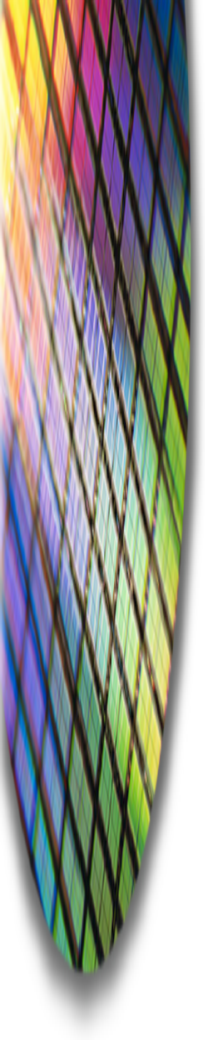

UT ECE

MOSAIC: Mask Optimizing Solution With Process Window Aware Inverse Correction

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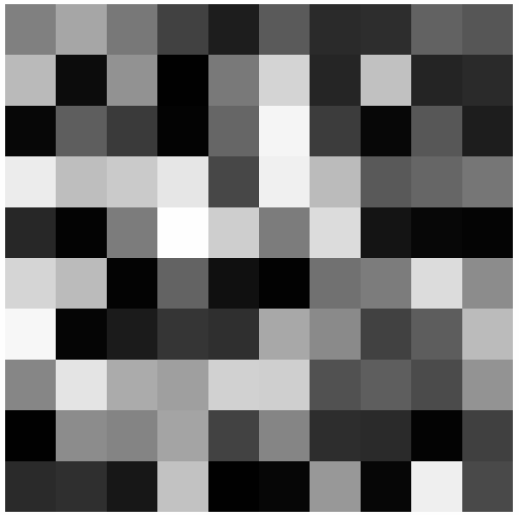
Supported in part by NSF, SRC, NSFC, and Oracle

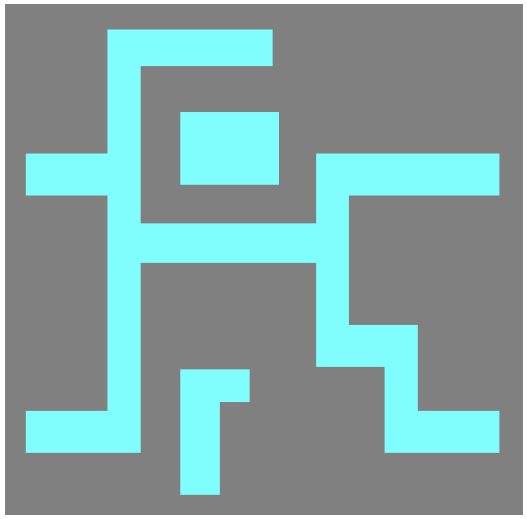
Outline

- Mask Optimization: Why & How?
- Proposed Approach: MOSAIC
- Experimental Results
- Conclusions



Sub-wavelength Lithography

Target

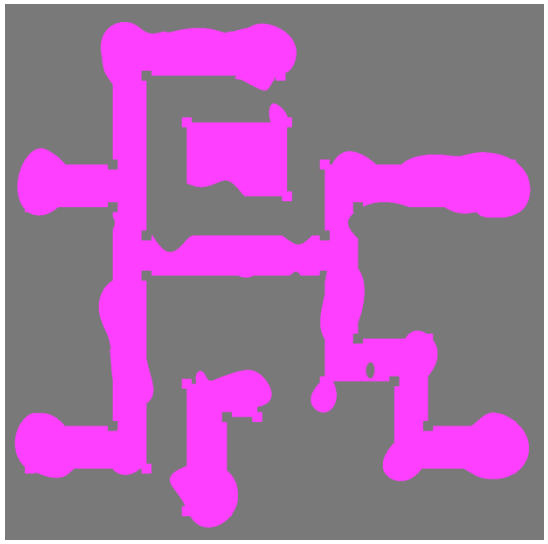


Mask

Printed Image

Image distortion due to light scattering

OPC Mask



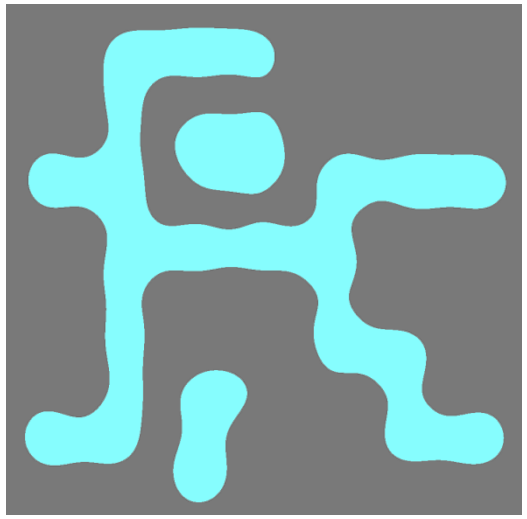
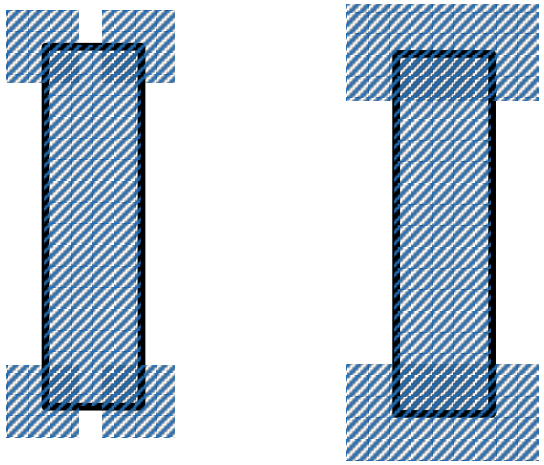


Image distortion is compensated

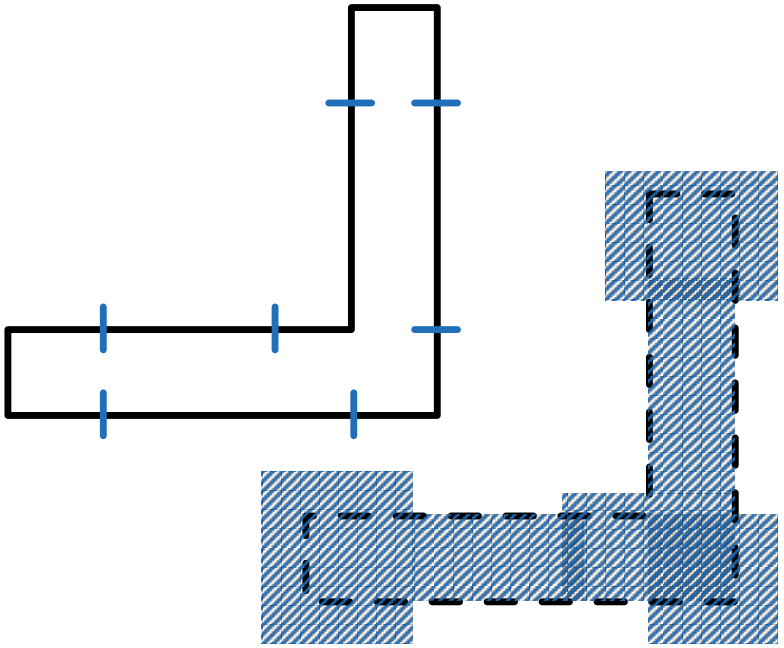
Optical Proximity Correction (OPC)

- Resolution enhancement technique
- Required for advanced technology nodes to ensure printability



Ruled-based

[A. K. Wong, SPIE Press'01]

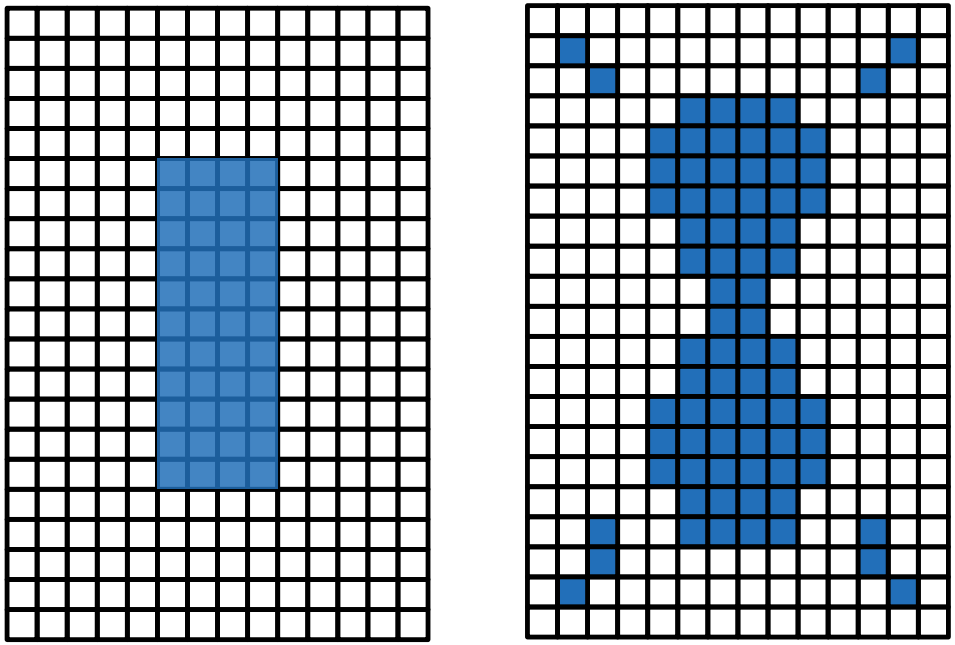


Model-based (Edge)

[N. B. Cobb+, SPIE'03]
[P. Yu+, ICCAD'07]

Inverse Lithography Technique (ILT)

- Further scaling demands more aggressive OPC
- Pixel-based OPC
  - Higher contour fidelity than conventional OPC methods



ILT-based OPC

[Y. Granik, JM3'06]
[A. Poonawala+, TCAD'07]
[J. Zhang, ICCAD'08]
[Y. Shen+, OpEx'09]
[N. Jia+, J. Opt.'10]
[J. Zhang, ASPDAC'10]
[X. Zhao+, VLSID'12]

Our Contributions

- Limitations of previous works
  - Design target optimization
    - Distortion Area → however, not all distortion matters
    - What really matters is edge placement error (EPE) beyond threshold
    - No study for direct EPE minimization
  - Process variations
    - Optical conditions: defocus, dose, …
    - One ILT study, [Jia+ J. Opt.'10], considered defocus only

- Our contributions
  - Provide exact optimization for EPE
  - Optimize both *Design Target* and *Process Variation*
  - Outperform the 1st place winner at 2013 ICCAD contest
    - 11% improvement for the overall score

Outline

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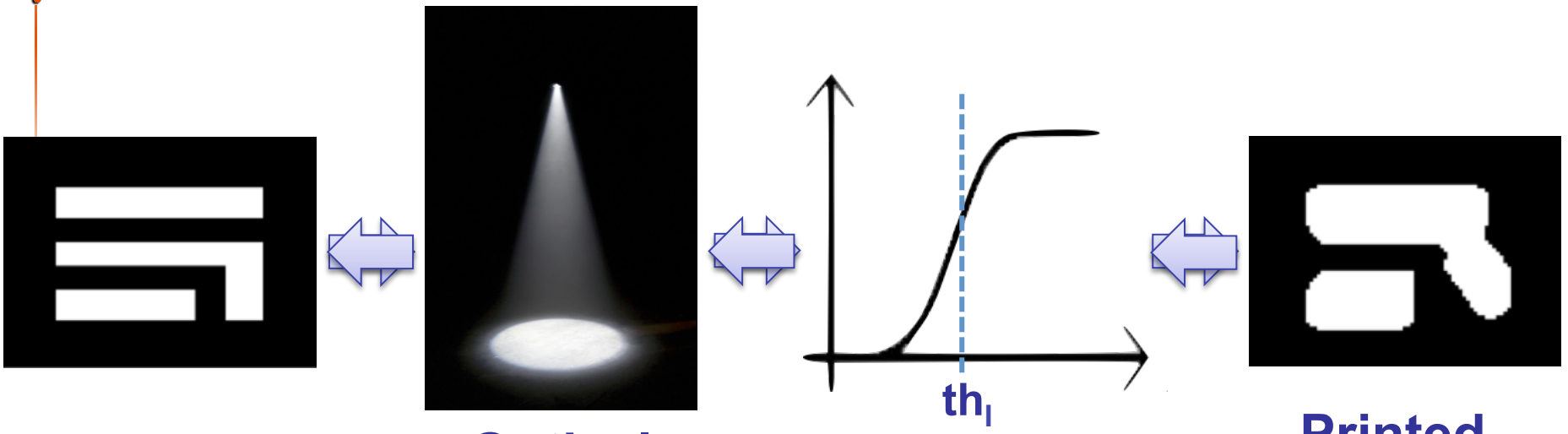
Forward/Inverse Lithography



- Forward lithography

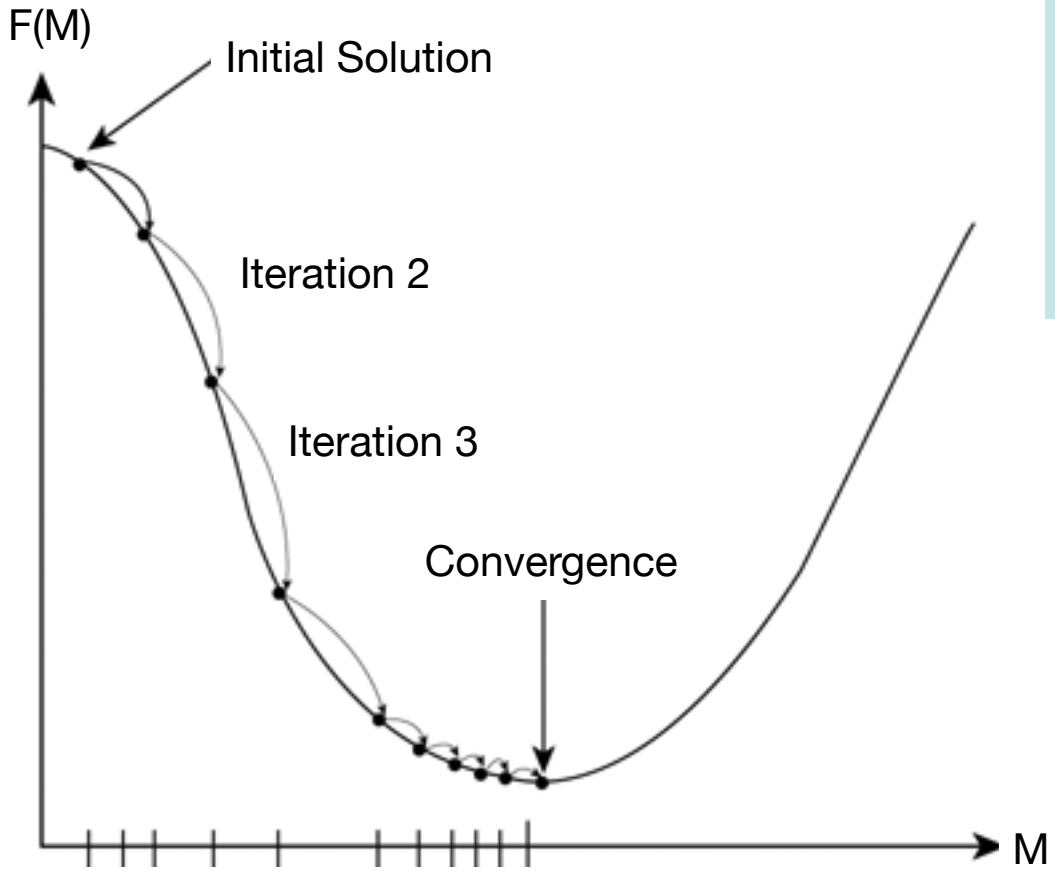
$$Z = f(M)$$

- Inverse Lithography

$$M_{opt} = f^{-1}(Z_t)$$

Difficulty
- **Ill-posed problem (not one-to-one mapping)**
- **No closed form solution**

Gradient Descent Based Approach



F ← obj(*M*) to minimize
repeat
M ← *M* – *stepSize* x ∇*F*
until *F* converges

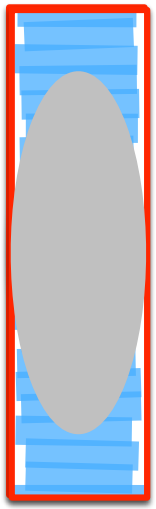
Still difficult

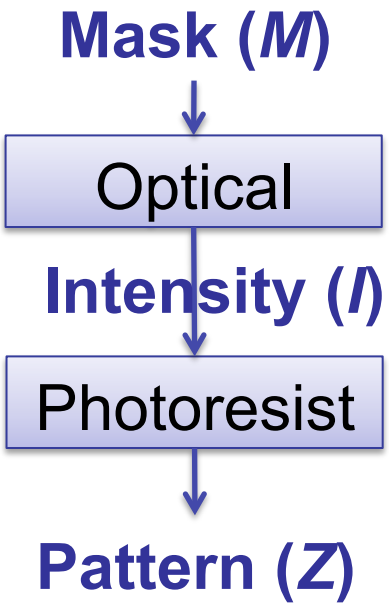
- **How to define *F* such that it**
  - ✓ **Integrates *Design Target* & *Process Variation***
  - ✓ **Is Differentiable**

Design Target Optimization (Fast)

- Total distortion minimization

$$F_{td} = \sum_{i=1}^{N}\sum_{j=1}^{N}(Z_{nom}(i,j) - Z_t(i,j))^{\gamma}$$





$$I(x,y) \approx \sum_{k=1}^{N_h} w_k |M(x,y) \otimes h_k(x,y)|^2$$

$$Z(x,y) = \begin{cases} 0 & \text{if } I(x,y) \leqslant th_r \\ 1 & \text{if } I(x,y) > th_r \end{cases}$$

$$= sig(I(x,y)) = \frac{1}{1+e^{-\theta_Z(I(x,y)-th_r)}}$$

Design Target Optimization (Exact)

- Edge Placement Error (EPE) violation minimization
  - Common measurement for yield impact (EPE > th_{epe})

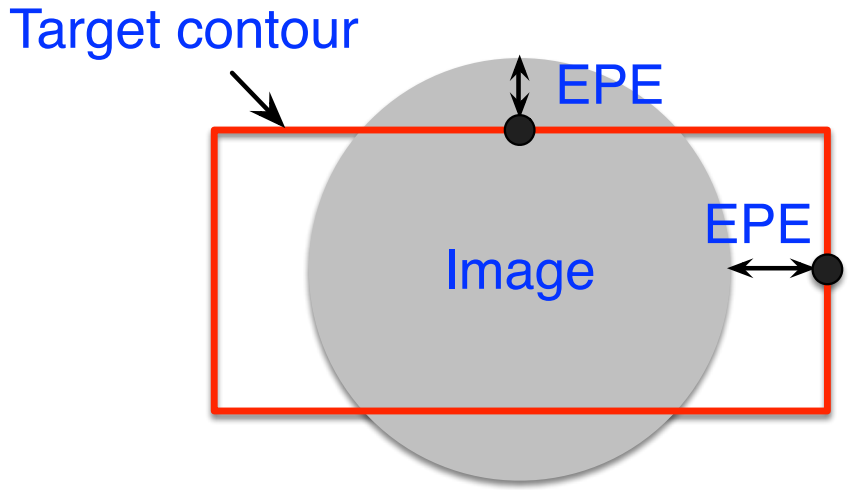


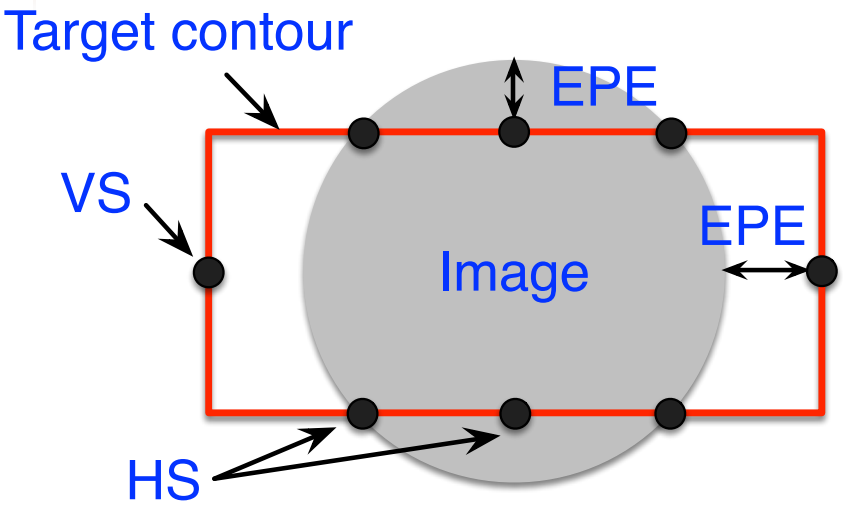
Image contour may be inside or outside of the desired boundary
➔Calculating boundary-to-boundary EPE is not a continues function

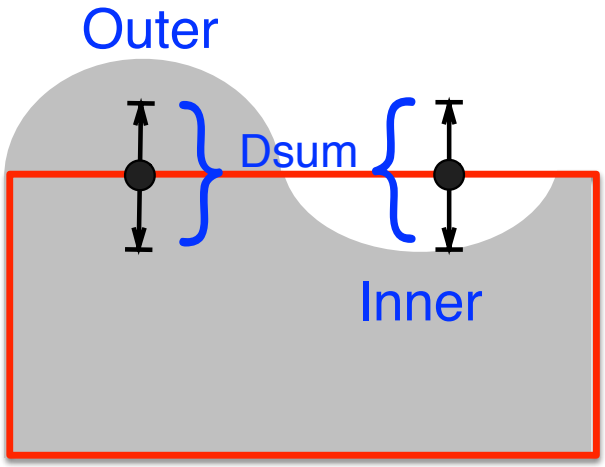
$$\text{EPE Violation} = \begin{cases} 0 & \text{if } EPE < th_{epe} \\ 1 & \text{if } EPE \geqslant th_{epe} \end{cases}$$

(Non-differentiable)

Design Target Optimization (Exact) (cont')

- EPE violation minimization
  - Formulated as a continuous function (Differentiable!)

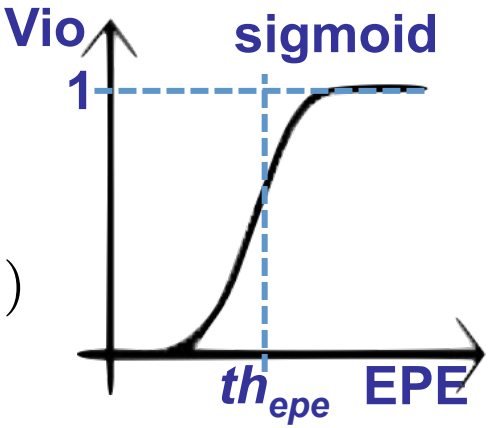




Observation: distortion is continuous

$$\text{EPE Violation} = \begin{cases} 0 & \text{if } Dsum_{i,j} \ll th_{epe} \\ 1 & \text{if } Dsum_{i,j} \gg th_{epe} \end{cases}$$

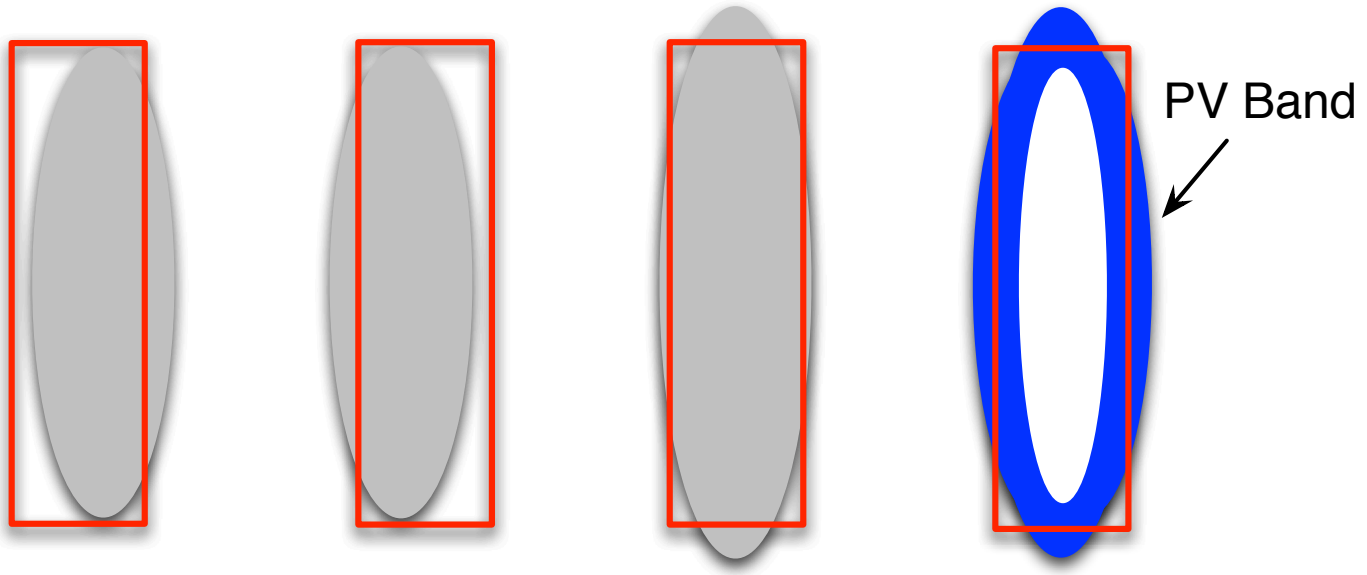
$$F_{epe} = sig(Dsum_{i,j}) + sig(Dsum_{i,j})$$



(Continuous/Differentiable)

Process Window Optimization

- Process variability band (PV band)
  - Area between the outermost and the innermost edges among all process conditions



$$F_{pvb} = \sum_{k=1}^{N_p} (Z_k - Z_t)^2$$

***Np*: #Process conditions**

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Experiment Setup

- MOSAIC_fast (Total Distortion + PV band)

$$F_{fast} = \alpha F_{td} + \beta F_{pvb}$$

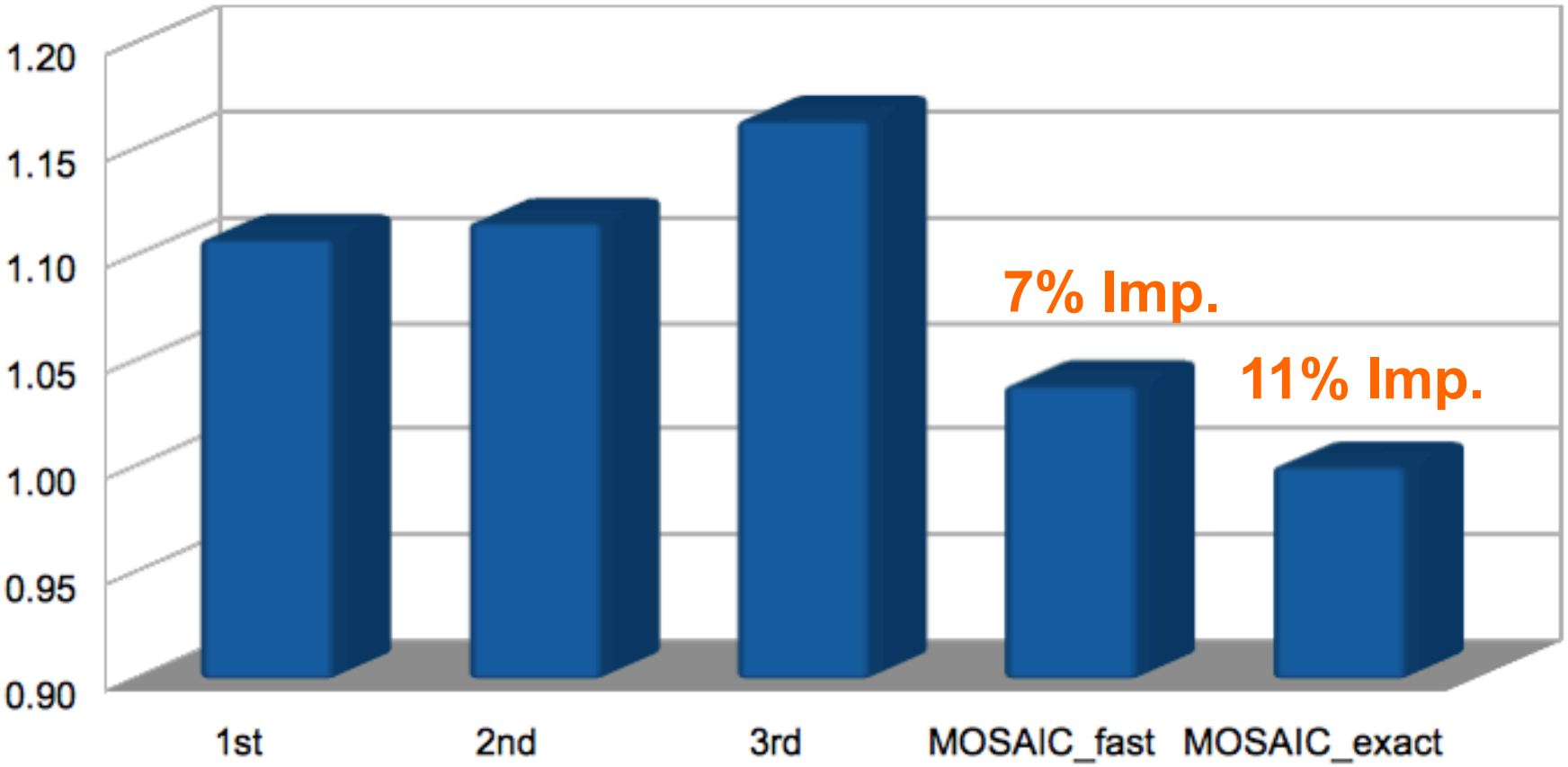
- MOSAIC_exact (EPE Violation + PV band)

$$F_{exact} = \alpha F_{epe} + \beta F_{pvb}$$

- Benchmark
  - 10 layout clips from 32nm M1 layer released by IBM
- Lithography parameters
  - 193nm wavelength
  - Process variations: ±25nm defocus, ±2% dose
- Evaluation (ICCAD Contest 2013)

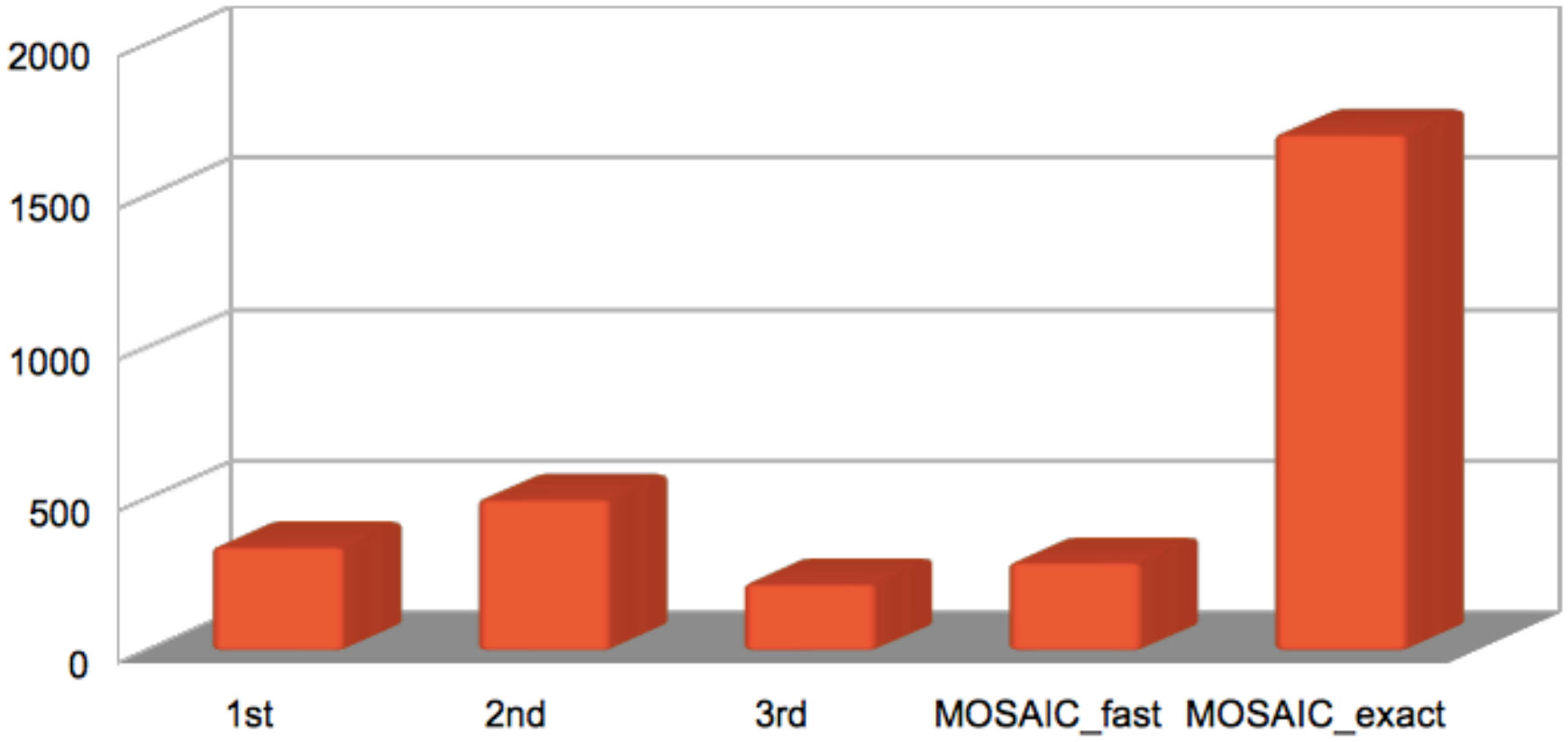
$$Score = Runtime + 4 \times PVB + 5000 \times \#EPE$$

Score Comparison



Both approaches outperform ICCAD'13 contest winners

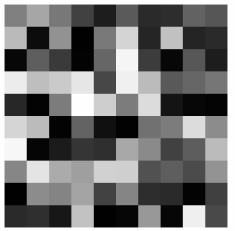
Runtime Comparison



Conclusion

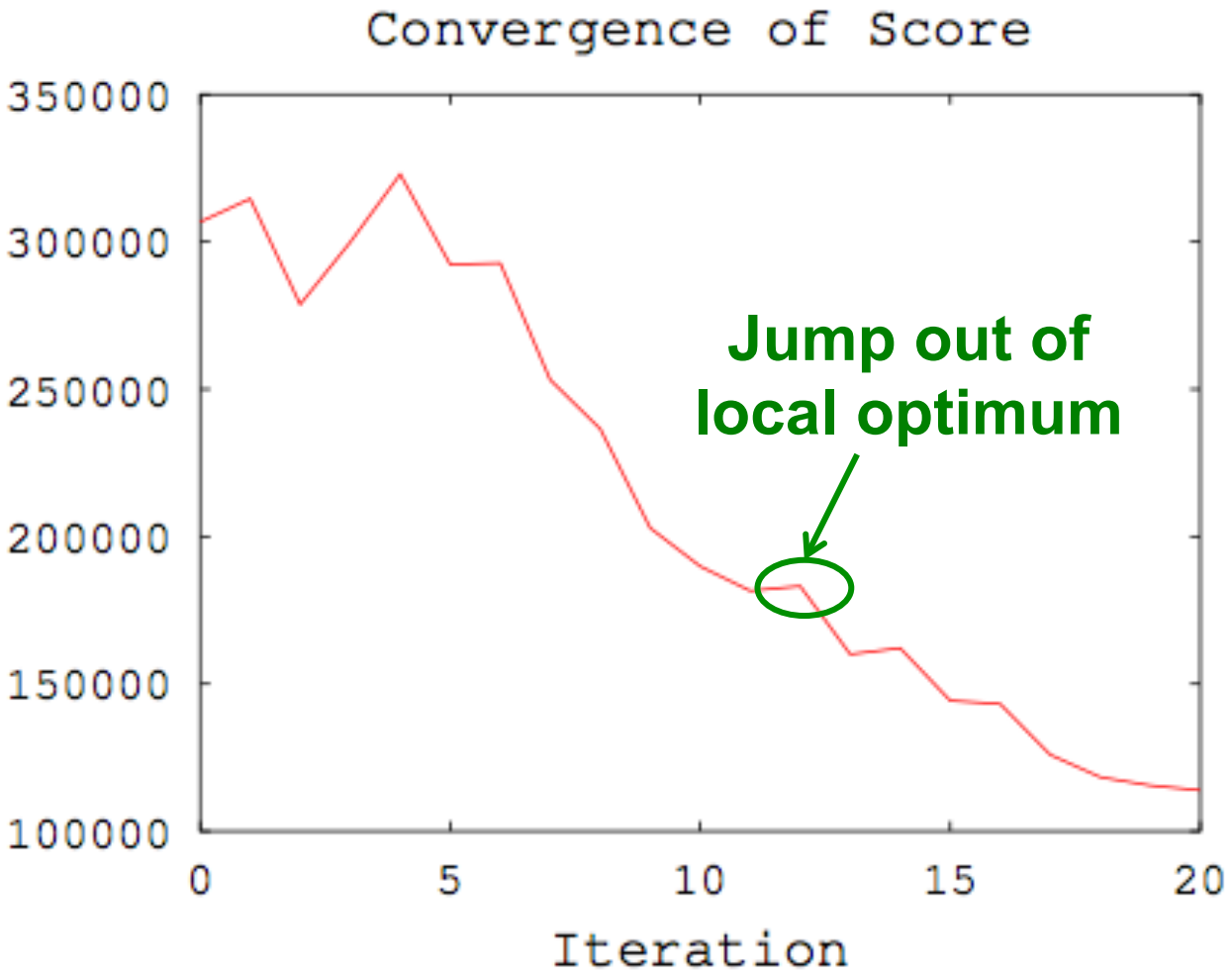
- ILT-based OPC that simultaneously optimizes *Design Target* and *Process Variation*
  - More accurate EPE formulation into the ILT engine
  - Continuous and differentiable
  - 11% overall improvement than the 1st place winner
- Future directions
  - Our framework can be extended to handle mask complexity
  - Multiple patterning, 3D effects
  - New emerging lithography such as DSA
  - Co-optimizations with design rules, hotspots, etc…

Thank you!



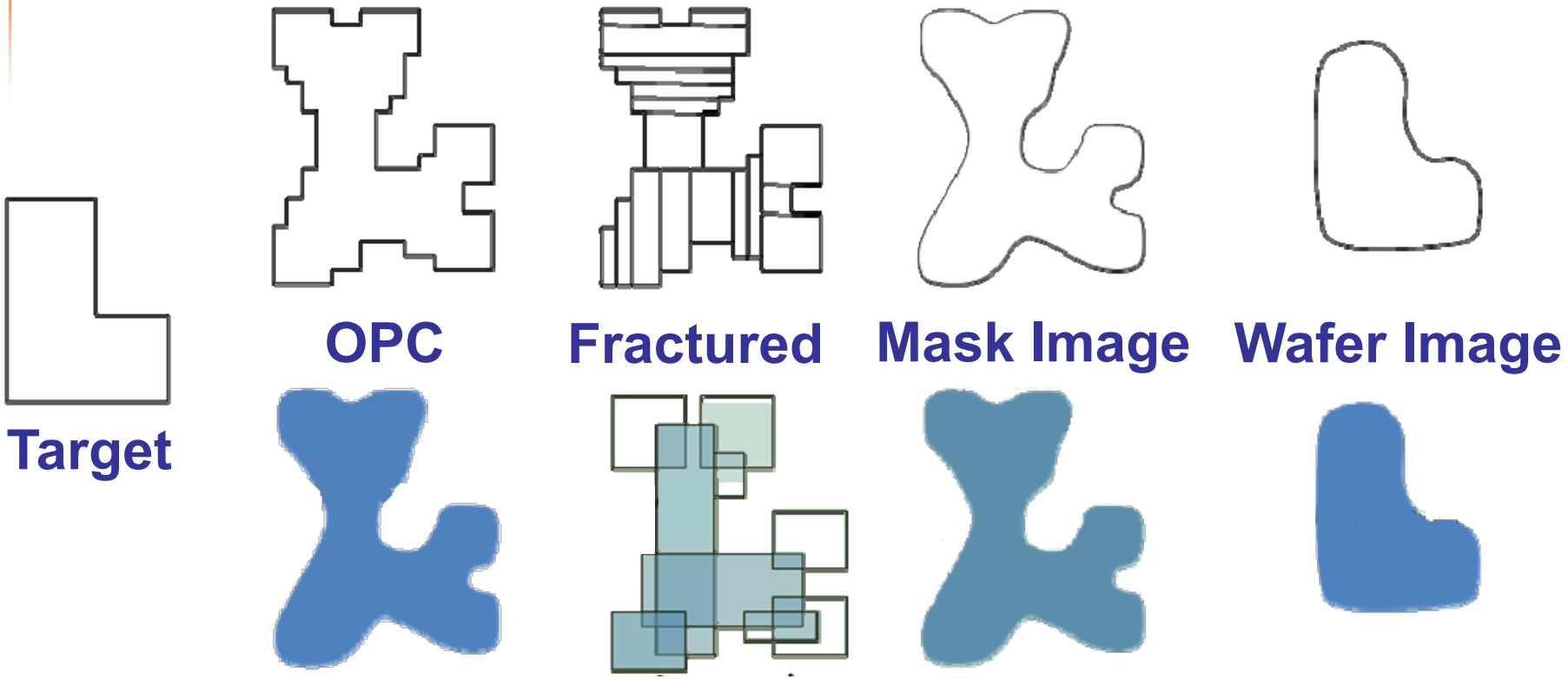
Gradient Descent Convergence

- All benchmarks converges within 20 iterations



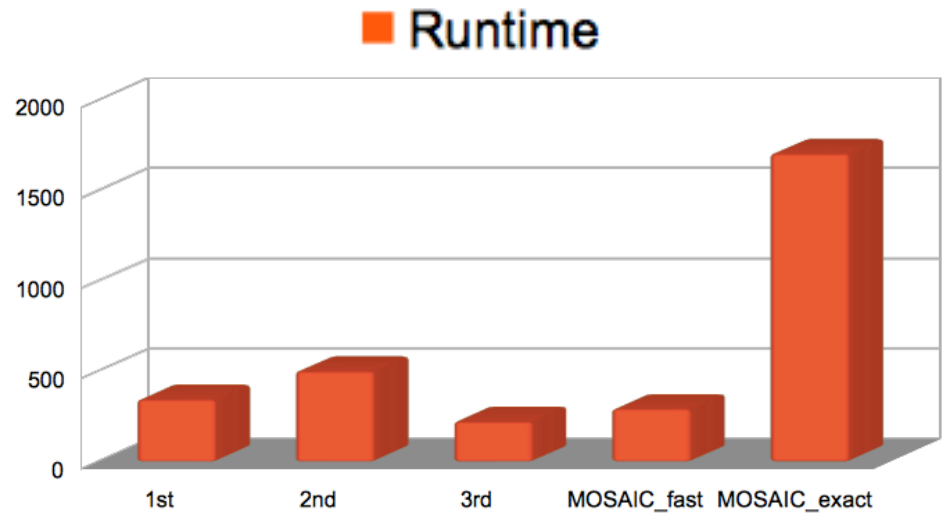
Regularization: Needed or Not?

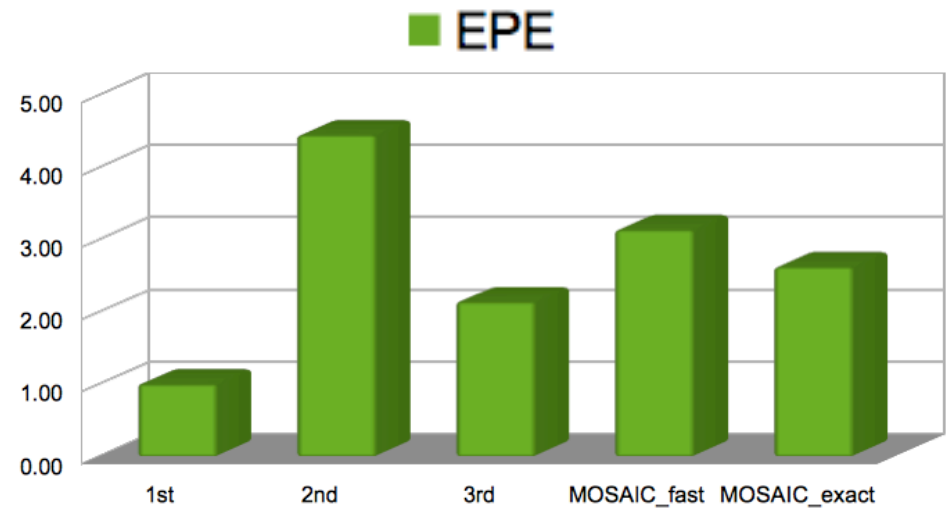
- An example of E-beam mask writing [Zable+, SPIE'2010]

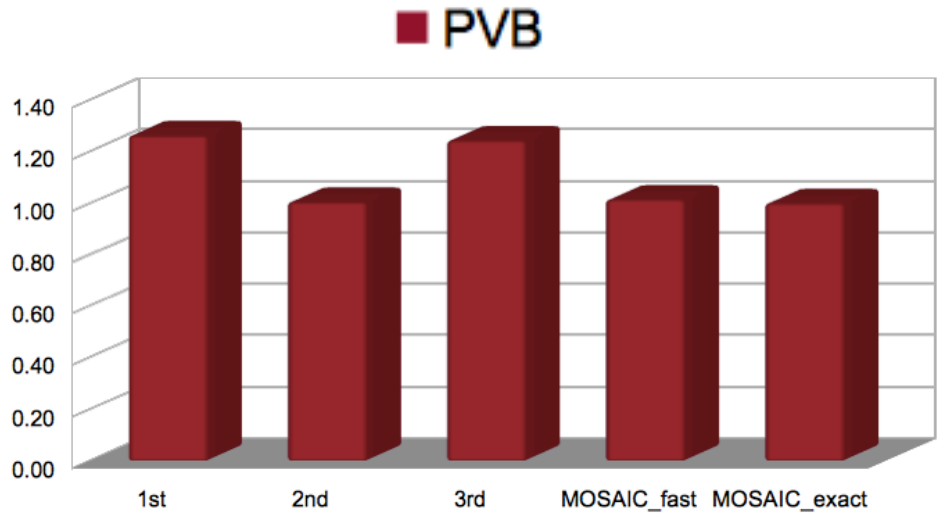


Curved lines may be well handled with advanced techniques

Runtime/EPE/PVB Comparison







OPC Results

Target	OPC Mask	Final pattern	PV Band