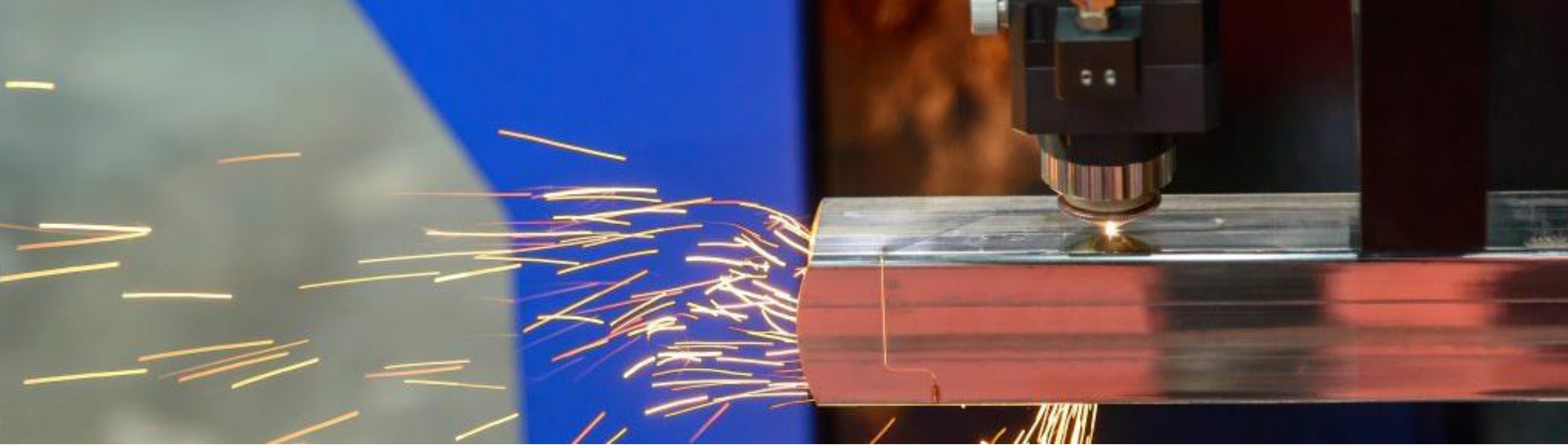

Adjustable-Function beam shaping methods for laser welding applications

Laser welding is used in a wide range of industrial applications including automotive, aerospace, semiconductors, electronics, medical, power, defense and others[1234].

The raw laser beam isn't the optimal shape for many industrial applications in general and especially in the field of welding, brazing, soldering and other similar processes. Compared to other laser material processing applications, these processes stand out in terms of the required laser power (multi kW) and the highly multimode beams often used. A process-specific tailored laser intensity distribution can improve throughput, seam height, strength and the edge smoothness of the joints.

In this article we review welding and brazing applications that already use diffractive beam shaping optics, as well as a few examples where current shaping technique can be replaced by diffractive optics. In addition, we discuss a few novel shaping concepts that can be implemented for welding and brazing applications.

Introduction

For welding and brazing purposes, the commonly used shaping is to round, square, line and ring intensity shapes, with uniform intensity profiles. Patterns with several intensity regions are also often used, including high central peaks or leading spots.

To achieve this shaping, many methods of beam shaping are employed in the laser welding industry. These include Diffractive Optical Elements (DOE), custom fiber bundles[5] with a special arrangement[6], shaped fiber cores[7], multiple laser combinations where each laser is shaped individually[8], galvo-scanners[9], digital mirrors devices (DMD) and refractive micro optics[10].

Compared to other methods, DOE have a few key advantages:

Shaping freedom- any shape can be designed, manufacturing flexibility, being passive components (no moving mechanical parts or electronics need) and high- laser damage threshold. A single diffractive optical element combined with a manual or automated translation/rotation stages can convert a limited laser machine to a versatile universal solution for a variety of processes without the need to change the laser construction, complex electronics or special fiber manipulations.

To show the potential of DOE for laser welding shaping, we will review some shaping concepts useful for these applications.

Adjustable Function concept

Adjustable shaping can be achieved by utilizing a sub apertures method. In this shaping method, the clear aperture of the optical element is divided to discrete or continuously changing regions, with each region having its own optical functionality. A laser beam incident on the element is divided by the sub-apertures to sub beams and each sub beam is affected by its individual modification. Sub apertures can have equal or different areas, and have different shapes – for example angular segments, stripes, or squares, as shown in figure 1.

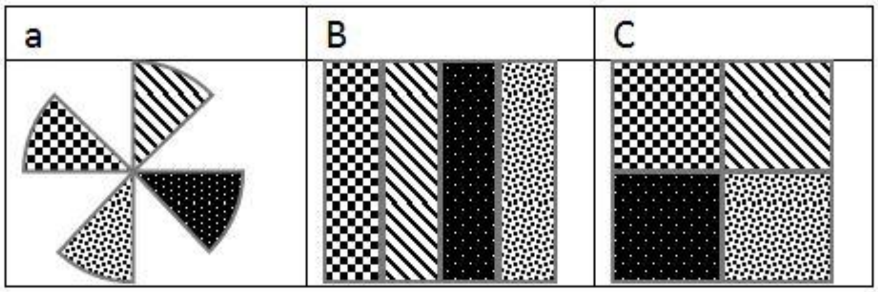

Figure 1. Clear aperture schematic view. (a) Angular Segments, (b) Stripes and (c) Squares.

Moving the laser beam within the clear aperture changes the amount of energy incident on each sub-aperture. This effect is used for overall optical functionality adjustment. Some basic configurations of optical elements with sub-apertures are shown in figure 2.

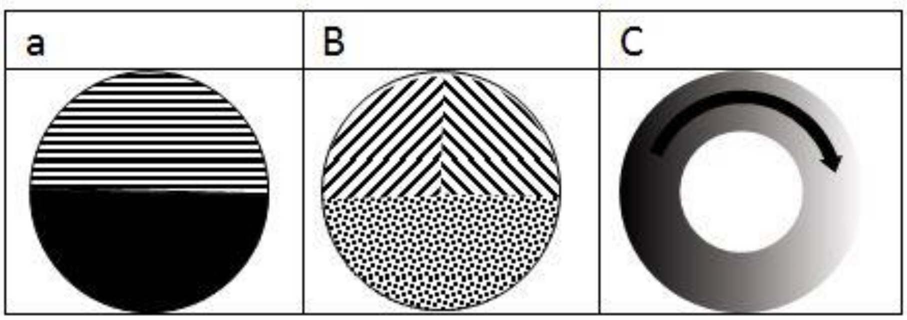

Figure 2. Schematic sketch of sub aperture elements for common cases. (a) Two spots welding, (b) Triple spot welding and (c) Continuous scanning.

The adjustment technique is schematically demonstrated in figure 3, for a DOE that shapes the beam to a central spot with a surrounding ring[11]. This intensity shape is used for cutting and welding by various integrators[12,13], and is known to give improved process results, with the ratio of central spot to ring tuned per specific application. The same sort of flexible shaping can be done by integrating an XY translation mount with a sub-aperture DOE beam shaper into a laser head. Position adjustment within the clear aperture of the DOE would control the ratio between the sub apertures and hence shaping.

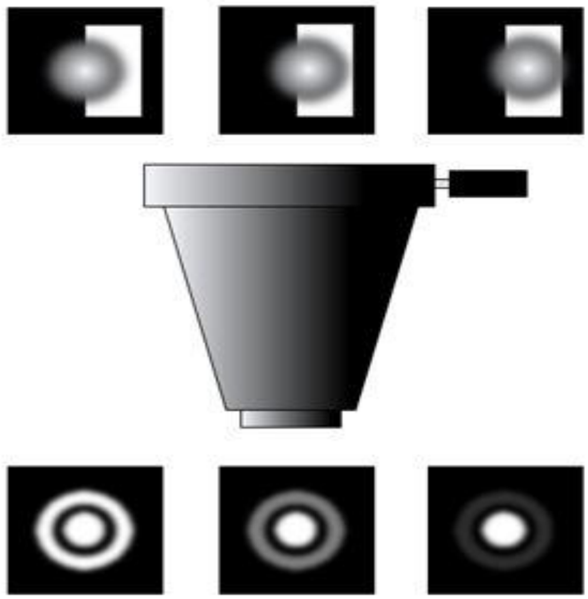

Figure 3. Schematic sketch of a laser head with an integrated DOE shaper with manual X stage. Left DOE region shapes the incident beam into a ring, while the right shapes into a central round spot. Moving the element in the x axis changes the power ratios between the ring and center spot.

An example of such a solution is the widely used triple spot concept with two stripe beams and one main beam implemented using three coupled fiber laser sources[14]. In the DOE based analogue method, the clear aperture consists of three sub-apertures. Two small apertures with a prismatic function to deflect two stripe beams and a large central sub aperture with a beam shaping function for the main spot. Schematically this concept is shown in figure 4.

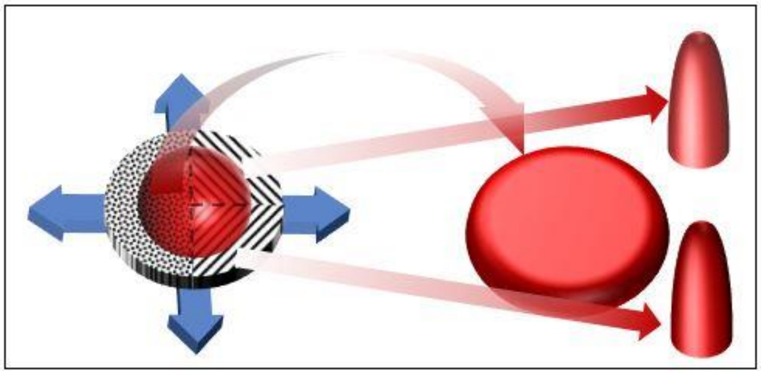

Figure 4. Schematic sketch of the principle of operation of a sub-aperture triple spot beam shaper for welding, adjustable power ratio is achieved by moving the element relative to the incident laser beam.

Another interesting adjustable shaping solution is by using 2 or more radially spread regions of the clear aperture as shown in figure 5.

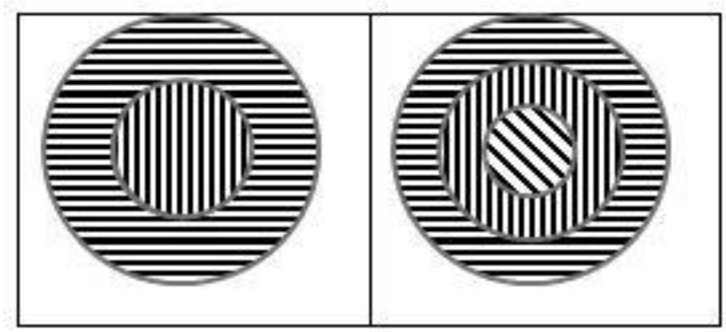

Figure 5. Schematic view of shaper clear aperture with two radial regions (left) and three regions (right).

The adjustment of the beam relative to apertures can be done with a manual or motorized beam expander/axicon telescope. Basic configurations are shown in Figure 6. The Amount of energy on the radial sub-apertures of the DOE can be controlled by the shape and size of output beam from Beam expander/axicon telescope. If using a normal beam expander, the method can be used for shapes where the central aperture always has some power (static shapes and multispots). If instead an Axicon Telecope is used, complete switching of shapes is possible by increasing and decreasing the ring diameter (i.e. changing the Axicon distance).

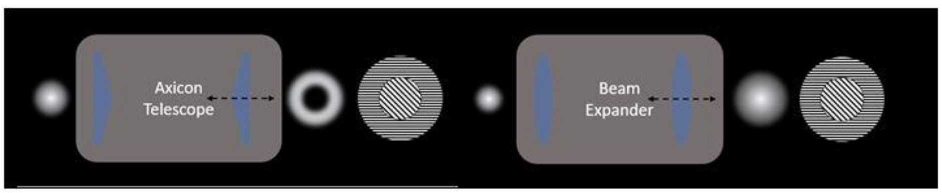

Figure 6. Schematic sketch of setup including DOE with radial apertures. Variable Axicon telescope (left) and beam expander (right). The Telescopes control the output beam/ring) diameter and adjust intensity distribution per sub-apertures.

Based on the sub apertures methods discussed so far, it is possible to offer a solution to any of the four main welding application categories. We define these categories according to their shaping needs, and they are detailed in table 1 below:

	**Scanning applications** are characterized by an unshaped laser spot that moves along certain route and typically implemented using galvo-scanner. Using a rotating sub-aperture DOE can provide fixed path scanning without a galvo-scanner. See shaping examples in figure 7.
	**Static application**s refer to cases where the power distribution required to achieve the process result is fixed in time. This distribution may be scanned along a line, or not, as the process requires. See shaping examples in figure 8.
	**Continuously changing intensity** is an application group where the laser intensity shape changes during the process. This change can be for example from a uniform small illumination area (to create the initial melt pool) to an increasing illumination area that heats the borders of the weld. See shaping examples in figure 9.
	**Switching method** is similar to continuously changing illumination, but with discrete shape change. This practice can significantly optimize the process. For example, in cases of two step processes where the first step requires a square shape and the second a round shape, this can be done by switching between two sub apertures. See shaping examples in figure 10.

Table 1: main application categories for laser welding, defined according to shaping needs

Shapes type with main spots:

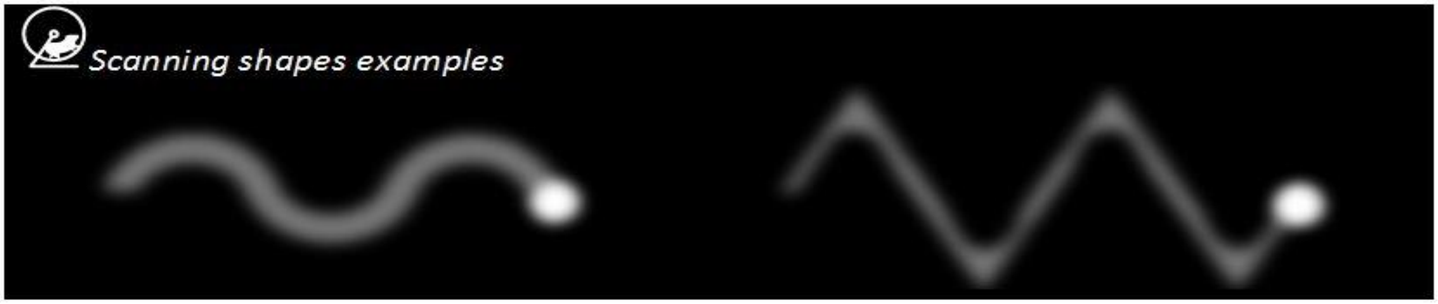

Figure 7. Sine scanning route, Zigzag scanning route.

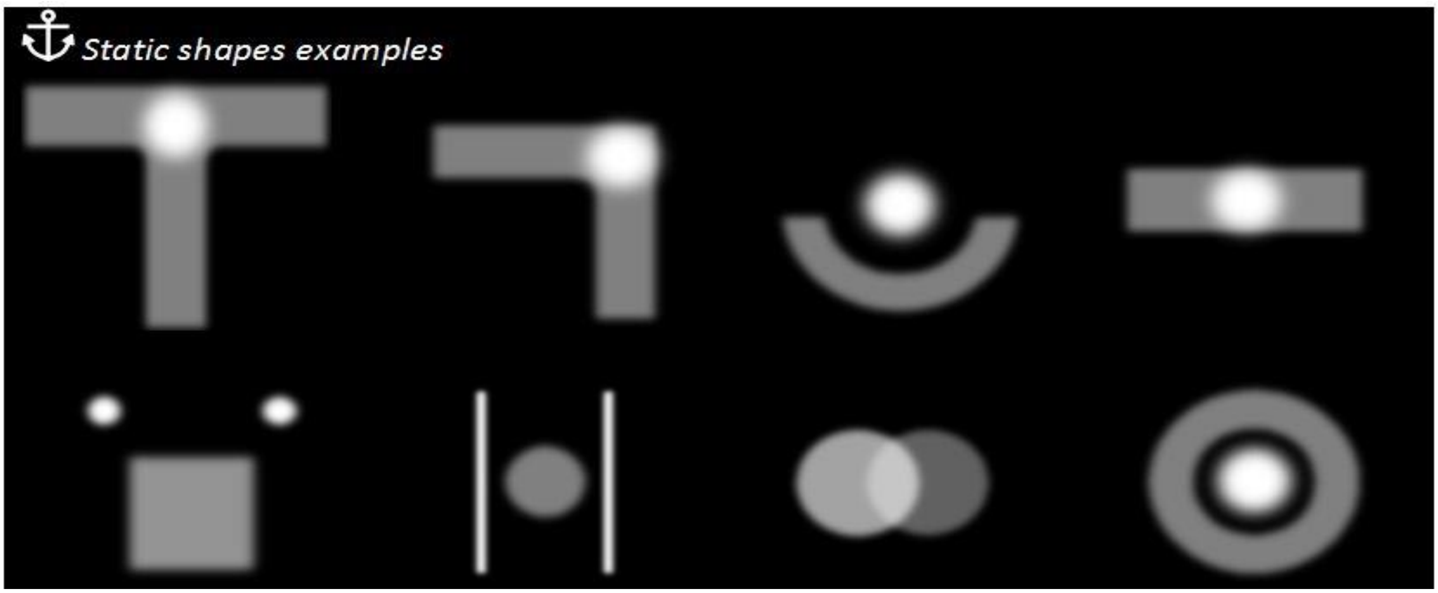

Figure 8. From left to right: Upper line: superimposed shapes with adjustable bright spot, T-shape, Corner- shape, Half circle-shape[15], I-shape. Lower line: Triple spot, Configuration of triple spot, twin spots[16], Ring.

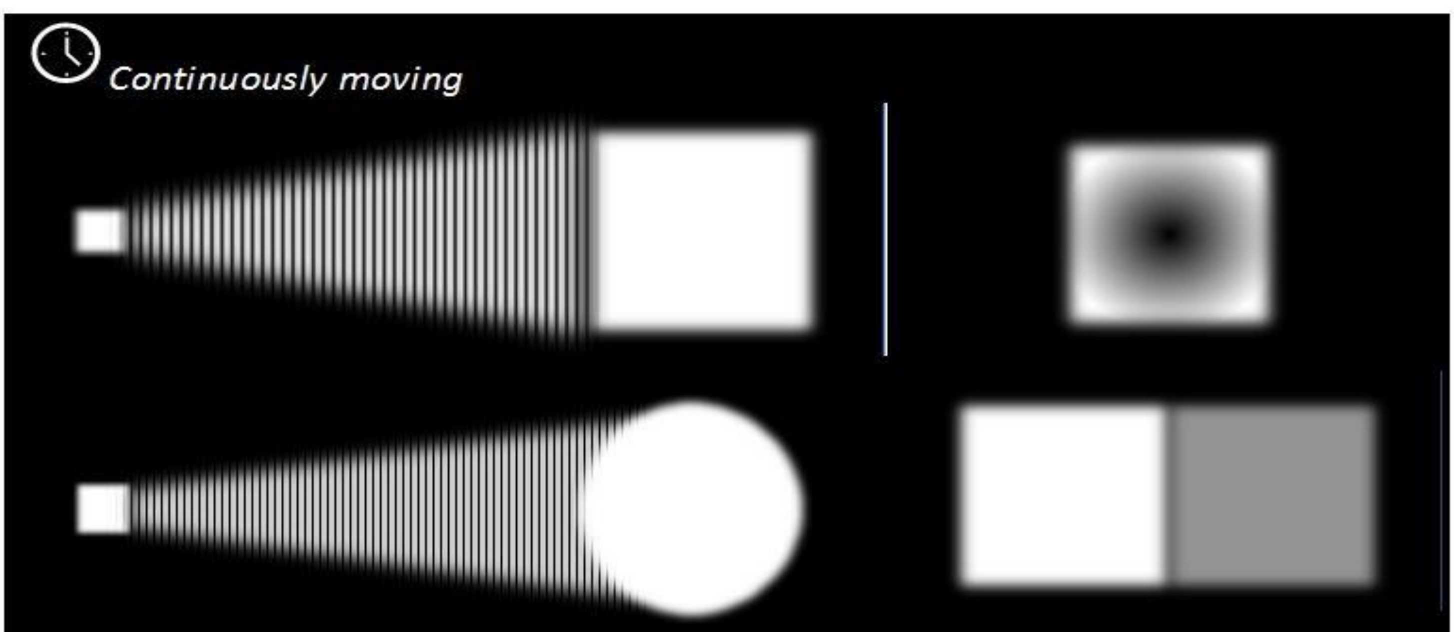

Figure 9. continuously changing shapes. Clockwise from upper left: Increasing size of square shape, Square M-Shape with adjustable level in center, two squares with changing relative intensity, square shape's size increases and changes to round shape.

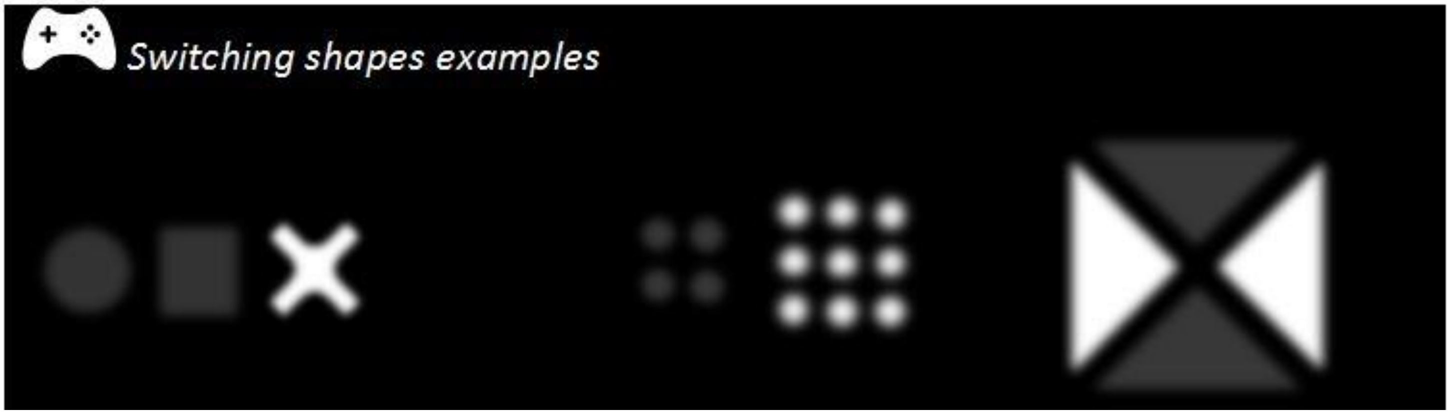

Figure 10. Example of switching configuration where only one shape is activated each time. From left to right. Round to square to cross, spots array 2x2 to 3x3, two triangles orthogonally oriented.

M-Shapers

For welding applications, the heat transfer function depends on many parameters such as exposure time, conductivity of the material, environment conditions and other.

A uniform shaped beam isn't optimal for welding application of relatively large areas where beam shaping is most often implemented. Typically, the center region overheats, and corners are underheated. This issue can be solved by an illumination distribution that is inverse to the heat map, where the center has the lowest intensity and corners have maximum intensity- this is called a Square M-Shape[17,18]. The intensity ratio between center and corners can be adjusted on fly to specific process need by the same methods described in the sub-apertures section above. Real time control and closed loop feedback can make this process even more precise. An example of a Square M-Shaper intensity distribution is shown in figure 9, upper right.

M^2 Transformation shaping

Other than standard beam shaping of laser output to a specific spatial intensity distribution there is another very interesting idea of anamorphic beam shaping (or M^2 transformation) for multimode lasers.

Typically, highly multi-mode lasers used in welding applications cannot be tightly focused due to their high M^2 values. For fiber-coupled KW lasers, there is an intrinsic connection between power and incoherence- in general, the higher the power, the larger the fiber numerical aperture (NA) and higher the M^2. Thus when working with very high power, tight focusing with good depth of focus is not achievable by standard shaping.

A way to enable narrow focusing and increase depth of focus of is to manipulate laser beam quality in orthogonal axes, so that one of the axes becomes very coherent and the second strongly incoherent. Overall the spatial coherence is only slightly increased. There are currently two main known configurations for M^2 transformation – in X, Y coordinates[19] and R, Theta coordinates[20].

In figure 11 we demonstrate how currently used shapes can be used after M^2 transformation. The small figures in lower left corner represent the existing shaping, with the large images referring to the improved shaping possible by using M^2 transformation.

On figure 11 left, a triple spot laser shaping method used[21] for brazing and welding is shown. In this method the spots are usually scanned in the arrow direction. By applying anamorphic M^2 transformation, it is possible to achieve a much narrower central lobe and side spots while maintaining the same power density as in the current shaping. This enables brazing of much narrower features and smaller seams.

Figure 11 center describes a similar concept but in polar coordinates. The ring shaped beam has the same power density with a much narrower ring thickness compared to the central spot.

Figure 11 right shows that one can achieve non-trivial distributions with M^2 transformation, which are not possible with normal shaping of highly multi-mode lasers. Without M^2 transform the rings would overlap, for smaller ring diameters, while for the transformed beam the rings can have small angular separations.

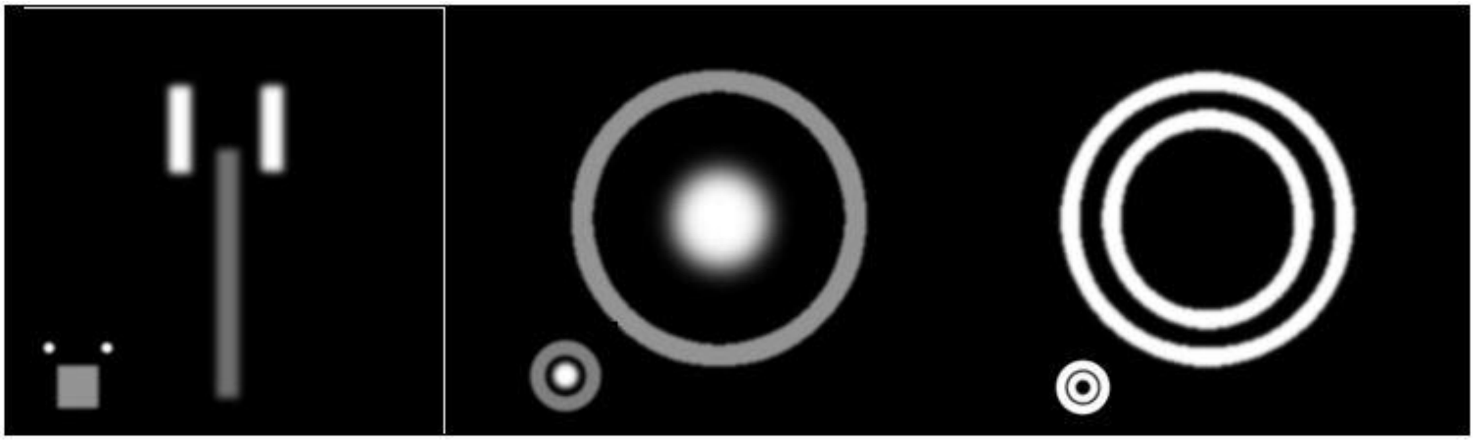

Figure 11. Welding shaping optimized by M2 transformation. Main picture after transformation and in left down corner version without transformation. Triple-spot welding shape after X, Y transformation left. Ring shaped beam with strong spot central spot after R, Theta transformation. Two rings with individual R, Theta transformation.

Summary

In this article, we have reviewed some approaches to the shaping of laser power for welding applications. The method of Adjustable-Function shaping using sub apertures was introduced, and various schemes discussed whereby active dynamic shaping can be done using sub apertures, by moving the beam relative to the sub-apertures on the shaper DOE. These methods can enable scanning without galvo-scanner, active shape switching in-process and even continuously changing laser distributions.

We discussed the specific case of M-Shaping as beneficial to welding applications, and how this method can be combined with sub-aperture shaping to give adjustable intensity ratios of edge to center spot.

Finally, we discussed the advantages of M^2 transformation for welding, namely the ability to work with tightly focused lines/rings even with highly multi-mode input lasers.

Holo/Or has extensive experience in the shaping of lasers for welding application and can offer solutions based on the methods discussed in this article.

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