Versatile stepper based maskless microlithography using a liquid crystal display for direct write of binary and multilevel microstructures

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Abstract. A versatile photolithographic photoplotter based on a standard photoreduction stepper, where the reticle is replaced by a commercial liquid crystal microdisplay, is reported. The microdisplay module is designed as a drop-in replacement, allowing the photoplotter to be simply and quickly converted into a standard stepper, making it an extremely versatile, low-cost research and development tool. Binary and multilevel plotting are demonstrated with plot rates of several Mpixels/s and 1-μm feature sizes into standard industrial photoresist. The limitations on plot rate and resolution are presented and techniques for overcoming them discussed. © 2007 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.2767331]

Subject terms: lithography; real-time imaging; liquid crystals; spatial light modulators; micro-optics; illumination.

Paper 06054R received Aug. 3, 2006; revised manuscript received Dec. 22, 2006; accepted for publication Mar. 29, 2007; published online Aug. 6, 2007.

1 Introduction

In recent years, substantial research engineering efforts have been directed toward the fabrication of arbitrarily shaped 3-D microstructures because of their broad field of applications in, for instance, the micro-optics, nanotechnology, and semiconductor industries.¹–⁶

These 3-D microstructures are generally fabricated either using multistep photolithography with standard binary masks (see for example Ref. 1), by grayscale photolithography with coded gray-tone masks,⁷ or by direct writing (laser beam,⁸ x-ray,⁹ electron beam, or ion beam).¹⁰ The first and second methods have the advantage of low-cost mass production. Mask fabrication is, however, a lengthy process and expensive for prototype production. For example, the cost of a set of masks for producing a chip can exceed $2 million.¹¹ Moreover, in most cases, masks present little design flexibility, i.e., once a design has been made on a mask, it cannot be changed unless a new set of masks is made. Direct writing, on the other hand, is a much more rapid technique for producing small numbers of prototype 3-D microstructures: a modulated laser spot (for example) exposes a pattern directly in a thin photosensitive layer, producing high quality 2-D and 3-D structures after development.¹² Its main disadvantage is its very slow write speed compared to mask-based lithography, because of the tradeoff between resolution and write time: for high-resolution structures the writing-spot diameter must be small, but this results in only small areas being written at a time, so the overall process is slow. Once a master structure has been made, replication techniques can in some cases be used to mass produce relief structures quickly and cheaply. The prototyping remains, however, slow and hence expensive.

Recently new photolithographic techniques based on real-time reconfigurable masks have been proposed. This real-time mask is usually either a liquid crystal display (LCD) or a digital or tilting micromirror device used as a spatial light modulator (SLM) to control system exposure.¹³ The displayed images can be modified on the SLM in real time. These techniques combine the advantages of a programmable digital LCD or digital micromirror device (DMD) system and a photolithographic projection system. Conventional photolithography is greatly simplified, as a single LCD or DMD mask can replace a set of conventional masks. For example, for fabricating 3-D structures, the alignment between different levels of masks in conventional photolithography is no longer necessary if the LCD or DMD mask is used, because the SLM can display successively different images corresponding to different masks without moving the substrate or the SLM, only the images displayed on the SLM change. The 3-D
microstructure design can be adjusted rapidly because no mask fabrication is required, only different data files need to be generated and then displayed on the SLM.

The standard SLM-based photoplotters present several other important advantages. First, production time is shorter than with conventional direct writing techniques for fabricating 3-D microstructures, because many (up to a million or more) modulated beams, corresponding to SLM pixels, simultaneously illuminate the photoresist. Second, because of this increased speed, short custom production runs can be performed for low cost. Finally, this technique can also constitute a powerful tool for fabricating photolithographic masks compared to the generally slower and more expensive single write-beam techniques, particularly in the case of low to medium resolution masks.\(^{11-13}\)

Unfortunately, putting this basic idea to practical use is often more difficult and expensive than it at first seems. To obtain a competitive performance in terms of structure resolution and plot area, reduction optics of high quality and low distortion are required, along with a high uniformity SLM illumination system and high resolution (nanometer precision) \(xy\) tables to hold and position the photoresist-coated substrate. This often results in practice in a relatively expensive machine.

We present here a prototype photoplotter based on a standard photolithographic stepper, where we replace the reticle with an LCD screen to directly produce the reduced pattern on the photoresist. Such steppers are readily available or already widely installed and highly optimized for high resolution and large area photoplotting. Compared to SLM-based photoplotters that are built from scratch, our system has the advantages of an existing high-performance professional lithographic stepper: reduction lens, autofocus, high precision \(xy\) tables, etc. The other major advantage is that the LCD module is designed as a “drop-in” reticle, so that the system can be converted from stepper to direct-write photoplotter and back again very simply and quickly. This opens the possibility of using the system in photoplotter mode to write conventional photomasks, and then using these masks in stepper mode for longer production runs once the prototype design has been perfected. The overall system is thus extremely versatile and particularly adapted to prototyping or custom production work with microstructures, with feature sizes in the 1-\(\mu\)m range for which there are many applications.

2 Photoplotter Design

2.1 Basic Principle

The prototype is essentially built of an SLM, projection lens, and an \(xy\) table. The basic photoplotter schema is shown in Fig. 1. A light source is used to illuminate an SLM and the pattern displayed on the SLM is imaged onto the substrate by the projection lens. The data content of a typical plot is usually much greater than the number of pixels on an SLM, so a block plotting technique is used. Once the first SLM pattern has been exposed, the illumination is blanked out, the \(xy\) table on which the substrate is placed moves, the next image block is sent to the SLM, the illumination system unblanked, and so on until all of the data have been plotted.

\[\text{Fig. 1 Versatile photoplotter prototype basic principle. Illumination system illuminates the LCD. The LCD is imaged onto a photore sist-coated substrate with a reduction factor lens.}\]

2.2 Overall System Design

The prototype we have built is based on a GCA 4800DSW photorepeater with a five-times reduction factor lens. Although more modern photolithographic steppers and photorepeaters offer a higher performance, as described later, several features of this photorepeater (and also of similar photorepeaters) make it particularly adapted to use with currently available, low-cost standard LCD SLMs. As is also shown later, steppers/photorepeaters of this generation have a very respectable performance even by today's standards and especially a high performance/cost ratio. The GCA photorepeater converted into the prototype photoplotter is shown in Fig. 2. Figure 3 shows the drop-in SLM module at the top of the reduction column. The advantages and features of the components of this prototype are described in detail next.

2.3 Illumination System

The illumination system is an important component of all photolithographic systems. Here the light source is a mercury arc lamp giving a power of 7.5 mW/cm\(^2\) over 10 \(\times\) 10-cm\(^2\) reticle area with a high degree of uniformity: \(\pm 1\%\) across the reticle area. At present, only a small part of this area is used because of the small size of currently available SLMs with the required pixel size. As display technology progresses, this large area and uniformity will allow us to use a larger, higher pixel count screen than our current screen without having to change the illumination system. The fact that the screen only uses the central reticle
area also improves the resolution performance slightly, since the performance of the projection lens is greater near the center.

We chose an illumination wavelength of 436 nm (g-line) to avoid absorption in the SLM, and because of the availability of high sensitivity photoresists for both binary and multilevel work at this wavelength. The use of wavelengths below about 400 nm is problematic when standard LCD are used, as the contrast drops (both polarizers and modulator) and the LC molecules can be damaged by high optical powers at such wavelengths.

The optical power of the illumination remains constant throughout the plots. Mercury arc lamps cannot be directly modulated, so an electromechanical shutter is used to illuminate the LCD screen only when a valid image is present.

2.4 Liquid Crystal Display Screen

Driven by the display industry, the characteristics of liquid crystals and LCDs have been investigated extensively during the last few decades. The technologies for manufacturing LCDs are so developed that high-performance and high-resolution LCD panels have become standard “off-the-shelf” inexpensive components that can be used as photomasks for real-time photolithography.

The LCD used in our system is a 600x800 pixel liquid crystal spatial light modulator (SLM) from TL Electronic GmbH (Munich, Germany). It is positioned using a specially adapted mount on the top of the reduction column with the required polarizers, such that the LC plane is in the same optical plane as a standard photolithographic reticle. The pixel pitch is 33 μm square with a rectangular transparent area in the center (more details in Sec. 2.8). The LCD is a monochrome device with gray-level bitmap images coded on 8 bits, theoretically giving up to 256 gray levels.

The manufacturer’s data give SLM response times at 25°C of 12 ms for an ON transition and 30 ms for an OFF transition. Different plot techniques are used for 2-D and 3-D structure. In practice in our system, the refresh rate of the SLM limits the maximum possible plot rate only for the direct write of 3D structures. Full details on these techniques and the limitation of plot rate for each technique are given in Secs. 2.8 and 3.3. For our current work, the plot rate is not a critical parameter for this prototype because of the plot rate advantage gained by the use of nearly one million modulated parallel beams, corresponding to the SLM pixels.

A PC graphics card is connected to the PC monitor and the SLM via a replicator, which allows us to simultaneously display images on the photoplotter SLM and to verify them visually on the ordinary PC monitor.

2.5 Reduction Column

The highly optimized photoreduction lens is the core component of the projection system and its imaging quality directly influences the plotted characteristics of the patterns in the photoresist. Our reduction lens is a Zeiss 5× with a numerical aperture of 0.30, giving a 1-μm resolution, over a potential 16×16 mm² writing field with a total distortion.

The SLM is positioned using a specially adapted mount on the top of the reduction column, such that the LC plane is in the same optical plane as a standard photolithographic reticle.
of less than 80 nm across this field. This lens can therefore easily resolve the central transparent area as well as the opaque interpixel space of the separate SLM pixels, whose exposed area at the photoresist level is approximately 5 \times 3 \mu m^2 on a 6.6-\mu m^2 pitch.

2.6 \textit{xy Tables}

The substrate is held on an \textit{xy} table with a vacuum chuck. The \textit{xy} tables included in the GCA photorepeater cover a total range of 15 \times 15 cm^2 using DC motors. To obtain the required accuracy, the tables incorporate electromagnetic tips, the DC motors giving the long range movement and voice coil motors giving the short range precise positioning using feedback from a laser-based interferometric position detection system with a manufacturer-specified theoretical resolution of 40 nm.

2.7 \textit{Electronics and Software}

Our prototype is based on a GCA stepper built using mainly 1990s technology. As indicated in the previous section, the optics, mechanics, and electronics still offer a very acceptable, performance for our applications, so there was no need to change them. On the other hand, the original software and the computer hardware (PDP11) was obsolete. We therefore chose to completely change the plotting module of the photoplotter software, but to keep the same electronics interface because we needed the original control electronics. We used a standard PC, with a card from H&L Associates (Ottawa, Canada)\textsuperscript{15} added to directly control the stepper electronics. We chose to work on Linux operating system because of the ease of manipulation of large amounts of memory (plot data) and the ease of access to low-level graphics routines bypassing the graphical user interface. A driver to make the interface between the kernel and the stepper electronics was designed using WinDriver Linux from KRFTech (San Jose, California).\textsuperscript{16}

The new software to control and synchronize the image display on the SLM, the \textit{xy} table, the position detection, the autofocus, and the shutter was written by ENST in collaboration with MIVA Technologies GmbH (Schönaich, Germany).\textsuperscript{17} It is important that the photoplotter accepts the different file formats used in the photoplotting industries in general. Since the SLM is pixelized, the internal data representation is fundamentally bitmap, however, software has been written to enable the photoplotter to accept vectorial image formats like Gerber, GDSII, and DXF. The photoplotter converts these formats into a compact internal run length encoded (RLE) format and places the image strip by strip into the PC RAM as a pixmap. This is then used by the image display software. As a result, the photoplotter can plot binary and gray-level images with bitmap formats (PGM, TIF, PCX, BMP, etc.) or binary plot data in vector formats (RLE directly, Gerber, DXF, GDSII, PostScript, etc., after translation).

2.8 \textit{Image Display}

The limited number of pixels and the less than 100\% fill factor of the SLM, along with the requirement that the same hardware should be used to plot large binary 2-D structures and multilevel 3-D structures, have led to some more sophisticated plotting techniques being developed. The corresponding software was written to correctly cut and display the image to be plotted into screen-sized blocks to be sent to the SLM. The basic principles and reasons for these techniques, which we term block plotting, super-resolution, step-and-repeat, and multilevel plot, are now described briefly.

2.8.1 \textit{Block plotting technique}

If the plot size is much greater than one SLM size, it cannot be plotted with one SLM exposure. It has to be plotted by a block-by-block technique. We extract and plot a part of the overall plot data, called a block image, whose size equals the SLM size. The stages are then moved to the next block position, a new image displayed, and so on until the whole pattern has been exposed (see Fig. 4). In this way the total plot size is limited only by the \textit{xy} table range: 15 \times 15 cm^2 rather than the SLM size.

2.8.2 \textit{Super-resolution technique}

Due to the less than 100\% fill factor of SLM pixels and the high resolution of the reduction lens, the surface etched in the photoresist is not flat: the opaque interpixel gap (corresponding to insulating tracks, transistors for the LCD active matrix, etc.,) is unexposed during the illumination. After development, this area is etched in the photoresist while the transparent pixel center, if exposed sufficiently (see Sec. 2.9), is etched down to the substrate. Figure 5 shows such a view of a part of the SLM pixel array exposed in the photoresist.
To resolve this unexposed interpixel area problem, we have developed a so-called super-resolution technique. Data are plotted by displaying several successive images onto the SLM and performing very small translations of the $xy$ tables, by distances that are a fraction (e.g., 1/6th) of the pixel pitch, between each exposure. This effectively fills in the unexposed areas by overlapping the active areas of the different images sent to the SLM. This super-resolution (SR) is performed in both the $x$ and $y$ directions. In general, for both binary and multilevel plots, we use a factor 6 super-resolution in both directions, giving 36 successive exposures. This is a good experimental compromise between plot rate and the elimination of the “staircase” pixelization effect on diagonal or curved plot patterns. This factor 6 super-resolution is also efficient to produce the desired smoothing effect for 3-D structures.\(^{18}\) Once calibrated it becomes possible to “sculpt” photoresist almost at will to fabricate a very wide variety of 3-D shapes (see Sec. 3.3).

Including all of these techniques, the overall architecture of the control software is as described next. Figure 4 indicates schematically how the different pixels of the plot data are assembled into data images sent to the SLM.

- Initialization: read plot data file (see Sec. 2.7 for formats), convert to bitmap, and calculate the number of image blocks.
- Image block loop ($\alpha$, $\beta$, $\gamma$, …):
  - Super-resolution loop (A, B, C, …)
    - Move $xy$ tables to correct position determined by image block and SR indices.
    - Assemble image to be sent to SLM screen by selecting pixels from the plot data bitmap determined by image block and super-resolution indicated in Fig. 4.
    - Send image to SLM, open shutter, expose each gray level for required time based on photoresist calibration LUT.
  - Close super-resolution loop.
- Close image block loop.

### 2.8.3 Step and repeat

To reduce plot data file size, the software also allows for any image to be repeated using a step-and-repeat technique: the pattern is plotted, the stages move, and the same pattern is replotted alongside on a regular matrix. This feature is particularly useful for plotting structures such as lenslet arrays or Fourier plane computer-generated holograms.

### 2.8.4 Multilevel plot

Etching 3-D data with several different etch depths is done by exposing the photoresist for different lengths of time, the deeper levels being exposed longer than the more superficial levels. The substrate remains fixed during these successive exposures. This type of multilevel plot could also be performed using the gray levels of the SLM: the lower the gray level in the data image (closer to 0 level), the darker the SLM pixel and the less exposed in the photoresist. However, with many SLMs and in particular with the SLM we use, the gray levels are designed for image display and therefore adapted to the human eye, so they are difficult to control photometrically. As a result, we decided to work with exposure time and successive binary images that are exposed one after the other for different exposure times.

To simplify and increase the speed of the operation, rather than separating the graylevel image into a series of binary images, only one gray-level bitmap (coded on 8 bits, so giving up to 256 gray levels) is sent to the SLM. The video palette changing routines of the video card are used to control how these images appear as full contrast black and white images on the SLM. Changing the palette is a much simpler and quicker operation than rewriting a whole SLM image. The appearance of the image displayed on the SLM changes in one video cycle, so blanking with the mechanical shutter between the different binary versions of the gray-level image is not required. This produces a significant increase in overall plot rate: the limiting factor is the relatively fast SLM refresh rate and not that of the slower mechanical shutter. The exposure dose for each level is determined from a look-up table (LUT), which is obtained from a calibration of the photoresist’s photochemical response. Because of the pixel overlap produced by the SR technique, different LUT calibrations are required for the different SR factors. Generally the higher the SR factor, the greater the overlap and hence the shorter the required exposure time for each individual image gray level. For large SR factors, the exposure time for each individual gray level corresponds to the SLM maximum refresh rate (~20 ms/image), effectively limiting the overall plot rate in such cases.

#### 2.9 Photoresist

In our experiments, we use the SHIPLEY S1800 photoresist series in layers ranging from a few hundred nanometers to a few microns. This resist is most sensitive at wavelengths near 436 nm, but can be used between 350 and 450 nm. After exposure, the resist is developed for 2 min, using the Microposit 303 developer diluted 1:12 with deionized water. This developer and dilution were chosen to give a relatively linear etch depth as a function of exposure characteristic simplifying the plotting of 3-D structures.\(^{18}\) Once
suitable development parameters (dilution and development time) have been determined, they are fixed. For a 1-μm photoresist layer and binary plots, we have empirically determined an exposure time of 400 ms without SR and 200 ms with a factor 6 SR. The optimal exposure time naturally varies with resist layer thickness and SR factor.

3 Experimental Results

The following experimental results were all obtained with a 1-μm layer of SU800 series photoresist using the development conditions described before. Only the exposure time was varied to adapt it to the requirements of the different plot techniques used: binary plots, 3-D structures, and with and without the super-resolution technique.

3.1 System Alignment

When setting up a stepper, several alignment steps have to be performed to obtain the specified performance: focus, parallelism of the reticle, and xy table planes (out-of-plane angle), alignment of reticle axes with the xy table translation axes (in-plane angle), and xy table step distances. We first set up the photoplotter as a conventional stepper and followed the standard manufacturer’s alignment procedure with a test reticle. We then adapted the standard reticle-based alignment procedure for use with our reconfigurable SLM reticle, making a series of test exposures as described later. All these alignment steps were performed without the SR technique to better judge focus and alignment between successive image blocks. The test image used was either an all-white image (all SLM pixels in the “on” state) or a specifically designed test pattern.

The first procedure is the adjustment of the autofocus system, which is adjusted manually as for a test mask reticle, with the focus micrometer until the shape of the SLM pixels is as clear as possible in the centre of the optical field of view in the test plots. This effectively ensures that the SLM LC layer is in the object plane of the projection lens, and the image plane coincides with the reference plane of the stepper system’s built-in autofocus system. This alignment is set once, after which the autofocus system automatically compensates for different substrate thicknesses and planarity defects. The typical depth of field of this type of stepper is around 2.5 μm.

The out-of-plane angle alignment is also adjusted once. It consists of placing various calibrated thickness metal shims in the SLM mount and performing test exposures until well-focused SLM pixels are obtained simultaneously for all corners of the SLM.

The in-plane angle between the stages and the SLM was adjusted next. It needs to be verified every time the prototype changes from stepper mode to photoplotter mode. However, once the SLM is aligned and fixed in its mount, this is a very quick procedure, as alignment marks can be included in the SLM mount, which then can be aligned like any new reticle. The initial alignment is performed by exposing one all-white SLM pattern, translating the stages in the x direction by a distance equal to the SLM size at the substrate level, and exposing another all-white pattern. This procedure is then repeated in the y direction. When the in-plane angle is incorrectly adjusted, a gap appears between the pixels of the successively exposed SLM patterns (see Fig. 7). When the angles and the translation distances are correctly adjusted, the join between different etched SLM blocks is no longer visible. Figure 8 indicates an angular alignment better than 1/3 pixel (less than 1 μm) over a field of 800 pixels. More sophisticated, vernier-based techniques would allow a further improvement in alignment precision, but for our present applications the precision of these simple visual alignments is sufficient.

3.2 Binary Direct Write

Binary direct write consists of sending binary images to the SLM and exposing for durations such that areas of photoresist corresponding to an illuminated SLM pixel are removed completely down to the substrate when developed. Figures 9 and 10 show the effectiveness of the photoplotter in binary direct writing. As mentioned before, the SR tech-
technique is used to fill in the gaps corresponding to the opaque "dead zone" between the SLM pixels. Figure 11 shows the resulting pattern in the photoresist. The SR technique, however, produces a problem, always present when the address grid is finer than the writing spot size: the written structures are wider than desired. The net effect is to produce what is referred to in the binary image processing field as an image "dilation." The solution is to precompensate the plot data (an image "erosion"), reducing the structure size by the required amount.

The number of pixels to be eroded depends on the SLM pixel size and the SR factor. If $S$ is the pixel size, $P$ the pixel pitch, $SR$ the SR factor, and $A = P/\text{SR}$ the addressing grid pitch, $N$ white pixels on the plot data should lead to an $N \times A$ etched distance in the photoresist. With the SR principle $N$, white pixels on the image lead to an $N \times A + (S - A)$ etched distance. The difference between the desired and obtained distance is therefore $S - A$, which means an erosion of $(S - A)/A$ pixels is required. As the pixel number has to be an integer, we take the nearest integer as the number of eroded pixels. Pictures of binary lines etched in photoresist without erosion and with erosion are shown in Figs. 12(a) and 12(b), demonstrating the effectiveness of the technique.

### 3.3 Multilevel Direct Write

Until recently, complex 3-D structures have generally been made with expensive and time-consuming multilayer photolithographic techniques, or slow single beam direct-write techniques. The use of gray-level SLMs, and more especially, time multiplexing techniques, open the possibility to write multilevel structures into photoresist in a single exposure step.

In our experiments, 3-D structures were etched using the...
techniques described in Sec. 2.8. In practice, eight gray levels are usually sufficient since, for a fixed resist thickness (1 μm) and with our development parameters (see Sec. 2.9), when used with large SR factors, the write pixels overlap because the width of the writing pixel covers several address grid points, and hence an overlap of light from neighboring points occurs. This produces a smoothing effect, which leads to practically continuous relief profiles such as those shown in Fig. 13. Obviously, the higher the number of levels, the shorter the time each individual binary image present on the SLM must be exposed.

Tests were also made successfully at 16 levels. However, in this case, the minimum required display duration for the individual binary images making up the full gray-level plot was under 20 ms, which is the practical limit for the nematic-based LCDs used here (see Sec. 2.4). Tests with delays down to 10 ms have produced an unacceptable loss in contrast and some partial SLM image loss. More levels could be plotted by either using a faster SLM (see Sec. 4.1) or by reducing the light power. The second technique would, however, have the drawback of reducing the overall plot rate.

A wide range of 3-D structures including cones, pyramids and circular, elliptical, spherical or aspherical micro lenses have been realized with the multilevel direct writing technique. Figure 14 shows an example of the sort of structures that can be written by our multilevel direct-write technique. Figure 15 demonstrates the level of control that has already been achieved: eight roughly evenly spaced levels are clearly visible, indicating a vertical control of approximately ±50 nm into the 1-μm photoresist layer. Through use of suitably designed calibration look-up tables, we were also able to write binary and multilevel structures side by side on the same substrate in the same exposure step.

3.4 Resolution

The minimum feature size of plotted structures is determined by the lens reduction factor and the SLM pixel size.
tions on photoplotters based on SLM reticles for photolithographic steppers and ways of overcoming these limitations.

4.1 Plot Rate

The plot rate can be improved in three major ways. The first and simplest is to use more recent LCDs with higher pixel counts: compatible 1024×768 and 1280×1024 pixel LCDs are now commercially available, and even higher HDTV-driven pixel counts are now appearing or planned. The maximum refresh rates of these new microdisplays are at least as high as our current SLM, so factor three to four increases in plot rate are immediately available for very minor modifications to the system. In addition, as LCD microdisplay technology progresses in the future, plot speed will be increased accordingly; the only change required in the photoplotter is a modified LCD mount, and when necessary, a more recent video card.

The second way to improve plot rate also concerns the SLM. The current plot rate is limited by the maximum display rate on the LCD. By using recent, alternative, commercially available microdisplay technologies such as liquid crystal on silicon (LCOS), ferroelectric liquid crystal (FLC), and Texas Instrument’s digital micromirror device (DMD), significantly higher refresh rates could be achieved. LCOS is a reflective technology where liquid crystals are present over the surface of a silicon chip coated with a reflective aluminized layer. The opaque interpixel space is greatly reduced, because the control circuit is in the silicon backplane, thus increasing optical efficiency. The close link between drive electronics and each pixel also greatly simplifies image update, often resulting in significantly improved display refresh rates. FLC devices use liquid crystal substances that have chiral molecules in a smectic C arrangement and allow microsecond switching times—often more than an order of magnitude faster than nematic LC-based devices. DMD technology consists of hundreds of thousands of moving micromirrors that are controlled by underlying CMOS electronics. Such devices can reach frame rates of 9800 Hz.

The practical use of such technologies is, however, not as straightforward as using higher pixel count transmissive LCDs. These new technologies are reflective, so a major redesign of the display illumination system would be required. Another practical difficulty concerns getting the plot data onto the devices quickly enough to be able to access such high refresh rates. Standard video cards are designed

![Fig. 13 A 3-D view of continuous relief diffractive structure obtained by direct write. The smooth surface is obtained thanks to a factor six super-resolution.](image1)

![Fig. 14 A 2-D interferometric microscope plot of different shapes simultaneously directly written into photoresist. The different gray levels code different etch depths.](image2)
for the human eye, so they generally have maximum refresh rates in the 100-Hz range. Custom-designed drive electronics are now appearing for some devices, but they are very significantly more expensive. Currently, the best compromise appears to be to use mass market PC video cards and drivers, which allow maximum refresh rates in the 100-Hz range. By using the three color channels (RGB) to each display monochrome plot data, the effective refresh rate can be tripled.

The other practical difficulty is that if such refresh rates can be achieved, plot rate will then be limited by available light power. The reflective technologies help in this direction, as they generally have higher fill factors and hence optical efficiency. However, with our current system, refresh rates in excess of 100 Hz (corresponding to a 10-ms display time for a given etch depth level in a multilevel plot) would again require an illumination system redesign with a higher power light source, and perhaps a different light source such as a pulsed laser, adding considerable complexity and expense.

The third, linked, technique for increasing plot rate is to use “on-the-fly” plotting, in which the $xy$ tables move continuously. This would remove the need to wait for the tables to reach the desired position and stabilize before exposing each SLM image. In this way, the full refresh rate of the SLM could be used at all times, significantly increasing the overall plot rate. The application of on-the-fly plotting, however, would entail a major modification of the current system, since a high power, short duration, pulsed source would be required along with redesigned $xy$ table drive electronics and software to be sure of a clearly exposed image. Problems such as potential SLM damage due to the high optical pulse power would also have to be addressed. These factors would make the reuse of existing steppers much more complicated: a complete system redesign would be required, greatly increasing costs and losing the advantages of the approach proposed here.

### 4.2 Resolution

As indicated before, the smallest feature size of plotted structures ($3 \times 5 \, \mu\text{m}^2$ structures with $1 \, \mu\text{m}$ gaps) is limited by the lens reduction factor and the SLM pixel size. The resolution can be improved simply in two ways: using an SLM with smaller pixels and using a lens with a greater reduction factor.

As SLM pixel count has increased in recent devices, the pixel size has tended to decrease, so simply replacing the existing SLM with a more recent one would improve both the plot rate and resolution. Typical current transmissive LCD microdisplays of the type mentioned in Sec. 4.1 have pixel pitches of 15 to 20 $\mu\text{m}$ with active areas of around 10 to 15 $\mu\text{m}$, giving roughly a factor of 2 gain in minimum feature size. Reflective LCOS or DMD generally have significantly smaller pixels (less than 10 $\mu\text{m}$ for the most recent LCOS devices, giving improved resolution at the expense of a redesigned illumination system).

Changing the lens reduction factor is also a relatively simple way to increase resolution, as 10:1 and 20:1 reduction factor lenses already exist for the type of stepper used as the basis for our photoplotter. Thus by combining smaller SLM pixels and available reduction factor lenses, it is relatively simple to reach resolutions limited by the resolving capabilities of the reduction lens—roughly 1 $\mu\text{m}$ for the g-line steppers compatible with LCD SLMs.

Going to feature sizes smaller than this would require the use of lenses optimized for shorter UV wavelengths (for

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**Fig. 15** A 2-D slice through a multilevel staircase diffraction grating obtained by direct write into photoresist showing that eight roughly evenly spaced levels are clearly visible, indicating a vertical control of approximately ±50 nm into the 1-$\mu\text{m}$ photoresist layer.

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**Fig. 16** By using the SR technique, it is possible to use a much smaller address grid (here 1.1 $\mu\text{m}$) and hence leave gaps between “written” structures of down to 1 $\mu\text{m}$. On this figure, horizontal etched 8-$\mu\text{m}$ width lines with 2-$\mu\text{m}$ unetched gaps, and vertical etched 9-$\mu\text{m}$ width lines with 1-$\mu\text{m}$ unetched gaps are plotted.
example, i-line). This, however, is problematic with standard LCD devices, since LC molecules can be damaged by UV light and high quality compatible polarizers are more difficult to find at these wavelengths. To be able to use such wavelengths other SLM technologies such as DMD are required, which in turn means the stepper illumination system would have to be redesigned to take account of the reflective display, again losing many of the advantages of the approach proposed here.

5 Conclusion
We show that, by combining a standard transmissive liquid crystal microdisplay with an existing g-line photolithographic stepper, a highly versatile direct-write photoplotter can be built simply and relatively cheaply. The resulting system has a respectable performance as a photoplotter in terms of plot rate, cost, and resolution with feature sizes in the 1-μm range. In addition, thanks to the drop-in nature of the microdisplay module, the photoplotter can be simply converted to a standard stepper in a few minutes. As such, it is particularly adapted for research and development laboratories and custom or short production runs. The same equipment can be used for both binary plots (e.g., for chrome photomask fabrication) and for the production of 3-D microstructures by gray-level, direct write into photore sist. The only change between these two operating modes is the control software, indeed, the simultaneous plotting of binary and multilevel data on the same substrate has been also demonstrated. The present performance can be very easily improved in both resolution and plot rate, thanks to ongoing improvements in LCD technology. We have indicated the current limitations on the approach and proposed ways of overcoming them.

Our current work in the field is centered on improving the resolution performance in two separate ways. The first involves a new prototype based on the same principle and software, but with a stronger reduction factor lens and a reflective micromirror device in place of the LCD microdisplay to enable a lower wavelength UV source to be used.

The second resolution-enhancing technique under investigation concerns the application of proximity correction techniques on the plot data. The surface relief obtained with the photoplotter can be modeled as the convolution of the point-spread function (PSF) of the optical instrument with the desired relief profile, which would have been obtained in the absence of this smoothing effect. This technique is well known in single-beam direct-write applications, and several techniques exist for precompensating the plot data to correct for this smoothing, and hence obtain plots closer to the desired profile. Adaptation of these techniques to our photoplotting technique with our non-standard write beam profiles and individually variable power levels is already showing promising results and will be presented in future work.

Acknowledgments
This research was mainly funded by EC through the Craft Drawmap project (BRST-CT98-5524). We also acknowledge the contribution of PM Professional Maintenance in setting the stepper, and Carole Moussu and Andreas Weber in the initial stages of this work.

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