Optical Lithographic Performance and Resolution Using Strong Dark-Field Phase-Shifting of Discrete Patterns

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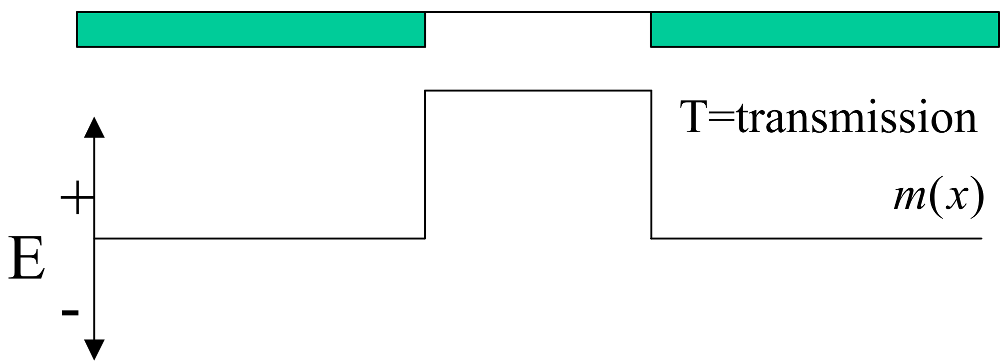
Isolated Space

Mask

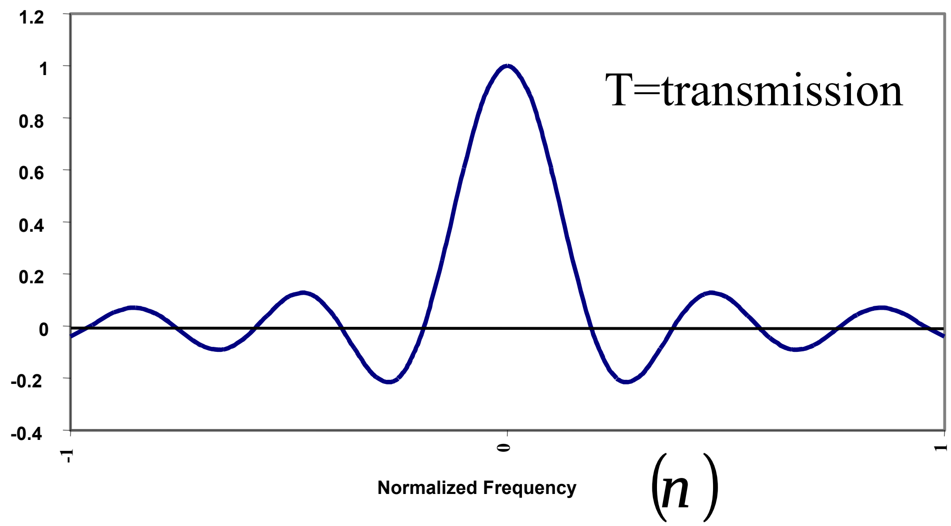
Mask Plane



$$m(x) = rect(x)$$

$$F\{m(x)\}$$

Fourier Plane



$$\text{sinc}(x) = \frac{\sin(x)}{x}$$

$$M(n) = F\{m(x)\} = \int_{-\infty}^{+\infty} m(x) e^{-i2pnx} dx$$

Common Optical Extension Techniques

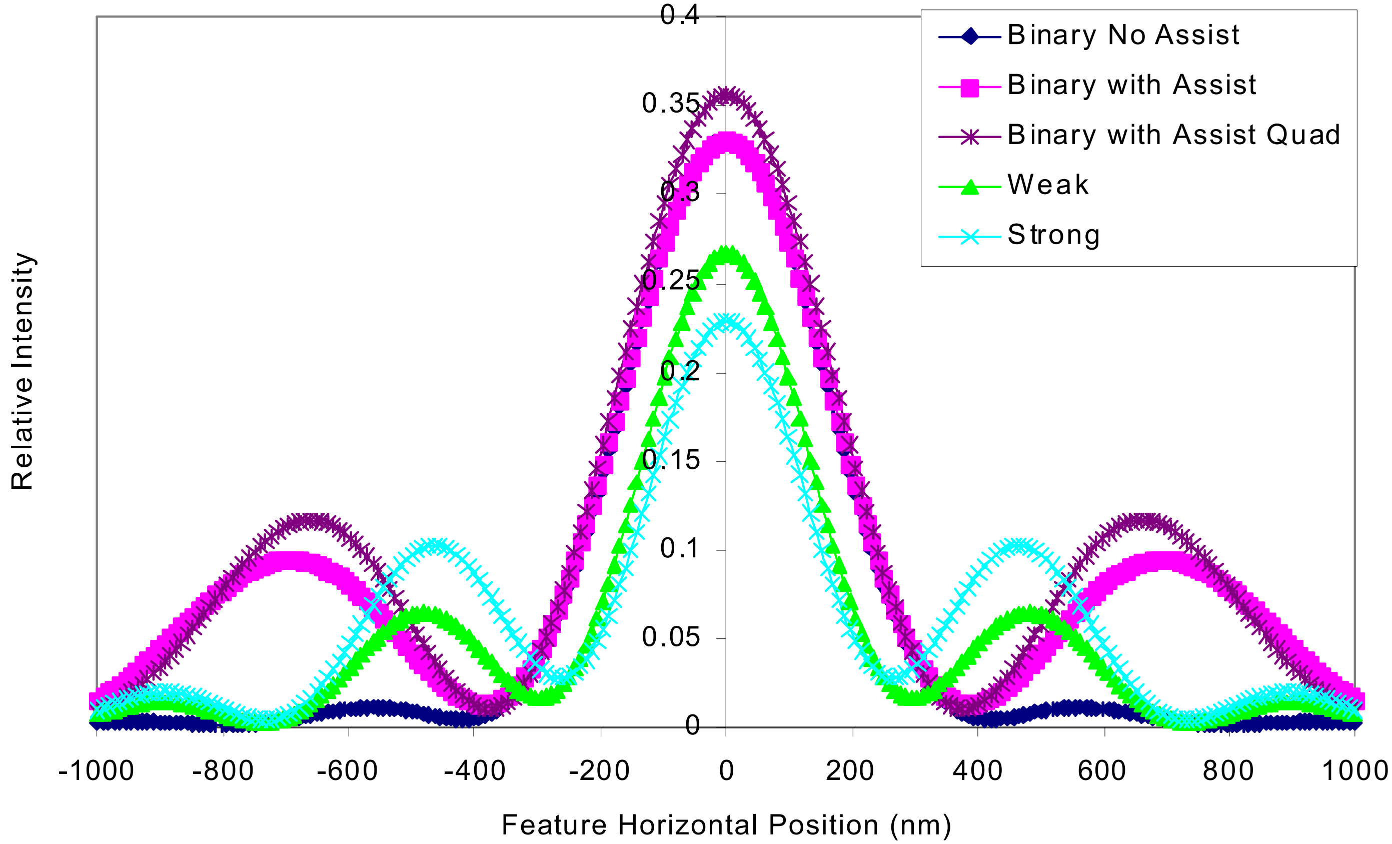
Technique	Challenge
Binary assist features with off-axis illumination	**Older steppers can't use off-axis illumination**
Dark-field, weak phase-shift with positive resist	**Limited Exposure-Focus Latitude**
Phase-edge lithography	**Requires negative resist—supply and control problems**
Shorter exposure wavelength and chemically-amplified resists	**Requires airborne-base free environments and full track-exposure tool integration**

Alternatively use GaAsMask™

GaAsMask™ Technology

- Uses "strong" phase-shift with sub-resolution assist features to shape the primary feature's diffraction pattern.
- Minimizes "zero order" amplitude, leaving two beams of light at the pupil plane to interfere and reconstruct the feature's image.
- Two-beam interference improves depth-of-focus (DOF) because so long as the beams maintain spatial and temporal coherence, the phase relationship required to create the image is maintained.
- Can be used with on-axis illumination (older exposure tools) and positive resists.

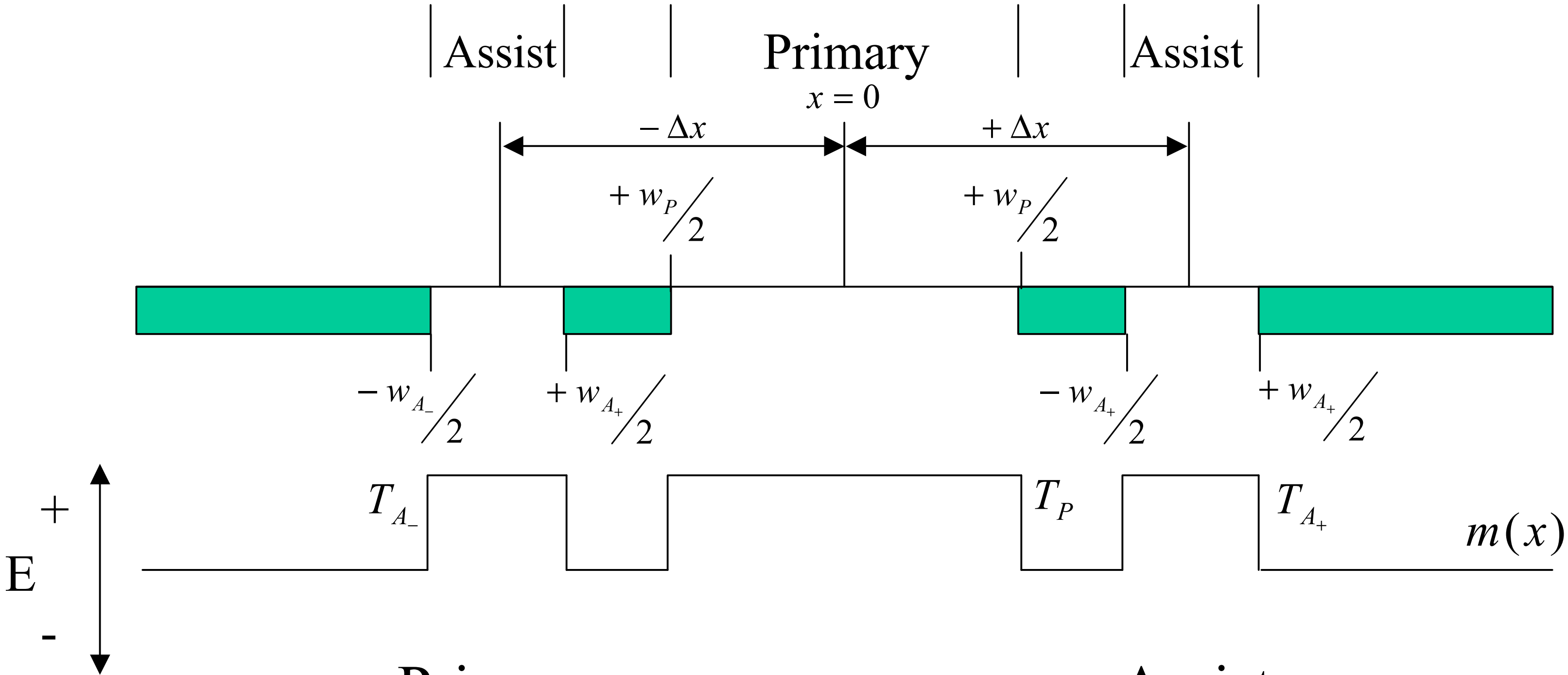
Aerial Image



Strong phase-shift mask has lowest intensity and narrowest image width.

Fourier Transform

For a Binary Mask with Assist Features:



Primary — Assists

$$F\{m(x)\} = T_P w_P \,\mathrm{sinc}(p n w_P) + 2T_A w_A \cos(2 p n \Delta x)\,\mathrm{sinc}(p n w_A)$$

Phase-Shifting

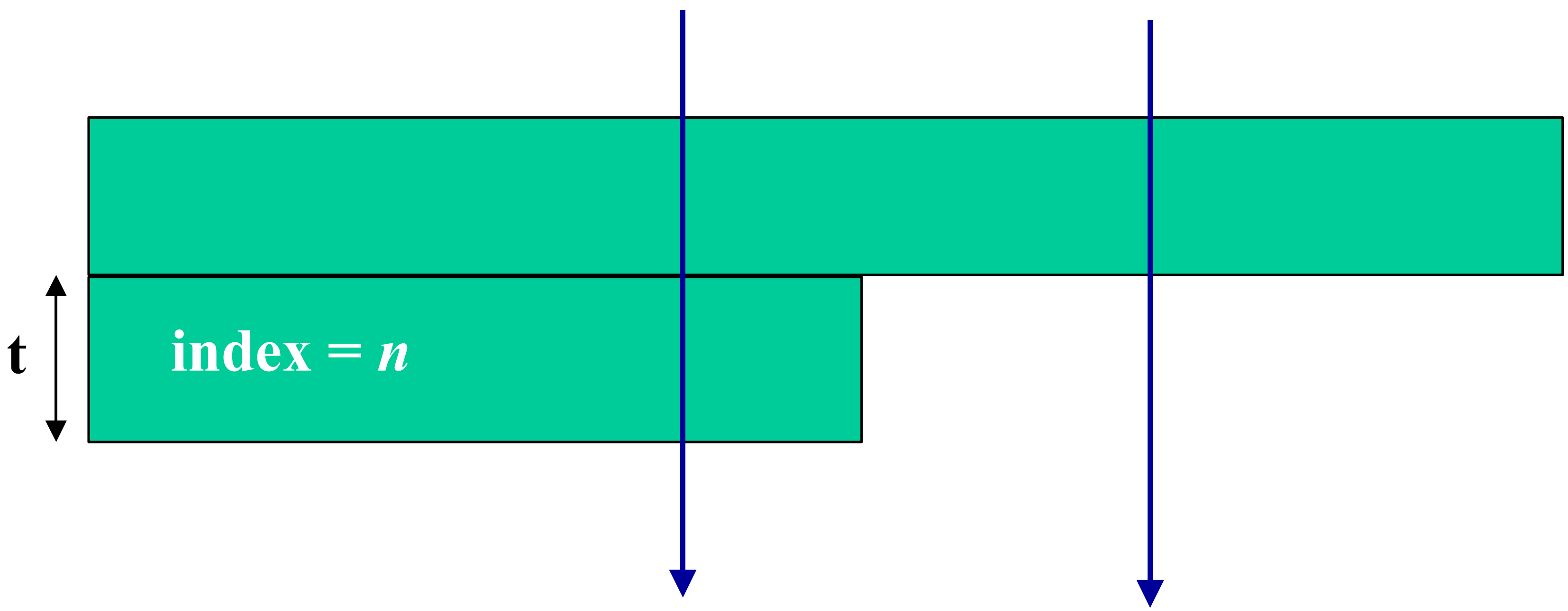
For a phase-shift mask, subtract either the primary term:

$$F\{m(x)\} = -T_P w_P \, \mathrm{sinc}(pnw_P) + 2T_A w_A \cos(2pn\Delta x)\,\mathrm{sinc}(pnw_A)$$

Or the secondary term:

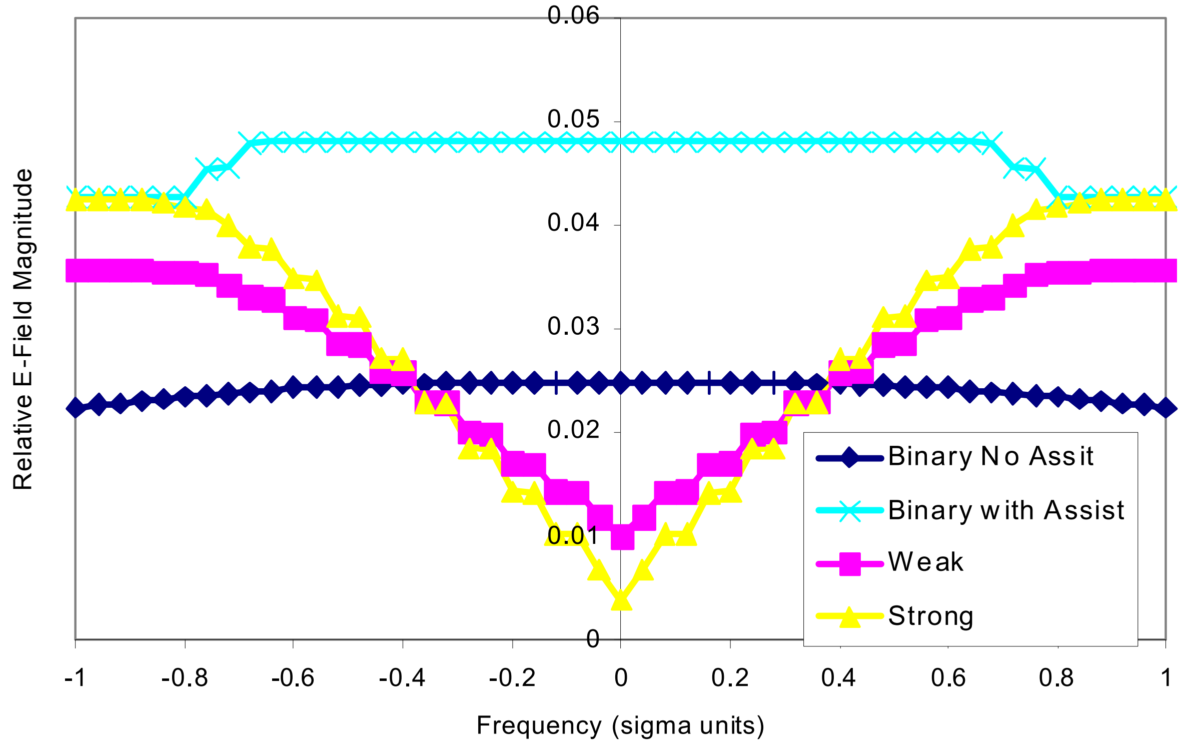
$$\mathrm{T_P w_P \, sinc}(\pi \nu \mathrm{w_P}) - 2\mathrm{T_A w_A} \cos(2\pi\nu\Delta \mathrm{x})\,\mathrm{sinc}(\pi\nu \mathrm{w_A})$$

Making a "Phase-Shift"



$$\Delta f = 2p\, t(n-1)\,/\ l$$

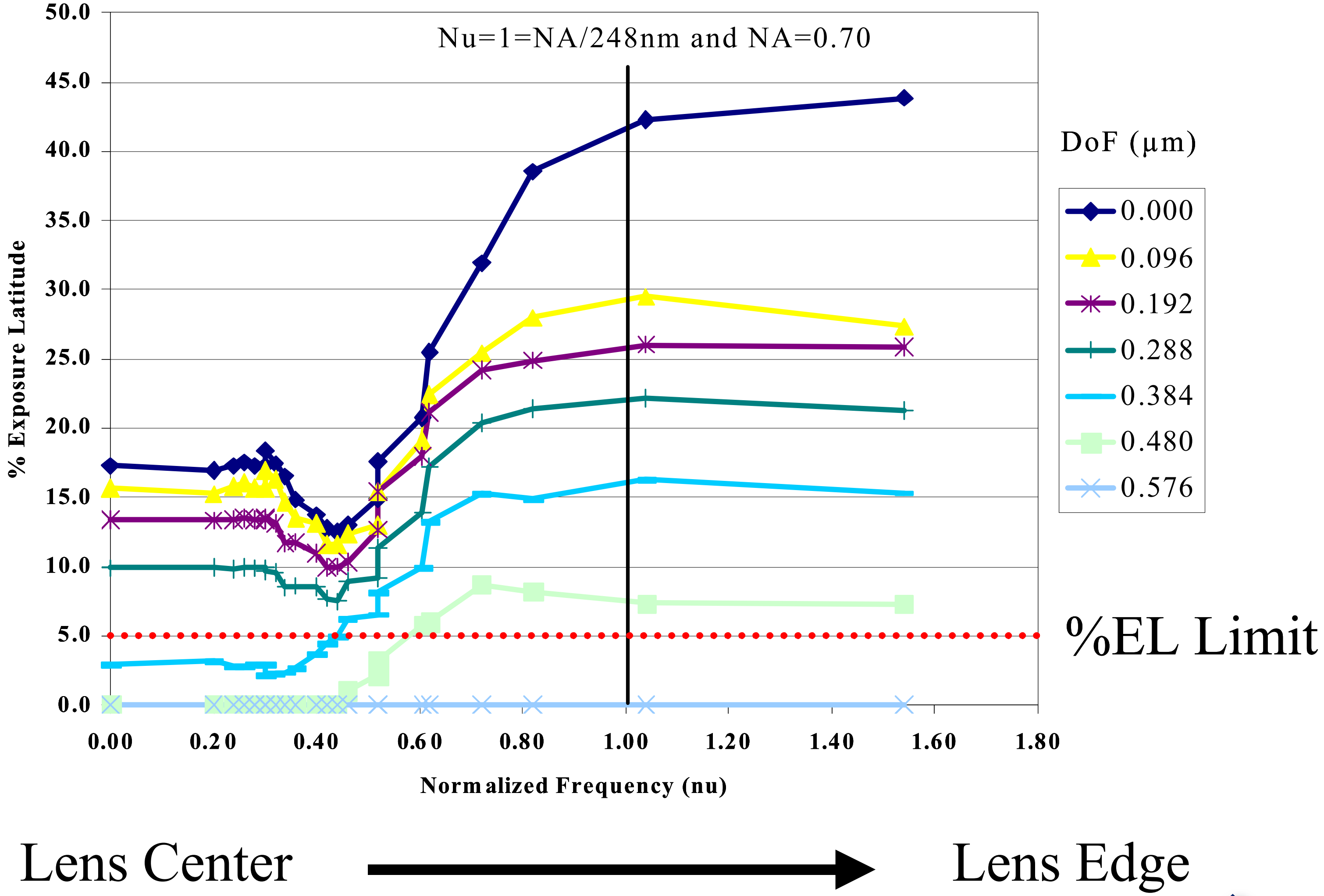
240 nm Diffraction Pattern, Various Masks



Spatial Frequency

- Frequency at the center of each node is driven by Δx.
- The smaller this value, the greater the absolute frequency.
- Focus tolerance changes with the nodal position in frequency space.
- Following figure shows the exposure range around dose to size 130 nm isolated feature with respect to frequency for different depths of focus.

Exposure Latitude vs. Depth of Focus



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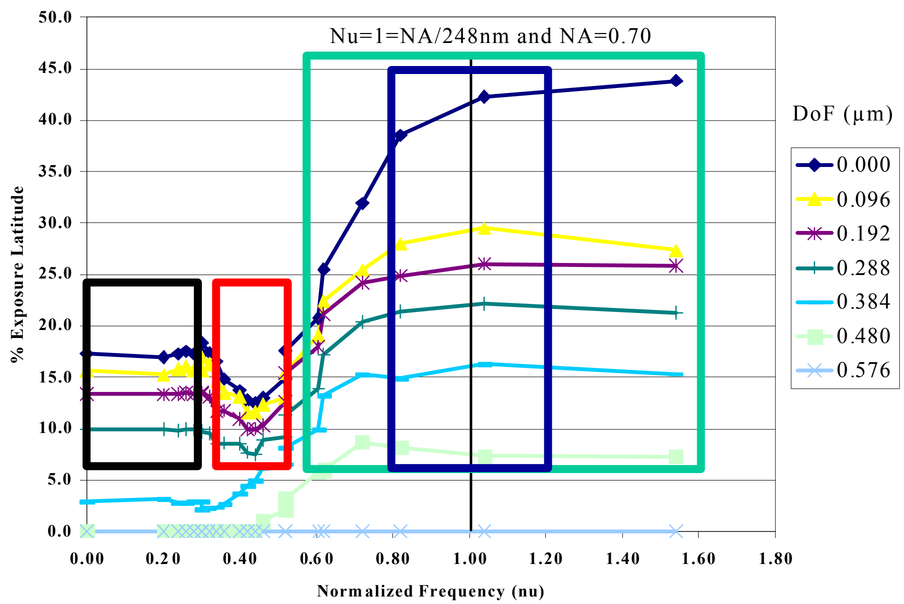
Exposure Latitude vs. Depth of Focus

- Generally, process is "production-worthy" if exposure latitude is ≥ 5% and has a focus tolerance of 0.4 µm (0.70 NA tool, 248 nm λ, partial coherence of 0.3)



Frequency	Performance
0 to 0.3	Same as unmodified sinc(x); phase-shift doesn't help performance
0.3 to <0.6	Performance worse than no phase-shift
>0.6	Process becomes "production-worthy"
0.8 to 1.2	Optimum performance frequency; achieves maximum DOF

Creating a Strong Shifter

Sum of complex transmittance and assist feature width cancel out electric field of primary feature; resulting amplitude at zero frequency = 0

For one set of assist features: $T_P \cdot w_P = 2 \cdot T_A \cdot w_A$

Assists are placed close enough to primary to position Fourier transform side-lobes at frequencies > 0.6 and less than or equal to:

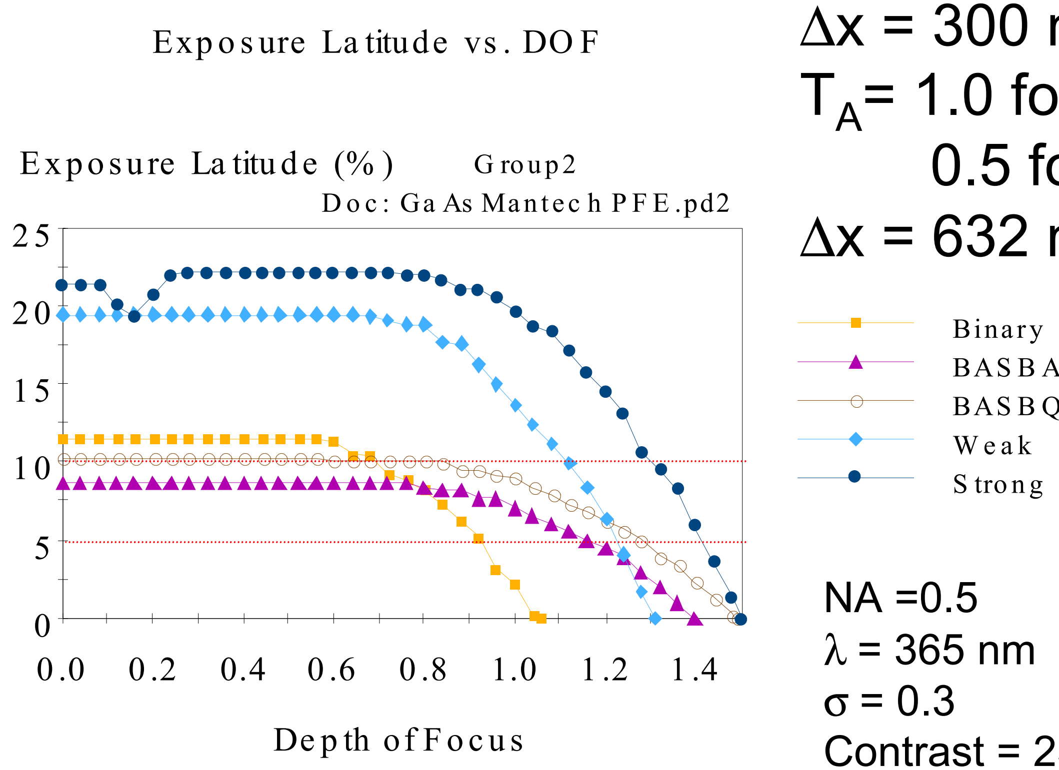
$$\nu \leq \frac{(1 + \alpha \cdot \sigma) \cdot \Delta x \cdot NA}{\lambda}$$

Where
σ = partial coherence
NA = numerical aperture, and
α = a factor > 1 that accounts for side-lobe's width

Creating a Strong Shifter

- Image forms when two lobes of modified sinc(x) function interfere at the image plane.
- Lobes are symmetric around the optical axis. Diffracted beams maintain uniform interference when equally aberrated, resulting in stable image size/shape in resist.
- If lobes were points with no radial distribution, depth-of-focus would be infinite. But they're not.
- However, DOF is still significantly better than that of unmodified sinc(x) functions or modified functions that have unbalanced electric fields.

Exposure Latitude vs. DOF for 250 nm Isolated Space



Δx = 300 nm

T_A= 1.0 for strong shift

0.5 for weak shift

Δx = 632 nm for binary w/assist

NA =0.5

λ = 365 nm

σ = 0.3

Contrast = 23

Film thickness = 700 nm

Absorbance = 0.2 per micron

Diffusion length = 10 nm

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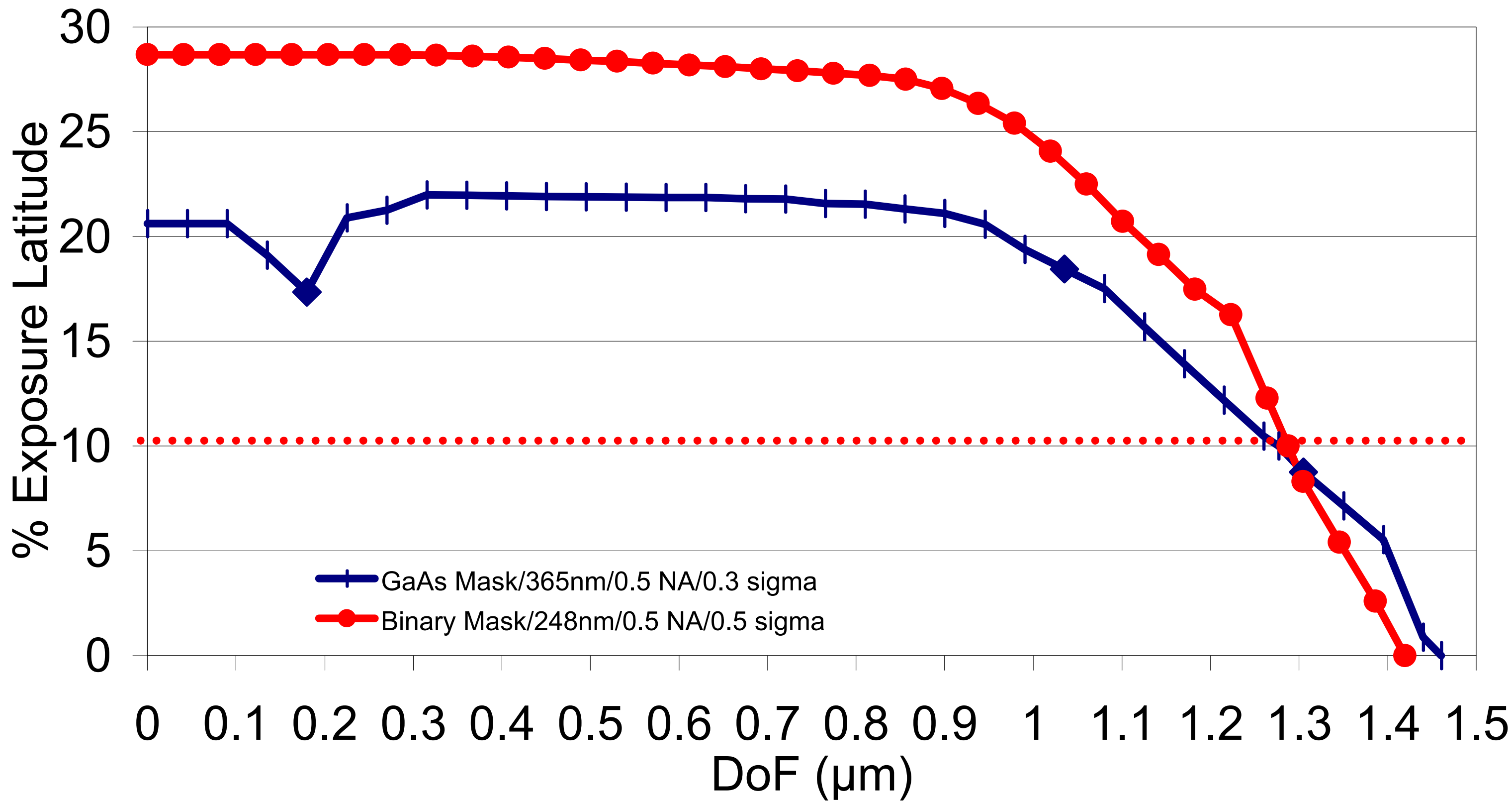
250 nm Feature Exposure Latitude Summary Table (365 nm)

Mask Type	Illuminator	5% EL	DoF @ % ExpLat
Strong	0.3 sigma	1.4	1.25 @ 10%
Weak	0.3 sigma	1.2	1.0 @10%
Binary w/Assist	Quad (0.62/0.2)	1.3	0.8 @ 9.6%
Binary w/Assist	Annular (0.65/0.55)	1.2	0.6 @ 8.7%
Binary w/Assist	0.7 sigma	1.0	0.7 @ 10.4%

Let's compare to 248 nm:

Comparison of 248nm Binary Mask and 365nm GaAsMask



LPM 23 contrast, 700 nm resist, 10nm diffusion length

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Conclusions

- Optical RET can yield 365 nm lithography of discrete isolated features to form 250 nm devices.
- For 248 nm lithography, 130 nm and smaller features are possible.
- GaAsMask has largest process window of the dark-field techniques examined.
- Choice of process will depend on manufacturer's process budget, and adaptability of exposure tools. Older tools could benefit from GaAsMask technology.

Acknowledgements

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Resolution Enhancement Trek

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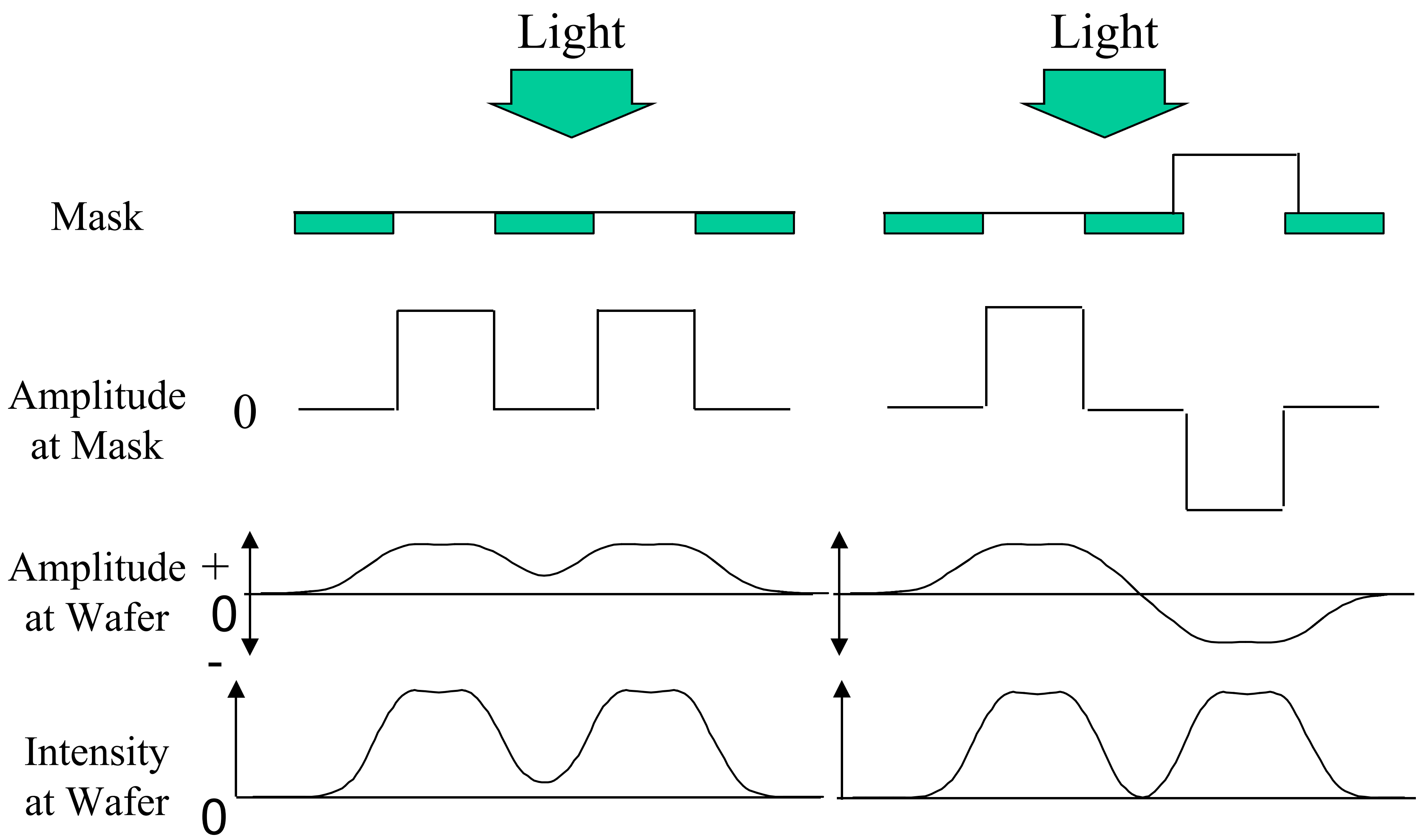
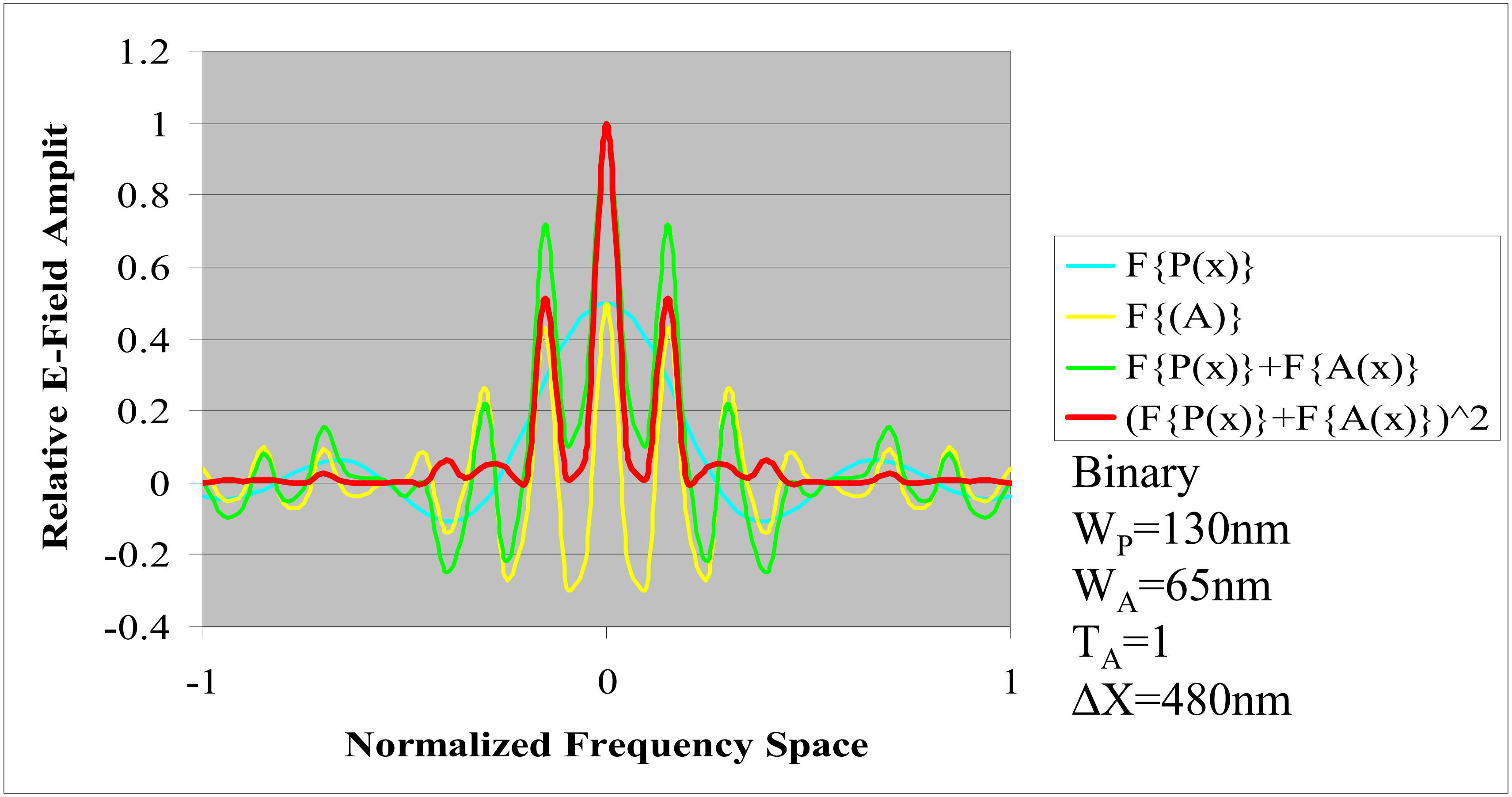
Phase-Shift Mask Concept



M. Levenson, Physics Today, pp. 28-36, July, 1993.

Dark Field Isolated Space: Binary



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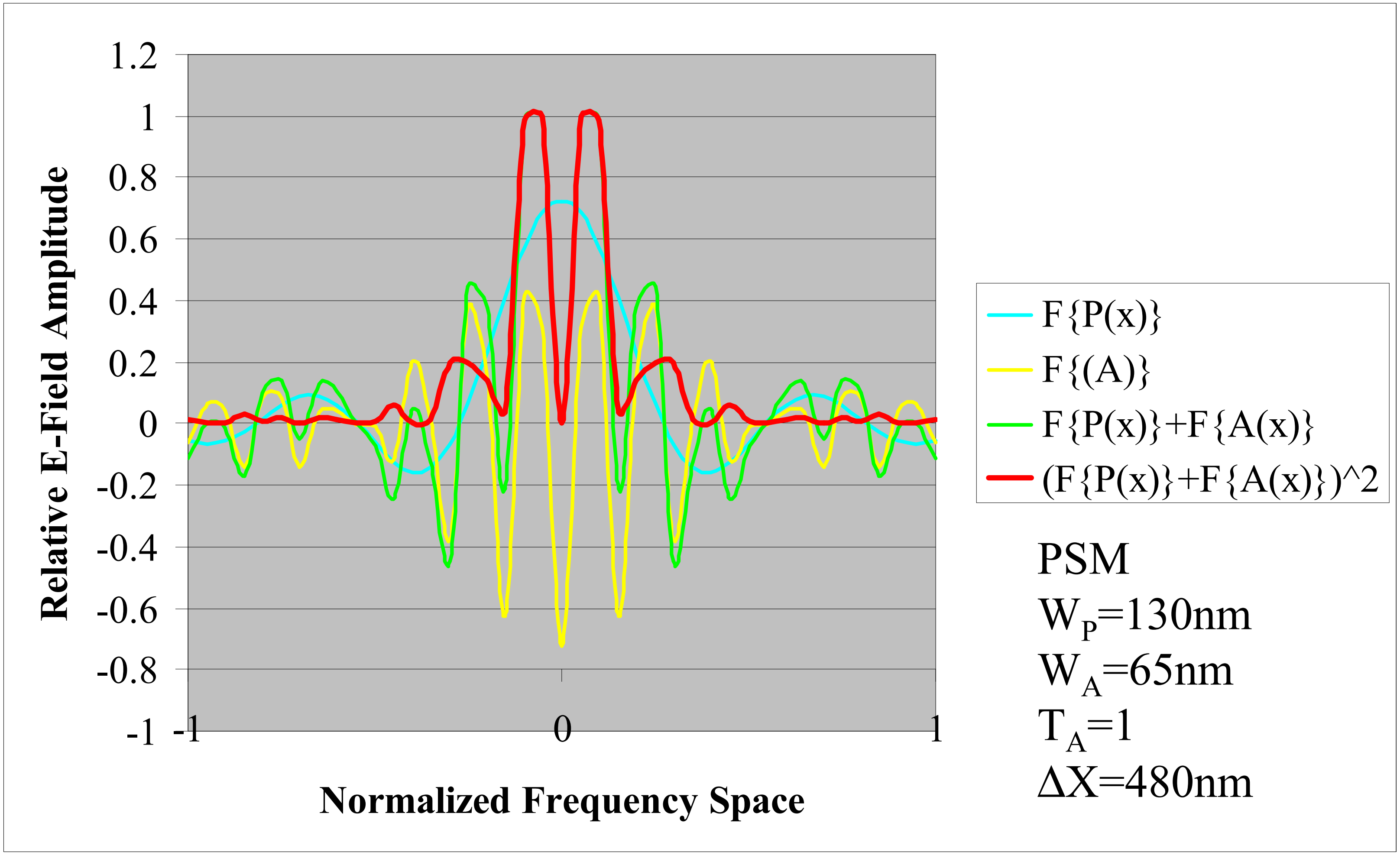
Isolated Space: Shifted



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