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# Comparison and Evaluation of Laser Beam Shaping Techniques

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## ABSTRACT

Over the past several decades, free-space optical (FSO) systems have gained a specific place in the wireless technology area. The application of these systems is advantageous for high bandwidths, a license free band and quick installation. The main drawback of FSO systems is their dependence on the state of the atmosphere causing deterioration of the FSO systems availability. One of the atmospheric effects which has an essential impact on the performance of the FSO systems is atmospheric turbulence. Atmospheric turbulence leads to fluctuation of the optical intensity in the plane of the receiving aperture. It has been shown that to reduce the effect of atmospheric turbulence, uniform distribution of the optical intensity within the cross section of the beam in the plane of transmitting aperture (phenomenon of diffraction is neglected) and a sufficiently large diameter of the circularly symmetric receiving aperture (to achieve aperture averaging effect) are needed. The main idea of our paper is the problem of beam shaping at the transmitter. In our contribution the technique of transformation of a Gaussian beam into a beam with uniform distribution of optical intensity is discussed. For the mentioned transformation we experimentally tested several shaping methods such as multi aperture beam integrators, diffractive diffusers, etc. Usage of laser sources with different degrees of coherence was considered.

The purpose of these techniques is to create an optical beam with uniform distribution of optical intensity on the transmitter output. In order to compare and evaluate the particular shaping techniques, a new Transformation Complex Quality (TCQ) parameter was defined. The TCQ parameter indicates the optimal shaping technique and also evaluates the quality of the resulting transformed beam with respect to its resistance towards atmospheric turbulence.

**Keywords:** Atmospheric turbulence, Gaussian beam, Top-hat beam, Laser beam shaping

## 1. INTRODUCTION

Laser beams are applied in a large number of applications ranging among various industries, from medicine to communication technologies. In some cases we require a laser beam with a uniform distribution of optical intensity in the beam profile. These so-called Top-hat (or Flat-top) beams may be obtained by transforming available optical beams. One of the possibilities how to get a flat beam is by using a Gaussian beam at the input plane of the transformation system. The desired result may have variable quality depending on the parameters of the transformation chain as well as on the quality of the input laser beam. Selected transformation techniques are mentioned in the corresponding section of this paper.

We need to define a beam with a uniform distribution of optical intensity in the profile to compare the quality of the transformation of a Gaussian beam to a Top-hat beam. Fermi-Dirac and Super-Gaussian approximations can be used for mathematical expressions of a Top-hat beam. The following expression describes a Fermi-Dirac beam with optical intensity $g_{FD}(r)$ in the beam profile[1]

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$$g_{FD}(r) = g_0 \frac{1}{1+\exp[\gamma(\frac{r}{R_0}-1)]} \tag{1}$$

where parameter $r$ is beam radius, $R_0$ is the radius at which the intensity has fallen to half of its value on the axis,$\gamma$ is a dimensionless parameter which determines the degree of beam flatness and $g_0$ is the maximal value of optical intensity on the beam axis.

The next possible approximation of the Top-hat beam can be provided by the Super-Gaussian function $g_{SG}$[1]

$$g_{SG}(r) = g_0 \exp\left[-2\left(\frac{r}{R_0}\right)^p\right] \tag{2}$$

where $p$ is a dimensionless parameter which determines the degree of beam flatness. The flatness of the beam profiles increases with increasing values of the parameters $\gamma$ and $p$.

The quality of the Top-hat beam output can be compared with an ideal Top-hat using the flat top factor.[2] This factor is, in the case of the ideal Top-hat, 1 and the Gaussian beam is evaluated using a value of 0.5. Most transformed beams reach values between 0.5 and 1. The contribution of our work is in introducing a complex transformation parameter which compares the quality of the input Gaussian beam with the quality of the output Top-hat beam. We have selected several transformation methods to convert input Gaussian beams to output Top-hat beams. They are described in the section Transformation Techniques. The experimental setups of transformations are described in section Experimental Measurement. We have designed a parameter for comparing the quality of the transformation, which is presented in the sections Transformation Complex Parameter and Results.

## 2. TRANSFORMATION TECHNIQUES

There exist many transformation methods to obtain the desired optical intensity distribution at the output plane. Some of the methods are appropriate for laser beams with a high degree of coherence, and other methods are applicable to non coherent optical sources. The transformation techniques can also be divided according to the measure of conversion losses. One group of shaping techniques is known as field mapping. It is suitable for coherent optical sources.[3] The other methods, which are cost effective and applicable also for non coherent sources, are beam integrators.[3] One of the basic techniques for laser beam shaping is a method which uses a lenslet array as a shaping element. The method belongs to the group of beam integrators. The basic concept of the usage of the lenslet array is in dividing the input Gaussian beam into sub-beams. The diameter of particular sub-beams depends on the lenslet structure. Afterwards, we fold particular sub-beams by an optical lens, which we call Fourier lens.[3] This transformation technique is also referred to as a non-imaging homogenizer.

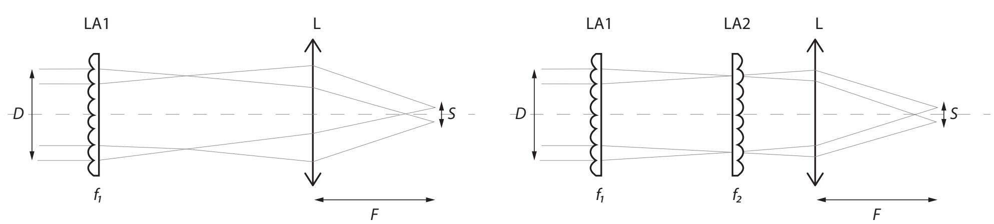


Figure 1. Non-imaging multiaperture beam integrator (left),imaging multiaperture beam integrator (right)

Fig. 1 shows the arrangement of a non-imaging homogenizer, where $D$ is diameter of input beam at multi aperture integrator, $d$ represents diameter of sub-aperture of lenslet, $f$ indicates focal length of array lenslet, $F$ is focal length of primary lens, and $S$ is diameter of target spot. The size of $S$ at the distance $F$ from the Fourier lens can be calculated by the following expression[4]

$$S = \left|\frac{d.F}{f}\right| \tag{3}$$

We can calculate Fresnel number $FN$ to consider application suitability of this method.[4]

$$FN = \frac{d.S}{4.\lambda.F} \tag{4}$$

We obtain sharper edges and smaller variations of the Top-hat profile for higher $FN$. If $FN$ is greater than 10, then the result is acceptable. For a high quality Top-hat profile, $FN$ higher than 100 is required. A resultant $FN$ smaller than 10 indicates that the Top-hat profile might be distorted by Fresnel diffraction. The next possibility how to evaluate the quality of transformation is to calculate the well known parameter $\beta$ which has the same form as the Fresnel number but differs by a constant factor.[3]

If the result of the transformation using the non-imaging homogenizer is unsatisfactory, we can employ a modified arrangement with a pair of lenslet arrays, which are similar to each other and have identical lens pitch. The arrangement is also known as imaging homogenizer. The diameter of the output Top-hat beam $S$ is given by the relationship[4]

$$S = \frac{d.F}{(f_1.f_2)}\left[(f_1 + f_2) - a\right] \tag{5}$$

where $f_1 < a < f_1 + f_2$.

The value $a$ is the distance between both lenslet arrays. Due to equation (5) the diameter of the output Top-hat beam can be set by the distance between the first and second lenslet array. The image homogenizer is depicted in Fig. 1.

Diffractive diffusers, also so-called homogenizers, are the next option how to get a desired distribution of the optical intensity at a chosen plane. These diffusers belong to the group of field mappers.[3] This type of diffractive optics is typically used when the monochromatic laser beam is applied. Among the advantages, we count the fact that they are not sensitive to alignment and do not affect the polarization of the input beam. The most common shapes of diffusers are square, round, rectangular and elliptical. The edges of the diffuser beam are generally steep. The disadvantage of the method is that the intensity profile of the output beam is speckled due to the pseudo-random energy diffusion.

A couple of plano-aspheric lenses is the next possibility, how to reach uniform beam.[1,5–7] The advantage of this field mapper is low loss in optical power. The Keplerian design[1] consists of two lenses, the first aspheric surface reshapes the intensity profile and the second one corrects the beam phase.[8]

Of course, there are also other methods for obtaining a desired optical intensity distribution,[1] but we are using only the above-mentioned shaping techniques in our work.

## 3. TRANSFORMATION COMPLEX PARAMETER

For comparing the ideal and measured Gaussian and Top-hat beam we defined a transformation complex quality (TCQ) parameter. The TCQ parameter is a complex number

$$q_1 + iq_2, \tag{6}$$

where $q_1$ is a quality parameter of a Gaussian beam and $q_2$ is a quality parameter of a shaped Top-hat beam. These two parameters describe deviations of a real (measured) beam from ideality. The TCQ parameter allows us to measure the quality of the selected transformation technique. The TCQ parameter can be viewed as a point in a two dimensional Cartesian coordinate system by using the horizontal axis for Gaussian beam quality parameter $q_1$ and the vertical axis for Top-hat beam quality parameter $q_2$. The parameters can be calculated from standard deviation of the ideal and measured beam as follows

$$q_1 = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Gid_i - Gmeas_i)^2},\; q_2 = \sqrt{\frac{1}{N}\sum_{i=1}^{M}(THid_i - THmeas_i)^2}, \tag{7}$$

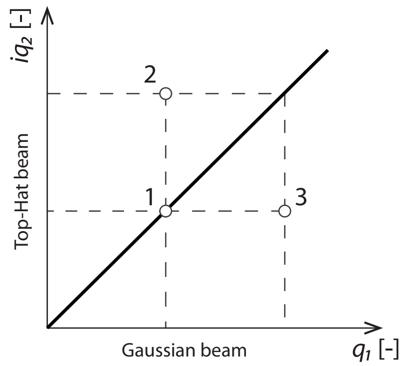


Figure 2. TCQ parameter.

where $N$, $M$ are numbers of points with nonzero values, $Gid/THid$ is a matrix of an ideal beam and $Gmeas/THmeas$ is a matrix of a measured beam.

Figure 2 shows the three model cases. The first point represents the case where the standard deviations stayed the same after beam shaping of the Gaussian to the Top-hat beam. If the quality of the shaped beam became worse, which would be indicated with higher values of standard deviations, the point would move to the top - the second point. The third point represents the case, where the quality of the Gaussian beam was worse, but the shaped Top-hat beam achieved higher quality.

## 4. EXPERIMENTAL MEASUREMENT

The measurement for four different shaping techniques was performed. For the measurement the He-Ne lasers with wavelength 543 nm, 633 nm and semiconductor lasers with wavelength 635 nm and 670 nm were employed. The parameters of the lasers are summarized in Table 1. The Gaussian beam was propagated through beam shaping optics and then was collimated with a biconvex lens. The collimated laser beam was focused with Lens 2 on beam profiler with resolution 640x480 pixels. The shaped beam was scanned by beam profiler Newport LBP-2-USB and the optical power was measured with Spiricon Vega power meter. The setup for the beam transformation experiment is depicted in Fig. 3.

Table 1. Parameters of the Gaaussian beams, where $2W_x$ is beam width in $x$-axis, $2W_y$ is beam width in $y$-axis, $P$ is measured optical power and $q_1$ is Gaussian beam quality parameter calculated from the values we have measured in our experiment.

| Laser | Wavelength [nm] | $2W_x$ [$\mu$m] | $2W_y$ [$\mu$m] | P [mW] | $q_1$ |
|---|---|---|---|---|---|
| L1 | 633 | 1068 | 1154 | 1.71 | 11.7 |
| L2 | 543 | 1059 | 1146 | 0.43 | 12.5 |
| L3 | 635 | 2444 | 747 | 0.86 | 22.1 |
| L4 | 670 | 2688 | 1021 | 0.40 | 23.7 |

The values from the Table 1 indicate, that the laser source L1 shows the best fitting with the ideal Gaussian beam. Resultant parameter $q_1$ of laser L2 has similar value, so we can say, that these He-Ne lasers have more quality than the semiconductor lasers L3 and L4 with the parameter $q_1$ higher than 22. The first transformation method was based on using a diffractive diffuser (DD). The diffractive diffuser used was the Engineered diffuser ED1-C20-MD with divergence 20°. The diffuser was generating a round Top-hat beam, as shown in Fig. 4.

Non-imaging homogenizer (LA) and imaging homogenizer (2xLA) can also be used for redistributing the energy of the initial Gaussian beam. Two microlens array MLA150-7AR-M with lens pitch 150 $\mu$m were used. For both methods we achieved Top-hat beams with similar quality, as shown in Fig. 4 and 5.

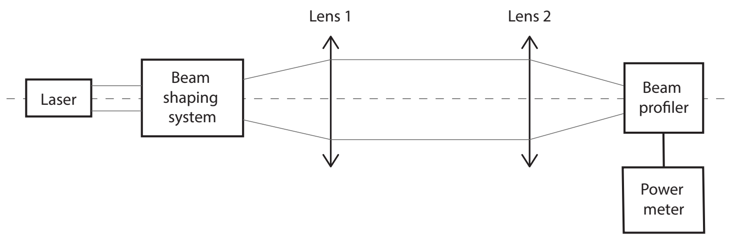


Figure 3. Experimental arrangement of beam shaping system.

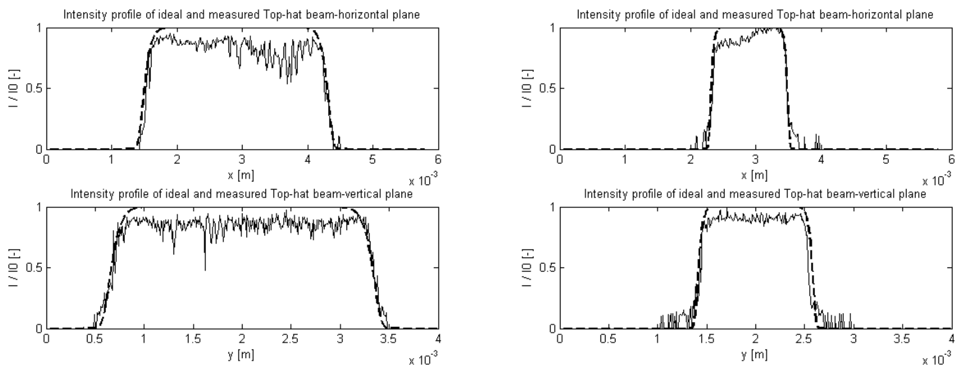


Figure 4. Measured Top-hat beam shaped by diffractive diffuser (left), non-imaging homogenizer (right)for laser with wavelength 633 nm (solid line) and calculated Top-hat beam (dashed line) for $x$ and $y$ axis.

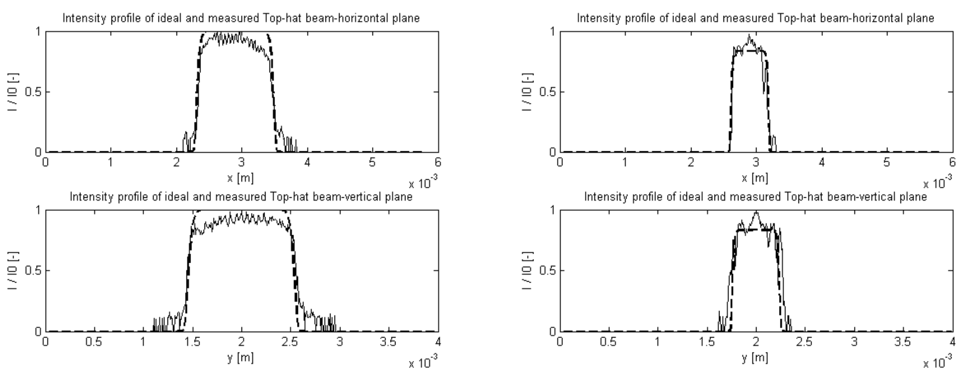


Figure 5. Measured Top-hat beam shaped by imaging homogenizer (left), two aspheric lenses (right) for laser with wavelength 633 nm (solid line) and calculated Top-hat beam (dashed line) for $x$ and $y$ axis.

The refractive method (R) was the last transformation method which was used. The beam shaping setup was based on a two apherical lens shaping system. The output profile of the beam shaper is depicted in Fig. 5.

## 5. RESULTS

For comparing the measured Top-hat beam with ideal Top-hat beam we used Super-Gaussian approximation with flatness parameter $\gamma$=10. Then we calculated TCQ parameters for all laser sources and shaping techniques (Fig. 6). The quality of the Gaussian beam input for laser sources L1 and L2 seems to be similar (6), which can be seen from the calculated TCQ parameters. The worst quality of the output beam for both lasers was the method based on the diffraction diffuser. The main drawback of these shaping techniques is that the output beam is speckled. This phenomenon rapidly decreases the quality parameter of the output beam. On the other hand, the non-imaging /imaging homogenizer and refractive beam shaper achieved very good results. The refractive beam shaper proved to be ideal for beam shaping of high quality Gaussian beams.

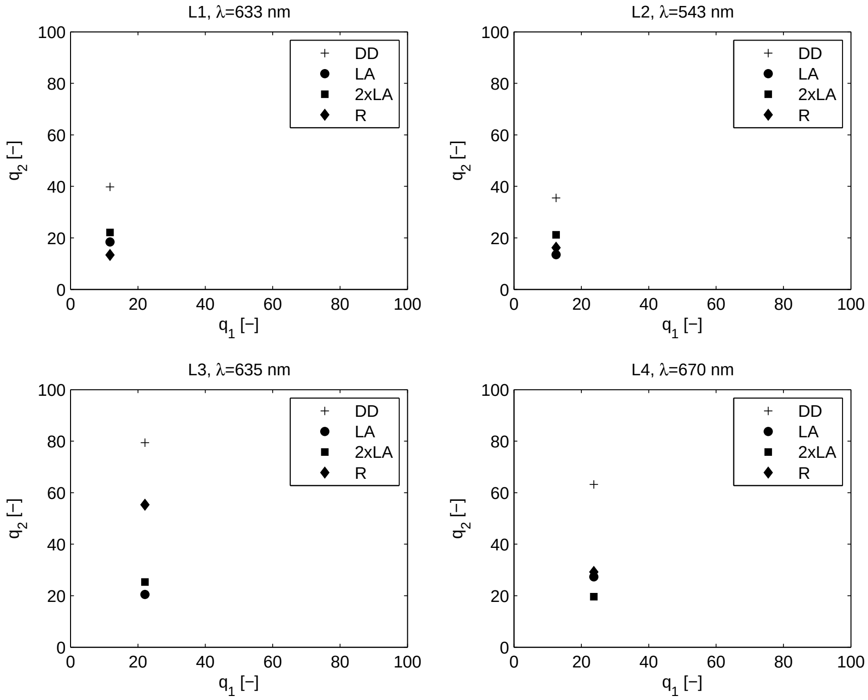


Figure 6. TCQ parameters for all four lasers.

Not only the quality of the output beam needs to be taken into account. Another aspect for evaluation of the beam shaping methods is effectivness. Figure 7 depicts beam attenuation for all laser sources. From this point of view it is advantageous to use the refractive beam shaper due to low loss in optical power.

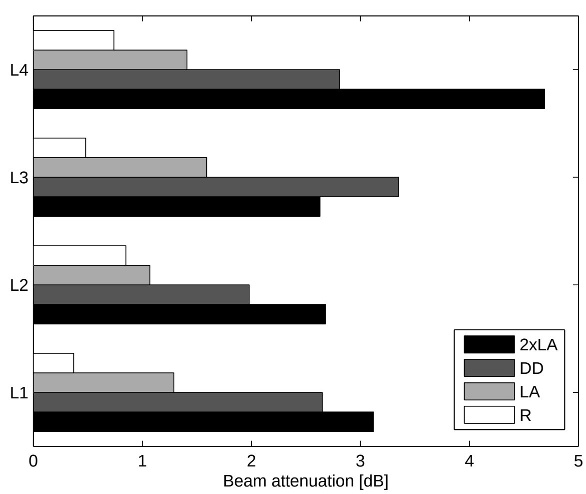


Figure 7. Laser beam attenuation after beam shaping

## 6. CONCLUSION

In this paper, we experimentally tested several shaping methods for sources with different quality of the input Gaussian beam. Thereafter, we defined a new TCQ parameter in order to compare and evaluate the particular shaping techniques. According to the TCQ parameters, the method based on refraction gives the best results for a beam with high Gaussian beam quality. The power effectivity of this technique is also very high. For Gaussian beams with poor quality, a multi-aperture beam integrator is the most suitable technique.

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