8. Zone-Plate-Array Lithography (ZPAL): Lithographic Performance

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In a direct-write system such as ZPAL, the major figures-of-merit are resolution and contrast. The resolution is quantified by the following equation:

\[ w_{\text{min}} = \frac{k_1 \lambda}{NA} \]  

where \( w_{\text{min}} \) is the minimum feature size, \( NA \) is the numerical aperture of the zone plate, \( \lambda \) is the exposure wavelength and \( k_1 \) is a proportionality factor that, in effect, indicates how close to theoretical limits one operates.

In order to reduce the minimum feature size, one can increase the NA of the zone plates. The results presented in figure 1, using NA=0.9, are the highest quality lithographic patterns ever produced with ZPAL, showing good fidelity, low edge roughness, and the ability to pattern very dense features down to the minimum spot size. It is worth noting that since all exposed pixels received the same dose, proximity effects are minimal in the exposures.

![Figure 1: Scanning electron micrographs of patterns exposed with our continuous-scan 0.9 NA UV-ZPAL system operating at \( \lambda \) = 400nm. (a) Dense nested Ls, (b) 2D photonic bandgap structures with 500 nm period, (c) 2D photonic bandgap structures with 360 nm period.](image-url)
The ability to pattern curved structures and non-manhattan geometries is important for a number of applications, and our ZPAL system, by employing sub-pixel stepping, can satisfy these needs, as illustrated in figure 2.

![Figure 2: Scanning electron micrographs of patterns exposed with our continuous-scan 0.9 NA UV-ZPAL system operating at \( \lambda = 400 \text{nm} \). Sub-pixel stepping enables patterning of curved structures with smooth edges. (a) waveguides with ring resonators, (b) one quadrant of a zone plate.](image)

The minimum feature size can be further reduced by reducing \( k_1 \). This corresponds to decreasing the size of the address grid, as illustrated in figure 3.

![Figure 3: \( k_1 \) in ZPAL. Decreasing \( k_1 \) decreases the minimum feature size. This is done by decreasing the address grid of the system i.e. the scan lines of the focused spot are brought closer together as shown. At some point, the final image will not have sufficient contrast to be resolved by the photoresist. That point determines the limiting \( k_1 \) factor.](image)
Figure 4 shows a set of scanning electron micrographs of dense lines and spaces with varying $k_1$'s, from 0.56 to 0.38. We are currently exploring the limits of how much lower we can go, since even at $k_1 = 0.38$ the quality of the patterning remains remarkable. Systematic characterization of lithographic exposures has also allowed us to determine that the process latitude for our current system is around 13% (even when operating at $k_1 = 0.38$). We believe the superior lithographic performance of ZPAL is connected with the fact that there is no phase relationship between sequentially exposed spots (i.e., incoherent imaging).

**Figure 4:** Exploring the limits of $k_1$ with ZPAL. High-numerical-aperture zone plates (0.85 and 0.9) can operate at low $k_1$ factors (below 0.4). Sub-70 nm patterning should be possible, by operating at the demonstrated $k_1=0.39$, with 0.9NA zone plates and $\lambda = 157\text{nm}$.

Image contrast is an important lithographic-figure-of-merit. This is particularly important since phase zone plates have higher (odd) diffraction orders which contribute to the background. Here, we show that large area patterning is indeed possible with zone plates, even without order-sorting apertures, and at very high numerical apertures.

For evaluating contrast, it is sufficient to pattern full fields at the maximum resolution. Figure 5 demonstrates that full fields of dense lines and spaces can be written with high-NA zone plates. The top of the figure provides a schematic of ZPAL (without the micromechanics) illustrating the concept of parallel writing by stitching multiple fields. The bottom of the figure contains an experimental result in which we exposed fields of $125\mu\text{m} \times 125\mu\text{m}$ (currently the scanning limit of our stage) with a 0.9 NA zone plate operating at $\lambda=400\text{nm}$ and a focal length of 40 $\mu\text{m}$. A field of $125\mu\text{m} \times 125\mu\text{m}$ corresponds to the area under a 0.85 NA zone plate, as indicated in the figure. The exposed pattern consists of 1:1 dense lines and spaces with a period of 440nm. The zoomed in scanning-electron micrograph of the bottom-right of figure 5 provides a clear view of what the pattern looks like, namely a 440nm-period dense 1:1 grating.

In summary, our results provide hard evidence that high-numerical-aperture zone plates are capable of providing sufficient contrast for state-of-the-art lithography. Although multiple diffracted orders exist, the background exposure that they produce is not deleterious. Moreover, the background can be further reduced by the utilization of order-sorting apertures.
Figure 5: Top: Schematic of the ZPAL system without the micromechanics. Large-area patterns are created by stitching adjacent fields, with a field defined as the square area located underneath any given zone plate. Bottom-left: Proof that full-field patterning is possible with ZPAL despite the existence of multiple orders. A dense 1:1, 440nm-period grating was exposed (with 400nm wavelength) covering the area of a 0.85 NA zone plate. Note that the inclined periodicity (~3μm period) observed in the left scanning-electron micrograph is the result of a moiré effect (resulting from the beating of the periodic sampling of the SEM with which the picture was acquired and the periodicity of the exposed grating. Bottom-right: Zoomed in SEM of the top-right corner of the large area grating.