities of both ions and neutrals, the latter of which cannot be measured with electrical probes. However, the obtainable velocity component is, in principle, limited to the projection onto the path of the laser. This limitation may be overcome by using Laguerre-Gaussian (LG) modes (optical vortex) instead of using conventional Hermite-Gaussian (HG) modes.

One of the remarkable properties of the LG beam is that it carries an orbital angular momentum (OAM) [1, 2]. It follows that an atom in the LG beam feels an additional Doppler effect even in the transverse direction against the wave vector. Therefore it is expected to give a new degree of freedom to LDS.

2. Optical vortex and azimuthal Doppler shift

The LG modes are a set of cylindrically symmetric solutions to the Helmholtz equation with the paraxial approximation. The complex amplitude u of the LG modes can be described as follows:

$$u_p^l(r,\phi) \propto L_p^l(2r^2/w^2)e^{-r^2/w^2}e^{-il\phi}, \qquad (1)$$

where L denotes a Laguerre polynomial with p+1 radial nodes, w the beam waist, and m the *topological charge*. Equiphase surfaces for HG and LG beams are shown in Fig. 1. The equiphase surface of HG beam is perpendicular to the wave vector. In contrast, the equiphase surface of LG beam is a helical sheet whose pitch is proportional to the topological charge m. Because of the phase structure, this propagation mode of light is called as optical vortex. The intensity of LG modes vanishes at the center of the beam, because a phase singularity is required to form such phase structure. As a consequence of the helical phase front, the Poynting vector draws a spiraling curve, which is the origin of OAM along the beam axis.

The principal part of the Doppler shift in the optical vortex is given as follows [3]:

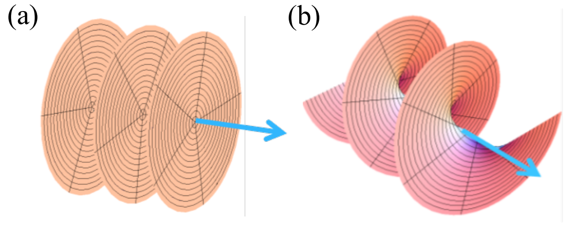

Fig. 1. Equiphase surface of (a) HG beam and (b) LG beam (m = -1). Arrows show the wave vectors.

$$\delta_{\mathrm{LG}} \approx -kV_z - \left(\frac{m}{r}\right)V_\phi. \qquad (2)$$

The terms arising from non-uniformity of the beam are neglected in the above expression. The first term is the usual axial Doppler effect. On the other hand, the second term is the azimuthal Doppler shift associated with the spatial phase structure of the optical vortex.

3. Producing optical vortex with hologram

There are several ways to produce optical vortex in a laboratory. In this study, we have adopted the hologram method because of the flexibility on wavelength selection and the controllability of topological charge [4]. A hologram on the spatial light modulator (SLM) is a calculated interference pattern between a fundamental HG beam and a desired LG beam. When the pattern is illuminated by the original HG beam, the LG beam is obtained as the first order diffracted light. An example of the hologram and the intensity distribution of resultant LG beam are shown in Fig. 2. Singularity at the center of the beam is clearly seen in Fig. 2 (b). The phase structures of higher-order LG beams with the topological charge up to ten have been measured by interference method. Although it is still needed to optimize the mode purity and the transmission optics, the controllability of topological charge has been confirmed.

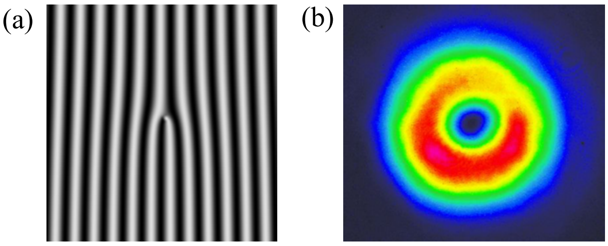

Fig. 2. (a) Computer-generated hologram (CGH) displayed on SLM. (b) Intensity distribution of LG beam.

4. Plans for proof-of-principle experiment

We have been considering proof-of-principle experiments for optical vortex laser Doppler velocimetry in the direction perpendicular to the laser path. As the first step, we have been developing laser absorption spectroscopy (LAS) for metastable argon neutrals (The laser wavelength is 696.7 nm, which excites the $4s'[3/2]^o_2$ state of argon atoms). Because the azimuthal Doppler shift in eq. (2) depends on the radial position from the center of the beam, two-dimensional (spatially resolved) transmitted light intensity measurement is required in the optical vortex LAS experiment.

In order to make the shift sufficiently large enough to measure, possible options are as follows:

(i) Using LG beam with large topological charge m.
(ii) Measuring at the immediate vicinity of the singularity.
(iii) Making high-speed flow across the beam.

Simultaneous attainment of the conditions (i) and (ii) has been difficult so far; it is because the size of dark region around the singularity expands with the number of topological charge. Optimization of the hologram and transmission optics may improve the situation. The condition (iii) is possible to realize by using a gas puffing system with a Laval nozzle that can produce supersonic neutral flow. Preparation of the system to install on the HYPER-I device [5] is now underway.

Another option is the saturated absorption spectroscopy (SAS), in which the HG beam is used as pump while the LG beam is used as probe light. In the conventional SAS using HG beams, the Lamb dip appears in the absorption spectrum. The width of the Lamb dip is significantly narrower than the Doppler broadening of neutral particles. In our previous work on high accuracy flow velocity measurement using laser-induced fluorescence (LIF) method, the Lamb dip was used as the frequency (wavelength) standard [6]. When the probe beam is replaced by LG mode beam, the resonant absorption condition is altered by the azimuthal Doppler shift, which may give rise to the modification of the shape of the Lamb dip. Because the original Lamb dip is completely Doppler shift free and Doppler broadening free, the slight modification in the spectrum imposed by the azimuthal Doppler shift can be noticeable.

Acknowledgments

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References

[1] L. Allen et al.: Phys. Rev. A **45** (1992) 8185.
[2] J. P. Torres and L. Torner (ed.): *Twisted Photons* (Wiley-VCH, Weinheim, Germany, 2011).
[3] L. Allen et al.: Opt. Comm. **112** (1994) 141.
[4] N. R. Heckenberg et al.: Opt. Lett. **17** (1992) 221.
[5] M. Y. Tanaka et al.: Rev. Sci. Instrum. **69** (1998) 980.
[6] M. Aramaki et al.: Rev. Sci. Instrum **80** (2009) 053505.