University of Arizona Optical Sciences Center

High Speed Maskless Lithography Phototool

EXECUTIVE SUMMARY

Introduction

Maskless lithography (ML) has wide applications, from next-generation semiconductor patterning to drop-on-demand inkjet fabrication of organic photopolymers and micro-optics. Most ML systems target binary imaging applications. In this paper, we describe a high speed grayscale Maskless Lithography phototool development program for UV exposure of photosensitive materials, such as photoresist and solgels. Sample images from the prototype phototool are included.

Whereas most ML systems target binary image applications, grayscale ML is an enabling technology for development of 3D structures such as micro-optics, multi-level computer generated holograms and micro-fluidic devices.

High speed grayscale ML provides an enabling technology for materials and device development. Fast, flexible imaging can be used to accommodate the lack of process control inherent in this type of research. Materials and process research often requires frequent re-optimization of the exposure profile, to account for variations in chemistry or other process parameters. For example, ultraviolet photosensitive materials (such as solgel and photoresists) have non-linear photo-response of exposure to material thickness. To create 3-D profiles, the material response must be linearized. Tailoring a linearized grayscale photomask to a specific material chemistry is impractical because conventional grayscale masks take at least several weeks to fabricate, and cost from several thousand to over ten thousand dollars. With high-speed-ML, a non-linear test image can be created then measured. Subsequent image pre-processing can be quickly applied to achieve the correct (linear) image exposure profile.

Our goal is to modify an existing ML phototool designed for binary imaging into a high-speed ML (HSML) grayscale phototool. While commercial ML phototools exist (for example Mask Pattern Generators for producing semiconductor photomasks, Laser Direct Imaging for printed circuit board fabrication), these tools are specialized for binary imaging, and do not meet the performance needs for grayscale lithography research. For example, commercial ML phototools typically require vector-based CAD data files (GDSII, DXF, Gerber 274, etc.) to produce binary images. Grayscale exposure with these tools can be achieved through multiple-exposure, which is practical for up to about 8 levels before registration errors are significant. Another method to achieve grayscale with a binary phototool requires use of a "halftone" technique, where each grayscale pixel is broken into "subpixels": for example, a 100-level "pixel" is written by imaging a 10x10 grid of "sub-pixels" to achieve the gray value. This technique requires at least 10 times the resolution and 100 times the speed of an equivalent grayscale ML phototool.

The OSC High-Speed Maskless Lithography (HSML) phototool is specifically modified to pattern grayscale images from JPEG, BMP or other common digital image formats. Additionally, the phototool is capable of high-speed imaging, enabled by the rotating polygonal mirror inherent with Raster Output Scanner technology. Presently, a 4k x 4k pixel image over a 30mm x 30mm area is imaged in less than 6 seconds. It is our goal to improve the electronic and mechanical performance to enable high-speed fabrication of a variety of optical and mechanical micro devices.

In addition to device fabrication, our intent is to provide a facility for hands-on education of graduate students in micro-optic fabrication and Computer Generated Holography techniques. We have the opportunity to operate two imaging platforms: one for reliable, accessible imaging for the research community, and the other for education and development of technology associated with high-speed grayscale ML..

Status of the OSC HSML phototool

At present, a single phototool has been developed and is capable of limited proof-of-concept component fabrication in a laboratory environment. It can also be used to provide the basis for a graduate educational laboratory in diffractive optics fabrication. The performance of the tool is limited by the donated electronics subsystems, as described below. It is currently unable to meet exacting specified research components, such as those indicated in the above list of applications. However, a variety of components have been fabricated to-date, including Fresnel Zone Plates, Binary Computer Generated Holograms (CGH's), Grayscale Zone Plates, and Grayscale CGH's. It is our intent to follow a staged development plan that will improve the performance, reliability, and usability for both research and educational purposes.

Applications

This phototool forms the basis of a system for fabrication of micro-optic elements, waveguides, Computer Generated Holograms, micro-fluidic devices, micro-mechanical structures, high-density electronic interconnects, and other maskless lithography applications.

At present, a short-list of potential research using HSML at the University of Arizona that may be served by this technology includes:

Micro-optics for medical devices..Prof. Michael Descour

Compensator optics for radiographic image evaluation...............Prof. H. H. Barrett

Generation of Guide Stars for the MMT Telescope......................Prof. Roger Angel

Multi-spectral array CGH and IR Gratings ....Prof. Eustace Dereniak

Ophthalmic Compensator holograms...Prof. Jim Schwiegerling

Optical Vortex and Optical Tweezer research.............................Prof. Grover Schwartzlander

Organic Display technology ....Prof. Ghassan Jabbour

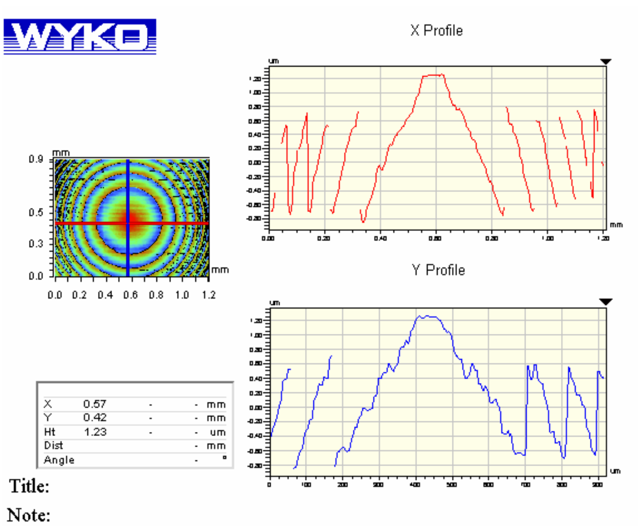
Fresnel zone compensators..Prof. Tom Milster

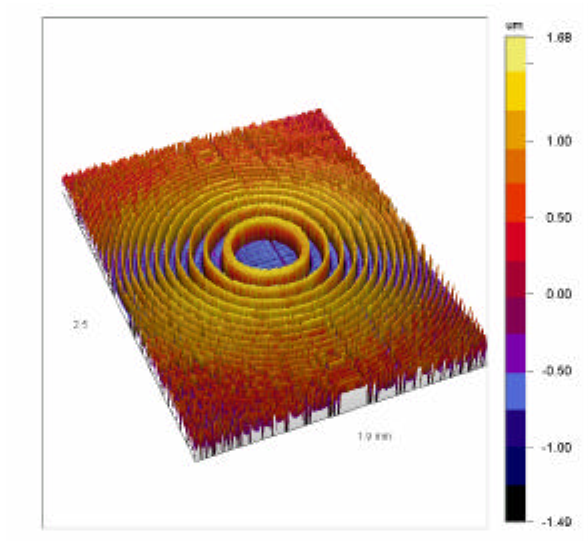
Graduate Laboratory Education in micro and diffractive optics ...Prof. Eustace Dereniak/Prof. Bill Dallas

Photo-imageable hydrogel material development........................Prof. Grant Willson (UTA)

With the exception of Prof. Willson at University Texas at Austin, all work to date is limited to the UofA Optical Sciences Center until further funding sources are found.

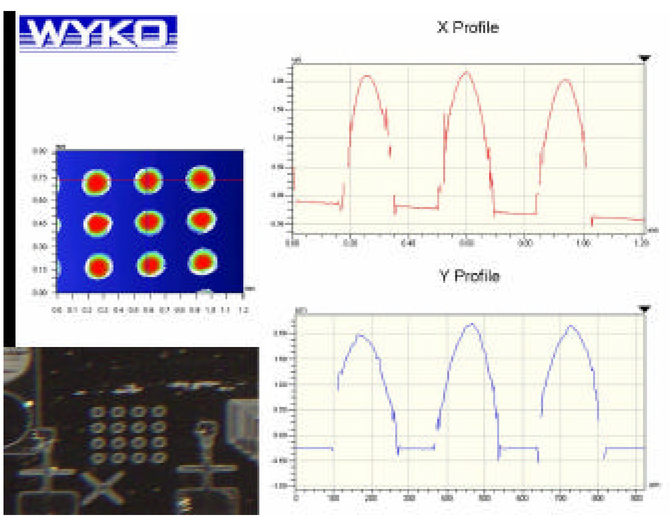
Examples

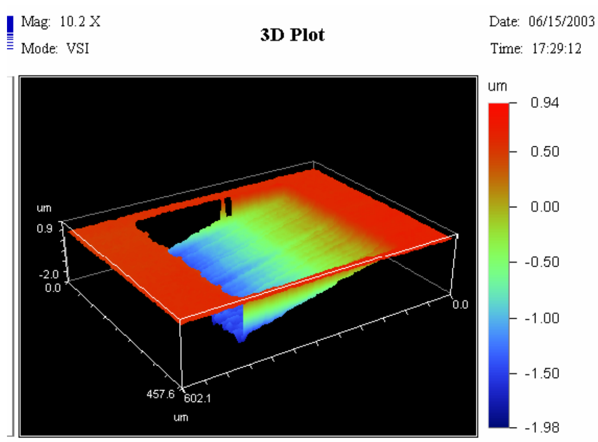




Grayscale Zone plate in photoresist

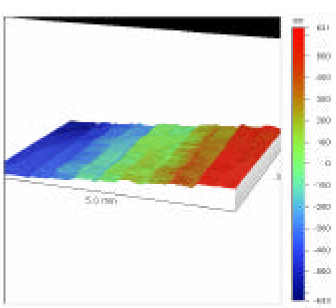
Binary Zone Plate in photoresist





Lenslet Array in solgel

Grayscale ramp in photoresist



Stepwedge in photoresist

Phototool Improvement Roadmap

The OSC HSML is a phototool derived from components of a DARPA program completed by Etec Systems in 1998. Proof-of-concept modifications have been made to permit grayscale exposure of UV materials. However, the limited electronics front-end does not support the full capability of the tool. We propose a staged development plan that will allow incremental improvement of the HSML phototool concurrent with materials and device research. The proposed plan will allow us to incorporate device fabrication knowledge gained during lower performance operation prior to development of the higher performance configurations.

Roadmap philosophy

We believe that undertaking this effort in a graduate studies environment provides invaluable opportunity for developing hands-on Electro-optic and Opto-mechanical, and Imaging Systems engineering skills at an advanced level. Furthermore, many of the applications for the tool are not mature, and application of high-speed grayscale ML for device fabrication belongs in a research environment. The technology inherent in the phototool requires understanding fundamentals from many disciplines: Classical Optics (systems, lens design, tolerancing) Physical Optics (Fourier theory, acousto-optic interactions, laser systems), Image Science, Precision Mechanics, Electronics (both digital and analog) and Instrumentation (software, control theory, etc.). Because the system improvement projects are multi-disciplinary but centered about the optical architecture, our funding strategy will require an Optical Sciences graduate student to assume the system responsibilities, and other disciplines will be filled by students from other fields, outsourced, or in certain instances, an extension of the OpSci graduate's system responsibilities.

Roadmap Summary

The roadmap has been developed so that multiple concurrent projects can be implemented, rather than a sequential approach. We believe that this will provide the greatest flexibility for funding and resource development.

Improvements to the tool fall into three basic categories: Performance, Human Factors, and Education. (Details of the roadmap are in Appendix A.) The trend for increased performance allows greater resolution, improved bit depth, larger imaging area, and faster speeds. We separate Human Factors specifically because we believe that successful application of this tool requires ease of use and flexibility for research. This requires a robust phototool interface, processes, and training tools that will allow both researchers and graduate students to quickly and effectively understand the technology. As an educational platform, basic training tools are extended into experiments and exercises demonstrating theory of operation, leading to extensions of the technology.

Funding

The prototype tool was developed as an unfunded project, relying heavily upon corporate donations for equipment and services,[1] and a 3-person team of self-funded graduate students. Currently, $100k of Arizona Prop. 301 funds have been designated to develop a graduate laboratory curriculum in fabrication techniques of computer-generated diffractive optics and holograms.

We are currently soliciting funding for this program from both commercial and government sponsors. For more information on participation, contact Mr. John Tamkin, Exec. Laboratory Manager, Diffractive and Micro-Optics Research Laboratory, at the University of Arizona Optical Sciences Center: jtamkin@optics.arizona.edu (520)-603-1778.

[1] See Appendix C for tool details. Corporate sponsors include Etec Systems, an Applied Materials Company, Agfa Corp., Lincoln Laser, Ramar Technologies, and Aerotech Corp.

APPENDIX A: PHOTOTOOL DEVELOPMENT ROADMAP

Task	Rationale	Improvement
Performance Improvements		
Increase pixels per scan line		
	LP-400 limited to 4230 pixels per scan line	Waveform generator card allows up to 24k pixels per scan line, 12-bit grayscale, 24 Mpix/sec. Software developed in LabView environment
Improve pixel placement accuracy/stability		
	Timing stability dependent on polygon speed control	Use timing grating to create reference clock to be phase-locked to data
	Laser beam exhibits thermal drift/wander	Include beam stabilization subsystem to scanner
	Cross-scan pixel placement accuracy limited by scan line design and manufacture	An acousto-optic deflector or MEMS mirror can be added to compensate for cross-scan errors
Improved Resolution		
	Existing optical system is telecentric, and thus the scan line may be reduced in length optically with an increase in resolution	Develop conventional reduction lens to improve resolution of system. Stage will need upgrade to air-bearings and interferometric feedback.
Increase bit depth		
	8-bit performance limits height resolution	2-stage AOM and/or high-extinction modulation system to achieve 12-14 bits
Machine Vision		
	Multiple substrate processes require registration of pattern to substrate features. This will allow front-to-back alignment and multiple lens element fab	a) Add vision camera to scanner, coupled to microscope which views real-time scan line
		b) Add photodetector & A/D to view retro-reflected image
Autofocus/ Serpentine scan		
	Uneven substrates and exposure media can exceed the depth of focus of the phototool. Either the substrate must be leveled, or the scan line adjusted to compensate	"Active Chevron" is a servo system which enables focal plane correction and serpentine operation, as described in US Pat.# 6107622
	Serpentine scanning allows large images to be patterned using multiple scan stripes. This technique is common in high-end binary scanners.	Electronic image "striping" correctly segments the image to seamlessly butt adjacent stripes. Software and electronics development task.
Increased Speed		
	Large image files causing long imaging times decrease flexibility of the tool	The optical system is designed for 8-channel operation, 24 Mpix/sec. Operation. Extending the electronics front-end and software to support multiple channels decreases imaging time, increasing tool flexibility.
Improve Human Factors		
Improve Graphical User Interface (LabView front-end)		

	At present, several software tools are used to print JPEG or BMP image files. These tools include image manipulation and transfer, and separate LabView tools for stage control…	Development within the LabView environment provides both research flexibility and end user simplicity
	Add image manipulation to interface	
Develop operational procedures and training doc		
	The laboratory will by its nature have high turnover of graduate personnel. Curriculum specific to the laboratory will also require development.	Development of effective communications tools will be critical to training new users of the laboratory. Web-based training collateral is essential for all levels of interaction with the laboratory.

APPENDIX B: Technology Background

Overview of Current Grayscale ML Technology

Photoresists are used to coat substrates in thickness up to 10's of microns to yield a sacrificial or protective patterned layer. This layer is subject to secondary processes, such as wet-etch or ion milling to produce the final component. Photosensitive solgel materials are imaged and developed, then undergo bake-out to yield glass patterns on the substrate. While the majority of ML exposure of UV materials has been targeted towards binary imaging applications, we focus on grayscale patterning of UV-sensitive materials with medium resolution (1 micron and above) at high speed (less than a few minutes) over large areas (200mm x 200mm).

Background of micro-optic fab methods

Grayscale ML has predominantly bee used for fabrication of micro-optic devices. Continuous surface relief microstructures have been built using mask and maskless lithographic techniques. Many of these are continuous-relief diffractive optics. Both optical and electron beam lithography techniques have been used, and an excellent review of electron lithography vs. optical lithography can be found in ref. 1[2]. Recently, efforts have been made to produce refractive surfaces using these techniques as well, with surface sag depths exceeding 10 microns[3]. The maskless optical lithography technique is also referred to as Laser Direct Write (LDW) or Laser Direct Imaging (LDI) technology. Grayscale ML phototools have historically been slow. The most prevalent tools operate by modulating a single laser spot focused through a microscope objective onto media translated by a mechanical stage. Both rectilinear raster scan and rotational scan techniques have been studied. The rotational scan spins the media on a rotary table, and the objective translates across a radius. Rectilinear scan by means of a translating X-Y stage allows patterning of non-rotational profiles with the advantage of patterning more than one element[4]. Both raster and vector scan methods have been studied. The raster method adds non-rotational pattern structure to the final image.

Background of raster output scanner technologies

Another method of creating an optical rectilinear raster pattern utilizes a rotating mirror to sweep a modulated beam across the media. Continuous-tone raster imagers that use rotating mirrors can be further sub-categorized to drum or flatbed scanners. As the name implies, drum scanners wrap the exposure media around the outside or inside of a drum, and expose the material with a translating or translating and rotating spot. Flatbed scanners use a rotating mirror (often a multi-faceted polygon) to sweep a beam across flat media in one direction (fast-scan). The media is transported in the orthogonal direction (slow-scan) using a linear stage.[5] This has often been referred to as "Flying Spot" raster scanning[6].

Flat-bed technology has been applied to exposure of UV-sensitive materials such as photoresist since the mid-70's.[7] Applications range from binary exposure of printing plates to exposure of photomasks for semiconductor lithography. This type of raster scanning technology has been applied to create photomasks for micro-optics[8], but to our knowledge has not been applied to grayscale HSML.

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[2] Klay, E.B., "Continuous profile writing by electron and optical lithography", Microelectronic Engineering, 34 261-298

[3] Ari H. O. Kärkkäinen et al. "Direct photolithographic deforming of organomodified siloxane films for micro-optics fabrication", *Applied Optics-OT*, **Vol. 41** Issue 19 Page 3988 (July 2002)

[4] M.T. Gale, "Fabrication of continuous-relief micro-optical elements by direct laser writing in photoresists", *Optical Engineering,* Nov. 1994/Vol. 33 no. 11, 3556-3566

[5] R.R. Firth, " A continuous-tone laser color printer" *Journal of Imaging Technology* **14**:78-89 (1988)

[6] John C. Urbach, "Laser scanning for electronic printing", *Proc. of IEEE* **vol 79** no. 6, June, 1982, p. 597-618

[7] J. P. Donahue, "Laser pattern generator for printed circuit board artwork generation" in *Proc.* SPIE Seminar on Laser Recording and Information Handling, **vol. 200**, pp 179-186, 1997

[8] T.J. Suleski, "Gray-scale masks for diffractive optics fabrication: 1. Commercial slide imagers" *Applied Optics* **vol. 34** no. 32, Nov. 1995, p. 7507-7517

Raster Imaging Fundamentals

The Rasterization Process

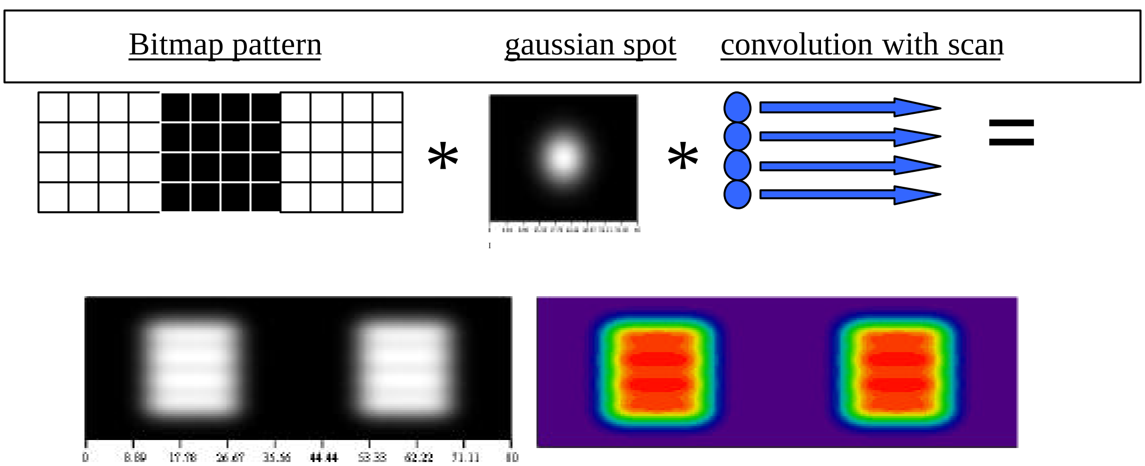
The ability of a Maskless Lithography phototool to pattern small features is determined by the optical performance coupled to the electronics performance. The imaging process is outlined in the following steps:

1) Pixelization of the pattern. The original image is segmented into a rectangular array of gray levels, called pixels. The spacing of pixels is determined by the electronic address resolution of the imaging system.

2) The optical system sweeps a single, focused laser beam along a precise line. For each row in the pixel array, the data is clocked out, and modulates the laser beam. Mathematically, this is represented by a convolution of the data stream for each row with the spot spatial profile, in this case, a 2-dimensional gaussian.

3) The next row follows a similar convolution. This row is added to the first convolved row, spaced one pixel down from the first row. Subsequent convolved rows are similarly added.

As a visual example, a series of 4x4 pixel black and white squares are convolved with the scan in the above manner:



Grayscale Aerial Image   Pseudo-color Aerial Image

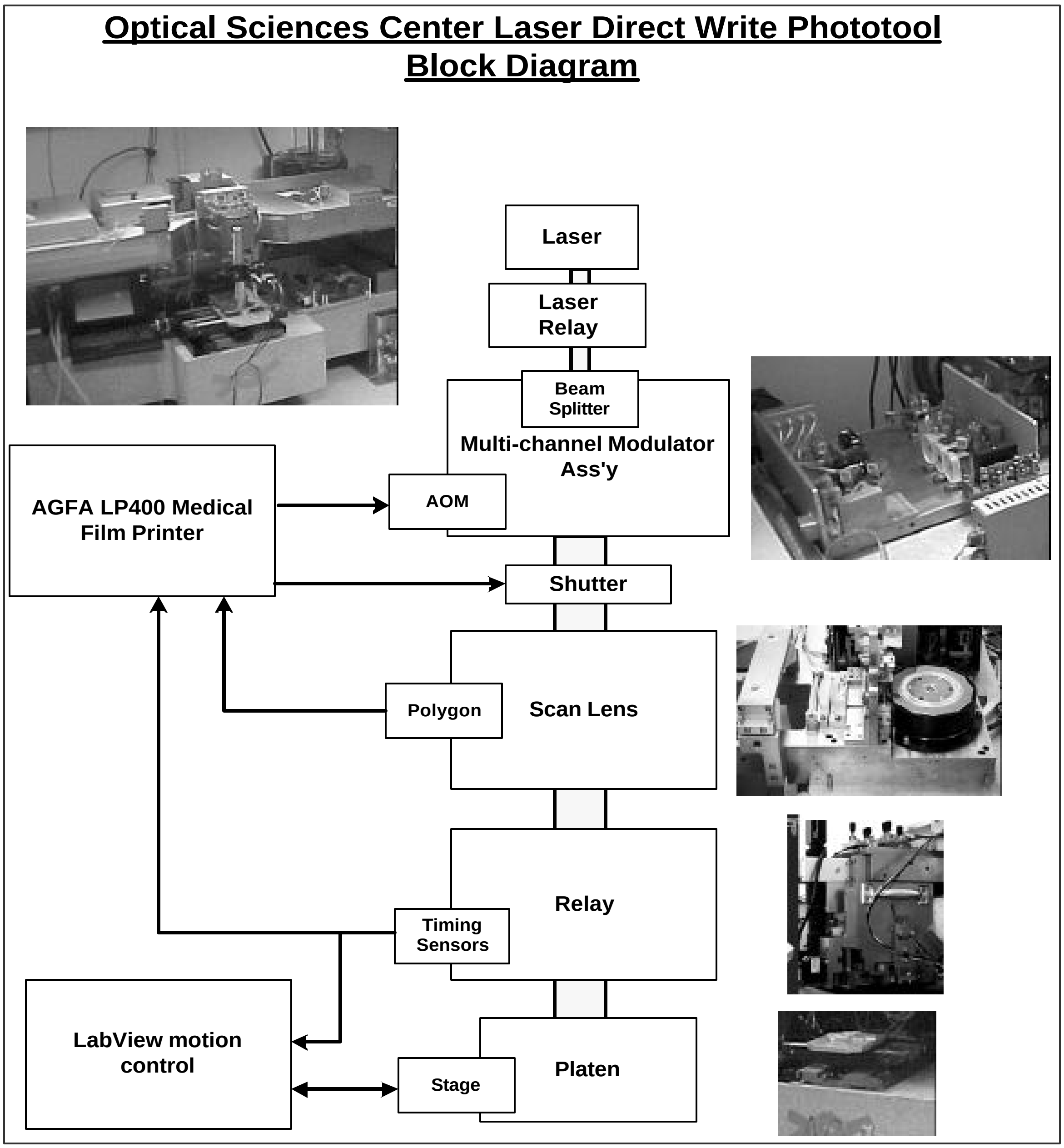
Note that the nature of the raster imaging process causes asymmetry in the maximum spatial frequency for horizontal and vertical lines. This is caused by the additional convolution in the fast-scan direction. As long as the pixel spacing and spot size are sufficiently small relative to the feature size (i.e. many pixels per feature), this effect is not noticeable. However, as the feature approaches a size imaged by few pixels, these raster effects become noticeable.

In summary, minimum feature size is application dependent, and requires multiple pixels per feature. Large numbers of pixels per feature increases the complexity, speed and cost of the imaging system. High speed operation requires the minimum number of pixels per feature, defined by an accurate understanding of the application.

Appendix C: Capability of the OSC HSML Phototool

The basic components to the phototool are similar to most raster output scanning devices[6], as shown in Figure 3. This system is based upon components for a high-performance binary UV phototool designed as a research prototype to image binary high-density interconnects patterns. Details of the system can be found in "High Speed Gray Scale Laser Direct Write Technology for Micro-Optic Fabrication" Proceedings of SPIE Volume: 4984 **Micromachining Technology for Micro-Optics and Nano-Optics**, p. 210-219. The

Figure 3: OSC HSML Phototool Block Diagram



The performance of the optical system is summarized as follows:

- Optical Scanner Parameters:
    - 2.5 micron fwhm gaussian spots
    - 30mm scan line length
    - 8-channel operation @ 24 Mpixel/sec per channel
    - 6 Watt polychromatic Argon Ion laser (CW)
    - 40% transmission efficiency
    - Achromatic optical system from 350-380 nm
    - Telecentric image plane
- Derived Attributes:
    - Exposure dose over 800 mJ/cm^2 (single channel operation)
    - 6 sec exposure time for 30mm x30mm area with 1 micron pixels

The electronics are "piggy-backed" off of a commercial grayscale film printer used for medical imaging (AGFA LP-400). An electronic interface was built for the phototool optical system to mimic the operation of the scanner resident in the film printer. The electronics for the film printer limited the performance of the optical system as follows:

- 4 Mpix/sec
- Single channel operation
- 4230 pixels per scan line

Therefore, the performance of the system is reduced in the following areas:

- 6.2 micron pixels[9]
- 26mm scan line length
- Single channel operation
- 3 micron feature accuracy
- 5 sec exposure over 26 x26 mm area with 6.2 micron pixels

While these specifications are adequate for large features, the phototool is capable of far better performance with upgraded electronic systems.

[9] The optics of the DARPA system are modified to provide a 6.5 micron fwhm spot size, accordingly