Characterization, wavefront reconstruction and propagation of ultra broadband laser pulses from Hartmann-Shack measurements

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Hartmann-Shack wavefront measurements of ultra-broadband pulses, produced by focusing pulses from a Ti-Sa oscillator-amplifier system into an Argon filled hollow fibre are presented, showing, that the total wavefront can be sensed reliably by a single wavefront measurement. Opportunities of the Hartmann-Shack technique in ultra-short pulse sensing are briefly discussed.

1 Introduction

During the last years improvements in laser beam quality led to near-diffraction-limited focusing [1], higher yield in second-harmonic generation [2], or improved output of XUV radiation [3] by using different methods for wavefront and beam profile characterization as an input for proper beam control and manipulation. The wavefront can be reconstructed by several different techniques [4-7], and the spatial irradiance distribution might be measured with a conventional CCD camera. However, some methods for wavefront reconstruction involve high experimental effort, others are slow or restricted to monochromatic light sources. Therefore, we use the Hartmann-Shack (H.-S.) sensor, which is simple to handle, fast in detection, compact and suitable for single-shot measurements [8-10]. Moreover, both, wavefront *and* irradiance distribution, which are needed for a reliable prediction of coherent beam propagation, are determined simultaneously by a H.-S. measurement.

2 Experimental Setup

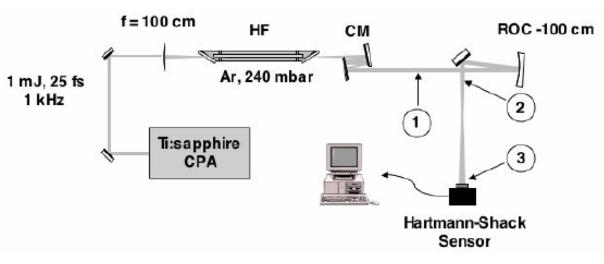

Fig. 1 *Experimental setup with Hartmann-Shack measurement positions (pos. 1, 2 and 3).*

The experimental setup is shown in Fig. 1. Pulses from a Ti:sapphire amplifier system, delivering 25 fs, 1 mJ pulses at a repetition rate of 1 kHz are focused into a 60-cm long glass capillary (inner diameter 400 µm), filled with 240 mbar of argon [11].

During propagation inside the capillary the laser pulse interacts with the gas and new spectral components are generated covering an ultrabroad spectral range of more than 190 THz (Fig. 2). The H.-S. sensor is used to detect wavefronts at three different positions along the beam path (fig. 1). It consists of a 40 by 30 micro-lens array, the spot positions being detected with a 12-bit CCD camera positioned in the back focal plane of the array. For verification of correct wavefront reconstruction, quasi-monochromatic wavefronts are generated by inserting interference filters in the beam path. Each of them exhibits a narrow-band transmission of 10 nm (FWHM) at different centre wavelengths varying from 550 nm to 850 nm in steps of 50 nm (Fig. 2).

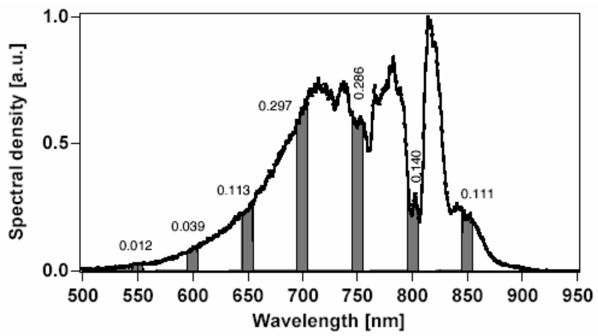

Fig. 2 *Normalized laser spectrum after broadening (cf. text). Grey boxes and numbers indicate the filter position and the normalization factors for wavefront reconstruction, respectively.*

3 Experimental Results

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 wavefront can be written as a sum of monochromatic wavefronts, each of them balanced with a factor given by the corresponding normalized spectral irradiance of the laser beam (Fig.2). Reconstruction of the polychromatic wavefront aberrations then leads to the results depicted in Fig. 3b. For comparison, a H.-S. measurement performed without any interference filters is given in Fig. 3a, which is evaluated for a mean wavelength of 750 nm. The accordance between measured and calculated data is remarkable and justifies the above-mentioned approximation.

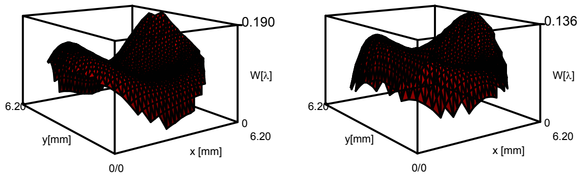

Fig. 3 *Wavefront aberrations reconstructed from a polychromatic measurement (left) and from incoherent superposition of spectrally resolved H.-S. records (right).*

Corresponding Zernike coefficients (see ref. [12] for definition) of both wavefronts (table 1) are almost identical for defocus, which contributes most, and for coma. Slightly larger differences are observed for spherical aberration (17 %).

Acq. Mode Aberration	Full spectrum measurement	Assembled from spectral components	Rel. Deviation
Defocus (Z_3)	$-1.76\ 10^{-3}$	$-1.73\ 10^{-3}$	1.7%
Coma$_x$ (Z_6)	$2.19\ 10^{-5}$	$2.16\ 10^{-5}$	1.4%
Coma$_y$ (Z_7)	$-6.2\ 10^{-6}$	$-6.3\ 10^{-6}$	1.6%
Spherical (Z_{12})	$-1.99\ 10^{-5}$	$-2.32\ 10^{-5}$	17%

Tab. 1 *Comparison of some lower order Zernike coefficients for different modes of data acquisition*

For numerical propagation of a polychromatic beam the Fresnel integral for each quasi-monochromatic field amplitude u_ω applies separately according to

$$u_\omega(x,y,z)=\frac{ike^{ikz}}{2\pi z}\iint_\infty \left\{ \begin{array}{l} \sqrt{I_\omega(x',y',0)}\cdot e^{ikw_\omega(x'y',0)} \times \\ e^{\frac{ik\left[(x-x')^2+(y-y')^2\right]}{2z}} \end{array} \right. dx'\,dy' \qquad (1).$$

With the spectral irradiance I_ω, the spectral wavefront w_ω, the propagation distance z and the wave number $k=\omega/c$. To verify the accuracy of numerical wavefront propagation the same set of measurements were performed at beam position 2 (fig. 1) and at farther position 3. Figure 4 shows good agreement of measured polychromatic aberrations at pos. 2 (right figure) and those numerically back-propagated over a distance of 66 cm from pos. 3 towards pos. 2 (left figure), passing the beam focus in between.

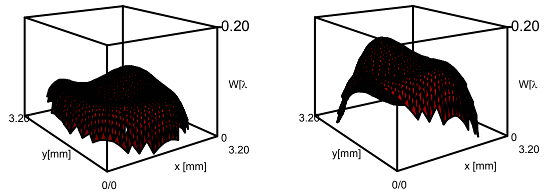

Fig. 4 *Wavefront aberrations from a polychromatic measurement (left) and from incoherent superposition of back-propagated spectrally resolved recordings (right).*

4 Conclusion

The results presented in section 3 show, that H.-S. sensors are appropriate for characterisation of ultra-broadband laser pulses. For an arbitrary pulse they deliver the spectrum averaged wavefront and irradiance distribution of the beam, enabling therefore beam alignment and adaptive control. Furthermore, beam propagation is possible from a set of spectrally resolved wavefront measurements. If beyond that all spectral components show up the nearly same wavefront and irradiance distribution, beam propagation is possible from one single measurement. Results of 7 fs Ti:Sapphire pulses from a hollow fibre deliver good agreement between spectrally resolved and overall measurements, showing that such pulses can be sensed even by a single H.-S. measurement.

References

[1] O. Albert, H. Wang, D. Liu, Z. Chang, G. Mourou, Opt. Lett. **25**, 1125 (2000)

[2] J. Queneuille, F. Druon, A Maksimchuk, G. Cheriaux, G. Mourou, K. Nemoto, Opt. Lett. 25, 508-510 (2000)

[3] P. Villoresi et al., Opt. Lett. **29**, 207 (2004).

[4] L.W. Austin, A. Giessen, D.H. Leslie, H. Weichel, SPIE **2375**, 261 (1995)

[5] N. Streibel, Opt. Comm. **49**, 6, (1984)

[6] R.N. Smartt, W.H. Steel, Jap. J. Appl. Phys., **14**, 351 (1975)

[7] T. Omatsu, K. Kuroda, T. Takase, Opt. Commun. **87**, 278 (1992)

[8] D. R. Neal, W. J. Alford, J. K. Gruetzner, M. E. Warren, SPIE vol. **2870**, 72 (1996)

[9] B. Schäfer, K. Mann, Appl. Optics **41**, 2809 (2002)

[10] V. Laude, S. Olivier, C. Dirson, J. P. Huignard, Opt. Lett. **24**, 1796 (1999)

[11] M. Nisoli, S. DeSilvestri, O. Svelto, R. Szipocs, K. Ferencz, C. Spielmann, S. Sartania, F. Krausz, Opt. Lett. **22**, 522 (1997)

[12] J.Y. Wang, D.E. Silva, Appl. Optics **19**, 1510 (1980)