16kW Single Mode CW Laser with Dynamic Beam for Material Processing

Eyal SHEKEL*1

*1 Civan Advanced Technologies, Kanfei Nesharim 64, Jerusalem, Israel

Civan has developed a novel technology which allows unprecedented versatility and flexibility in laser material processing. Relying on Coherent Beam Combining (CBC) and Optical Phase Array (OPA) technologies, Civan's technology and products are able to dynamically tailor beam parameters to the required application. 2D position, focus, shape and power are all controlled digitally and can be modulated at tens of MHz frequencies. Compared to the existing state of the art High Power lasers, the CBC Laser's unique features are to introduce major breakthroughs in industrial processes such as metal cutting, welding, drilling and metal additive manufacturing, as well as enabling an entirely new set of applications, such as processing difficult materials, welding dissimilar materials and high throughput surface modification and functionalization, among others. Civan's products, which represent the first time that CBC is deployed in a commercial product, have been demonstrated to support the quality and robustness required by the industry. This article presents the technology and the benefits it provides, and offers a few examples of how processes can be improved by utilizing it, as well as a number of novel processing strategies.

Keywords: Coherent Beam Combining (CBC)**,** Optical Phase Array (OPA), laser welding laser cutting.

1. Introduction

In the last decades, lasers have become an important tool in many industrial processes. Lasers have allowed users to retain their competitive advantage by making processes more efficient and reliable and cutting down on manufacturing costs, by replacing traditional systems in processes such as cutting and welding, and allowing completely new methods and applications such as metal additive manufacturing (metal 3D printing), lasers have allowed users to retain their competitive advantage by making processes more efficient and reliable and cutting down on manufacturing costs. As technology and research advanced, new and improved lasers appeared in the market, improving on previous achievements and allowing improved performance and novel processing strategies.

Recent advances in technology enable the production of a number of products which presents advancements in both power and versatility over existing laser systems. Laser systems utilizing Coherent Beam Combining (CBC) technology, can achieve power levels of 21 kW Single Mode (SM) Continuous Wave (CW) beam. This allows significant improvements in several core processes in industry, such as cutting and welding. Optical Phase Array (OPA) technology, allows rapid modulation of beam parameters. Depth of field, 2D position and power can all be modulated at tens of MHz frequencies using digital electro-optic controls. This introduces previously impossible versatility and flexibility in operation. Moreover, OPA also allows a digital and dynamic control of the beam shape. These abilities allow users to precisely and dynamically tailor the beam to needs.

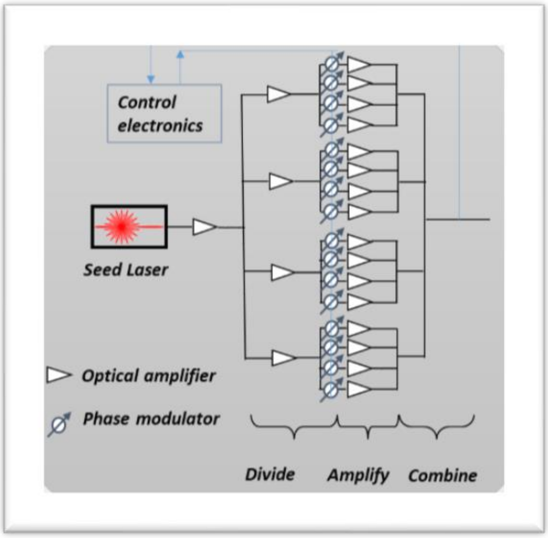
Civan has developed three commercial laser systems utilizing CBC and OPA technology, which will enable users to take advantage of these advancements. This essay will describe CBC and OPA technology, present their capabilities and give a number of examples as to how they improve on existing processes and enable novel processing strategies.

2. Technology

Lasers are currently used in industry for a variety of applications. Processes such as welding, cutting and drilling, as well as metal additive manufacturing are routinely performed by lasers. Based on existing CBC technology and propriety OPA technology, Civan is offering three industrial products which allow dramatic improvements in these application, whether by making current processes more efficient, or by enabling novel processing strategies.

In CBC, a seed laser is split into a number (between 10s and 100s) of channels which are then amplified individually and recombined into one high power beam [Illustration 1]. CBC allows a higher power output in single mode (SM) beam, which enables remote operation. This higher power output and remote operation offer significant improvements in various processes. The beam can be employed in either continuous wave (CW) or quasi-continuous wave (QCW) affording further flexibility and enabling additional processes. Section 3 describes the advantages afforded by CBC.

Illustration 1 CBC principle of operation



Optical Phase Array (OPA), is a method of recombination in which the channels are electro-optically controled and recombined in the far field by means of an interference pattern. This allows an unmatched degree of control and flexibility of the beam - beams can be tailored to precisely match users' needs. Shaping, steering and refocusing of the beam can all be done in MHz frequencies through electro-optical means and with no moving parts, allowing the user to dynamically tailor the beam to their precise needs. Thus openeing opportunities in an unmatched degree of control and flexibility of the beam - beams can be tailored to precisely match users' needs, enabling not only improved results in current industrial processe, but opens venues for novel processing strategies. Section 4 discusses OPAs capabilities, how it can be used to improve current processes, and offers a few examples on how it can be used in novel processing strategies.

2.1 Coherent Beam Combining

CBC technology is a method of achieving a high power, Single Mode beam. In CBC, a seed laser is split into a number (between 10s and 100s) of channels. Each channel is amplified individually, and the channels are then recombined into one high power beam. Civan uses two recombining methods[1]:

I. Filled aperture: In this method, the channel beams are recombined in the near field, through a grating, resulting in a high power (in the order of magnitude of 18kW) *static* Single Mode (SM) beam.

II. Tiled aperture: In this method the channels are recombined in the far field, by means of an interference pattern. The interference pattern is controlled electro-optically by rapidly modulating the phases of each channel. This method results in a *dynamic* beam, which can be rapidly shaped, steered and refocused to precisely match the user's needs.

2.2 Optical Phase Array

OPA makes use of the laser's wave-like properties to create the desired beam at the desired spot by means of an interference pattern. The individual channels are all directed at the worked piece, and a complex algorithm electro-optically manipulates the phases of the individual channels, in order to create a specific interference pattern. This specific interference pattern determines the properties of the combined beam: 2D position, depth of field, shape and power.

This technology represents a revolutionary way of using lasers in material processing. Today, beam parameters such as 2D position, depth of field and shape are controlled mechanically, by the use of robotic arms, or optically, using mirrors and diffractive optical elements (DOEs). This limits the speed at which they can be altered and therefore imposes severe limitations on processing speed and abilities. In some cases the paremeters cannot be altered during operation at all. Mechanical means also include numerous moving parts and require heavy maintenance. In OPA, the beam is electro-optically controlled, which allows each of these parameters to be modulated at MHz frequencies, during processing, and with no moving parts. The result is an extremely dynamic and flexible beam, which can be tailored to the specific needs of the user.

In section 4 we discuss how these capabilities not only afford significant improvement over common processes such as cuting, welding, and metal additive manufacturing, but also open venues for novel processing strategies, by allowing the user to precisely and dynamically tailor the beam to the exact needs of the process

3. Advantages of Filled Aperture Coherent Beam Combining

In Filled aperture CBC, The channels are combined in the near field, by means of a grating. The result is a high power SM beam. For 1064 nm wavelength, Civan's products reach power levels of over 18 kW SM output, a level comparale to that of state-of-the-art multi-mode laser systems. Along with remote operation abilities and the ability to modulate the power output between 10%-100% of maximum power, they allow the user maximal versatility in use and application.

3.1 High Power Remote Operation

Two of the most common processes in material processing are cutting and welding. Both are routinely performed by lasers, and both can benefit from higher power output. For example, it was shown that increasing the power of the laser by a factor of 5 (from 3.4 Kw to 16 Kw) increased the speed of welding by a factor of 8 (from 4 m/min to 30 m/min) and at the much better quality [2]. Higher power also means the depth of the process can be increased, allowing processing of thicker sheets. Another advantage of SM lasers over multi-mode ones is that it enable remote operation. Today, many processes require the laser to be situated very close to the work piece and moved by a robot, requiring complicated machinery and many moving parts, and also limiting the processing speed to that of the robotic arm. High Power SM laser enables remote operation, removing both restrictions. This, combined with the high power density, enable processing speed to increase by a factor of 10-50 [2], while at the same time simplifying the system and saving on maintenance, and potentially replacing multiple lasers on the production line with one machine.

3.2 Filled Aperture CBC at Different Wavelengths

While laser with a wavelengths of 1064 nm is ideal for steel processing, highly reflective metals, such as gold, copper and aluminium, require a much shorter wavelength such as "green laser" 532 nm. Processing these metals at the right wavelength is not only more economical, but produces better results. However, the power output of these "green" lasers is limited by the physical properties of the crystals used for the frequency doubling process. By using CBC, we can bypasses this limitation by using multiple modules - each laser channel is converted individually and they are then recombined into a SM high power beam. This allows the creation of green beams with power of up to 1 kW. Currently, Civan has a commercial product which produces 532 nm laser at up to 150 W, with future products of up to 1000W in developement.

As with 1064 nm laser, the higher power output translates into a much more efficient process, allowing faster and cleaner processes, and a higher quality end product at a lower cost of production.

3.3 Power Modulation

CBC also allows for rapid (10MHz) power modulation, in the range of 10%-100% of it's maximum power. This allows for versatility in operation, and is also useful in certain applications.

For example, metal additive manufacturing relies on selectively melting a fine atomized metal powder, distributed over a metal substrate. One way of doing so is scanning in a fixed pattern, and modulating the intensity of the beam. Increasing the rate at which the power can be modulated improves the speed and resolution attainable for this process.
Rapid power modulation can also be used to speed up certain welding operations, such as ones that require a large number of micro welds. In such cases, the laser has to be deactivated or set to low power in between welds. Due to long turn on and off times, processes requiring a large number of small weldscan become time consuming. Rapid power modulation decreases turn on and off times, thereby speeding up the process considerably. The same is also true for surface allteration processes, in which a precise power setting is required for different parts of the work piece.

4. Optical Phase Array

In OPA the channels are combined in the far field by means of an interference pattern. All the beams are projected onto the work piece, and their phases are electro-optically controlled to create the desired interference pattern at the focus. This allows for an extremely precise control of the beam, in terms of 2D position, depth of field, beam shaping, and power. In essence, OPA allows the user to tailor the beam to their own needs. Moreover, it allows dynamic control of the beam - each of the parameters can be changed at MHz frequencies, during operation. This level of control allows not only for improvements over the industry standard in various applications, such as cutting, welding and 3D metal printing, but also affords opportunities for entirely novel processing strategies.

In this section we describe OPA technology, its capabilities and advantages to the user, and describe a number of ways in which it can be used to improve upon existing processes, to enable novel processing strategies and to be integrated with existing technologies.

4.1 Precision Beam Tailoring

The main advantage of Civan's products and technology is their versatility. Our propriety OPA technology enables the user to dynamically tailor the beam to their precise specifications.

Spot diameter and depth of field - Currently, spot diameter and depth of field adjustments are made through optical and mechanical means. This approach not only adds moving parts, and therefore increases maintenance, but also limits the speed at which they can be adjusted. This limits the laser's utility and flexibility.

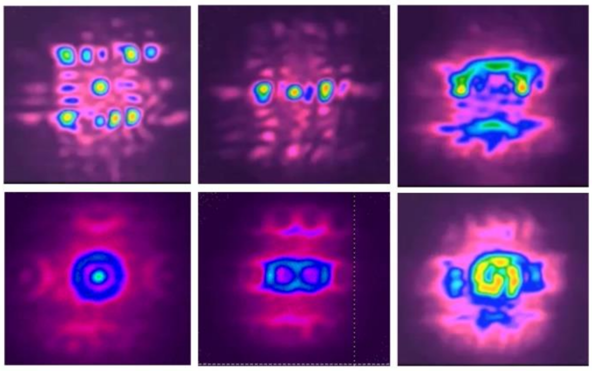
Using OPA, Civan's products adjust their depth of field electro-opticlly, allowing for a much faster rate of change. This not only allows unparalled flexibility in the materials that can be processed (allowing for the same laser to process materials of varying thicknesses), but also speeds up processess considerably and allows for novel processing strategies, as shown later.

Steering - Using OPA, the beam is steered through digital, electro-optical controls. This allow for an extremely rapid and precise control of the beam than current technology. Using mechanical means, such as a robotic arm, the beam can be steered at 1 Hz frequencies and with a resolution on the order of magnitued of 1 cm. Using scanning mirors, a frequency on the order of kHz and resolution of several millimeters can be acheived. With OPA the beam can be placed anywhere withing its scanning range with a precision of microns, and can be repositioned at MHz frequencies.

The scanning range is dependent on the number of channels in the product. Currently Civan has two commercial products available, OPA 6 and OPA 20. OPA 6 uses tens of channels and has a scanning range of 6 times spot diameter, while OPA 20 uses hundreds of channels and has a scanning range of 20 times spot diameter. In addition, Civan can produce custom products, to accommodate clients' particular requirements Moreover, OPA can be integrated with scanning technology, utilizing the advantages of both methods. In 4.3 we present an example of such integration and how it improves cutting processes.

Shaping - a lot of research has been conducted in recent years on the possibilities and advantages in the field of beam shaping [4,5,6]. Various beam shapes have been shown to increase the efficiently of various processes. This field is expected to continue and evolve, with new beam shapes being developed to match various processes. In most commercial products, beam shaping is achieved through optical means, by means of various optical modules or specially manufactured optical fibres. These modules offer only limited versatility, if any, and offer no dynamic modulation. Moreover, this method requires that each module be purchased separately as new beam shapes are developed.

Illustration 2. Examples of possible beam shapes



Civan's products and technology allow unlimited beam shapes, by electro-optically manipulating the phases of individual channels. This allows the user to immediately implement advances in research and remain at the forefront of laser material processing, at no additional cost. As there is no need to replace modules, the beam can be shaped during processing, reducing processing time further and allowing for advanced manufacturing techniques.

4.2 Applications

Many of the challenges of industrial welding today, such as achieving a high quality weld, welding with large gaps and welding dissimilar materials, can be addressed using precision beam tailoring.

Rapid 2D steering, for example, allows a better control of the melt pool by creating a rapid wobble, accompanying the laser's linear motion. Instead of a large static spot, a smaller rapidly moving one can be used. This allows the extension of the melt pool lifetime, and therefore more degassing time and a slower, more homogenous solidification, resulting in a higher quality weld.

By adjusting the parameters of the wobble, materials can also be welded over larger gaps. It also significantly improves welding of different materials, as it allows the beam to deliver different amounts of power, to the different materials. This improves not only the homogeneity of mixing and extent of the intermetallic phase, but allows better control on the mixing ratio and electrical resistance.

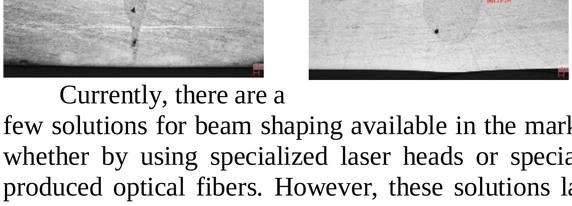
As OPA offers dynamic control of steering, it can be used in processes were the parameters needs to be varied throughout the process. One example of such a process is keyhole extension, in which the beam first oscillates along a relatively small ellipse until the required depth of penetration has been achieved. Once the required depth has been reached, the ellipse can be widened to create a wider keyhole. This allows a cleaner process, with less pores and less spattering.

High frequency depth of field adjustment has important applications in cutting. Currently, focal point is adjusted either mechanically or using optical means. This limits the frequency at which the depth of field can be adjusted. Consequently, the standard laser cutting technique consists of focusing the laser beam on a fixed depth, usually the center of the material to be cut. This means that for most of the depth of the cut, the beam has a large spot diameter, resulting in an inefficient process and a very rough cut, which requires further processing. OPA allows for a drastically improved method, in which the focal point is dynamically adjusted at high frequency. This affords a number of advantages: first, since the focus is continuously shifted to match the cut depth, the result is a much cleaner cut. Dynamic focal point depth also allows for a much faster cut by keeping a smaller spot size at the required depth. Lastly, the process is more efficient, since less energy is wasted on a large spot diameter. A cleaner cut also reduces the need for additional processing, or even eliminates it entirely.

Recent studies show that *beam shaping* can provide significant improvement in traditional laser applications. For example, surrounding the central spot with an annulus can substantially improve the stability of keyhole weld, reducing spatter and porosity.[4] Another application in which beam shaping has been shown to provide dramatically improved results is surface treatement. Differently shaped beam dictate different patterns of heat diffusion. A sub-optimal heat diffusion pattern requires a larger dwell time of the beam, and therefore a larger heat-affected zone. Using a suitably shaped beam would not just increase speed and accuracy, it would allow completely new technique, such as using higher temperatures without reaching the damage threshold of the substrate material.[5]

The exact parameters of the required shape are determined by the property of the materials processed and the requirements from the finished product. Different shapes have different advantages in different processes Illustration 4 presents two welds, one (on the right) was done using a single point Gaussian beam and the other using a 2 point beam. The two welds are obviously different, each corresponding to different needs in different circumstances.

Illustration 3. Comparison of welds done using different beam shapes – Gaussian on the right and 2 points on the left.



Currently, there are a few solutions for beam shaping available in the market, whether by using specialized laser heads or specially produced optical fibers. However, these solutions lack the flexibility afforded by OPA. For one, they only offer a limited, predetermined selection of shapes, with each shape requiring different hardware. Secondly, they offer static beam shapes, and do not allow for beam shape modulation during processing. OPA offers not only unlimited beam shapes, all electro-optically controlled, it also allows the beam to be reshaped while processing. This allows the user to immediately take advantage of new advances in research, without needing to purchase and handle new hardware.

The greatest advantage of OPA is its versatility. Instead of bulky equipment and numerous modules and changeable parts, one compact machine offers not only the whole range of options available today, but also unlimited possibilities for adjustments as research advances and new processing methods are developed. This allows users of Civan's products to not only remain at the forefront of material processing technology, but to research novel processing strategies, increasing their competitive advantage. In the next section we discuss a number of such novel processing strategies.

4.3 Novel Processing Strategies

In addition to the improvements in traditional processing methods which OPA allows, it also affords the user a large degree of flexibility in operation. This flexibility allows for the creation of novel processing strategies, tailored precisely to the needs of the user and their product. In this section we will describe a number of ways in which OPA can be used not merely to improve on existing processes, but in completely new ways.

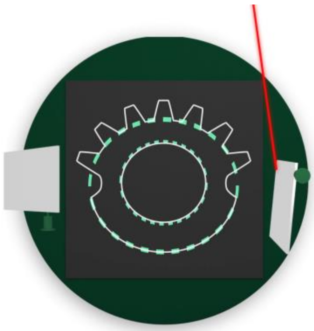
OPA assisted scanning - OPA can be integrated with existing technologies, such as scanning. Today, scanning is performed by mechanically controlled scanning mirrors, which must trace the exact shape in which the laser operates. This is a time consuming process which has severe limitations on accuracy. The more intricate the pattern is, the slower the scanning mirror can be moved. Fine details may not even be possible at all.

Using OPA, scanning is dramatically altered. Rather than have the scanning mirrors trace every minute detail, they can be made to move in simple, fast routes, while finer details are filled in by the use of OPA. As OPA allows for a much faster and accurate steering, this allows for faster results, without sacrificing accuracy.

For example, say the user wants to cut out a cog-shape [Illustration 2] from a sheet of metal. Traditional scanning technology would require the scanning mirror to trace each tooth. This produces not only a much longer route, but also a much more intricate one. Each turn and direction change would require the mechanically operated scanning mirror to slow down and accelarate.

In OPA assisted scanning the operation would be much simpler. Instead of an intricate route the scannig mirrors could take a much simpler one - for example a circle around the circumferance of the cog. The beam would then be steered by OPA to fill in the details, the teeth in this example.

Illustration 4 OPA assisted scanning. The scanning mirrors trace the dashed lines, and OPA is used to fill in details.



Obviously, the more intricate the pattern, the more significant the improvement would be. Moreover, the extremely precise electronic control of beam afforded by OPA would allow for previously impossible patterns.

OPA assisted metal additive manufacturing - Another example of how OPA can be used to not only achieve better results in existing processes, but allow entirely new processing strategies can be seen in metal additive manufacturing. In metal additive manufacturing a layer of atomized fine metal powder is distributed to a metal substrate, and then fused by selectively melting the powder in the required shape by means of a high power laser. Currently, the speed of the process is limited by the time taken to melt the powder, as the laser must heat each spot until completely melted. OPA technology allows a dramatic improvement of this process by rapidly cycling through multiple points. When cycling in a high enough frequency, heat from each spot doesn't have enough time to dissipate until the cycle is completed and the spot is heated again. In effect, multiple points are worked at the same time, reducing the processing time by a considerable factor.

These are only a few examples of how OPA can be used to facilitate new processing methods. OPA puts an unparalleled dynamic and flexible tool at the hands of its user, allowing it to tailor the beam to their exact needs. As research advances and new methods and techniques become available, OPA users will be in position to implement them immediately, without requiring to purchase and install new equipment.

5. Conclusion

Ever since their introduction into the industry in the second half of the 20th century, lasers have been playing an important role in material processing. As old technology is improved and new technologies are introduced, the scope and type of processes performed by lasers constantly increase. Advanced laser systems can both improve on traditional processes and offer novel processing strategies, and by that help a manufacturer retain and increase their competitive advantage.

Civan is introducing three new laser products, based on existing CBC technology. These products represent the first time CBC technology is available in a commercial product and offer a high-power (21kW) SM CW beam. More importantly, Civan's propriety OPA technology offers unparralled flexible and dynamic operation. Beam paramaters such as depth of field, 2D position, shape and power can be modulated at 10MHz frequencies. These abilities allow the user to tailor the beam to their precise needs. Furthermore, Civan's products can be integrated with existing technology, such as scanning lasers, to further increase their utility and versatility. The result is an extremely flexible and versatile product, which offers both a dramatic improvement in traditional processes and numerous opportunities for novel processing strategies.

In this essay we reviewed the technology and capabilities of Civan's products, described how they can be used to improve on traditional processes and described a few examples for novel processing strategies, utilizing these capabilities.

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