An Innovative Tool for Fabricating Computer-Generated Holograms

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Abstract. Based on research at MIT, LumArray, Inc. has developed a maskless photolithography tool, the ZP-150, designed to cover an entire 15-cm substrate with a continuous, coherent high-resolution pattern, thereby avoiding the “stitching problem” and making it ideal for fabricating computer-generated holograms (CGH). No mask is required, as data is transferred directly from a computer to a spatial-light modulator that adjusts the intensity of 1000 beamlets, and directs them to 1000 diffractive-optical lenses. Patterns of arbitrary geometry, with placement precision ~1 nm, are written by scanning the stage in coordination with modulation of the beamlets by the spatial-light modulator. A fully automated proximity-effect-correction algorithm enables fine and large features to be written with equal ease, as well as the creation of 3-D structures. The ZP-150 uses stable, non-chemically amplified photoresists. Extension of resolution from the current 150 nm to the sub-100 nm domain is planned. In addition to providing rapid turn-around on designs, we envisage the ZP-150 being used in customized manufacturing of CGH’s by virtue of its modest cost and low maintenance.

1. Introduction
In 1996 the MIT team began exploring an approach to micro- and nanolithography that deviated significantly from preexisting methods such as scanning-electron-beam lithography (SEBL) and optical-projection lithography (OPL), both of which employ a single projection lens. By employing instead a large array of lenses, in conjunction with a spatial-light modulator that directed beamlets to the individual lenses, one could create patterns of arbitrary geometry at high speed while circumventing the conventional coupling between lens numerical aperture and field of view [1-7]. The basic concept is shown in figure 1, with the lenses being diffractive-optical elements; hence the name “zone-plate-array lithography” (ZPAL).

The initial proposal called for using collimated 4.5 nm x-rays from an undulator and predicted resolution below 25 nm [1]. Subsequently, the use of ultraviolet radiation rather than x rays was explored in two Ph.D. theses at MIT [2-7], and a company, LumArray, Inc., founded [8].
Figure 1. Schematic of the basic principle of zone-plate-array lithography (ZPAL). A spatial-light modulator directs beamlets to the individual lenses, which form focal spots on a substrate. By scanning the stage that holds the substrate, while modulating the beamlets under computer control, patterns of arbitrary geometry are written via the superposition of focal spots.

2. The ZP-150 system
Figure 2 is a schematic depicting the ZPAL configuration being commercialized by LumArray. The light source is a 405 nm GaN laser that illuminates a spatial-light modulator (SLM) from Silicon Light Machines. Each of the 1086 pixels of the SLM directs a beamlet to one of the 1086 zone plates of the array. The beamlet intensity can be controlled from zero to full on in 256 steps. This so-called gray scaling plays an important role in linewidth control, proximity-effect correction and 3D patterning.

Figure 3 depicts the writing strategy. In brief, the substrate is mounted on an air-bearing stage and raster scanned across its full width. The pattern to be written is first described as a superposition of rectangles and other geometric figures. The software for the ZP-150 converts that description into commands to the spatial light modulator that are coordinated with the stage motion such that the focal spot intensity is non-zero where an element of a pattern is to be written.
Figure 3. Depiction of the writing procedure used in LumArray’s ZP-150 system at an intermediate stage in writing a particular pattern element. After a first scan in the X direction, the stage moves down in Y by one increment of the address grid (depicted as an 80 nm shift) and an X scan in the opposite direction is carried out. Three focal spots are depicted: #1 is about to make a second pass through and exposure of the pattern element, #2 is part way through its second pass, #3 has completed its second pass. The lightly shaded region shows the desired pattern element.

Figure 4 is a photograph of the ZP-150 alpha system located at the National Institute of Standards and Technology (NIST) in Gaithersburg, MD where it will be used to write large area computer-generated holograms and other nanostructured optics.

Figure 5 is a portion of a computer-generated hologram written for a potential customer. The jogs evident in the pattern are not defects but rather an intentional part of the desired hologram. In addition to writing binary type patterns, LumArray’s system has also been used to write 3-dimensional patterns such as blazed diffraction gratings.

The throughput of LumArray’s system (in units of area per time) is given by the following equation

\[
\text{Throughput} = NRd^2, \quad (1)
\]

where N is the number of lenses (equal to the number of pixels in the spatial-light modulator), R is the refresh rate of the modulator (currently 290 kHz) and d is the spatial period of the address grid. The latter is an adjustable parameter, typically set to be ½ of the desired minimum feature size. For a 150 mm-diameter substrate, covered over its entire area with minimum features of 150 nm the information content is \(\sim 4 \times 10^{12}\) bytes. The writing speed in this case would be about 1.5 mm\(^2\)/sec. Patterns that are laid out on a coarser address grid (i.e., larger value of d) can generally be written more quickly.
3. Innovations inherent in ZPAL

The ZPAL concept, as well as the design of LumArray’s ZP-150, represent a number of innovations. We summarize them here and comment briefly on each.

a. **Maskless photolithography** – This eliminates the need for masks, enables rapid turn around and rapid convergence to optimal design.

b. **Patterns are formed from overlapped focal spots** – Because the spots that form a pattern are exposed at different times, there is no coherent relationship between them and hence no troublesome interference effects. Focal spot intensities are additive and hence the mathematics of linear superposition applies.

c. **Stage is moved, not the focal spots** – The encoder that reads stage position provides nanometer-level precision. Because focal spot positions are fixed in a rigid frame, by calibrating their positions and correcting any positional errors in software, nanometer-level pattern precision should be achieved. In contrast, maskless systems that utilize beam deflection are subject to several sources of error.

d. **Multiple lenses operated in parallel** – Throughput increases directly in proportion to the number of lenses—see equation (1). Throughput in the ZP-150 is currently limited primarily by the framing rate of the spatial-light modulator.

e. **Pattern size is decoupled from its resolution** – The pattern size depends only on the range of the X-Y stage travel, while pattern resolution depends on the numerical aperture of the lenses. The two are decoupled, unlike the situation with a single projector lens. A continuous, coherent pattern can cover an entire substrate, or multiple variations on a design can be written on the same substrate.

f. **Use of diffractive-optical lenses** – Diffractive-optical lenses can be made in large arrays at very low cost using planar-fabrication techniques such as scanning-electron-beam lithography (SEBL). Moreover, with sufficiently advanced patterning techniques, focusing efficiency can approach 100%.

g. **Freedom from aberrations** – Diffractive-optical lenses focusing on axis are aberration free.

h. **Focal-spot intensity variable in 256 steps** – By controlling focal-spot intensity, so-called gray scaling, linewidths and proximity effects can be controlled, and 3-D patterns written in photoresist.
i. **Wavefront engineering** – One can engineer the progression of zones in a diffractive-optical lens, and achieve thereby focal spots other than the conventional Airy distribution. This can be advantageous in some circumstances.

j. **Circumventing the diffraction barrier** – In recent years techniques have been proposed and demonstrated that break the long-standing diffraction barrier [9-13]. In brief these techniques take advantage of wavelength-selective chemistry and optical nonlinearities. Simulations indicate resolutions below 1/20th of the optical wavelength are feasible.

### 4. Impact on Computer-Generated Holography

ZPAL has the potential to impact the fabrication and use of computer generated holograms for a variety of reasons:

a. **Very large area holograms** – With ZPAL, the area of a hologram is limited only by range of the stage motion, currently 150 mm x 150 mm in the ZP-150. This could be increased by employing a larger stage.

b. **Multiple designs on the same substrate** – ZPAL enables a designer to put multiple designs on the same substrate. This would facilitate a more rapid conversion to an optimal design.

c. **Customization for security** – Maskless lithography in general, and ZPAL in particular, enable one to customize holograms. If the cost and convenience are appropriate this could lead to new security markets for holograms.

d. **Higher resolution** – The ZP-150 promises higher resolution than many of the other lithography techniques currently used to make holograms. This opens the door to higher performance, higher information content and operation at shorter wavelengths.

e. **Three-dimensional holograms** – Just as a blazed grating yields higher diffraction efficiency and asymmetric beams, a capability for sculpturing the holographic medium in 3-dimensions opens the door to higher efficiency. The ZP-150 system is especially well suited to this application due to the intensity control afforded by the spatial light modulator and grayscaling.

### 5. Summary

When a disruptive technology comes along, its first use is generally an existing and well known application. But soon thereafter, the innovation inherent in the disruptive technology becomes more evident, giving rise to new applications and new ideas. It is our expectation that bringing zone-plate-array lithography to the attention of the holography community will open the door to new forms of holograms as well as applications not previously envisaged.

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