The Impact of Phase Errors on Phase Shifting Masks, part 2

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In the last edition of this column we examined the impact of phase errors on the printing of a phase edge, adjacent clear (transmitting) regions with nominally a 180º phase difference. The impact of a phase error is to prevent complete cancellation of the light at the edge so that the resulting dark line is not completely dark. The result was found to be equivalent to the addition of flare to the imaging tool. Further, going out of focus was seen to cause a small shift in the position of the dark line as a function of phase error. Now let's look at the same effects for an alternating phase shifting mask, a pattern of lines and spaces where every other space is phase shifted.

Consider a pattern of lines and spaces with spacewidth w_s and linewidth w_l. Assuming that the lines have zero transmittance, we shall let two adjacent spaces have arbitrary transmittances and phases of T_1, φ_1 and T_2, φ_2, respectively. Because the mask is a repeating pattern of lines and spaces, the resulting diffraction pattern will be discrete diffraction orders. For high resolution patterns only the zero and first diffracted orders will pass through the lens and be used to generate the aerial image. Defining a coordinate system with x=0 at the center of the first space and letting $p = 2w_s + 2w_l$ = the full mask pitch, the amplitude of the zero and first diffraction orders will be given by

$$a_0 = \frac{w_s}{p}\left(T_1 e^{ij_1} + T_2 e^{ij_2}\right)$$

$$a_1 = a_{-1} = \frac{\sin\left(pw_s / p\right)}{p}\left(T_1 e^{ij_1} - T_2 e^{ij_2}\right) \qquad (1)$$

The electric field of the aerial image (assuming coherent illumination for simplicity) will be

$$E(x) = a_0 + 2a_1 \cos(2px / p) \qquad (2)$$

The intensity of the aerial image is proportional to the magnitude of the electric field squared.

For an ideal alternating PSM, $T_1 = T_2 = 1$, $\varphi_1 = 0$, and $\varphi_2 = \pi$ (180º). For a mask with phase error, we can let $\varphi_2 = \pi + \Delta j$. Using these values in equation (1),

$$a_0 \;=\; \frac{w_s}{p}\left(1 - e^{i\Delta j}\right) \;\approx\; -\,i\Delta j\left(\frac{w_s}{p}\right)$$

$$a_1 \;=\; \frac{\sin\left(p w_s \,/\, p\right)}{p}\left(1 + e^{i\Delta j}\right) \;\approx\; \frac{\sin\left(p w_s \,/\, p\right)}{p}\left(1 + \frac{i\Delta j}{2}\right) \qquad (3)$$

where the approximate relations on the right make use of a small angle approximation. Using these values in equation (2) and squaring the magnitude of the electric field to obtain the intensity of the aerial image,

$$I_{alt-PSM}(x) \;\approx\; \left(1 - \frac{\Delta j^{\,2}}{4}\right) I_{ideal}(x) + \Delta j^{\,2}\left(\frac{w_s}{p}\right)^2 \qquad (4)$$

where I_{ideal} is the image of the alternating PSM for no phase error. Just as in the case of the phase edge discussed in the last edition of this column, the impact of phase error on the image of an alternating PSM looks just like the addition of flare to the image. In this case, however, the amount of effective flare is reduced by the duty ratio of the mask (w_s/p) so that the impact of this "flare" is very small for any reasonable phase error on the mask.

It would seem, then, that the wonderful properties of the alternating phase shifting mask make them relatively immune to the small phase errors that will inevitably occur during mask fabrication. Unfortunately, a closer look reveals a more insidious problem. When the image goes out of focus any phase error in the mask will interact with the defocus to cause an asymmetry between the shifted and unshifted spaces. The culprit lies in the zero order.

For no phase error, the zero order is completely missing ($a_0 = 0$). As a result, the image is formed completely by the interference of the two first orders. Since these orders are evenly spaced about the center of the lens they have a natural immunity to focus errors, making improved depth of focus one of the most attractive qualities of the alternating phase mask. As the zero order grows (with increased phase error on the mask), this third beam ruins the natural symmetry of the first orders and adds a focus dependency. Again for the case of coherent illumination and assuming small phase errors, the aerial image when out of focus will be

$$I_{out-of-focus}(x,\Delta) \;\approx\; I_{in-focus}(x) + 2\Delta j\left(\frac{w_s}{p}\right) E_{ideal}(x)\sin(\,\Delta) \qquad (5)$$

where E_{ideal} is the electric field for the no phase error, no defocus case (*i.e.*, equation 2 with $\Delta j = 0$) and the defocus angle Δ is related to the defocus distance δ by

$$\Delta \;=\; 4 p d\, l \,/\, p^2 \,. \qquad (6)$$

Obviously, the interaction of phase error Δj and defocus distance δ adds an error term to the in-focus aerial image as shown in equation (5). What is the nature of this error term? The key lies in the nature of the electric field E_{ideal}. Unlike the intensity, the electric field can be negative. In fact, the electric field will be negative under the phase shifted spaces and will be positive under the unshifted spaces. Thus, for a positive focus error ($\Delta > 0$) and phase error ($\Delta j > 0$) the error term in equation (5) will make the shifted space dimmer and the unshifted space brighter. For a negative focus error the opposite will be true. This effect is largest for smallest pitches p as can be seen from equation 6. This asymmetry between adjacent spaces through focus is the most detrimental effect of phase errors for an alternating phase shifted mask and is illustrated in Figure 1.

The lithographic consequences of this intensity imbalance of adjacent spaces through focus is quite interesting. Form the perspective of the space, the brighter space will print wider (assuming a positive resist), so that one space will be wider on one side of focus while its neighbor will be wider on the other side of focus. Things look quite different from the perspective of the line, however. As the space to one side of the line gets wider with a focus error, the space to the other side of the line will get narrower. As a result, the linewidth remains about constant but its position shifts away from the brighter space and towards the dimmer space. Thus, the impact of the interaction of phase and defocus errors for an alternating PSM can be seen as an error in the placement of the line in the PSM array. When both transmission and phase errors are present, the two effects on space image brightness can cancel at some defocus. The resist image with the best fidelity would then appear out of focus!

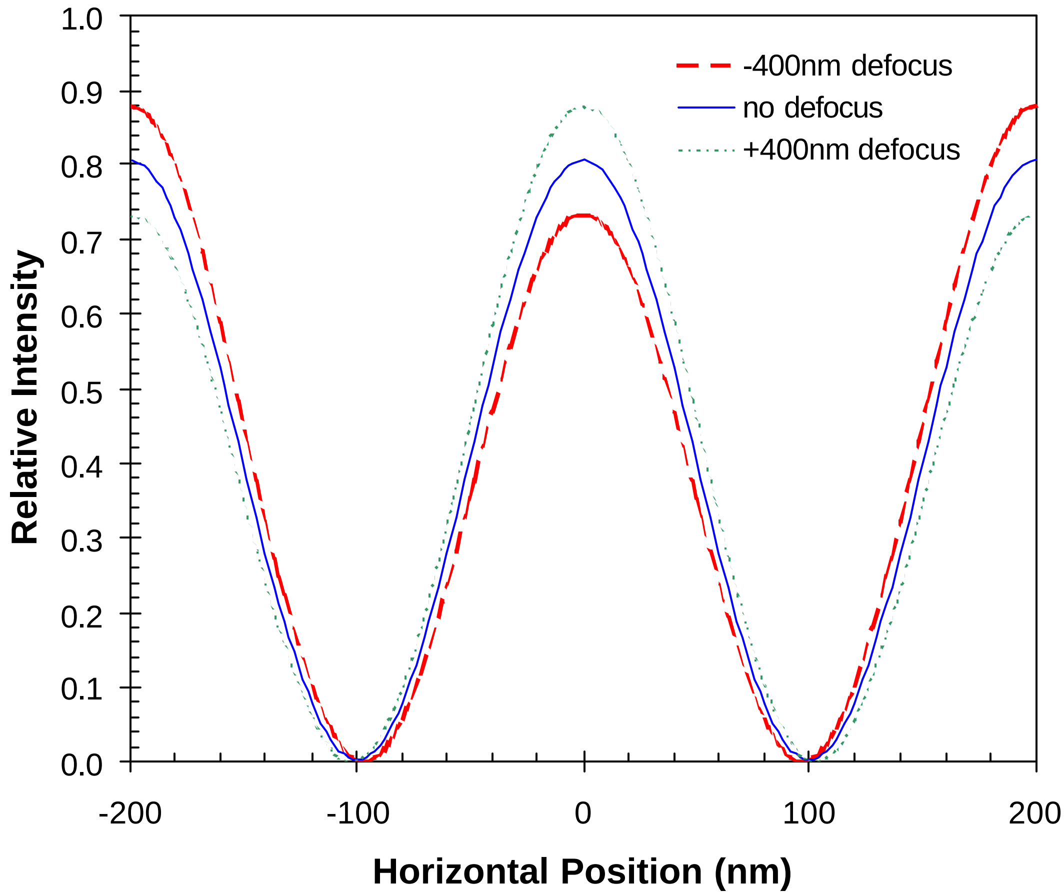

Figure 1. Aerial images for an alternating phase shifting mask with a 10º phase error for +400nm defocus (green), no defocus (blue), and –400nm of defocus (red). (100nm lines and spaces with λ = 248nm, coherent illumination, $0.25<k_1<0.5$).