

非干涉光学相干合成孔径成像 研究进展

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目 录 content

01

背景简介

02

傅里叶叠层成像简介

03

FP远距离成像应用

04

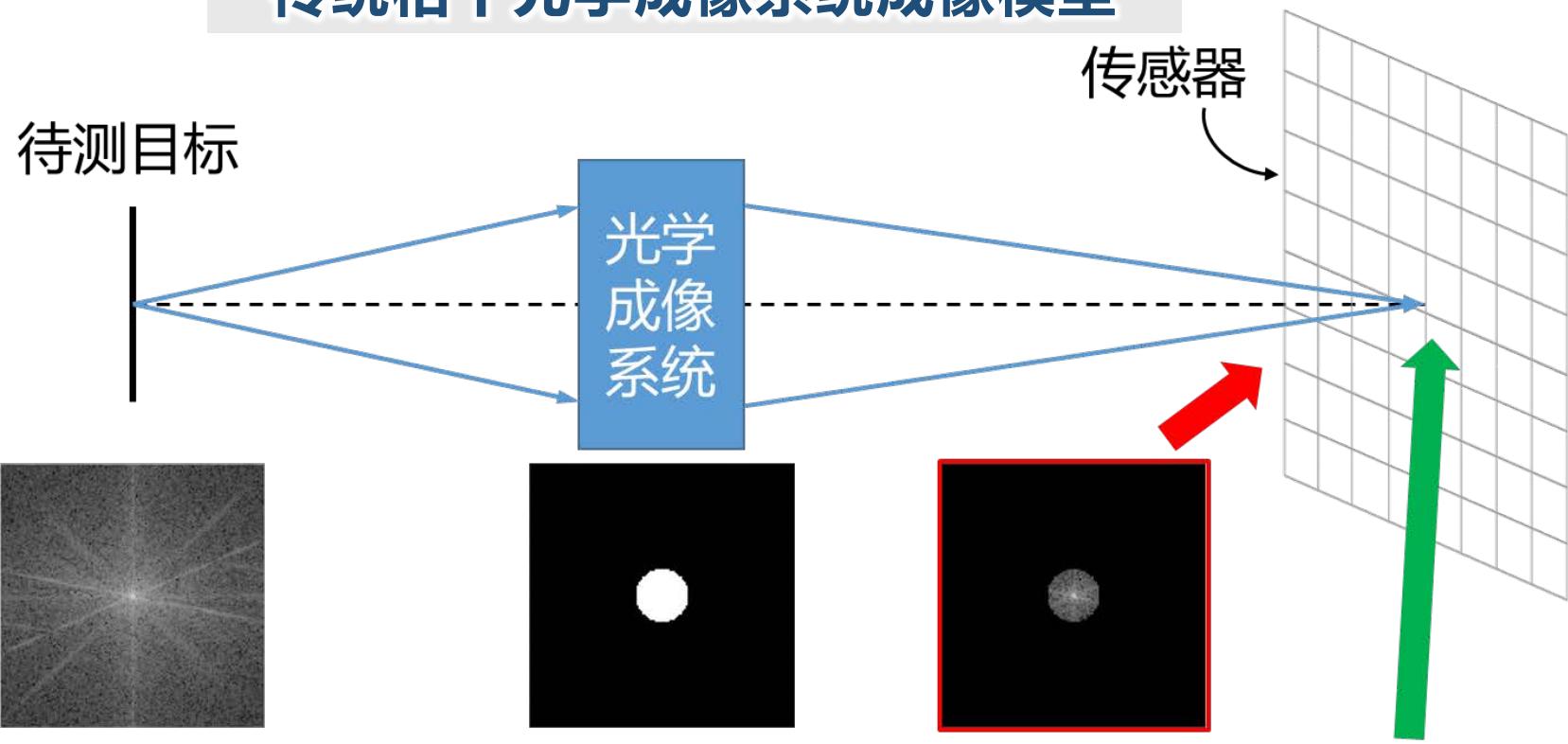
FP优化算法

05

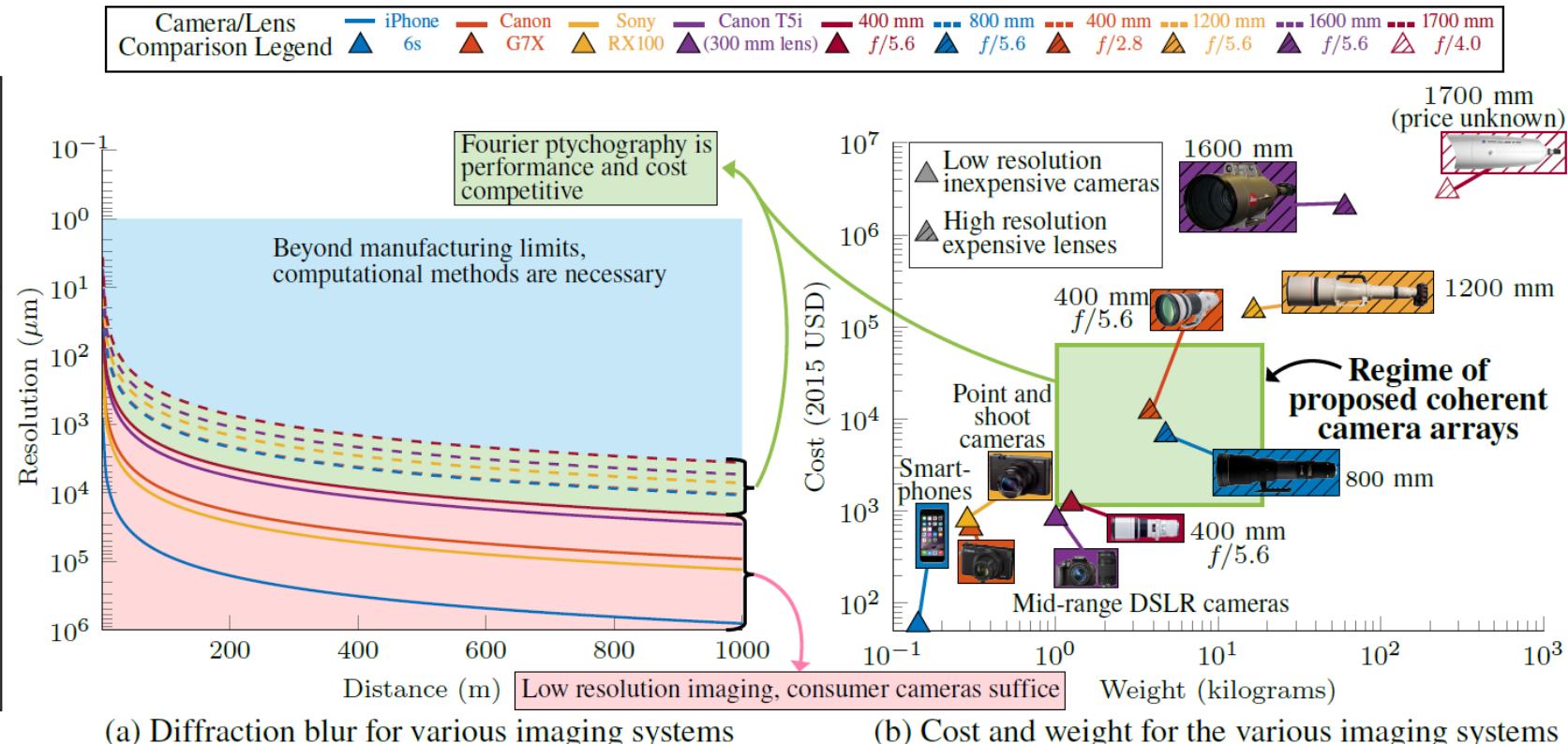
总结与展望



传统相干光学成像系统成像模型

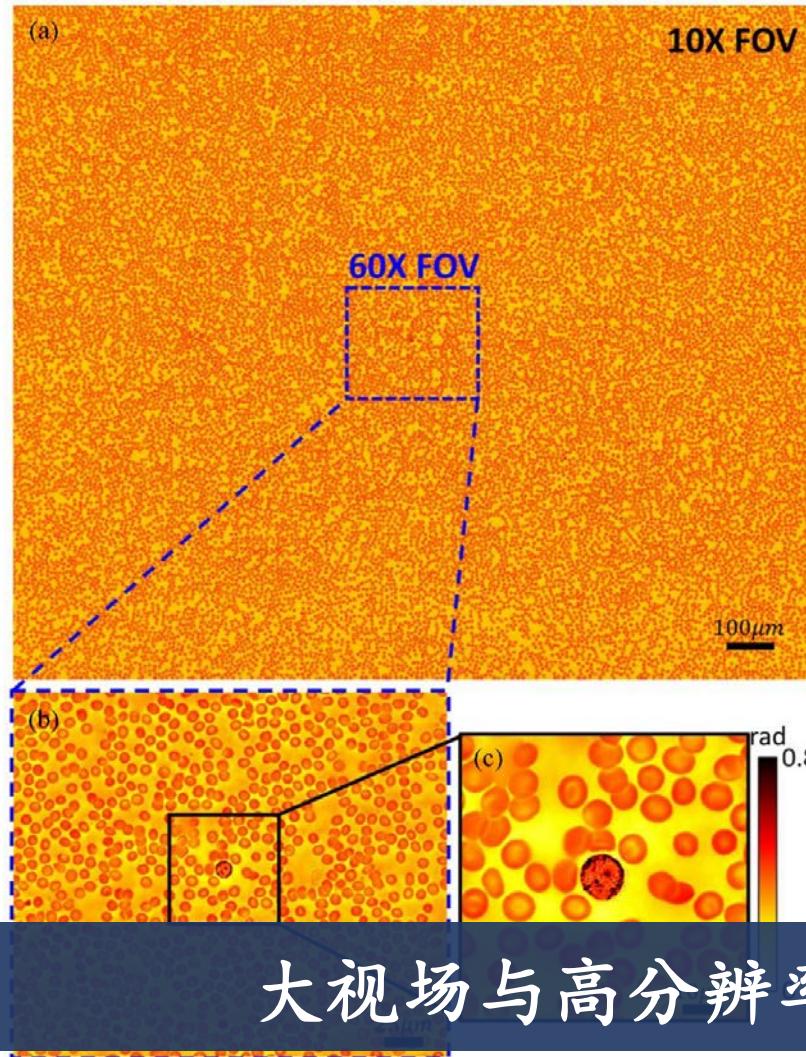


像素尺寸和衍射极限综合限制了光电成像系统的探测性能



需要引入新的计算光学成像技术，突破大视场高分辨率成像系统的技术难点

传统显微系统的空间带宽积限制



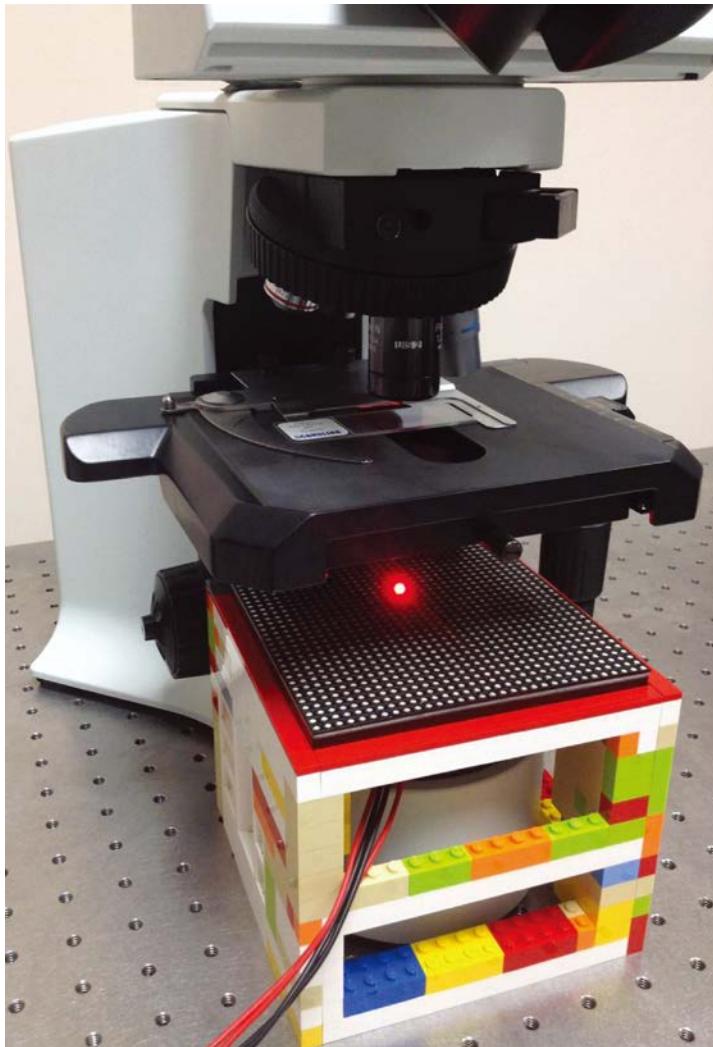
$$SBP = \frac{FOV}{(\delta/2)^2}$$

10倍物镜
大视场，低分辨率

60倍物镜
小视场，高分辨率

大视场与高分辨率相互矛盾，SBP受限

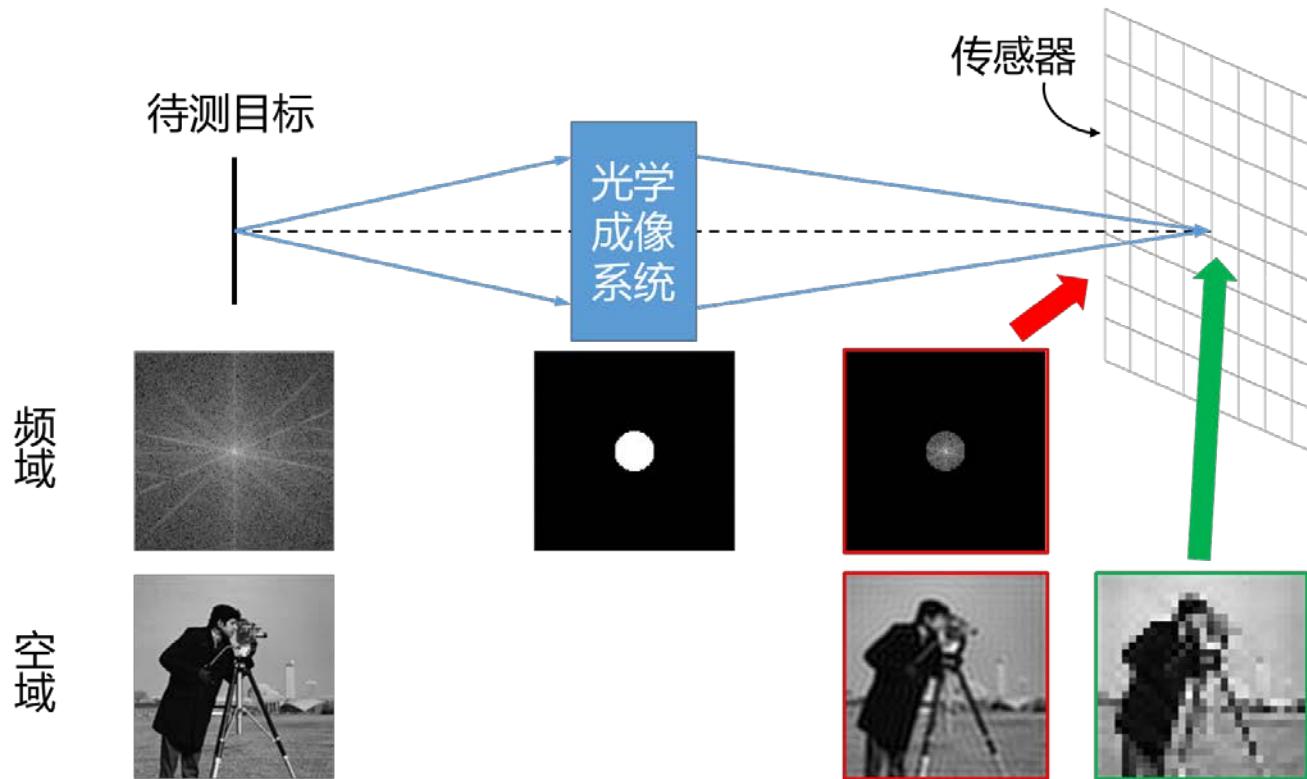
傅里叶叠层成像 (FP) 的基本概念与方法原理



2013年，郑国安等人首次提出了傅里叶叠层显微成像技术（Fourier Ptychographic Microscopy, FPM）

将傅里叶叠层成像应用在显微成像领域中，利用**不同角度LED光源照明**的低分辨率图像，在频域中对相应位置的频谱进行更新，从而**扩展物体的频谱**，增大空间带宽积（SBP），解决了传统显微成像系统中的视场和分辨率的矛盾，在保持大视场的同时提高分辨率

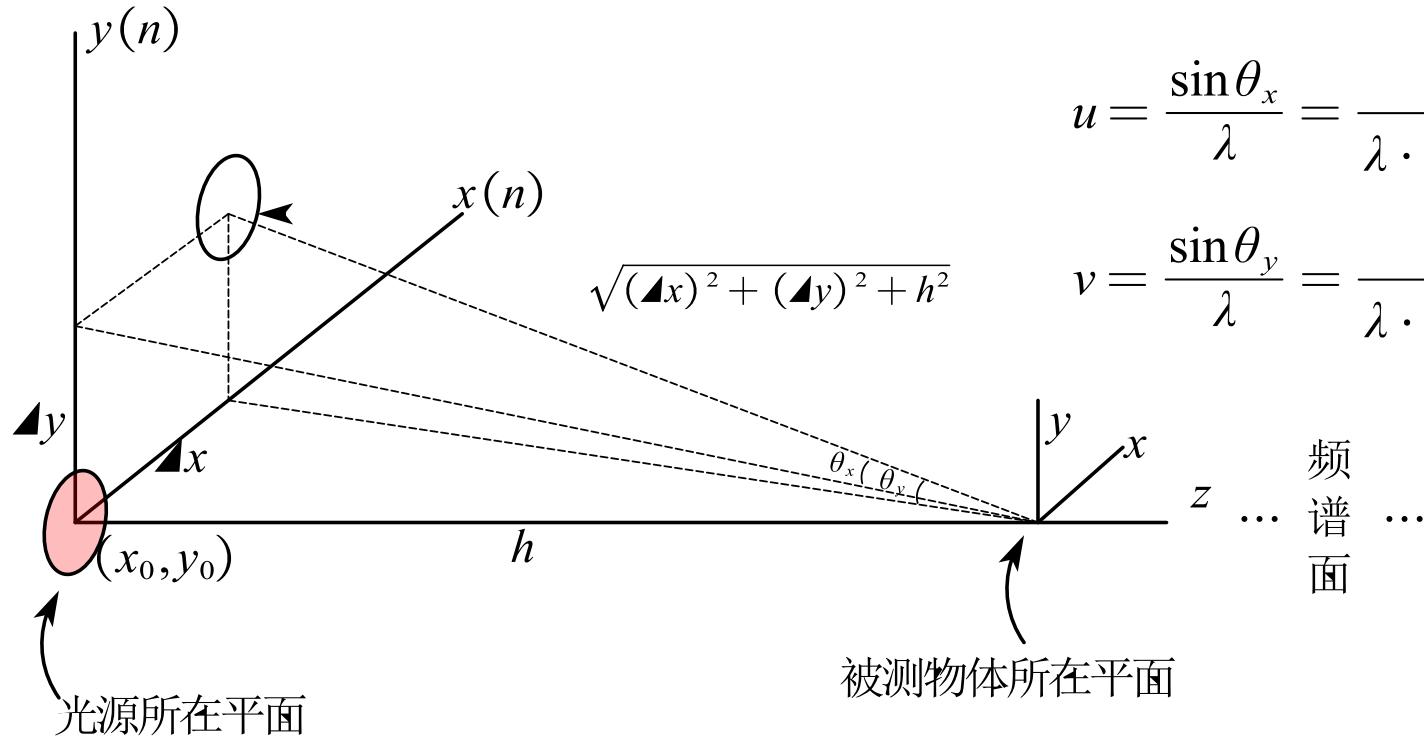
传统相干光学成像系统成像模型



$$A_{output}(x,y) = h(x,y) \otimes A_{input}(x,y)$$

$$F_{output}(k_x, k_y) = H(k_x, k_y) \cdot F_{input}(k_x, k_y)$$

傅里叶叠层成像的基本成像模型



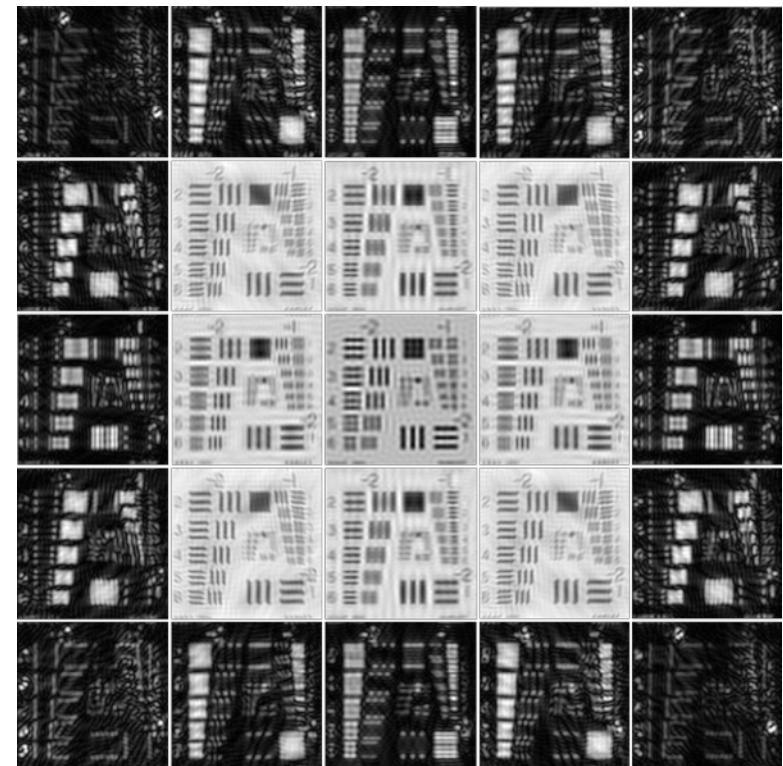
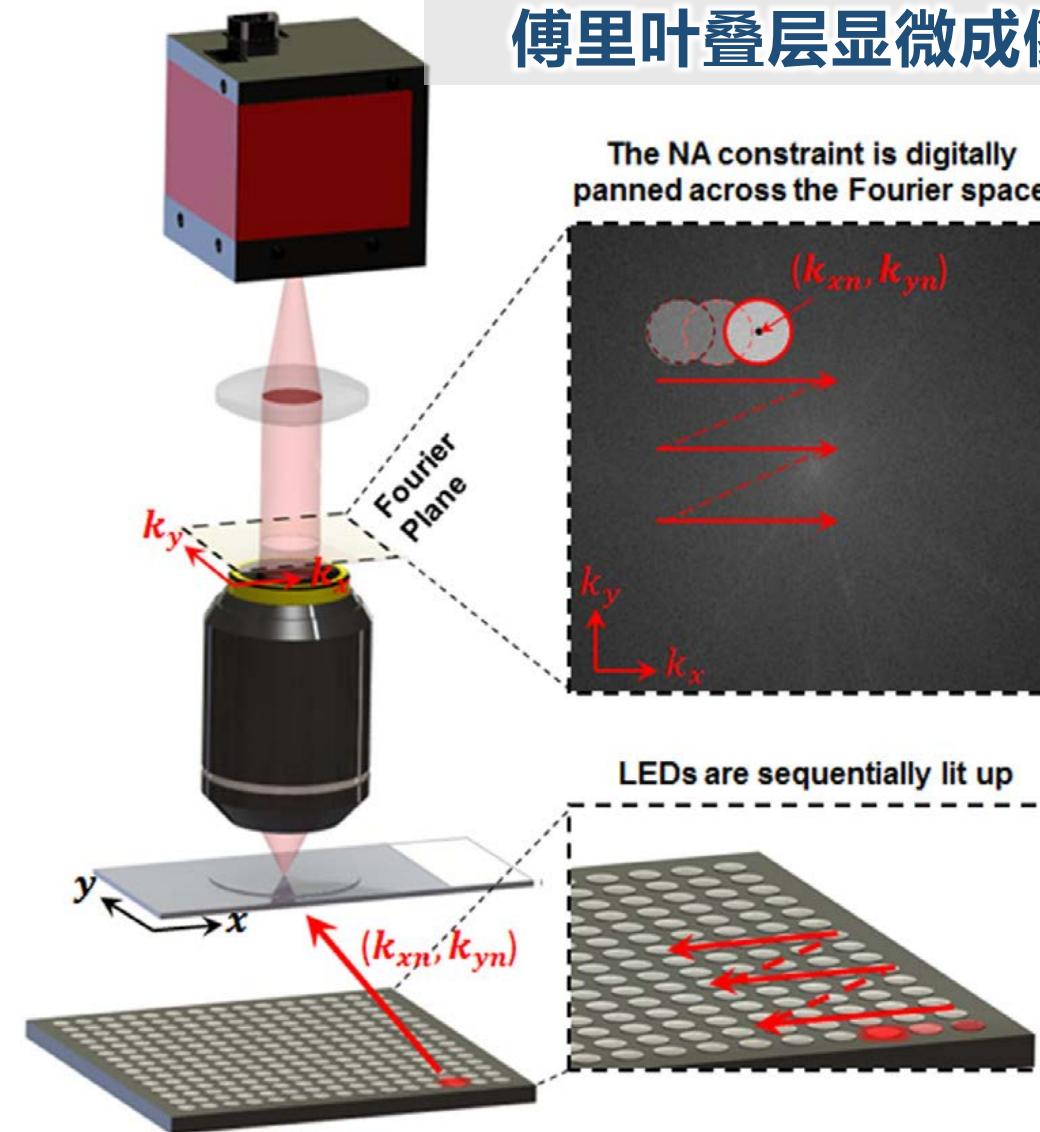
$$A_{output}(x, y) = h(x, y) \otimes (A_{input}(x, y) \cdot \exp [i2\pi(u \cdot x + v \cdot y)])$$

$$F_{output}(k_x, k_y) = H(k_x, k_y) \cdot F_{input}(k_x - k_{xn}, k_y - k_{yn})$$

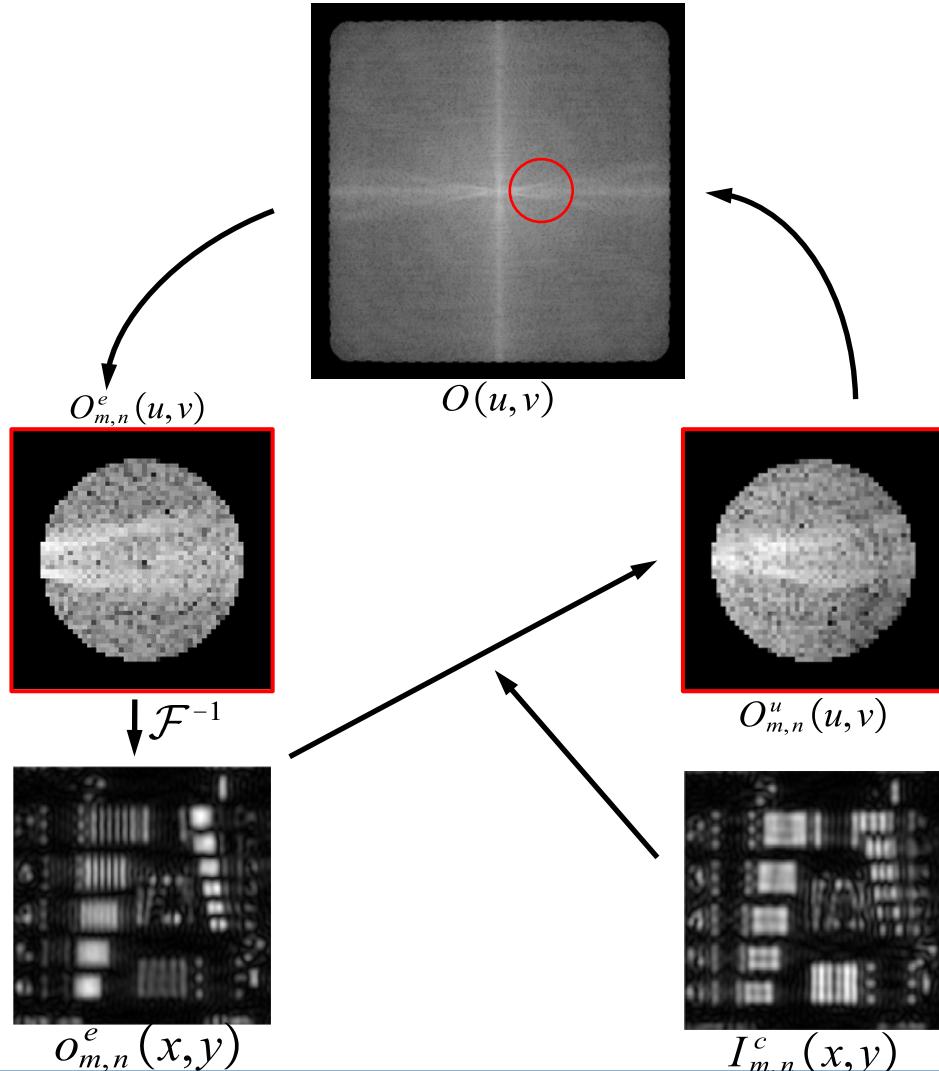


傅里叶叠层成像简介

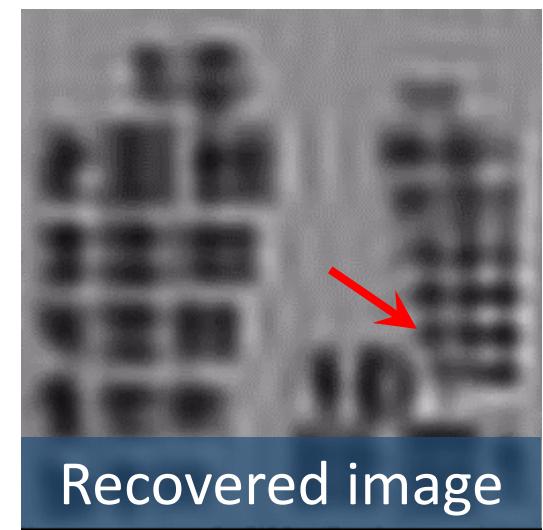
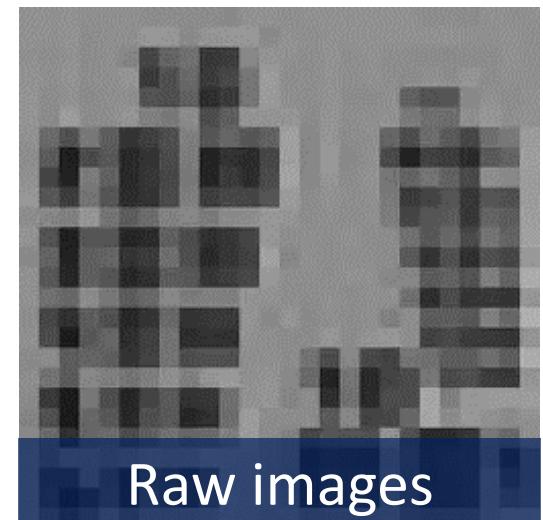
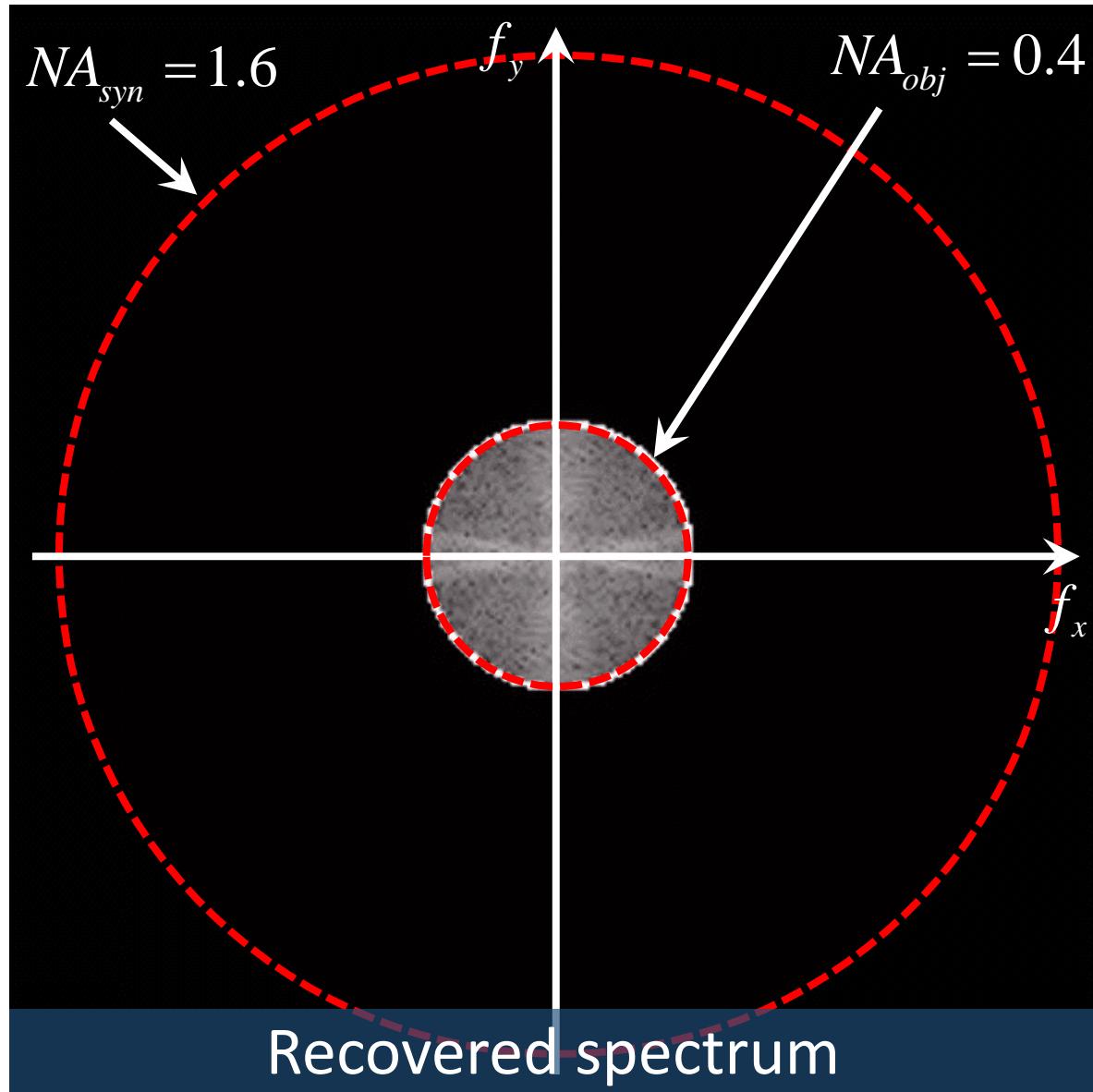
傅里叶叠层显微成像的数据获取



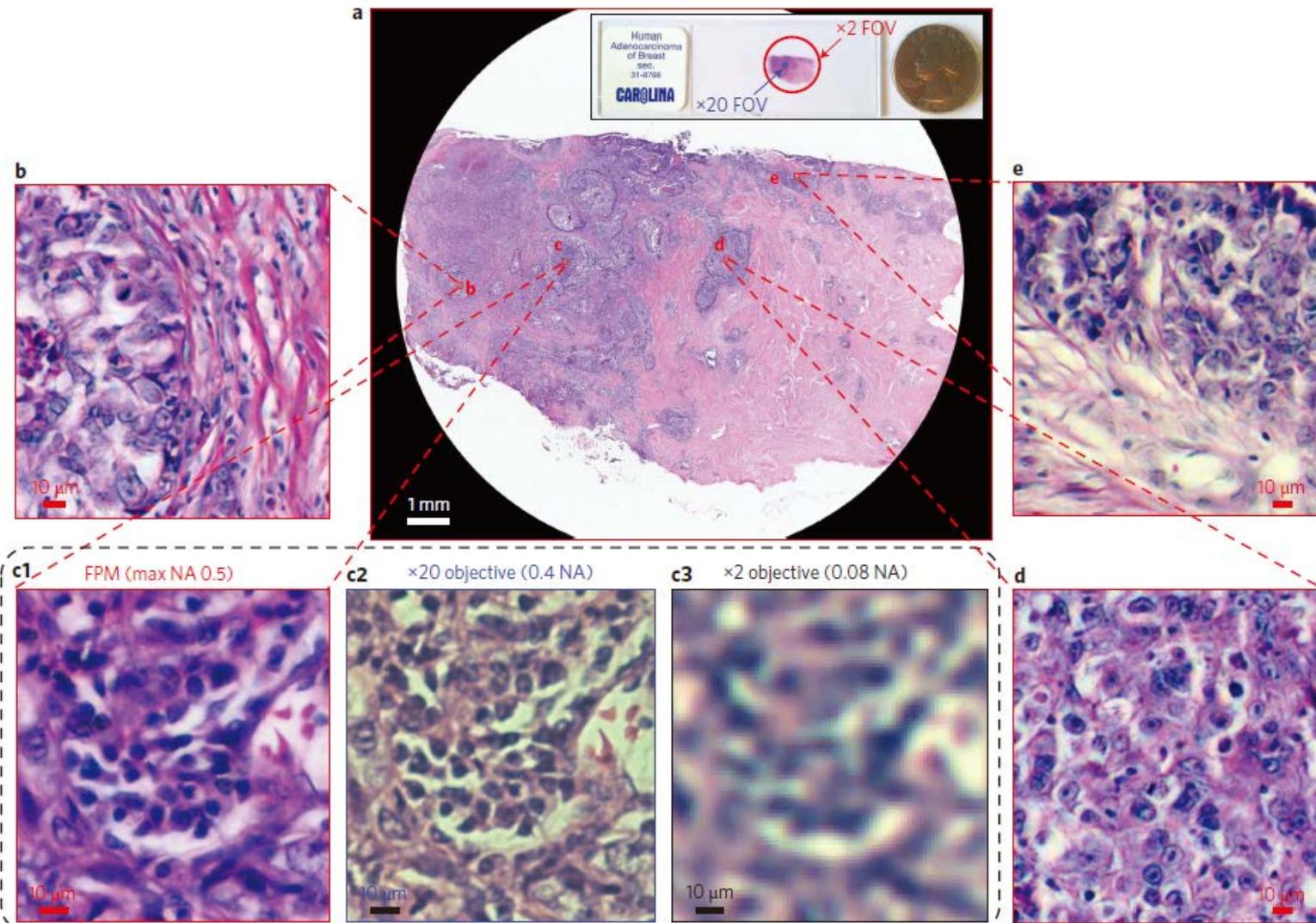
傅里叶叠层成像重构算法



傅里叶叠层成像简介

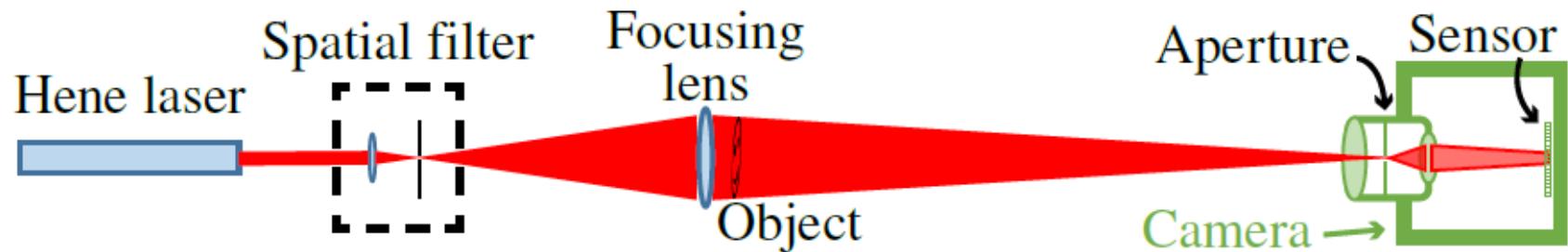
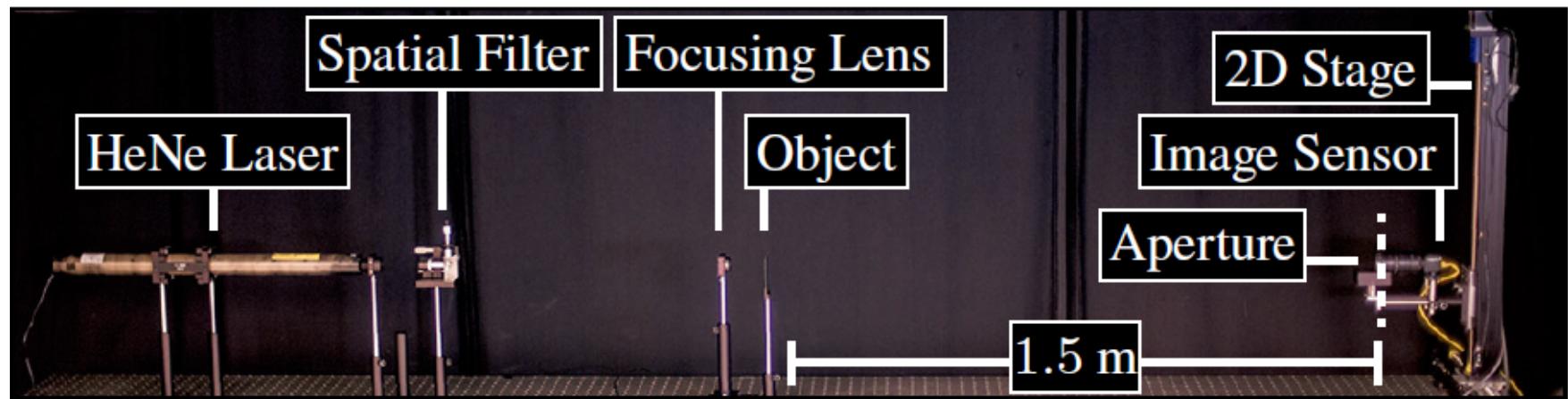


重构结果展示





宏观傅里叶叠层成像 (MFP) 简介



$$\Psi(u, v) = \frac{\exp(jkz) \cdot \exp\left(jk \frac{u^2 + v^2}{2z}\right)}{j\lambda z} \mathcal{F}_{1/\lambda z}[\psi(x, y)]$$

$$I(x, y, u_c, v_c) \propto |\Phi(x', y')|^2 = |\mathcal{F}[\Psi(u, v) \cdot P(u - u_c, v - v_c)]|^2$$

关于傅里叶平面对应关系的推导

取经过 f_1 汇聚后的光源为点光源，紧靠Lens2前表面的光场为：

$$\tilde{E}(x_1, y_1) = A \exp(i k l) \cdot \exp\left[\frac{ik}{2l}(x_1^2 + y_1^2)\right]$$

经过Lens2的傅里叶变换之后，在Lens2后表面的光场分布为：

$$\tilde{E}'(x_1, y_1) = A \exp(i k l') \cdot \exp\left[-\frac{ik}{2l'}(x_1^2 + y_1^2)\right]$$

再经过被测物体之后，带有被测物体的透过率信息：

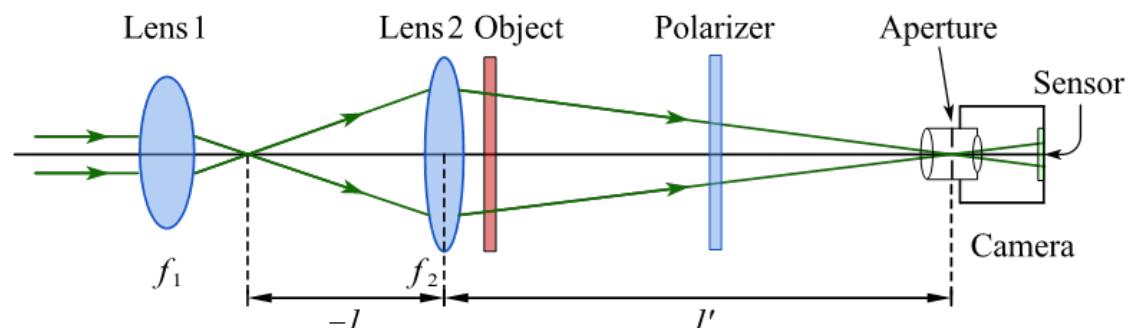
$$\tilde{E}''(x_1, y_1) = \tilde{t}(x_1, y_1) \cdot \tilde{E}'(x_1, y_1)$$

从Object平面到Aperture平面，使用菲涅尔衍射公式：

$$\begin{aligned}\tilde{E}(x, y) &= \frac{\exp(ikl')}{i\lambda l'} \iint_{-\infty}^{\infty} \tilde{E}''(x_1, y_1) \cdot \exp\left\{\frac{ik}{2l'}[(x - x_1^2) + (y - y_1^2)]\right\} dx_1 dy_1 \\ &= \frac{\exp(ikl')}{i\lambda l'} \iint_{-\infty}^{\infty} \tilde{E}''(x_1, y_1) \cdot \exp\left[\frac{ik}{2l'}(x^2 + y^2)\right] \cdot \exp\left[\frac{ik}{2l'}(x_1^2 + y_1^2)\right] \cdot \exp\left[-\frac{ik}{l'}(xx_1 + yy_1)\right] dx_1 dy_1 \\ &= \frac{\exp(ikl')}{i\lambda l'} \cdot \exp\left[\frac{ik}{2l'}(x^2 + y^2)\right] \iint_{-\infty}^{\infty} \tilde{E}''(x_1, y_1) \cdot \exp\left[\frac{ik}{2l'}(x_1^2 + y_1^2)\right] \cdot \exp[-i2\pi(\frac{x}{\lambda l'}x_1 + \frac{y}{\lambda l'}y_1)] dx_1 dy_1\end{aligned}$$

将 $\tilde{E}''(x_1, y_1)$ 代入上式，并用 C 表示 $\frac{\exp(ikl')}{i\lambda l'}$ ，用 C' 表示 $C \cdot A \exp(-ikl')$ 则有

$$\begin{aligned}\tilde{E}(x, y) &= C \iint_{-\infty}^{\infty} \tilde{t}(x_1, y_1) \cdot A \exp(-ikl') \cdot \exp[-i2\pi(\frac{x}{\lambda l'}x_1 + \frac{y}{\lambda l'}y_1)] dx_1 dy_1 \\ &= C' \iint_{-\infty}^{\infty} \tilde{t}(x_1, y_1) \cdot \exp[-i2\pi(\frac{x}{\lambda l'}x_1 + \frac{y}{\lambda l'}y_1)] dx_1 dy_1 \\ &= C \cdot \mathcal{F}[\tilde{t}(x_1, y_1)]|_{u=\frac{x}{\lambda}l', v=\frac{y}{\lambda}l'}\end{aligned}$$

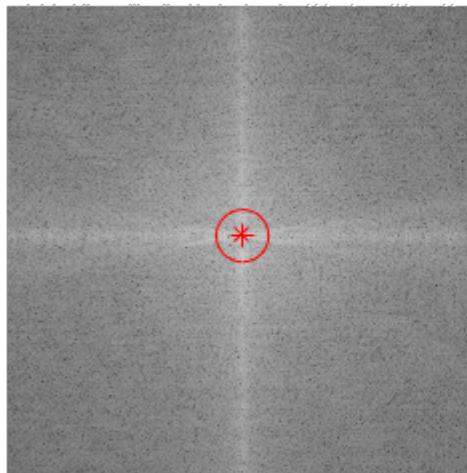




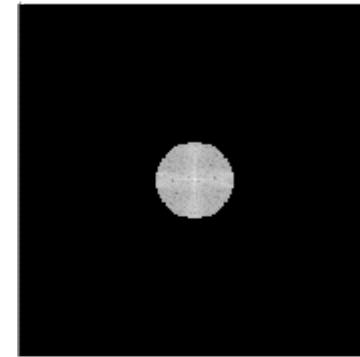
宏观傅里叶叠层成像

宏观傅里叶叠层成像（MFP）仿真实验与分析

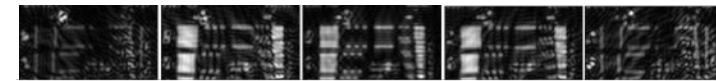
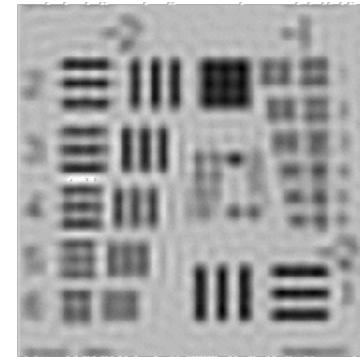
从高分辨率频谱上截取子孔径 num = 1



取下来的子孔径 num = 1



对应低分辨率图像 num = 1



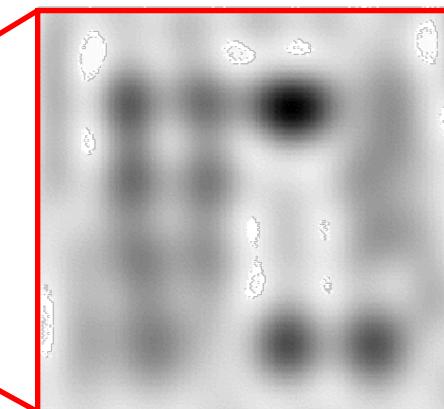
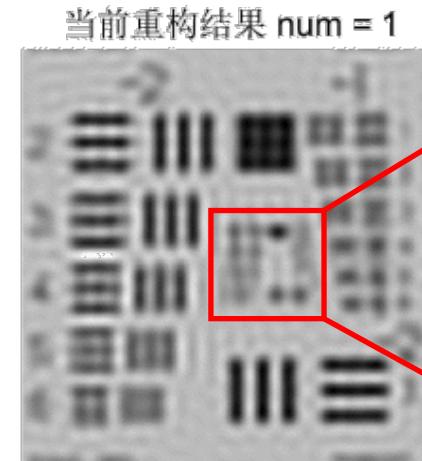
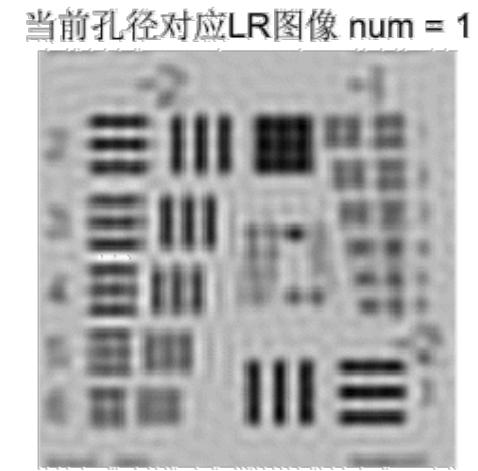
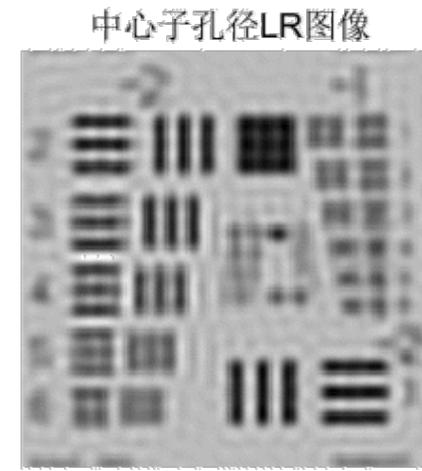
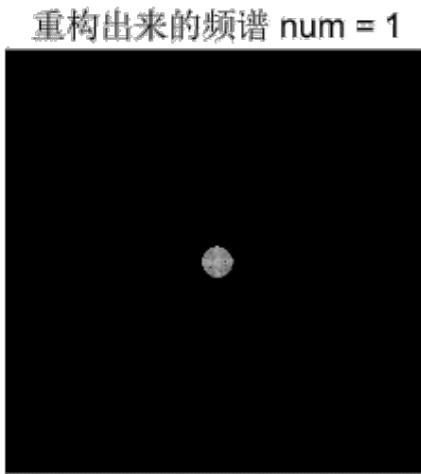
仿真参数设置

成像距离	1700mm
像素尺寸	$3.75 \mu\text{m}$
镜头焦距	75mm
F#	32
图像数量	25×25
相机移动间隔	0.7mm
频谱重叠率	~70%
合成孔径比	~8

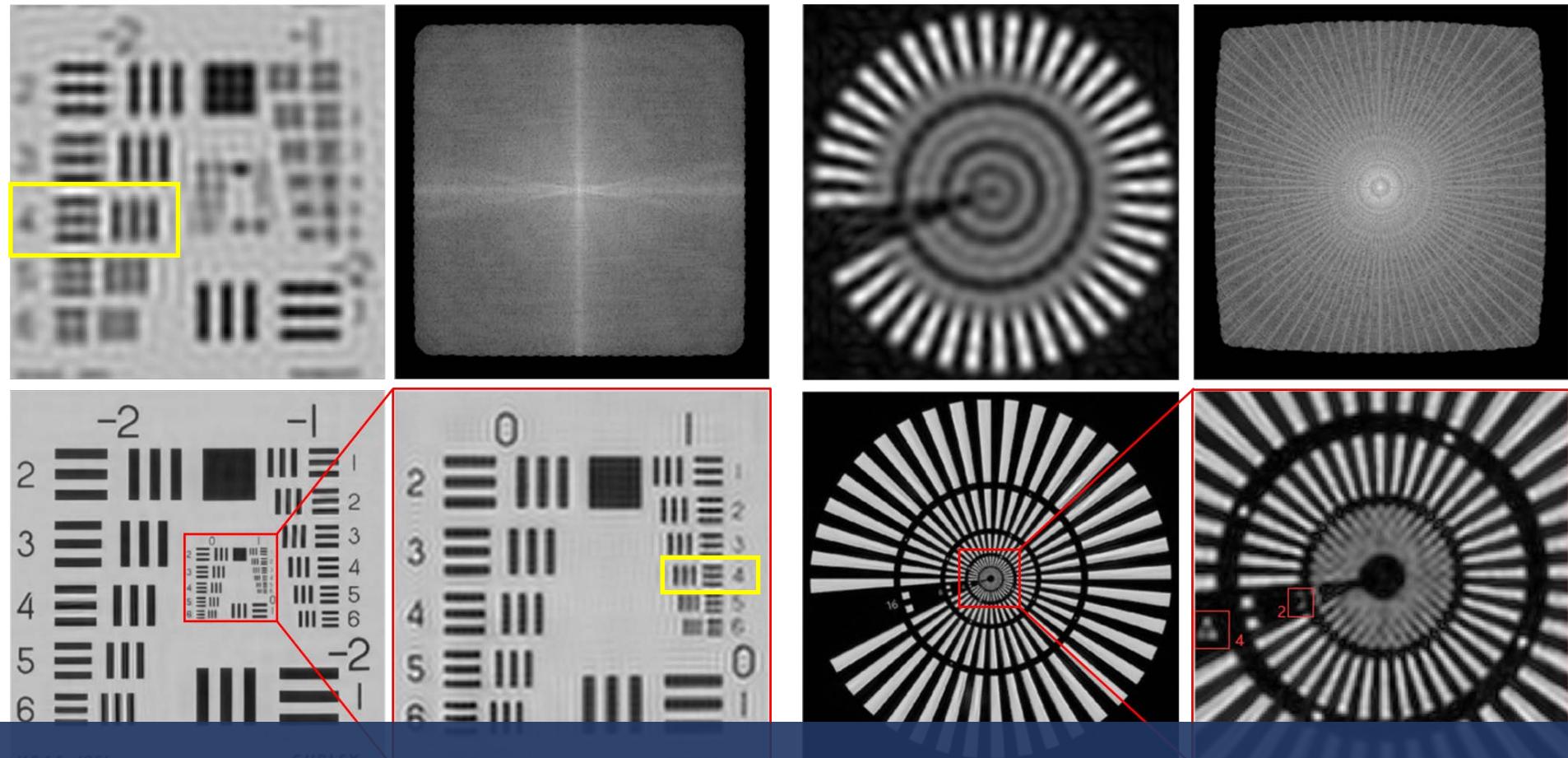
**Group-2 Element4
(0.353lp/mm)**



宏观傅里叶叠层成像（MFP）仿真实验与分析

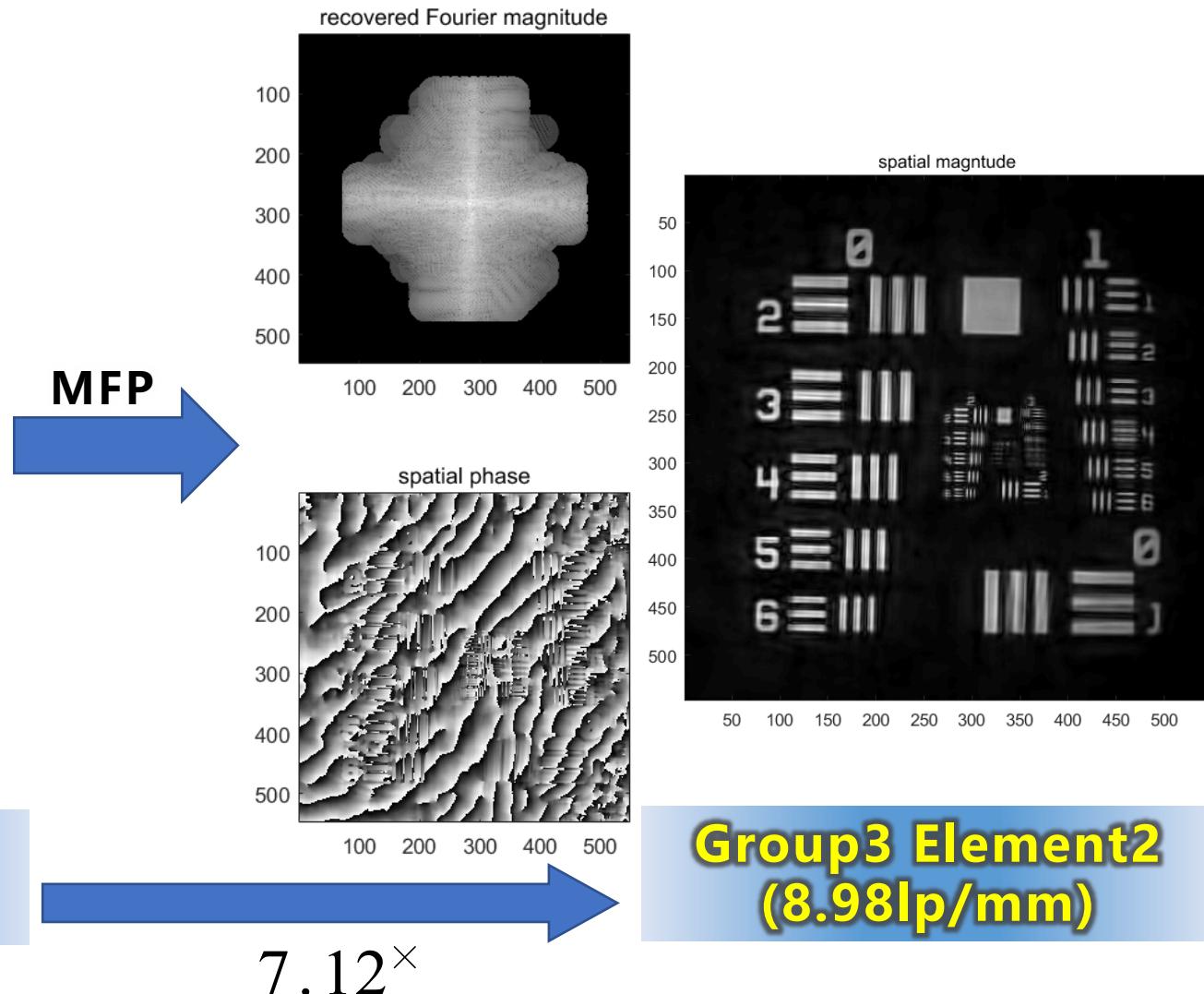


宏观傅里叶叠层成像（MFP）仿真实验与分析



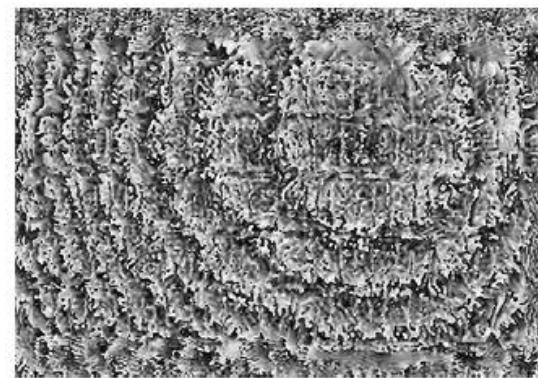
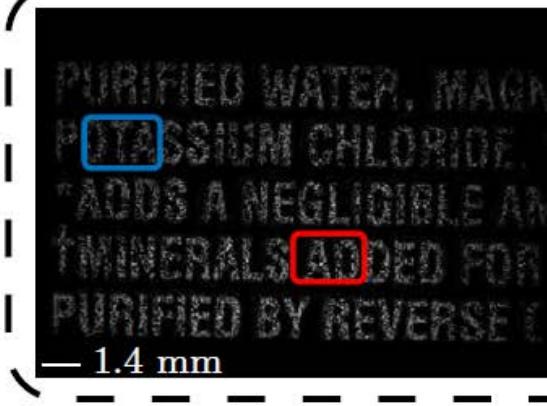
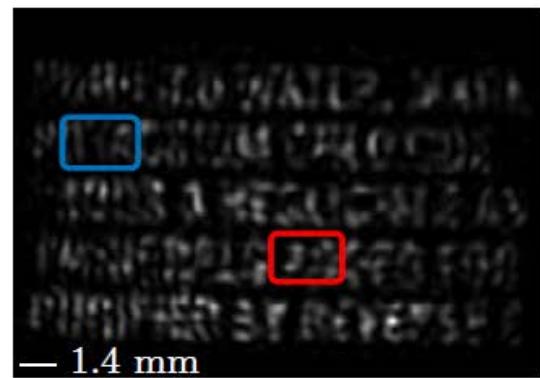
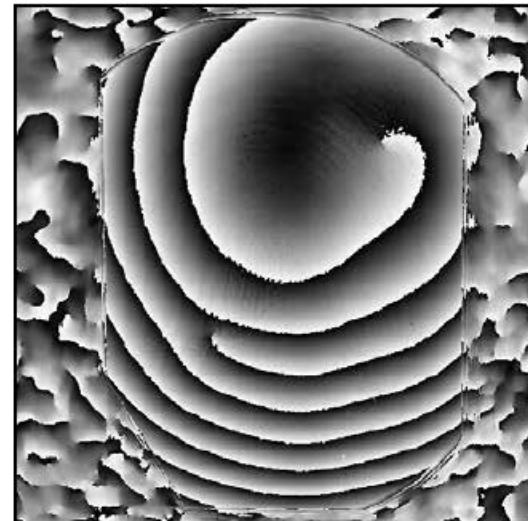
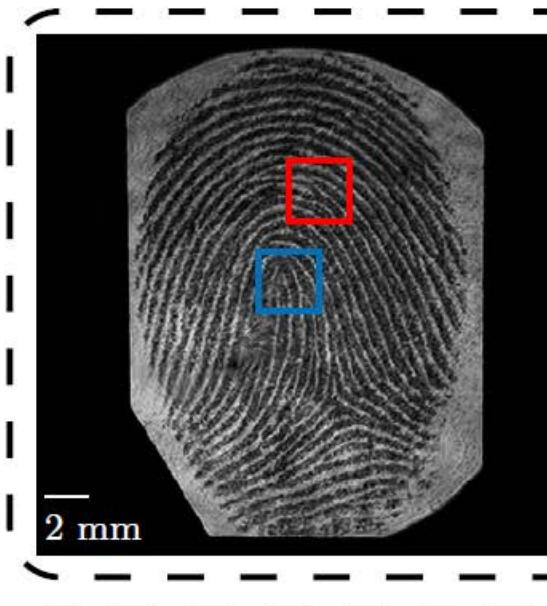
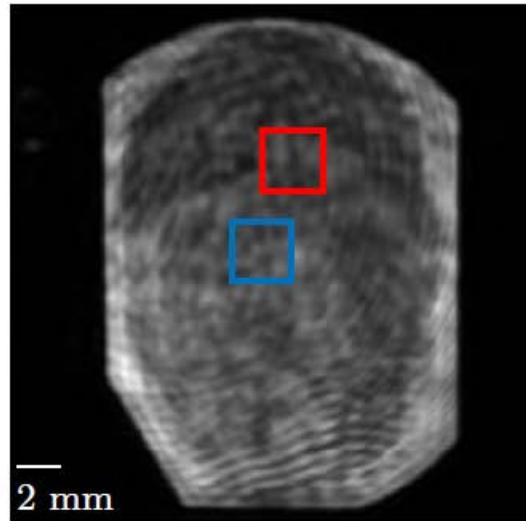
仿真实现合成孔径超分辨成像

宏观傅里叶叠层成像（MFP）实验与分析





宏观傅里叶叠层成像（MFP）实验与分析



结合特定场景的优化算法

提高重构精度

最优化求解

模拟退火算法校正定位误差

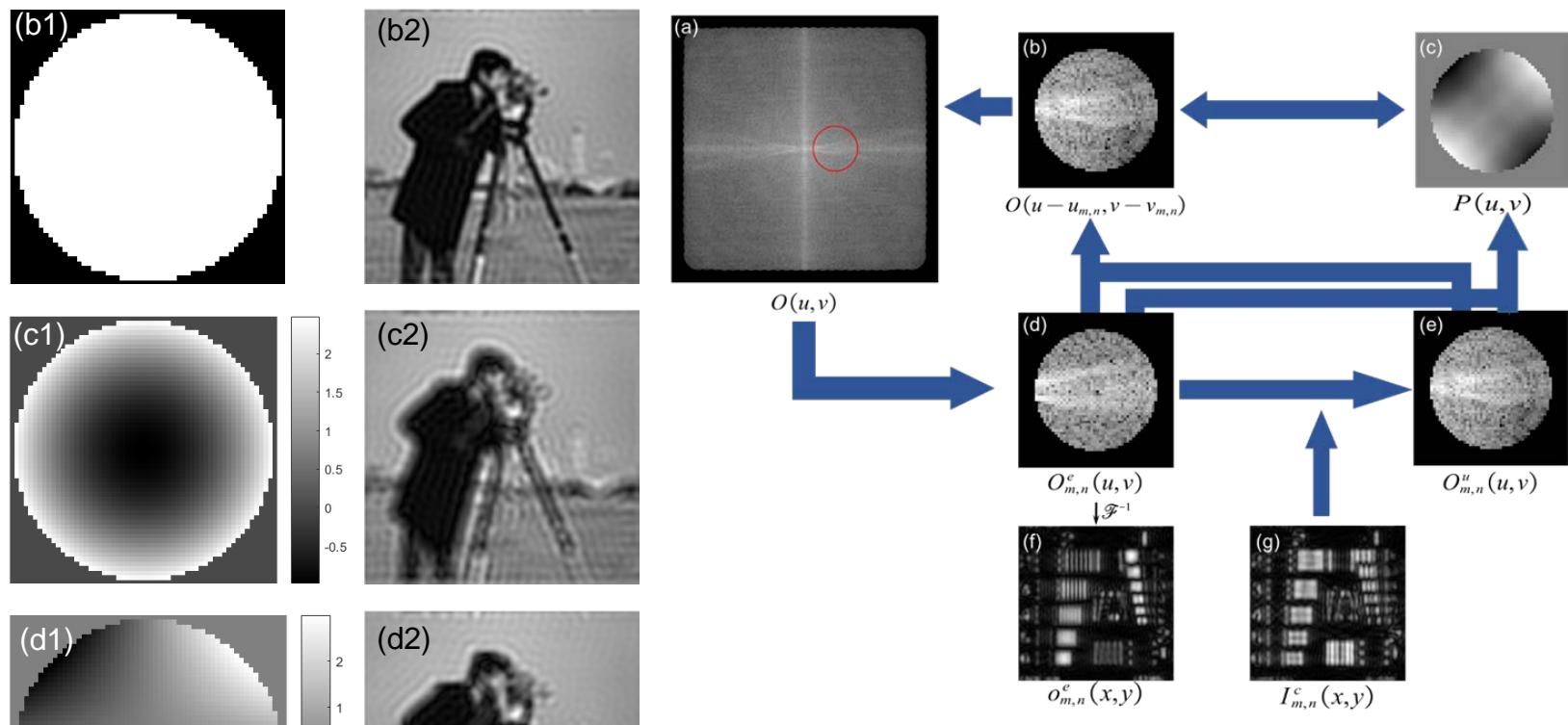
提高图像采集效率

频谱重叠率问题研究

采样方式研究

信息复用（角度复用、波长复用）

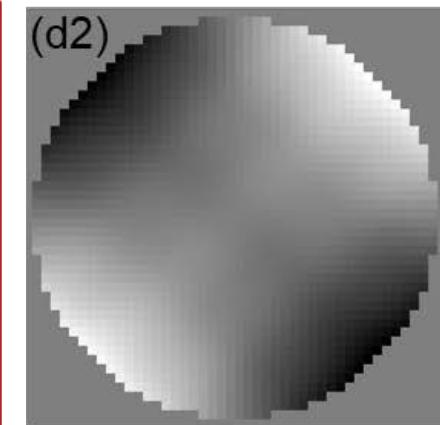
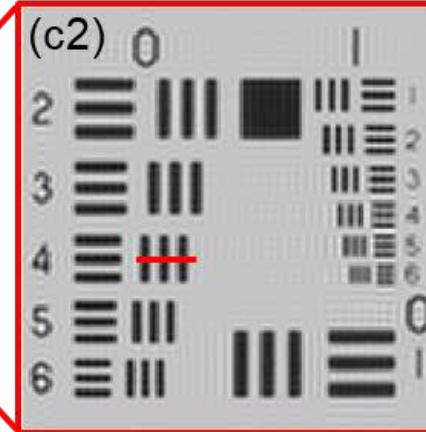
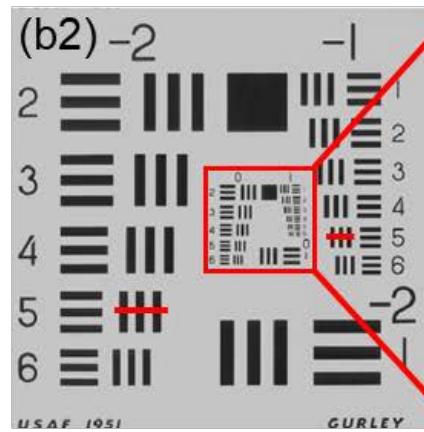
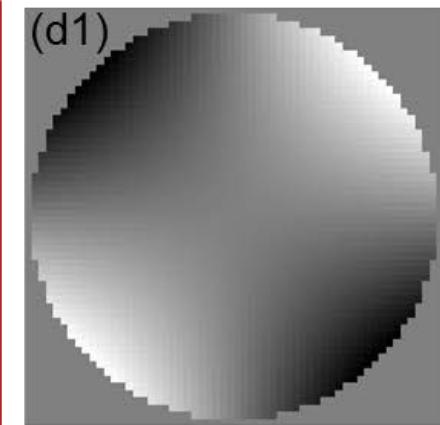
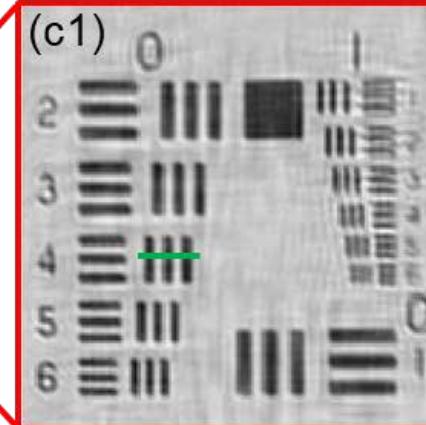
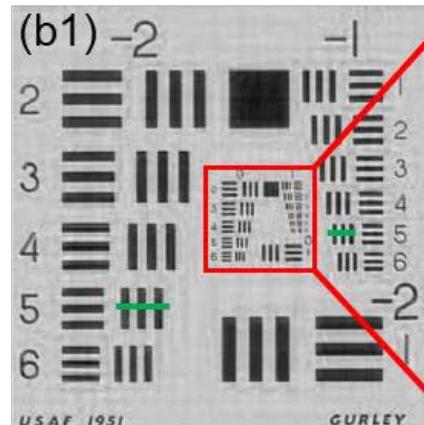
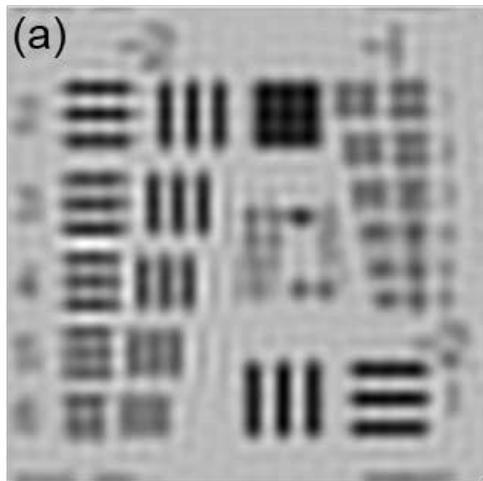
最优化求解算法



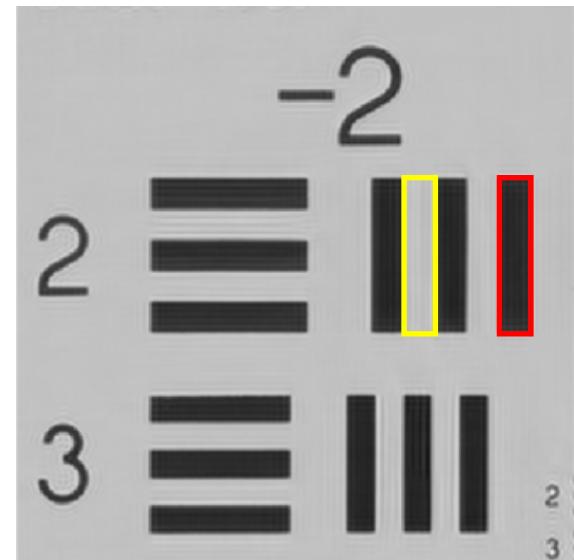
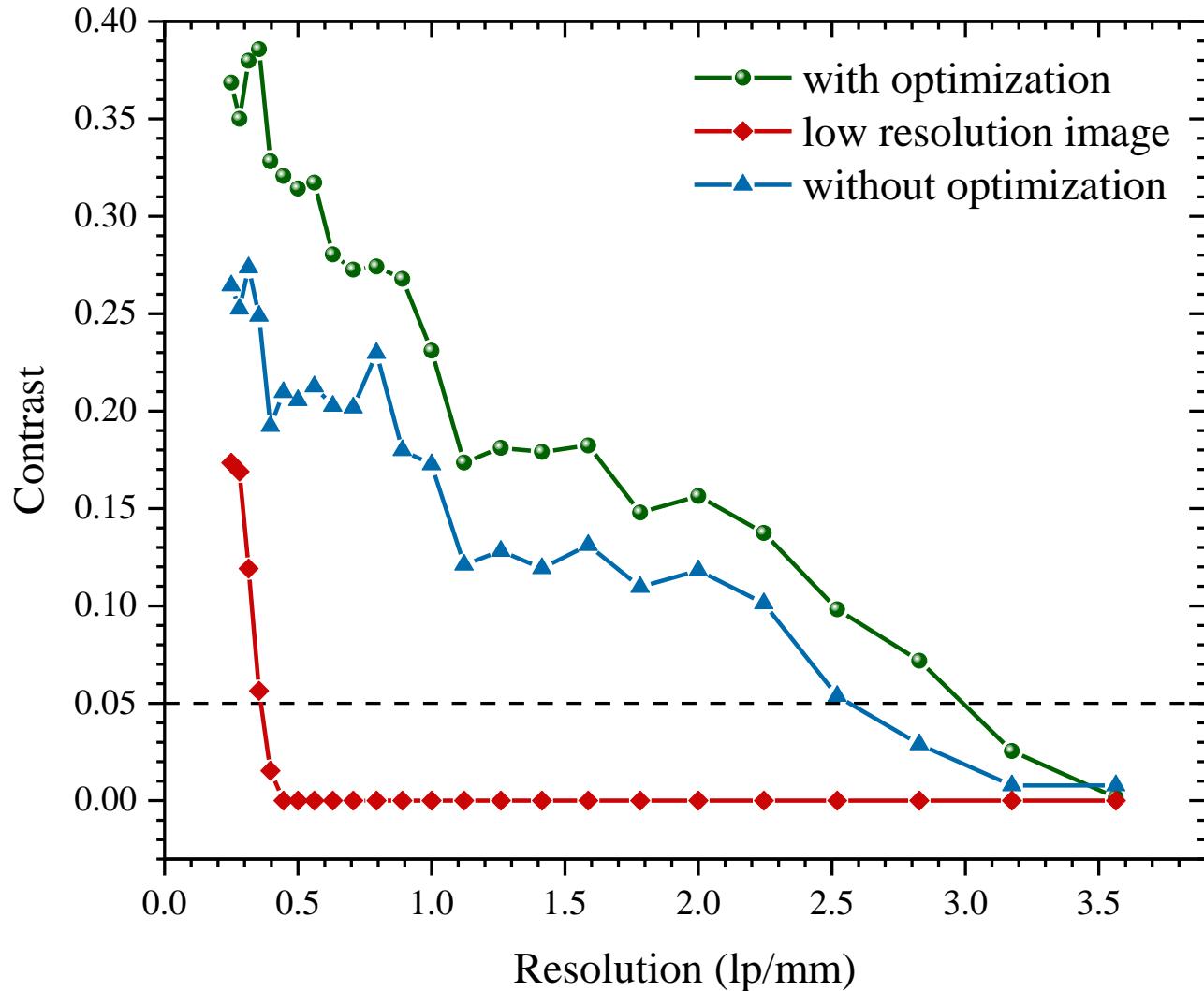
$$O(u - u_{m,n}, v - v_{m,n}) = O(u - u_{m,n}, v - v_{m,n}) + \alpha \frac{|P(u, v)|^2}{|P(u, v)|_{\max}^2} \frac{P^*(u, v)}{|P(u, v)|^2 + \delta} [O_{m,n}^u(u, v) - O_{m,n}^e(u, v)]$$

$$P(u, v) = P(u, v) + \beta \frac{|O(u - u_{m,n}, v - v_{m,n})|^2}{|O(u - u_{m,n}, v - v_{m,n})|_{\max}^2} \frac{O^*(u - u_{m,n}, v - v_{m,n})}{|O(u - u_{m,n}, v - v_{m,n})|^2 + \gamma} [O_{m,n}^u(u, v) - O_{m,n}^e(u, v)]$$

仿真实验结果对比与分析

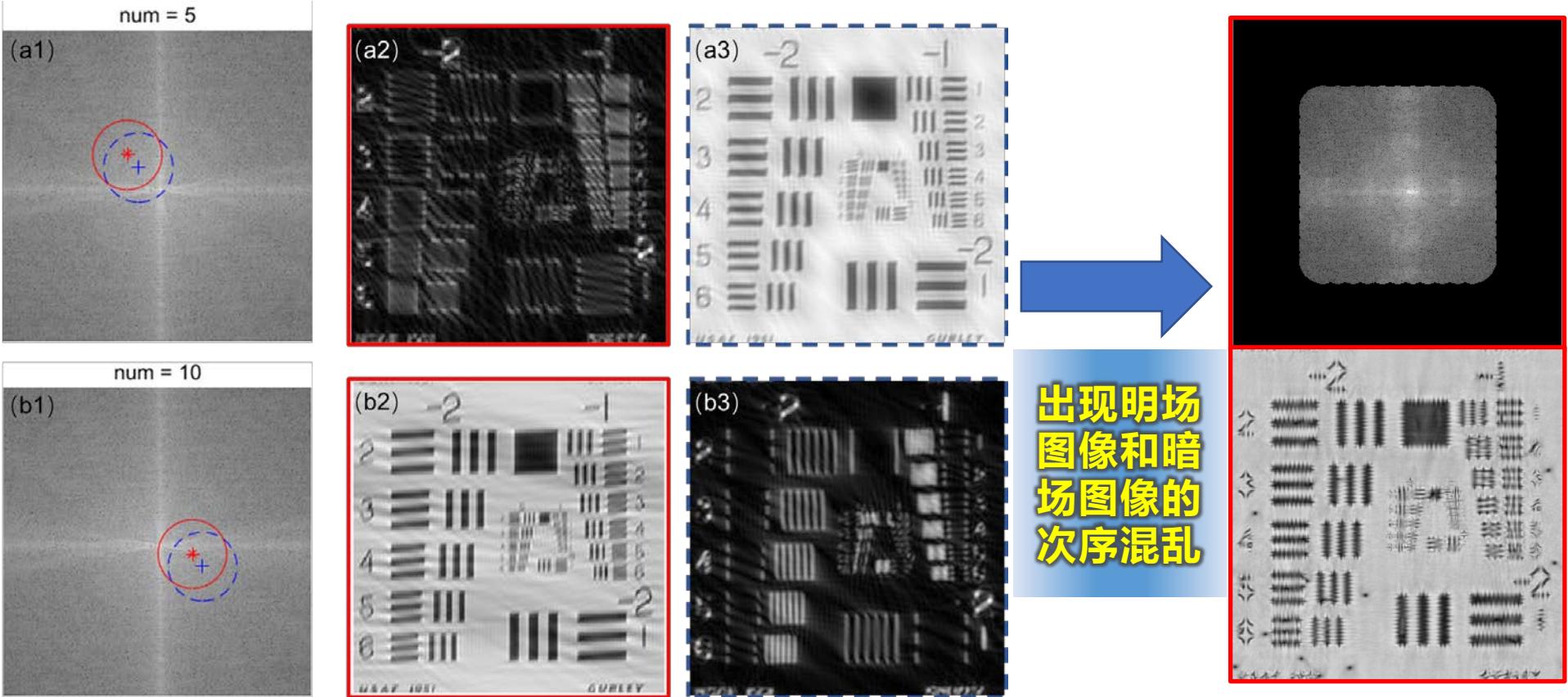


仿真实验结果对比与分析



$$C = \frac{\bar{w} - \bar{b}}{\bar{w} + \bar{b}} \cdot \bar{w} \cdot (1 - \bar{b})$$

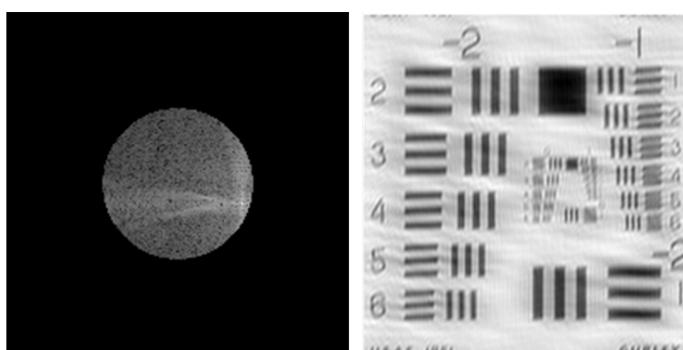
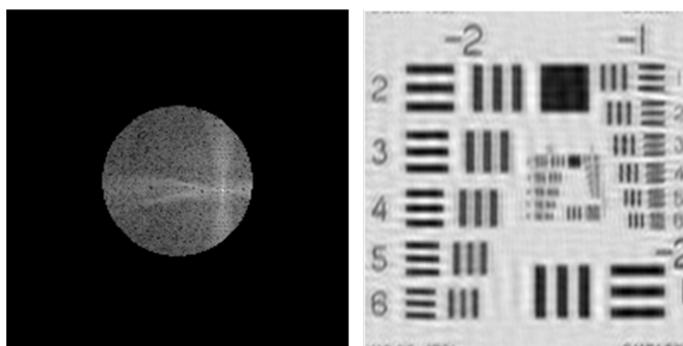
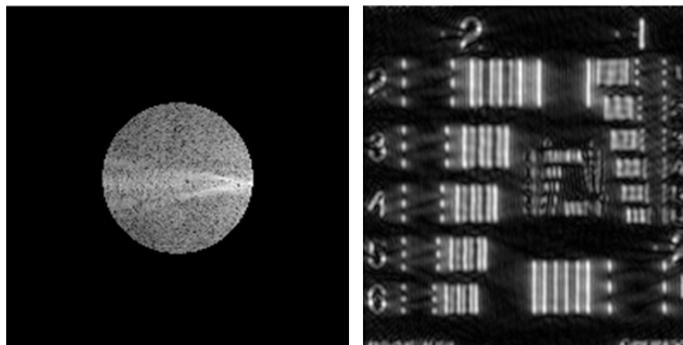
基于模拟退火算法的子孔径定位误差校正





优化2—模拟退火校正位置

基于模拟退火算法的子孔径定位误差校正算法流程

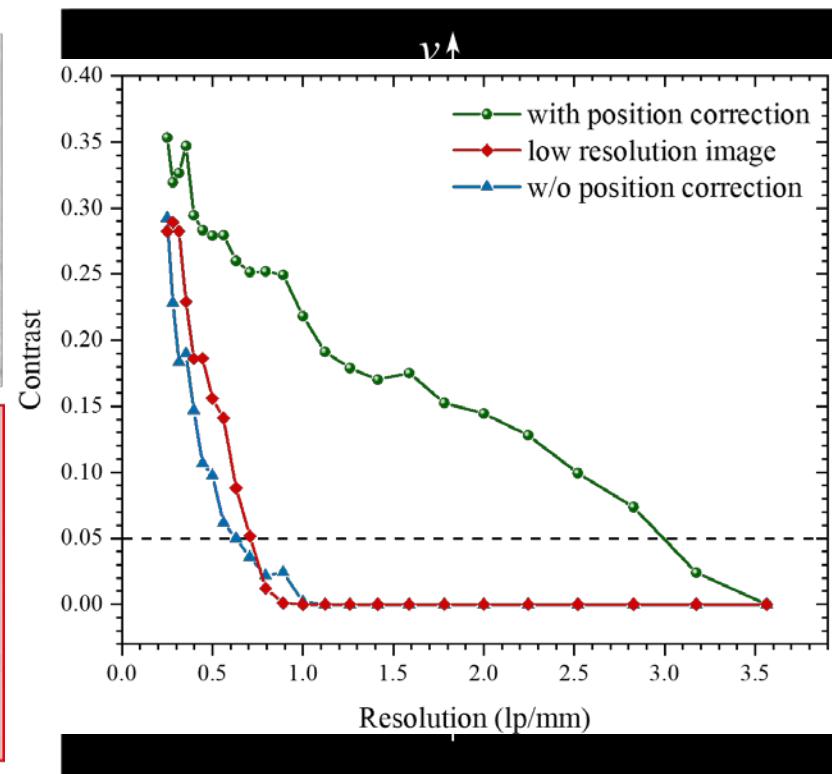
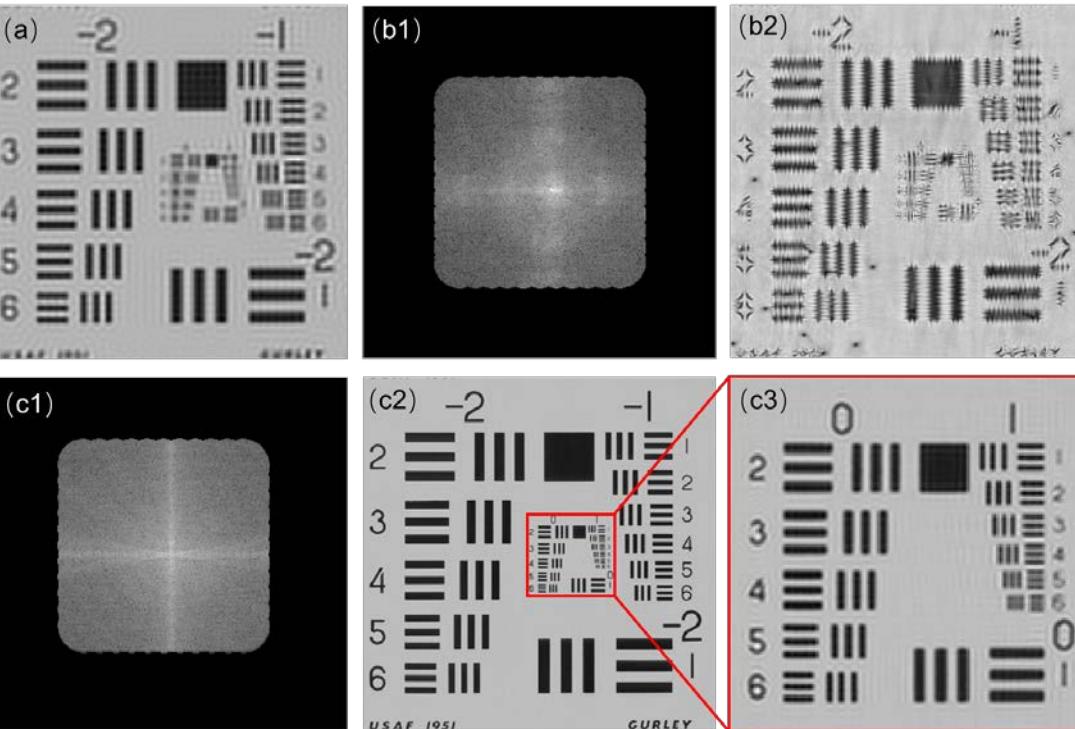


初始位置

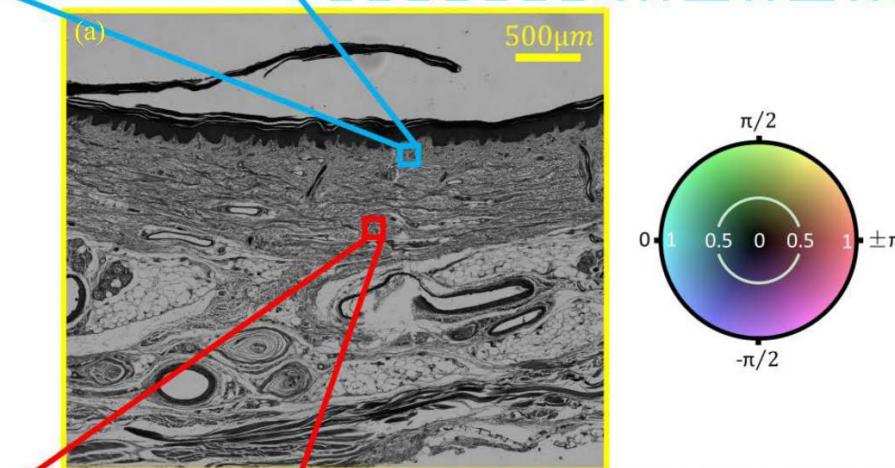
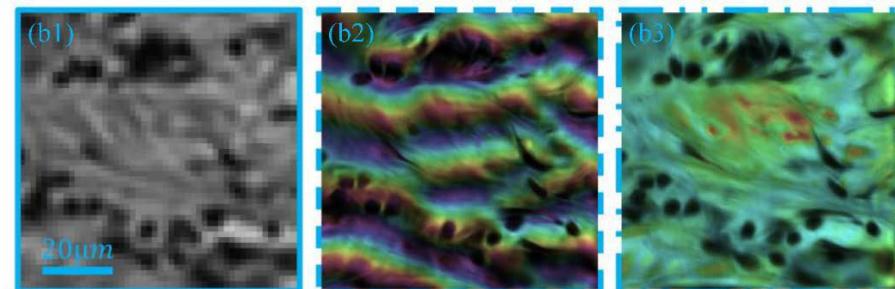
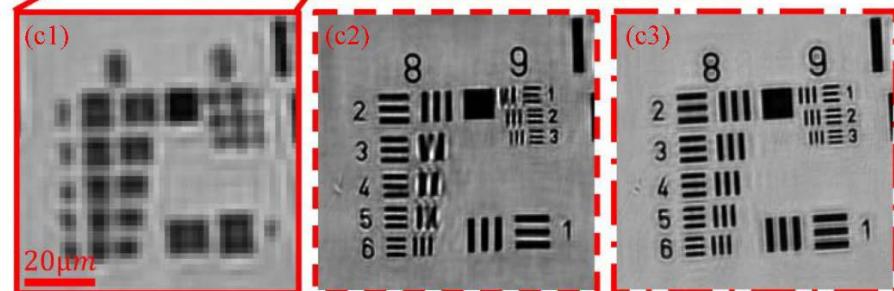
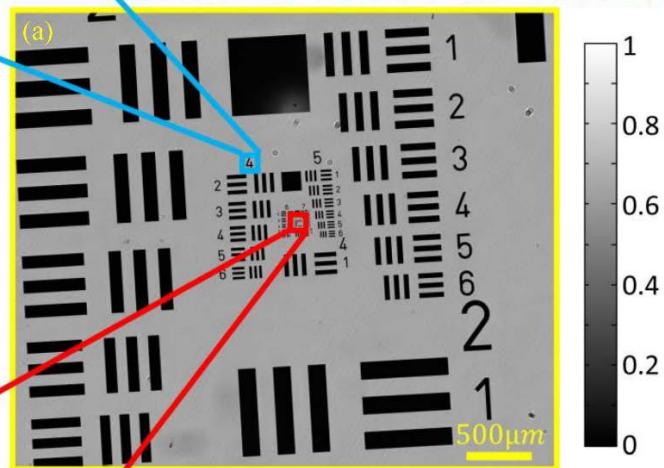
模拟退火算法搜
索中

搜索结果

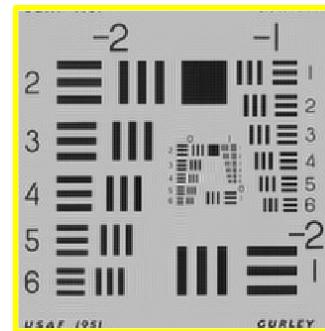
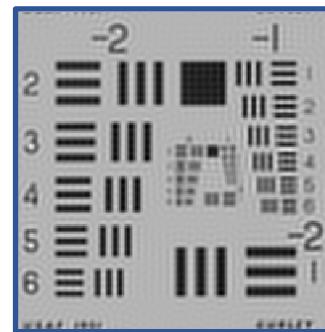
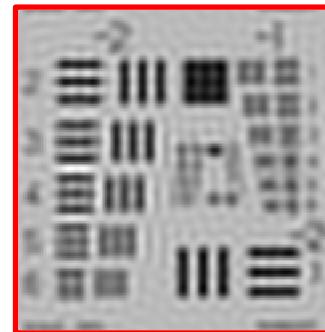
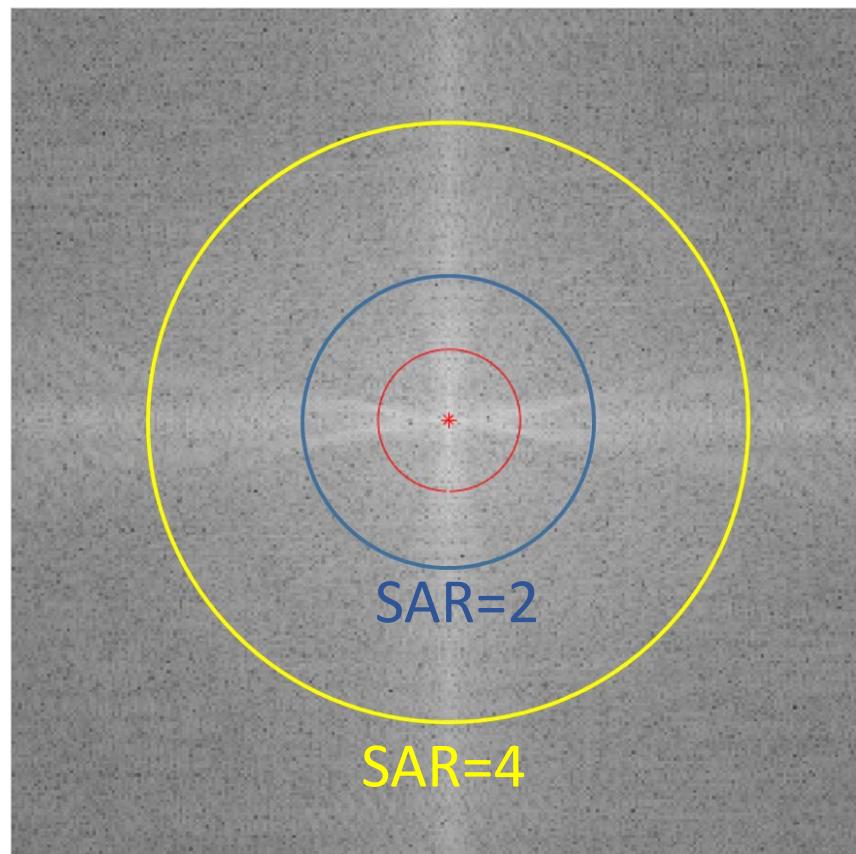
仿真实验结果与分析



显微领域中LED阵列位置校正实验结果展示



用较少的图像重构出分辨率更高的结果



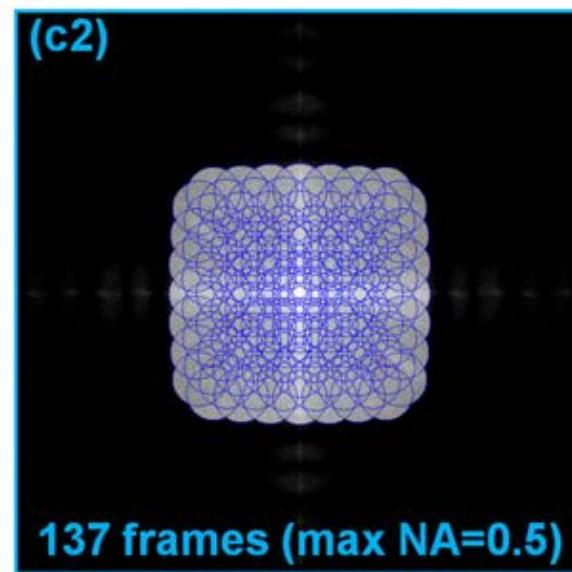
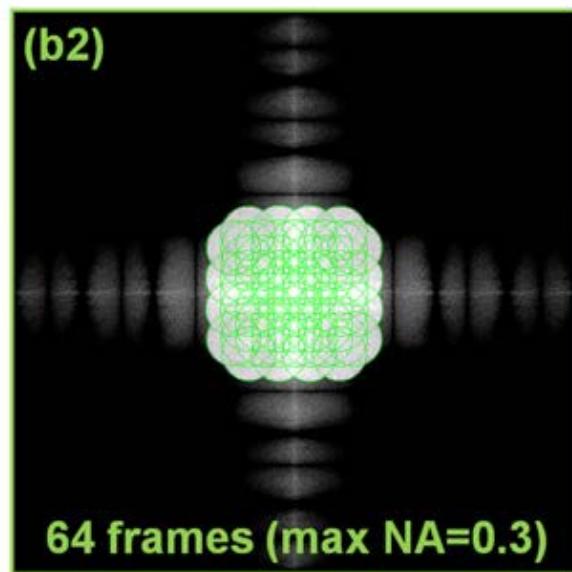
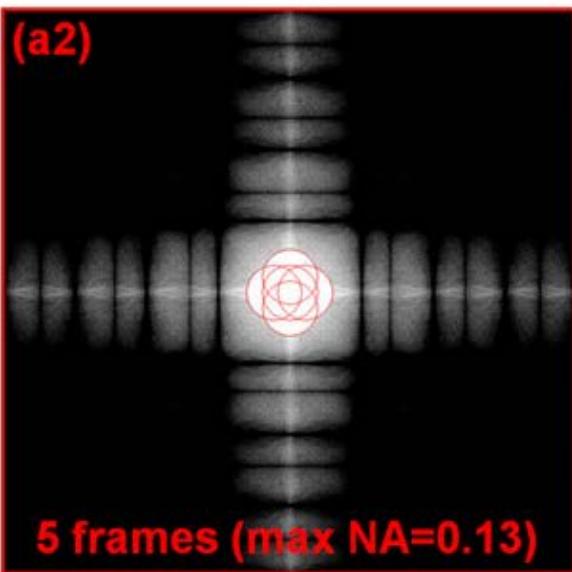
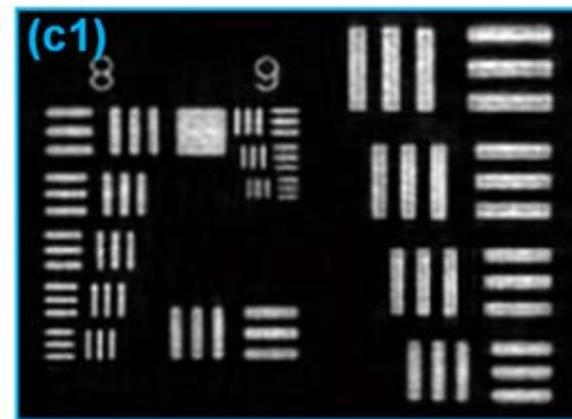
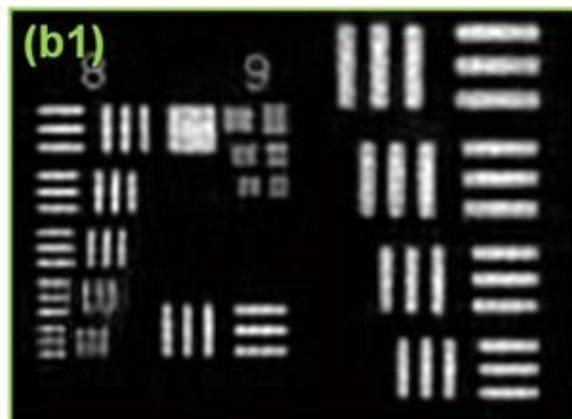
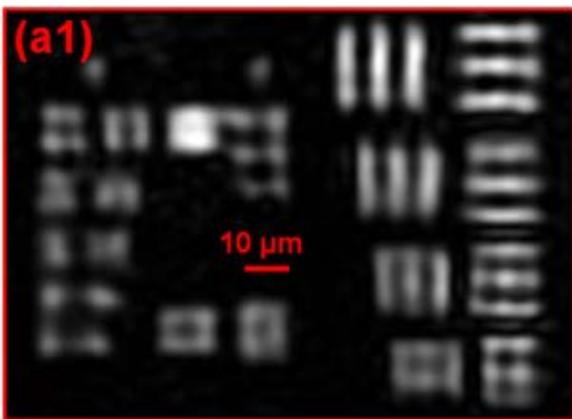
$$SAR = \frac{D + (N - 1) \cdot \delta}{D}$$

D 为镜头孔径的直径
 δ 为相机的移动间隔

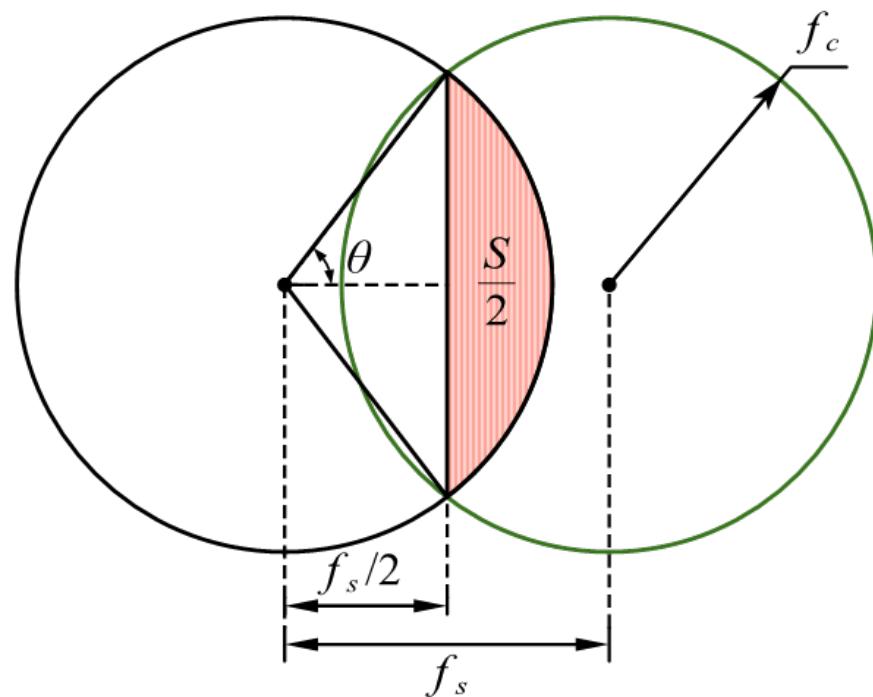
**增大移动间隔
(频谱重合率问题)**

**增加采集图像数量
(采样方案问题)**

不同图像数量对应重构结果



频谱重合率模型



$$f_c = \frac{NA}{\lambda} = \frac{1}{2F\lambda}$$

$$f_s = \frac{1}{\lambda} \cdot \frac{\delta}{\sqrt{\delta^2 + (L \cdot |\beta|)^2}} = \frac{f_c}{NA} \cdot \frac{\delta}{\sqrt{\delta^2 + (L \cdot |\beta|)^2}}$$

$$S = 2 \left(\pi f_c^2 \cdot \frac{2\theta}{2\pi} - \frac{1}{2} \cdot \frac{f_s}{2} \cdot 2\sqrt{f_c^2 - (f_s/2)^2} \right)$$

$$= \left(f_c^2 \cdot 2\theta - f_s \cdot \sqrt{f_c^2 - (f_s/2)^2} \right)$$

$$overlap = \frac{S}{\pi f_c^2} \times 100\%$$

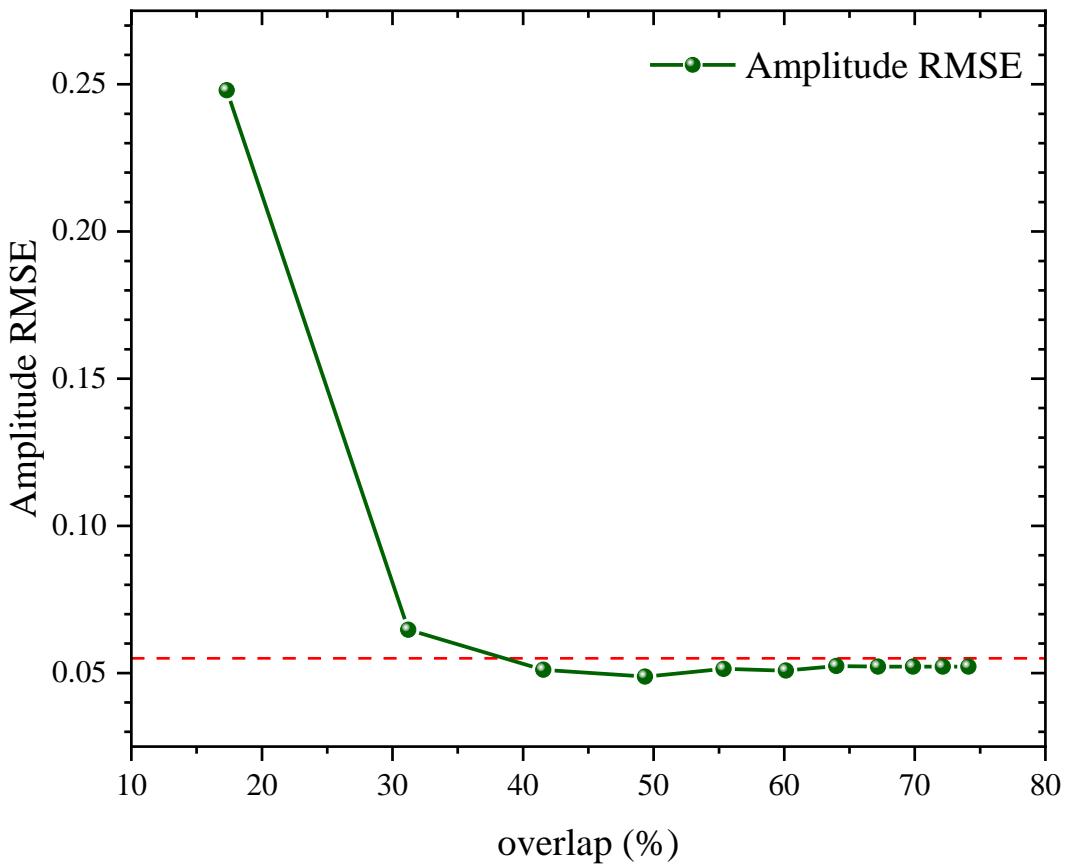


优化3—数据冗余度研究

数据冗余度的研究（频谱重合率研究）

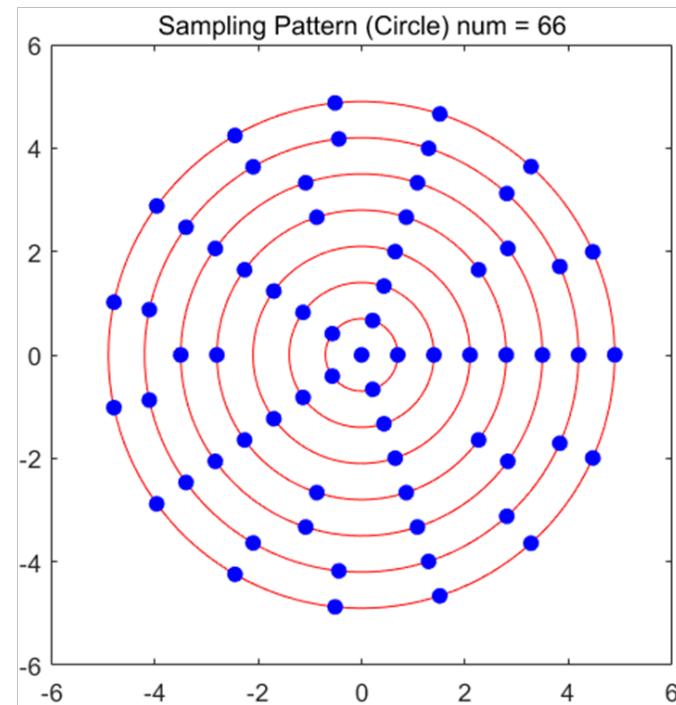
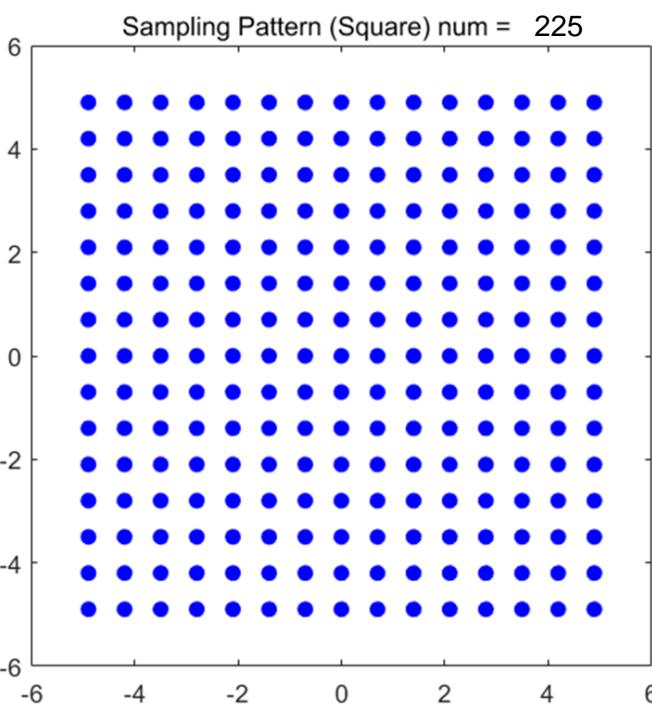
	输入高分辨率	$overlap = 17.31\%$	$overlap = 31.21\%$	$overlap = 41.55\%$	$overlap = 69.87\%$
振幅					
相位					
频谱					

数据冗余度的研究（频谱重合率研究）



频谱重叠率	图像数量	RMSE
17.31%	81	0.2480
31.21%	121	0.0647
41.55%	169	0.0511
49.34%	225	0.0488
55.36%	289	0.0514
60.13%	361	0.0508
64.00%	441	0.0524
67.19%	529	0.0522
69.87%	625	0.0522
72.14%	729	0.0522
74.11%	841	0.0522

采样方案研究



先确定同心圆周

圆周半径由频谱重合率决定 (这里选取 64.15%)

再确定子孔径位置

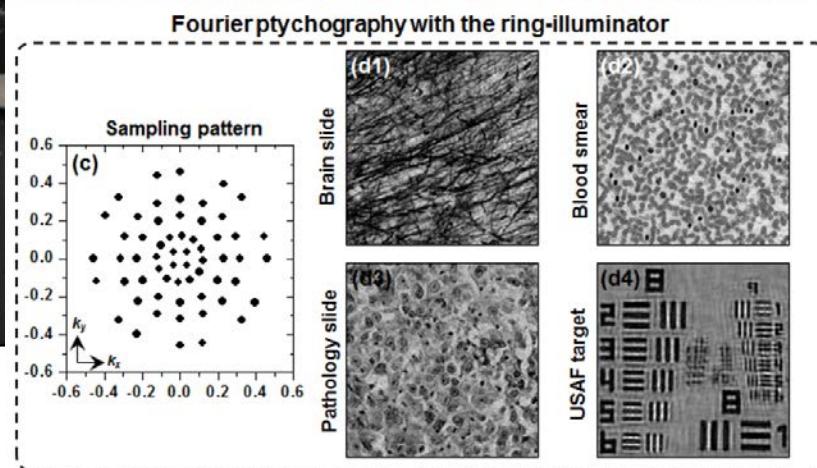
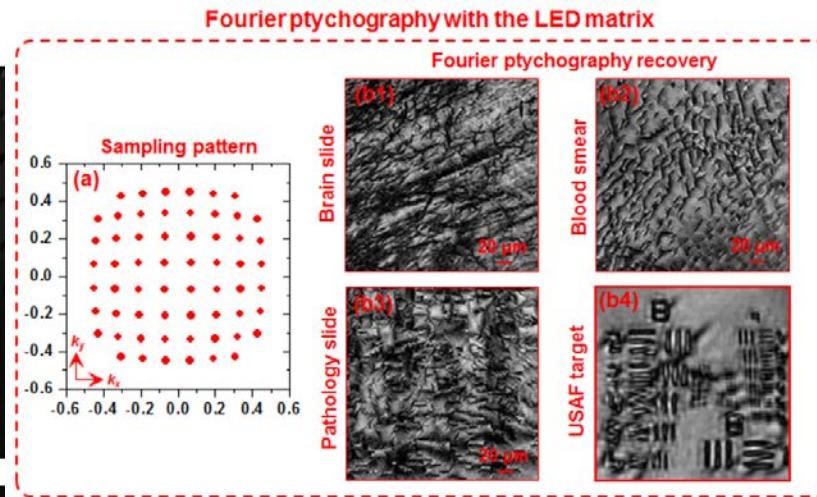
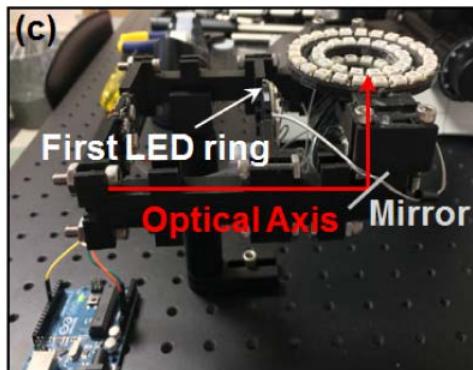
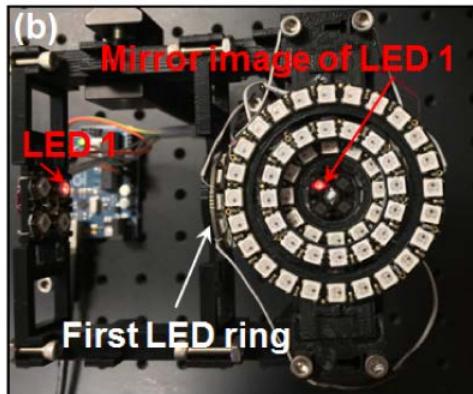
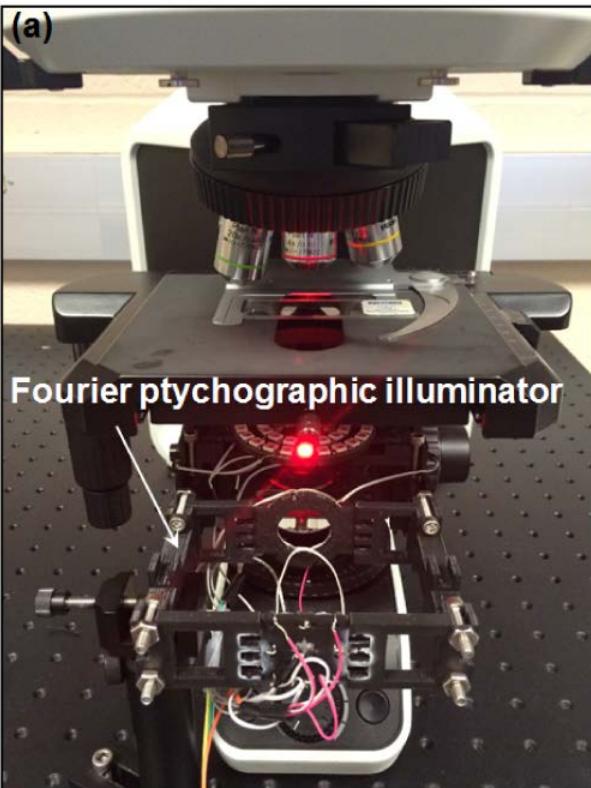
子孔径等间距均匀分布

采样方案研究

原始高分辨率目标	传统225张低分辨图像重构结果	优化后66张低分辨图像重构结果	局部细节放大图
(a1) 	(a2) 	(a3) 	(e1)
(b1) 	(b2) 	(b3) 	(e2)
(c1) 	(c2) 	(c3) 	(e3)
(d1) 南京理工大学 NANJING UNIVERSITY OF SCIENCE & TECHNOLOGY 电子工程与光电技术学院 School of Electronic and Optical Engineering 	(d2) 南京理工大学 NANJING UNIVERSITY OF SCIENCE & TECHNOLOGY 电子工程与光电技术学院 School of Electronic and Optical Engineering 	(d3) 南京理工大学 NANJING UNIVERSITY OF SCIENCE & TECHNOLOGY 电子工程与光电技术学院 School of Electronic and Optical Engineering 	



显微领域中的环形照明方案



傅里叶叠层成像的主要优点总结

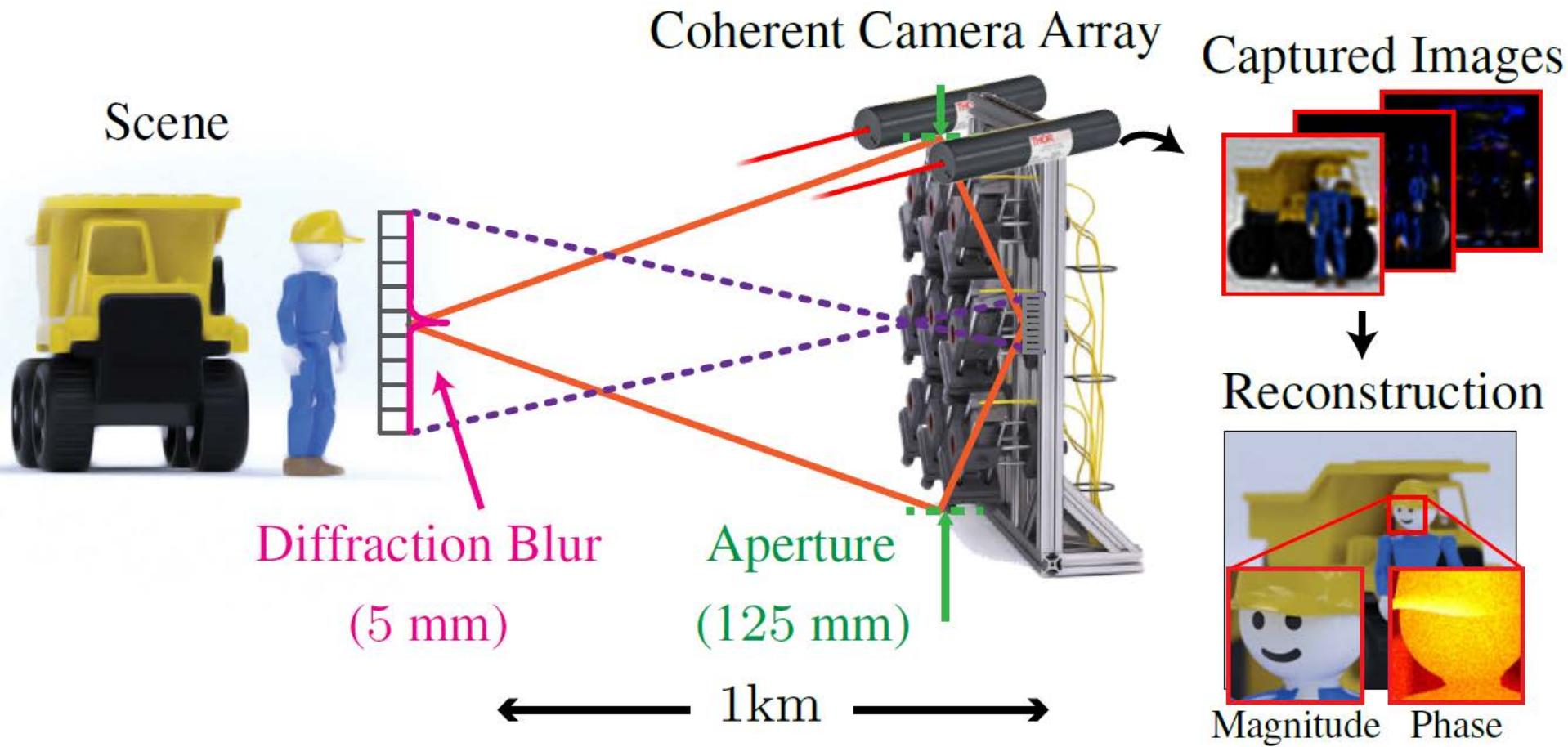
1. 在原有系统的基础上添加LED阵列即可，结构简单，**无需精密机械扫描装置**
2. 在保持大视场的同时，显著提高分辨率，**增大空间带宽积**
3. 迭代过程中对孔径函数进行更新，**校正像差**
4. 不仅能获得高分辨率**光强**信息，可以获得高分辨**相位**信息

1. 显微领域的展望

1. 需要采集多张图像，能否实现**动态测量**？
2. 能否实现更高倍数的**超分辨率倍数**（更大的合成孔径比）？
3. 暗场图像中的**信噪比问题**，怎么提高信噪比？
4. 被测样品近似为平面，被测物体厚度**不能近似为平面**怎么办？
5. 各种微小误差的解决，光源亮度一致性、相机噪声问题、平面波近似程度等

2.能否实现远距离漫反射物体反射式探测？

3.能否实现远距离高速动态场景测量?





3.能否实现远距离高速动态场景测量？

用多光源照明来提供频域的偏移量（不同照明角度对应不同的相位因子）

3.75um像素尺寸， $f=75\text{mm}$ 下，F#6 ($D=12.5\text{mm}$) 左右就会出现像素混叠

使用的相机尺寸为30mm，在保证相邻孔径频谱重合率不小于50%的情况下，使用的光源数量非常多（10个以上）

缩小相机的像素尺寸，以增大无像素混叠下的最大孔径，减小光源数量
用孔径编码的方法来解决像素混叠的问题

- [1] Zheng G. Fourier ptychographic imaging: a MATLAB tutorial[M]. Morgan & Claypool Publishers, 2016.
- [2] Holloway J, Asif M S, Sharma M K, et al. Toward long-distance subdiffraction imaging using coherent camera arrays[J]. IEEE Transactions on Computational Imaging, 2016, 2(3): 251-265.
- [3] Holloway J, Wu Y, Sharma M K, et al. SAVI: Synthetic apertures for long-range, subdiffraction-limited visible imaging using Fourier ptychography[J]. Science advances, 2017, 3(4): e1602564.
- [4] Zheng G, Horstmeyer R, Yang C. Wide-field, high-resolution Fourier ptychographic microscopy[J]. Nature Photonics, 2013, 7(9): 739–745.
- [5] Bian Z, Dong S, Zheng G. Adaptive system correction for robust Fourier ptychographic imaging[J]. Optics express, 2013, 21(26): 32400-32410.
- [6] Sun J, Chen Q, Zhang Y, et al. Efficient positional misalignment correction method for Fourier ptychographic microscopy[J]. Biomedical optics express, 2016, 7(4): 1336-1350.
- [7] Chen X, Wu J, Ma C, et al. Advanced Illumination Pattern in Fourier Ptychographic Microscopy[C]//Mathematics in Imaging. Optical Society of America, 2016: JT3A. 41.
- [8] Guo K, Dong S, Nanda P, et al. Optimization of sampling pattern and the design of Fourier ptychographic illuminator[J]. Optics express, 2015, 23(5): 6171-6180.
- [9] 张艳. 基于傅里叶叠层理论的计算显微成像方法研究[D]. 中国科学院大学(中国科学院西安光学精密机械研究所), 2018.

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Basic-Fourier-Ptychography

Fourier Ptychography can be used in both Microscopy & Macroscopic

Fourier Ptychographic Microscopy

Ref. Guoan Zheng [\[Site1\]](#) [\[Site2\]](#)

Ref. Zheng G. Fourier ptychographic imaging: a MATLAB tutorial[M]. Morgan & Claypool Publishers, 2016.

Macroscopic Fourier Ptychography

<https://github.com/Hao-Xu-optics/Basic-Fourier-Ptychography>