Planar Light Valve (PLV™) for High Throughput Multi-Beam Materials Processing

The available output powers and energies of laser sources have continued to increase rapidly, allowing for higher throughput materials processing tools. Many applications cannot fully utilize high power laser sources because the intensity would become too high for the material, and it is not desirable to sacrifice precision by using a larger beam size. Some systems have begun using multiple lasers and scanning systems to increase throughput. Static diffractive optical elements are also used to deliver multiple beams to a material, but the pattern cannot be changed at runtime. A programmable spatial light modulator enables the use of a multi-beam swath that can be changed on the fly. Such a spatial light modulator needs to have high power handling and fast switching speeds to offer a competitive throughput advantage over typical single-spot systems.

The Planar Light Valve (PLV™) is a spatial light modulator that can handle 1kW laser power and switch patterns at 200kHz which greatly increases processing speed for many applications. It can be used at many wavelengths from UV to NIR and supports femtosecond pulsed through continuous wave lasers. In a materials processing system, the PLV can create a 1D programmable swath on the work surface consisting of up to 1,000 beams. Each beam is individually addressable and supports 10-bit analog modulation to enable gray scale and dedicated raster scanning strategies. Working with a swath allows for a large area of material to be exposed at once, rather than a single, small point. As the swath is scanned across the material, the pattern is changed to build up a full image, shown in Figure 1.

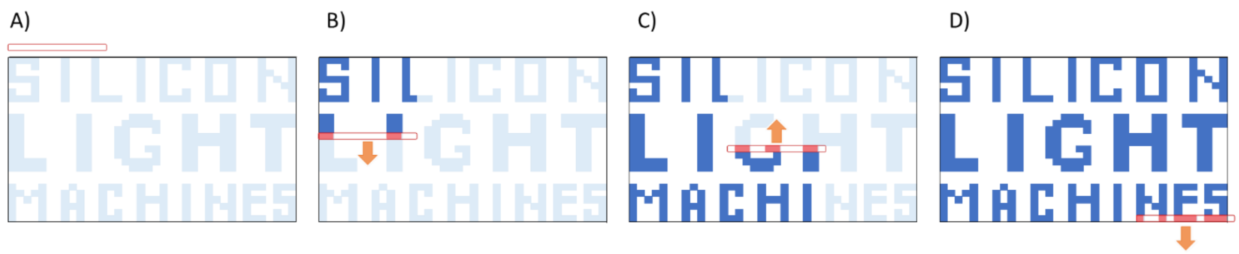

Figure 1 Depiction of marking with a swath containing multiple beams. A) The swath is at the top-left of the image, the pattern to be marked is shown in light blue. B) The swath is scanned down the media, while the PLV turns on only the beams where marking is desired. Marked areas are shown in dark blue. C) The swath has been translated by one swath-length and is now being scanned up the media. D) The swath has been translated by one swath-length and is completing the final scan down the media.

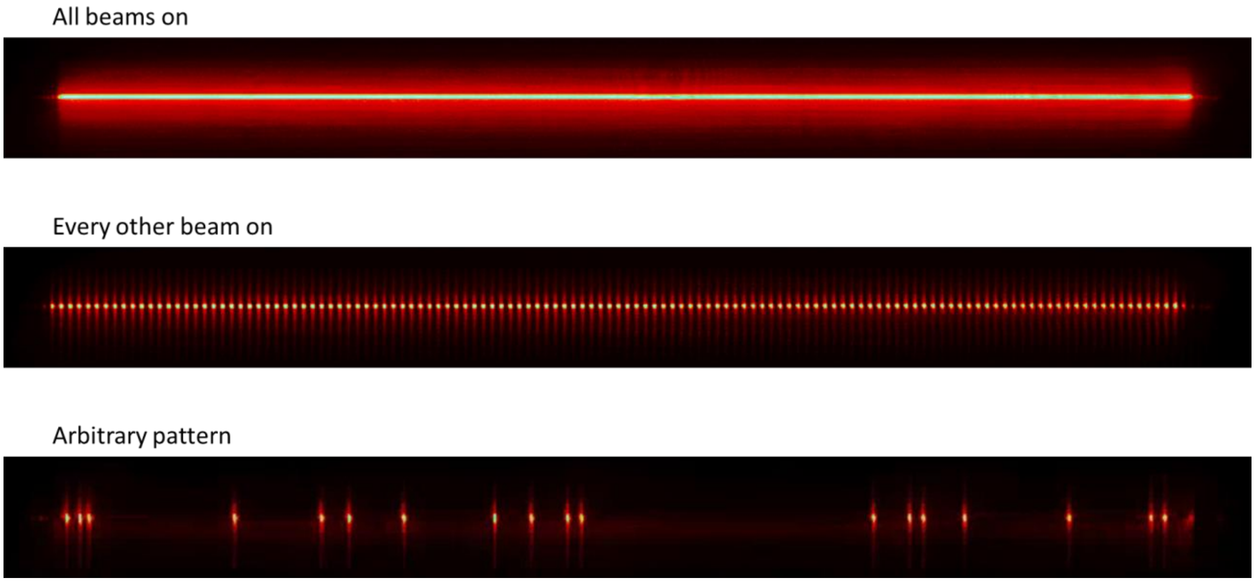

Figure 2 Camera image of a multi-beam swath that would be used for materials processing. Each image shows a different programmed pattern on the PLV module.

Figure 2 shows recorded images from a 1070nm optical head. Working with a swath of many beams can be applied to many direct write and laser assisted applications. The multi-beam device has shown throughput improvements in laser marking, micromachining, lithography, and additive manufacturing, where LIFT and beam shaping by phase modulation is being evaluated. Typically, the pattern data is pre-loaded to a controller which updates the PLV pattern quickly at runtime. For some systems it may not be possible to calculate and load the data beforehand, and in these cases a real-time controller loop can be used to update the PLV pattern with feedback from the system. This has been used for imaging through media [1] and could also be used with temperature feedback to manage heating of a material in processing applications.

PLV Device Introduction

The modulation principle of the PLV is based on diffraction and is akin to the Grating Light Valve (GLV) which is also a line beam modulator that is found in commercial printing systems. Compared to the GLV, the PLV accommodates more than an order of magnitude of incident optical power. The key to the high-power handling is the use of our new piston technology which allows us to greatly expand the active optical area of the modulator. The PLV features a 27mm by 1mm optical area that is fully usable. Figure 3(a) shows a schematic of the array. Figure 3(b-c) contrasts the large-area array of the PLV to the narrow “sweet spot” of the ribbons on the GLV. Figure 3(d) shows a SEM close-up image of the surface of the piston array [2].

Figure 4 (a-c) shows the measured optical/mechanical performance of the device. The device is compatible with a wide spectrum of laser sources, from 355nm to 1070nm. It supports both CW and pulsed laser applications.

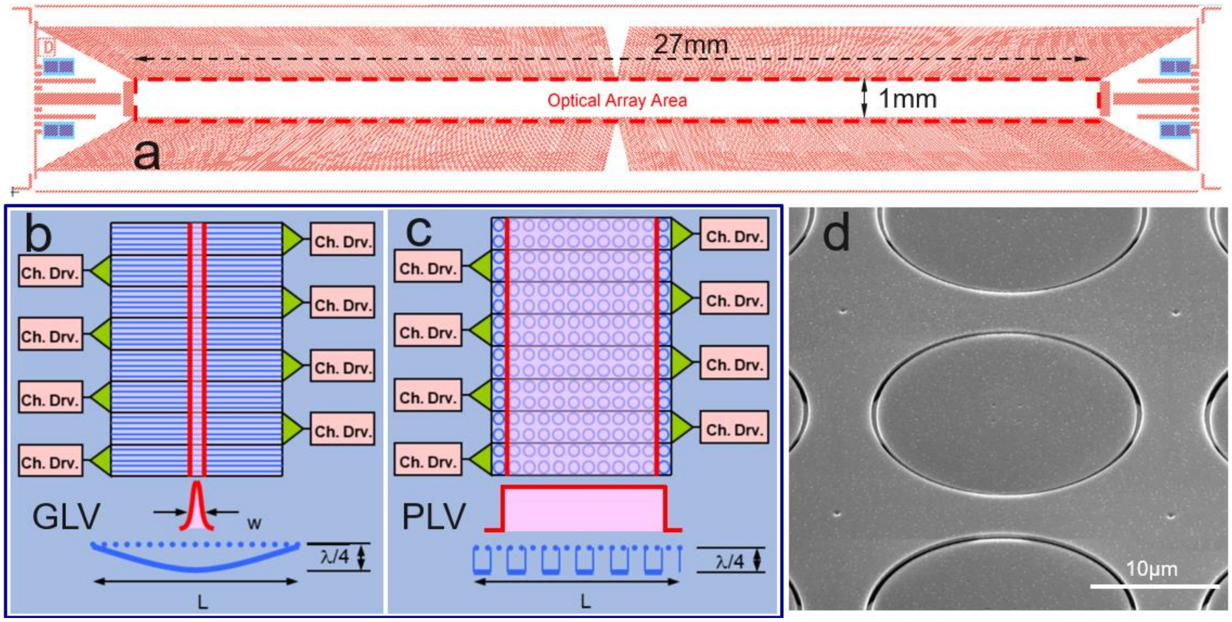

Figure 3 (a) PLV device schematic. (b-c) GLV vs PLV. (d) Array surface. [2]

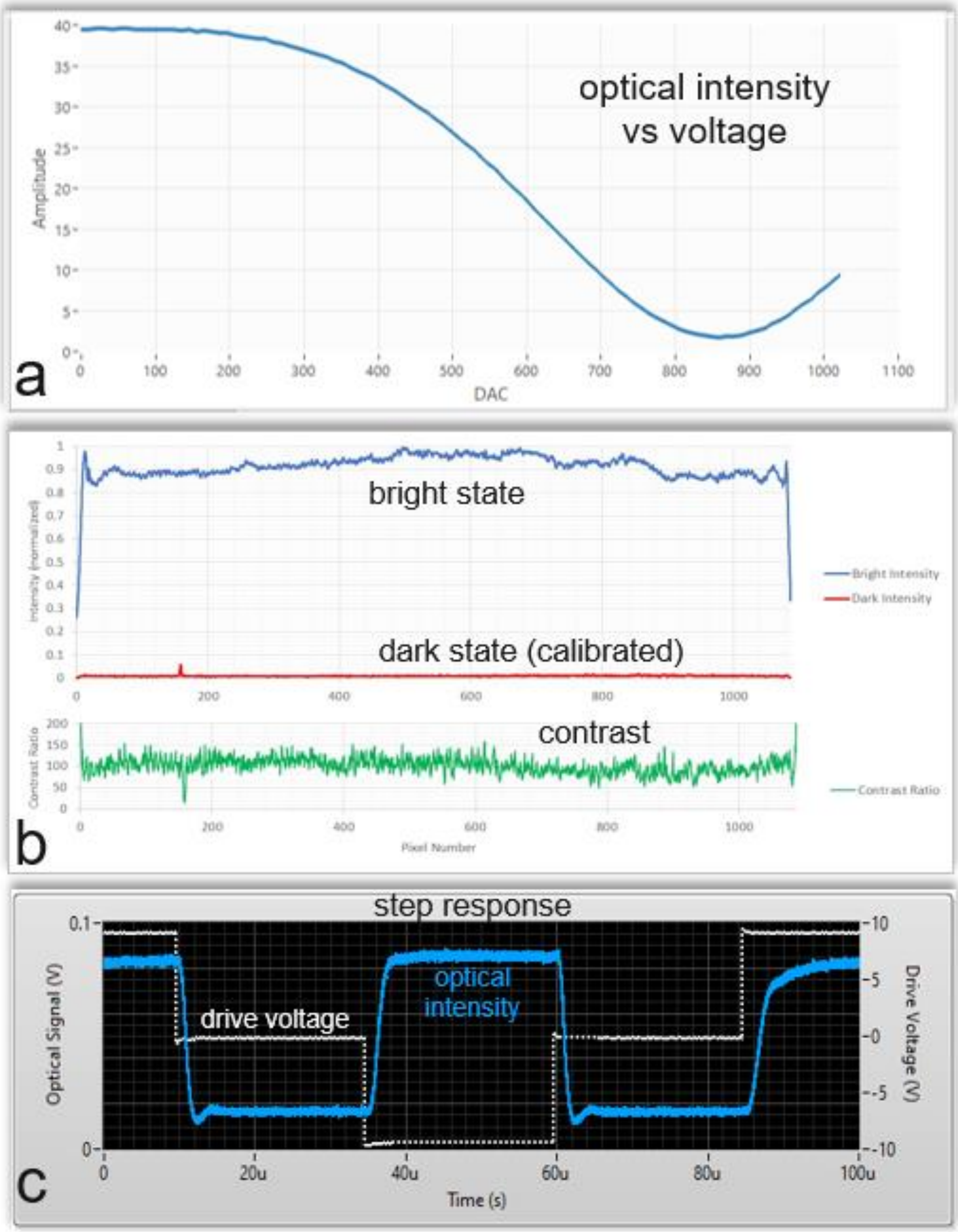

Figure 4 (a) Measured intensity as a function of voltage. (b) Bright/dark state uniformity and contrast across array. (c) Step response.

For CW (NIR) applications, we have demonstrated 4000 hours of continuous operation at 720W of incident power with only minor degradation in system efficiency. To our knowledge, this is the highest power handling MEMS spatial light modulator on the market today. Simulations show that 1kW of power handling is possible with further optimization of our current MEMS design. We have plans to achieve over 2kW with future MEMS designs. When the 1000 channels are operated at a refresh rate of 200 kHz, there are 200 megapixels generated per second offering a substantial advantage over single beam scanning.

For pulsed laser applications (laser marking), our LIDT testing shows the device can operate at up to 500µJ pulse energy.

Table 1. Forecast of optical head output

MEMS Design	CW Laser Power Handling 1064nm	Pulsed Laser	
		Energy	Properties
PLV2.1 (current)	800W	0.5mJ	1064nm, 10ps
PLV2.2 (upcoming)	1000W	0.75mJ*	1064nm, 10ps
PLVx (next gen.)	2000W	1.5mJ*	1064nm, 10ps

*estimated energy values

PLV Imaging

To maximize the PLV performance, the PLV must be integrated into an optical setup consisting of "illumination optics" and "projection optics". Figure 5 shows an example of how to create a multi-spot beam. The illumination optics transform an incident gaussian laser beam into a top-hat rectangular shape by using a beam shaper so that the PLV can handle higher laser power in comparison to gaussian illumination. It also gives the PLV surface a coherent light source to get modulation with high contrast. Then PLV reflects the illumination light and generates the diffracted light two dimensions. The projection optics cut the 1st-order diffraction light with a spatial filter which is installed at the Fourier transform plane and only 0th-order light passes through the filter. The aperture size of the spatial filter is determined by parameters such as wavelength, pitch of the PLV structure, and focal length of the lens. Thus, a multi-spot beam is created with the PLV imaging optics. Often, a 1D multi-spot beam is desired. This is obtained by adding anamorphic lenses in the projection optics to condense the short axis.

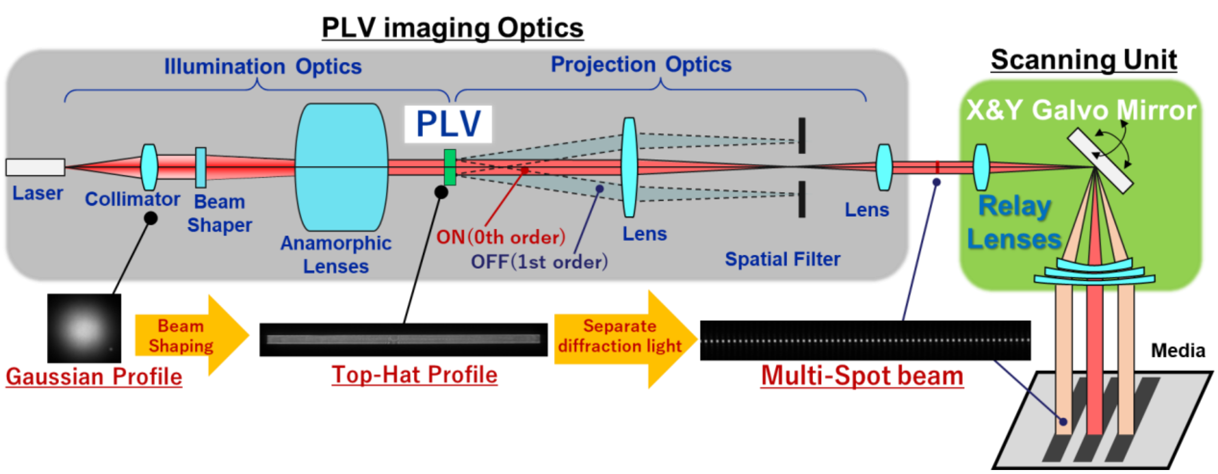

Figure 5 Basic concept of PLV imaging optics

This PLV imaging optics can be easily coupled to scanning optics. Figure 6 shows an example of scanning optics which has a 2-axis galvo mirror and relay lenses. For scanning, a 2-axis motorized stage can be used instead of a galvo mirror. The combination of 1-axis galvo mirror and 1-axis stage is also possible to create a two-dimensional image on the media.

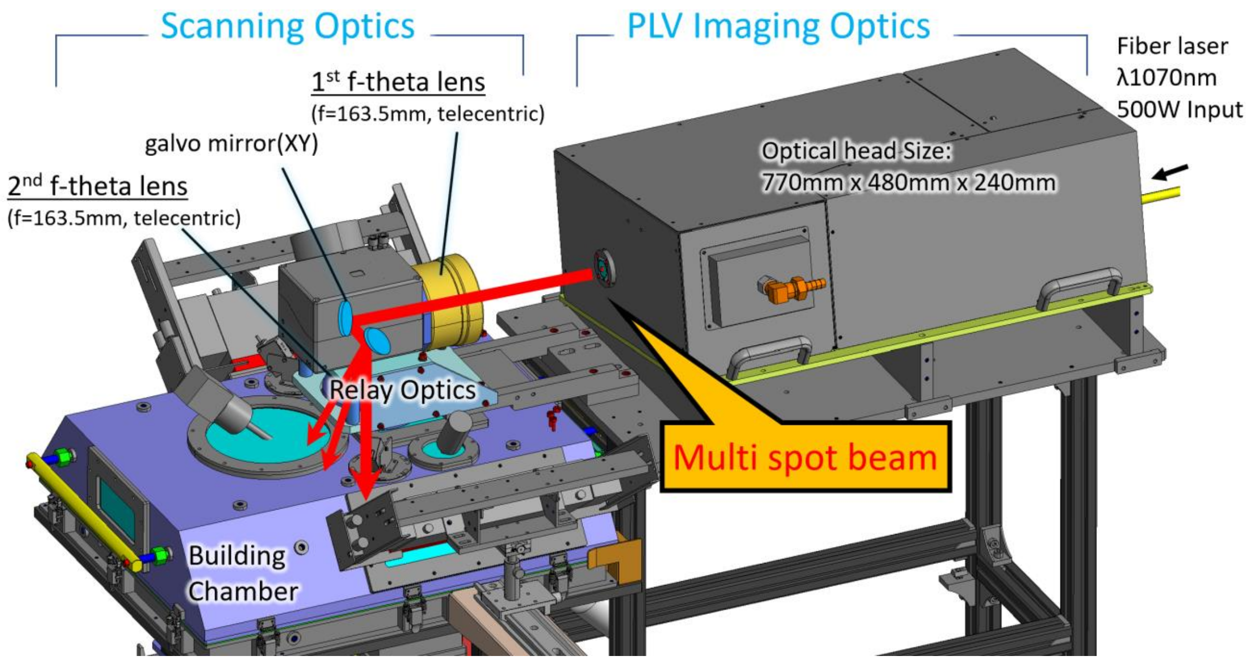

Figure 6 Example of scanning system configuration with PLV imaging optics

Laser Marking Printing Methodologies

Full Piece Coverage

The optical head output is a multi-beam pattern ready for material processing at a certain swath width and resolution. Different configurations can implement optics for different wavelengths. If desired, the swath width and resolution of the pattern may be adjusted with simple relay and magnification optics after the optical head output to bring the adjusted pattern on to the material. Example optical designs may be illustrated to achieve common magnifications and working distances, but every application can be different and so a complete design space cannot be provided.

Once the desired swath width and resolution is achieved, full workpiece coverage can be achieved in many ways. The simplest configuration is a single pass such that the swath entirely fills the workspace in one axis with the desired number of spots. In this case, a single axis of motion is necessary and can be achieved with any common industrial conveyance such as roll to roll, rollers or chutes. Of course, scanners or motion control stages may be used as well. For applications where a single swath is not feasible, a secondary axis scan is needed. For example, the laser marking demonstration uses 2D linear stages to sweep the work piece beneath the patterned swath in a raster scan, as described above. However, any combination of scanners, motion control or conveyor may be possible. Scanners may include devices such as galvos, polygonal mirrors, or more exotic scanning such as a secondary spatial light modulator. Motion control could include using linear stages to move the workpiece such as used for the marking demonstration or moving the optical head using e.g. stepper motors. Figure 7 illustrates several example configurations for different applications. Depending on the patterns and power needed for the material processing, further multiplexing may also be achieved using prisms or diffractive optical elements.

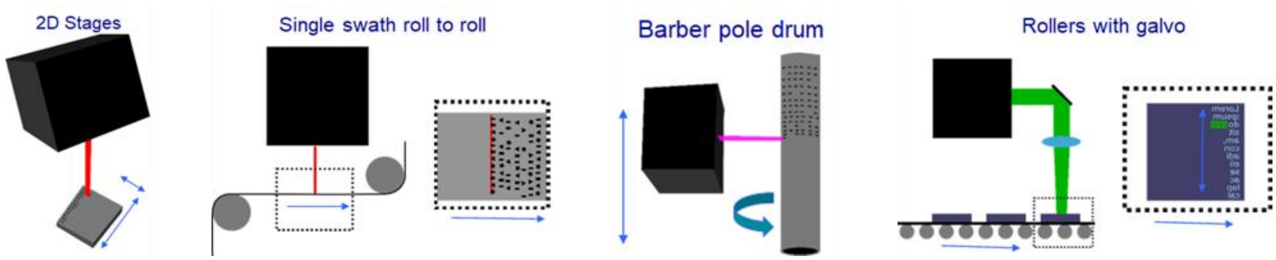

Figure 7 Different configurations for workpiece coverage. (a) 2D swath scanning with motion control, (b) Roll to roll with a single pass, (c) Barber pole scanning for drum coverage, (d) Galvo scanning with a 1D conveyer

Beam Overlap and Interleaving

PLV optical systems often utilize 2D top-hat illumination to reduce the peak intensity on the PLV and allow the highest power usage. The pixel array short axis is condensed to ~10-20um spot size with a sinc profile. The pixel array long axis is also imaged to a 10-20um spot size, with the magnification depending on how many pixels are grouped to create a spot. The large aperture of the long axis ensures a uniform distribution and creates a top-hat sinc spot profile onto the work piece. A top-hat profile on the long-axis is usually the preferred choice. Pixel-wise shaping can be done to customize the long-axis profile. Alternative designs could use "top-hat by Gaussian", or "top-hat by other" illumination. "Top-hat by Gaussian" illumination will result in a Gaussian distribution in one axis which is easier to relay with optics. Other schemes for long-axis illumination are possible, but all will result in higher "hot spots" than top-hat illumination.

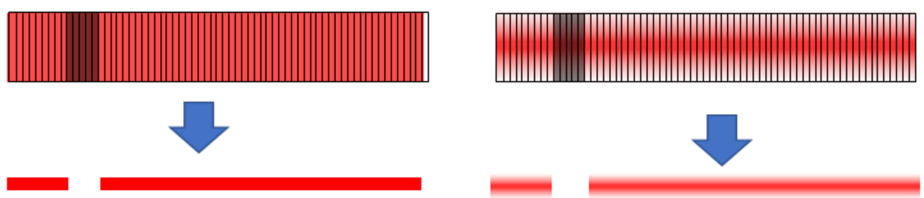

Figure 8 (a) Top-hat by top-hat and (b) Top-hat by Gaussian illumination. Darkened pixels are in the "off" state.

Generally, multiple pixels will be grouped together to form a single spot. This grouping increases the energy and power per spot and improves contrast. Pixels can be controlled in such a way to create spots or other patterns. The exact nature of this shaping depends on optical considerations and the specific application. For certain applications, every pixel will correspond to a single spot. Spots cannot be shaped by PLV pixel amplitude in this case, but additional optics may be used such as a lenticular or microlens array.

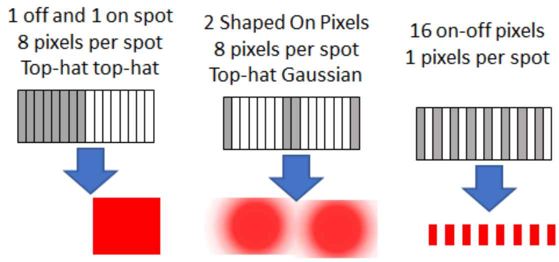

Figure 9 Examples of different spot shapes created by the pattern of the PLV

Beam overlap in the scanned direction is determined by pulse rate versus media movement. For LIPSS, we are employing a top-hat by sinc profile with high overlap (>90%). Beam overlap in the patterned axis is contiguous in the basic configuration. This contiguous design will often give the best multiplexing benefit with the highest efficiency, and we would recommend reexamining process parameters to fit within this scheme if possible. Pixel shaping or spot spacing enables more overlap options in the array long-axis, which will help reduce the thermal load on the material. Motion control or pixel shifting may enable more overlap options. Motion control multiplexing throughput and efficiency depends on the number of passes needed and spacing, while pixel shifting maintains the throughput advantage, though efficiency depends on the desired pixel shape.

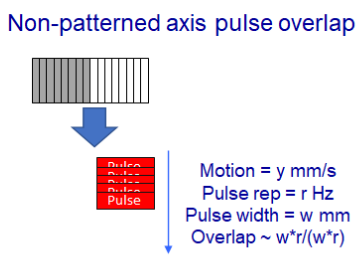

Figure 10 Overlap of pulses in the scanned axis is very similar to using a spot beam. Gray pixels are "off" and white pixels are "on", controlled by the PLV.

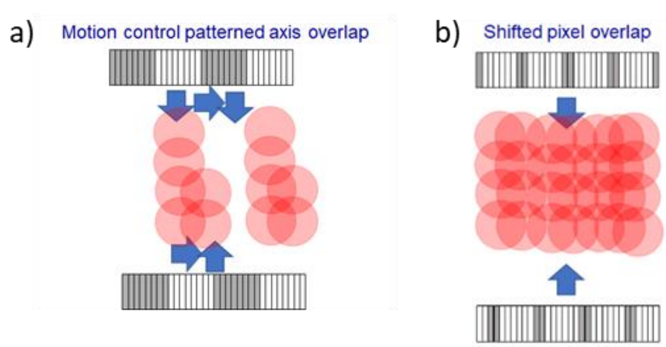

Figure 11 Some possibilities for overlapping spots in the patterned axis. Spots are created by the white pixels which are in the "on" state. A) Shift the spots by a small amount using motion control mechanism, and scan back in the other direction. B) Create discrete spots by keeping some PLV pixels in the "off" state. The spot edge placement is controlled by the PLV pixels and shifted by changing the PLV pattern.

PLV Throughput Advantage for Laser Marking

By leveraging higher power and energy lasers, the PLV can enhance throughput and resolution by enabling multi-beam materials processing systems. The greatest gains will be realized when the areas to be processed have very dense features exposed by the laser such as a datamatrix, high quality imaging (personalization applications), or roll-to-roll applications. Processing using a line-scanning scheme will naturally provide coverage of the entire processing area, unless there is a large empty area where no exposure is needed. When adjacent beams are turned on, they form a continuous line segment with no gap in between. Compared to a single-spot system, most of the cross-scan hatching is eliminated, and only a small overlap at the edge of the swath is needed.

		PLV Systems					Single Spot Systems	
		50um	40um	30um	20um	10um	50um	20um
PLV Length	mm	27.74	27.74	27.74	27.74	27.74		
PLV Width	mm	1	1	1	1	1		
Demag - Long Axis		2	2.5	3.3	5	10		
Demag - Short Axis		40	50	66.7	100	200		
Number of Pixels		1088	1088	1088	1088	1088		
Pixel Grouping		4	4	4	4	4		
Number of Spots		272	272	272	272	272	1	1
Swath Length - Long Axis	mm	13.87	11.10	8.41	5.55	2.77		
Spot Size - Long Axis	um	51.0	40.8	30.9	20.4	10.2	50	20
Spot Size - Short Axis	um	25.0	20.0	15.0	10.0	5.0	50	20
Pulse Separation Distance	um	0.25	0.20	0.15	0.10	0.05	0.50	0.20
Scanning Speed	mm/s	19	24	32	48	96	1000	1000
Laser Rep Rate	kHz	77	120	212	481	1922	2000	5000
Target Fluence	J/cm2	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Pulse Energy	uJ	2601	1665	945	416	104	6	0.94
Average Power	W	200	200	200	200	200	11.8	4.71
Image Size (Square)	mm	100	100	100	100	100	100	100
Time per Swath	s	5.20	4.16	3.15	2.08	1.04	0.100	0.100
Number of Swaths		7.2	9.0	11.9	18.0	36.0	3000	7500
Time per Jump	s	0.6	0.6	0.6	0.6	0.6	-	-
Time per Image	s	41.23	42.31	44.04	47.71	58.53	300.00	750.00
Aerial Write Rate	mm2/s	242.6	236.4	227.1	209.6	170.9	33.3	13.3

Figure 12 Throughput comparison of a PLV-based and single-spot marking system at different resolutions

The analysis in Figure 12 shows how the throughput of PLV-based marking systems compares to single-spot systems at different resolutions. In all cases, the fluence at the media is held constant. For the PLV-based systems, a 200W laser is used and it is assumed laser repetition rate and pulse energy can be traded off as desired. The PLV is demagnified by anamorphic optics to create beams of different sizes. The single-spot systems have a 33% cross-scan overlap with a fixed scan rate of 1m/s. The time to cover a 100 x 100 mm square area is calculated, and then normalized out to calculate the aerial write rate.

For 50um resolution marking, the PLV-based system gives a 7.3x improvement, and for 20um resolution we see a 15.8x improvement in aerial write rate. The PLV-based systems pay a small penalty for higher resolution, as more time is required to jump between swaths. All the required scanning speeds are <100mm/s. In contrast, single-spot systems pay a significantly larger penalty in writing time for higher resolution, as the speed is limited by the available laser rep rate.. Combining the swath with a galvo scanner enables jumping. This jumping reduces dead time and enables skipping areas where no printing is needed. This combination further increases the PLV's competitive advantage over single beam galvo scanning.

Examples of Written Media

We have created a laser marking system to demonstrate the benefits of using the PLV. This system uses a 1064nm, 10ps, 20W laser to illuminate the PLV. The PLV is then imaged with a demagnification of 10x to give high fluence with 20um resolution at the work surface. This system was designed for making black marks on stainless steel, but has also been used on aluminum, plastic, and graphite.

Figure 13 Images of varying sizes marked on stainless steel

The figure above shows various patterns marked on 304 stainless steel with a brushed finish. The line beam is ~1mm long and scanned along the long dimension of each image. The features are well-defined with sharp edges and text is crisp and easy to read.

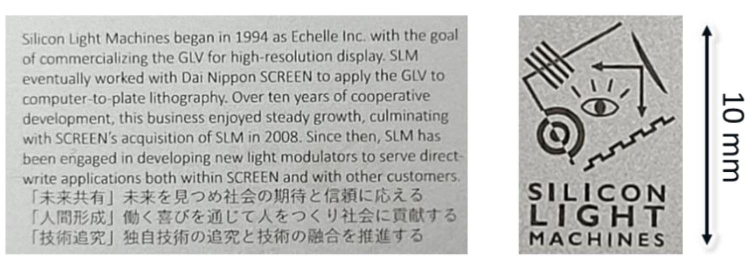

Figure 14 Images marked on aluminum

While the system was optimized for stainless steel, it can be used on other materials as well. Figure 14 shows high-resolution images on aluminum.

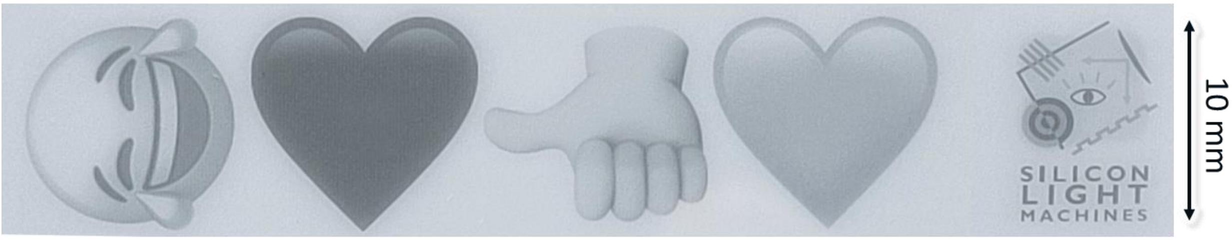

Figure 15 Images marked on generic white plastic index card using 515nm femtosecond laser

In a slightly different system, we demonstrated marking on plastic using a 515nm laser with 260fs pulse width. The sample images in Figure 15 show a gray-scale effect that is created by dithering the image data. All of the marks made are of similar darkness, but the density of the marks gives different areas their relative darkness. The high resolution of the system gives a very smooth appearance to changes in shading.

References:

[1] Tzang, Omer, et al. "Wavefront shaping in complex media at 350 KHz with a 1D-to-2D transform." *arXiv preprint arXiv:1808.09025* (2018).

[2] Liu, Tianbo, et al. "High Power MEMS Planar Light Valve." *2021 Conference on Lasers and Electro-Optics (CLEO)*. IEEE, 2021.