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We3E-4

Geometric Optics with Uniform Asymptotic Physical Optics for Ray Tracing of Compound GRIN Lens Systems

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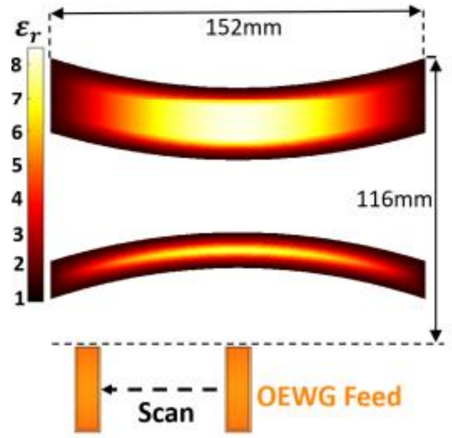
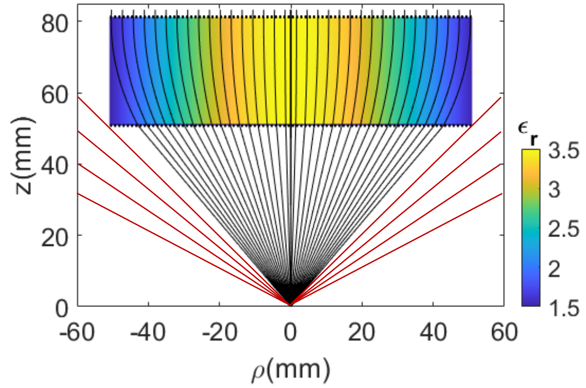
Main thrust

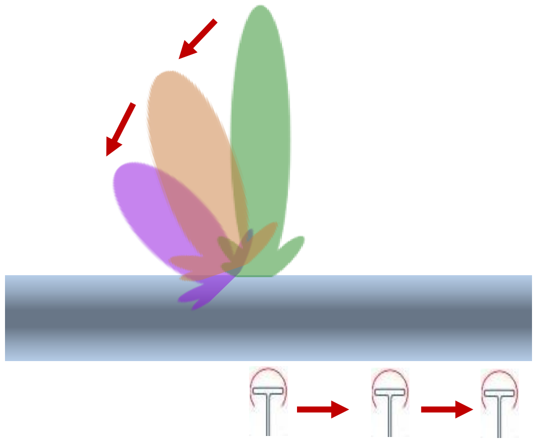
- MMW beam-scanning: GRIN lens → compound(double) GRIN lenses
- Previous work in IMS: single lens ray-tracing with diffraction theory (GO+UAPO)
- GO+UAPO is not sufficiently **accurate** with compound lenses
- Investigate compound lens ray tracing model

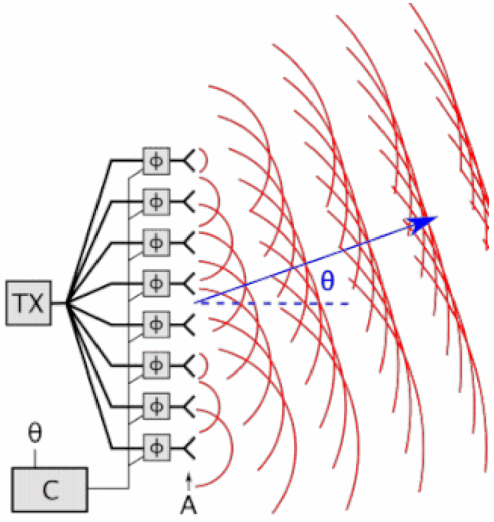


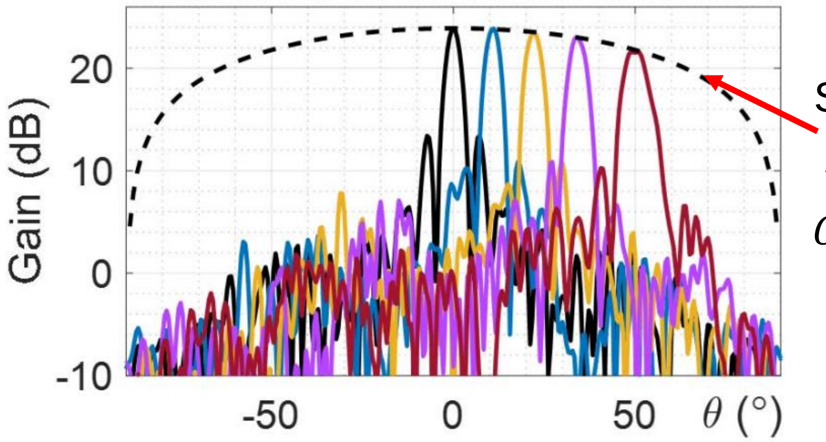


Beam scan solution

- Phased arrays:
  - High gain and wide-angle beam scan
  - Costly, power-hungry, usually narrow band
  - Good scan loss (ns~1, 1.5)
- Gradient Index lenses:
  - Geometric Optics (GO) ray-tracing design
  - High gain but discrete beam scan
  - Power-saving, wide band
  - Scan loss (n_s) is generally high







Scan loss fitted curve(dB):
$f(\theta) = \cos^{n_s}(\theta) + G_0$

G_0: broadside gain

Single lens state-of-the-art

GRIN lens	Freq(GHz)	Scan range	n_s
[1]	12	$\pm 25°$	4
[1]	12	$\pm 40°$	5.4
[2]	9	$\pm 30°$	7
[3]	13.4	$\pm 38°$	6.3
[4]	26	$\pm 47°$	4.4

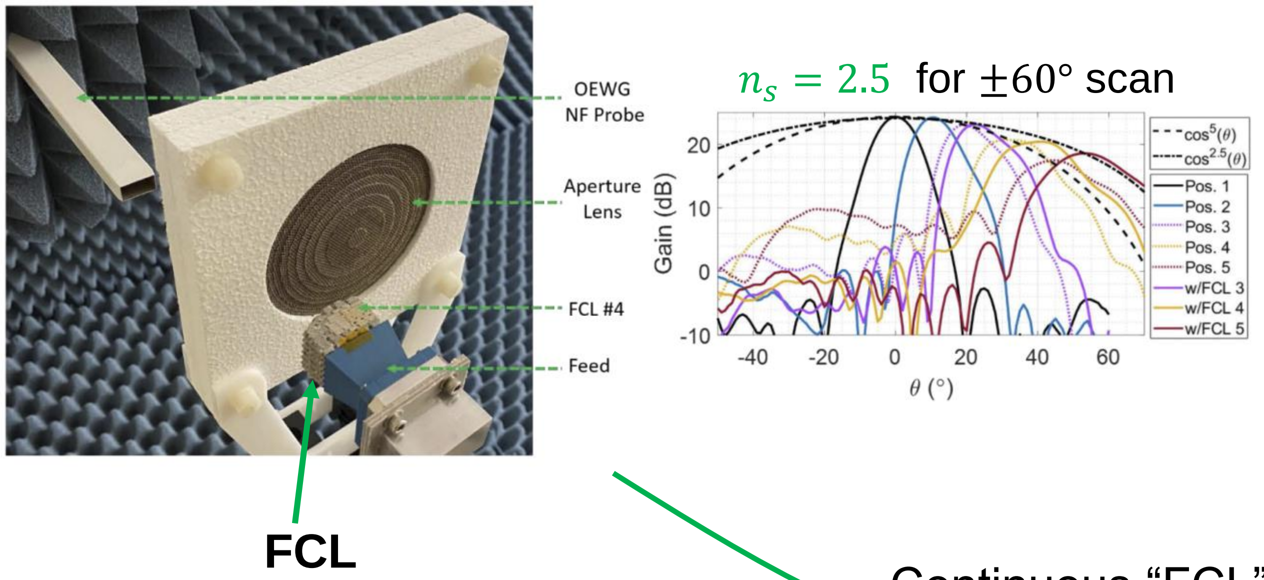
$n_s > 4$

Compound lens system

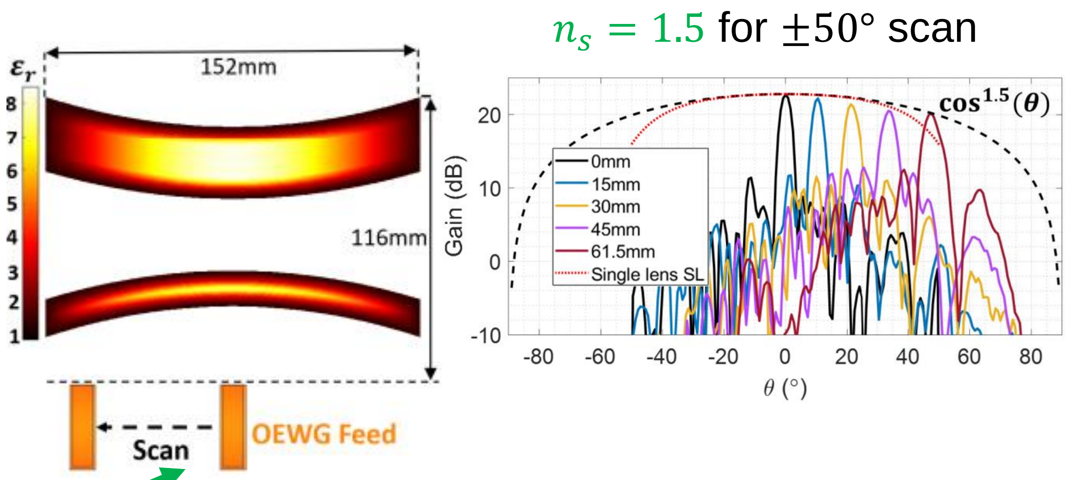
Beam scanning challenges:
- Single focal point design
- Spillover loss
- Flattened focal surface

Solutions:
- Multiple focal point design
- Phase correction
- Beam squinting

Feed corrective lenslets (FCLs)[5]



Compound lenses in parallel-plate waveguide [6]



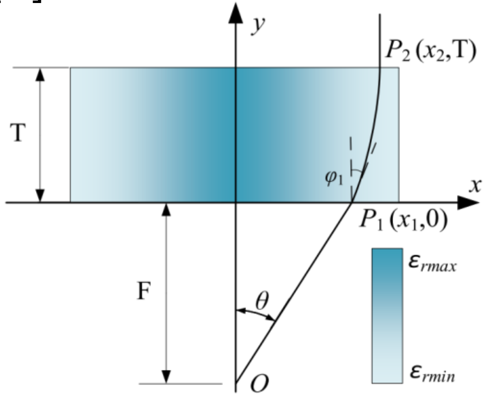
Continuous "FCL"

[1]S. Zhang, *et.al,* IEEE TAP, July 2021

GO Lens design solvers

1D closed-form lens

[1]



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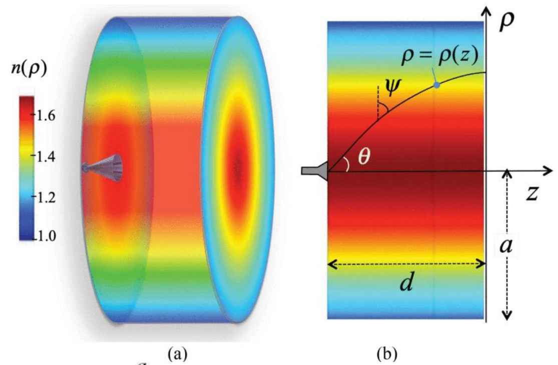

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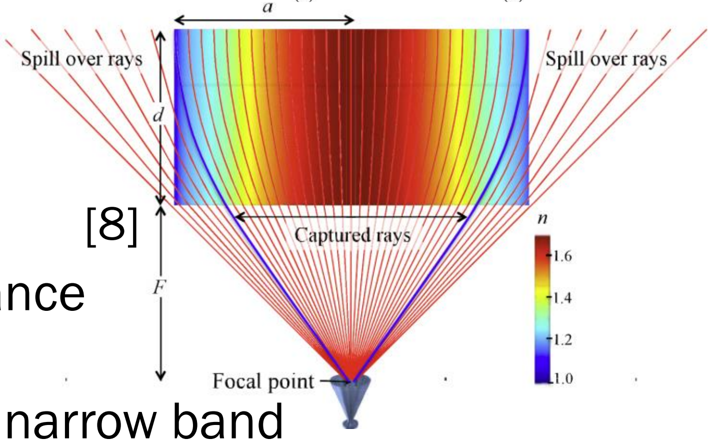
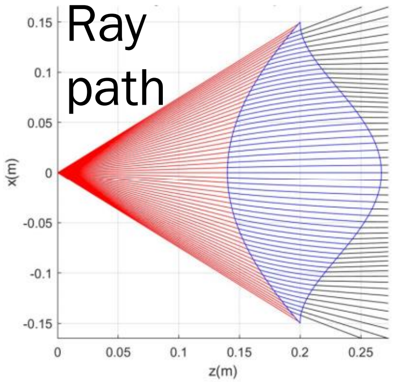


- Good broadside performance
- No optimization needed
- No impedance matching: narrow band
- Scan not considered

[1]S. Zhang, *et.al,* IEEE TAP, July 2021
[7] F. Maggiorelli, *et.al.,* IEEE OJAP, Feb. 2021
[8] A. Paraskevopoulos , *et.al.*, IEEE TAP, Sept. 2021
[9] J. Budhu, et.al, IEEE TAP, June 2019
[10]W. Wang, et.al, IMS 2022

2D curved ray tracing[9]



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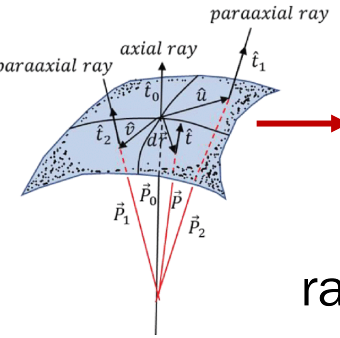


→ Complex E field vector → radiation pattern

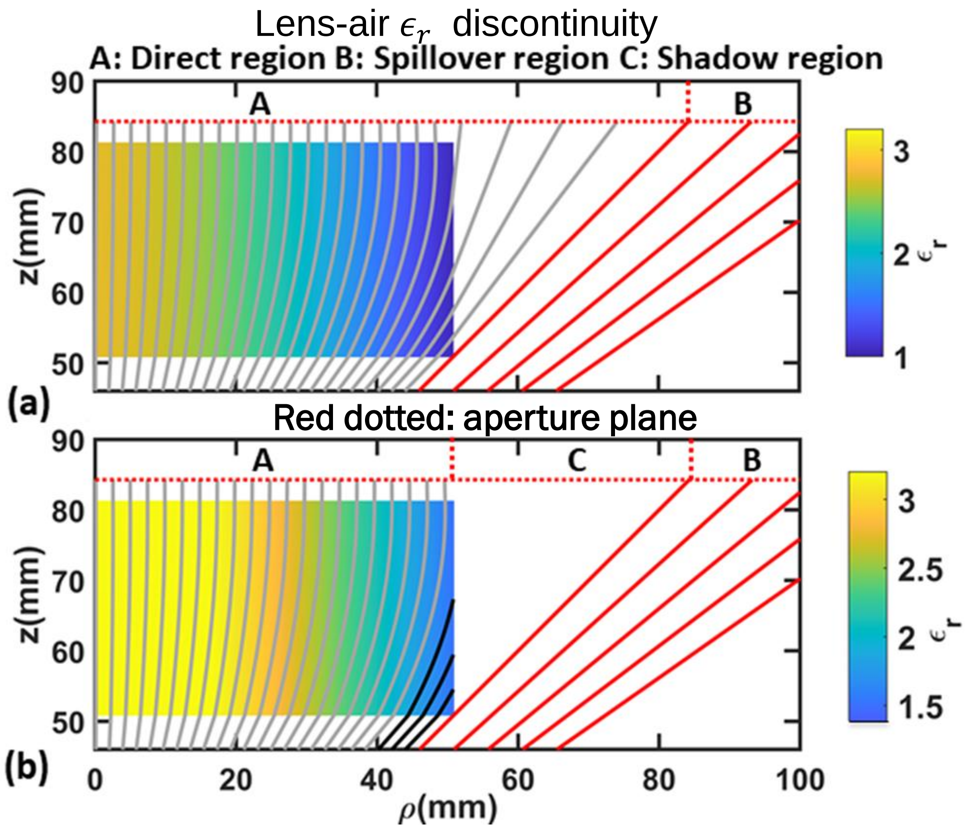
Wavefront curvature

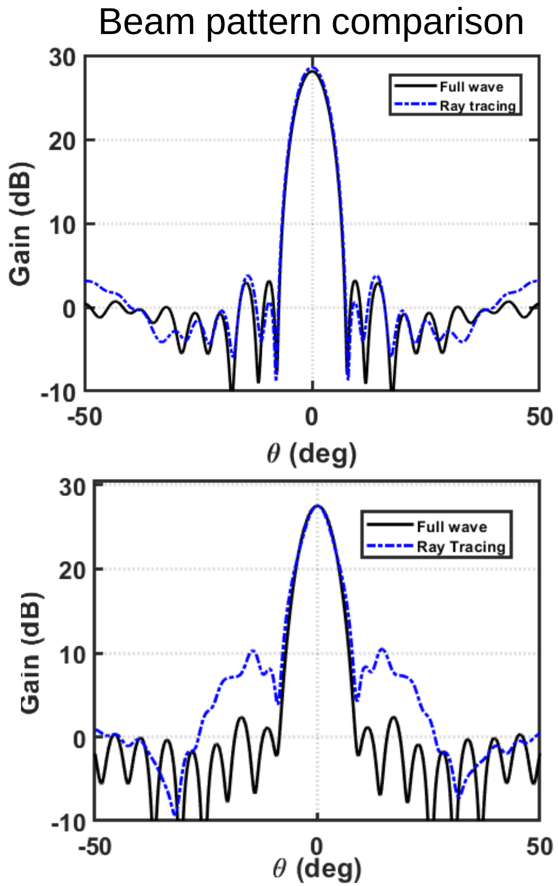
- Arbitrary shape and GRIN profile
- Complex aperture field → radiation pattern
- Multi-objective PSO

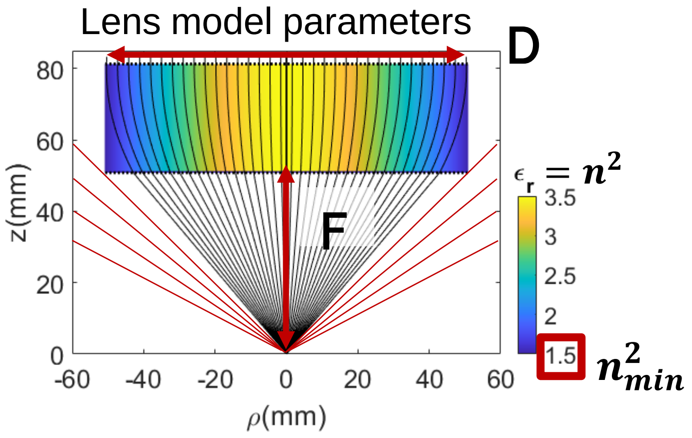
2D curved ray tracing + UAPO[10]

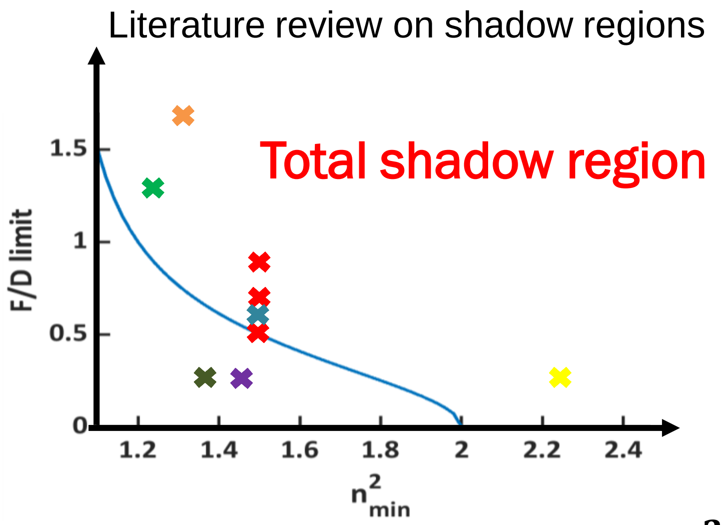
- Considering lens-air ϵ_r gap and shadow region
- Calculate shadow region E field using Uniform asymptotic physical optics (UAPO)
- Accurate (~half dB) and fast (1 minute)
- Multi-objective PSO

2D curved ray tracing : Shadow region[10]









- ϵ_r discontinuity causes the shadow regions(SR)
- SR perturbs the curved ray tracing accuracy

- SR can be evaluated by **F,D,** n^2_{min}
- Total SR commonly exists

[10] : W. Wang, et.al, IMS 2022
[11]N. C. Garcia , *et.al.*, IEEE TAP, Aug. 2020
[12]A. Patri , *et.al.*, IEEE (APS/URSI), 2016
[6]S. Zhang, *et.al.*, IEEE TAP, July 2021
[13]J. Poyanco, *et.al.*, 15th EuCAP, 2021
[14]S. Jain, *et.al.*, IEEE AWPL, June 2013
[15]M. Imbert, *et.al.*, IEEE AWPL, Oct. 2014

Uniform Asymptotic Physical Optics Diffraction[16]

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UAPO Procedure:

Incident plane wave E_i

↓ Reflection, refraction

surface current J_s, J_{ms}

↓ Surface integral

Diffracted field E_d

→ Combining GO and UAPO fields

↓

Near field to far field

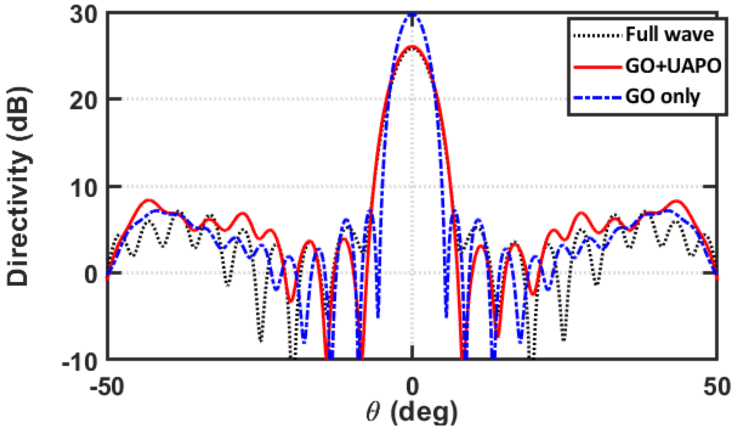
[16]

$$E_d = \left(D_\perp E_\perp^i + D_\parallel E_\parallel^i\right) \frac{e^{-jkr'}}{A}$$

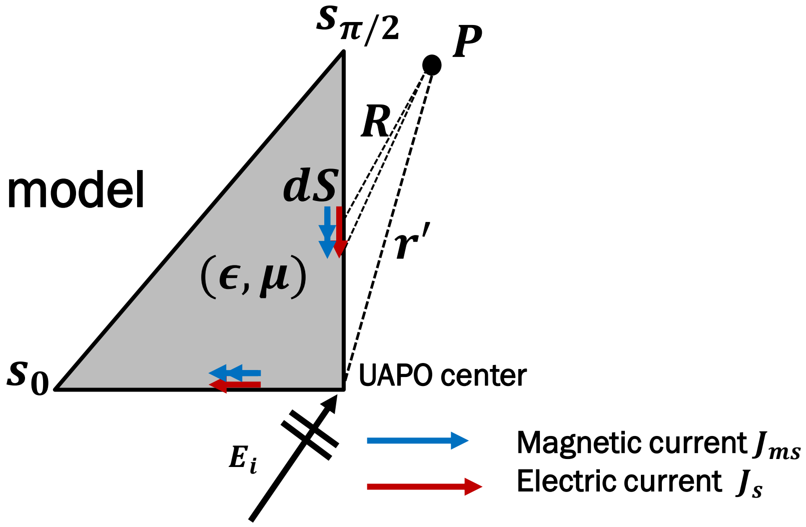
Wave phase

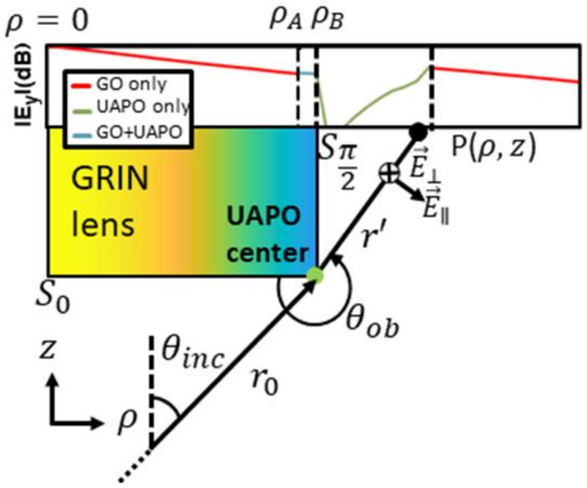
Diffraction coefficient — *Incident field* — *Attenuation factor*

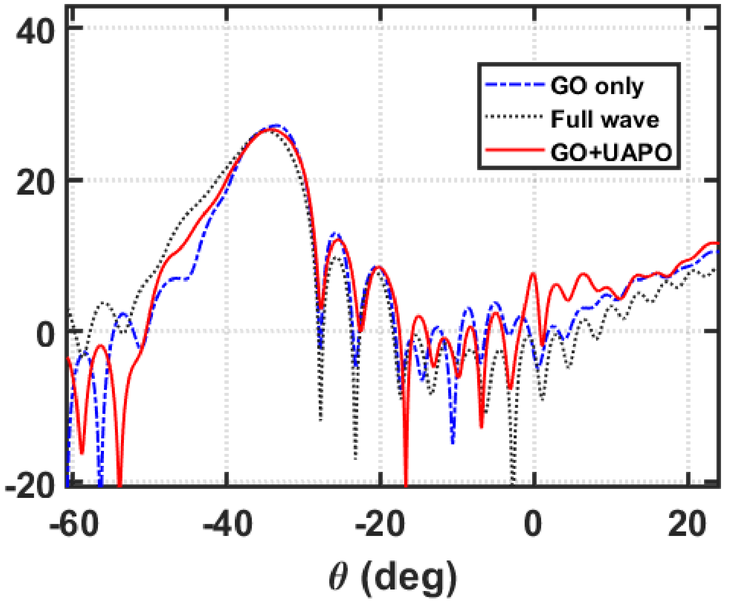
Framework in [17] to represent integral



UAPO model

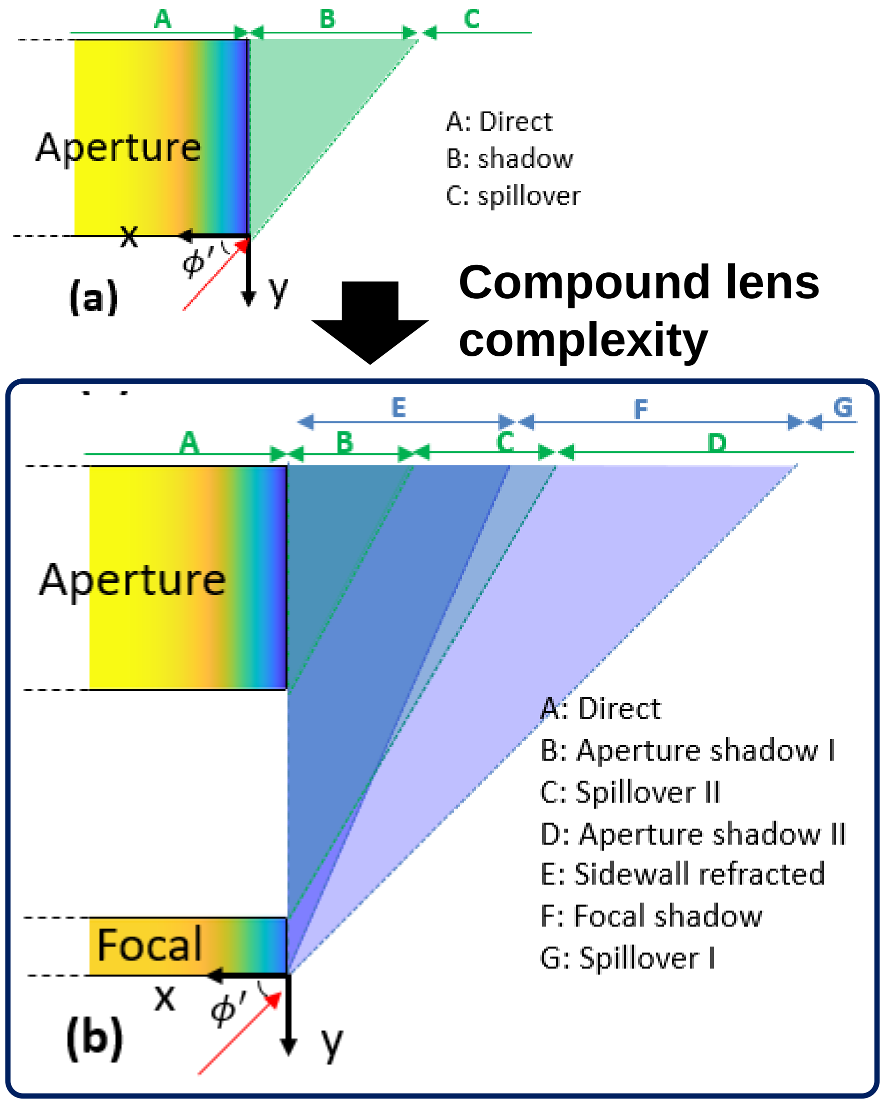


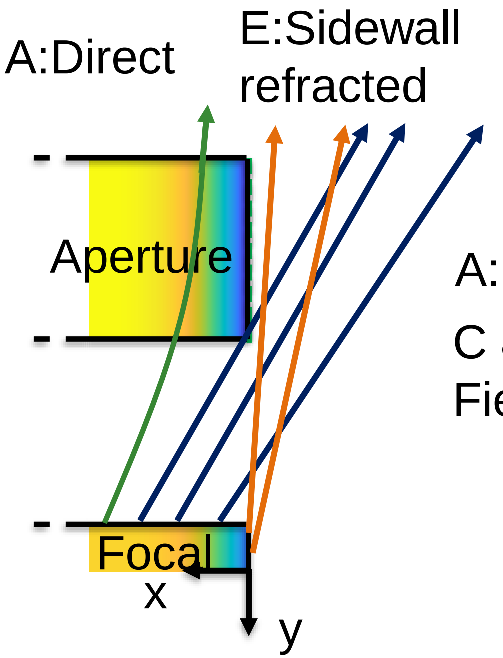




Time: 3h vs. 1min

Compound lens field distribution





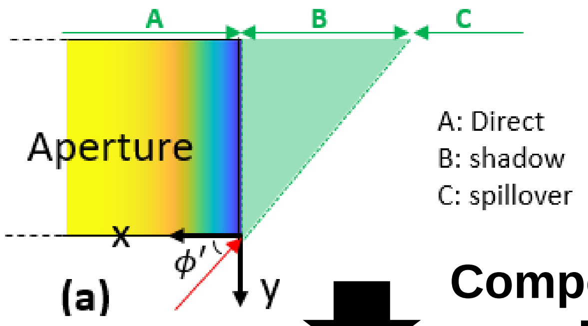
A: focal + aperture lens ray tracing

C & E: by focal lens ray tracing

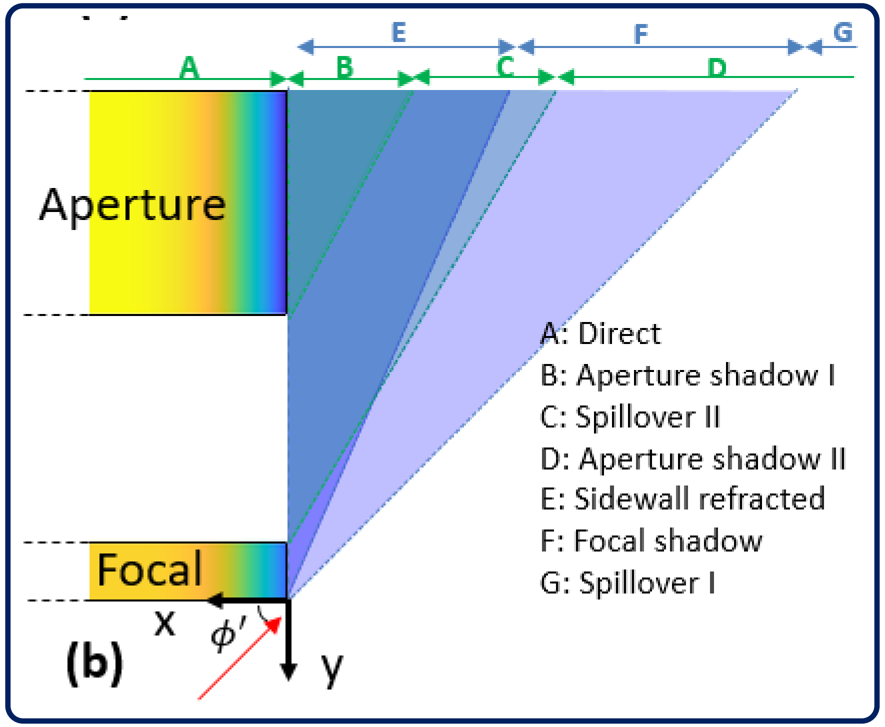
Field E is very small

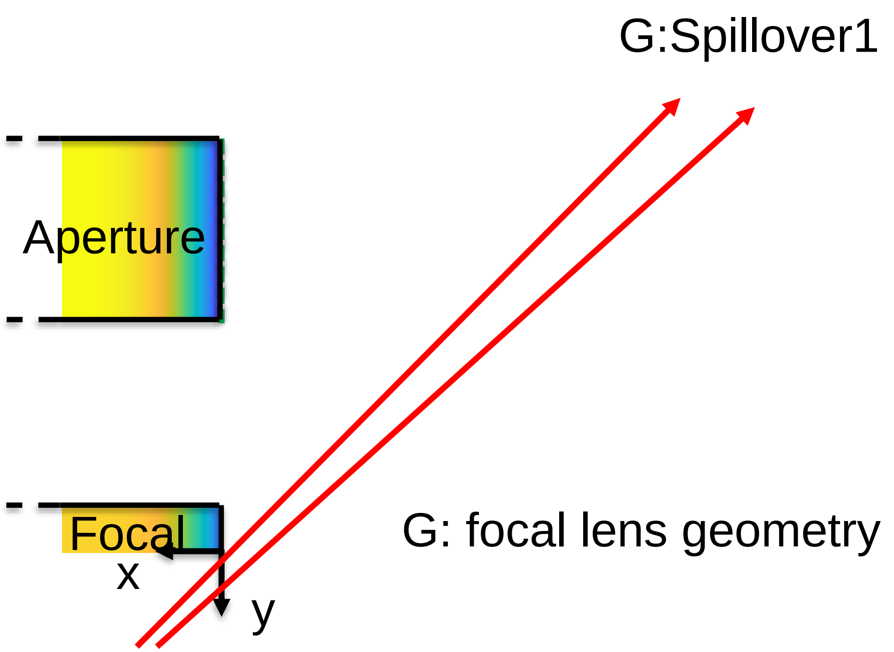
Ray tracing related

Compound lens field distribution



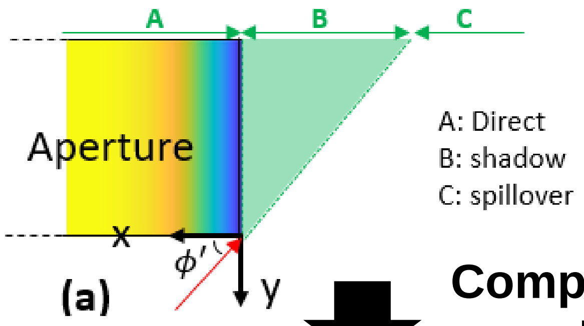
Compound lens complexity



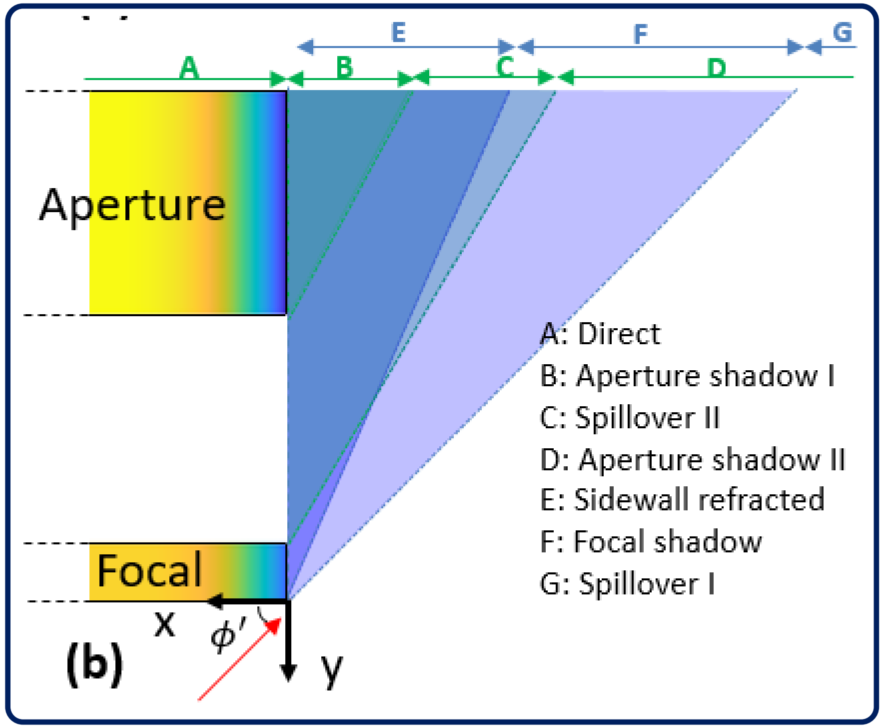


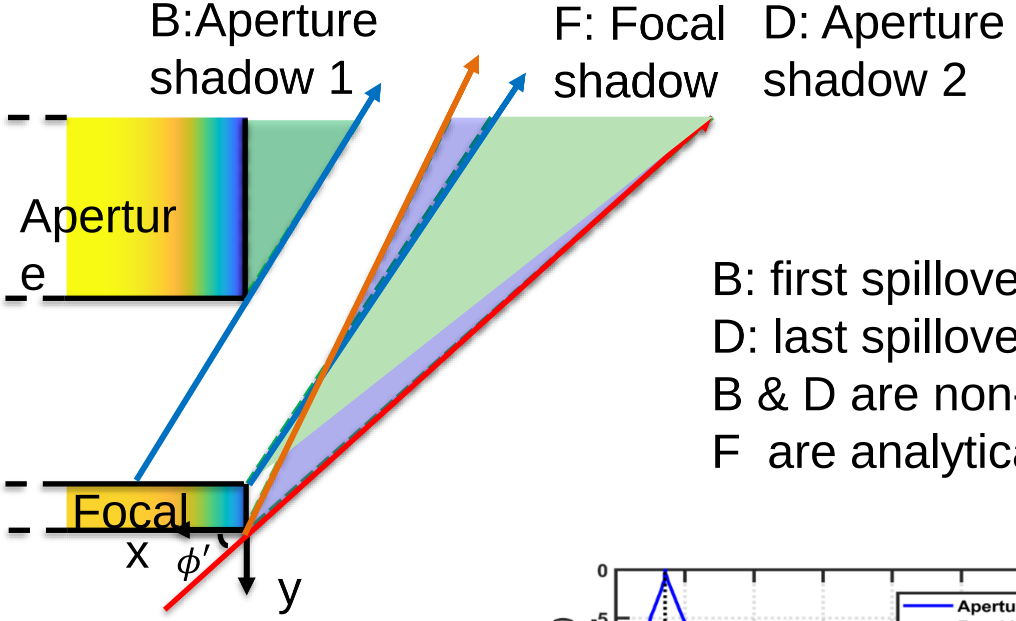
Analytical:
determined by focal lens geometry

Compound lens field distribution



Compound lens complexity





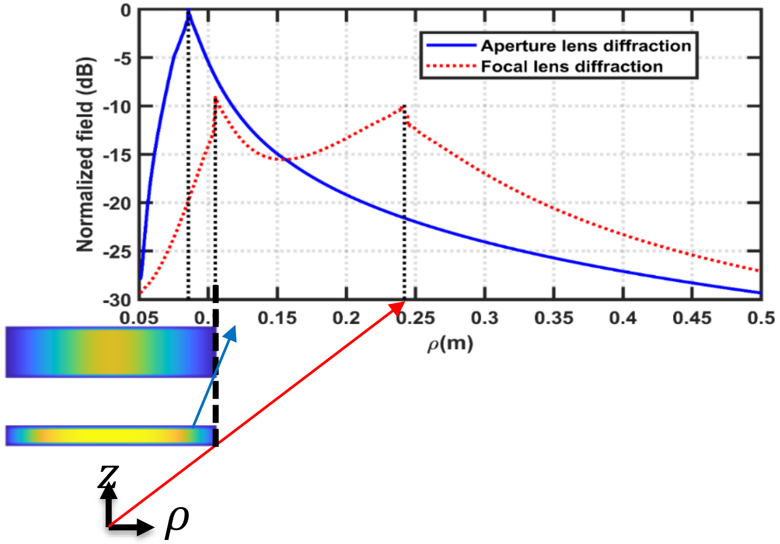
B: first spillover ray
D: last spillover rays
B & D are non-analytical
F are analytical

[16]

$$E_d = \left(D_\perp E_\perp^i + D_\parallel E_\parallel^i\right) \frac{e^{-jkr'}}{A}$$

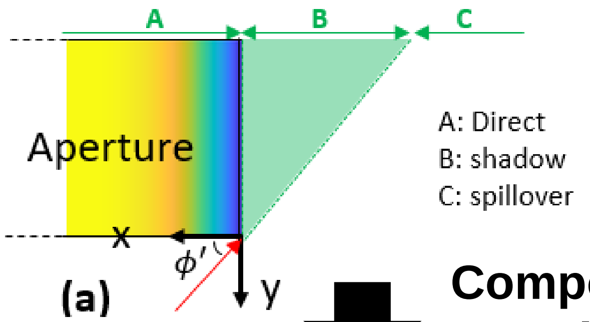
Wave phase

Diffraction coefficient · *Incident field* · *Attenuation factor*

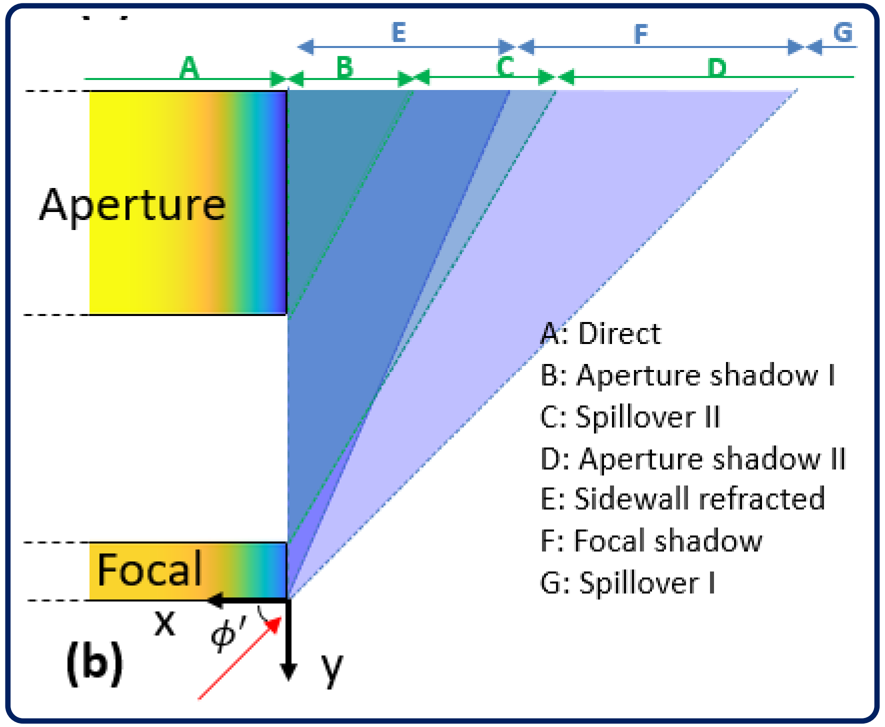


$E_{d,Ap}$ depend upon ray tracing solution through focal lens (blue rays)

Compound lens field distribution



Compound lens complexity



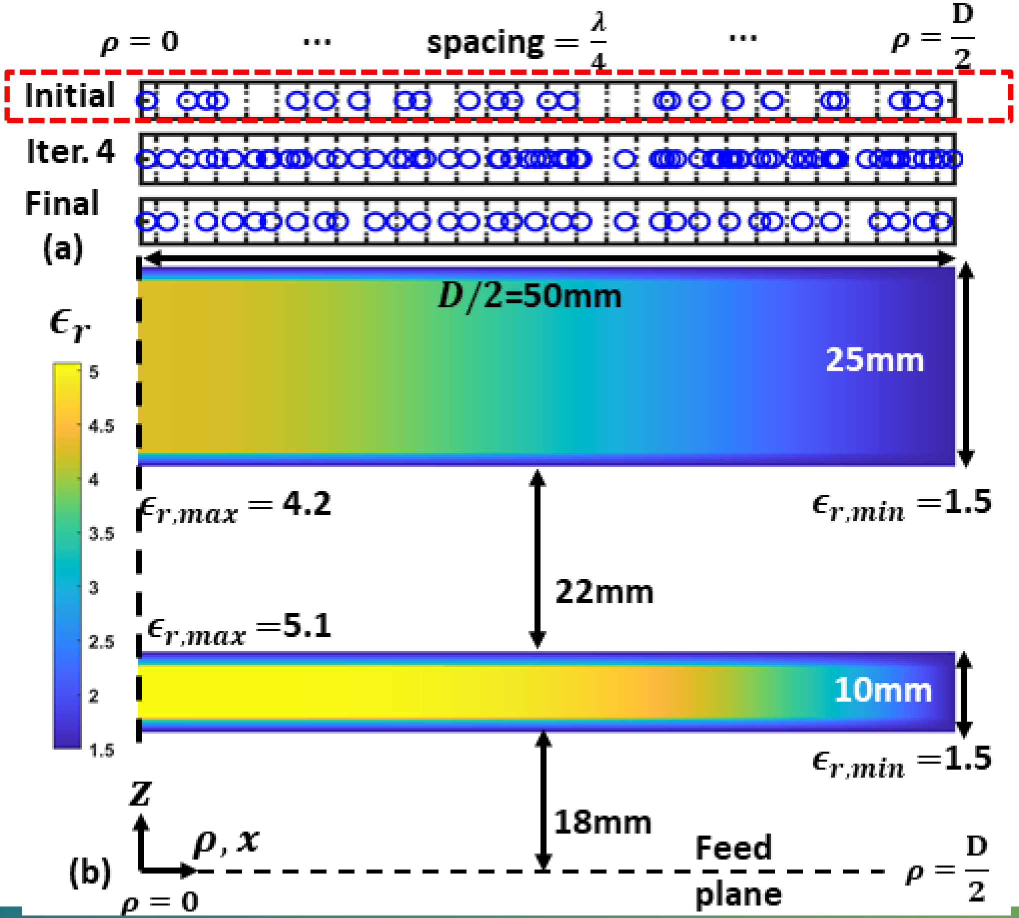
- Single lenses:
  - Single shadow region
  - Analytical diffracted field calculations
- Compound lenses:
  - Multiple shadow regions
  - Diffraction sources computed from ray traced fields “close to” corner
  - May require **ray tracing iterations** to find “close enough” ray

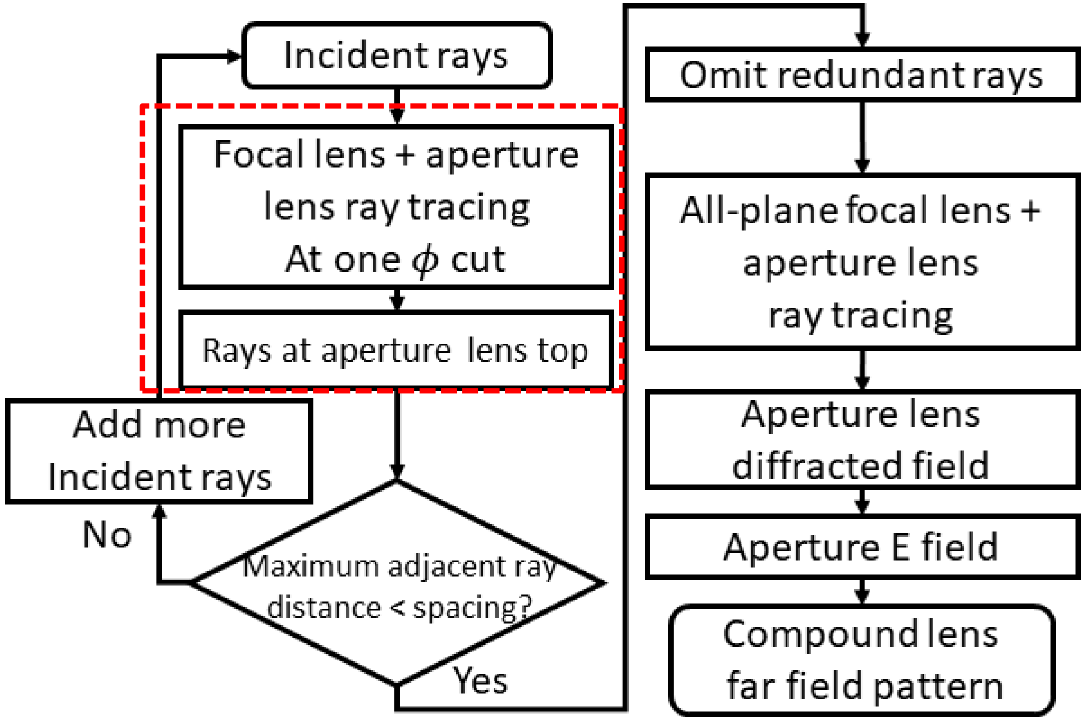
Iterative ray tracing

Ray distribution in the aperture at $\phi = 0°$

NF->FF requires lambda/2 aperture sampling

Goal: ray fills all $\frac{\lambda}{4}$-spaced units





Iterative ray tracing

Ray distribution in the aperture at $\phi = 0°$
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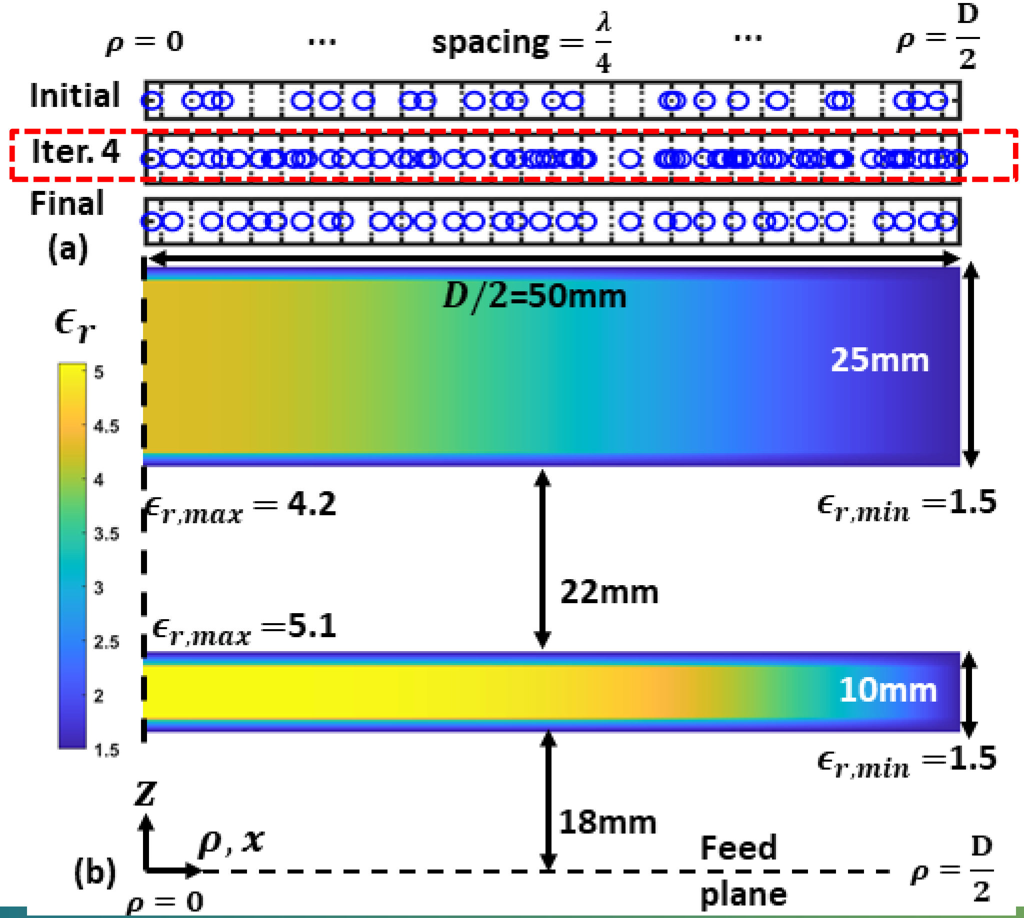
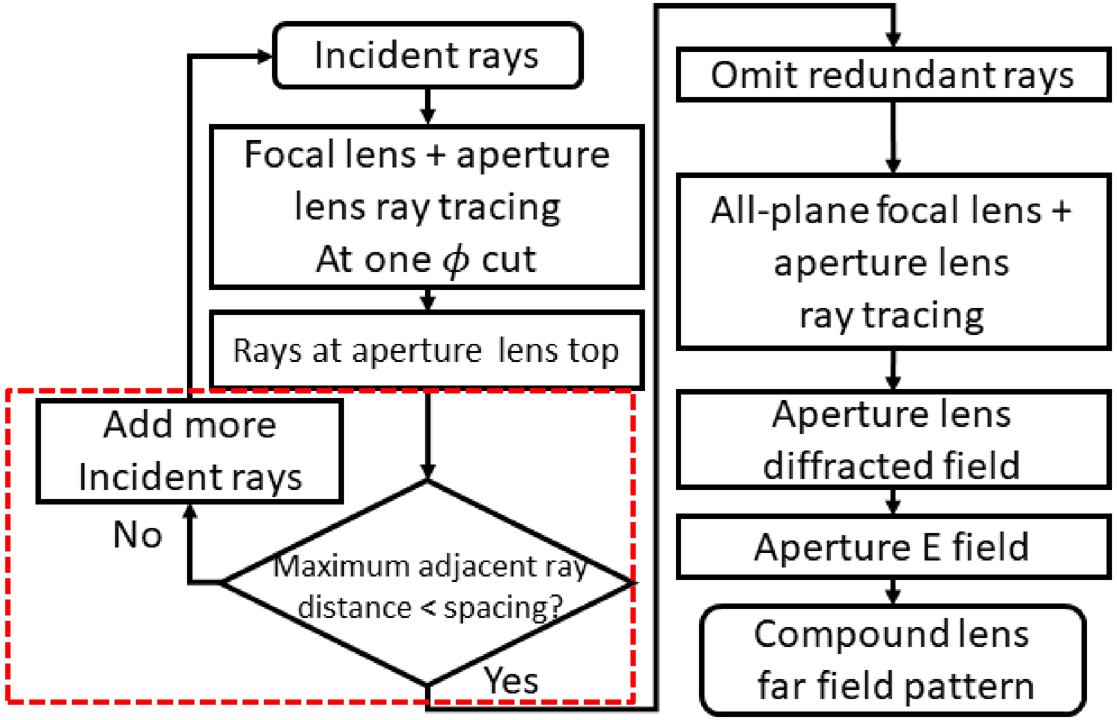




accuracy

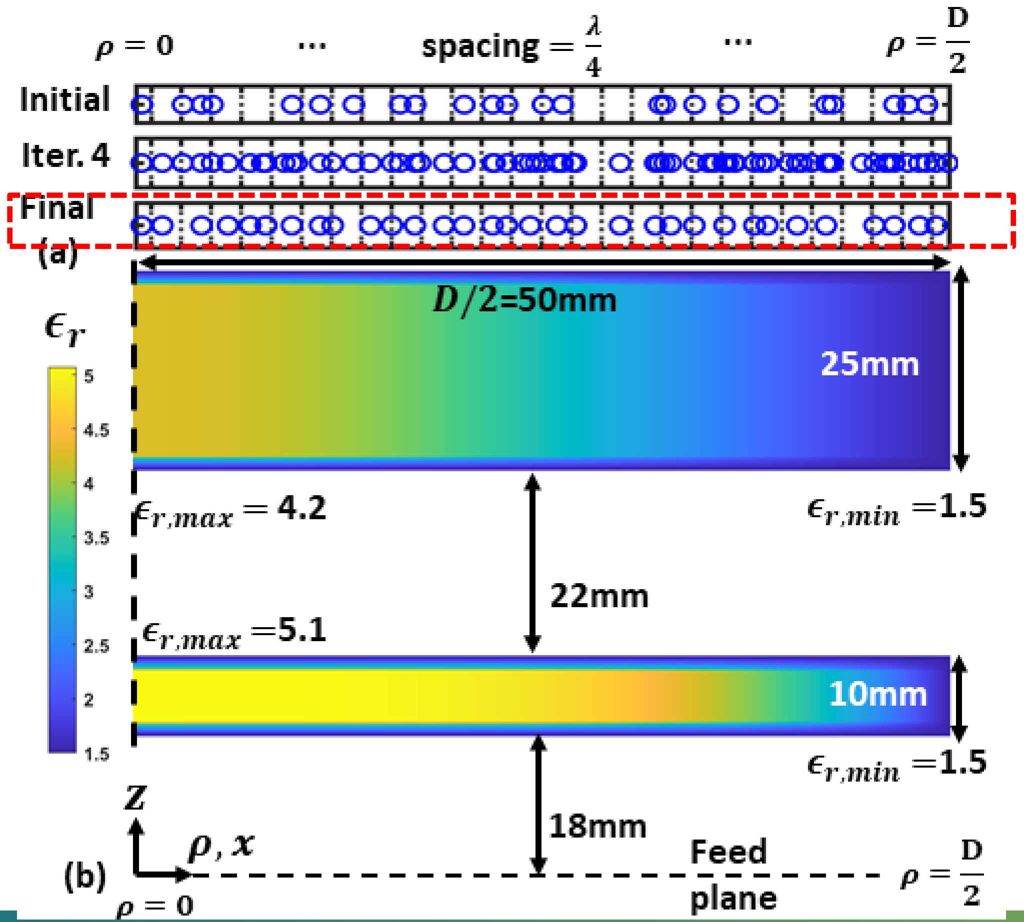
Iterative ray tracing

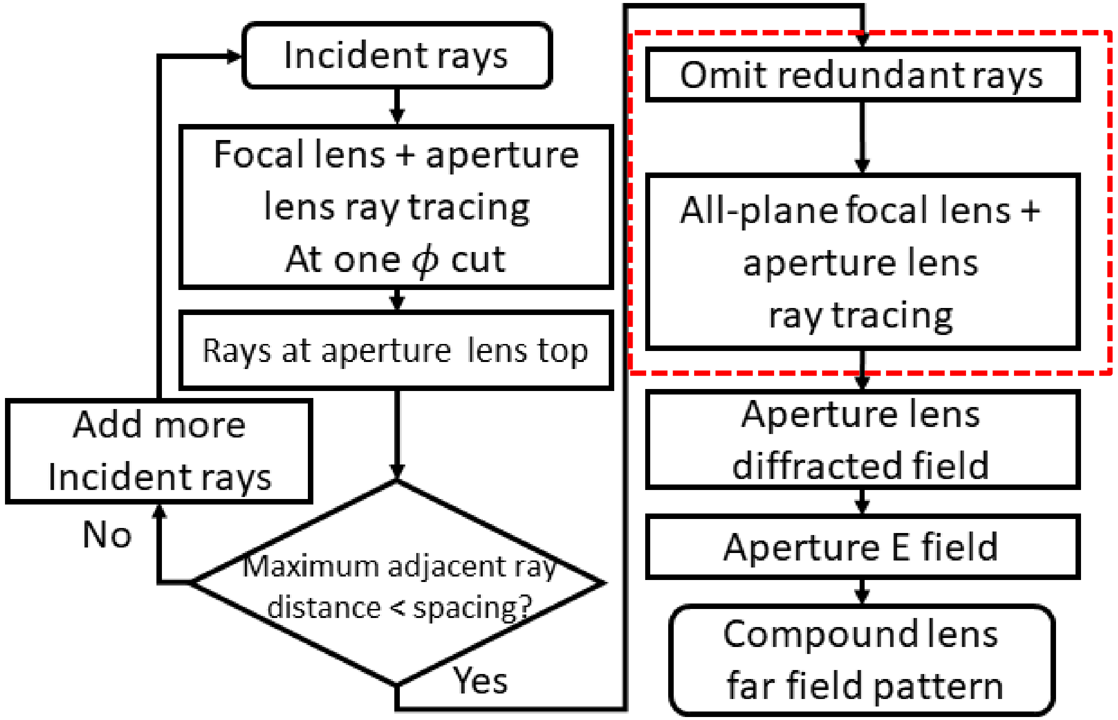
Ray distribution in the aperture at $\phi = 0°$

NF->FF requires lambda/2 aperture sampling

Goal: ray fills all $\frac{\lambda}{4}$-spaced units

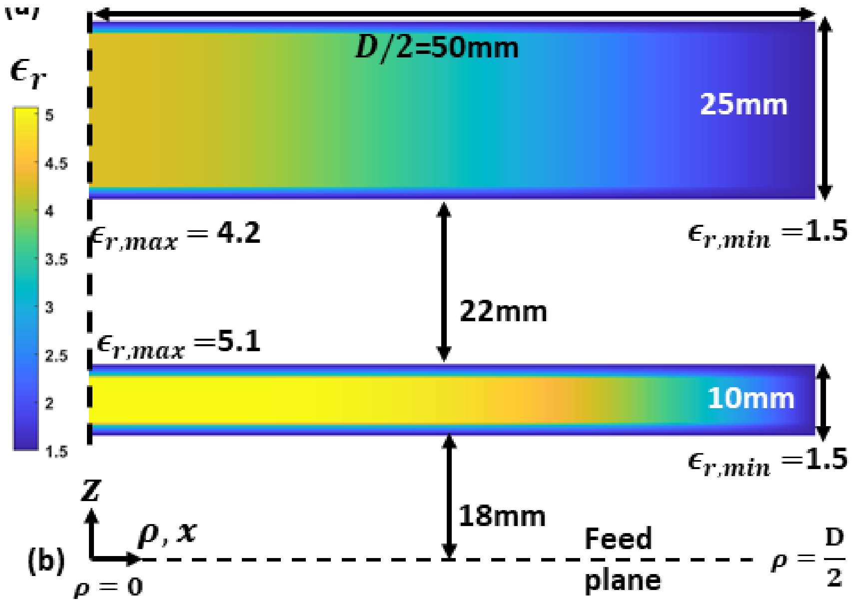
Speed





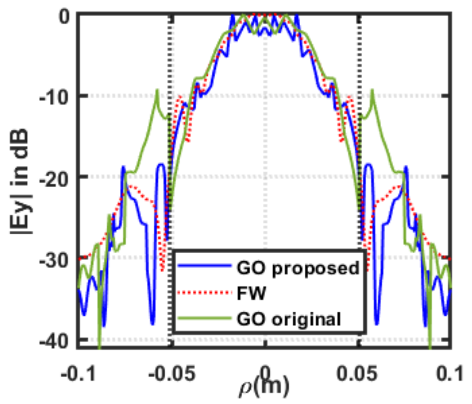
Compound lens results

Lens model: 4” lens

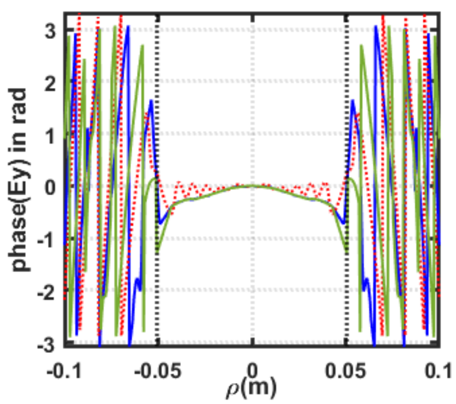


Method	Lens performance			Time
	Directivity (dB)	SLL (dB)	3dB BW (°)	
FW	31.4	34.1	4.0	3h
GO proposed	31.2	29.4	4.1	2.5min
GO original	31.0	24.0	4.1	2.5 min

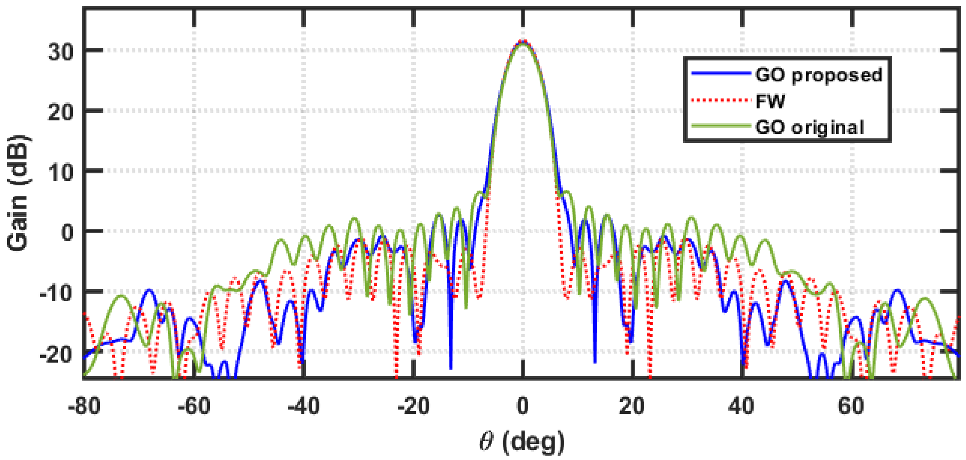
Aperture field magnitude



Aperture field phase



Far-field pattern



Conclusion & Future Work

Conclusion

- realized numerical solver for the compound lens simulation
- Analyzed the field distribution of compound lenses and proposed an iterative ray tracing method

Future Work

- Confirmation of theoretical assumptions
- improve the beam scanning performance

Reference

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Thanks !