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Laser beam shaping and stabilization for single-mode laser material processing based on Multi-Plane Light Conversion

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Abstract

Laser beam parameters vary over time: tilt, shift, defocusing or modal imperfections can negatively impact the applications. It can drastically degrade the performance of a beam shaping setup (DOE, SLM, etc.), especially with pulsed laser processing.

We present a novel approach for beam shaping coupled with passive modal filtering that compensates for the imperfections and temporal variations of the laser beam parameters. The non-ideal, misaligned beam is projected on an adapted transverse mode basis. The unwanted energy is routed onto higher order modes and dumped or used as a feedback signal, while the energy in the fundamental Gaussian mode is shaped into the spatial mode of interest (e.g. flat-top, Bessel beam, etc.). This approach is implemented with Multi-Plane Light Conversion technique, whose high flexibility and shaping performance enable efficient, versatile and robust shaping for applications where beam pointing accuracy and beam quality are crucial, such as micro-processing and ultrafast laser processing.

Keywords: Multi Plane Light Conversion ; modal filtering ; laser beam shaping ; USP laser ; laser microprocessing

1. Introduction

The range of applications of Ultra-Short Pulse (USP) laser-based material microprocessing is broadening to include consumer microelectronics as well as the automotive or aerospace industries. More and more materials are becoming processable, including metals, ceramics, semiconductors, polymers and organic materials.

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USP laser-based processes offer a great advantage compared to traditional processes thanks to its inherent capability to deliver energy over an extremely short duration. The very high peak power allows matter ablation without melting the material thus increasing the process quality, accuracy and reproducibility.

In order to improve the quality of those processes, it is key to associate beam shaping to the USP laser. Beam shaping maximizes the useful energy and increases the process yield by decreasing scrap rate as well.

Since the targeted quality is very high the need to have a stable shape is key to the process development. However, USP lasers generally show instabilities and beam variation over time: tilt, shift, defocusing or simply modal imperfection. Most beam shapers cannot handle the instabilities and the output shape will not be stable enough to ensure a high process quality.

Thanks to Multi-Plane Light Conversion (MPLC) technology, Cailabs has designed a modal filtering feature which compensates for beam parameter variations. With this feature the USP laser parameters are preserved and the output shape is stable. We describe here the passive modal filtering principles and theoretical performances compared to other filtering options.

The passive modal filtering feature has been manufactured on a MPLC module producing a top-hat square output shape. We demonstrate its compatibility with actual processing set-up, and we describe the process tests results.

2. Passive modal filtering for laser beam parameters variations compensation

2.1. Modal filtering principle

The input beam is projected over an adapted transverse mode basis which is the standard Hermite Gauss basis (see Figure 1 – [1]). The Hermite Gauss modes are orthogonal and described over the cartesian basis x,y by their order (n,m), each mode being referred to as TEM_{nm} for Transverse Electro-Magnetic.

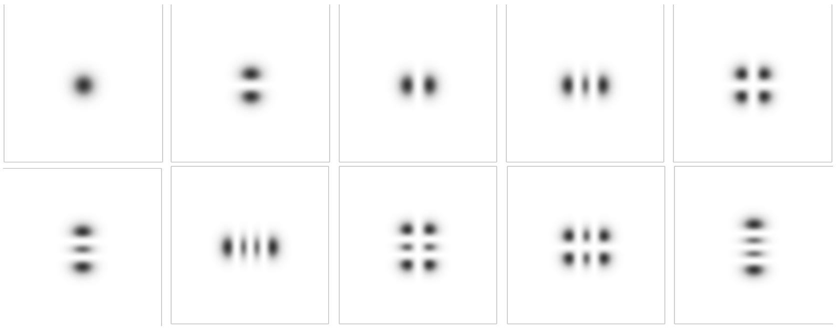

Fig. 1. Examples of Hermite-Gaussian modes

The TEM_{00} mode is the fundamental Gaussian mode which is the theoretical mode of a stable USP laser. The main instabilities to be addressed by modal filtering are the beam tilt, shift and defocusing. If any perturbation appears in the input beam, the beam decomposition over the Hermite Gauss basis shows higher order modes presence. Those modes are referred to as perturbation modes.

The principle of modal filtering is the preservation of the TEM_{00} at the required spatial position, whereas higher order modes are transformed into other modes and separated spatially.

In figure 2 we describe a simplified example in which the perturbation is an elongation of the beam in one direction.

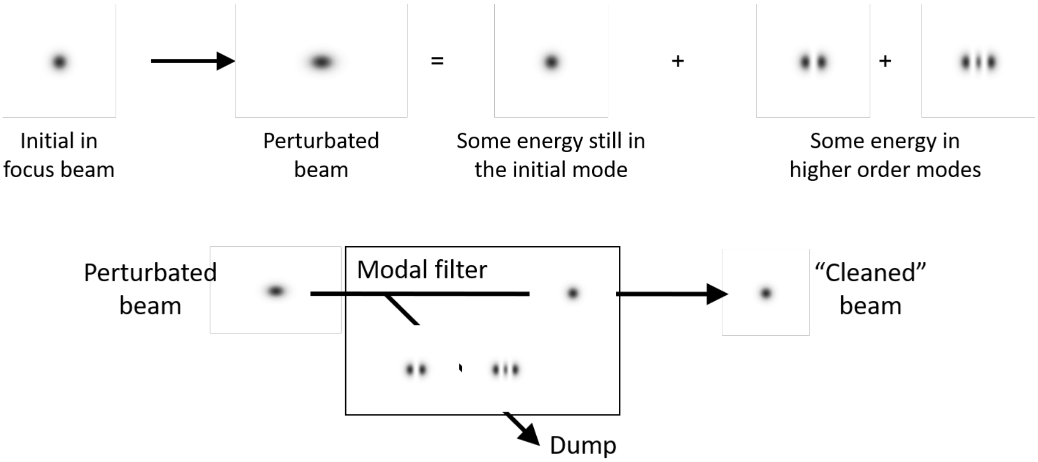

Fig. 2. Modal filtering principle. Top: Pertubated beam modal decomposition; Bottom: Modes handling

Once the transformed modes are properly separated spatially, the higher perturbation modes can easily be dumped or used as a feedback signal, whereas the transformed TEM_{00} mode propagates alone to the scanning and imaging system for material processing leading to an always stable shape.

2.2. Multi-Plane Light Conversion principle

Multi-Plane Light Conversion (MPLC) is a technique that allows performing any unitary spatial transform. Theoretically, it enables the lossless conversion of any set of N orthogonal spatial modes into any other set of N orthogonal modes through a succession of transverse phase profiles separated by free-space propagation serving as a fractional Fourier transform operation. The principle of the MPLC is shown schematically in Figure 3.

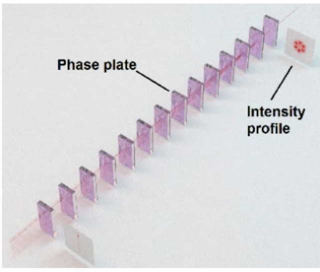

Fig. 3. Principle of MPLC

Practically, MPLC is implemented using a multi-pass cavity, in which the successive phase profiles are all manufactured on a single reflective phase plate (see Figure 4) [2]. The cavity is formed by a mirror and the reflective phase plate and performs the successive phase profiles.

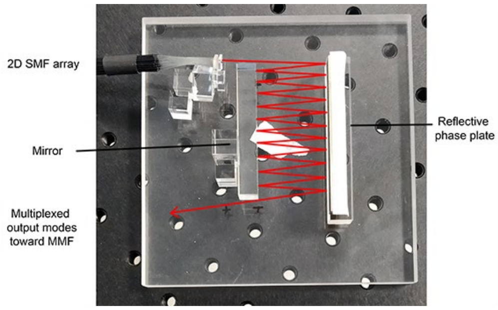

Fig. 4. Picture of a MPLC with fibered inputs. The beam path is shown in red.

MPLC technology enables complex beam shapes with a high control over amplitude and phase. The free-space reflective design allows for high beam shaping quality whilst conserving the ultra-short property of the laser pulses, which is not usually achievable through other beam shaping methods. Moreover, MPLC technology may be adapted to a wide range of wavelengths from visible to IR. Therefore, MPLC technology is well adapted to laser processing [3].

These characteristics of MPLC make it a suitable candidate for implementing modal filtering. By choosing the perturbation modes as input modes of the MPLC, and spatially separated modes as output modes of the MPLC, one can easily see that such MPLC implements modal filtering. Additionally, beam shaping can be performed with the same MPLC, enabling to transform input TEM00 mode into a useful shape for laser processes, for example a top-hat (see Figure 5).

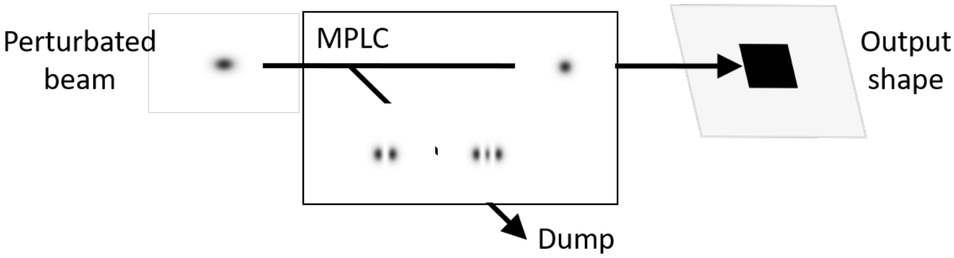

Fig. 5. Principle of a MPLC implementing modal filtering and beam shaping into a square top-hat.

2.3. Passive modal filtering performance

The modal filtering may be applied by using different size of mode basis to project the laser instabilities. We manufactured a MPLC implementing modal filtering over a 9-mode basis and shaping the input TEM00 mode into a square top-hat.

The global efficiency is the ratio between the input average power and the output average power. We measured an efficiency of more than 70 %.

A key parameter of a proper integration with a USP laser is the ability to preserve the pulse duration. The pulse duration has been measured after the MPLC cavity including the modal filtering option using autocorrelation. The duration of around 300fs was preserved through the cavity as shown in figure 6 (autocorrelation of 445fs equivalent to 314fs pulse width).

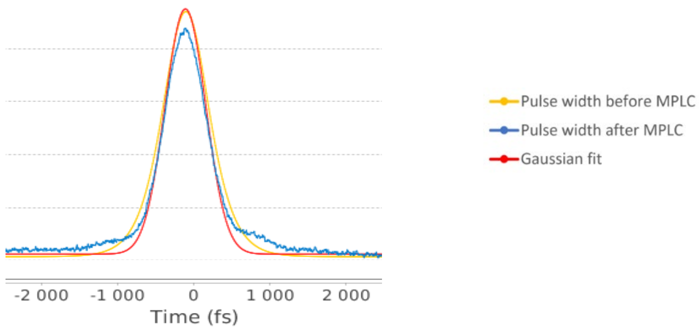

Fig. 6. Experimental pulse duration measurement after the MPLC cavity including modal filtering (445fs Gauss fit)

At last, the output of the MPLC cavity including the modal filtering was conform to the expectations. Its integration with a USP laser was possible despite the laser instabilities, and the output shape is shown on figure 7.

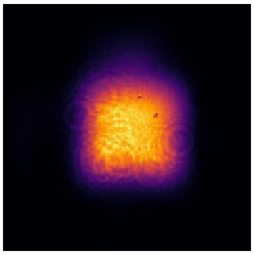

Fig. 7. Output beam shape in an imaging lens focal plane.

2.4. Passive modal filtering performance compared to other filtering options

The main interest of passive modal filtering is the output shape stability over time. In order to characterize the shape stability, we compare in figure 7 the calculated overlap between the output shape and the target shape for a modal filtering on a MPLC module and a more classical filtering technique using irises. When a tilt angle is introduced in the beam, the beam shaping system with modal filtering has an overlap superior to 90 % with the original beam up to 1.25 times the beam divergence whereas the classical irises filtering only has an overlap of 60 % in the same case.

The available output energy in the proper shape is described as well in figure 8, and the modal filtering solution is having a normalized available energy higher than the two irises one of more than 10 % up to a tilt angle of 1 time the divergence of the beam.

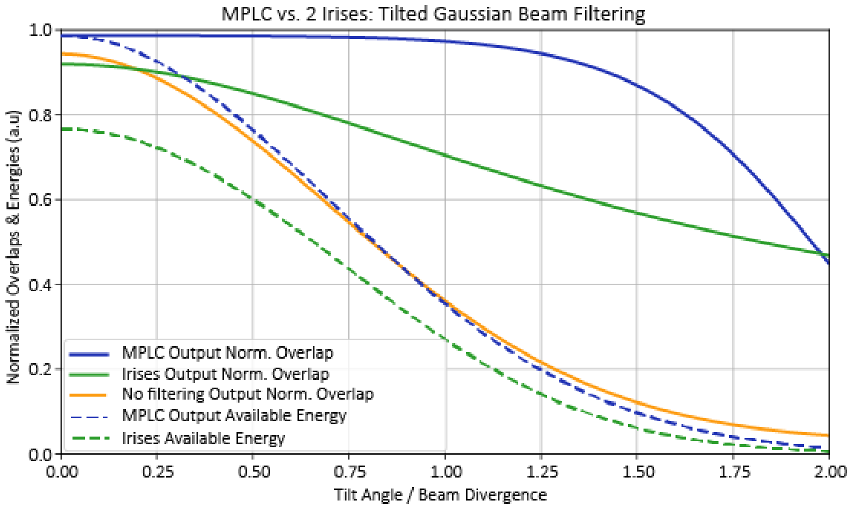

Fig. 8. Performance comparison between no filtering, irises filtering, and modal filtering.

Therefore, the modal filtering associated to a MPLC-based beam shaper improves the shape overlap with the target shape as well as the available energy compared to a classical iris-based filtering for tilted inputs.

3. Material-processing test results with USP laser

The performance of modal filtering has been tested in the configuration of the targeted application: the modal filtering option is implemented in a MPLC cavity designed to produce a top-hat shape for USP laser for microprocessing. We describe here the set-up and the process test results and conclude on the actual validation of modal filtering advantages [4].

3.1. Microprocessing Set-Up

The target output beam shape is a 50µmx50µm top-hat shape in the focal plane of a 100mm LINOS F-Theta-Ronar lens. In order to proceed to process test, the beam propagates through a scanning system as well, the LS-Scan XY15 laser head from Lasea with a 15mm entrance beam diameter has been chosen.

The process tests have been realized using the Ultra Short Pulse laser Tangor from Amplitude. The 1030nm laser shows a 100W average output power, and the process tests have been carried out with 500fs 50µJ pulses, which is equivalent to 100MW of peak power.

3.2. Process test results

The experimental tests have been carried out on three different metals representative of the automotive and aerospace needs: Aluminum, Copper and Invar. Moreover, these metals have different thermal properties as shown in table 1: Aluminum has an expansion ratio two times higher than copper, and Invar will conduct heat more than 100 times less than Aluminum and Copper. Testing those material validates the process efficiency for a broad range of metal.

Table 1. Thermal properties of Microprocessing test metals

	Aluminum	Copper	Invar
Heat conduction coefficient k (W/m/K)	237	400	13
Thermal expansion coefficient α_L (K^{-1})	$23.5x10^{-6}$	$17x10^{-6}$	$1,8x10^{-6}$

3.2.1. Copper processing

The first tests on copper were realized on 20µm thin foils with at a Pulse Repetition Frequency (PRF) of 500kHz and an energy of 15µJ per pulse. We stress that there has been no thermal damage observed at such a high PRF. Staying 1ms per spot leads to square crater of 6µm depth (figure 9a) and staying 10ms per spot leads to drilling through the 20µm thin foil (figure 9b).

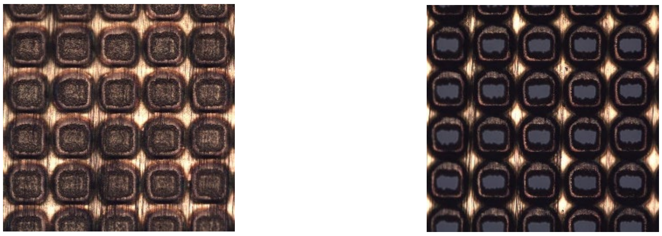

Fig. 9. Copper square processing (a) 1ms per spot; (b) 10ms per spot

The second test performed are trenches generation by scanning the sample at the proper speed. The test results shown in figure 10 are with 60 % overlap in between the squares (2m/s scanning speed and 100kHz PRF) with an energy of 20µJ per pulse. 200 passes lead to a trench of 50µm width, 400 passes cut through the sample.

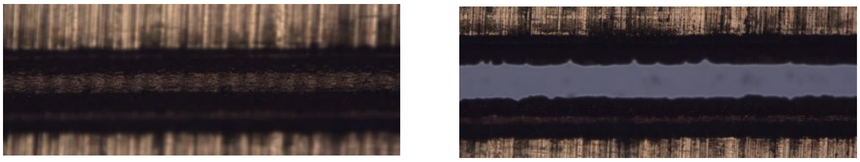

Fig. 10. Copper trench processing (a) 100 passes; (b) 200 passes

3.2.2. Aluminum processing

As with Copper, single squares have been realized scanning at a speed of 6m/s with a PRF of 50kHZ and 20µJ per pulse leading to high quality squares (see figure 11a). Trenches have been realized too with 20 % overlap in between squares with a scanning speed of 2m/s at a 50kHz PRF still with 20µJ per pulse. Figure 11b et 11c show the trench for 10passes and the drilling through for 100 passes on the 20µm foil.

Fig. 11. Aluminum squares and trenches processing (a) 1 pass; (b) 10 passes; (c) 100 passes

3.2.3. Invar processing

Single squares have been realized on Invar too, scanning at a PRF of 100kHZ with 16µJ per pulse. After 1000 passes the 20µm thin foil was drilled through (Figure 12a). Trenches have been realized as well with 92% overlap in between squares at a scanning speed of 2m/s and a 500kHz PRF with 8µJ per pulse. Figure 12b et 12c show a trench for 50 passes and the drilling through for 200 passes on the 20µm foil.

Fig. 12. Invar square and trenches processing (a) 1 pass; (b) 10 passes; (c) 100 passes

3.2.4. Test results conclusion

The tested samples all show a very high quality thanks to a stable top-hat shape which was enabled by the MPLC enabled modal filtering and beam shaping associated to the USP laser.

The ablation rate is 0.08mm^3/min/W for Copper and 0.64mm^3/min/W for Aluminum.

No thermal damage was observed on the Copper sample processed at a very high PRF of 500kHz.

The depth of field at the focal point of the F-theta lens was ±100µm which eases the process by relaxing the constraint on sample positioning.

4. Conclusion

In conclusion we demonstrate the performance of the modal filtering for shape preservation despite input laser instabilities. Compared to other filtering options the shape is preserved over a higher tilt angle of the input whilst maintaining a good efficiency.

The modal filtering option has been tested on a MPLC module designed for a square top-hat shape output. It has been used associated to a USP laser and has preserved the USP pulse duration. The set-up includes a F-theta lens and a scanning system, the manufactured MPLC was compatible with the whole system.

Process tests have been carried out showing a very good process quality over time thanks to the modal filtering option which enabled a stable output shape.

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