Time-resolved phase imaging of femtosecond laser-induced air plasma with high spatial resolution

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Femtosecond laser pulses focused in ambient air can ionize gas molecules and generate air plasma. Such air plasma is routinely utilized in some well-known applications, such as long-range atmospheric filamentation propagation [1] and two-color terahertz generation [2] and is also expected to affect other ambient-condition laser applications, such as laser processing [3]. For advancing the understanding or use of such phenomena, clarifying the basic physics of the highly non-linear air-ionization process is important; the precise measurements of air-plasma characteristics then become necessary for physical model validation [4].

Air plasma is often measured by time-resolved pump-probe experiments. By using phase-sensitive detection of the probe light, for example, by interferometry, one can determine the complex refractive index of the plasma. This allows for the direct determination of both time- and space-resolved dynamics of physical quantities such as electron density and plasma temperature [5]. On the other hand, a major difficulty for interferometric measurements is realizing a high spatial resolution; a low resolution will lead to spatially averaged results with low accuracy. The spatial resolution of interferometric images is determined not only by the numerical aperture of the microscope objective, as in traditional microscopy, but also by the spatial pitch of interference fringes [6]. Finer fringes will tend to higher resolution, but this requires larger shearing angles between the interference and reference light; such efforts have not been well-explored due to a more complicated experimental setup.

In this study, we constructed a time-resolved optical phase imaging system based on a combination of the pump-probe setup and a Nomarski interferometer, a type of polarization interferometer where a Wollaston prism separates a beam into two diverging beams, which are then sent through a second polarizer to create spatially shifted interference images (Fig. 1). While Nomarski interferometers typically use Wollaston prisms with small separation angles of a few milliradians [7], here we specially design a setup using a large separation angle (5°) prism, to form interference fringes with fine fringe spacing. This configuration enables the acquisition of the whole spatial frequency domain determined by the objective lens aperture and probe light wavelength. The spatial resolution is characterized as 0.87 µm with a homemade resolution target, as shown in Fig. 2(a). We show a time-resolved phase image (delay time of 1 ps) of air plasma measured with our system in Fig. 2(b). Air plasma (the negative phase-delay region) is generated along the optical axis and splitting behavior caused by laser-plasma interactions can be clearly observed. Such precise and accurate results are important for the qualitative comparison with nonlinear air-propagation models of femtosecond laser light.

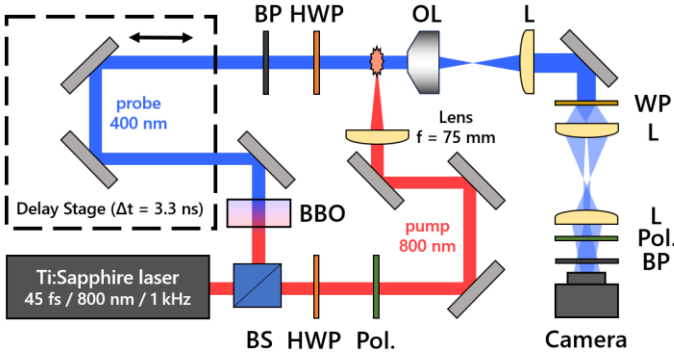

Fig. 1: Experimental setup for our experiments. BS: beam splitter, HWP: half waveplate, Pol.: polarizer, L: lens, BP: bandpass filter, OL: objective lens, WP: Wollaston prism.

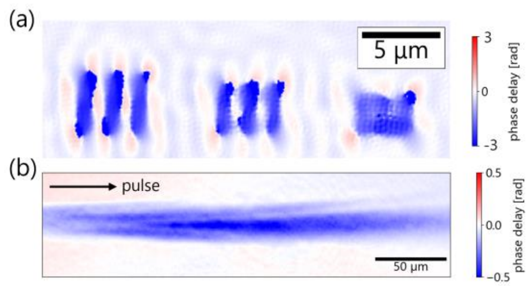

Fig. 2: (a) Phase image of homemade resolution target. (b) Obtained side-view phase shift by laser-induced air plasma (delay time of 1 ps).

References

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