6-26-2003

Forbidden Pitch or Duty-Free: Revealing the Causes of Across-Pitch Imaging Differences

Bruce W. Smith
Rochester Institute of Technology

Forbidden Pitch or Duty-Free: Revealing the Causes of Across-Pitch Imaging Differences

Bruce W. Smith, Microelectronic Engineering Department, Rochester Institute of Technology, Rochester, NY 14623

ABSTRACT

As resist image responses vary with duty ratio, the identification of a particularly challenging instance leads to its classification as a "forbidden pitch." The increased application of various RET methods has often resulted in the misuse of this label for anything unexplained by linear effects. This paper attempts to dispel the myths regarding the imaging variations that occur with pitch. Furthermore, by describing the basis of these behaviors, insight is provided for the appropriate design of mask, illumination, OPC, and exposure parameters to best accommodate a broad range of duty ratio values.

Keywords: Forbidden pitch, problematic pitch, optical microlithography.

1. INTRODUCTION

The term "forbidden pitch" has been used to describe image performance differences with pitch including CD, placement error, modulation, NILS, profile and the like. Though this term may be a useful message for designers, it should not be considered as a directive for lithography. Physical diffractive laws describing a minimum pitch value as l/2NA is the only real limitation to pitch. There may be particular pitch values that are problematic, leading to a more appropriate designation "problematic pitch". Figure 1 shows an arbitrary example of the behavior of a response with changing pitch. There is a region indicated in the plot where the response decreases.

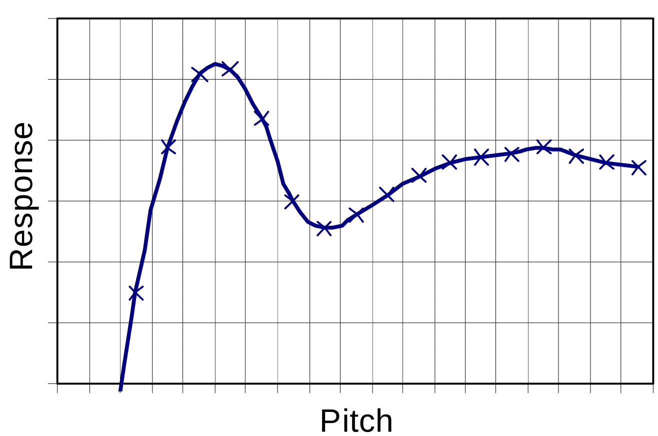


Figure 1. Problematic pitch – variation of an image response with increasing pitch.

The cause of this type of effect are addressed in this paper. Specific causes of problematic pitch can include the following:

A. *The variation in imaging (CD, DOF, NILS, and EL) through pitch with illumination.* The distribution of diffraction information within a projection lens is a direct consequence of the illumination condition. While custom illumination design should target the distribution of zero and first diffraction order information at equivalent radial locations within the pupil, this is difficult over a large pitch range. Non-ideal situations occur as first order energy is directed toward the center of the pupil, the classical condition of “problematic pitch.” Improvement is possible with the collection of higher orders but degradation is also possible as these orders occupy the pupil center. Illumination design can be carried out to avoid as many of these instances as possible.

B. *The sensitivity of sidelobes with contact duty ratio.* Sidelobes artifacts can occur with contact and trench imaging as a result of the insufficient weighting of first diffraction order energy with a DC term. The result is the printing of the negative node of the cosinusoidal image function. Contrary to popular belief, this is not a second diffraction order effect. Since it is driven by first and zero order diffraction weighting, there are duty ratios that are most sensitive to sidelobes. The effect is magnified with APSM transmission.

C. *The variation of aberration effects with pitch.* Symmetrical aberrations (such as spherical) and asymmetrical aberrations (such as astigmatism, coma, and 3-ponit) result in unique wavefront deformation. As diffraction energy samples an aberrated wavefront, characteristic pitch dependant aberration effects will result. Coma for instance can cause a pitch dependant image placement error which varies with the order of the aberration.

D. *Assist feature OPC correction.* Assist feature OPC accomplishes a threshold leveling effect across duty ratio when applied properly. Though the optimum bar conditions should be based entirely on the localized duty ratio, mask design and fabrication constraints can limit this. Some pitch values can therefore be more correctable than others.

2. THE VARIATION IN IMAGING THROUGH PITCH WITH ILLUMINATION

Conventional binary masking and partially coherent illumination can result in the variation of feature size with pitch. Figure 2 shows a plot of aerial image CD vs. pitch (normalized to wavelength and numerical aperture) for two cases of illumination. The variation in feature size can be described in four zones. Zone A is the region of first order capture, where additional first order results in imaging energy beyond the zero order. Zone B is the location where first diffraction order capture is complete (or near complete) and increasing pitch causes a larger weighting of the zero order. Image intensity bias increases and CD decreases. Zone C is the onset and increase in second order and zone D is the zero order increase once most second order is captured. These zones can be described analytically using the equations shown in Figure 2.

Off axis illumination (OAI) results in the characteristic “forbidden pitch” effect that is often discussed. Figure 3 shows how normalized image log slope (NILS) changes with pitch for a 0.70 sigma dipole and $0.6\lambda/NA^2$ of defocus. There are also four regions of image behavior. Zone A is first order capture, Zone B is zero and first order overlap, zone C is the movement of the first order toward the center of the lens pupil, and zone D is second order capture. When considered along with the quadratic DOF aberration effect, the behavior can be understood. Ideally, all diffraction order energy should be contained at a single radial location in the pupil. This is accomplished in zone B. As pitch progresses to zone C, the separation of diffraction orders moves away from this ideal. Figure 4 confirms the second order effect of zone D. This plot is for increasing pitch values for a constant duty ratio of 1:1. Since equal line/space features produce no second order, the effect of zone D is removed. Image quality continues to decrease until third order capture. Similar analysis can be carried out for other illumination types. Figure 5 and 6 show the effects of increasing pitch for annular and quadrupole illumination.

3. ASSIST FEATURE OPC AND PITCH

Assist features (scatter bars for example) are subjected to the same illumination considerations as main features. Such features will print at the problematic pitch values and their harmonics for a given illumination condition. This should be avoided through the sizing and spacing of bars. An alternative is to orient assist features in directions that do not coincide with the orientation of the main feature, decreasing their potential to print with OAI. Figure 7 show examples of bar orientations that would not be sensitive to dipole illumination problematic pitch.

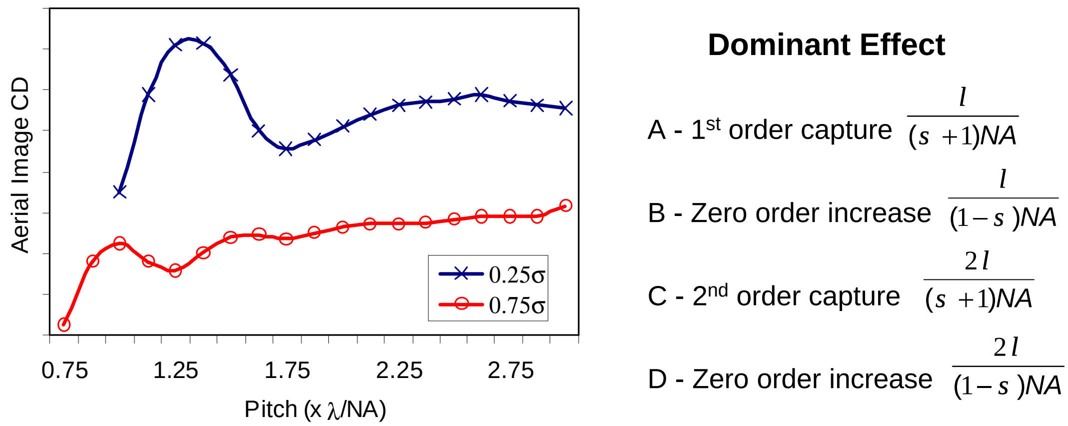


Figure 2. CD variation with pitch for binary masking and partially coherence illumination.

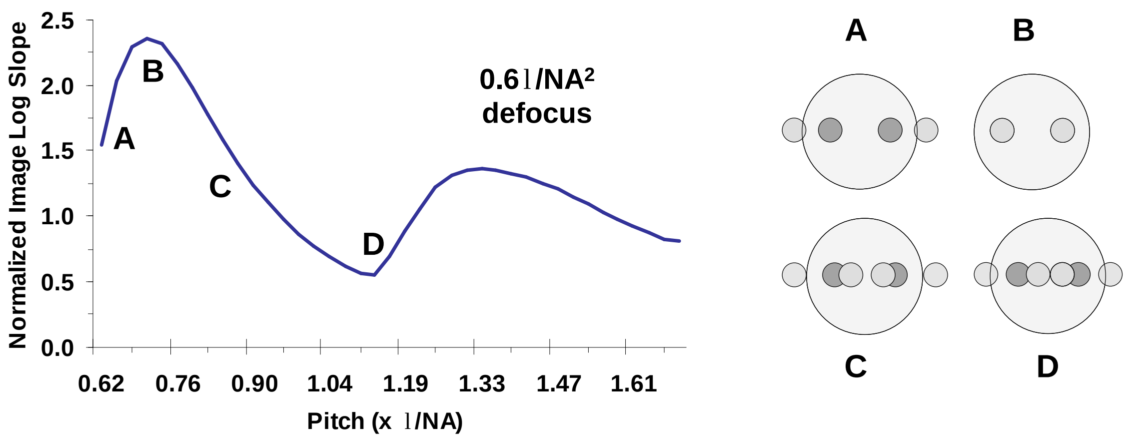


Figure 3. The effect of dipole illumination on the image response to pitch variation.

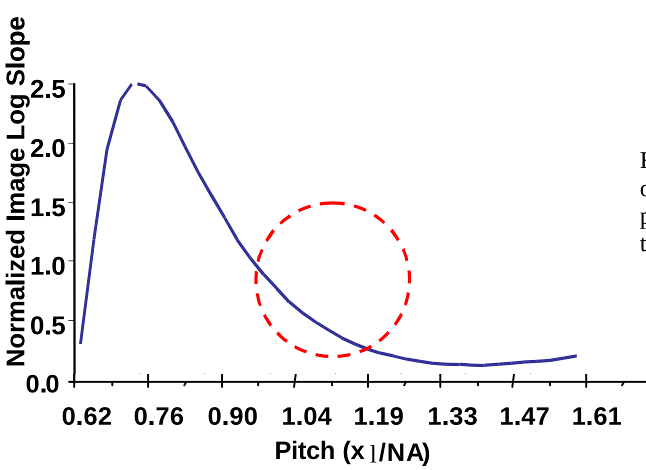


Figure 4. The effect of dipole illumination on the image response to 1:1 duty ratio pitch variation showing the elimination of the second order effect.

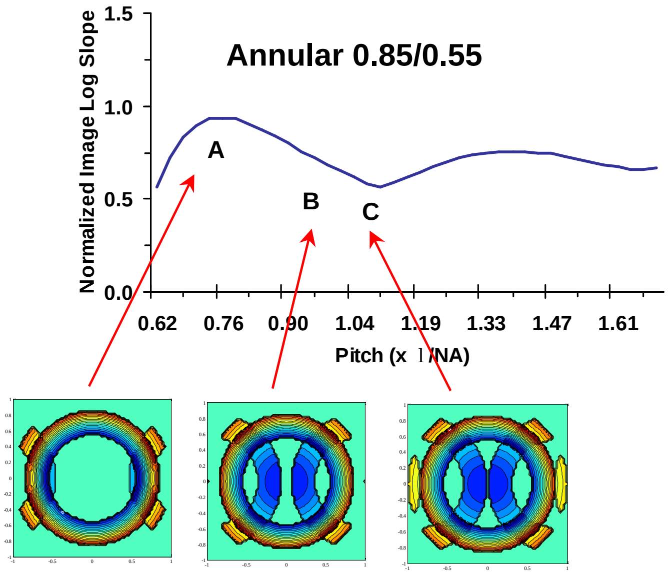


Figure 5. The effect of annular illumination on problematic pitch.

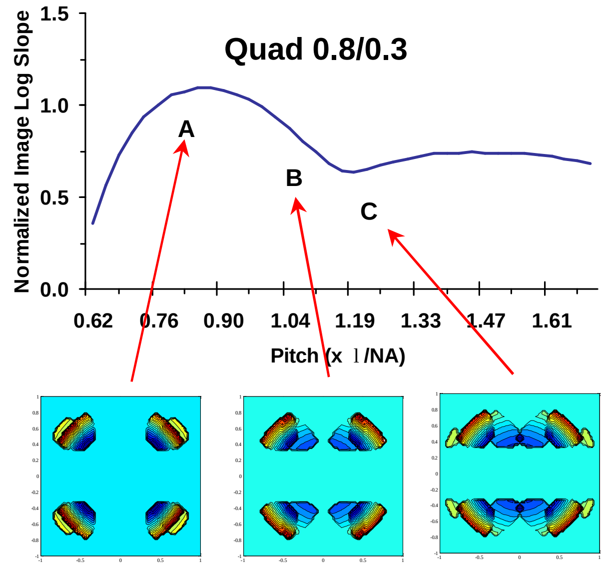


Figure 6. The effect of quadrupole illumination on problematic pitch.

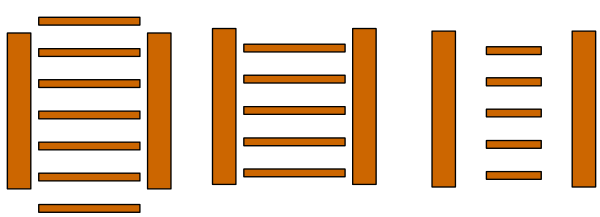


Figure 7. Horizontal assist bar orientation for reduction of problematic pitch for dipole illumination.

The elimination of problematic pitch values from OPC features may not remove all occurrences of pitch effects. Consider the case for a single pair of bars, shown in Figure 8. A linear systems description of this geometry shows the fundamental pitch of bars exists within the pattern. This can cause a sensitivity of a single pair of bars to illumination effects. Figure 9 shows how a single bar may also have sensitivity. A bar (b) is spaced from a main feature (L) by a distance (s). This combination has a fundamental frequency as the basis of the bar plus space distance. Figure 10 shows how combinations of bar width and spacing can lead to a pitch dependency, which is repeated at harmonics corresponding to multiples of this sum.

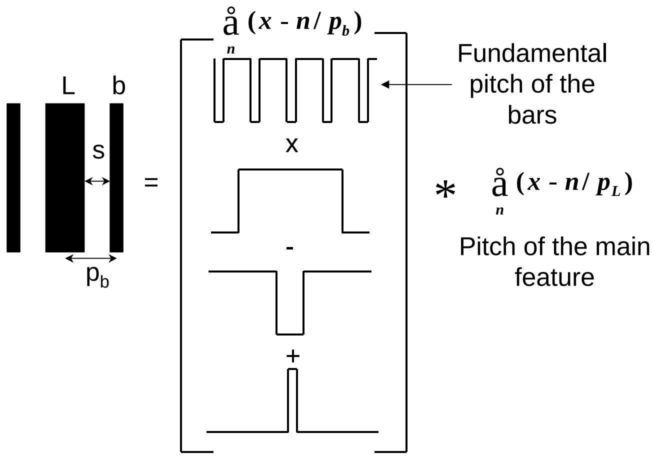


Figure 8. The fundamental frequency of a single pair of assist feature bars.

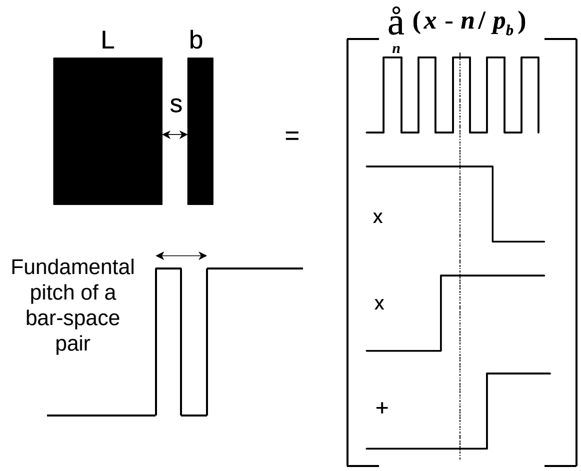


Figure 9. The fundamental frequency of a single bar and space combination.

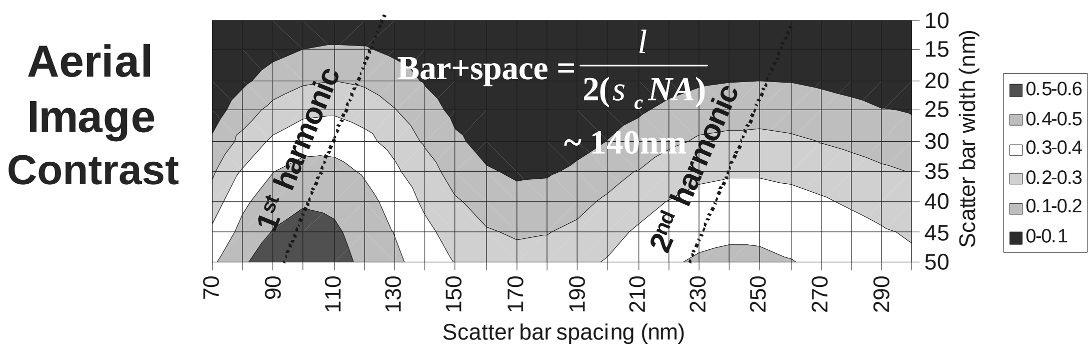
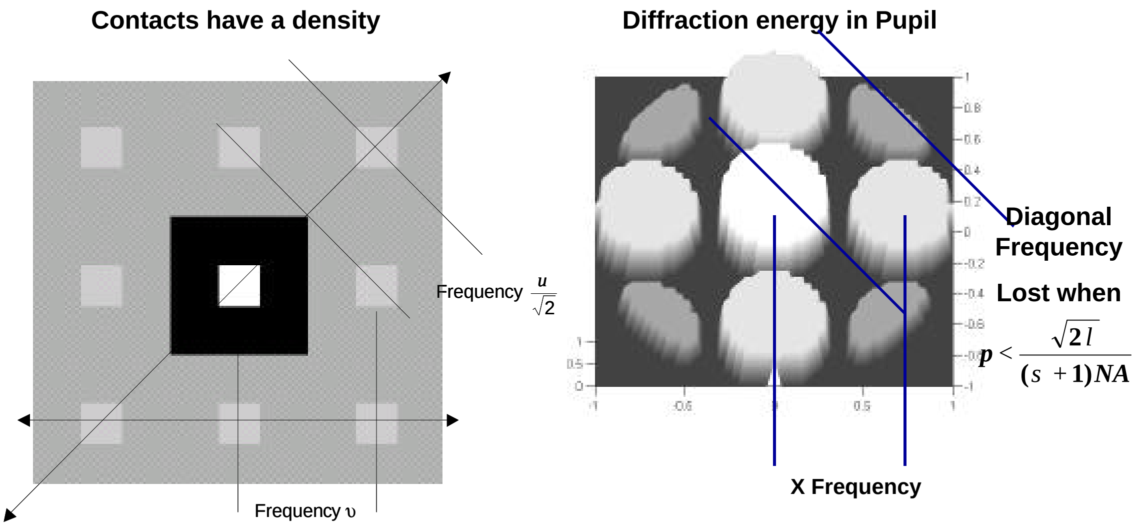


Figure 10. The aerial image contrast for combinations of assist bar width and spacing.

4. CONTACT SIDELOBES

There is a misconception about the side lobe artifacts that arise when imaging contacts. This effect has been described as an overlap of the second node of the point spread function of an isolated contact, a Gibb's phenomenon resulting from a truncated Fourier series, and second diffraction order effects. In reality, the presence of sidelobes in not a consequence of any of these. Figure 11 shows the frequency distribution for a contact feature, with diagonal frequency terms at a higher frequency than axis terms by a factor of root-2. The image of a contact is the biased cosinusoidal image function shown in Figure 12. The sidelobe is the squared negative cosine lobe energy that is not biased with sufficient energy from the zero order. Since the zero to first diffraction order weighting is determined by the contact to pitch ratio, a pitch dependency of the sidelobe magnitude is expected. Without sufficient zero diffraction order to bias the primary harmonic resulting from the first order, the squared magnitude of both lobes of the amplitude image may have sufficient intensity to influence resist exposure. This can be



$$|\text{Mag.}|_{\text{zero order}} = (s/p)$$

$$|\text{Mag.}|_{\text{first order}} = \left|\left(\frac{s}{p}\right)\text{sinc}\left(\frac{s}{p}\right)\right|$$

Figure 11. Contact features and corresponding frequency plots.

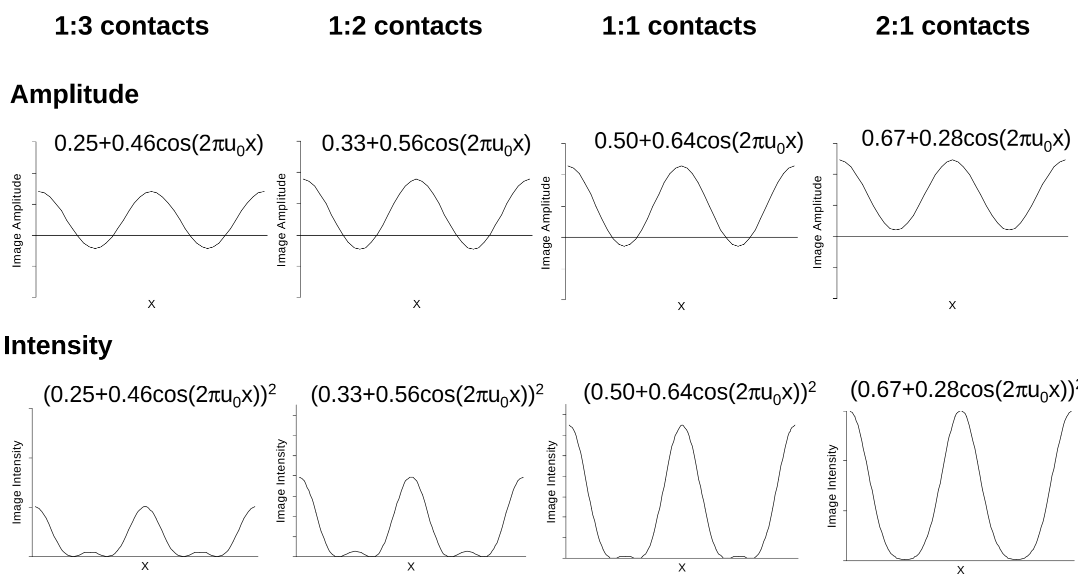


Figure 12. Coherent contact amplitude and intensity images from zero and first orders with varying duty ratios.

estimated from the difference between the values of the zero and first orders, or where side lobe magnitude is defined below and is influenced by the resist process:

$$(2 \times |Mag|_{first} - |Mag|_{zero}) < \text{Resist amplitude threshold}$$

Problems arise if the side lobe magnitude rises above the resist threshold. A resist intensity threshold of 0.3 corresponds to an amplitude threshold of 0.55. Figure 13 shows how APSM parameters can lead to side lobe susceptibility. The plot indicates that APSM values above 6% could be problematic, especially at a critical fractional space width near 0.3. This corresponds to a 1:2.33 duty ratio for maximum sensitivity to side lobe artifacts. For contacts designed on a square array, the diagonal contact frequency or duty ratio becomes a concern. Contacts with a 1:1.36 duty ratio on X/Y axes will provide the greatest opportunity for diagonal side lobe printing of contacts. As fractional space increases or decreases from this point, opportunities for higher transmitting APSM increase. Figure 14 shows the three dimensional intensity plots for 1:1.4 contacts and 10% APSM. The sidelobe energy is indicated between main contact features.

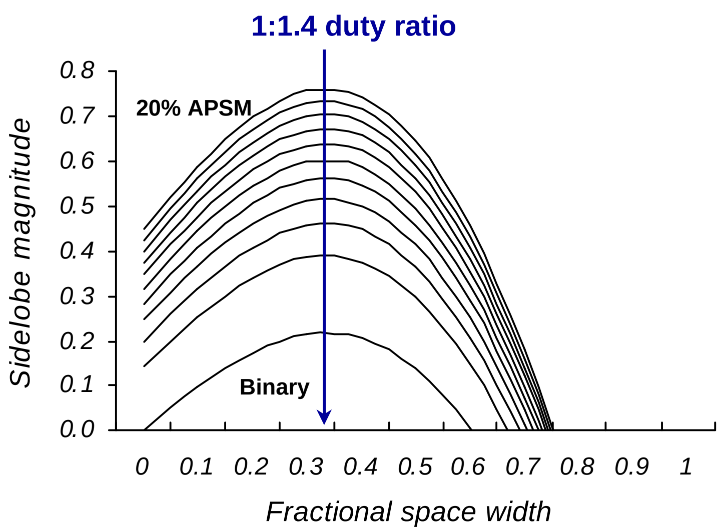


Figure 13. The coherent side lobe magnitude for APSM with transmission values between 0% (binary) and 20% for fractional space width values from zero to one. The maximum sensitivity to side lobe printing with APSM occurs at a 0.30 fractional space width. The maximum sensitivity to contact side lobe printing across the diagonal occurs when contacts are spaced 1:1.36 duty ratio along an X/Y axis. The likelihood that side lobe artifacts will print decreases for line features and is of little concern for fractional space values above 0.7.

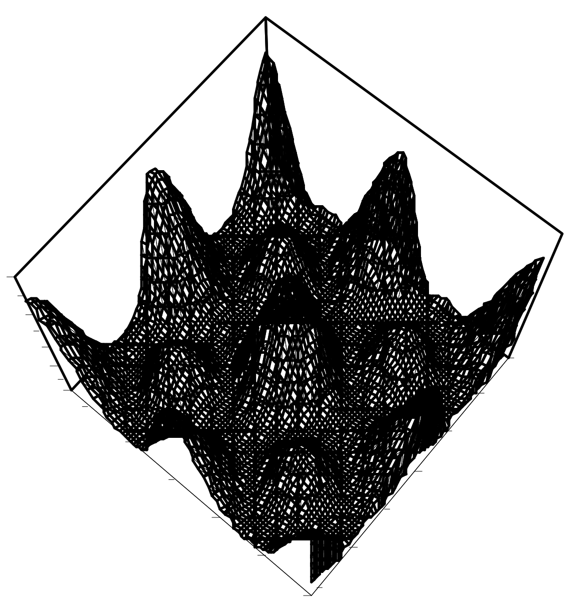


Figure 14. Three dimensional intensity plot for a 1:1.4 duty ratio contacts with 20 % APSM, showing the presence of sidelobes arising from the combination of cosinusoidal first diffraction order energy and zero order biasing.

5. PITCH SENSITIVITY TO ABERRATION

The radial behavior of a lens pupil can lead to pitch induced image variation from aberration. Figure 15 shows how primary coma can influence aberration as pitch alues increase. Five zones are identified. In zone A the first diffraction order moves to a maximum coma location, zone B. Zone C corresponds to the first order moving to the center of the pupil. Zones E and F are equivalent effects for second diffraction orders. The sensitivity to coma effects can be understood by finding the radial locations of maximum wavefront error. These occur where the derivative of the Zernike polynomial description of the aberration is zero, as shown in Figure 16. A similar analysis can be carried out for spherical aberration. These locations are shown in Figure 17. A plot of the image degradation (as NILS) for primary spherical aberration with pitch is shown in Figure 18.

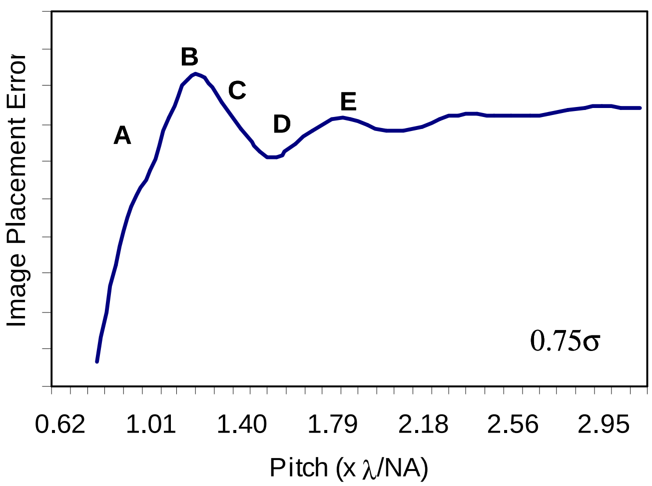


Figure 15. Image placement with primary coma as pitch increases.

Dominant Effect

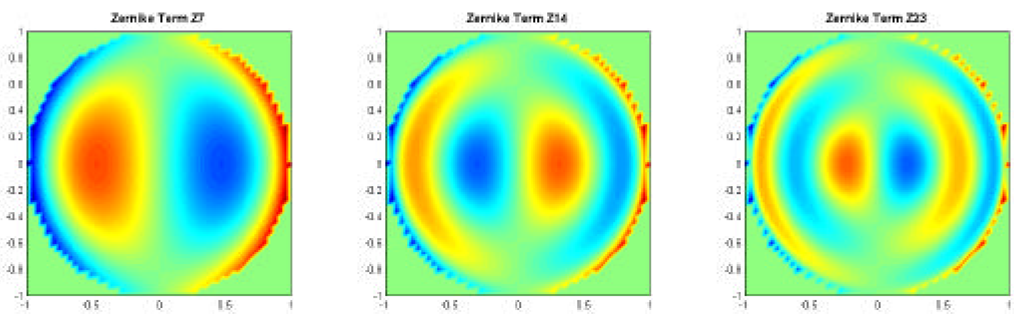
A - 1st order to coma max

B - 1st order at coma max

C - 1st order to center

D - 2nd order to coma max

E – 2nd order at coma max



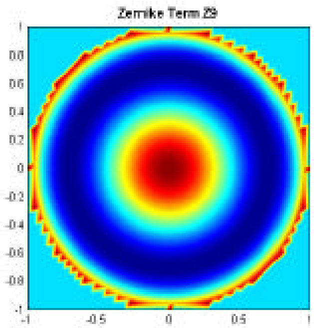
$$\frac{d}{dr}\left[\left(3r^3 - 2r\right)\cos(\theta)\right]$$

$$\frac{d}{dr}\left[\left(10r^5 - 12r^3 + 3r\right)\cdot\cos(q)\right]$$

$$\frac{d}{dr}\left(\left(35r^7 - 60r^5 + 30r^3 - 4r\right)\right)$$

Radius = +/- 0.46 **Radius = +/-0.31** **Radius = +/-0.23**

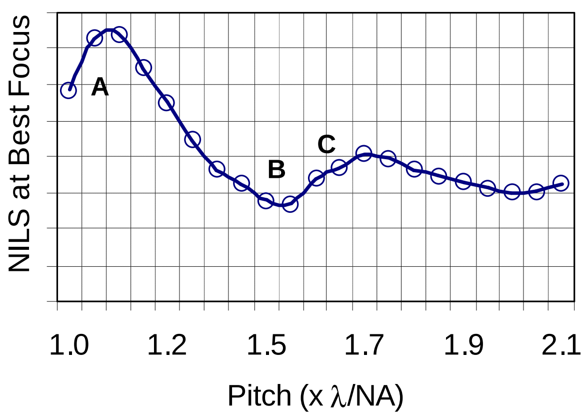
Figure 16. The radial location of maximum coma wavefront error .



$$\frac{d}{dr}\left[\left(6 \cdot r^4 - 6 \cdot r^2\right) + 1\right] = 0$$

Radius = 0.705

Figure 16. The radial location of maximum primary spherical wavefront error .



Dominant Effect

A – 1st order collection

B - 1st order at spherical max

C – 2nd order collection

Figure 17. The image variation (as NILS) with spherical aberration for increasing pitch values.

6. SUMMARY

The concept of "forbidden pitch" has been described more appropriately as various conditions of "problematic pitch" related to the fundamental physical considerations of illumination, masking, and aberration. The following generalizations exist:

1. Binary problematic pitch follows the following relationship and its harmonics:

$$\frac{m l}{(1 \pm s)NA}$$

2. Off-axis illumination follows the following relationship, determined by specific illumination conditions (R):

$$\frac{m l}{R(s_c + s_r + 1)NA}$$

3. Assist features have pitch and (bar+space) sensitivity.
4. Contact side-lobes are a primary order effect.
5. Aberration sensitivity follows the derivative of the aberration.