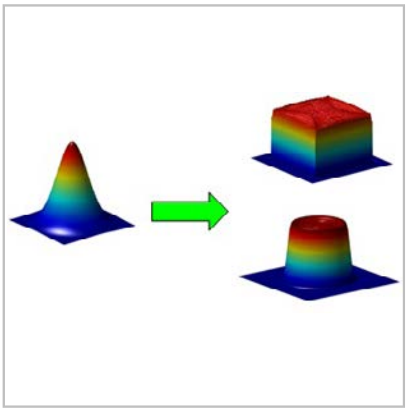
Optics

TopHat – StableTop Beamshaper



The top-hat beam shaper is a diffractive optical element (DOE) used to transform a near-gaussian incident laser beam into a uniform-intensity spot of either round, rectangular, square, line or other shape with sharp edges in a specific work plane.

A uniform spot enables equal treatment to a surface, excluding over/under-exposure of specific areas. In addition, the spot is characterized by a sharp transition region that creates a clear border between the treated and untreated area.

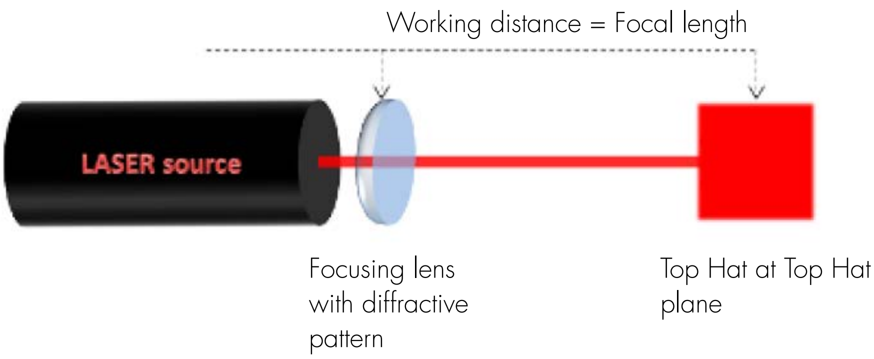
The StableTop element is comparable to the TopHat element, the main difference is that it is less sensitive in tolerances of input beam and focal length, the drawback is a less homogenous intensity profile specifically at the edge of the spot.

The beam shaper can be a:

Focal Beamshaper

Hybrid element or module, which give a Top-Hat intensity distribution at a specific working distance (BFL of the lens or distance from exit location of the module to Top-Hat plane).

Diffractive structure is on the plane surface of a plano convex lens, spherical aberrations can be corrected with the diffractive structure.



01/20 / V04 / IF / holo-or/top-hat_beam-shaper

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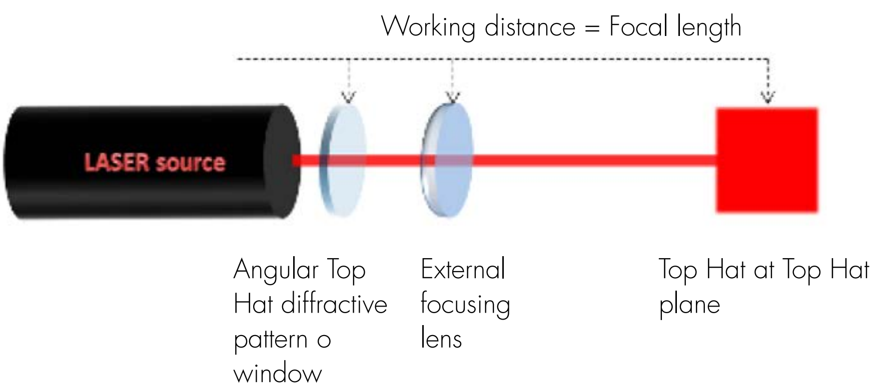
Angular Beamshaper

Window which give a Top-Hat intensity distribution at infinity or focal length of aberration free customer's lens. The diffractive pattern is on a window, an additional lens is needed, by variation of the focal length spot sizes can be adjusted.



Introduction

In various industries there is a need to focus a laser beam to a well-defined size and shape with uniform intensity (flat top). A uniform spot enables even laser treatment of the working surface.

In addition, the sharp edges of the spot – or narrow "transition region" - create a clear-cut border between treated and untreated zones. Typical applications include:

- Laser ablation
- Laser welding
- Hole drilling
- Laser scribing
- Laser displays
- Filters for cigarettes
- Medical and aesthetic laser applications

This application note is meant to aid the user's understanding of the functionality and considerations when using a Beam shaper/ Top-Hat diffractive element.

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Principal of Operation

The most rudimentary set-up in a Beam Shaping / Flat Top application consists of a laser, a diffractive beam shaper element and the surface to be treated. See fig.1 below.

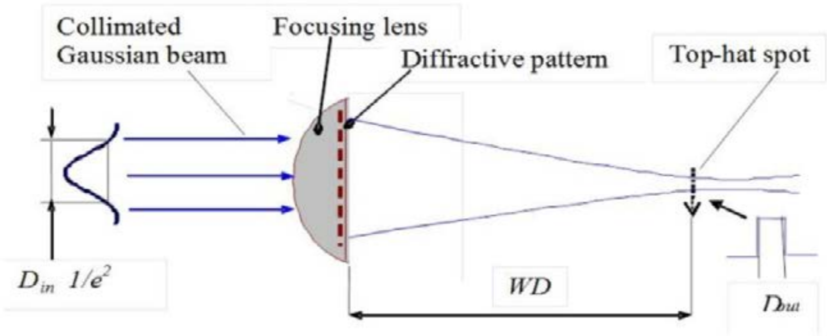

Figure 1: Basic Operation.

The diffractive Top-Hat beam shaper is a phase element that transforms the Gaussian input beam into a uniform spot with sharp edges at a specific working distance WD.

**Note that the Top-Hat spot is NOT at the minimum spot location (minimum waist), but near it.

Each TH shaper is designed for specific use with a unique set of optical system parameters:

1. Wavelength
2. Input beam size (Din)
3. Working distance (WD)
4. Output spot size (Dout)

Altering any one of the values in this parameter set will degrade the performance of the Top-Hat beam shaper element, and possibly render it useless.

For instance, a beam shaper designed for 50mm working distance will not produce a good Top-Hat spot at 100mm; a new working distance will often require a separate Top-Hat element to correct aberrations from new lens.

Design Considerations

For good quality Top-Hat beam shaper performance, the laser output should be **Single Mode** (TEM00) with an **M2** value under 1.3. Even if the M2 is higher, it may still be possible to reduce the M2 value by inserting a spatial filter in between the laser and the DOE lens component.

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The **spatial filter** consists of a focusing lens, a small aperture in the focal plane, and a collimating lens. The spatial filter aperture acts to reduce parasitic modes, whose presence in the laser output causes a high M2 value and degraded Top-Hat performance. The user must take care to use a small aperture, BUT no smaller than 2x the beam size at the aperture plane. Too small an aperture will give rise to a parasitic interference pattern or ripple in the beam shaper output spot. By manipulating the focal lengths of these two lenses, the spatial filter can also be used as a **beam expander**. See fig.2 below for visual aid of spatial filter set-up functioning also as a beam expander.

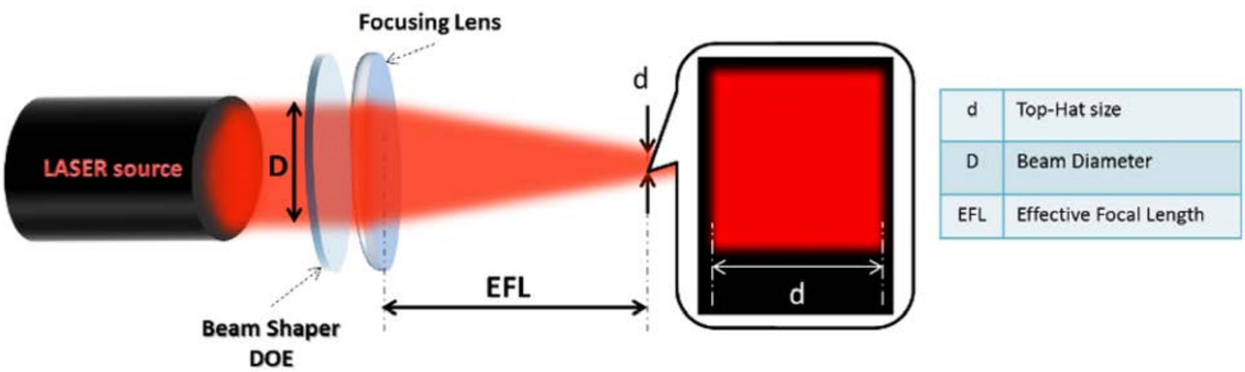

Figure 2: Typical Set Up.

The advantage of working with a larger input beam is twofold. First, a larger beam reduces somewhat the sensitivity of the Top-Hat output to tolerances. Secondly, a larger input beam will enable achieving a smaller output spot, which is a desired outcome for many beam shaper applications.

The two translation stages in fig.2 above are meant to give the user precise control of elements' locations, to reduce tolerance effects. This is discussed further in the section on Tolerances.

As was mentioned regarding the spatial filter aperture, ALL apertures in the beam path must be **at least 2x** as large as the beam size ($1/e^2$) on the aperture plane (best over 2.5x). These often include mirrors (for beam folding), beam expander, beam splitter and filter/diaphragm.

All optics in the beam path should be of high quality, i.e. **low irregularity** figure, so as not to introduce wave-front errors which would degrade the Top-Hat performance. This includes mirrors which should have **high flatness** specification. Here, too, a larger beam size incident on the mirror will reduce its sensitivity to aberrations.

As was mentioned above, the beam shaper element requires that the input beam be **collimated**.

For this reason, as well as for purposes of stability, it is recommended to work with the beam shaper element **in the waist of the laser.** Nonetheless, if the beam has a **small divergence angle** (<1°), there should not be any noticeable effect on the Top-Hat output quality, but only on the exact working distance.

If, due to mechanical or other constraints, the diffractive optical element (DOE) will be located at a distance from the beam waist, it is important to take this distance into consideration, along with the beam divergence, in the designing of the DOE. Otherwise, the resultant wave-front aberration can generate an interference/ripple pattern over the output beam, whose intensity will grow as a function of the DOE's distance from waist and the divergence angle.

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When designing the desired output Top-Hat size, it is important to be familiar with the physical limits of the minimum spot size. The formula for the diffraction-limited spot size:

$$\frac{4 \times L \times \lambda}{\pi \times D} \times M^2 = D.L.spotsize$$

L: Working distance
λ: Wavelength
D: Input beam size
M2: M2 value of input laser beam

As a rule of thumb, the minimum **Top-Hat beam shaper spot size** will be between 3 to 5 times the diffraction-limited spot size given by the above formula. The precise factor depends on the whether the element is a Top-Hat or Stable Top-Hat. See final section for comparison.

Characteristics

- **Uniform intensity profile:** Typically +/-5%.
- **Steep transition region:** Typically similar to diffraction-limited spot with the same input diameter and working distance.
- **High power threshold**
- **High efficiency:** > 95%
- **Sensitivity to X-Y displacement:** 5% of the input beam, in order to keep acceptable performance.
- **Sensitivity to input beam diameter:** 5% of the input beam in order to keep acceptable performance.
- **Rotation insensitive:** For round shape.
- **Sensitivity to working distance:** smaller than 50% of the spot size in order to keep acceptable performance.

Consideration of Top Hat (TH) size as a number of diffraction limits

Some basic rules:

- It is impossible to get a Top Hat size less than the diffraction limited spot size
- The Factor between the Top Hat size and the diffraction limited spot size defines the quality and efficiency of the Top Hat. A larger factor enables sharper edges
- The transfer region of the Top Hat can't be < 0.5 DL size. Generally ~1 DL

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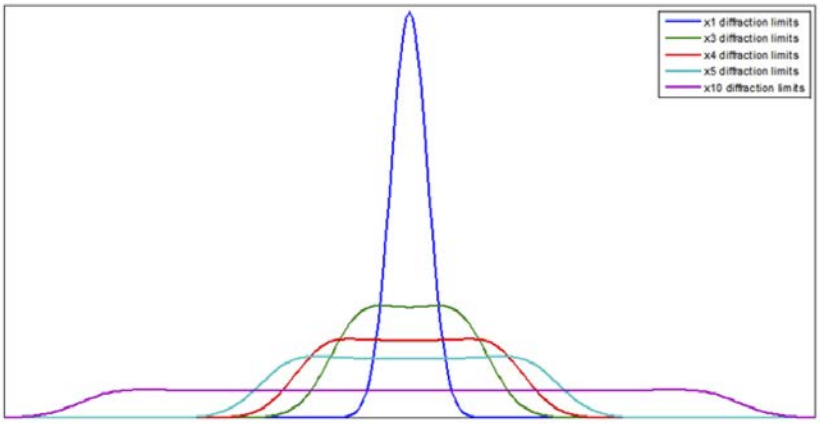
Example of same size TH with different DL number:



A typical application prefers the transfer region (13.5-90 %) to be as small as possible and the Top Hat profile to have a maximum relative size of uniform area.

The TH's quality (Qth) parameter can be defined as relation:

$$Q_{TH} = \frac{TH\ size}{DL}$$

Sensitivity to Alignment and Beam Tolerances

Beam shaper elements are sensitive to various parameter tolerances [mentioned under the section characteristics]. When one goes about designing a set-up that includes a diffrative optical element (DOE), one should take care to ensure control and stability of these system parameters.

As depicted in the typical set-up of figure 2, accurate translation stages, high quality laser beams, spatial filter and beam expander all contribute to the stability of the optical system.

Many of the Top-Hat output specifications depend on the relative displacement and/or mismatch of the input beam diameter. Therefore, the system can be made less sensitive by expanding the input beam prior to the design. For example, for an input beam of 10mm diameter, a mismatch of 5% gives 0.5mm tolerance, while for a beam diameter of 2mm, a 5% tolerance affords only 0.1mm.

https://www.youtube.com/watch?x-yt-ts=1421828030&v=79GlQdgFxbI&x-yt-cl=84411374

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Simulated Effects of Tolerances on Top-Hat beam shaper Profile

The best performance will be obtained for a well-positioned perfectly aligned part, located precisely in the plane of the nominal working distance. To illustrate the sensitivity of Top-Hat performance to different tolerance parameters, several graphs are included here for a standard beam shaper element (WD: 120mm, λ: 532nm, Din: 10mm).

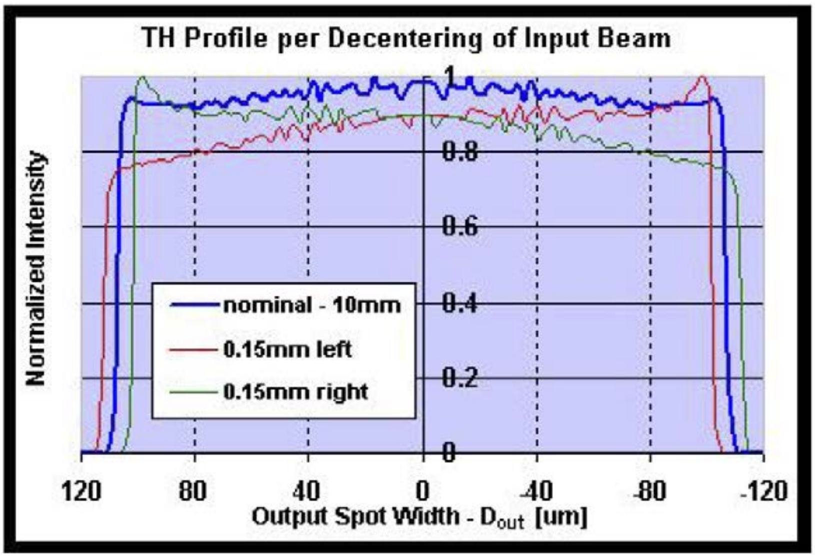

Fig. 4: Effect of x-axis or y-axis de-centering of input beam on Top-Hat Profile

**Noteworthy in figure 4 above is the „tilted" Top-Hat profile due to de-centering; i.e. a slope in the intensity going from one side of spot to the other.

Sensitivity of Top-Hat due to <u>high</u> decentering of input beam in relation to the element center.

https://www.youtube.com/watch?v=bjXRG7fGC48&x-yt-ts=1421828030&x-yt-cl=84411374

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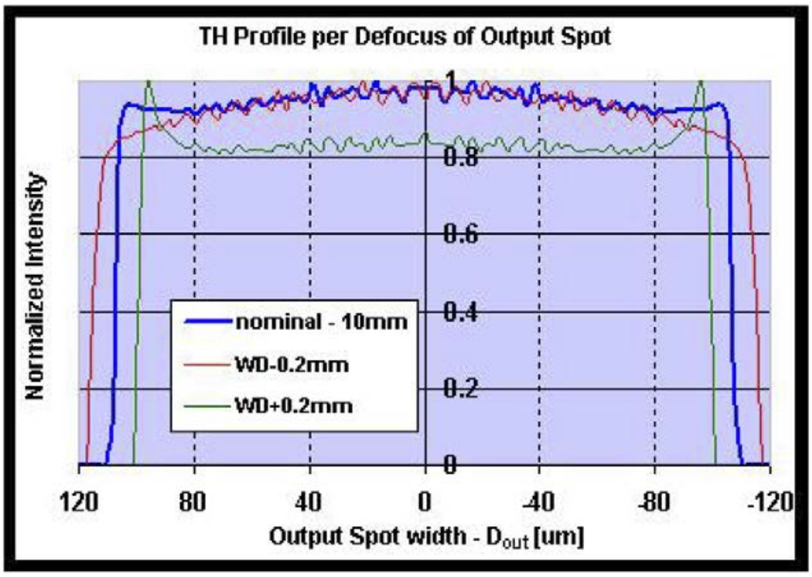

Fig. 5: Effect of Working Plane Defocus on Top-Hat Profile

**Note the different behavior of Top-Hat profile when located too close (red curve) as opposed to being too distant (green curve). The uniformity suffers a drop in both cases, while the extended distance gives rise to narrow peaks at the Top-Hat spot periphery (a.k.a „dog ears").

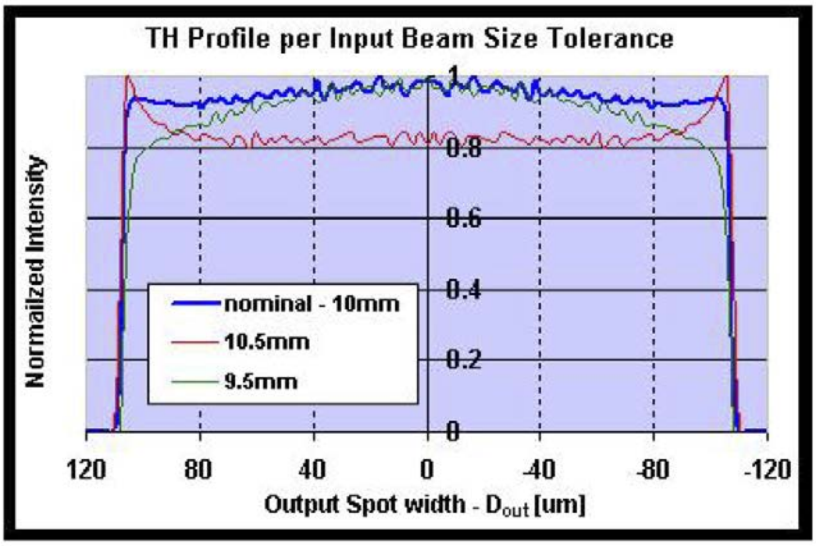

Fig. 6: Effect of Input Beam Size Tolerance on Top-Hat Profile

**Interesting to note in fig.6, a very similar effect as in fig.5. There is clear parallel between too large beam size and extended defocus. The „dog ears" effect is the same.

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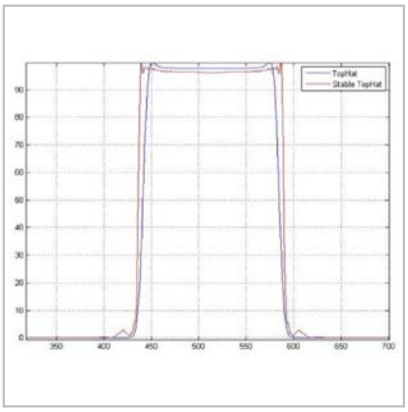
Comparison of Top-Hat and Stable Top-Hat

Holo-Or uses two slightly different algorithms for the Top-Hat diffractive pattern, each algorithm with its own advantages. The original Top-Hat algorithm produces a higher level of uniformity than its „ST" counterpart, and is also less sensitive to errors in manufacturing. On the other hand, the „ST" algorithm can achieve smaller spot size (1.5x diff. limit) than the „Top-Hat" (5x diff. limit), and smaller transition region.

Included below is a typical graph superposition of equivalent designs – same spot size.



Comparison of Top-Hat and Polychromatic Top-Hat

The standard Top-Hat is manufactured for specific wavelength. Other wavelength will affect the Top-Hat performances. However, if the customer's application requires a polychromatic source, the polychromatic Top-Hat will be the solution. The polychromatic Top-Hat presents the advantage to work well for many wavelengths and also, in some case, a cheaper solution. However, this product can be less accurate in the Top-Hat size and shape.

You can find below a summary table of comparison between standard Top-Hat and Polychromatic Top-Hat:

Type	Standard	Polychromatic
Wavelength dependence	YES	NO
Material	Fused silica, ZnSe, plastic	Fused Silica, optical glass
Top-Hat shape	any	round, square, rectangular, line
Efficiency	> 95%	> 95%
Uniformity	< 5%	< 10%
Top-Hat size	very precise	precise
Top-Hat shape	very accurate	accurate
Top-Hat quality factor (in units of diffraction limits number)	not depends on wavelength	inverse proportional to wavelength
Top-Hat diffusion angle	proportional to wavelength	proportional to refractive index

The polychromatic TH appears in angular TH product page with format **PT**-123-A-B-C

Top-Hat design tool for MATLAB

Holo/Or published a Top-Hat design tool for MATLAB. This free of charge service provides intensity distribution for any Top-Hat. The designer is free to choose the wavelength, input diameter, spot size and working distance of his preference. For download please use

http://www.holoor.co.il/Diffractive_optics_Applications/Application_Notes_BeamShapers.htm

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