Application of Phase Retrieval for Predicting a High-Intensity Focused Laser Field

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Abstract: Multiple-focal-plane spatial phase retrieval for a chirped-pulse-amplification laser is demonstrated for the first time. Advantages of this method are simplicity of setup, ability to measure angular dispersion, and potential integration into precision, on-shot focal-spot diagnostics.

OCIS codes: (100.5070) Phase retrieval; (120.3940) Metrology; (320.7100) Ultrafast measurements

Phase retrieval is a powerful technique for wavefront sensing and optical metrology [1,2]. Despite this, the application of phase retrieval to ultrafast laser wavefront characterization has been scarce [3]. The lack of interest so far may have come from the necessity of intensive numerical processing involved with phase retrieval, whereas Shack–Hartmann wavefront sensors or lateral-shearing interferometers can obtain a single-shot wavefront in real time. One may find, however, the usefulness of phase retrieval in cases where direct wavefront sensing is difficult to implement, such as inside an experimental target chamber. Phase retrieval can be performed by using multiple near-field intensity measurements [3] or multiple-plane focal-spot measurements [2]. For characterization of the focusing beam inside the target chamber, it is suitable to use multi-plane focal-spot measurements. This approach is also practical because a focal-spot microscope is readily available as one of the basic diagnostics for any experiment. The present summary consists of two parts: We first present a working strategy for retrieving wavefront from a chirped-pulse–amplification (CPA) laser system using multi-plane focal-spot measurements. In the second part, we show a successful prediction of the focal spot from a modified input beam using the retrieved phase information.

Subtle modifications in the phase-retrieval strategies are required for ultrafast laser beams compared with simple continuous-wave-laser sources based on the following observations: First, laser-beam shapes from high-power lasers often have deviations from perfect geometrical figures such as a circle or a rectangle because the beam shapes are determined by pump beams and apodizers in the source. Second, the spatial field of ultrafast laser beams might be wavelength dependent due, for example, to angular dispersion or longitudinal chromatic aberrations.

The irregularity of the laser-beam boundary does not pose a serious problem if a point-by-point phase-retrieval approach is used [1]. In the presence of noise, however, the retrieved point-by-point phase map may contain many discontinuous regions. Thus we apply a modal approach that is more robust to noise. Basis functions for irregular boundaries can be rigorously constructed by the Gram–Schmidt process. We may, however, satisfactorily use well-known basis functions such as Zernike or Legendre polynomials with the constraint that the integration needed for modal coefficient calculation is performed only within the laser-beam boundary. These quasi-basis functions were found suitable for our calculations. In our case, we have used the Legendre basis with up to 120 terms.

We measured focal spots of an attenuated optical-parametric-chirped-pulse–amplified (OPCPA) beam [4] focused by an *f*/4 off-axis paraboloid at five different planes near focus. The distances to each plane measured from the focus are –500, –250, 0, 250, and 500 μm, respectively. The OPCPA is attenuated by half-wave plates and polarizers, Fresnel reflection, and neutral-density filters inside the microscope. The focal spot was imaged to an effective 14-bit, scientific-grade charge-coupled device by an infinity-corrected microscope system (Mitutoyo 10X, numerical aperture = 0.26). The objective was mounted on a remotely controlled translation stage, and the position of the objective was optically monitored using a target-viewing system. We obtained a set of modal phase coefficients that minimize an error metric, which quantifies the difference between the measured data and the intensity computed from the phase estimate, by an optimization routine under the assumption that the field is monochromatic. Figure 1 shows lineout comparisons at each plane after completion of the algorithm. We note generally good agreement in every plane except at the focused plane (first row, third column); the blurring of the focal spot in the horizontal direction is due to angular dispersion caused by a slight misalignment of the compressor gratings. The angular dispersion was independently measured to be 47 μrad over 7-nm bandwidth by marking the band-pass–filtered focal-spot position change from 1050 nm to 1057 nm. Thus we find it better to exclude the zero-defocus plane measurement in the search algorithm. On the other hand, the focus plane measurement can be used to estimate the amount of angular dispersion. The amount of angular dispersion estimated from phase-retrieval results is 50 μrad, which agrees with the independently measured value within 7 % relative error.

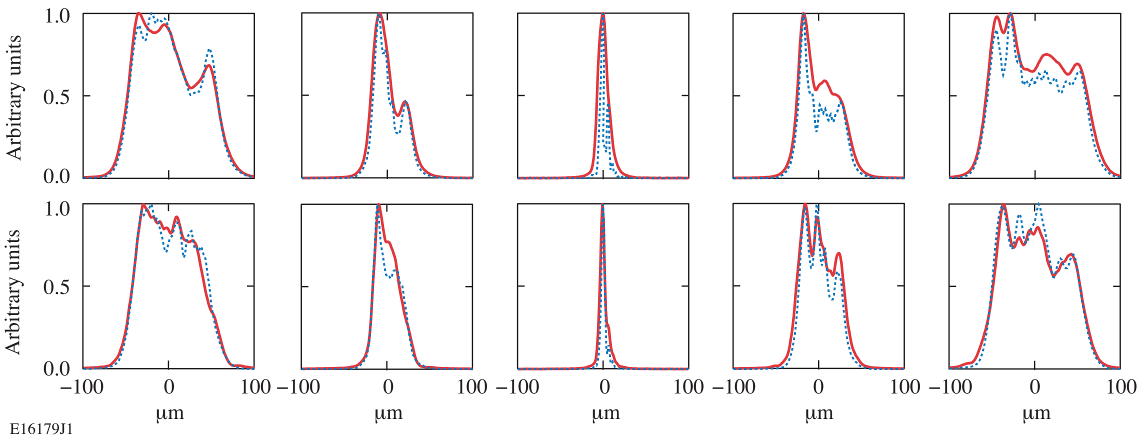

Fig. 1. Horizontal (first row) and vertical (second row) lineout comparisons at each plane. The solid lines are from measurements, and the dashed lines are from the phase-retrieval calculations. Distances are 500, 250,0, –250, –500 μm from the left column to the right.

Once the wavefront of the focusing beam is successfully characterized, this information can be used to predict focal spots at higher energies by separately measuring the differential wavefront change. As shown in Fig 2(a), a Shack–Hartmann sensor (Imagine Optic, 128 by 128 lenslets) on the diagnostic table measures sets of wavefronts belonging to the same beam used in the phase retrieval. The difference in the two wavefronts should explain the non-common-path aberrations from the wavefront sensor location to the target chamber. With the non-common-path aberrations quantified, the prediction of focal-spot distribution under a different circumstance should be possible by a single wavefront measurement at the diagnostic table. To validate this idea, an aberrated, transmissive element was placed before the leaky mirror. The directly measured focal spot [Fig. 2(b)], is in good agreement with the predicted focal spot as shown in Fig. 2(c).

We have shown that the application of phase retrieval helps to extend our focal-spot diagnostics capability for high-intensity lasers beyond conventional direct wavefront measurements. Not only does it add versatility in the wavefront sensing methods, but it also provides additional information such as residual angular dispersion from the CPA system.

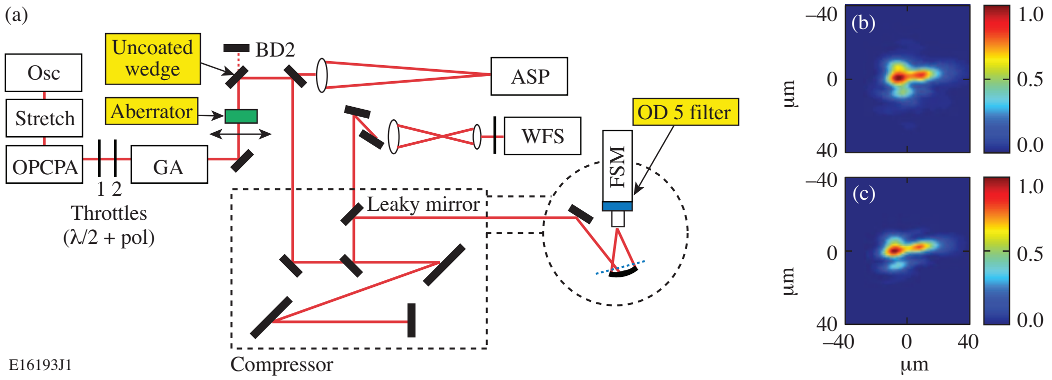

Fig. 2. (a) Experimental setup for predicting focal spot. GA: glass amplifier (turned off); FSM: focal-spot microscope; WFS: wavefront sensor; ASP: pointing sensor. OD5 filter is placed between the objective and the tube lens. (b) Measured focal spot. (c) Predicted focal spot.

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