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High-throughput homogenization of a quasi-Gaussian ultrafast laser beam using a combined refractive beam shaper and spatial light modulator

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Abstract. Efficiently shaping femtosecond, transverse-Gaussian laser beams to flat-top beams with flat wavefronts is critical for large-scale material processing and manufacturing. Existing beam shaping devices fall short either in final beam homogeneity or efficiency. This paper presents an approach that uses refractive optics to perform the majority of the beam shaping, then uses a fine tune device (spatial light modulator) to refine the intensity profile. For the beam we selected, circularly asymmetric with intensity fluctuations, our method achieved a uniformity of 0.055 within 90% of the beam area, at 92% efficiency. The optimization involved an iterative beam shaping process, which converged to optimum within 10 iterations.

Keywords: laser beam shaping, spatial light modulator, beam homogenization, laser material processing, refractive beam shaper.

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1 Introduction

High-power ultrafast fiber laser and regenerative Titanium-sapphire (Ti:S) amplifier, have Gaussian or quasi-Gaussian output profiles. However, various important applications—namely material surface processing,[1] drilling,[2] laser additive manufacturing,[3] lithography,[4] and surgery[5]—demand a flat-top profile for its spatial uniformity. In particular, the future high-speed, large-scale material applications require processing or manufacturing a large number of samples in fast turn-around settings, which need large, high-energy, homogenized ultrafast laser beams with some degree of flexibility on the longitudinal sample position. Thus, efficiently shaping quasi-Gaussian laser beams to large flat-top beams is critical.

Many beam shaping and homogenization techniques have been developed for such applications.[6–11] In a simplified description, beam shapers can be categorized as beam integrators (diffusion of randomized beam profiles at image plane) and field mappers (controlled intensity re-distribution). Beam integrators can include an array of optical lenslets or a transverse distribution of diffractive optical elements, which forms a sum of diffraction patterns at the focal plane. Not only is the homogeneous output profile only realized at a discrete target plane, but strong speckles will occur for beams with spatial coherence.[6] These drawbacks limit the integrators' applications mainly to spatially incoherent sources, and not to single-mode lasers like the femtosecond Ti:S system we employed.

Field mappers allow for the controlled re-direction of the various transverse segments of the input laser.[6] A good example of such a device is the multi-lens refractive beam shaper which turns a TEM00 Gaussian input into a flat-top beam without speckles. The drawback of field mappers is their requirement of a fixed input profile at a fixed diameter. Deviation in beam size and input profile will compromise the uniformity of the output flat-top. However, material processing laser systems such as the Ti:S system we employed, outputs quasi-Gaussian beams. This significantly hinders the refractive beam shaper's performance.[7]

The SLM is another example of a field mapper. Through Gerchberg-Saxton (GS) algorithm, an SLM can produce a computer-generated hologram (CGH) that turns any input profile into any desired output. However, strong speckles arise from the complicated nature of diffraction-based shaping.[8] These speckle patterns can be reduced with weighted algorithm[12,13] or selected initial phase,[14] but these improved algorithms still produce speckles at the target plane. An alternative application of the SLM is to use it as an intensity attenuator,[9–11] thus removing energy locally till the desired output profile is obtained. However, using this method to shape a Gaussian beam to a top-hat beam will have a theoretical efficiency limit of 36.8% — not sufficient for high-volume material processing. These challenges highlight the pressing need for an improved beam shaping method to deliver the desired profile uniformity while maintaining high throughput for efficient, high-quality applications.

There have been prior research focus on using multiple optical shaping device with SLM: Laskin et al. (2012) used a refractive beam shaper to improve the quality of SLM CGH projection;[15] Li et al. (2019) used an SLM to shape the region of interest before projecting the beam onto a secondary SLM for CGH projection.[16] In contrast, our study uses a refractive optics to approximate the desired beam shape and then uses the SLM as an intensity attenuation to polish the profile.

In this paper, we present an approach that transforms a quasi-Gaussian ultrafast beam into a flat-top profile by combining a refractive beam shaper and an SLM. We leveraged the refractive beam shaper's ability to approximate a flat-top profile and the SLM's capability of precise, residual intensity correction. This approach results in a high uniformity of 0.055 over 90% of the beam area and a high system efficiency of 92% for our laser. This work provides a path to advance laser-material processing and manufacture with improved operational efficiency, processing quality, and scalability, as well as other applications that benefit from such improved laser beam homogeneity and throughput efficiency. Other potential shaping capabilities with the approach of using a refractive optics to approximate desire beam shapes and polish with a minor-phase correction device are discussed in the conclusion section.

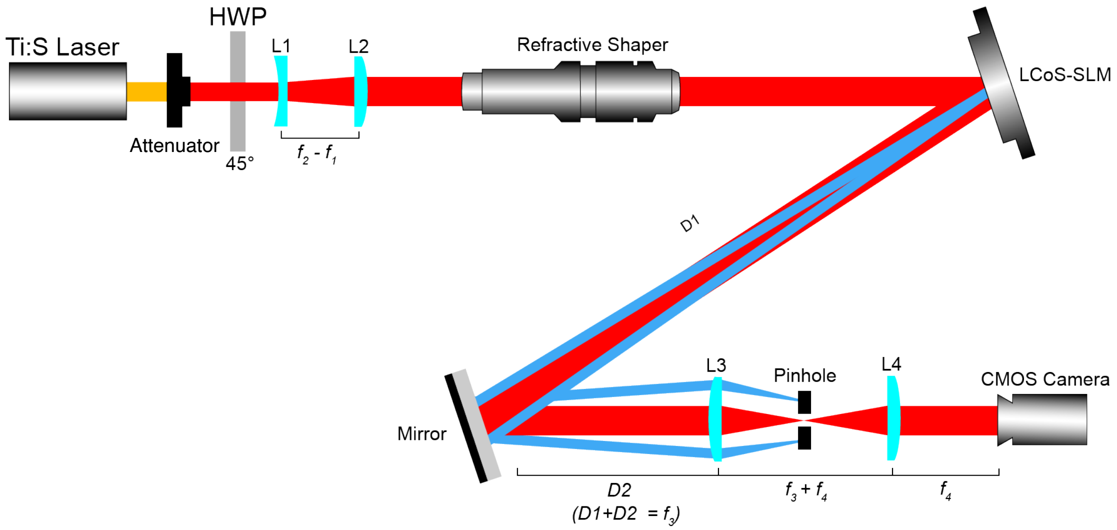


Fig 1: Schematic of the experiment setup. The red lines indicate ray tracing of the beam line (not to scale) while the blue lines indicate unwanted higher order diffraction.

2 Experiment Setup

The schematic of the beam homogenization experimental setup is shown in Fig. 1. It consists of a Ti:S laser system with a central wavelength at 800 nm (pulse width 40 fs, repetition rate 1 kHz, pulse energy up to 1 mJ). Since this is a demonstration experiment, the average power of the beam was attenuated to the order of mW using a neutral density filter. However, the particular SLM (Hamamatsu X13138-02) we used has the capability of handling average power of 2.7 W and peak power of 54.6 GW without the water-cooled heat sink add-on. It is crucial to align the beam polarization with SLM cells' orientation to achieve full functionality. To determine the optimal polarization, when full blazed gratings are applied on the SLM, the half-wave plate is rotated until the complementary metal-oxide semiconductor (CMOS, Basler 1600-60gm) camera registers the minimum intensity, indicating the full functionality of the SLM cells.

The refractive beam shaper we used (AdlOptica piShaper 6_6_TiS) is designed for use with circularly symmetric TEM00 beams[7] at 6.4 mm diameter. 1 mm deviation from the correct input beam size would result in 25$\%$ error in the output top-hat. To test our beam shaping system's versatility, the original beam was kept asymmetric with $1/e^2$-size 3.1 mm in the horizontal plane and 2.7 mm in the vertical. To reduce the power loss in the later process, we expanded the beam so the major axis of the oval beam just meets the requirement of the refractive shaper. This expansion is achieved with a beam expander consisting of lenses L1 ($f_1 =$ -100 mm) and L2 ($f_2 =$ 200 mm). Subsequently, the enlarged beam is shaped into an imperfect flat-top profile by the refractive beam shaper. The imperfect flat-top is then illuminated onto the SLM that is aligned away from the beamline by 8 degrees, for further refinement of the beam profile.

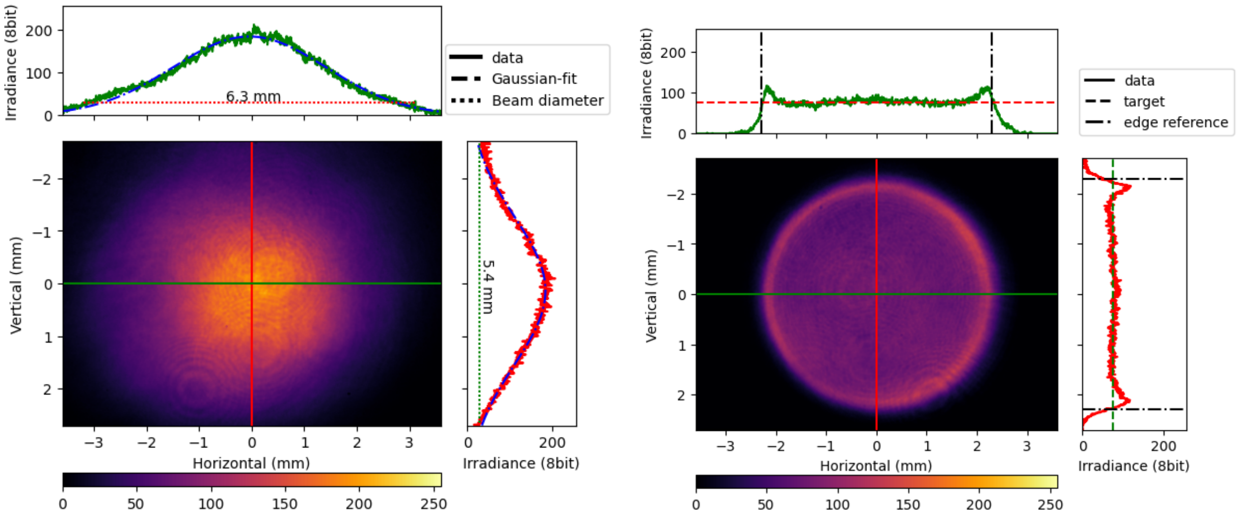
The SLM control software accepts a user-defined intensity target. By comparing the real time camera feed intensity with the target, the SLM applies diffraction gratings where the amplitude is locally adjusted according to the amount of attenuation needed. This process is iterative to achieve minimum error with the resultant intensity profile.[9–11]

During this process, higher-order diffracted intensity is blocked by an iris, placed at a focus of the first lens of a telescope consisting of lenses L3 ($f_3 =$ 200 mm) and L4 ($f_3 =$ 200 mm), allowing only the desired flat-top profile to pass through. Finally, the flat-top beam profile is captured by the CMOS camera.

3 Results

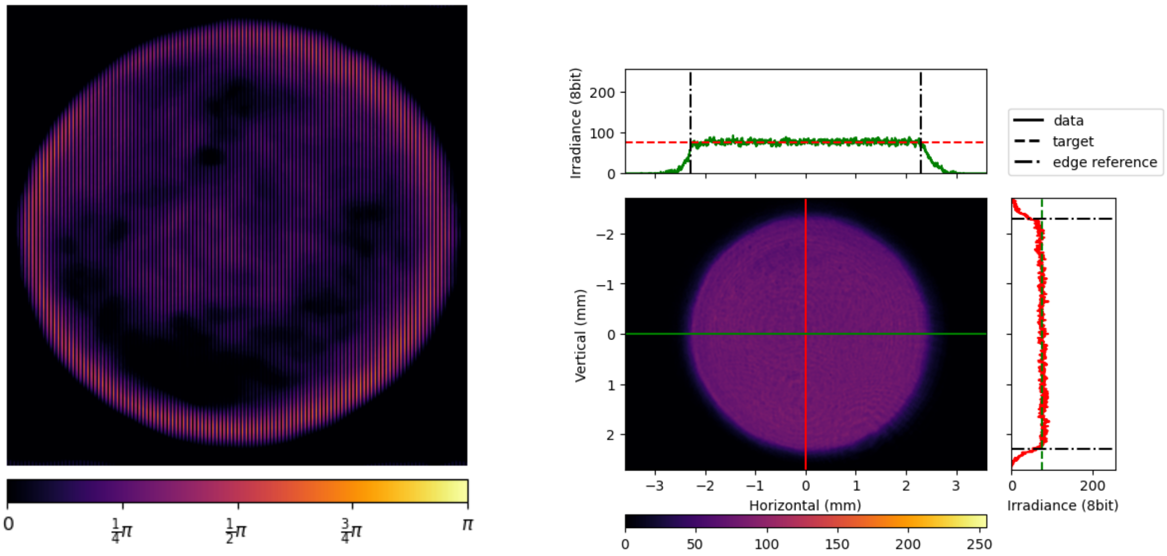
The objective of our experiment was to reshape a quasi-Gaussian laser beam into a uniform top-hat profile, aimed towards large-scale, high-precision material processing and manufacture. This is achieved through the combination of a series of beam-shaping devices and iterative procedures, the outcomes of which are presented herein.

It is productive in the evaluation of beam uniformity[17] of a flat-top circular beam to define a



(a) Raw beam input

(b) refractive shaper output



(c) SLM phase mask

(d) Result flat-top

Fig 2: (a) Quasi-Gaussian beam profile after expansion with $2w_{0x}$ at 6.3 mm and $2w_{0y}$ at 5.4 mm. (b) refractive beam shaper output beam profile. (c) Phase profile pattern on the SLM, where the colormap range from 0 to π. This encodes the phase modulation necessary for the desired beam shaping. (d) Achieved flat-top beam at the CMOS camera. The adjacent graphs in (a,b,d) with green and red curves show the cross-sectional intensity profiles (solid lines) alongside the designated target threshold (dashed lines). The vertical dashdot lines in (b,d) correspond to the same dashdot line in Fig. 3.

measure of uniformity U, defined for a region of radius R, or $\hat{R}$ in units of pixels. Based on the count intensity level I for each pixel number $(\hat{x}, \hat{y})$, with $N(\hat{R})$ the number of pixels that satisfy the condition $\hat{x}^2 + \hat{y}^2 < \hat{R}^2$, and I_{ave} the average intensity value over that region, we can define $U(\hat{R})$ as:

$$U(\hat{R}) = \frac{1}{I_{ave}} \sqrt{\frac{\sum_{\hat{x}^2+\hat{y}^2<\hat{R}^2} [I(\hat{x}, \hat{y}) - I_{ave}]^2}{N(\hat{R})}} \tag{1}$$

Our beam-shaping process results in a flat-top beam profile with a high degree of uniformity, as evidenced by a uniformity of 0.055 within 90% of the beam area in Fig. 3. A perfect top-hat would exhibit a uniformity of 0 within the beam profile.

It is also useful to define an evaluation metric of the efficiency of the beam shaping system η_{total}. In the following equations, $\eta_{SLMcleaning}$ is defined as the total intensity count with SLM cleaning on divided by that with SLM cleaning off (but with the SLM still used as a flat mirror). η_{shaper} and $\eta_{SLMinsertion}$ are the efficiency of the refractive shaper (98.8%) and the light utilization rate (97%) of the SLM given by the manufacturers.[7]

$$\eta_{\text{total}} = \eta_{\text{shaper}} \cdot \eta_{\text{SLM insertion}} \cdot \eta_{\text{SLM cleaning}} \cdot 100\% \tag{2}$$

$$\eta_{\text{SLM cleaning}} = \frac{\sum I_{\text{cleaning on}}(\hat{x}, \hat{y})}{\sum I_{\text{cleaning off}}(\hat{x}, \hat{y})} \tag{3}$$

For the beam we employed, this beam shaping system achieved an SLM cleaning efficiency ($\eta_{\text{SLM cleaning}}$) of 96% compared between data in Fig. 2d and Fig. 2b, and a total efficiency (η_{total})

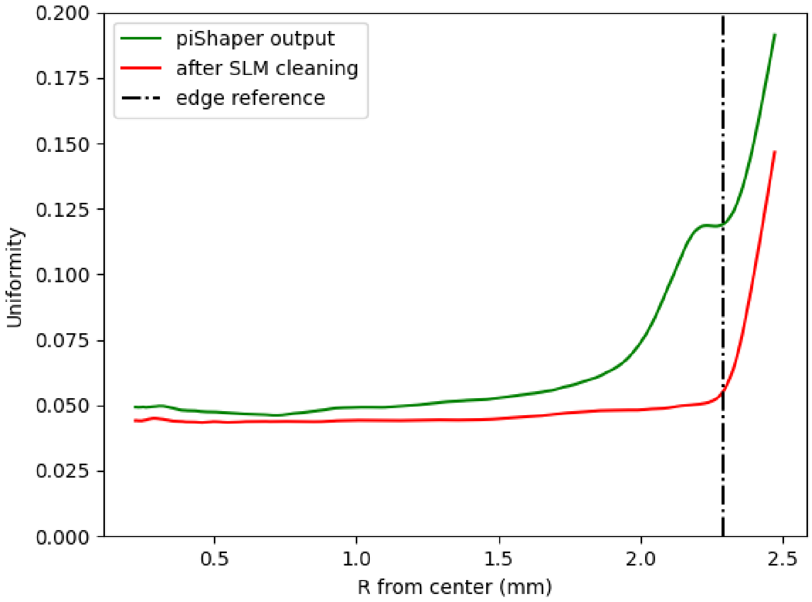


Fig 3: The coefficients of variance as a function of radius from beam center of refractive beam shaper output (Fig. 2b) versus final flat-top (Fig. 2d). The vertical dashdot line corresponds to the dashdot lines in Fig. 2b and Fig. 2d.

of 92% considering the optical efficiencies of the refractive shaper and the SLM. These results demonstrate high beam uniformity after shaping together with high throughput efficiency.

While the refractive beam shaper flattens the input beam, its performance was hindered by the quasi-Gaussian and circularly asymmetric nature of the input beam (Fig. 2a). Comparing side-by-side with the refractive shaper's output (Fig. 2b), the original beam's deviation from a TEM00 profile produced the uneven bumps in the center flat-top region while the asymmetry in beam size caused the sharp ring on the edges. The uniformity at the edge reference line in Fig. 3 highlights the limitation of the refractive beam shaper, setting the stage for SLM's precise intensity modulation.

Further intensity smoothing is achieved through the calculated phase profile applied to the SLM as shown in Fig. 2c. The brighter areas of the SLM diffraction grating corresponds to the regions of the beam that require more attenuation. Fig. 3 demonstrates the differences in beam quality before and after SLM cleaning. Prior to the SLM cleaning, the beam exhibits obtuse edges and a less uniform surface, in contrast to the more uniform flat-top beam with sharper edges post-cleaning. Additionally, The beam post SLM-cleaning has a uniformity below 0.55 in 90% of the beam area while the beam before SLM-cleaning only has 47%. This shows that the optimized beam has an increased usable flat-top area which will enhance the efficiency and quality of any pulsed laser-material interaction for surface processing, micro/nanofabrication, and additive manufacturing, towards improved laboratory and industrial scale applications.[1,18]

4 Conclusion

We demonstrated combining a refractive beam shaper and an SLM to shape a quasi-Gaussian beam to a flat-top beam with a uniformity of 0.055 within 90% of the beam area and a system efficiency of 92%. Compared to beam shaping with refractive shaper or SLM only, our method shows a marked improvement in the combined performance of uniformity and efficiency. The approach also proved its versatility by shaping a circularly asymmetric beam. Leveraging the rapid development of actively-cooled, large-area SLMs, this method can be scaled up to high average laser power, high pulse energy, and large beam size.

The significance of this study lies in its potential to enhance the precision and efficiency for laser applications, presenting new possibilities for efficient, large-scale, high quality material processing, discovery, and manufacture. The shaping approach of using refractive optics to approximate a desired beam shape and then refine the profile with a phase correction device such as the SLM or a deformable mirror has more portential applications. The next step will be investigating its reverse application to shape a super-Gaussian beam to Gaussian and test its performance in plasma-laser acceleration.

Disclosures

There is no conflicts of interest to be declared.

Code and Data Availability

The software used to realize the technique described by this paper and the raw data can be found in the following github open repository: https://github.com/hpan24/open-source-for-SPIE.git.

Acknowledgments

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Biographies and photographs of the other authors are not available.

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