Fracturing-aware Curvilinear ILT via Circular E-beam Mask Writer

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Introduction

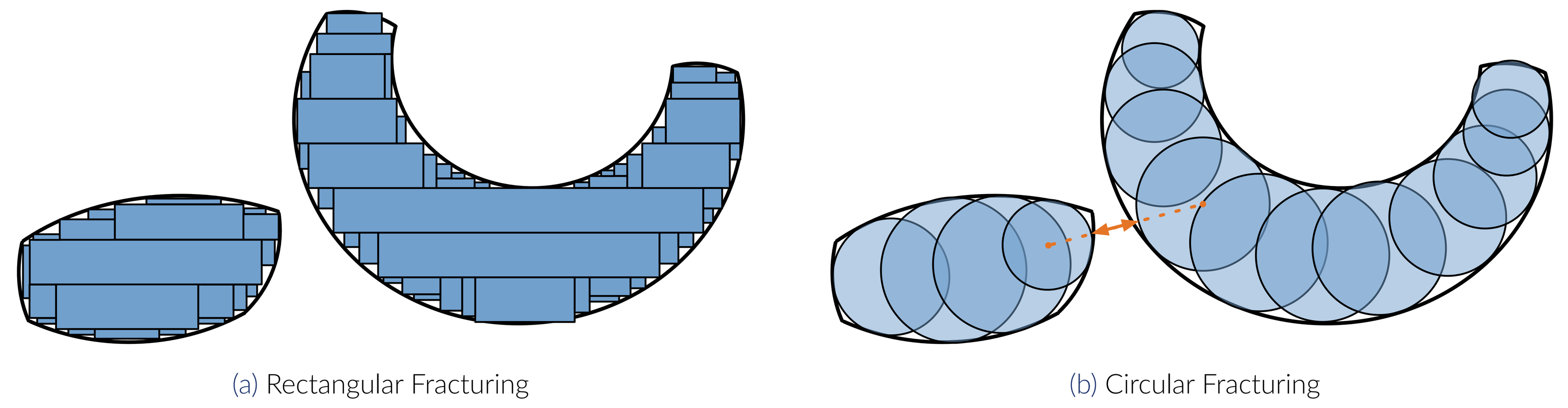

Figure 1. Fracturing pattern comparison. Circular fracturing requires much fewer shots for curvilinear masks compared with rectangular fracturing and is MRC-friendly.

Motivation:

- Traditional Variable Shaped-Beam (VSB) machines utilize varying sizes of rectangular shapes, requiring Mask Data Preparation (MDP) to fracture these shapes into non-overlapping rectangles or VSB shots for printability.
- The Manhattanization-based fracturing of curvilinear shapes, especially small sub-resolution assist features (SRAFs), results in a substantial increase in the number of shots.
- [2] introduces a new circular e-beam mask writer that writes a variable-radius circle for each shot and allows overlapping writing, as shown in Figure 1b.
- The circular mask writer requires **much fewer shots** than rectangular-based ones.
- The circularly fractured curvilinear masks are also **mask rule checking (MRC)-friendly** since we can effortlessly check the distances between the circular shots with their positions and radii.

Problem Formulation:

Given a target pattern $\boldsymbol{T}$, our goal is to obtain a mask $\boldsymbol{M}$, which is perfectly fractured into a set of overlapping circles with a radius within a proper range, to minimize the squared L2 loss, PVB and the shot count.

Rule-based method: CircleRule

Overview

- Find the skeleton in each shape.
- Construct the skeleton graph, as shown in Figure 2a.
- Sample the circle centers.
- Find a proper radius for each circle, as shown in Figure 2b.

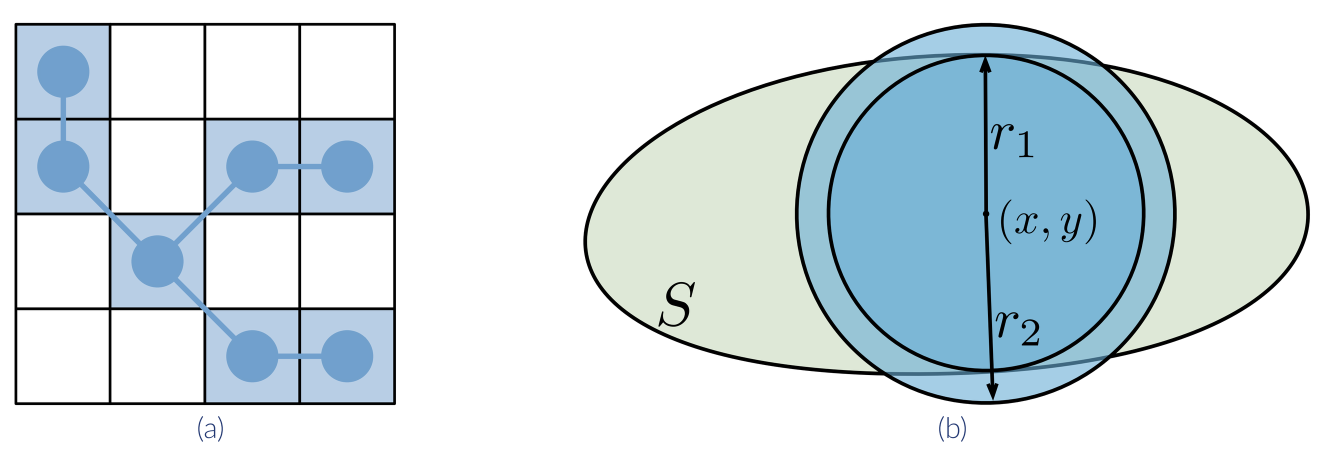

Figure 2. Illustration of the key steps in CircleRule. (a) Construction of the skeleton graph; (b) the spanning process of the circle radius.

Algorithm 1 The Rule-based Method for CFAOPC

Input: Raw mask A, sample distance m, maximum radius $R_{\max}$, minimum radius $R_{\min}$, cover rate threshold I.
Output: Circular fractured mask $\tilde{A}$.
Initialize an empty stack t;
$V \leftarrow \emptyset$, $\tilde{A} \leftarrow \emptyset$;
$\{A_1, \cdots, A_n\} \leftarrow$ `findConnectedRegions`(A);
for $i \in \{1, \cdots, n\}$ **do**
  $S_i \leftarrow$ `findSkeleton`(A_i);
  Randomly sample a point p_i in S_i;
  Push $(p_i, 0)$ to t; ▷ DFS-based point sampling
  while t is not empty **do**
    $(u, cnt) \leftarrow$ `Pop` t;
    if u not in V **then**
      $V \leftarrow V \cup u$;
      $N \leftarrow$ `findNeighborPoints`(u);
      for $n \in N$ **do**
        if $n \notin V$ **then**
          Push $(n, cnt + 1)$ to t;
      if $cnt \mod m == 0$ **then**
        for $r \in \{R_{\min}, \cdots, R_{\max}\}$ **do** ▷ Circle radius selection
          cover rate $\leftarrow \frac{|C(u,r) \cap A_i|}{|C(u,r)|}$;
          if cover rate $< I$ **then**
            $\tilde{A} \leftarrow \tilde{A} \cup C(u, r)$;
            break;

Optimization-based method: CircleOpt

Overview

- Pixel-level initialization
- Sparse circular re-parameterization
- Differentiable circle-to-pixel transformation

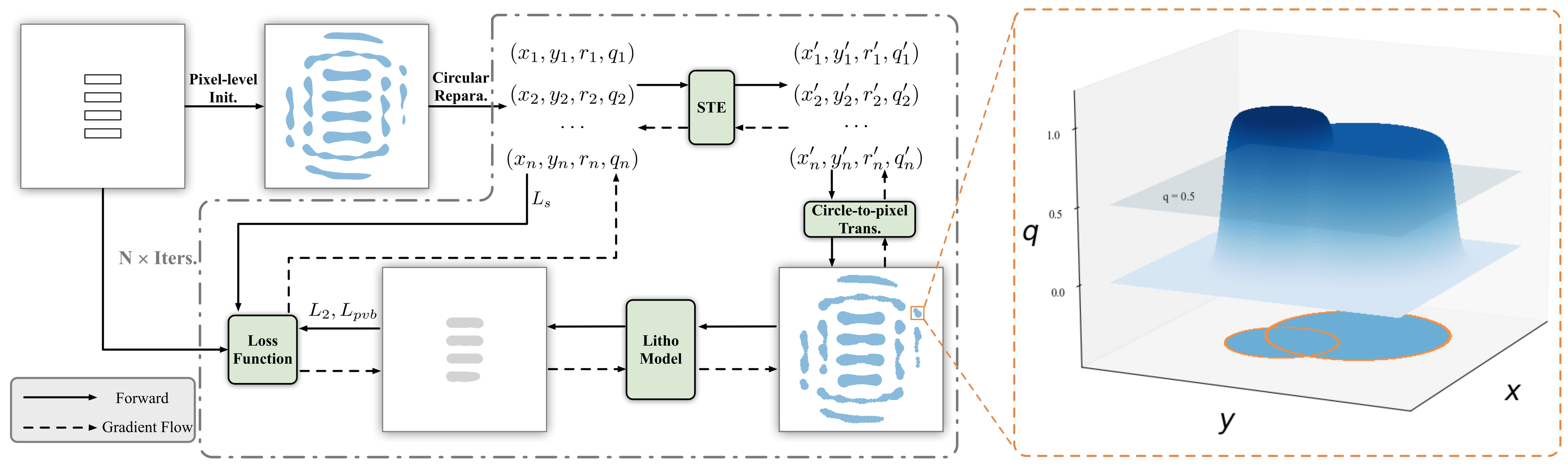

Figure 3. Overall flow of CircleOpt.

Differentiable circle-to-pixel transformation:

- Quantization of the coordinates and radius using a straight-through estimator (STE).

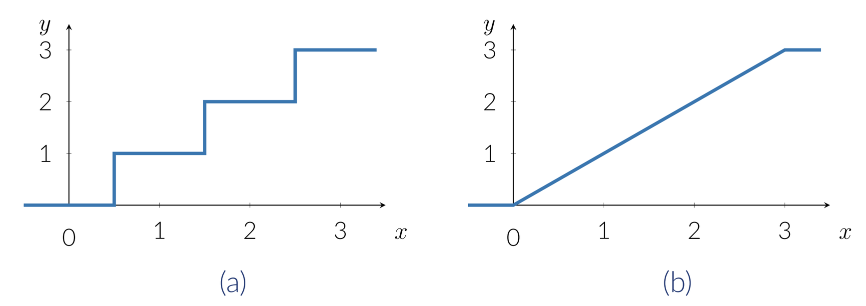

Figure 4. Visualization of the straight-through estimator. (a) STE forward; (b) STE backward.

- For each circle, we define a window function as:

$$f_{x_i', y_i', r_i'}(x, y) = \frac{1}{1 + e^{-\alpha(-\sqrt{(x-x_i')^2 + (y-y_i')^2} + r_i')}}, \tag{1}$$

where (x, y) are the variables and can be any position in a 2D dense mask, and α is a hyper-parameter for adjusting the steepness of the window function.

- With this window function, we can define the transformation as:

$$\tilde{\boldsymbol{M}}(x, y) = \max_{i \in \{1, \cdots, n\}} \{q_i f_{x_i', y_i', r_i'}(x, y)\}. \tag{2}$$

This transformation is differentiable. A schematic illustration is shown in Figure 5.

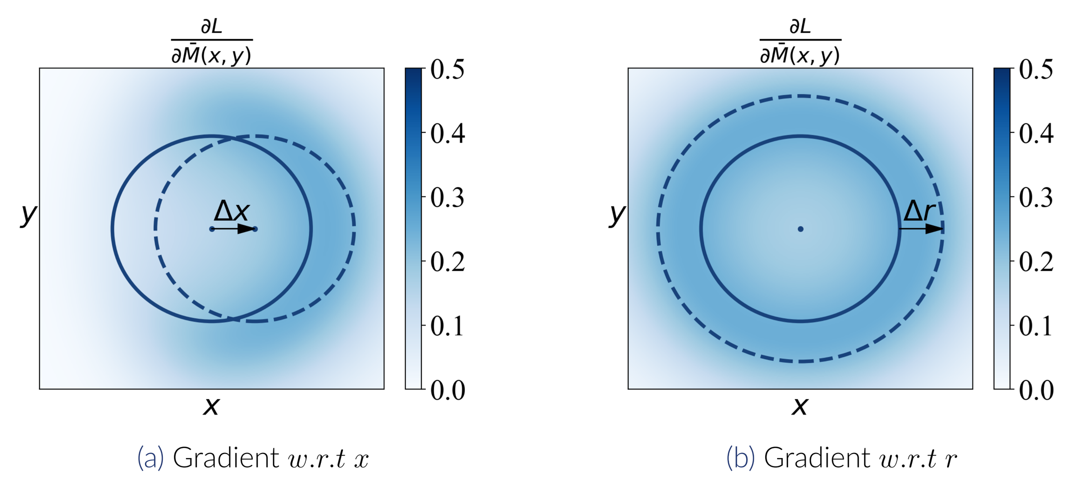

Figure 5. Schematic illustration of the updates of the circular representations from the gradient of the dense mask $\tilde{\boldsymbol{M}}$.

Experiments

Main results:

Table 1. Mask Printability, Complexity Comparison for CircleRule and CircleOpt.

Bench	Area(nm^2)	Develset [1]+CircleRule				NeuralILT [3]+CircleRule				MultiILT [4]+CircleRule				CircleOpt			
		L_2	PVB	EPE	#Shot	L_2	PVB	EPE	#Shot	L_2	PVB	EPE	#Shot	L_2	PVB	EPE	#Shot
case1	215344	59632	51087	23	102	53005	57775	13	170	49293	46945	8	253	43358	46905	3	214
case2	169280	53240	42993	19	80	45662	53770	13	128	39583	38565	2	236	35496	37920	1	215
case3	213504	107342	70906	69	205	93116	92536	61	213	105217	64381	69	242	75206	66241	32	194
case4	82560	21512	25623	7	44	18912	28873	6	73	14209	23649	2	164	13205	23234	1	104
case5	281958	53242	52706	4	140	52714	53575	8	192	32398	51711	0	317	34938	53110	1	172
case6	286234	52837	48595	5	203	48805	52200	7	190	38767	48290	1	313	36797	44629	0	252
case7	229149	36973	43124	0	146	24560	47353	0	146	17391	38744	0	335	21036	41118	0	175
case8	128544	18209	22917	1	65	16730	27114	2	89	12516	19968	0	181	13906	19859	0	169
case9	317581	62119	59295	8	214	53743	70986	9	221	40871	58311	1	407	47844	54625	1	251
case10	102400	27205	16825	8	39	9959	20025	0	77	9034	16694	0	152	9107	16969	0	83
Average		49231.1	43407.1	14.4	**123.8**	41720.6	50420.7	11.9	149.9	35790.0	40725.0	8.3	260.0	**33089.3**	**40451.5**	**3.9**	182.9

† *L_2 and PVB unit: nm^2.*

References

[1] Guojin Chen, Ziyang Yu, Hongduo Liu, Yuzhe Ma, and Bei Yu. DevelSet: Deep neural level set for instant mask optimization. In *Proc. ICCAD*, 2021.

[2] Aki Fujimura, David Kim, Tadashi Komagata, Yasutoshi Nakagawa, Vikram Tolani, and Tom Cecil. Best depth of focus on 22-nm logic wafers with less shot count. In Kunihiro Hosono, editor, *Photomask and Next-Generation Lithography Mask Technology XVII*, volume 7748, page 77480V. International Society for Optics and Photonics, SPIE, 2010.

[3] Bentian Jiang, Lixin Liu, Yuzhe Ma, Bei Yu, and Evangeline FY Young. Neural-ILT 2.0: Migrating ilt to domain-specific and multitask-enabled neural network. *IEEE TCAD*, 2021.

[4] Shuyuan Sun, Fan Yang, Bei Yu, Li Shang, and Xuan Zeng. Efficient ilt via multi-level lithography simulation. In *Proc. DAC*, 2023.