Validity of wave-front reconstruction and propagation of ultrabroadband pulses measured with a Hartmann–Shack sensor

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Wave-front reconstruction for ultrabroadband laser pulses is verified by use of a Hartmann–Shack sensor. We estimate the accuracy of numerical wave-front propagation by comparing numerical with experimental results and verify that wave fronts of ultrabroadband laser pulses from a hollow fiber can be propagated correctly by a single polychromatic wave-front measurement to a place where detection is not practicable, e.g., inside a vacuum chamber or laser focus. © 2005 Optical Society of America

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Many experiments in laser physics profit from the knowledge and control of the laser beam wave front. In the past, improvements in laser beam quality led, for example, to near-diffraction-limited focusing,[1] higher yield in second-harmonic generation,[2] and improved output of extreme-ultraviolet radiation[3] using different methods for wave-front characterization. Beam wave front, spatial irradiance distribution, and coherence properties are needed for a reliable prediction of beam propagation. The wave front can be reconstructed by several different techniques, such as the Wigner distribution function,[4] transport equations of intensity,[5] point diffraction interferometry,[6] and lateral shearing interferometry.[7] Coherence properties can be determined analogously to the Young's double-slit experiment, and the spatial irradiance distribution might be measured with a conventional two-dimensional CCD camera. In our experiment we use a Hartmann–Shack sensor for wavelength detection, which is simple to handle, fast in detection, compact, and suitable for single-shot measurements.[8–11]

Wave-front measurement, reconstruction, and numerical propagation are unambiguously defined only for monochromatic radiation.[12] To our best knowledge, none of the above-mentioned wave-front sensors' accuracy has been investigated for ultrabroadband laser pulses (spectral bandwith larger than 100 THz). We demonstrate, for what is believed to be the first time, that a Hartmann–Shack detector can be used to measure broadband pulses and that numerical propagation of a broadband laser pulse's wave front, based on this measurement, is indeed accurate. Moreover, we demonstrate that a single Hartmann–Shack measurement of a broadband laser pulse is sufficient to predict its wave front at a different beam position. Therefore, our results show that such a wave front can be numerically propagated correctly to places where detection is not practicable (for example, in a vacuum chamber or a laser focus) but where knowledge of the wave front is important for studying physical processes depending highly on beam quality parameters.[3]

The following procedure is used for checking proper reconstruction of a broadband pulse's wave front: First, the wave front of the laser pulse is split into contributions of individual quasi-monochromatic subwavefronts. Each is then accurately reconstructed by a separate Hartmann–Shack measurement. Second, these individual wave-front contributions are added with an algorithm described below. The resulting wave front is finally compared with the measured laser beam's wave front comprising all spectral parts.

Accurate propagation of a broadband laser pulse's wave front is verified in a similar manner. Quasi-monochromatic wave fronts measured at one point are numerically propagated individually to another beam position and compared with the corresponding measured wave fronts. All measurements described above are performed with the main objective to demonstrate that numerical wave-front propagation of a broadband laser pulse requires just a single measurement of the spectrally integrated wave front.

The experimental setup is shown in Fig. 1. Pulses from a conventional Ti:sapphire amplifier system

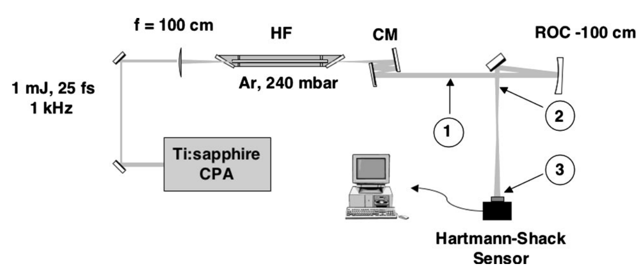

Fig. 1. Experimental setup with a Ti:sapphire chirped-pulse amplification (CPA) system and a hollow fiber compression stage: HF, hollow fiber with an inner diameter of 400 μm filled with Ar (240 mbars); CM, chirped mirrors for pulse compression, a focusing mirror [radius of curvature (ROC) −100 cm]; Hartmann–Shack sensor with computer and positions of wave-front measurements [positions (pos.) 1, 2, and 3].

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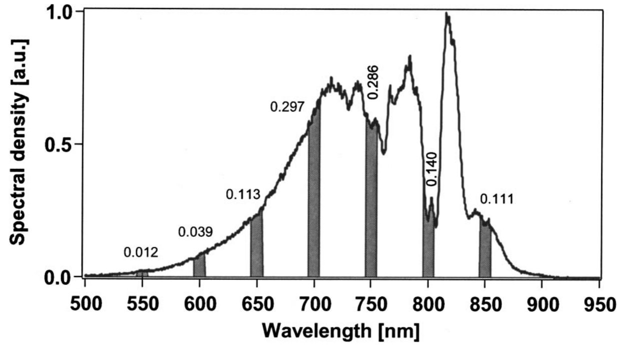

Fig. 2. Normalized laser spectrum after spectral broadening in an Ar-flooded hollow fiber. The gray bars represent locations of spectral filters used in the experiment. The values show the normalization factors used for constructing the wave front from individually spectral wave-front contributions.

(25-fs, 1-mJ, 1-kHz) are focused into a 60-cm-long glass capillary (inner diameter 400 μm, 240 mbar Ar), yielding an ultrabroadband spectrum (Fig. 2). The Hartmann–Shack sensor is used to detect wave fronts at three different positions in the beam path (Fig. 1), 140 cm behind the capillary (position 1), 30 cm after a focusing mirror with a focal length of 50 cm (position 2), and finally 25 cm behind its focus (position 3). Information about the sensor and its calibration can be found in Ref. 9.

For verification of correct wave-front reconstruction, quasi-monochromatic wave fronts are generated by inserting high-surface-quality interference filters (D-Series, Chroma Technology) into the beam path. Each exhibits a narrowband transmission of 10 nm (FWHM) at different center wavelengths varying from 550 to 850 nm in steps of 50 nm (Fig. 2). These individual wave fronts W are detected by the Hartmann–Shack sensor at position 1. Under the assumption that a polychromatic laser beam can be described in good approximation by a superposition of slightly distorted monochromatic plane waves, the overall polychromatic wave front can be visualized as a sum of monochromatic wave fronts, each balanced with a factor given by the corresponding normalized spectral irradiance of the laser beam (Fig. 2). Reconstruction of the polychromatic wave front and its aberrations then leads to the results depicted in Figs. 3(a) and 3(c). For comparison, a Hartmann–Shack measurement performed without any interference filters that is evaluated for the mean wavelength (750 nm) is given in Figs. 3(b) and 3(d). The accordance between the measured and calculated data is remarkable and justifies the above-mentioned approximation: the corresponding Zernike coefficients (see Ref. 14 for definition) of both wave fronts (Table 1) are almost identical for defocus (1.7% deviation), which contributes most to the wave front, and for coma (<1.6%). Slightly larger differences between measured and reconstructed wave fronts are observed for spherical aberration (17%) and fourfold astigmatism (10%). The measured wave-front aberration surface shows a dip in the center of the beam, which is a consequence of higher-order beam distortions' also being retrieved nicely in the reconstructed wave front. Small irregularities are observed only at the beam's edge and may be partially ascribed to the reduced accuracy given by weak illumination of the sensor. Chromatic aberrations of the detector's microlens array appear to be negligibly small since only the center of gravity of each beamlet is determined. Any influence of the spectral bandwidth on wave-front reconstruction is therefore expected to remain below the uncertainty level given by statistical fluctuations, cross talk, background, and imperfections of the reference wave front. The excellent overall agreement clearly indicates that a single Hartmann–Shack measurement of an ultrabroadband pulse evaluated for the mean wavelength is accurate for satisfying wave-front reconstruction.

For numerical propagation of a wave front one can apply the Fresnel integral, if the laser beam is monochromatic and in the paraxial approximation. Since the latter condition is satisfied in our experiment, subdividing the broadband laser pulse in quasi-monochromatic subwavefronts permits individual propagation and subsequent reconstruction of the polychromatic wave front following the method described above. We verified the accuracy of numerical wave-front propagation by performing the same set of measurements at beam position 2 (Fig. 1) and at farther position 3. The wave-front aberrations of different spectral components were numerically propagated from position 2 toward position 3 and were found to deviate only barely from the measured aberration at position 3. The high similarity in the aberration of different spectral wave-front components suggests that numerical propagation of a beam's wave-front recorded by a single Hartmann–Shack measurement is feasible without the need for spec-

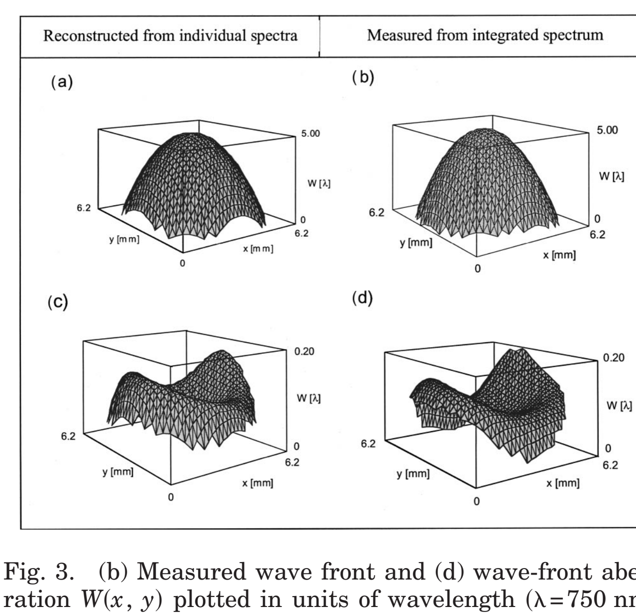

Fig. 3. (b) Measured wave front and (d) wave-front aberration $W(x, y)$ plotted in units of wavelength ($\lambda = 750$ nm) for a polychromatic laser pulse 140 cm behind the hollow fiber exit (position 1), evaluated for a mean wavelength of 750 nm on a circular area of 3.1 mm radius. Reconstruction by spectral contributions yields (a) the wave front and (c) its aberration, showing good agreement with corresponding measured quantities (see Table 1).

Table 1. Comparison of Zernike Coefficients for the Polychromatic Wave Fronts Shown in Fig. 3, Recorded by a Single Hartmann–Shack Measurement (Measured) and Reconstructed by Its Spectral Wave-front Components (Calculated), Evaluated on a Circular Area of 3.1 mm Radius

Acquisition Mode	Defocusing (μm)	Coma (nm) (x dimension)	Coma (nm) (y dimension)	Spherical Aberration (nm)	Fourfold Astigmatism (nm)
Measured	−1.76	21.9	−62.0	−19.9	−10.6
Calculated	−1.73	21.6	−63.0	−23.2	−9.5
Difference	0.03 (1.7%)	0.3 (1.4%)	1.0 (1.6%)	3.3 (17%)	1.1 (10%)

tral filtering: depicted in Figs. 4(b) and 4(d) is the polychromatic wave front and its aberrations measured at position 3 and evaluated for mean wavelength 750 nm, respectively. Under the same conditions a wave front is recorded at position 2 and numerically propagated to position 3, yielding the result shown in Fig. 4(a). The curvature stems from the beam's sphere and is in good agreement with the corresponding quantity of the measured wave front. The residual aberrations [Fig. 4(c)] are determined to be small. This excellent agreement shows that prediction of a wave front at a certain beam position is accurate even for broadband laser pulses. The M^2 value, obtained from a single Hartmann–Shack measurement, is close to 1.1, in agreement with earlier measurements.[15]

In conclusion, we have demonstrated that the Hartmann–Shack sensor is suitable for characterization of broadband laser pulses by reconstruction of a polychromatic wave front from its quasi-monochromatic subwavefronts. We showed furthermore that numerical propagation is accurate by applying just one single Hartmann–Shack detection to the laser beam, making wave-front prediction possible at places where recording is not practicable.

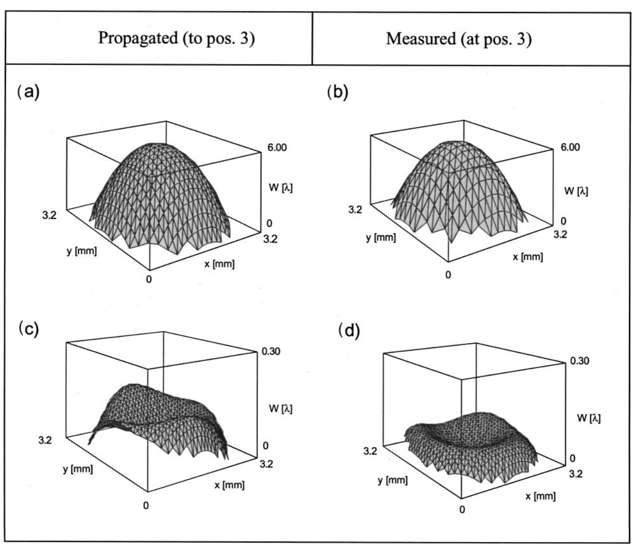

Fig. 4. (a) Spectrum-averaged wave front and (c) its aberrations obtained by propagation from position 2 to position 3 and corresponding (b) measured wave front and (d) aberrations at position 3.

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