IIL Imaging Model, Grating-Based Analysis and Optimization

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Overview of Activities

- Optimization for IIL
  - Frequency coverage
  - Relative intensity ratios
  - Pupil filters
- Multichannel imaging model
  - Regularization and restoration
  - Iterative optimization
- Imaging interferometric microscopy (IIM)
  - Noise removal and enhancement
  - Exploiting channel redundancy

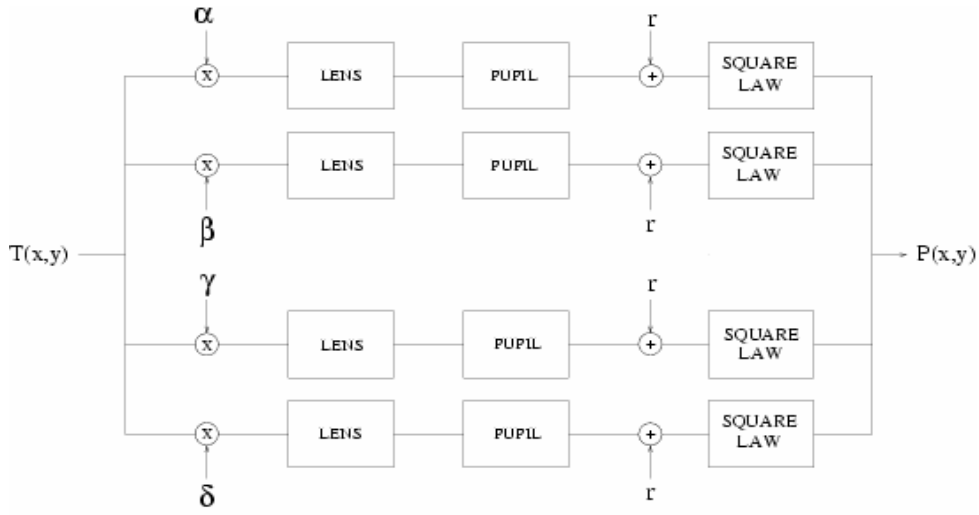
Outline of Talk

1. IIL Imaging Model
2. Resolution Enhancement
3. Aerial Image Quality Assessment
4. Grating-based Analysis of IIL
5. Optimization for IIL
6. Multichannel nonlinear image restoration
7. Continuing Research Directions

Motivation for RET Methods

- Resolution limitations
  - Process latitude
  - NA of optical system
  - Exposure wavelength
- Approaches hitting fundamental limitations
- RET methods: aerial image enhancement

Wavelength Division Multiplexing

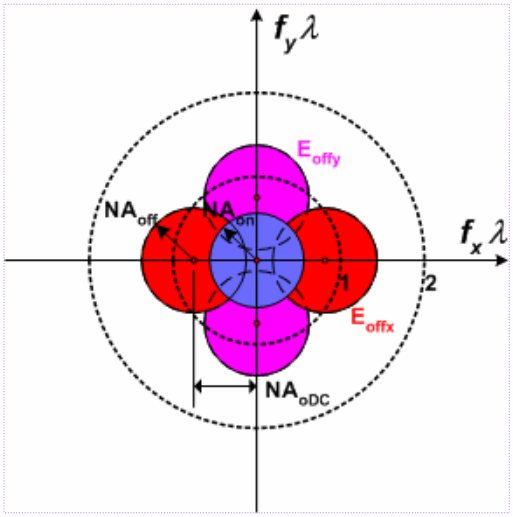


IIL Imaging Model

$$y = t\{CS(PBD(x) + r)\}$$

- D : diagonal matrix of frequency shifts modeling OAI frequency downshifting.
- B : lowpass lens filtering operation modeling diffraction limited optics.
- P is a diagonal matrix of complex weights modeling pupil filtering.
- C the combination operator combines outputs from different channels.
- S : magnitude square non-linearity modeling aerial image intensity evaluation from electric field.
- r: reference signal, x: mask image

IIL Image Formation



- Coverage parameters: NA_{on} , NA_{off} , NA_{oDC}.
- Tilt angle determines DC offset for off-axis exposure.
- Coverage parameters specify center frequencies and bandwidths of exposures.

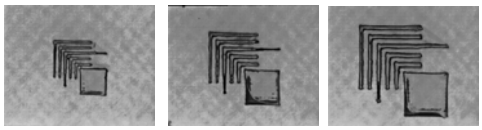
Enhancement/Resolution Increase

- OPC : boosts strength of higher mask frequencies.
- PSM : modifies phase associated with mask frequencies.
- OAI : tilts axis of illumination allowing access to higher mask frequencies.
- IIL : multiple exposures, frequency down-shifting & up-shifting.
- For large NA systems, IIL is OAI with multiple exposures and pupil filtering.

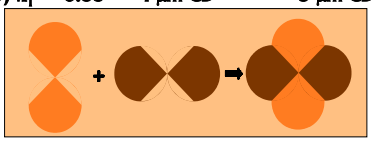
Effect of Frequency Parsing

OAI - SYMMETRIC PUPIL PLANE FILTER

I-LINE, NA = 0.04, $f_{offset} = 0.04/\lambda$



3-μm CD; κ_1 = 0.33 4-μm CD 5-μm CD



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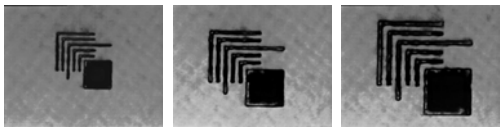
OAI WITH PUPIL PLANE FILTER - OFFSET WITHIN PUPIL

I-LINE, NA = 0.03/0.04, $f_{offset} = f_{opt}$



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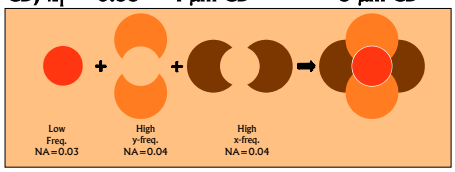

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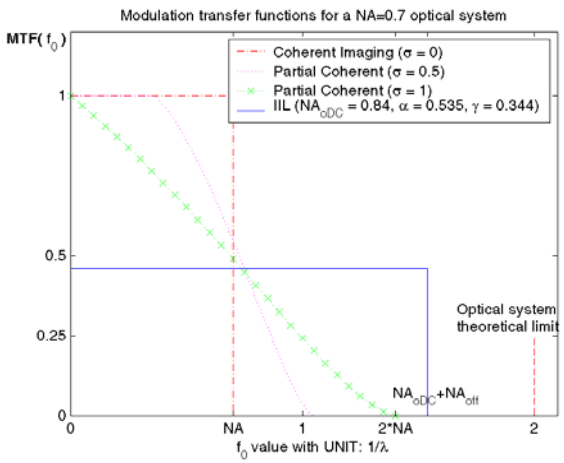
Characteristics of IIL

- Different frequency allocation schemes with identical frequency coverage produce different aerial images.
- High frequency information added rather than just providing enhancement of the aerial image.
- Pupil filtering eliminates duplicate frequency coverage and reduces redundancy in the branches.

Transfer Function Analysis



- Coherent imaging has limited bandwidth of f_o.
- Partial coherent illumination (PCI) coverage up to $2f_o$.
- PCI-MTF magnitude decays rapidly after f_o.
- IIL extends coverage further than PCI.

Mask Error Enhancement Factor

- MEEF : ratio of change in printed CD to change in mask CD.
- In the linear regime: MEEF approximately 1. For nonlinear regime, i.e., sub-wavelength lithography MEEF is different than 1.
- MEEF > 1 : amplifies mask defects, forces tighter mask tolerances and reduces aerial image quality.
- MEEF for dense patterns different than the MEEF for isolated features: a MEEF gap or bias exists.

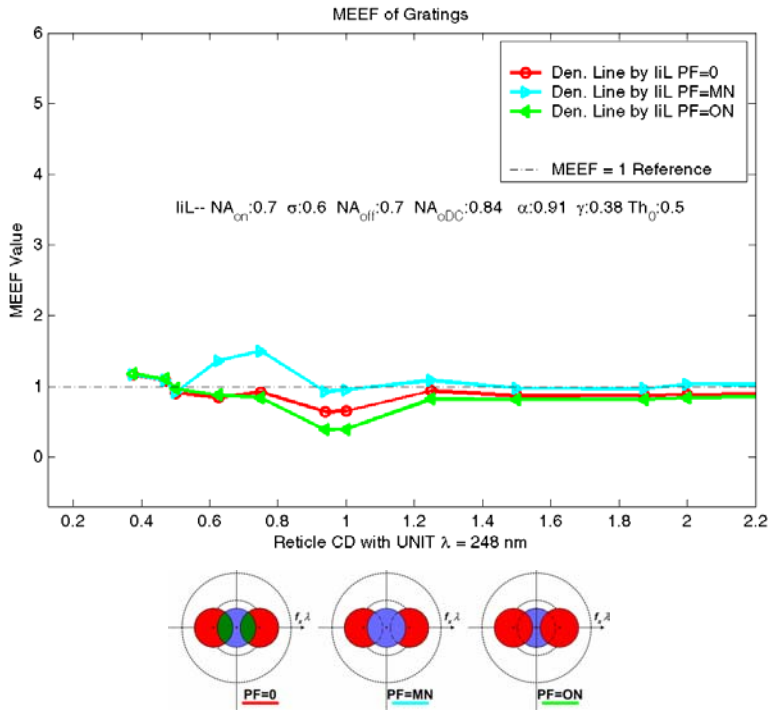
Aerial Image Defects

- Island errors, keyhole errors, break errors, and connectivity errors cause circuit failure.
- Line-edge shortening, line-edge roughness, corner rounding measure aerial image edge quality.
- Line edge shortening , corner rounding affect device speed and performance and line edge roughness causes increased leakage currents.
- Mask error enhancement: amplifies mask defects.

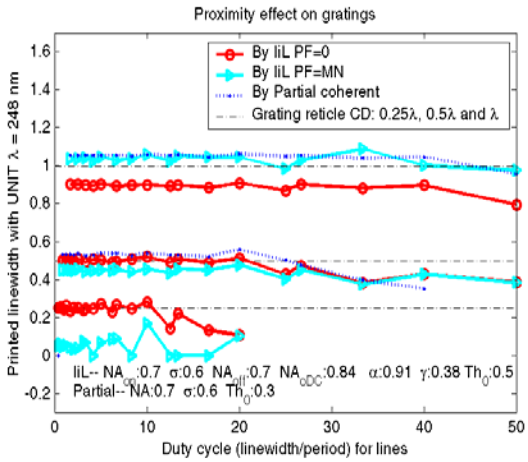
Grating-based Analysis

- Motivation: Grating-based analysis could provide clues for IIL analysis, optimization for complicated masks.
- On-axis exposure provides frequency coverage for smaller frequencies up to diffraction limit. Off-axis exposures cover higher frequencies.
- Dense gratings: off-axis exposures provide better higher-frequency coverage than partially-coherent illumination (PCI) method.

MEEF for Grating Analysis

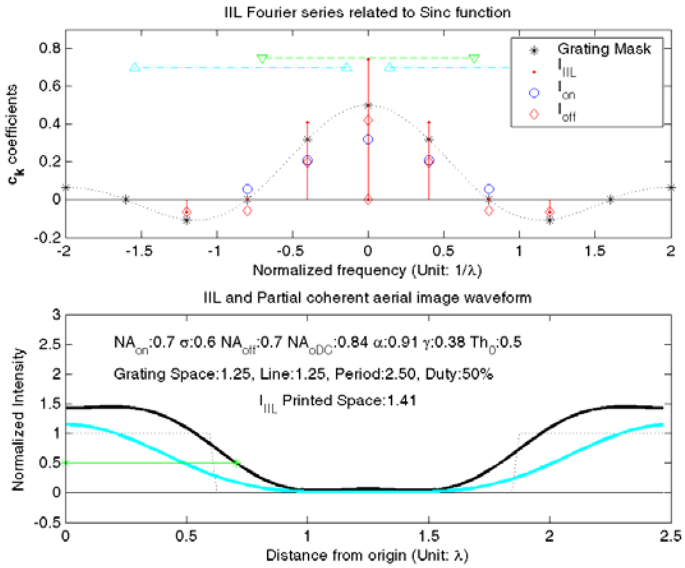


Grating-based Analysis



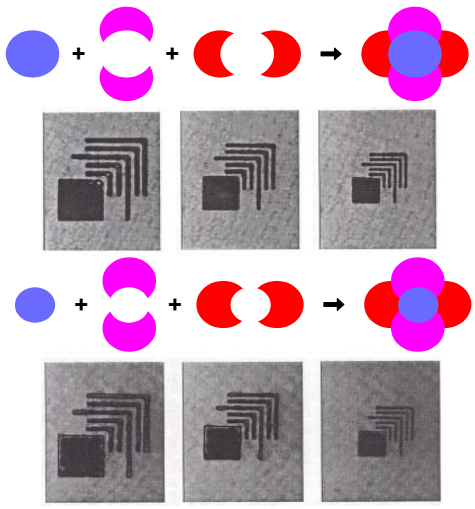
- MEEF for IIL grating simulations smaller than PCI method.
- Extended coverage enables printing of small features where PCI method fails.
- MEEF and printed CD variations occur when mask frequency moves from on-axis to off-axis exposure.

Grating Analysis: IIL Vs. PCI



Optimization Goals for IIL

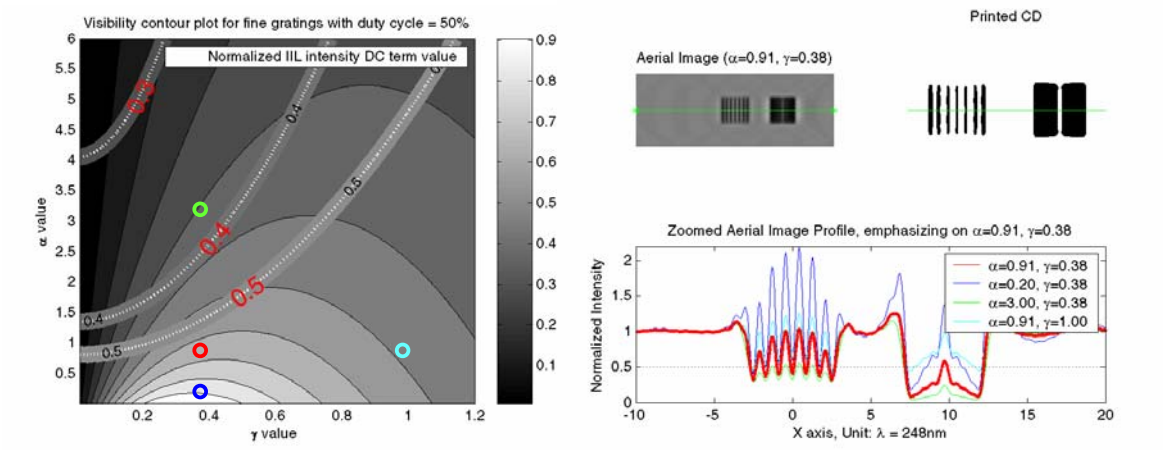
$$I_{IIL}(x,y) = \alpha \cdot I_{on}(x,y) + \left| E_{off}(x,y) + \gamma \right|^2$$



- Minimize |MEEF-1|
- Optimize frequency coverage parameters
- Design apodized pupil filters and overlap exposures.
- Optimize intensity ratios.
- Penalize fatal errors heavily.
- Error criteria should reflect aerial image defects

Optimization for IIL

$$I_{IIL}(x,y) = \alpha \cdot I_{on}(x,y) + \left| E_{off}(x,y) + \gamma \right|^2$$



Approach to Optimization

- Optimize 2 intensity parameters and 3 exposure coverage parameters.
- First optimize relative intensity parameters α,γ to maximize visibility of smallest mask feature.
- With optimized intensities determine appropriate settings for coverage parameters.
- Successively optimize relative intensities and coverage parameters until constraints are met.

Multichannel Nonlinear Restoration

- Single channel nonlinear regularization framework: linearization, regularization, least-squares.
- Iterative implementation of nonlinear regularization uses steepest decent methods.
- Multichannel restoration framework: constrained least-squares, exploit cross-channel correlation.
- IIL optimization: combination of nonlinear regularization and multichannel restoration.

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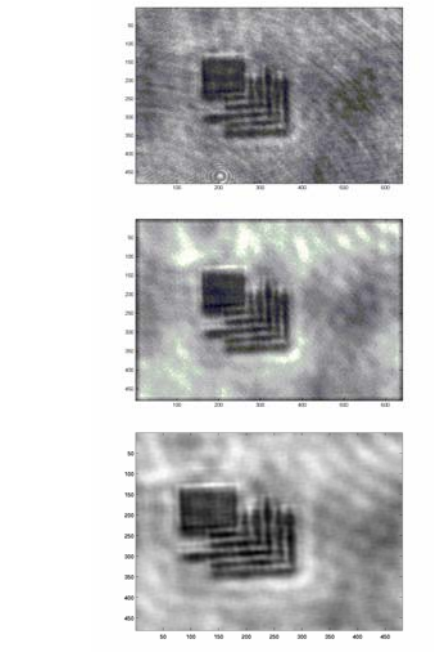
Multichannel Nonlinear Restoration

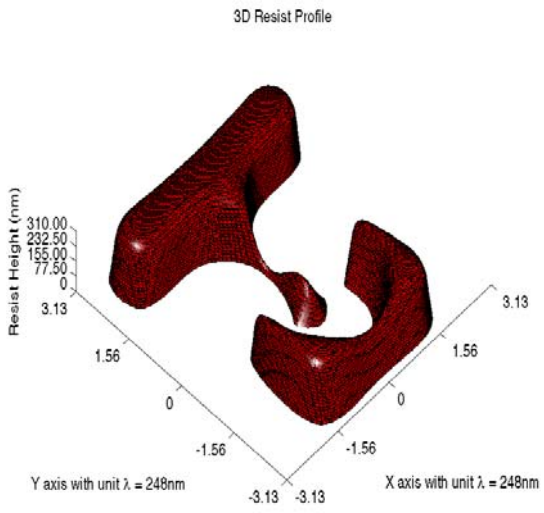
- Cross-channel redundancy introduced by overlapping pupil filters can be exploited in restoration.
- Optimization over IIL frequency coverage parameters and relative intensities subject to constraints.
- Choice of error norm determines the complexity of optimization.
- Nonlinearity : Multimodal error surface with multiple local minima.

Imaging Interferometric Microscopy



- Inverse problem: aerial image known and object required.
- Access to individual channel gray scale aerial images.
- Multichannel noise removal and restoration problem.
- Adaptive noise cancellation to remove noise and retain image features.

Research Map



- Use Gaussian pupil filters to overlap exposures to reduce ripples and improve resolution.
- Apply concepts of quadrature mirror filtering and other filterbank related ideas to IIL.
- Iterative constrained optimization problem.
- Application to imaging interferometric microscopy.
- Incorporating realistic 3D model for photoresist processing into the optimization.