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Wavefront-correction for nearly diffraction-limited focusing of dual-color laser beams to high intensities

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Abstract: We demonstrate wavefront correction of terawatt-peak-power laser beams at two distinct and well-separated wavelengths. Simultaneous near diffraction-limited focusability is achieved for both the fundamental (800 nm) and second harmonic (400 nm) of Ti:sapphire-amplified laser light. By comparing the relative effectiveness of various correction loops, the optimal ones are found. Simultaneous correction of both beams of different color relies on the linear proportionality between their wavefront aberrations. This method can enable two-color experiments at relativistic intensities.

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1. Introduction

Laser beams with two different colors are often used simultaneously in conventional low-power optical science and applications. Recently, this technique has also been used with ultra-high peak power lasers to study high field interactions of light with matter. For generating the two different colors, the standard approach is to use the fundamental frequency of laser light and its second-harmonic generated (SHG) frequency. For instance, SHG radiation is advantageous for high-order harmonic generation (HHG) from solid targets [1,2] and proton-acceleration from thin foils [3,4]. The much higher intensity contrast of pulses of SHG light, as compared with pulses at the fundamental wavelength, reduces the detrimental effect of low-density plasma generated by the foot of the laser pulse. SHG light is also advantageous for the production of high energy x-rays by Thomson scattering because of the linear scaling of x-ray photon energy with the incident photon energy of the scattering light [5,6]. Recently, Yu et al. proposed using two-color high-intensity laser pulses, the fundamental and second harmonic, from a Ti:sapphire CPA system to produce ultra-low emittance electron beams by means of laser wakefield acceleration [7].

For all of these applications, the ability to optimally focus the two laser beams at different frequencies is crucial to achieving high laser intensity on target. However, obtaining a high quality SHG focal spot from ultra-fast, high-intensity lasers is not a trivial task [8,9]. Poor focusability of SHG light arises primarily from the fact that during the process of upconversion, phase aberrations in the fundamental light are doubled, \( \phi_{2\omega} = 2\phi_{\omega} \) [10] (neglecting nonlinear effects from the crystal). An adaptive optic system is generally used to correct aberrations in laser beams and thus improve focusability [11–13]. For example, Queneuille et al. [14] demonstrated improvement of SHG wavefront using a deformable mirror placed after the SHG crystal. However, this arrangement is not yet shown to be adequate for high-field two-color experiments. Wavefront correction at only a single wavelength is reported, and the focal spot quality of the SHG light is not reported.

Fortunately, another solution exists. The linear relationship between the phase aberration of the SHG light and the fundamental radiation (\( \phi_{2\omega} = 2\phi_{\omega} \)) [10] makes it feasible to minimize wavefront aberrations of both colors simultaneously, by correcting the wavefront of the fundamental beam. In this paper, we report experiments proving this concept by demonstrating dramatic improvements in the focusability of two high-power 800-nm and 400-nm beams.
2. Experimental setup

The experiments were performed using the 100-TW, 30-fs Diocles laser system [15]. The schematic of the experimental setup for SHG generation and wavefront correction is depicted in Fig. 1. An attenuation system composed of a half-wave plate (HWP) and thin-film polarizers (TFPs) is used before the compressor to sample the high-power, stretched pulse. This approach enables measurements to be done at lower power without altering the properties of the high-power beam. The attenuated pulse at 800 nm is compressed to 34 fs using a grating pulse compressor [16]. A bimorph deformable mirror (NightN) located after the compressor is used to correct the distortions in the laser pulse. The corrected pulse is then focused by an off-axis parabolic reflector with a focal length of 1 meter. The beam diameter on the paraboloid surface is 60 mm. The focused beam is reflected off mirror M1 and incident on a lithium triborate (LBO) crystal placed before the focus, as shown in Fig. 1. LBO was chosen as the frequency-doubling crystal because of its high nonlinear coefficient, high damage threshold, and the fact that it can be manufactured in large sizes (>100 mm) [17,18]. The uncoated LBO crystal was cut to 0.5 mm thick with type I phase matching, and the beam size on the surface of the LBO crystal was 9.5 mm. The beam was then reflected off an uncoated wedge to further attenuate the beam energy. We used a four-wave shearing interferometer device (SID4, Phasics Inc.) as the wavefront sensor to measure the wavefront [19]. The SID4 was placed after the focus to measure the aberration from the entire system, including that from the parabolic mirror. The deformable mirror is within the depth of field of the SID4 imaging system. The focal spot was measured by inserting a silver mirror (M2) before the focus and imaging the focal plane using a 20X microscope objective and a 12-bit CCD camera. The energy in the second harmonic beam is measured by replacing the wedge with a dichroic mirror (HR@400 nm & HT@800 nm) and using a calibrated photodiode.
3. Experimental results and discussion

In the experiments, the energy of the 800-nm beam incident on the LBO crystal was set to 9.5 mJ, corresponding to an intensity of 394 GW cm$^{-2}$ on the crystal, with pulse duration of 34 fs. The SHG conversion efficiency was measured to be 7.6%. The relatively low efficiency is due to the fact that a focused beam is incident on the crystal. Higher conversion efficiency (~30%) is achieved when a collimated beam is incident on the crystal. Based on the beam intensity of 394 GW cm$^{-2}$ on the crystal, for the collimated laser beam with diameter of 60 mm, the equivalent power is 17 TW. This demonstrates that the experimental parameters used in this work are relevant to ultra-intense laser pulses.

In order to determine the optimal focusability for 400-nm (blue) light, three experimental scenarios were used to correct the wavefront, as shown in the lower panel of Fig. 1. For each of these scenarios, the focal spot for 800-nm and 400-nm light was measured.

In the first scenario (I), the SHG crystal was removed from the beam path to eliminate its effects on wavefront. The wavefront of the 800-nm (red) light was measured and then corrected with the feedback loop composed of the deformable mirror and wavefront sensor. This resulted in an 800-nm beam with nearly flat spatial phase (800-nm loop).

In the second scenario (II), the LBO crystal is inserted in the beam path. An 800-nm interference filter is used to block blue light into the wavefront sensor, and the wavefront for the red light is measured. As in the previous case, a feedback loop is then implemented to obtain a flat spatial phase for the red light (unconverted 800-nm loop).

Finally, with the crystal in place, the 400-nm interference filter on the wavefront sensor is used to block 800 nm. The feedback loop is then used to obtain a flat phase for the blue light (400-nm loop), as shown in scenario (III).

In what follows, we first show measurements of the phase front of the uncorrected laser beam and the corresponding energy distribution at the focus. This is followed by our results for the phase front maps and the corresponding focal spot for 400-nm and 800-nm beams, for each of the three wavefront correction loops described previously. For each scenario, we used one typical wavefront and focal spot to show the results with the correction loop. To compare the three scenarios in more detail, we averaged 10 shots for each scenario and present the results in tabular form.

The quality of the focusing is quantified by measurement of several parameters. The wavefront distortion for the uncorrected and corrected cases is specified by the peak-to-valley (PtV) and the root mean square deviation (RMS). The focal spot quality is quantified by the measurement of the spot size (FWHM), as well as the enclosed energy in the central spot. Based on the diffraction-limited focal spot size and optimized focal spot size, the focusability of the beam was quantified by measurement of the enclosed energy in 10 μm (20 μm) diameter for 400-nm (800-nm) light.

3.1. Wavefront and focal spot without adaptive loop

The wavefront and focal spot of the 400-nm and 800-nm beams at 394 GW cm$^{-2}$ with no wavefront correction are shown in Fig. 2. The wavefront of the 800-nm beam (Fig. 2(a)) has a PtV of 1.17 λ with RMS of 0.21 λ. For the wavefront of the upconverted blue light (Fig. 2(b)), the PtV and RMS values were 2.61 λ and 0.43 λ, respectively. The results show that the spatial phase variation of blue light is approximately twice that of red light. This is consistent with the fact that the phase distortion for the 400-nm beam is twice that at 800 nm [10].

The wavefront measurements are complemented by measurement of the focal spot quality. The amplified beam has a super-Gaussian spatial profile, and the calculated focal spot (FWHM) for 800 nm is ~13.7 μm with a 60 nm flat-top beam profile and 1-m focal length. The theoretical enclosed energy in 20 μm (13.7 μm) is 71.9% (47.4%). The corresponding 400-nm theoretical enclosed energy in 10 μm (6.8 μm) is 71.9% (47.0%). The focal spot for 400 nm and 800 nm are shown in Figs. 2(a’) and 2(b’), respectively. The color scale is

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normalized to unity for Figs. 2(a') and (b') as well as subsequent figures. The area over which the enclosed energy is computed is indicated by a 10-μm diameter dashed-white circle in Fig. 2(a') and a 20-μm diameter dashed-white circle in Fig. 2(b'). Based on these measurements, the energy enclosed in a 20 μm diameter spot for red light is 23.3%, and for blue the enclosed energy in a 10 μm diameter spot is 10.8%. The focal spot for 400 nm is significantly degraded as compared to the spot for 800 nm because of the larger wavefront distortion in the former case.

![Fig. 2. (a) Wavefront of 400-nm beam without loop; (a') Focal spot of 400-nm beam without loop. The enclosed energy is computed over a 10 μm diameter area indicated by the dashed white circle. (b) Wavefront of 800-nm beam without loop; (b') Focal spot of 800-nm beam without loop. The enclosed energy is computed over a 10 μm diameter area indicated by the dashed white circle. The color scale on the left of (a') and (b') is normalized to unity.](image)

3.2 Wavefront and focal spot with 800-nm loop (scenario I)

We next implemented the 800-nm loop, and measured both the corresponding wavefront and focal spot. The results for this case are shown in Fig. 3. The PtV and RMS at 800 nm is 0.53λ and 0.09λ, respectively, and the corresponding values for 400 nm are 1.18λ and 0.17λ, respectively. Measurement of the focal spot indicates that 33.6% of the energy is contained in the central 20-μm diameter for red light and 18.1% in the central 10-μm diameter for blue. The latter represents a significant (factor of two) improvement over the uncorrected case, but there still exists significant aberration. This is easily understood when considering that the wavefront for red light before the LBO crystal is flat. However, after propagation through the crystal, the wavefront for both red and blue light would be expected to degrade. This is demonstrated by the measurements shown in Fig. 3.

Several factors can contribute to the wavefront distortion in the crystal. The most likely factor would be imperfections on the crystal surface since it is only 0.5 mm thick. The high-intensity of the incident beam could also lead to distortions in the spatial phase on account of...
nonlinear effects as the beam propagates through the crystal. We calculated the B-integral to be 0.294 rad for a 0.5-mm-thick LBO crystal at an intensity of 394 GW cm$^{-2}$, resulting in a PtV aberration of 0.05 $\lambda$ [20]. This is small compared to the overall aberrations, indicating that nonlinear modulation of the beam can be neglected in these measurements. The presence of a large aberration on the edge of the beam, as shown in Fig. 3, indicates that the crystal imperfections are the primary source of aberrations.

![Graphs](image.png)

Fig. 3. (a) Wavefront of 400-nm beam with the 800-nm loop; (a') Focal spots of 400-nm beam with the 800-nm loop; (b) Wavefront of 800-nm beam with the 800-nm loop; (b') Focal spots of 800-nm beam with the 800-nm loop.

3.3 Wavefront and focal spot with unconverted 800-nm loop (scenario II)

Results for the unconverted 800-nm loop are shown in Fig. 4. The PtV and RMS for the 800-nm beam were 0.30$\lambda$ and 0.04$\lambda$, respectively, and for the 400-nm beam were 0.78$\lambda$ and 0.12$\lambda$, respectively. The distortions are reduced compared to the previous case because the loop now corrects the aberrations introduced by the crystal. Measurement of the focal spot in Fig. 4 indicates that 39.8% of the energy is contained in the central 20-µm diameter for the 800-nm beam, and 33.6% in the central 10-µm diameter for the 400-nm beam.
3.4 Wavefront and focal spot with 400-nm loop (scenario III)

Finally, we implemented the 400-nm loop to optimize the wavefront and focus the 400-nm laser pulse. The results for this case are shown in Fig. 5. The PtV and RMS values for the 400-nm wavefront distortion were 0.61 $\lambda$ and 0.09 $\lambda$, respectively. The PtV and RMS values for the 800-nm beam were 0.42 $\lambda$ and 0.06 $\lambda$, respectively. Measurement of the focal spot indicates that 39.1% of the energy is contained in the central 20-$\mu$m diameter for the 800-nm beam, and 33.6% in the central 10-$\mu$m diameter for the 400-nm beam. A comparison of the results shown in Figs. 3 and 4, demonstrates that the enclosed energy in the 400-nm and 800-nm focal spots, using the unconverted 800-nm loop, are nearly the same as those obtained with the 400-nm loop. This shows that the aberrations in the 400-nm and 800-nm beams were both compensated simultaneously with use of either the unconverted 800-nm loop or the 400-nm loop.
A more detailed quantitative comparison of the results is performed by statistical analysis of the relevant measurements for each of the three scenarios. For each measurement, we compute the standard deviation based on the results of ten shots, and show the results in Tables 1 and 2. This deviation quantifies the error associated with the measurement of focal spot and wavefront. From Tables 1 and 2, as well as the results shown in Figs. 3–5, we conclude that the enclosed energy and wavefront of the 800-nm (400-nm) beams are nearly identical, when either the 400-nm loop or unconverted 800-nm loop are used, and that any difference is within the error associated with the measurement.

As mentioned previously, the wavefront aberration of SH is approximately twice that of the fundamental aberration \(\phi_{\text{SH}} = 2\phi_{\text{fs}}\). Therefore, our results show that the 800-nm and 400-nm beams were optimized simultaneously, using either the 400-nm loop or the unconverted 800-nm loop. The theoretical FWHM focal spot size for 800 nm is 13.7 \(\mu\)m, and the measured focal spot of 800-nm beam, with either 400-nm loop or unconverted 800-nm loop, is \(\sim 17 \pm 1\) \(\mu\)m, close to the diffraction limit. Since the near field of the 800-nm beam profile intensity drops from the center of the beam to its edge, and the SH near field beam profile intensity is proportional to the square of fundamental beam intensity, the near field beam profile of the 400-nm beam is therefore expected to be smaller than the 800-nm beam profile. This explains why the optimized SH focal spots is slightly larger than half of optimized 800-nm focal spots.

Our approach demonstrates that the foci of both beams of different wavelength can be simultaneously optimized with a single correction loop. The enclosed energy in the central spot increases by a factor of 1.5 for red light and by a factor of 3 for blue light, representing significant focusability improvement.
Table 1. The 10-shot averaged FWHM focal spot size, encircled energy distribution, PtV and RMS value of 400-nm light, obtained with various correction loops, at input intensity of 394 GW cm$^{-2}$.

<table>
<thead>
<tr>
<th>Focal quality of 400-nm beam</th>
<th>No loop</th>
<th>800-nm loop</th>
<th>Unconverted 800-nm loop</th>
<th>400-nm loop</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWHM beam size of 400-nm focal spot ($\mu$m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X: 12.6 ± 2.1* Y: 17.0 ± 1.9**</td>
<td>X: 10.4 ± 1.2 Y: 15.6 ± 1.4</td>
<td>X: 10.8 ± 0.6 Y: 13.0 ± 0.9</td>
<td>X: 10.5 ± 0.5 Y: 10.8 ± 0.8</td>
<td></td>
</tr>
<tr>
<td>10-µm beam-size encircled energy distribution of 400-nm focal spot (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.7 ± 3.0</td>
<td>18.3 ± 2.6</td>
<td>33.4 ± 2.0</td>
<td>33.6 ± 1.7</td>
<td></td>
</tr>
<tr>
<td>PtV value ($\lambda$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.50 ± 0.17</td>
<td>1.20 ± 0.15</td>
<td>0.78 ± 0.15</td>
<td>0.61 ± 0.14</td>
<td></td>
</tr>
<tr>
<td>RMS value ($\lambda$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.14 ± 0.02</td>
<td>0.18 ± 0.02</td>
<td>0.10 ± 0.02</td>
<td>0.09 ± 0.02</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. The 10-shot averaged FWHM focal spot size, encircled energy distribution, PtV and RMS value of 800-nm light, obtained with various correction loops, at input intensity of 394 GW cm$^{-2}$.

<table>
<thead>
<tr>
<th>Focal quality of unconverted 800-nm beam</th>
<th>No loop</th>
<th>800-nm loop</th>
<th>Unconverted 800-nm loop</th>
<th>400-nm loop</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWHM beam size of 800-nm focal spot ($\mu$m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X: 20.4 ± 3.6 Y: 19.5 ± 2.2</td>
<td>X: 21.5 ± 3.4 Y: 19.3 ± 2.0</td>
<td>X: 17.5 ± 1.0 Y: 17.0 ± 0.6</td>
<td>X: 17.1 ± 1.1 Y: 17.6 ± 0.9</td>
<td></td>
</tr>
<tr>
<td>20-µm beam size encircled energy distribution of 800-nm focal spot (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24.0 ± 3.0</td>
<td>33.4 ± 2.4</td>
<td>39.2 ± 1.5</td>
<td>39.6 ± 1.9</td>
<td></td>
</tr>
<tr>
<td>PtV value ($\lambda$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.18 ± 0.1</td>
<td>0.52 ± 0.09</td>
<td>0.32 ± 0.06</td>
<td>0.36 ± 0.07</td>
<td></td>
</tr>
<tr>
<td>RMS value ($\lambda$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.21 ± 0.01</td>
<td>0.09 ± 0.01</td>
<td>0.04 ± 0.01</td>
<td>0.05 ± 0.01</td>
<td></td>
</tr>
</tbody>
</table>

* X represents FWHM of 10-shot averaged focal spot in the horizontal direction.
** Y represents FWHM of 10-shot averaged focal spot in the vertical direction.

4. Conclusion

We have shown that it is possible to simultaneously correct the wavefronts of two-color laser light pulses, both the fundamental and second harmonic, with either of two correction loops, one based on measurement of the SHG light, or one based on measurement of the unconverted fundamental light. Dramatic improvements in focusability are found. The amount of energy enclosed within the 800-nm and 400-nm focal spots is improved by factors of 1.5 and 3, respectively. The results are consistent with expectations: in particular, that the phase aberration of SHG light is twice that of the fundamental ($\phi_2=2\phi_1$) [10]. Also, the use of a collimated beam, rather than a focusing one, would result in higher SHG conversion efficiency. This, together with scalability to higher laser power, will enable future two-color experiments at relativistic intensity levels.

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