Analysis of OPC Features in Binary Masks at 193nm

Konstantinos Adam, Andrew R. Neureuther
EECS Department, University of California at Berkeley
Berkeley, CA 94720

email: kadam@eecs.berkeley.edu, neureuth@eecs.berkeley.edu

Keywords: Optical Proximity Correction, OPC, Scatter Bars, Serifs, Line-End Shortening, LES, Simulation

Abstract

The effectiveness of OPC features in binary masks is characterized using rigorous 3D electromagnetic simulation (TEMPEST) and linking of the transmitted fields to SPLAT for the aerial image calculation. Scatter bars (SB) and OPC serifs are treated separately. At 193nm illumination wavelength the correction in the aerial image CD at best focus and at out-of-focus locations of 130nm isolated lines is examined in the presence of a single pair of scatter bars. The LES_{aerial} (line-end shortening) of the aerial image is found, when placing square OPC features near the corners of the line. Data is provided on the dependence between the size and placement of the OPC scatter bars or serifs and the magnitude of the CD_{aerial} and LES_{aerial} corrections, and general rules of thumb regarding their design process are given. The necessity of rigorous 3D electromagnetic simulations (TEMPEST) as compared to simulations using a thin mask approximation (SPLAT) is also assessed in each case and found to be of limited concern for binary masks.

1. Introduction

Image quality issues in optical projection printing can be addressed to some extent through the adjustment or addition of pattern shapes on photomasks. The addition of scatter bars is a good example where the quality of isolated lines through focus can be improved to be more similar to that of dense lines [1], [2]. The quality of corners and line-ends of features can be improved by adding serifs. Quantitatively designing image improvements is difficult, even under scalar imaging assumptions, due to the non-linearities introduced by partial coherence. In addition, the introduction of several new parameters in each dimension to define mask geometries even further compounds the complex interplay of mask properties with optical system properties. Since the mask modifications involve features that are wavelength sized where scalar approximations are questionable, it is important to examine how light propagates through and around small features and if polarization effects occur. The properties of the image recording resist material also play an important role.

We have been using simulation to investigate mask OPC issues ([3], [4]) and in this paper we looked more extensively at scatter bars and OPC serifs for both clear field and dark field masks. Much of the design data presented here has been generated using the scalar approximation (SPLAT, [8]), which assumes that the fields propagate vertically, directly through the mask. We then used rigorous electromagnetic simulation with TEMPEST ([6], [7]) to check for deviations from the simpler scalar model.
The paper begins with a systematic study of scatter bars including the importance of placement in improving through focus behavior and the advantage of adjusting the scatter bar size to achieve the desired CD. Polarization effects of scatter bars are then assessed. In section 3, line-end shortening and the role of OPC shape and placement are examined. We also explored how shape fidelity such as corner rounding and “mouse ear” OPC can be characterized using equivalent area in a perturbational model [5].

2. Scatter Bars

The mask designer has essentially three parameters at hand by which she can optimize the aerial image of an isolated line, namely the size of the scatter bar, the exact location of the scatter bar and the linewidth of the main feature. In this particular study, the targeted feature size is 130nm (1X) and the illumination parameters of the optical system are: \( \lambda = 193\text{nm}, \) Magnification Factor=4, NA=0.7 and partial coherence factor \( \sigma = 0.6, \) unless stated otherwise. Figure 1 depicts the simulated geometry of the isolated line assisted with two symmetrically placed scatter bars. The distance from the center of the line to the center of each scatter bar, denoted as \( d \), is expressed as the sum of one \( \text{CD}_{\text{target}} \) plus \( p \text{CD}_{\text{target}} \). This implies that if the scatter bars are replaced by lines of width equal to \( \text{CD}_{\text{target}} \), then \( p=1 \) corresponds to 1:1 dense lines (\( d=2\text{CD}_{\text{target}} \)).

2.1 Designing the Placement and Size of the Scatter Bars at Best Focus

The placement of the scatter bar has a profound effect on the main feature. This is shown here by aerial image simulations, in which the only thing that varies is the parameter \( p \). The results of these simulations are summarized in Figure 2. Observe that when the scatter bar approaches the main feature beyond \( p=1 \) the CD_{aerial} increases rapidly, until the point that the image of the scatter bar completely merges with that of the main feature. In the opposite direction, when \( p>>1 \) the line behaves as isolated, as one would expect. For intermediate values of \( p \) (1<\( p<3 \)) the placement of the scatter bar controls the CD_{aerial} of the line in a fashion captured in Figure 2(b), where it is obvious that the CD_{aerial} is more sensitive to \( p \) for smaller values of \( \sigma \). This behavior appears to be independent of scatter bar size, as is also shown in Figure 2(b) for \( \text{SB}=55\text{nm and }65\text{nm (1X)} \).

The second design parameter is the size of the scatter bar. The general rule of thumb here is that a larger scatter bar causes a smaller CD_{aerial} of the line for every \( \sigma \) (at best focus), but for larger values of \( \sigma \) the CD_{aerial} becomes progressively insensitive to the scatter bar sizing. This is depicted in Figure 3(a), where we plot the CD_{aerial} vs. SB size for various \( \sigma \). Note that in all these cases the SB is placed at \( p=1 \). The slope is steeper for small \( \sigma \) and flattens out for \( \sigma \geq 0.8 \). The designer needs to take provision not to oversize the SB, otherwise the SB becomes resolvable by the stepper. This fact is depicted in Figure 3(b), where it is shown that the intensity underneath the scatter bar drops linearly when increasing the size of the SB. Increasing values of \( \sigma \) shift the line upward. Figure 3(c) depicts the aerial images at best focus for \( \sigma=0.6, \) \( p=1 \) and various sizes of the SB.
Figure 2. (a) Aerial images at best focus with $\sigma=0.6$, SB=55nm(1X) at various placements of the SB. (b) Aerial image CD at best focus at the 30% intensity level for various $\sigma$ and SB sizes of 55nm(1X) and 65nm(1X).

Figure 3. (a) Aerial image CD at the 30% intensity level vs. scatter bar size at SB position $p=1$, for various $\sigma$ (at best focus). (b) Intensity dip below the SB vs. SB size at SB position $p=1$, for various $\sigma$ (at best focus). (c) Aerial images at best focus with $\sigma=0.6$, $p=1$ for various sizes of the SB.
Next, we are interested in understanding the role of the partial coherence factor \( \sigma \) on the effectiveness of the scatter bar. To this extent, we assume a specific design of SB (placement at \( p=1 \), size of SB=55nm at 1X) and vary \( \sigma \) in the simulations. Figure 4(a) shows aerial images for various \( \sigma \) and Figure 4(b) shows the changes of CD\(_{\text{aerial}}\) vs. \( \sigma \). An important observation here is the fact that the location of the shadow of the SB shifts with \( \sigma \). For large \( \sigma \) it approaches the location of its geometrical shadow. This lateral shift implies that in the case that the two scatter bars are misaligned (not symmetrically positioned around the feature) the main feature will be displaced! Observe in Figure 4(a) that the minimum intensity underneath the main feature is increased when \( \sigma \) is increased and in Figure 4(b) that the CD\(_{\text{aerial}}\) changes significantly with \( \sigma \). For larger \( \sigma \) there is a trade-off between smaller CD\(_{\text{aerial}}\) and reduced contrast.

![Figure 4](image)

**Figure 4.** (a) Aerial images at best focus for \( p=1 \), SB=55nm(1X) for various \( \sigma \). (b) Aerial image CD at the 30% intensity level vs. \( \sigma \) for SB=55nm(1X) at position \( p=1 \) (at best focus).

### 2.2 Out-of-focus Performance of Scatter Bars

The out-of-focus characterization of scatter bars was also performed with SPLAT simulations. The results are shown in Figure 5. The CD\(_{\text{aerial}}\) at the 30% intensity level with \( \sigma=0.6 \) is plotted in Figure 5(a) versus defocus for various placements (different \( p \) values) for SB=55nm(1X). From these plots it is clear that the defocused aerial image is poor when no scatter bars are used, but also that the placements at \( p=1.5 \) and \( p=2 \) do not improve the situation. Once the scatter bars are brought nearer to the feature the CD\(_{\text{aerial}}\) vs. defocus curves flatten out and this is indicative of improved through focus aerial images. The best placement in this situation is for \( p=0.8 \). Sizing the scatter bar when \( p \) is kept constant does not alter the aerial image through focus significantly, as is shown in the CD\(_{\text{aerial}}\) vs. defocus plots of Figure 5(b), where \( p \) is kept constant at 1 and the scatter bar size is increased from 45nm to 75nm in steps of 10nm.

In summary, the design process and verification of performance of scatter bars next to isolated features should proceed as follows: First, according to the illumination conditions (\( \lambda \), NA, \( \sigma \)) we pick the scatter bar size from the design graph of Figure 3(a) that is consistent with the discretization of the mask making tool and results in the required correction of the CD\(_{\text{aerial}}\), making sure that the scatter bar is below the camera resolution and will not print (using Figure 3(b)). Second, from Figure 2(b) we determine the acceptable range of \( p \) so that the CD\(_{\text{aerial}}\) remains close to its minimum for \( \sim p=1 \), say...
0.75<p<1.2. Third, through aerial image simulation we determine the position p (0.75<p<1.2) that shows the best performance through focus. Figure 5(b) gives convincing evidence that the size of the scatter bar does not affect the out-of-focus performance. Any residual difference from the target CD_aerial will have to be corrected by biasing the main feature. (This makes things a bit more complicated, because biasing the feature changes p and iteration may be needed). Finally, the ability to adjust the partial coherence factor $\sigma$ gives us one extra knob to control the CD_aerial, as is apparent from Figure 4(b).

2.3 Polarization Effects of Scatter Bars

The simulations in the above discussion were performed with SPLAT, which is based on the 'vertical propagation model', where the mask is assumed to vertically transmit the incident field. It is of interest to know, how well the above assumptions agree with a rigorous, vector based electromagnetic simulation, such as that in TEMPEST, and also how scatter bars near isolated features behave at different polarizations of the incident light. Figure 6 depicts a sample TEMPEST simulation where p=1 and SB=50nm(1X). The near field amplitude at a zx cut plane is shown in (a) for TE polarized incident light (electric field parallel to the line) and in (b) for TM polarized light (electric field perpendicular to the line). Observe that in the TM case the electromagnetic field underneath the mask corresponds to a travelling diffracted wave, whereas in the TE case the field also exhibits a standing wave pattern along the x-axis. This can be explained as follows: In the TE case there exist induced currents onto the chromium layers, that are aligned with the incident radiation. These currents at the edges of the feature and the scatter bars radiate cylindrical waves which interfere constructively or destructively and result in the peaks and valleys along x that are spaced by ~100nm (i.e. ~$\lambda$/2). In the TM case the induced currents are weaker, because the field is now perpendicular to the line and they cannot redirect energy in the region underneath the mask. This makes the transmitted field to be basically just the incident field in the open areas.

The aerial images for the TE and TM cases are compared for this example simulation in Figure 7, together with the SPLAT simulation. The aerial images when no scatter bars are used are also shown for comparison. Observe that the scatter bars and the main feature appear wider in TM excitation than in TE and narrower with SPLAT simulation. Figure 7(b) depicts the intensity dip underneath the scatter bar for various sizes of scatter bars for the TE, TM and SPLAT cases. This dip is
always larger (smaller intensity) for the TM case and smaller (higher intensity) for the SPLAT case and the TE case falls in between. Observe also that for larger sizes of scatter bars the three cases give even more similar results. For smaller sizes of scatter bars we can use a simple perturbational model, in which the intensity dip is approximated by the square root of the intensity dip of an opaque pin spot. Although there is a difference of up to 10% between the TEMPEST and SPLAT simulations, the general guidelines for the proper design of the scatter bars discussed in paragraphs 2.1 and 2.2 still hold, but a final fine-tuning using the rigorous TEMPEST simulation may be necessary, especially when we want to account for polarization effects.

![Diagram](image.png)

**Figure 6.** Amplitude of the near field for (a) TE polarization - \( E_y \) only and (b) TM polarization - \( E_x \) only. In this example \( p=1 \) and SB=50nm(1X). Note that because of the symmetry the TEMPEST simulation is performed only on the right half of the mask geometry.

![Graph](image.png)

**Figure 7.** (a) Aerial images at best focus without OPC and with a SB=50nm(1X) at \( p=1 \) for TE and TM polarizations. The SPLAT simulation result is also shown. (\( \lambda=193nm, NA=0.7, \sigma=0.6, \text{Mag.}=4X, \text{CD target}=130nm(1X) \)) (b) Intensity dip of the scatter bar for various scatter bar sizes as predicted by SPLAT, TEMPEST (TE and TM polarizations) and a simple perturbational argument, when SB is placed at \( p=1 \).
3. Serifs

3.1 Modeling OPC serifs through simulation

Square serifs are typically introduced at the corners of lines in order to locally correct the aerial image and in an effort to reduce the line-end shortening. In this section we first attempt to model the effect of the size and placement of the OPC serif on the LES_aerial correction of the aerial image. Then, we determine the additional accuracy from rigorous 3D electromagnetic simulation (TEMPEST) in predicting the correction in the LES_aerial introduced by a specific OPC design. To do the latter, we need to compare a number of cases that are simulated with both TEMPEST and SPLAT. In the following, the targeted feature size is 130nm (1X) and the illumination parameters of the optical system are: \( \lambda=193\text{nm} \), Magnification Factor=4, NA=0.7 and partial coherence factor \( \sigma=0.6 \). Since we are interested in the aerial image improvements near the end of the isolated line, no scatter bar OPC is used for linewidth correction and out-of-focus improvement of the aerial image.

Figure 8 depicts four different OPC placements for a clear field (CF) mask: (a) diagonal non-overlapping, (b) 3/4 diagonal overlapping, (c) side and (d) top. Intermediate cases where the OPC is shifted along the diagonal to render different than 3/4 diagonal overlapping or up-down for different side and left-right for different top placements were also simulated. In Figure 9 an example 3/4 diagonal overlapping design is compared with the reference case (no OPC used). The side of the square serif is 65nm (1X) and it is positioned so that the center of the serif is located at the corner of the line. This geometry is simulated with TEMPEST and SPLAT and the contours of the 30% clear field intensity of the aerial images are shown in Figure 9(b). In the same plot the 30% contours for the reference case are also drawn, which again is simulated with TEMPEST and SPLAT. The ideal rectangular image is also shown for comparison. Note that both simulators predict a \(~10\text{nm} \) linewidth bias on each side of the CD_aerial, which is the approximately the same value with that resulting from Figure 2(b) for \( p=5 \) (nearly isolated line) and \( \sigma=0.6 \), but they differ in their line end predictions. The LES_aerial resulting from a TEMPEST simulation is always smaller (i.e. longer line) than that resulting from a SPLAT simulation of the same CF (clear field) geometry. But what is a more meaningful comparison, is rather one between the correction in the LES_aerial from the reference to each OPC case resulting from the TEMPEST and SPLAT simulations of the same CF masks. In the example shown in Figure 9 this correction comes out to be 31nm or 34nm from the SPLAT or TEMPEST simulations respectively.

In Figure 10 the square root of the correction of the LES_aerial is plotted vs. the equivalent size of OPC, where the equivalent size is the square root of the non-overlapping area, for all the different OPC serif sizes and placements that we simulated with TEMPEST and SPLAT, and for both mask polarities (dark field, clear field). For a CF mask the correction in the LES_aerial predicted by TEMPEST is larger by \(~9\% \) than that predicted by SPLAT, for all OPC designs, whereas for a DF mask TEMPEST predicts a smaller LES_aerial correction by \(~6\% \) compared to SPLAT, for all OPC designs. Why this is happening can be explained by invoking the boundary conditions of the electromagnetic field in the vicinity of the serif: The electric field that is parallel to the square serif sides (as is true for good conductors) has to vanish within the chromium, which requires the tangential fields in the neighboring open areas to rapidly vanish as we approach the chromium. This effectively implies that the electromagnetic size of a dark serif (CF mask) is somewhat larger than its geometrical size and that the electromagnetic size of an open serif (DF mask) is somewhat smaller than its geometrical size. Hence a dark serif will actually be responsible for a bigger correction in the LES_aerial (\( \Delta \text{LES}_{aerial,\text{TEMPEST}} > \Delta \text{LES}_{aerial,\text{SPLAT}} \)), whereas a clear serif for a smaller correction (\( \Delta \text{LES}_{aerial,\text{TEMPEST}} < \Delta \text{LES}_{aerial,\text{SPLAT}} \)). The above trend with serif area can be further pursued by using perturbational arguments to relate the size of a small pin-hole with the peak intensity of light that goes through, and also the size of a
small opaque pin-spot with the minimum intensity that appears at its shadow. In that respect, from previously proposed model [5]:

\[ I_{\text{peak PH}} = 8.5 \left( \frac{\text{CD}}{\lambda/\text{NA}} \right)^4 \]

and using perturbational arguments:

\[ I_{\text{dip PS}} = 1 - 2 \sqrt{I_{\text{peak PH}}} \]

For example, the 65nm x 65nm (1X) square opaque pin-spot used in the simulations shown in Figure 9, when simulated by itself only with TEMPEST, results in an intensity dip of 0.64, whereas the intensity dip resulting from the SPLAT simulation is only 0.69. This renders an equivalent electromagnetic size of 69nm x 69nm from TEMPEST or 63.5nm x 63.5nm from SPLAT, i.e., a difference in their side of ~8%, which correlates with the ~9% difference in the effectiveness of this serif when placed near the corners of the isolated line. An open square pin-hole of the same dimensions appears smaller by ~5.5% in TEMPEST than in SPLAT. Therefore, its effectiveness is reduced when it is placed near the corners of an isolated open line (DF mask), and the reduction in the correction of the \( \text{LES}_{\text{aerial}} \) is ~6%, as shown in Figure 10.

Note that in Figure 10 the points that do not fall on the respective straight line correspond to OPC designs where the serif was placed in highly off-diagonal locations, but even in those situations the TEMPEST-SPLAT correction bias is close to the 9% (CF) and 6% (DF) values that we found above. The important result that the graph of Figure 10 conveys is exactly the fact that a rigorous electromagnetic simulation is not necessary in order to predict the correction in the \( \text{LES}_{\text{aerial}} \) that a certain OPC serif design will cause. This can be done with the thin mask approximation approach (SPLAT) just as well, but we do need to account for the 9% (CF), or the 6% (DF) TEMPEST-SPLAT difference. Viewed a little differently, in order to correct for a certain amount of \( \text{LES}_{\text{aerial}} \), we can use SPLAT simulations for the design process, but in the case of a CF mask we have to correct for 9% smaller \( \text{LES}_{\text{aerial}} \) and for the case of a DF mask we have to correct for 6% larger \( \text{LES}_{\text{aerial}} \).

---

**Figure 8.** Different OPC placements for a clear field (CF) mask: (a) diagonal non-overlapping, (b) 3/4 diagonal overlapping, (c) side and (d) top. Note that because of the 2-fold symmetry with respect to the x, y axes only the top right quadrant of the simulation domain is shown.
3.2 Corner Rounding

Here, we consider isolated lines on both clear field and dark field masks with rounded corners. The reason why we examine corner rounding of the mask feature, is because its aerial image behavior with respect to the degree of roundness resembles the OPC serif design, where now the roundness of the corner can be thought of as an anti-serif, as it will be obvious shortly. Figure 11(a) depicts the amplitude of the near field of a reference (not rounded) and a rounded case for a clear field CD=130nm (0.47 λ/NA) Serif size=65nm (0.24 λ/NA) (µm) (µm) (µm) (µm) Figure 9. An example 3/4 diagonal overlapping OPC design is compared with the reference case (no OPC used). (a) The side of the square serif is 65nm (1X) and it is positioned so that the center of the serif is located at the corner of the line. (b) Contours of the 30% clear field intensity of the aerial images from TEMPEST and SPLAT simulations. The ideal rectangular image is also shown for comparison.

Figure 10. Square root of the correction of the LES_{aerial} vs. equivalent size of OPC (the equivalent size is the square root of the non-overlapping area) for all the different OPC serif designs considered, and for both mask polarities (dark field, clear field). The points that do not fall on the respective straight line correspond to OPC designs where the serif was placed in highly off-diagonal locations.

equiv. size of OPC in λ/NA (1X)
mask and Figure 11(b) for a dark field mask. In both (a) and (b) the incident light is parallel to the line (TE). Varying the radius of curvature of the rounded mask feature we examine the resulting aerial image and deduce the amount by which the contour of 30% intensity retreats from the respective contour of the ideal (right angled) mask, i.e. the increase of the \( \text{LES}_\text{aerial} \). The increase of the \( \text{LES}_\text{aerial} \) with respect to the reference is plotted versus the radius of curvature for both clear and dark field masks in Figure 11(c). From these plots it is apparent that the \( \text{LES}_\text{aerial} \) increases quadratically versus the radius of curvature, which implies that it is proportional to the area missing from the corner due to the roundness, hence it is valid to think of corner rounding as anti-serif OPC in a CF mask or serif OPC in a DF mask, which lead to the opposite than the desired direction of \( \text{LES}_\text{aerial} \) reduction.

![Figure 11](image)

**Figure 11.** Amplitude of the near field of a reference (not rounded) and a rounded case (a) for a CF mask and (b) for a DF mask. (c) Increase of the \( \text{LES}_\text{aerial} \) vs. radius of curvature for CF and DF masks.

### 3.3 Shape fidelity requirements for good performance of OPC serifs

Knowledge of the required shape fidelity for the OPC serif is of paramount importance to the mask designer and especially to the mask manufacturer. From the above discussion it is apparent that the increases or decreases of the \( \text{LES}_\text{aerial} \) correlate linearly with the feature area that is missing or is extra near the corners. If that is the case, why should the mask manufacturer invest in time and effort to faithfully replicate "perfect" square OPC features onto the mask? Can we possibly get by with an easier to print OPC serif shape that still introduces the same non-overlapping area? The answer to the above questions, as far as aerial image simulation is concerned is that indeed, it is the extra area introduced by the serif that is responsible for the correction in the \( \text{LES}_\text{aerial} \), whereas the details of the shape are second order important. Figure 12 depicts one example, where a square OPC of side 0.1\( \lambda/\text{NA} \) is compared with a "mouse ear" (circular) OPC of radius 0.06\( \lambda/\text{NA} \). They are both placed with their geometrical centers coinciding with the corners of the isolated line, therefore having equal non-overlapping areas. Figure 12(a) depicts the amplitude of the near field for the reference case, the square OPC and the "mouse ear" OPC, (b) depicts the aerial image intensity contours for the two OPC shapes and in (c) a cut-line along y at x=0 is shown,
from which it is obvious that the two aerial images are nearly identical. In Figure 13 the $\text{LES}_{\text{aerial}}$ correction vs. the non-overlapping area of the serif is shown for DF masks and various sizes of square and "mouse ear" serifs, when their center is aligned with the corner of the main feature.

![Figure 12](image1.png)

**Figure 12.** (a) Amplitude of the near field of the reference (no OPC), a square OPC with side $0.1\lambda/\text{NA}$ and a "mouse ear" OPC with radius $0.06\lambda/\text{NA}$, so that they have the same non-overlapping area. (b) Aerial image intensity contours of the square and "mouse ear" OPC. (c) Cut-line of the aerial images along the y-axis at x=0.

![Figure 13](image2.png)

**Figure 13.** $\text{LES}_{\text{aerial}}$ correction vs. the non-overlapping area of the serif for DF masks and various sizes of square and "mouse ear" serifs, when their center is aligned with the corner of the main feature.
4. Conclusions

Scalar imaging and rigorous electromagnetic simulation have been used to generate quantitative design data on the placement and sizing of OPC features. Studies of scatter bars showed that both the best-focus and out-of-focus aerial image CD are more sensitive to the scatter bar placement rather than size. For very high $\sigma$ the CD$_{aerial}$ is a weaker function of both placement and size of the scatter bars. The TEMPEST-SPLAT difference for scatter bar simulations can be ~10%, but the same trends for scatter bar placement and size still apply.

Using a perturbation approach, it is shown that OPC serifs can be adequately characterized by SPLAT simulations only. The TEMPEST-SPLAT results’ bias corresponds well with the bias of the two simulators in the case of small isolated holes and posts. This model is accurate for diagonal placements of the serifs, but for off-diagonal placement further characterization is needed. The actual shape of the serif is shown by rigorous 3D electromagnetic simulation to be less important than what was believed so far. It is shown that the correction of the LES$_{aerial}$ is proportional to the non-overlapping area of the serif. Corner rounding can be regarded as an anti-serif case in clear field masks and serif in dark field masks. The hit in the LES is proportional to the area missing because of the feature roundness.

Acknowledgments

The lithography research was supported by industry and the State of California under the SMART program SM97-01.

References


