Uniform and efficient beam shaping for high-energy lasers: supplement

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1. CALCULATION OF THE APPLIED LENS TERM ON THE SECOND SLM

![Diagram showing distances and angles in the setup.](image)

**Fig. S1.** Distances in the setup: The spherical lens term \( f_{\text{defocus}} \) is applied to the target distribution. \( f_{\text{defocus}} \) the distance \( a \) and the corresponding lens term \( f_2 \) change with the target size \( s_{\text{target}} \) and the chosen defocus \( d_2 \). The two presented configurations of the main publication are indicated in red \((d_2 = 50 \text{ mm})\) and blue \((d_2 = -50 \text{ mm})\). In both cases the target size \( s_{\text{target}} \) stays the same. In our presented implementation the value for the distance \( d_1 \) is chosen close to the focal length \( f_1 \) \((d_1 = 180 \text{ mm})\). (distances and angles are not to scale)

The relation between the size of the target object \( 2s_{\text{target}} \), the size on the second SLM \( 2s_{\text{SLM}_2} \), and the applied focal length \( f_2 \) can be determined with the matrix method:

\[
\begin{pmatrix}
s_{\text{target}} \\ s_{\text{SLM}_2}
\end{pmatrix} =
\begin{pmatrix}
1 & d_2 + f_3 \\
0 & 1
\end{pmatrix}
\begin{pmatrix}
1 & 0 \\
-\frac{1}{f_2} & 1
\end{pmatrix}
\begin{pmatrix}
1 & f_3 + d_1 \\
0 & 1
\end{pmatrix}
\begin{pmatrix}
s_{\text{SLM}_2} \\ \theta_{\text{SLM}_2}
\end{pmatrix},
\]  
(S1)

Equation S1 can be solved for \( f_2 \), where \( \theta_{\text{SLM}_2} \) is substituted with \( \theta_{\text{SLM}_2} = \frac{s_{\text{SLM}_2}}{f_2} \), corresponding to the largest angle of incidence (compare Figure 1 in the main document). Finally, \( f_2 \) reads:

\[
f_2 = \frac{d_2^2d_2 - d_1f_3^2}{2d_1d_2 - f_2^2 + d_1f_3^2_{\text{SLM}_2}},
\]  
(S2)

The effective defocus of the target distribution changes with the applied focal length \( f_2 \) on the SLM. Since the field on the second SLM is derived by back-propagation starting from the target distribution, we need to calculate the corresponding defocus \( f_{\text{defocus}} \). In that way, the focal length \( f_2 \) is automatically encoded in the resulting wave front. The defocus is defined by:

\[
f_{\text{defocus}} = f_2 + f_3 - a.
\]  
(S3)

Thereby, \( a \) is the distance from the second lens to the position of the focus (compare Figure S1). At this point, the calculated height \( s_{\text{focus}} \) needs to vanish \((s_{\text{focus}} = 0)\) and we can take the definition of Equation S1 to calculate \( a \). Therefore, \( s_{\text{target}} \) is substituted with \( s_{\text{focus}} \) and we define \( a \) to be the last propagation distance instead of \( d_2 + f_3 \). In that way we can determine an equation for \( a \) and solve Equation S3:

\[
f_{\text{defocus}} = d_2 - \frac{f_2^2(d_1 - f_2)}{d_1(d_1 - 2f_2)},
\]  
(S4)

The calculated distance \( f_{\text{defocus}} \) is the focal length of the target wave front:

\[
\Phi_{\text{target}} = \Phi_{\text{lens}} - f_{\text{defocus}}.
\]  
(S5)
2. ALIGNMENT

There has to be a perfect mapping between the shaped amplitude and the applied correction wave front. We perform the alignment whilst we image the plane of the second SLM on a camera. This shows the shaped intensity pattern. If a phase mask is applied on the second SLM, the contours of this pattern slightly emerge. We choose the phase mask to be identical to the target distribution. This gives the opportunity to compare the shaped outcome with the theoretical expectations. If those structures match perfectly, the setup is well-aligned.

A good choice for a target pattern is a grid with several crossings as illustrated in Figure S2. If the grid appears blurred, the calculated propagation distance might not agree with the experimental setup such that the target intensity pattern appears in a slightly shifted plane. Either the setup or the distances in the algorithm can be adjusted but it is usually easier to adapt the propagation path in the algorithm and see if the outcome improves. Besides the axial alignment, the two patterns need to be adjusted laterally. This can be done with the two mirrors in the setup. It makes sense to use two mirrors since this not only allows for shifting the shaped intensity pattern laterally but also for correcting slight rotations.

Ideally, the two patterns match over the whole area. We observed a slight mismatch in the aspect ratio between the shaped and expected structure. Therefore it is useful to display a grid since it is sensitive to a distortion of the pattern. It is likely that those effects appear since the beam impinges on the SLM under a certain angle and it is practically impossible to work completely distortion-free. However, a simple compression/stretching can easily be compensated beforehand by giving the GS algorithm a target distribution with the opposite stretching/compression.

3. EVALUATION OF DIFFERENT RECTANGLES

The recorded rectangular structures in Figure S3 are the basis for the evaluation of the efficiency $\eta$, beam uniformity $U$, and flatness factor $FF$. The inner outline marks the area for the calculation of beam uniformity $U$ and flatness factor $FF$. It is slightly smaller than the shaped structure to exclude the abrupt transition at the edges. The outer rectangle includes the full signal area to calculate the efficiency $\eta$. The results can be found in Table 1 in the main publication.

4. SIMULATION

A. Simulation parameters

The simulation area is preliminarily defined by the dimensions and pixel size of the SLM (960x960 px with a pitch of 9.2 µm). To take diffracted light under large angles along the propagation path into account, the simulation area is increased with zeropadding by 1000 px in each direction. The FT is energy conserving and light cannot leave the boundaries of the modelled area. The padded range is chosen to contain the light field over the whole propagation path. The simulation area could be chosen even larger but it has proven experimentally that this is sufficient for the chosen path lengths, major diffraction angles and optics in the setup. Otherwise the calculation time increases rapidly.

After the phase masks are calculated, we probe them on the incoming light field and simulate the expected outcome. To counter potential numerical instability we use subsampling. Therefore
the initial light field is meshed with finer steps (1/4 of the SLM’s pixel size). The resolution of
the iteratively calculated phase masks is limited by the resolution of the SLM and is thus only
subsampled by repeating the same pixel value within the initial pixel area. This step is done to
test the phase masks for potentially under-sampled structures which would significantly impair
the quality in the experimental result.
The calculation of the two phase masks takes about 1 min on a 4-core Intel i5-7500 CPU at
3.4 GHz with 8 Gb RAM (the individual matrices are 2960x2960 complex double). Calculating the
simulated results with subsampling (11840x11840 complex double) takes around 5 min.

B. Evaluation of misalignment on rectangular structures

We addressed different kinds of misalignment on simulated rectangular structures. Even though
we already showed misalignment on snowflakes in the main publication, we would like to add a
simulation for rectangular structures in Figure S4. The beam uniformity $U$ and flatness factor $FF$
can be calculated easily on a plain structure. It is worth noticing that a misalignment does not
cause major drops in efficiency for our proposed method in contrast to a direct Fourier relation.
The development of the beam quality parameters depends on the applied misalignment. They
remain relatively constant for a lateral misalignment in case of our proposed method in contrast
to a setup in a direct Fourier relation. The beam uniformity shows a similar behaviour in case
of axial misalignment. The flatness factor drops more rapidly for our proposed method due to
pronounced overshoots at the edges. A rotational misalignment around the z-axis affects our
proposed method more strongly than a setup in direct Fourier relation. In general, a misalignment
seems to cause more blurry structures for a direct Fourier relation whereas our proposed method
starts to suffer from emerging speckle.
Fig. S4. Various misalignment applied to rectangular structures. The upper row of images shows the impact on the efficiency for our proposed method (solid line) and for a setup in direct Fourier relation (dashed line). The light blue curve underneath shows the development of the flatness factor $FF$ and the dark blue curve illustrates the beam uniformity $U$. Again, the solid line shows our proposed method and the dashed line stands for a setup in direct Fourier relation. The images underneath show exemplary results for the marked misalignment in the upper cases.