LASER COMPONENTS®

Application Note Top-Hat

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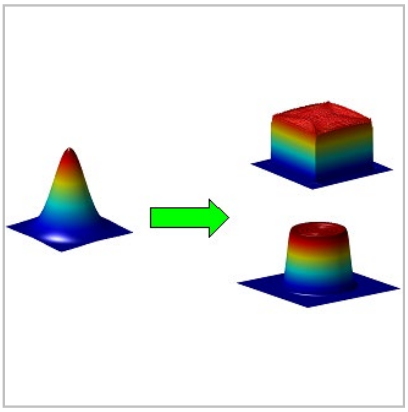

Introduction

In various industries there is a need to focus a laser beam to a well-defined size and shape with uniform intensity. 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 Top-Hat diffractive element.

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Principal of Operation

The most rudimentary set-up in a Top-Hat application consists of a laser, a diffractive Top-Hat element and the surface to be treated. See fig. 1 below.

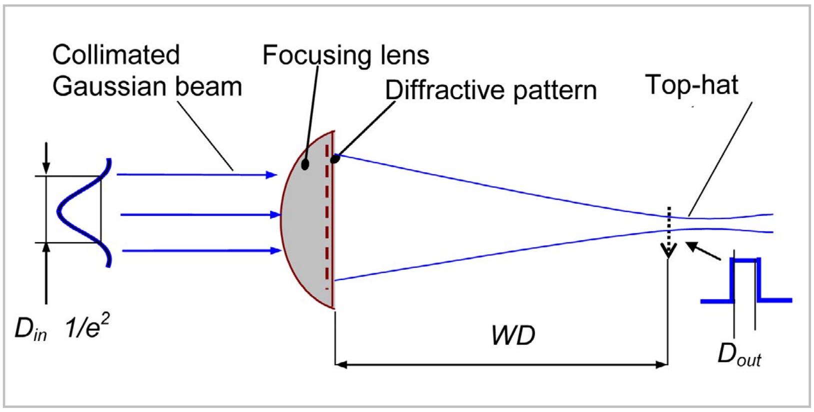

Figure 1: Basic operation

The diffractive Top-Hat 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 TH 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 (D_{in})
3. Working distance (WD)
4. Output spot size (D_{out})

Altering any one of the vales in this parameter set will degrade the performance of the Top-Hat element, and possibly render it useless.
For instance, a Top-Hat designed for 50 mm working distance will not produce a good Top-Hat spot at 100 mm; a new working distance will often require a separate Top-Hat element to correct aberrations from new lens.

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Design Considerations

For good quality Top-Hat performance, the laser output should be **Single Mode** (TEM_{00}) with an M^2 value under 1.3. Even if the **M^2** is higher, it may still be possible to reduce the M^2 value by inserting a **spatial filter** in between the laser and the DOE lens component.
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 M^2 value and degraded TH 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 TH 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.

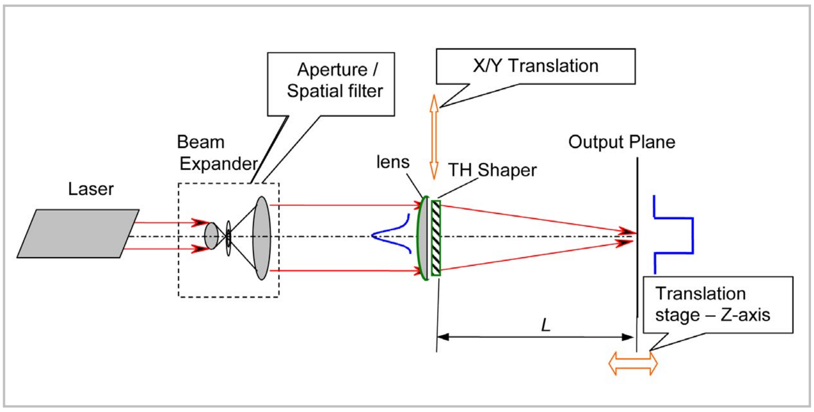

Figure 2: Typical set up

The advantage of working with a larger input beam is twofold. First, a larger beam reduces somewhat the sensitivity of the TH output to tolerances. Secondly, a larger input beam will enable achieving a smaller output spot, which is a desired outcome for many TH 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 TH 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 TH 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 TH 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 TH output quality, but only on the exact working distance.

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If, due to mechanical or other constraints, the 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.

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 spot size** will be between 3 to 5 times the diffraction-limited spot size given by the above formula. The precise factor depends on 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.

Sensitivity to Alignment and Beam Tolerances

Top-Hat elements are sensitive to various parameter tolerances [mentioned under the section characteristics]. When one goes about designing a set-up that includes a 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 TH 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 10 mm diameter, a mismatch of 5% gives 0.5 mm tolerance, while for a beam diameter of 2 mm, a 5% tolerance affords only 0.1 mm.

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Simulated Effects of Tolerances on Top-Hat 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 Top-Hat element
(WD: 120 mm, λ: 532 nm, D_{in}: 10 mm).

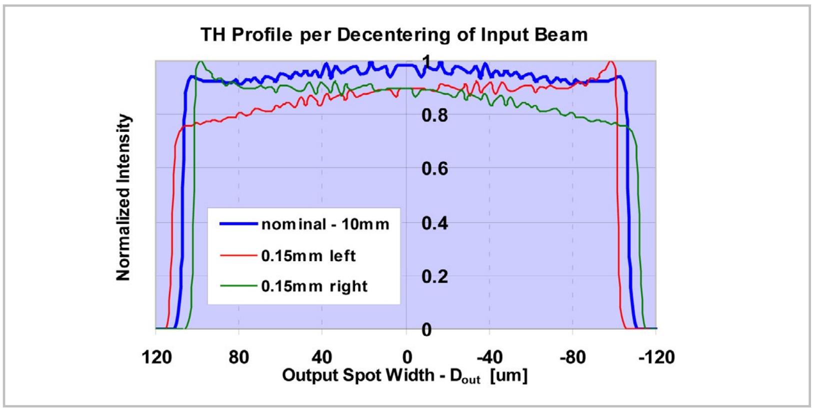

Fig. 3: Effect of x-axis or y-axis de-centering of input beam on Top-Hat profile

**Noteworthy in figure 3 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.

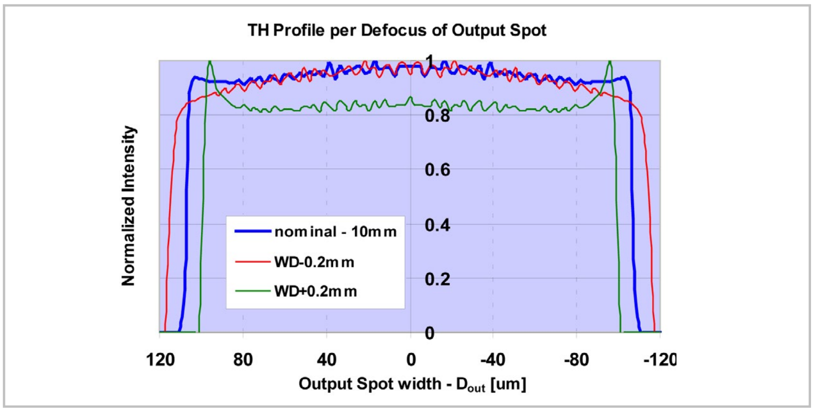

Fig. 4: Effect of working plane defocus on Top-Hat profile

**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 TH spot periphery (a.k.a „dog ears").

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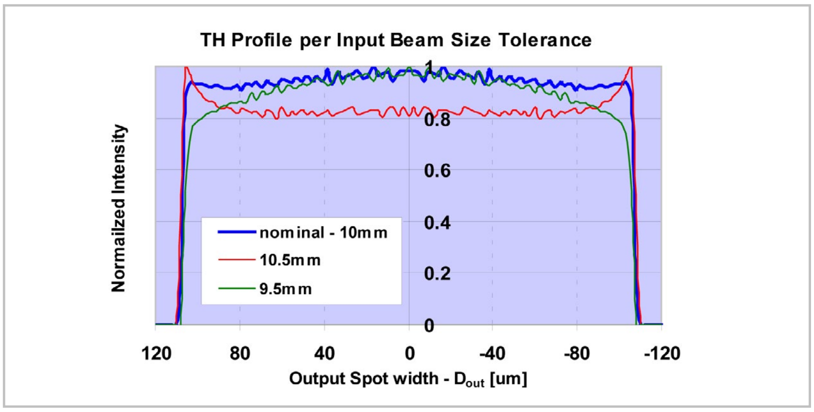

Fig. 5: Effect of input beam size tolerance on Top-Hat profile

**Interesting to note in fig. 5, a very similar effect as in fig. 4. There is clear parallel between too large beam size and extended defocus. The „dog ears" effect is the same.

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 (3x diff. limit) than the "TH" (5x diff. limit), and smaller transition region.

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

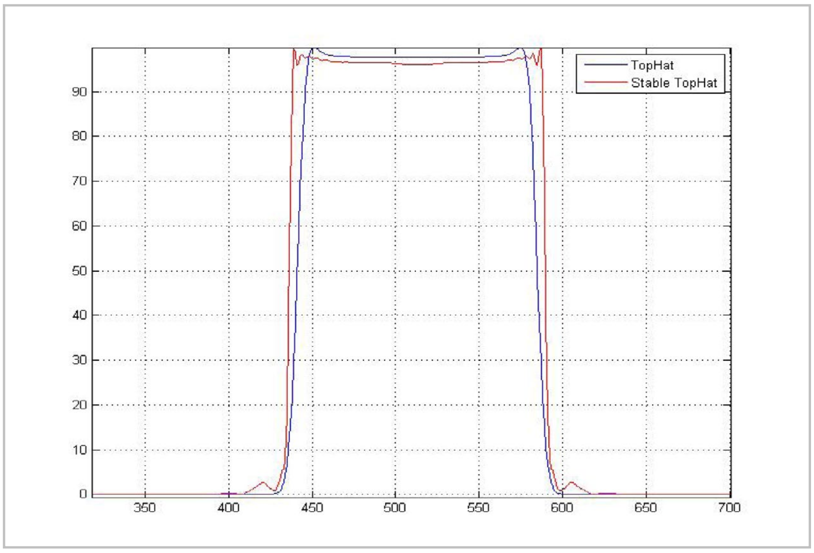

Fig. 6: Comparison top-hat and stable top-hat

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