Manipulated Bessel Beams and their Applications

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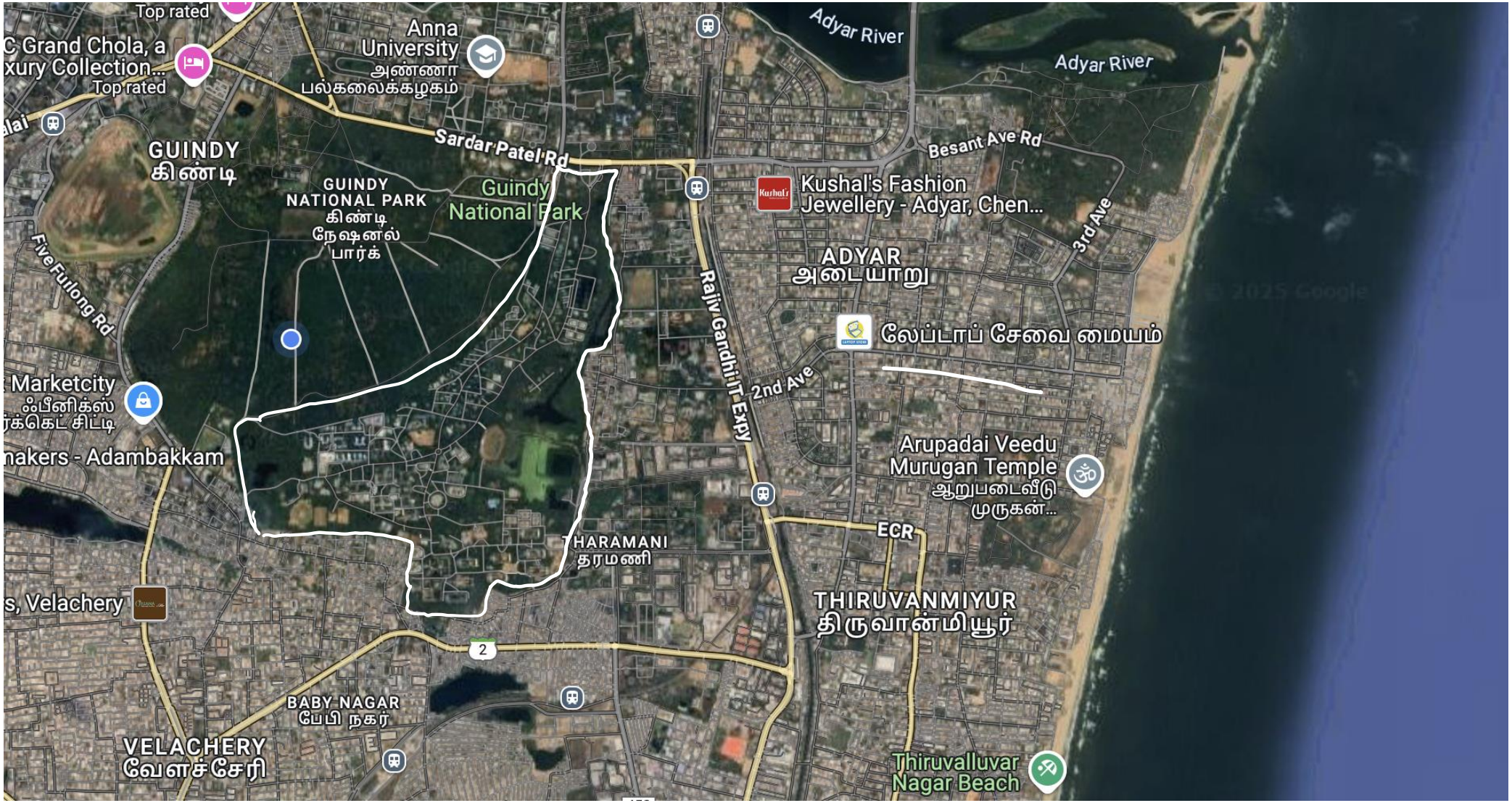
Chennai/Madras

IIT Madras: A forest in the middle of the city



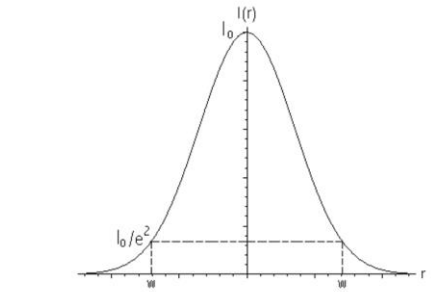
https://www.google.com/maps

Inside the forest

- Centre for teaching, research and industrial consultancy
- A residential institute with nearly 700 faculty, 12000 students and 1250 administrative & supporting staff
- A self-contained campus located in a beautiful 2.5 km^2 forested land

Beam Shaping

$$E_{out}(x,y) = t(x,y)E_{in}(x,y)$$



Light Manipulating Element t(x,y)

Incident beam

Shaped Light or Complex Light

Desired beam, $E_{out}(x,y)$

Incident beam, Eg Gaussian $E_{in}(x,y)$

Research Questions

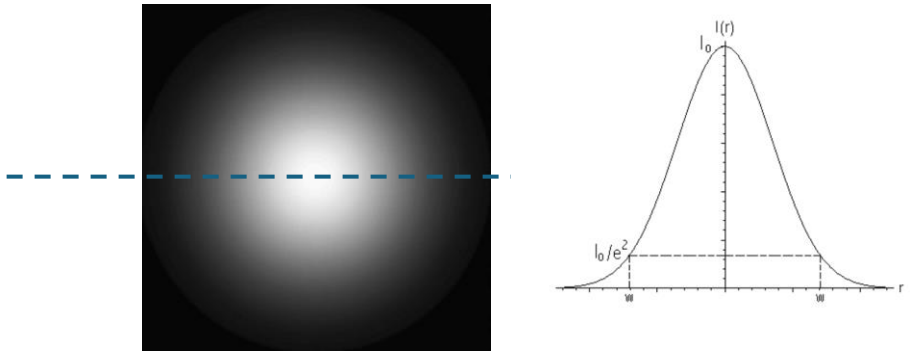
- What t(x,y) do we need to get a specific $E_{out}(x,y)$?
- How to design or calculate t(x,y)?
- Should the phase element be
  - Refractive
  - Diffractive
  - Meta
- What is the best way to fabricate the element?

Application: Generation of Sidelobe Suppressed Bessel Beams

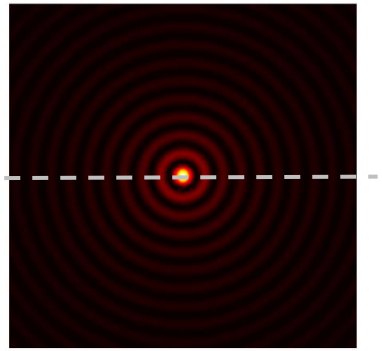
Bessel Beams

Gaussian versus Bessel Beam

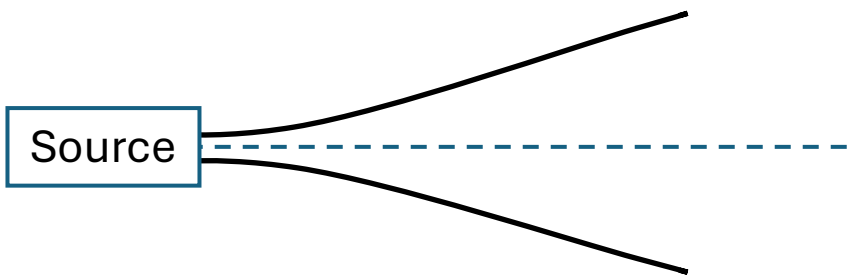
Gaussian Beam Cross Section



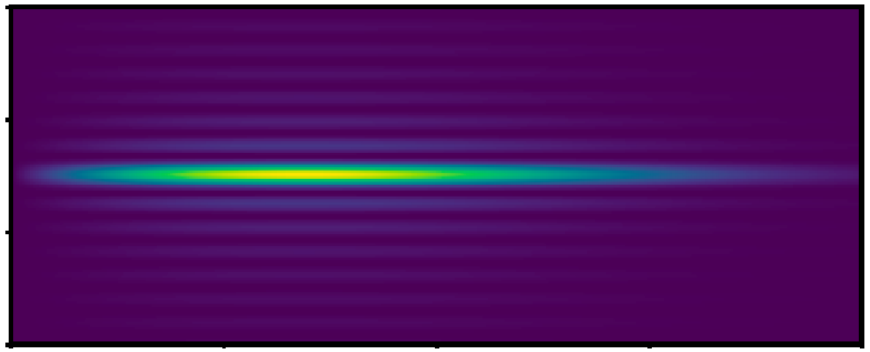
Bessel Beam Cross Section



Direction of propagation

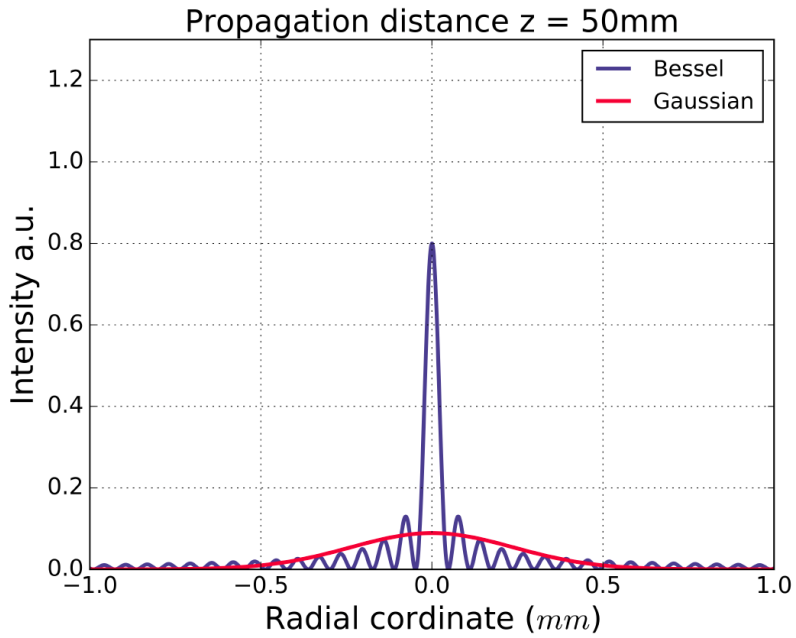


$$\psi(r, z, t) = J_0(k_r r)e^{i(k_z z - \omega t)}$$



Durnin, J., JOSA A 4.4 (1987): 651-654.

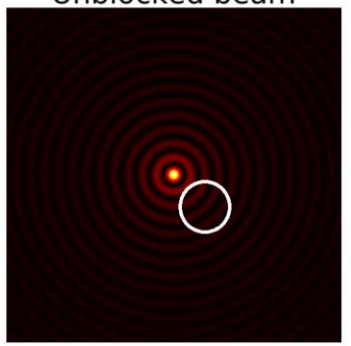
Bessel Beam: Diffraction-free

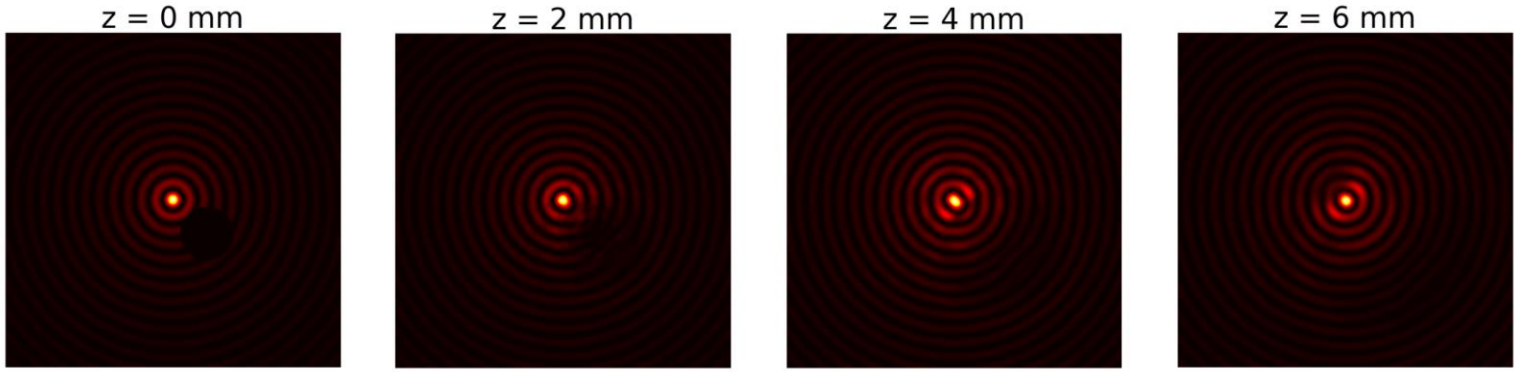


Self Healing Property

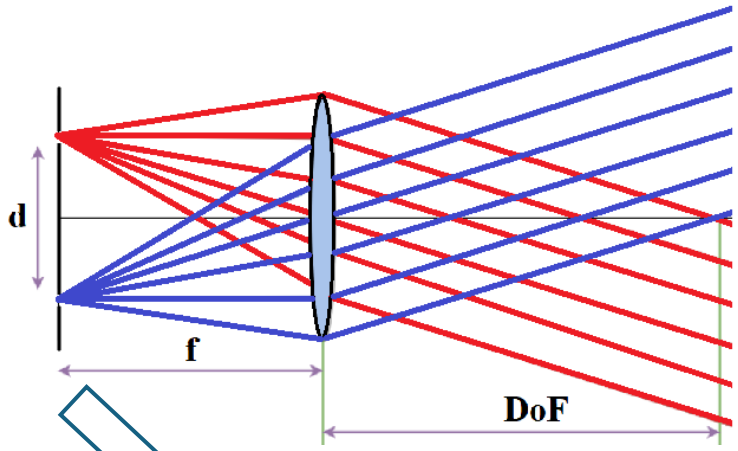
Self healing:

- Ability to reconstruct original shape
- **Advantages:**
  - Multiple particle trapping
  - Speeds up Light microscopy

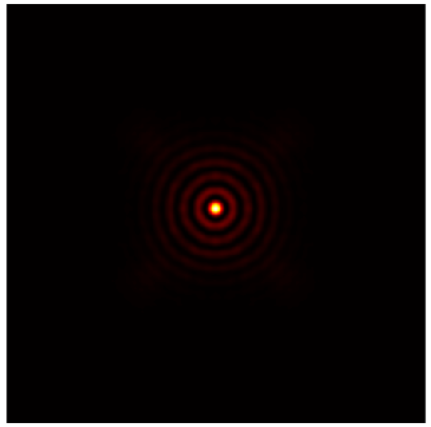


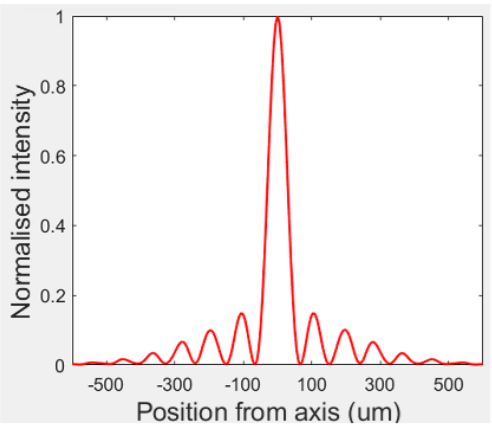


Bessel Beam Generation

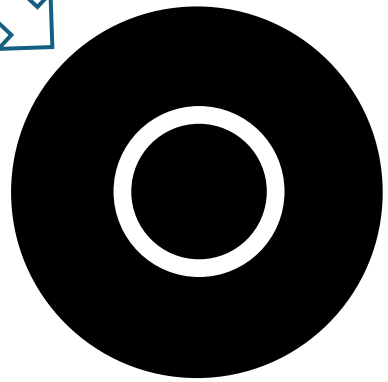


Intensity Cross section





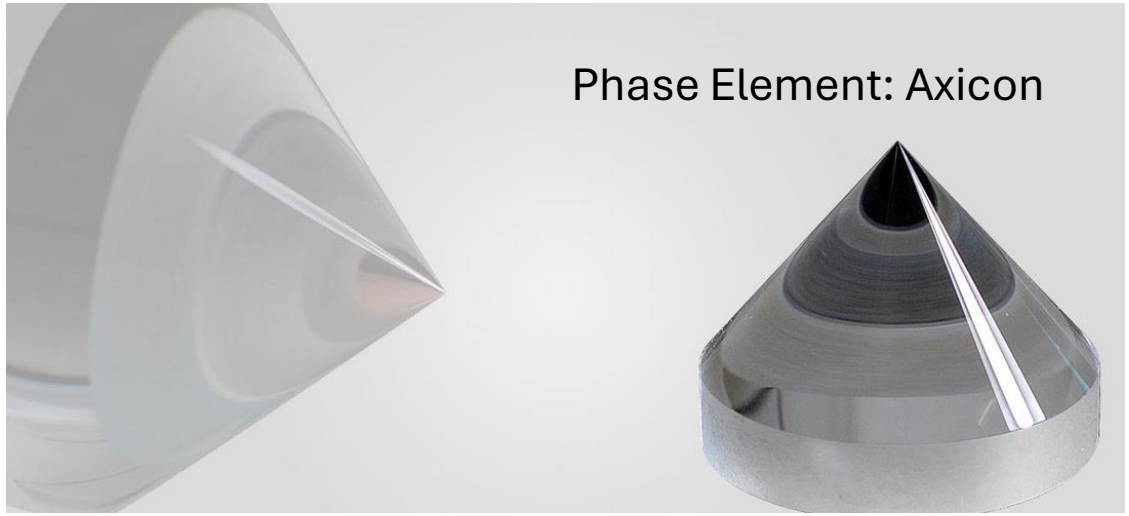
Amplitude Element



Durnin, J., JOSA A 4.4 (1987): 651-654.

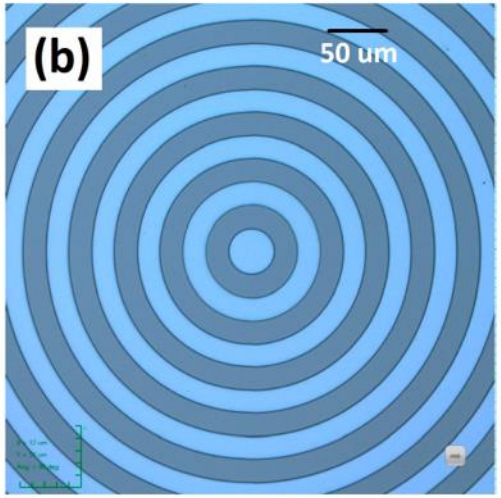
Phase Elements

Refractive

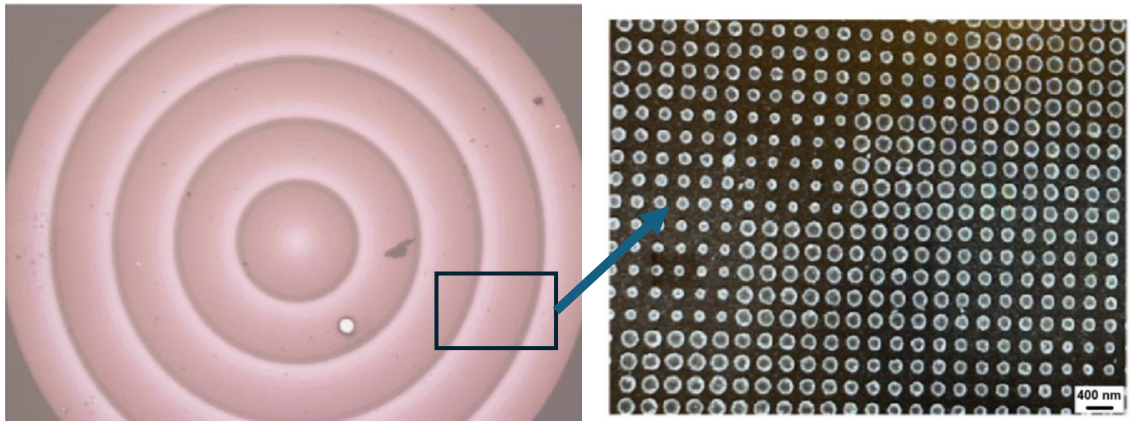


Modulo 2π Operation

Diffractive



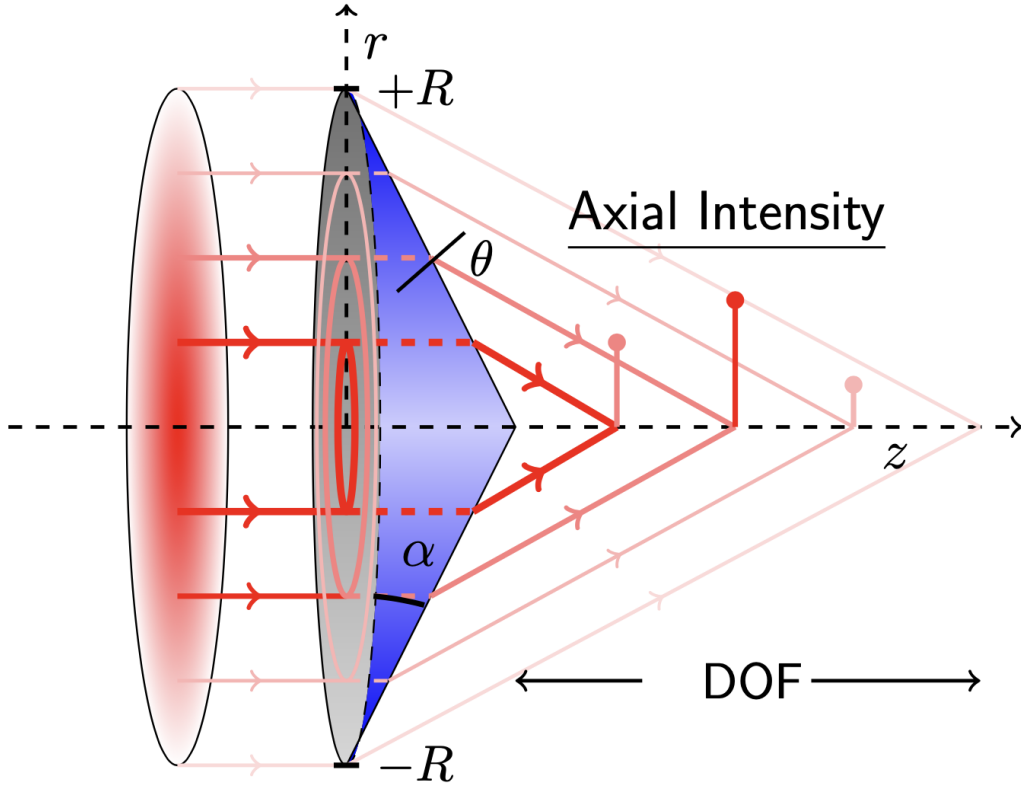
Meta-surface

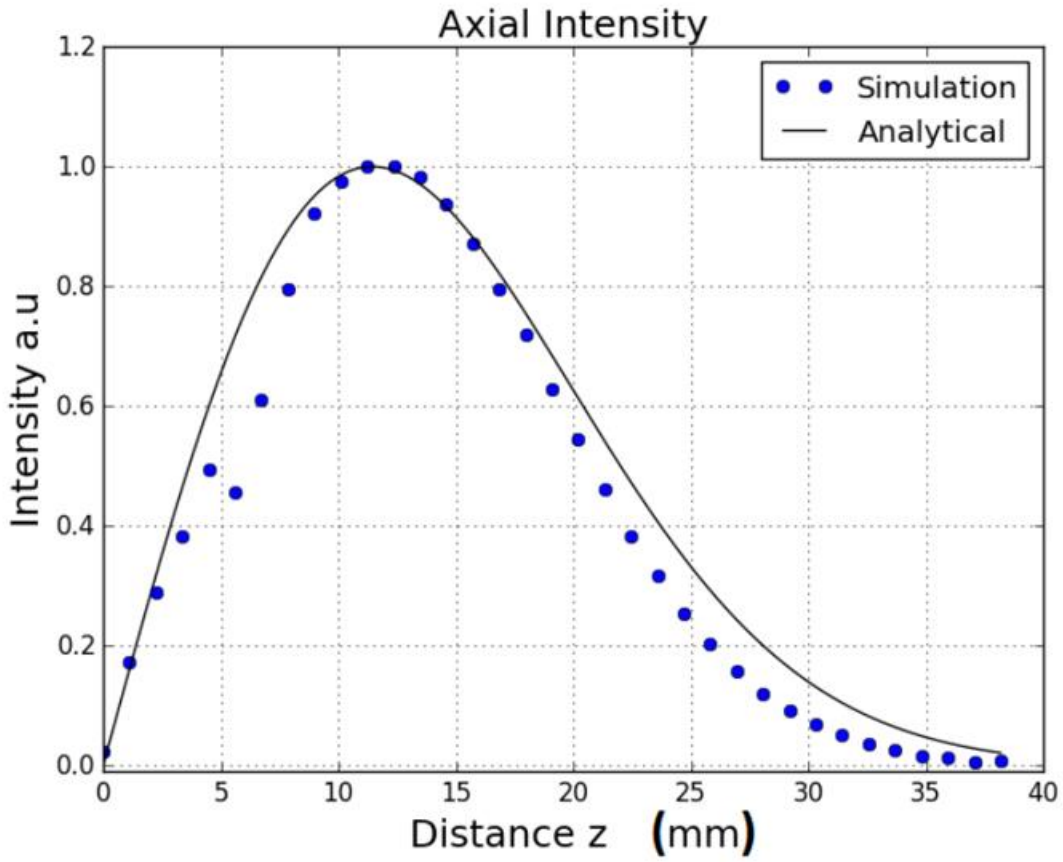


What they don’t tell you about Bessel Beams

(Problem 1)

Axial Intensity



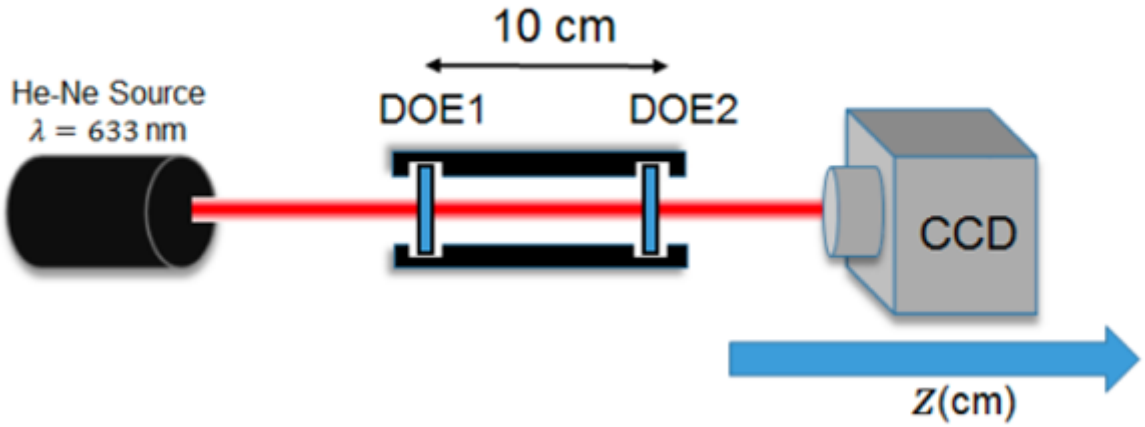


General relationship between $AI(z)$ and $I_{in}(r)$:

$$AI(z) = MI_{in}(r)z$$

M(n, α)

Engineering Axial Intensity with a pair or DOEs

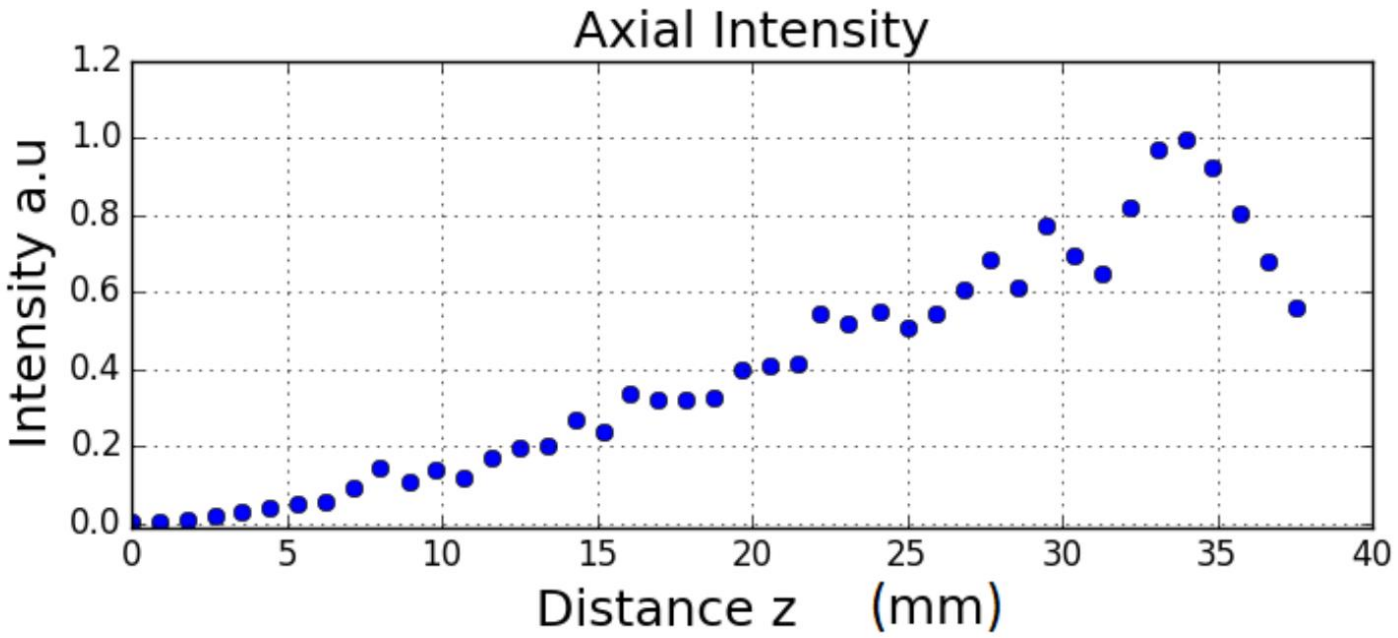


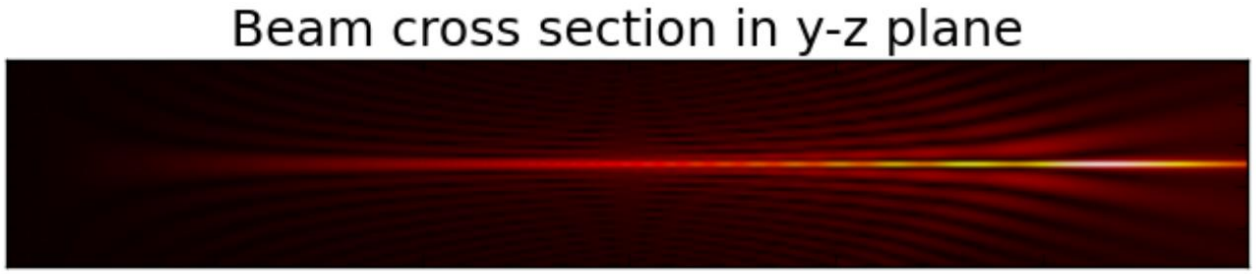
- Axicon illuminated with incident beam of desired cross section I(r)
- Fresnel integral used to compute the transverse intensity at different z distances
- DOE1 – I(r)
- DOE2- Axicon

Raghu Dharmavarapu, Shanti Bhattacharya and Saulius Juodkazis, “Diffractive optics for axial intensity shaping of Bessel beams," JOPT, **20**(8), 085606 (2018)

Linearly Increasing axial intensity

Simulations





$$AI(z) = MI_{in}(r)z$$

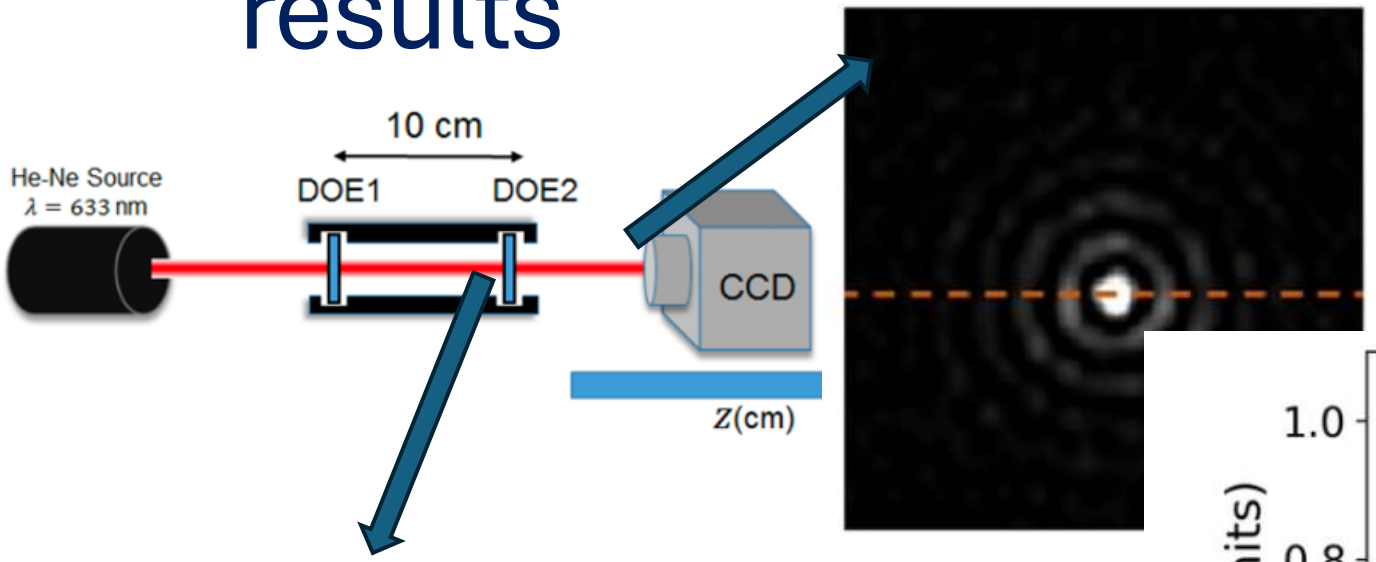
AI(z) = az

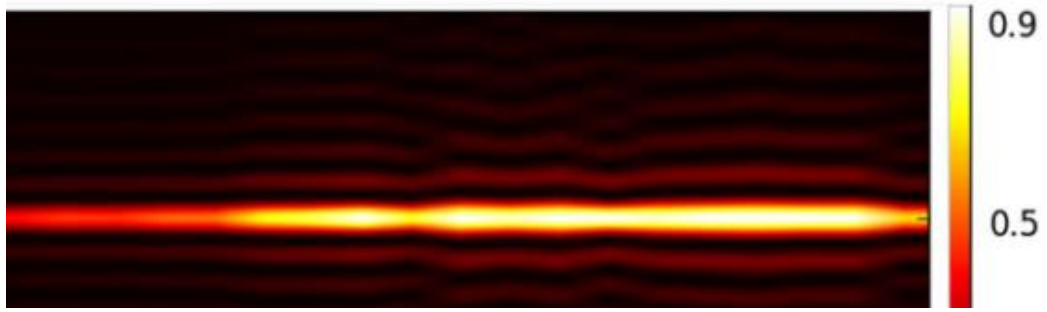
$I_{in}(r) = a/M$

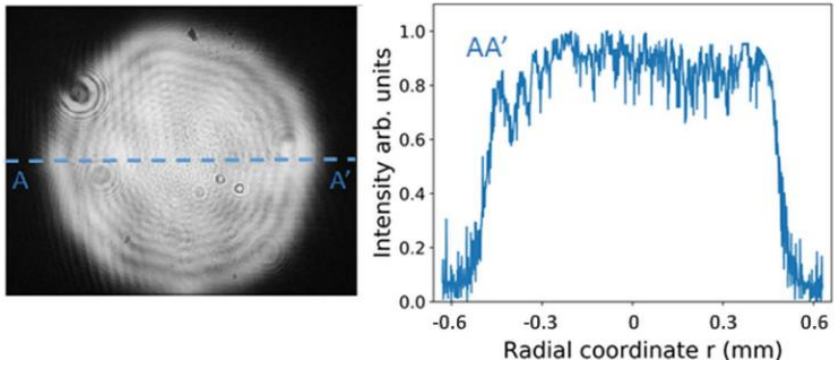
constant

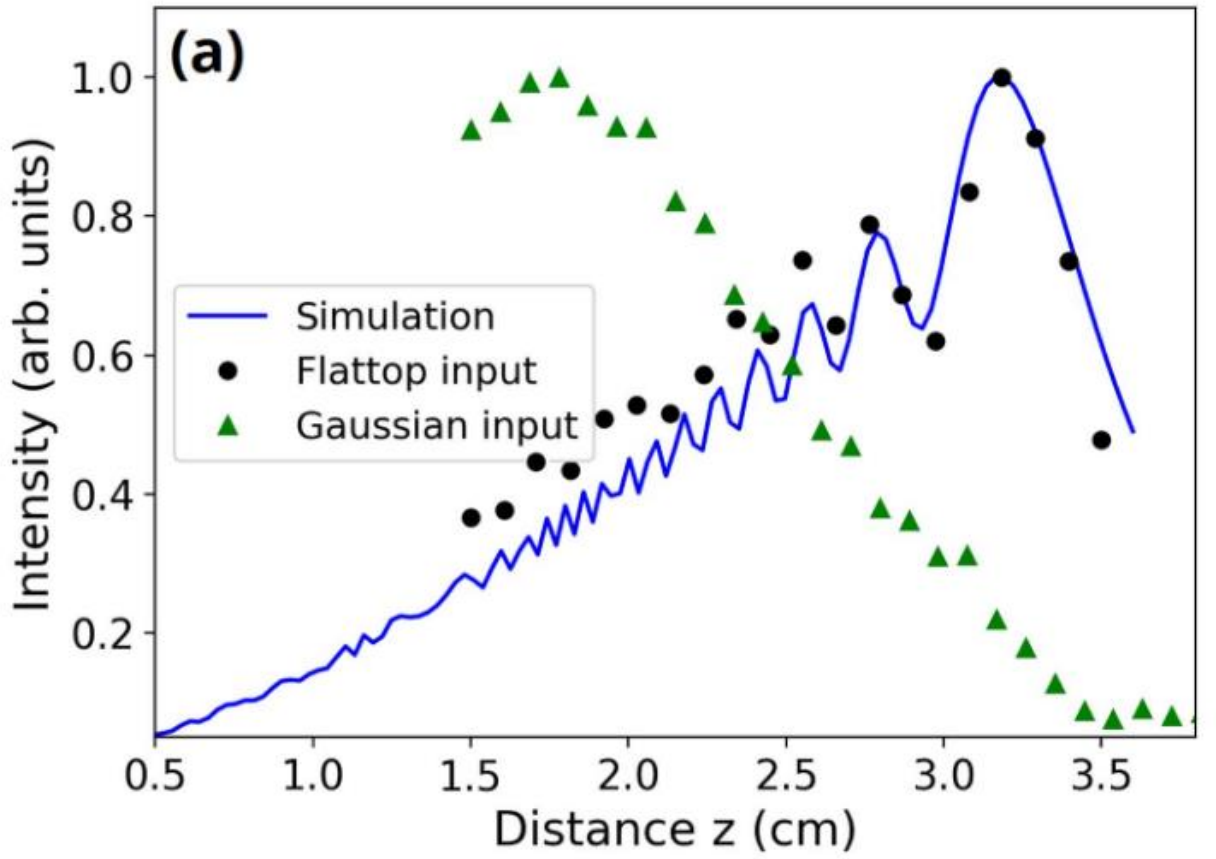
Input beam: Tophat intensity

Linearly increasing – Experimental results





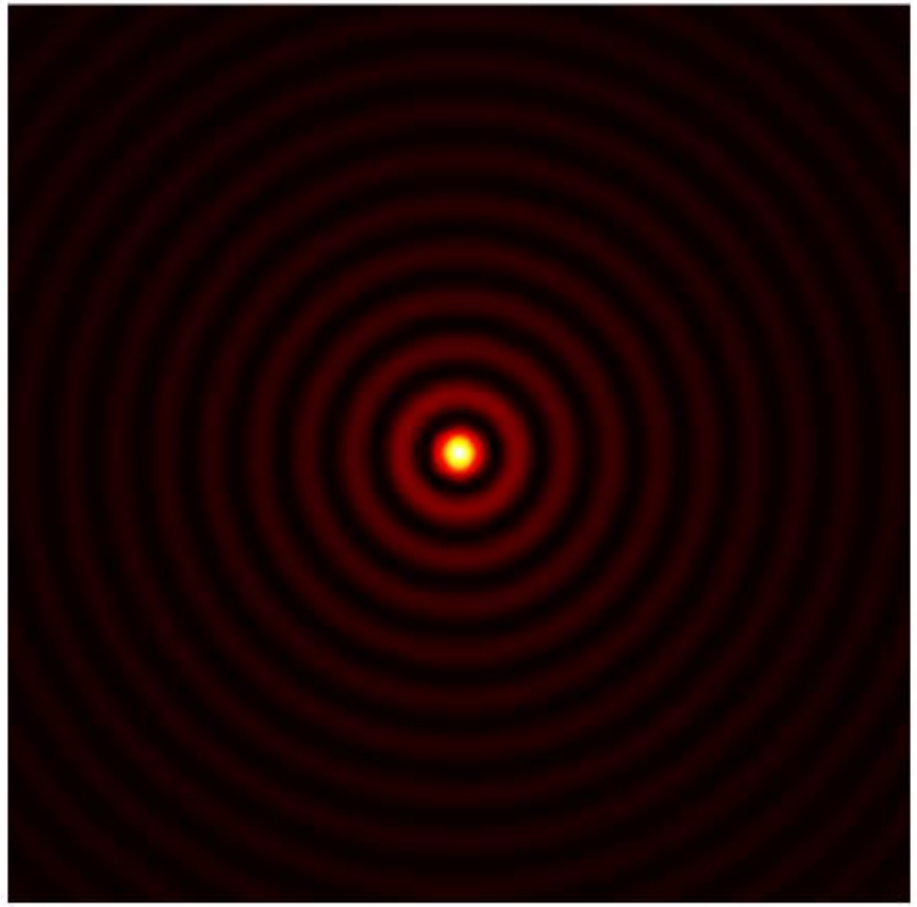




Raghu Dharmavarapu, Shanti Bhattacharya and Saulius Juodkazis, “Diffractive optics for axial intensity shaping of Bessel beams," JOPT, **20**(8), 085606 (2018)

BB Problem 2: Sidelobes cause unwanted illumination

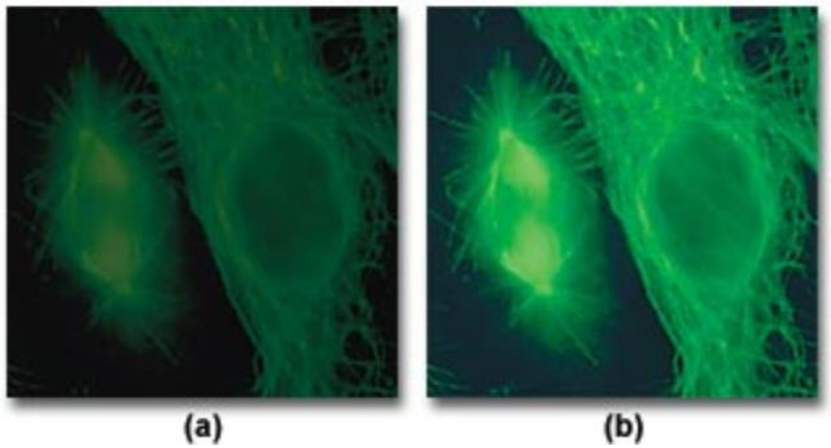
- Goal: Design a sidelobe suppressed Bessel beam



Sidelobe suppressed Bessel beams: Application

Photobleaching

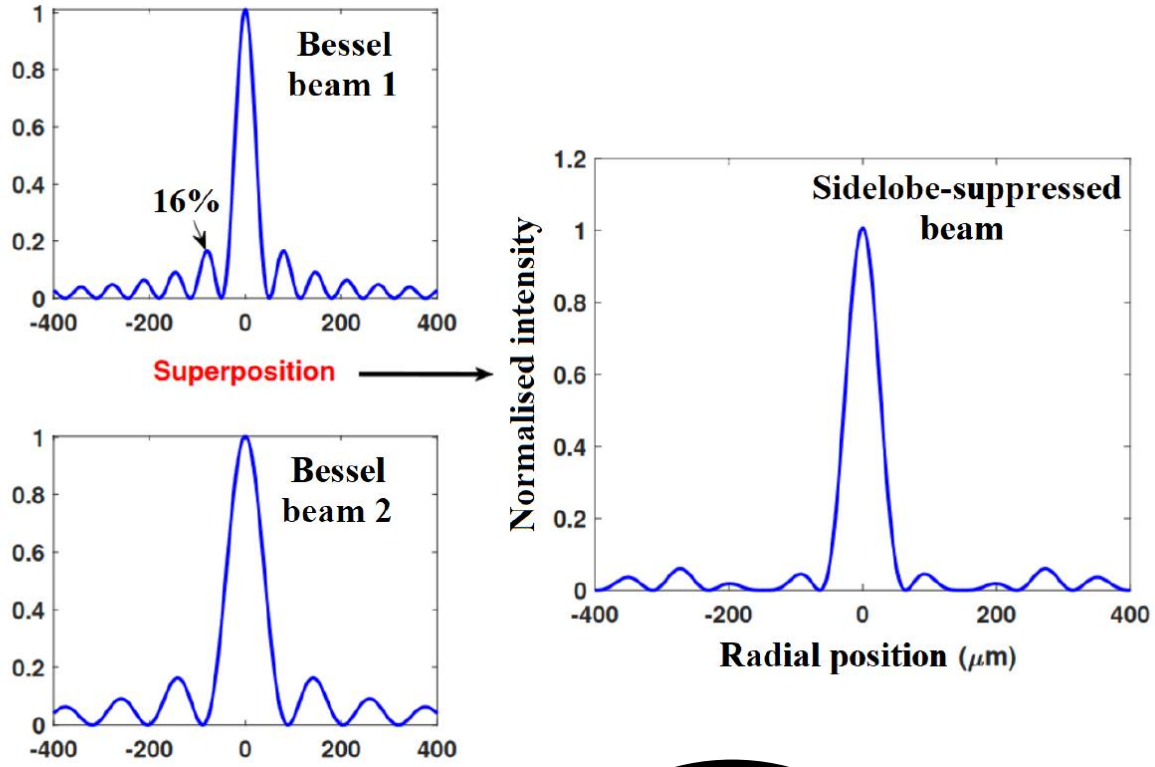
Fluorophores exposed to unwanted radiation – lose ability to fluoresce.

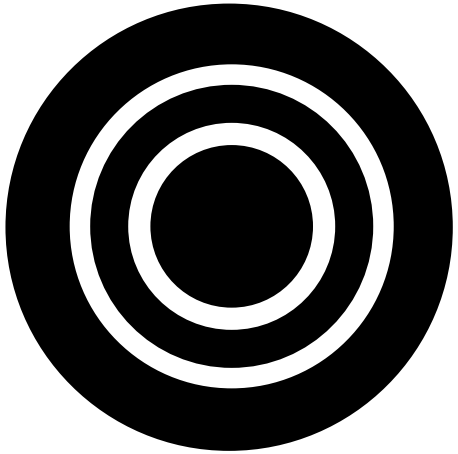


https://www.olympus-lifescience.com/en/microscope-resource/primer/photomicrography/fluorescenceerrors/

Superposition of two Bessel beams

- **High sidelobe energy** - first sidelobe peak intensity is 16%
- Superposition of two Bessel beams – **sidelobes interfere destructively**





Sadao Mori et. al. (2015). In: Precis. Eng. 39, pp. 79–85

Optimising Bessel Beam Parameters

- The **superposed beam** can be represented by,

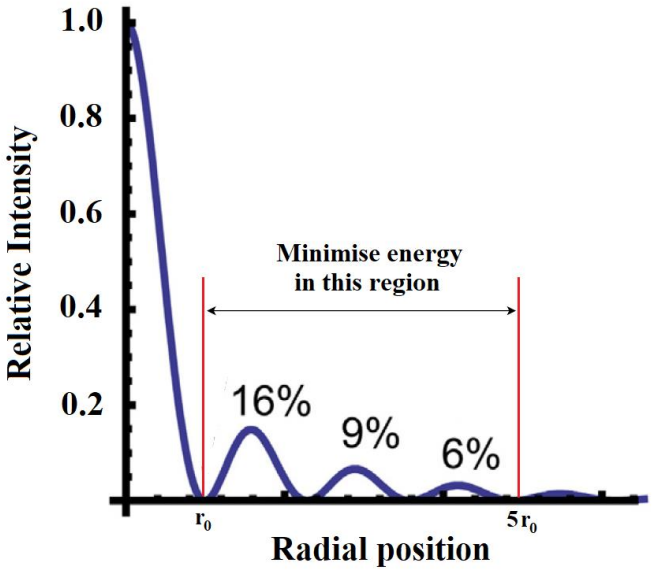
$$SP(r,z) = A_1 J_o(k_{r1}) \exp(jk_{z1}z) + A_2 J_o(k_{r2}) \exp(jk_{z2}z)$$

- The **intensity** of the superposed Bessel beam where k_z **vectors coincide** is,

$$I(r) = |A_1 J_o(k_{r1}) + A_2 J_o(k_{r2})|^2$$

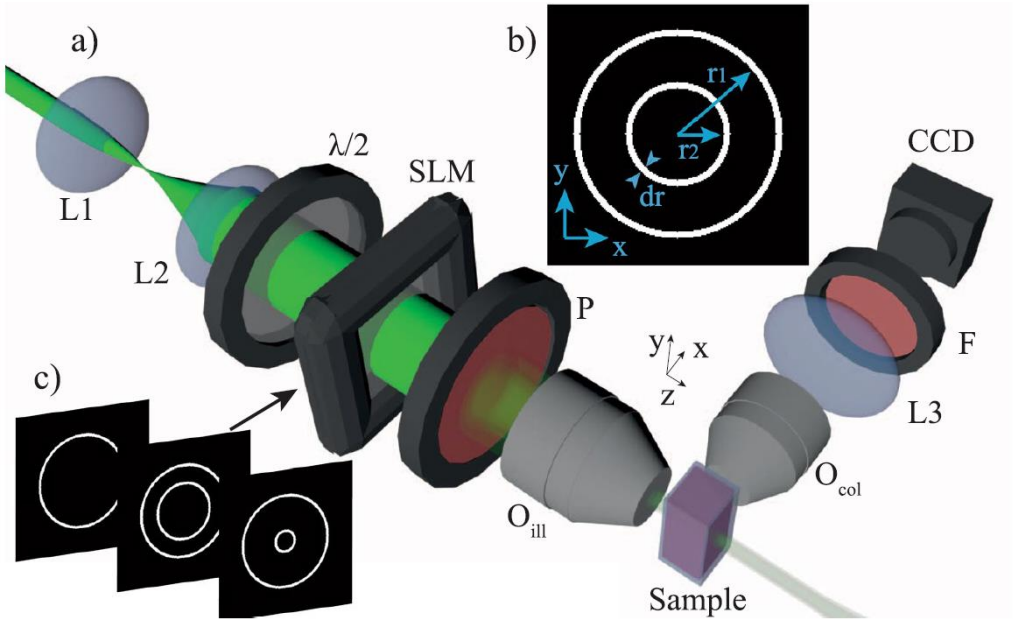
- **Sidelobe intensity** in the desired region (r_0 - r_1) is reduced by **minimising** the following integral

$$I = \int_{r_0}^{r_1} |A_1 J_o(k_{r1}) + A_2 J_o(k_{r2})|^2 \, dr$$



Control of A_1, A_2, k_{r1}, k_{r2}

Sidelobe Suppressed Bessel Light Sheet



G. Di Domenico, G. Ruocco, C. Colosi, *et al.*, "Cancellation of bessel beam side lobes for high-contrast light sheet microscopy," Sci. Rep. **8**(1), 17178 (2018).

Increasing efficiency

Bessel beams generated by annular rings

- Amplitude elements
- Poor efficiency

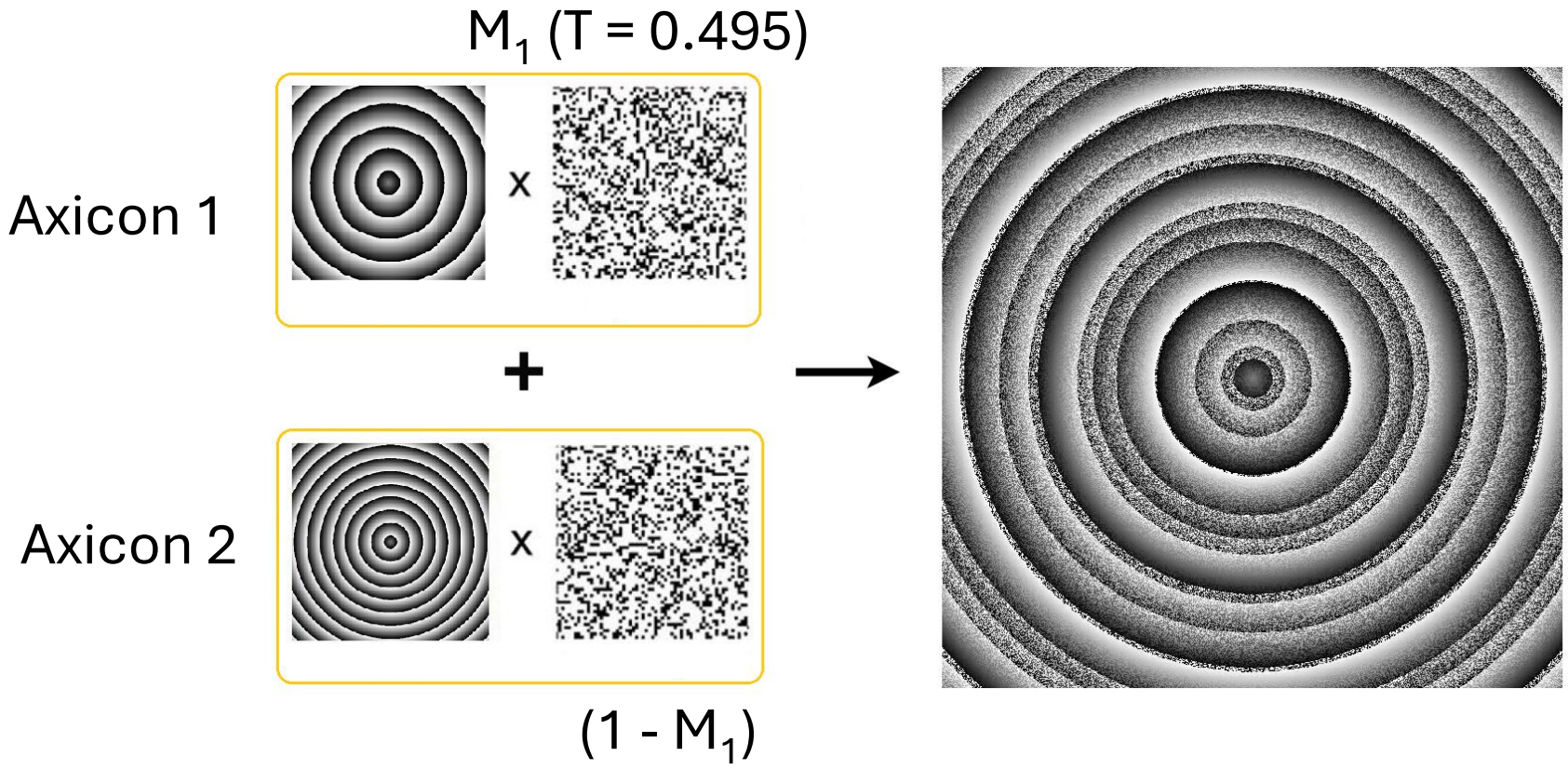
To improve efficiency – phase elements

1. Phase hologram to create the combined Bessel beams
   - Tilted plane wave added to

$$\mathrm{E}(r) = A_1 J_o(k_{r1}) + A_2 J_o(k_{r2})$$

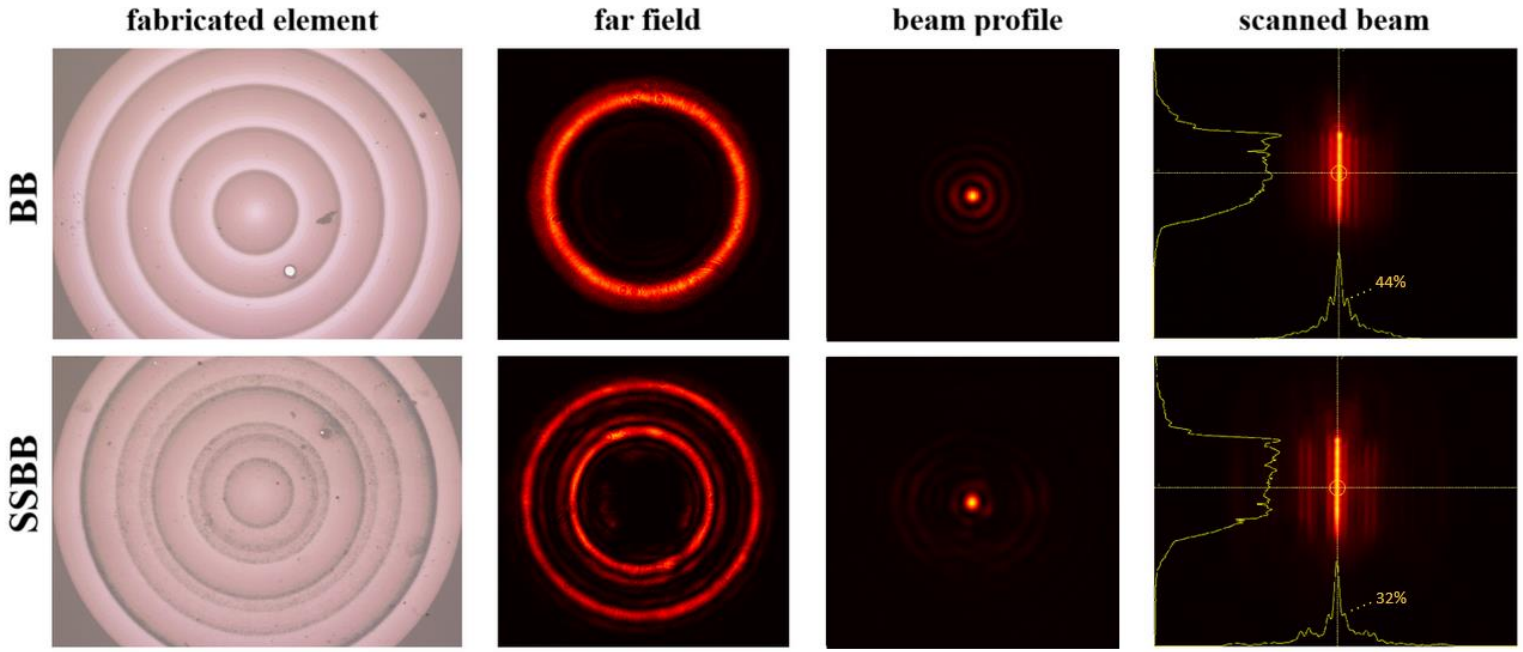
2. Multiplexing

Efficient Multiplexing of Axicons

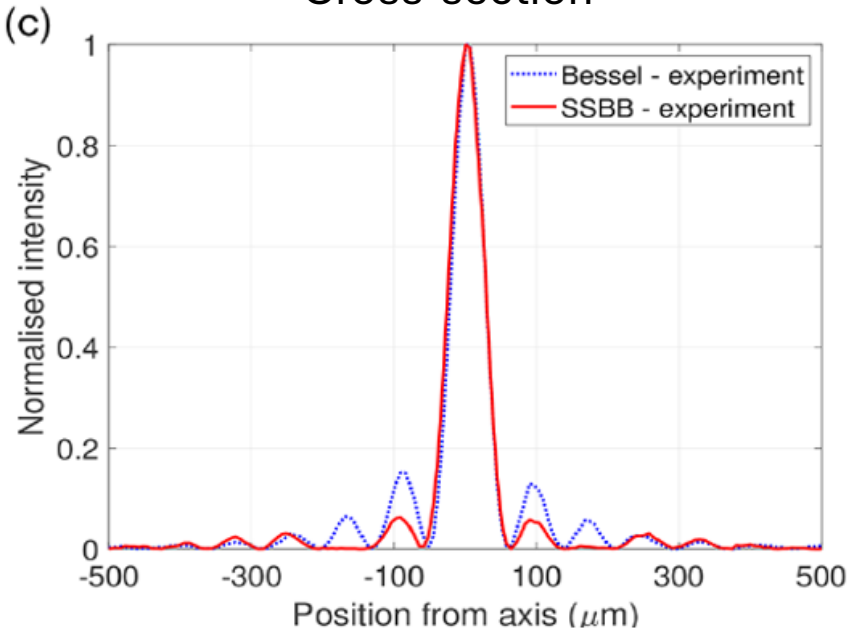


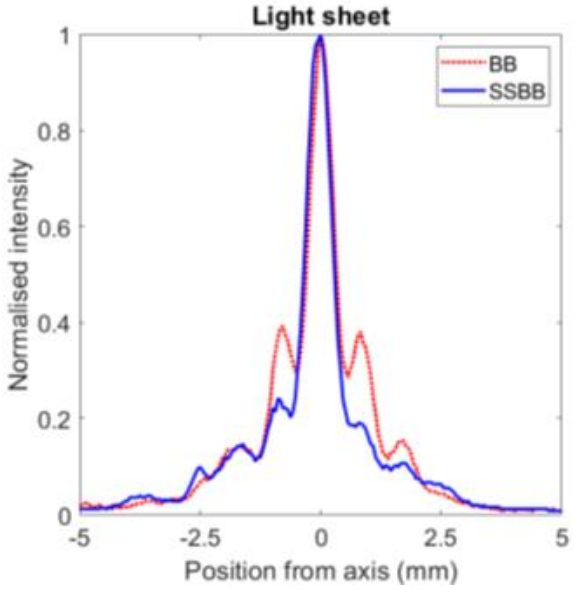
Jerin Geogy George, Kishan Dholakia, and Shanti Bhattacharya, "Generation of Bessel-like beams with reduced sidelobes for enhanced light-sheet microscopy," Opt. Continuum 2, 1649-1660 (2023)

Experimental Results



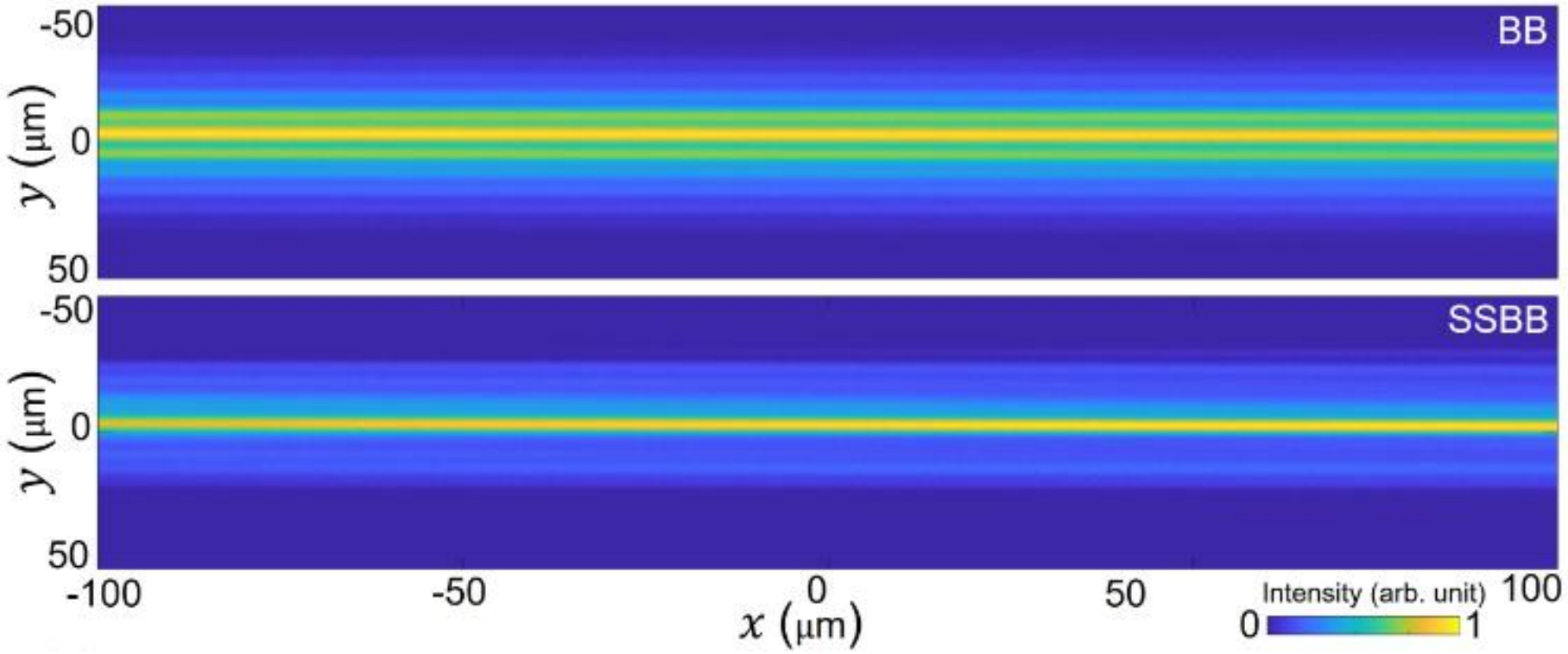
Cross-section





Jerin Geogy George, Kishan Dholakia, and Shanti Bhattacharya, "Generation of Bessel-like beams with reduced sidelobes for enhanced light-sheet microscopy," Opt. Continuum 2, 1649-1660 (2023)

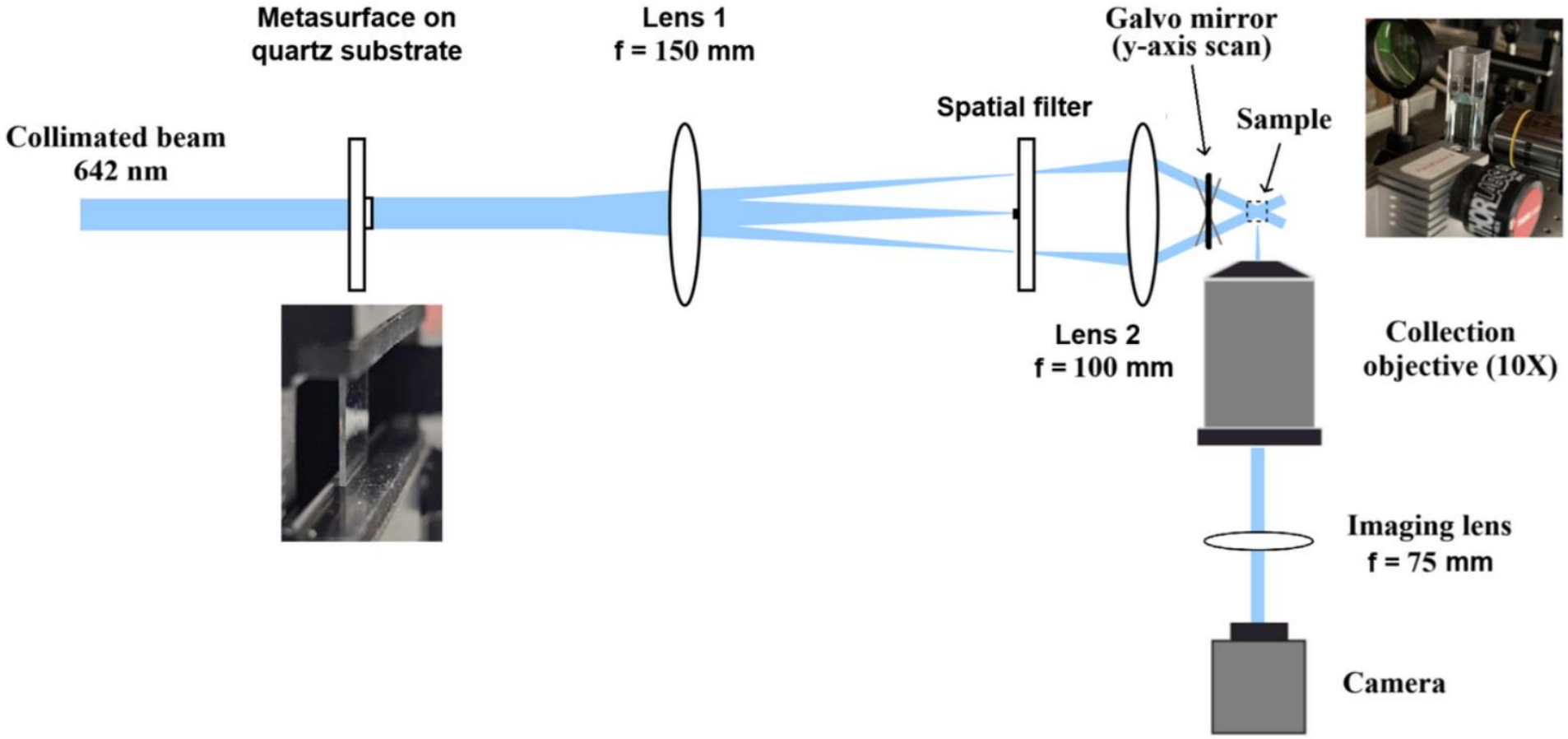
BB and SSBB (experimental) Intensity profiles in fluorescein solution



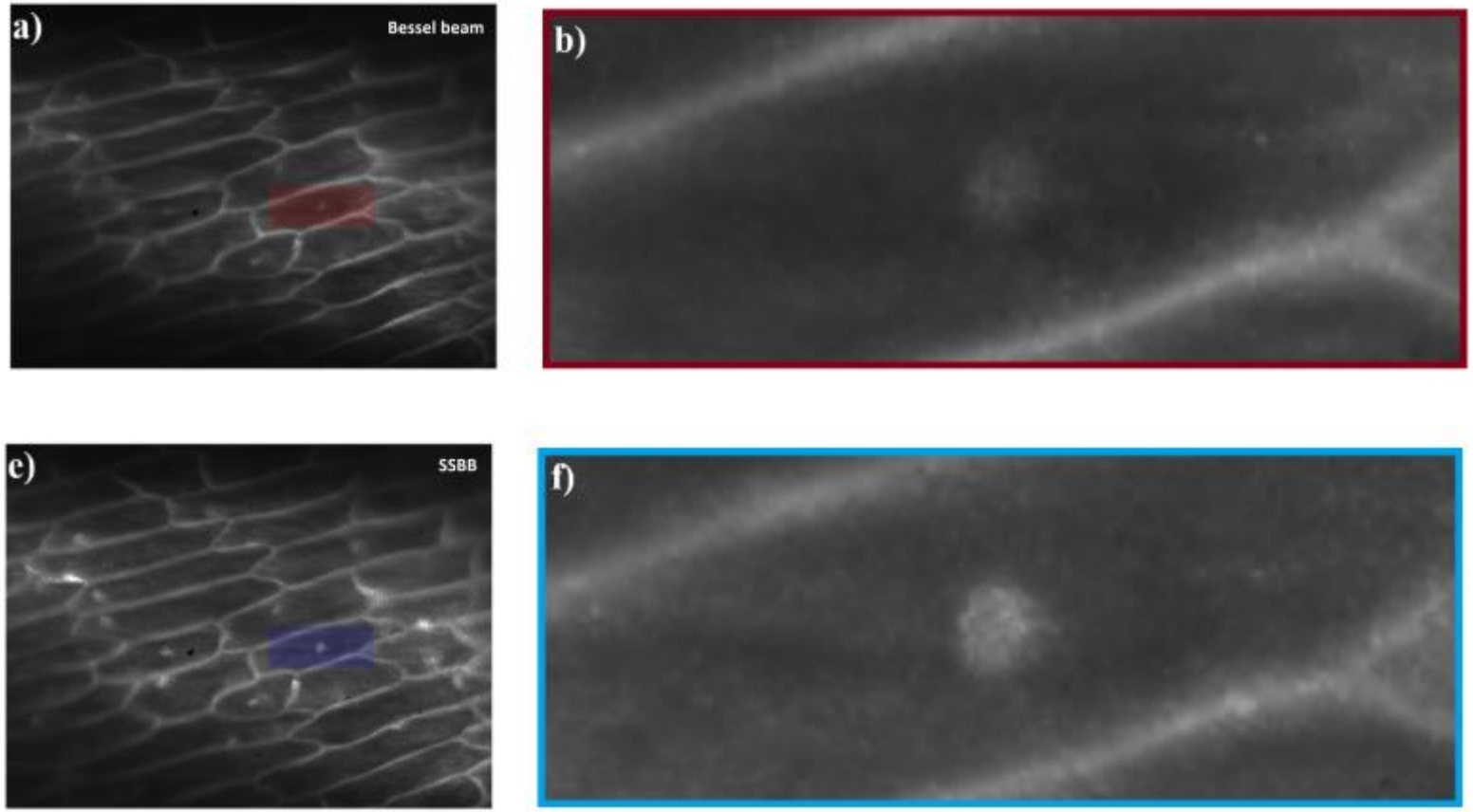
Direction of propagation

Collaborative work with Prof. Kishan and his group in Scotland

Lightsheet Imaging Set-up



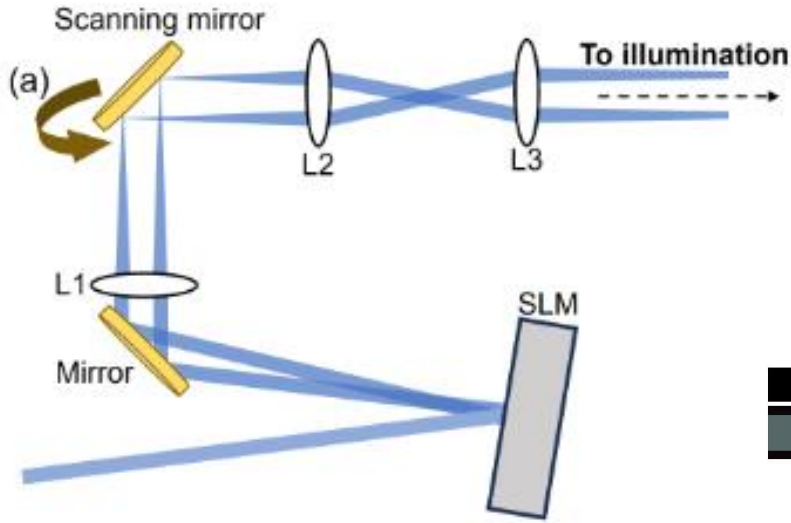
Experimental light-sheet imaging of onion epidermal cells

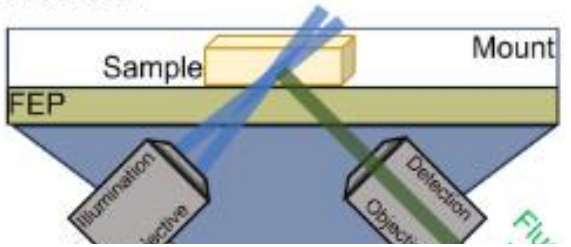


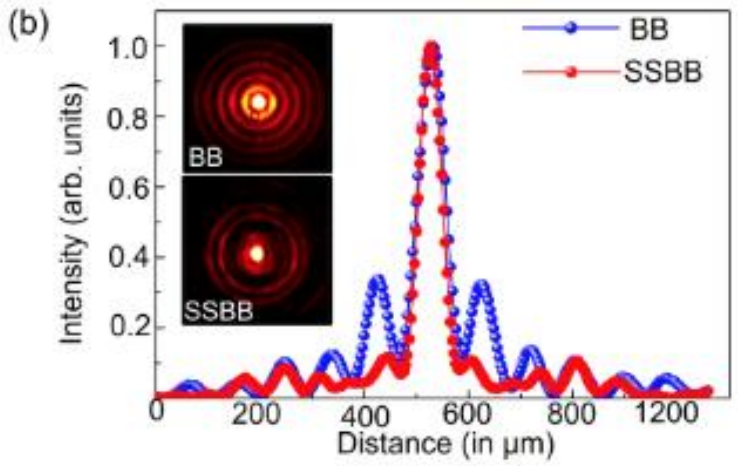
Bessel beam

Sidelobe Suppressed Bessel beam

Sidelobe Suppressed Bessel Beams for LSM







Research Article Vol. 15, No. 11 / 1 Nov 2024 / Biomedical Optics Express 6183
Biomedical Optics EXPRESS

Sidelobe suppressed Bessel beams for one-photon light-sheet microscopy

CHETNA TANEJA,[1] JERIN GEOGY GEORGE,[2] STELLA CORSETTI,[1] PHILIP WIJESINGHE,[1] GRAHAM D. BRUCE,[1] MAARTEN F. ZWART,[3] SHANTI BHATTACHARYA,[2] AND KISHAN DHOLAKIA[1,4,*]

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[2]*Department of Electrical Engineering, IIT Madras, Chennai, India*
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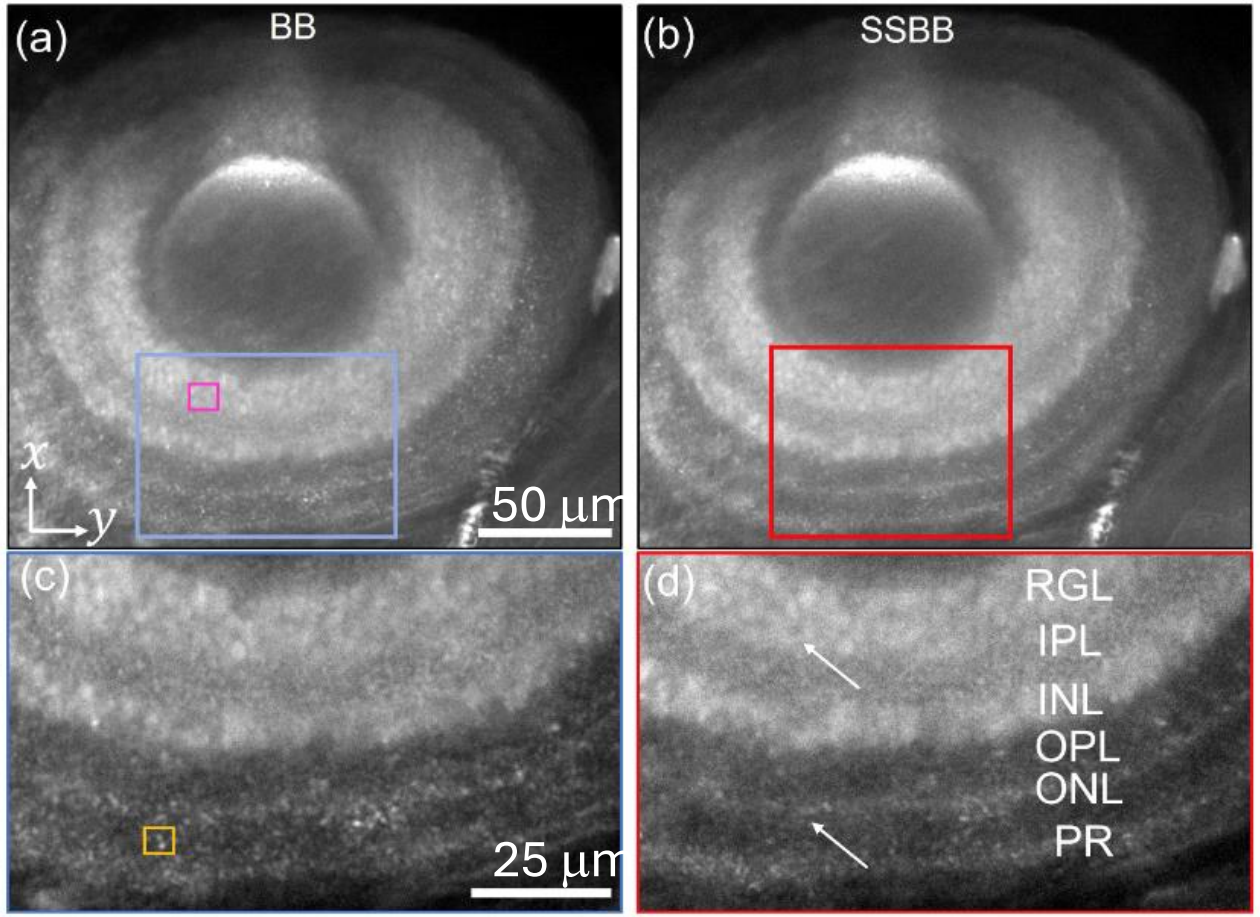
[4]*Centre of Light for Life and School of Biological Sciences, University of Adelaide, Adelaide 5005, Australia*

Imaging GCaMP labelled cell nuclei of the zebrafish (4-5 dpf) eye

Magnified views

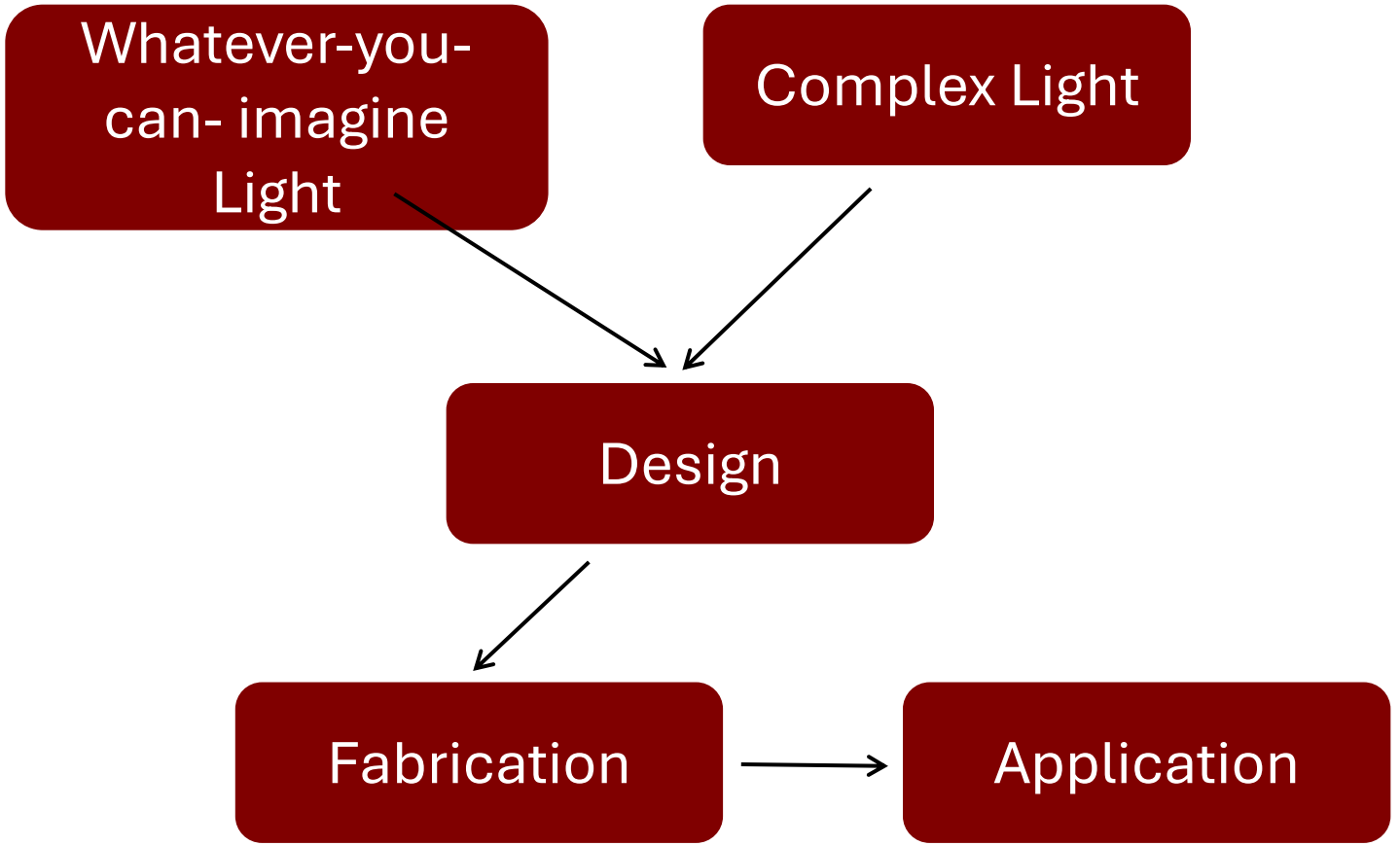


C. Taneja, J.n G. George, S. Corsetti, P. Wijesinghe, G. D. Bruce, M.n F. Zwart, S. Bhattacharya, and K. Dholakia, "Sidelobe suppressed Bessel beams for one-photon light-sheet microscopy," Biomed. Opt. Express **15**, 6183-6197 (2024)

Summary: Shaping Light

- Introduction to Bessel beams
- Ways of improving them
- Applications (in imaging)

Summary: Shaping Light



More information and downloadable software at:
http://www.ee.iitm.ac.in/AppliedOptics

Work presented today

Jerin George

Meta-optics for PSF Engineering

Raghu D

Design and Fabrication of Meta-optics for Complex Light Generation

Prof. Kishan Dholakia School of Physics and Astronomy
Sir James Mackenzie Institute for Early Diagnosis
Centre for Biophotonics, Univ. of St. Andrews, Scotland

Acknowledgements

- Funding agencies:
  - SPARC project, MHRD
  - MeitY
  - DST
- Centre for NEMS and Nanophotonics, IIT Madras

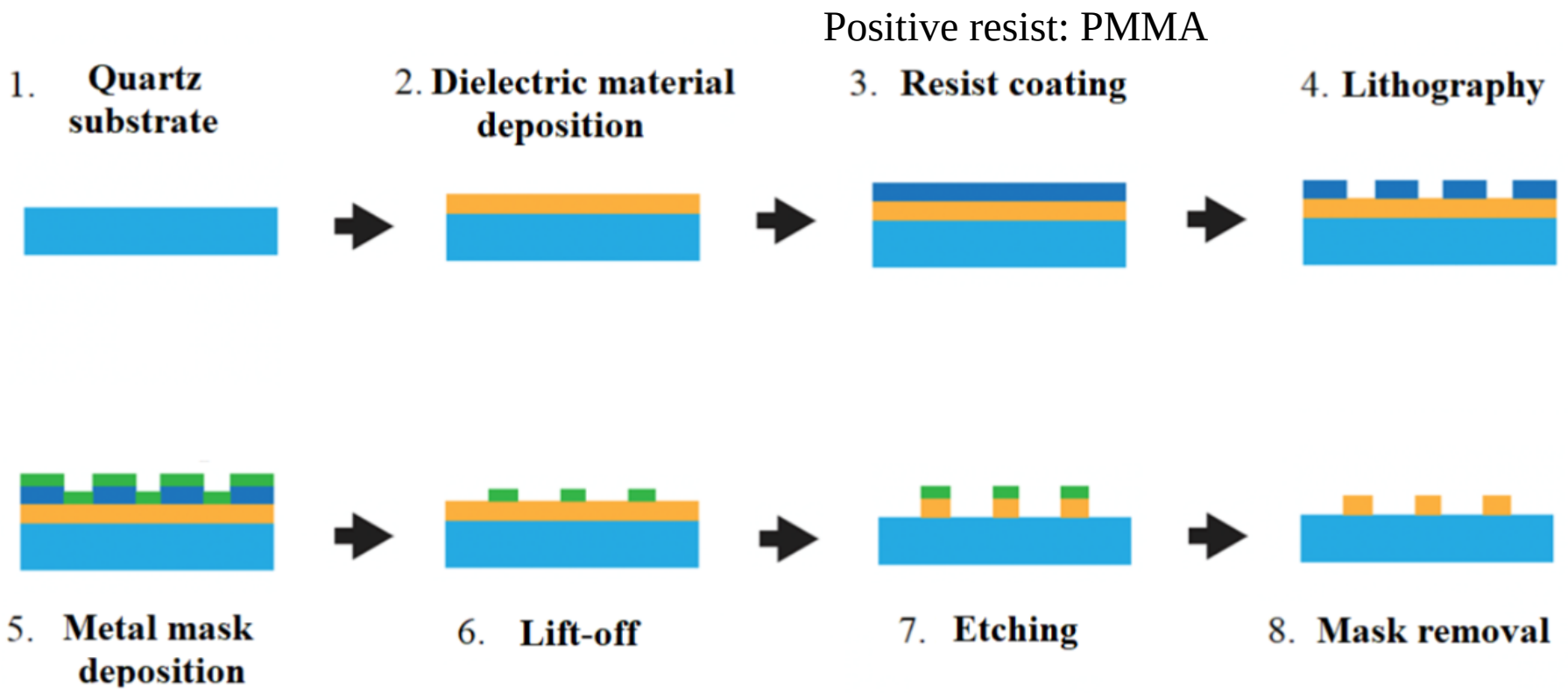
- Support from conference organisers for this trip

Thank you

Table 1. Experimentally calculated DOFs of the BB and the SSBB light sheets compared to a theoretical Gaussian light-sheet of equal thickness. To attain the same DOF as the SSBB, the Gaussian light-sheet thickness would have to be increased to ~ 6.5 μm at the expense of axial resolution.

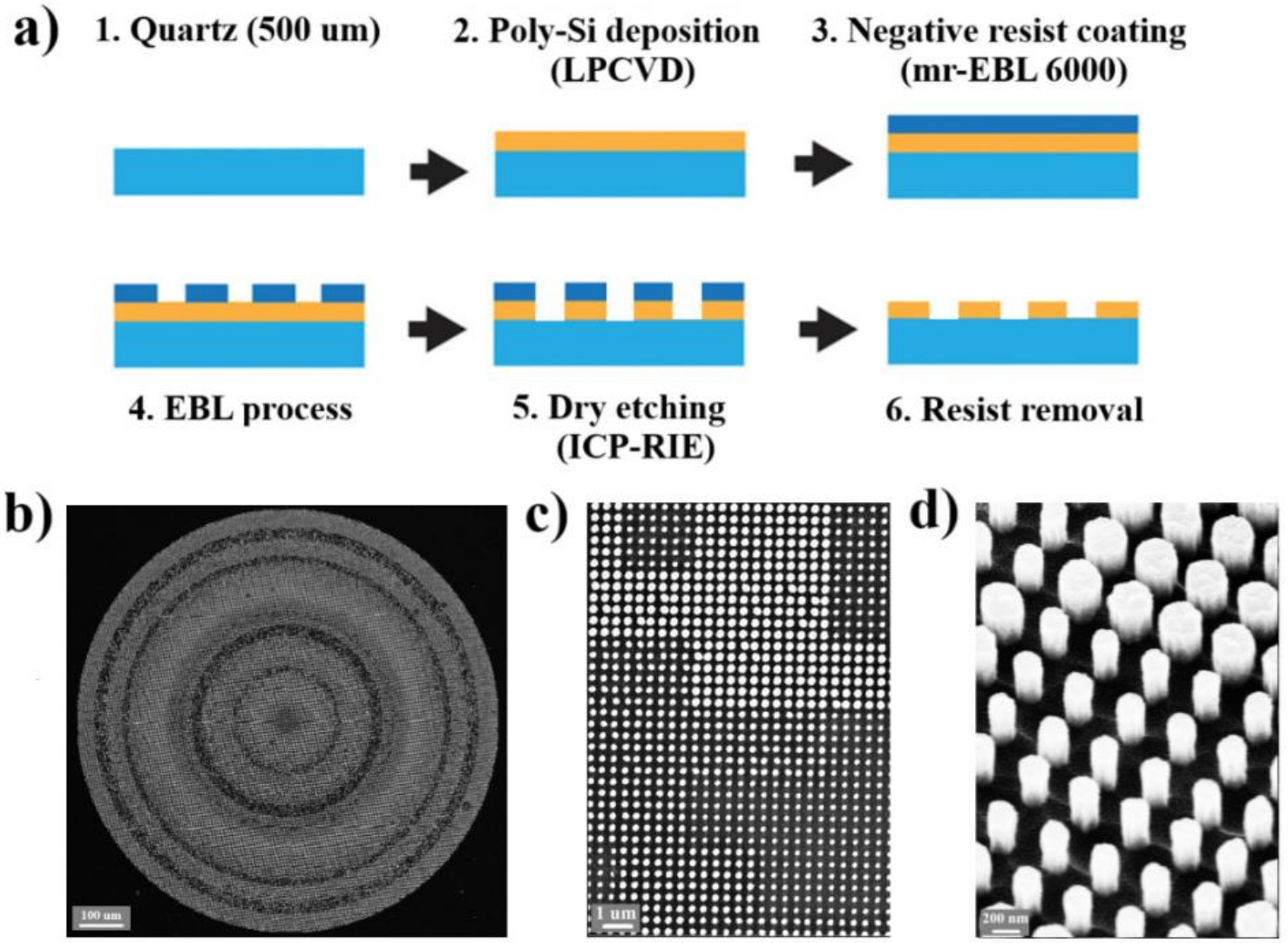
	BB	SSBB	Gaussian (Theoretical)	
			Matched thickness	Matched DOF
Thickness of light-sheet	4.8 μm	4.8 μm	4.8 μm	6.5 μm
Depth of focus (DOF)	1.4 mm	540 μm	296 μm	540 μm

Fabrication – Metaoptics



G. Yerragadda, Raghu Dharmavarapu. Saulius Juodkazis and Shanti Bhattacharya, "Design and optimized fabrication techniques for highly-efficient dielectric meta-optical airy beam generators," SPIE PW2021 Proc. Vol. 11695 116951G (2021)

Fabrication – Metaoptics



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