International Conference on Applied Physics and Imaging

Generation of Double-ring POV beams by modulating Bessel-Gaussian phase with conical phase and its characteristics

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20 – 21 September 2025

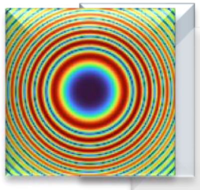
Outlines

- Structured Beams
- Vortex Beams and Perfect Optical Vortex (POV) Beams
- Conical POV Beams
- Propagation Characteristics of Conical POV
- Double-ring POV Beams
- Results
- Conclusions

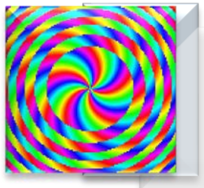
Structured light beams

Gaussian Beam

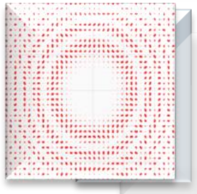
+



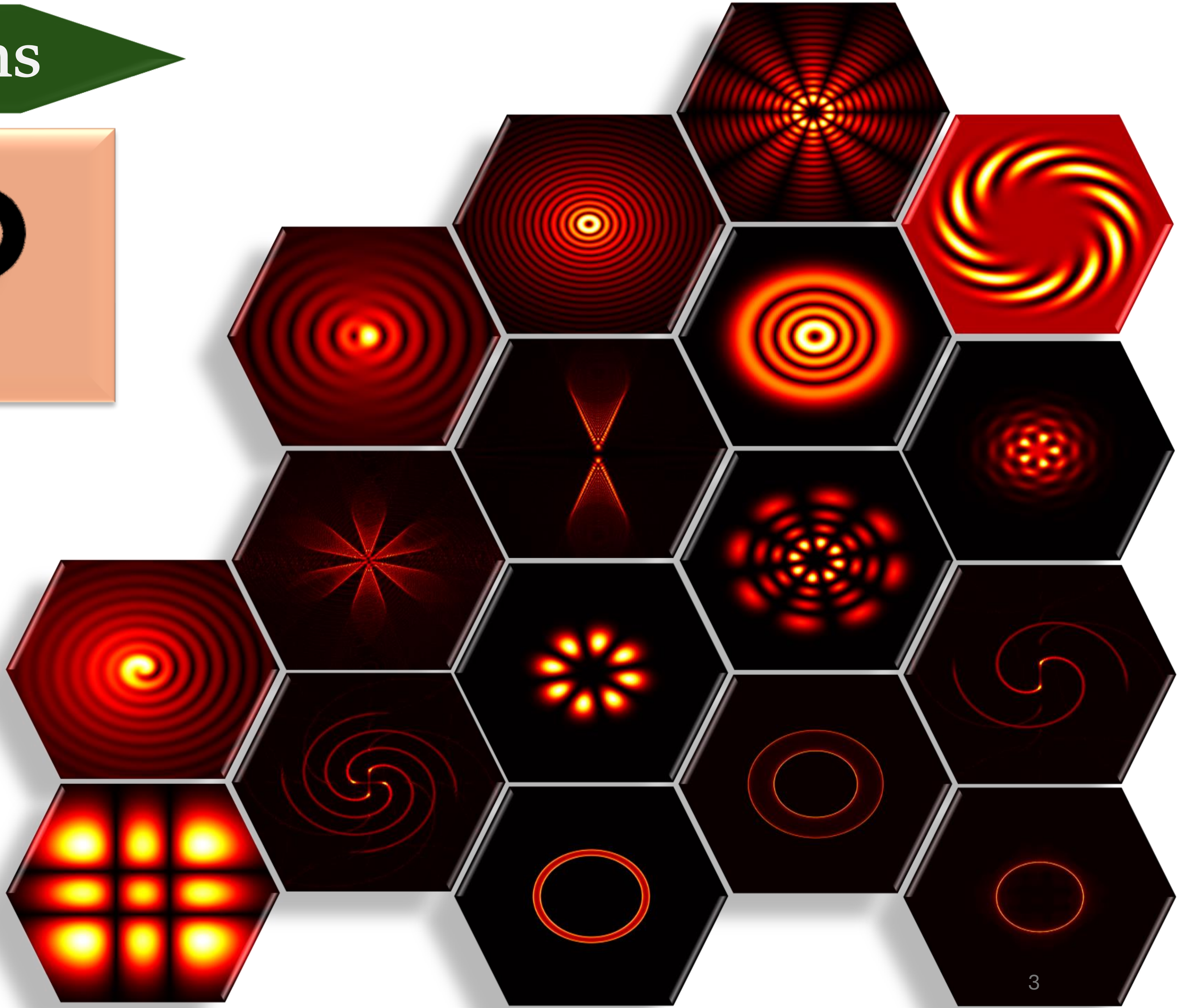
Amplitude



Phase



Polarization



Ref: J Wang et.al ,*Frontiers in Physics* 9, 688284, (2021).

Applications of Structured light beams

- Metrology and Sensing
- Medical Imaging and Therapy
- Optical Trapping & Manipulation
- Quantum Information & Computing
- Super-Resolution Microscopy
- Holography
- Optical Encryption
- Free-space Optical communication
- 3D Imaging

Why Structuring??

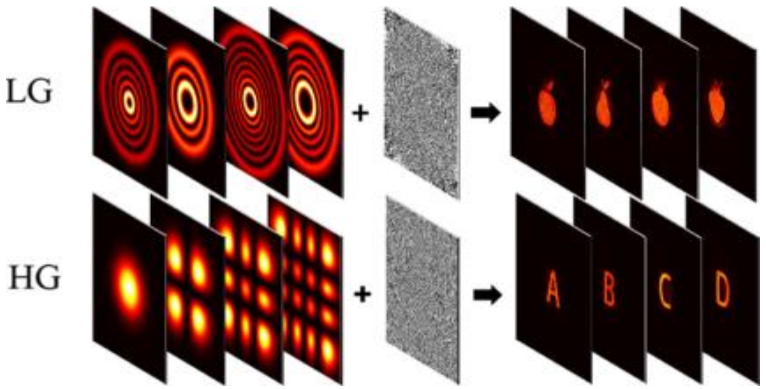
Pushing the limits in what you can do with light…..

etc . . .

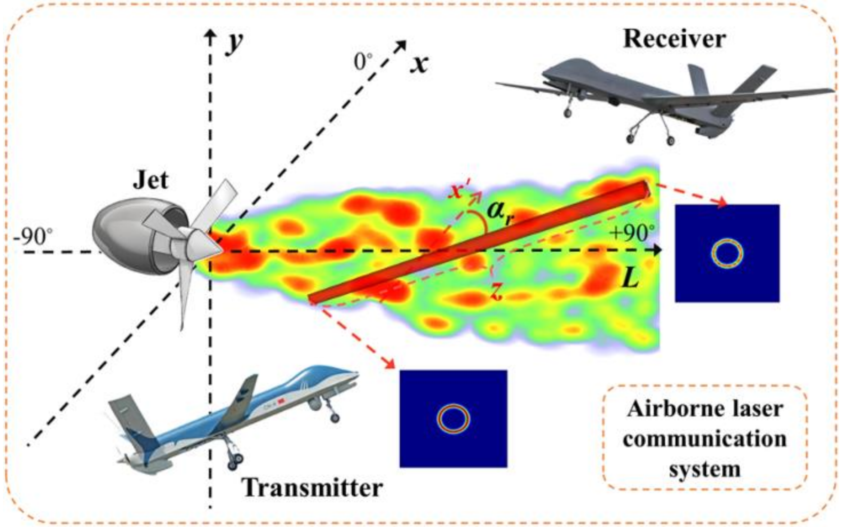
Ref: **A Forbes et.al, *Nature Photonics* 15(4), 253-262, (2021).**

Ref: **J Wang et.al, *Frontiers in Physics* 9, 688284, (2021).**

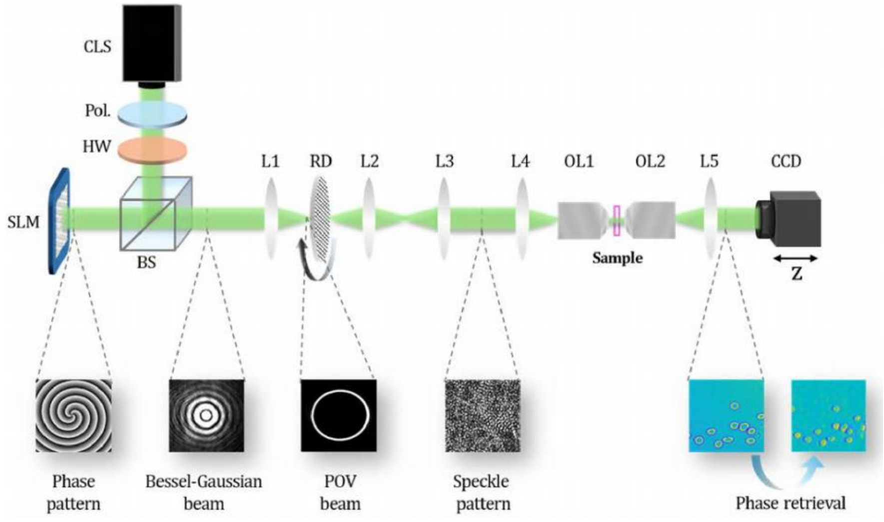
Applications of structured light beams



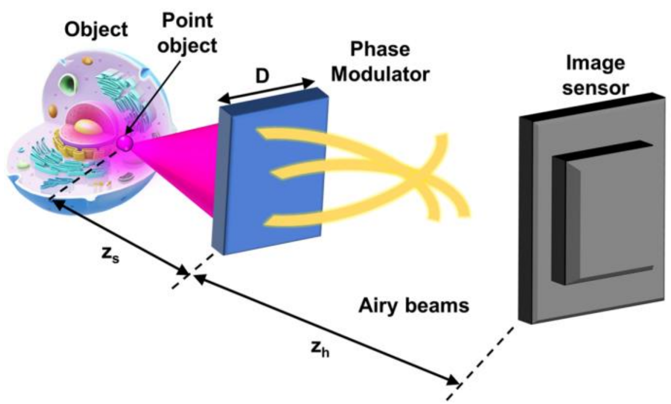
- Holography and Optical Encryption (for example: structured modes, polarization states … etc.)



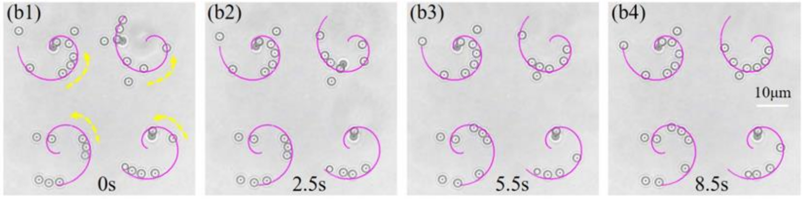
- Free-Space Optical Communication (for example: Resilient to atmospheric turbulence).



- Microscopy & Imaging (Speckle illumination, Polarization-structured beams).



- 3-Dimensional Imaging



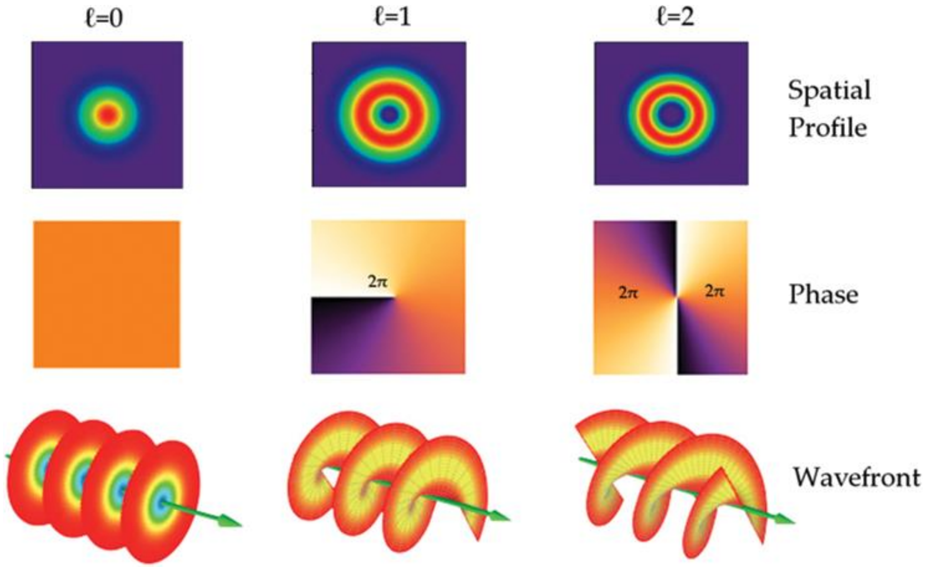
- Optical Manipulation (for example: for trapping, rotating, and manipulating micro/nano-particles)

Refs: **J Guo, et al, ACS Photonics 10 (3), 757-763 (2023),**
S Zhong et al, *Biomedical Optics Express* 16(6), 2275-2282 (2025),
S Wang, et.al, *Optics Express*, *33*(3), 4998-5011 (2025),
R Kumar et.al, *Scientific Reports* 13(1), 2996 (2023),
J Hu, et al, *Optics & Laser Technology* 181, 111708 (2025).

Vortex beams

- Donut shape Intensity distribution with helical phase fronts and zero field amplitude at the center.
- Carries OAM equal to $l\hbar$
- The electric field expression for a vortex beam can be expressed as:

$$E(x,y) = E_0(x,y)exp(il\varphi)$$



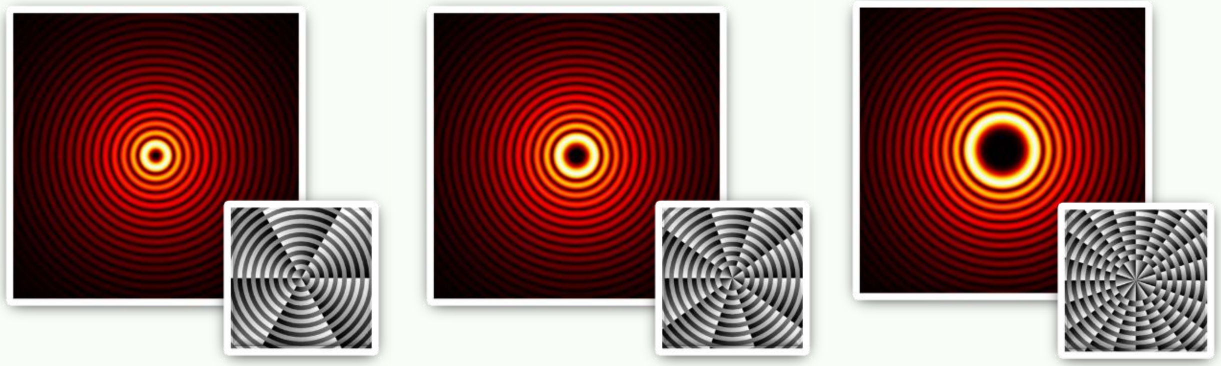
Ref: AV Carpentier et.al, *American Journal of Physics*, *76*(10), 916-921, (2008).

Bessel Gaussian beams

$$E_{BG}(r,\varphi) = J_l(k_r r) \quad exp(il\varphi) \quad exp\left(\frac{-r^2}{w^2}\right)$$

l^th order Bessel function of 1^st kind — Spiral phase — Gaussian term

$l = 3$	$l = 5$	$l = 10$



- Non-diffracting beams in a limited propagation distance.
- An approximation of Bessel beams.
- Intensity exists only in central area.
- Finite cross-section area.

Ref: A.S. Rao, *preprint arXiv:2401.04307* (2024).

Perfect Vortex beams (POV)

- An intensity profile independent of topological charge.

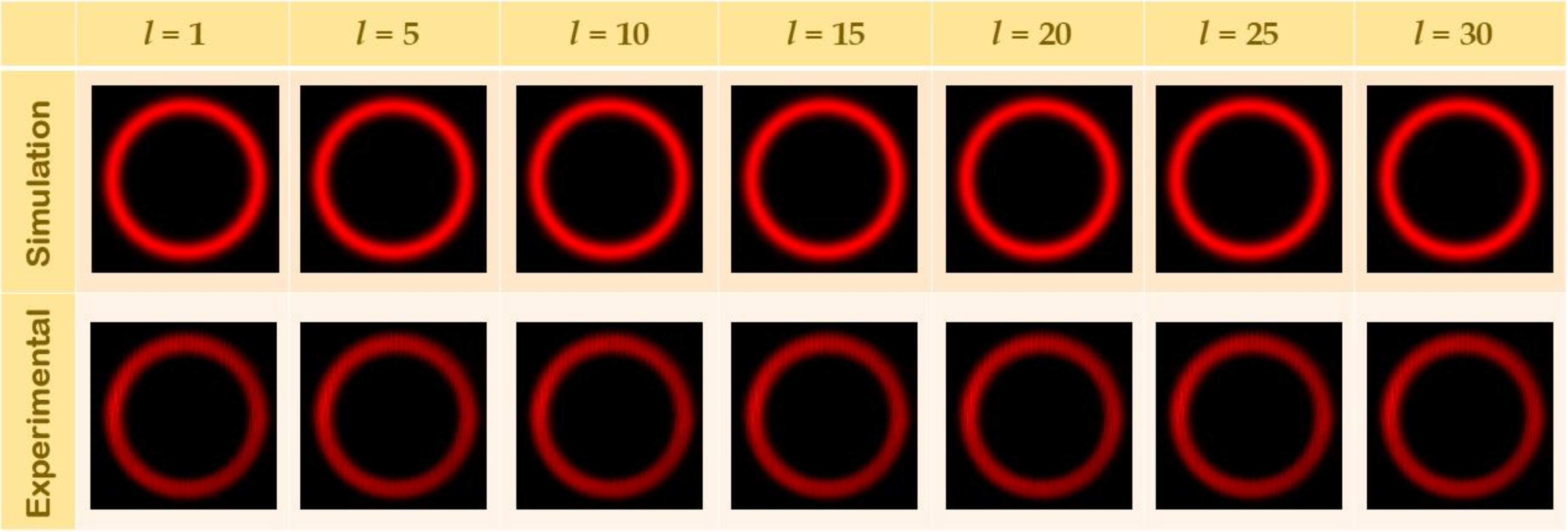
Bessel Gaussian Beam —*Fourier Transform* ($\mathfrak{I}$)→ **Perfect Vortex Beam**

$$\mathfrak{I}\left[J_l(k_r r)\,exp(il\varphi)\,exp\left(\frac{-r^2}{w^2}\right)\right] \longrightarrow A_0\,exp(il\varphi)\;\;exp\left(-\frac{r^2}{w^2}\right)\;\;I_l\left(\frac{2r_r r}{w^2}\right)$$

Spiral phase

Gaussian term

l^{th} order modified Bessel function of 1^{st} kind



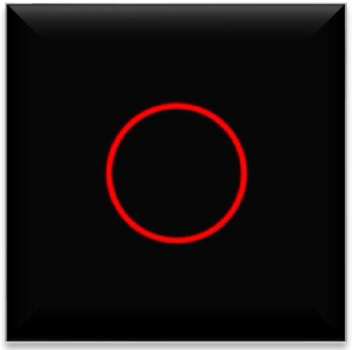
w = beam waist
r = radial coordinate
l = topological charge
φ = azimuthal angle
p = radial index
r_r = radius
A_0 = Amplitude

Ref: **P Vaity et.al, *Optics Letter* 40(4), 597-600, (2015).**

POV with Radial modulation (Conical POV)

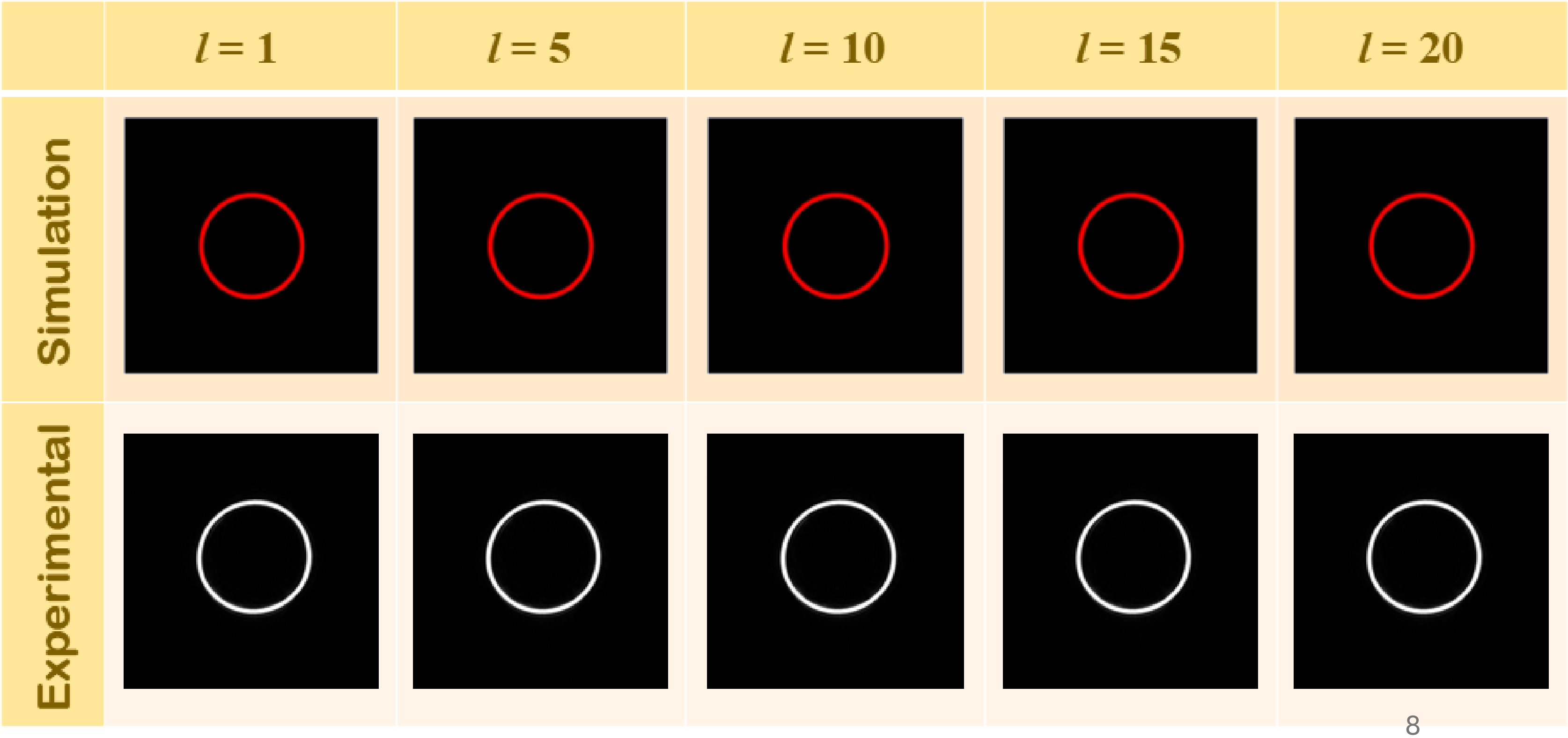
$$\mathfrak{I}\left[exp(il\varphi)\quad exp\left(-i\frac{r}{r_0}\right)\quad exp\left(\frac{-r^2}{w^2}\right)\right]$$

Spiral phase — Conical term — Gaussian term

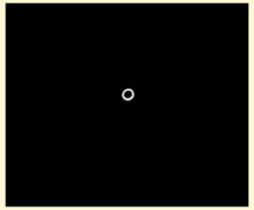
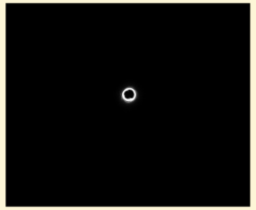
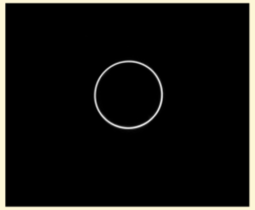
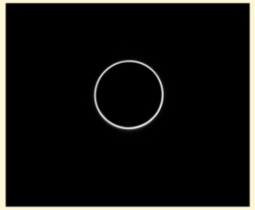
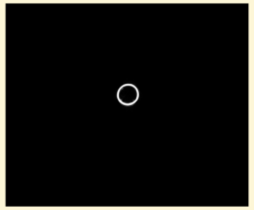
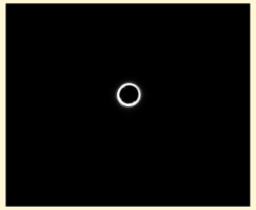
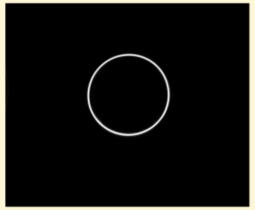
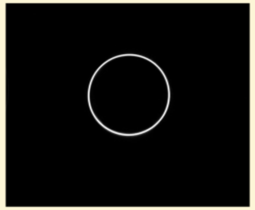
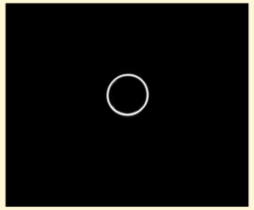
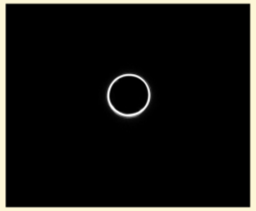
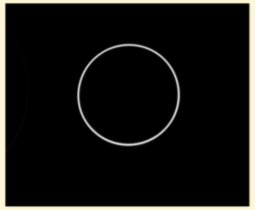
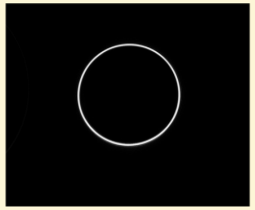
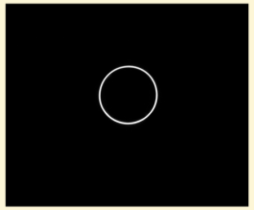
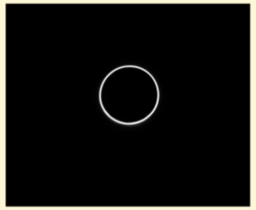


w = beam waist
r = radial coordinate
l = topological charge
φ = azimuthal angle
r_0 = constant

- A newly introduced conical term produces an intensity profile independent of topological charge.
- Radius of the beam is controlled by the r_0 parameter.

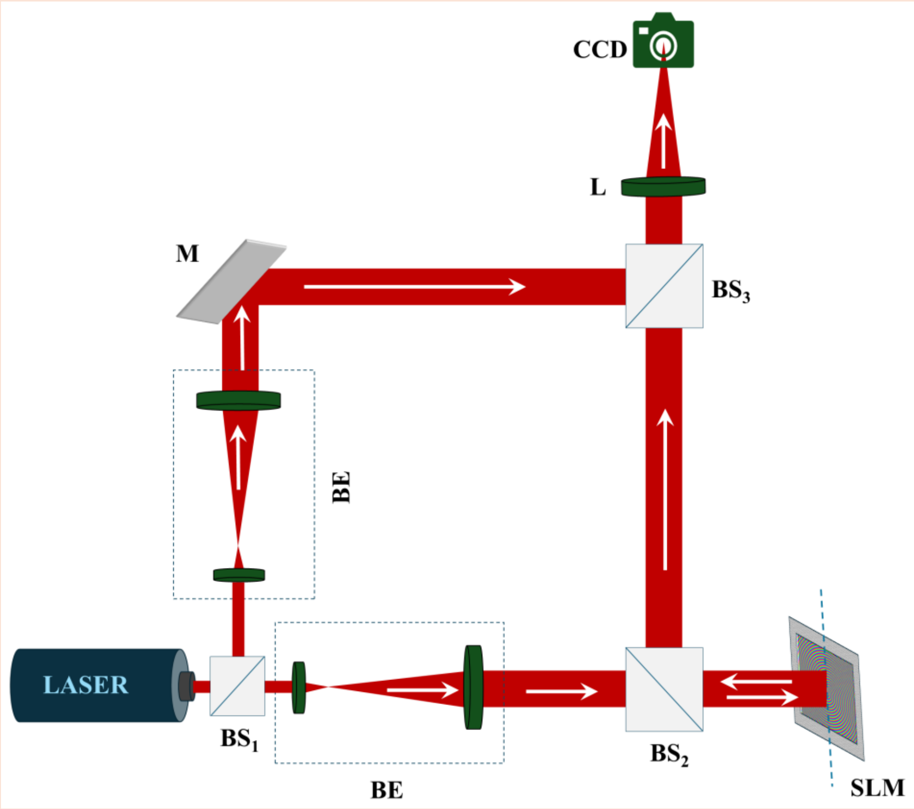


POV with Radial modulation (Conical POV)

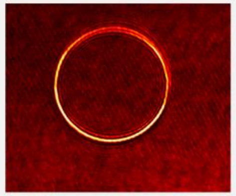
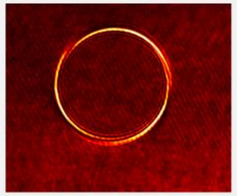
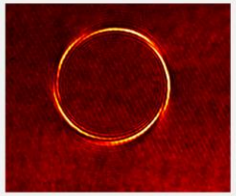
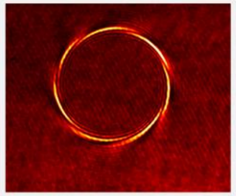
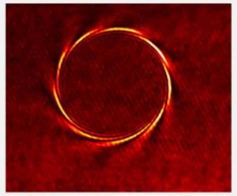
	$l = 1$	$l = 10$		$l = 1$	$l = 10$
$r_0 = 0.04$			$r_0 = 0.006$		
$r_0 = 0.02$			$r_0 = 0.005$		
$r_0 = 0.01$			$r_0 = 0.004$		
$r_0 = 0.007$			$r_0 = 0.003$		

Experimentally captured images for different l values by controlling their radius by $\mathbf{r_0}$ parameter

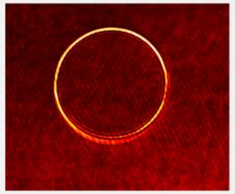
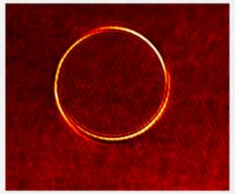
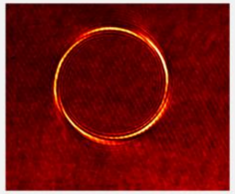
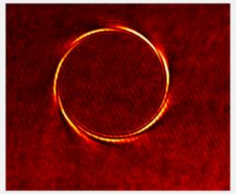
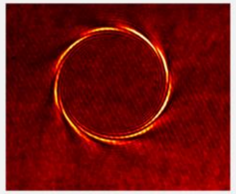
Identification of TC presence in Conical POV



- The conical POV beams were interfered with Gaussian beam using Mach-Zehnder interferometric setup.
- This resulting interferogram obtained contains a spiral-like pattern where the fringes extend outward from the center.
- The number of spiral fringes gives us the TC, and direction gives the helicity

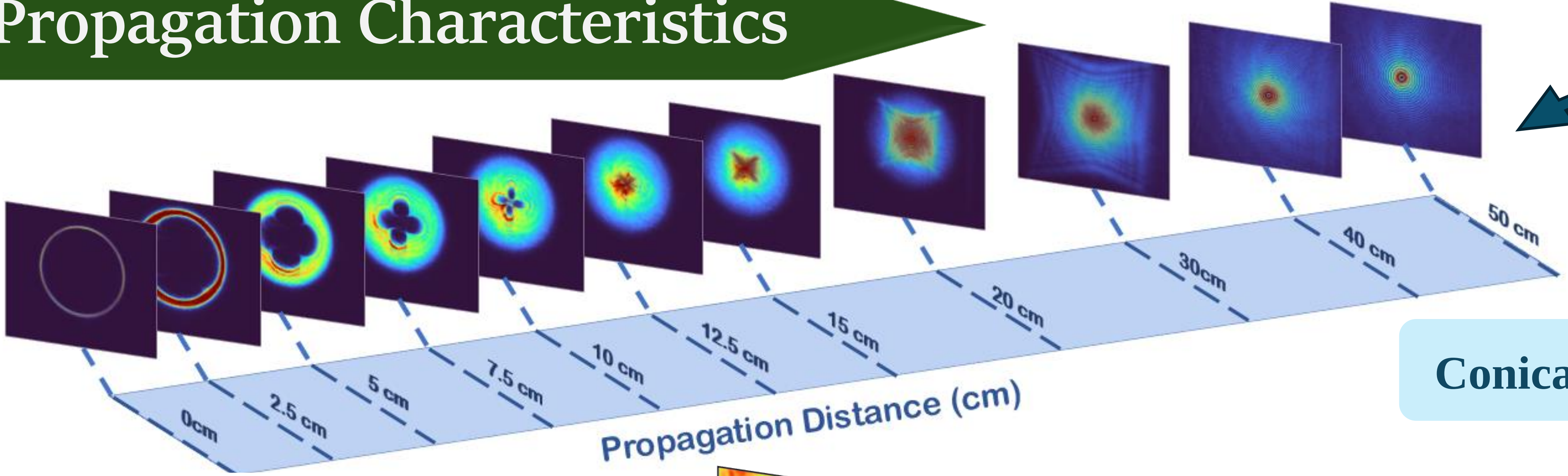
$l = 1$	$l = 3$	$l = 5$	$l = 7$	$l = 9$
				

Experimentally captured images of the interference pattern for positive values of *l*

$l = -1$	$l = -3$	$l = -5$	$l = -7$	$l = -9$
				

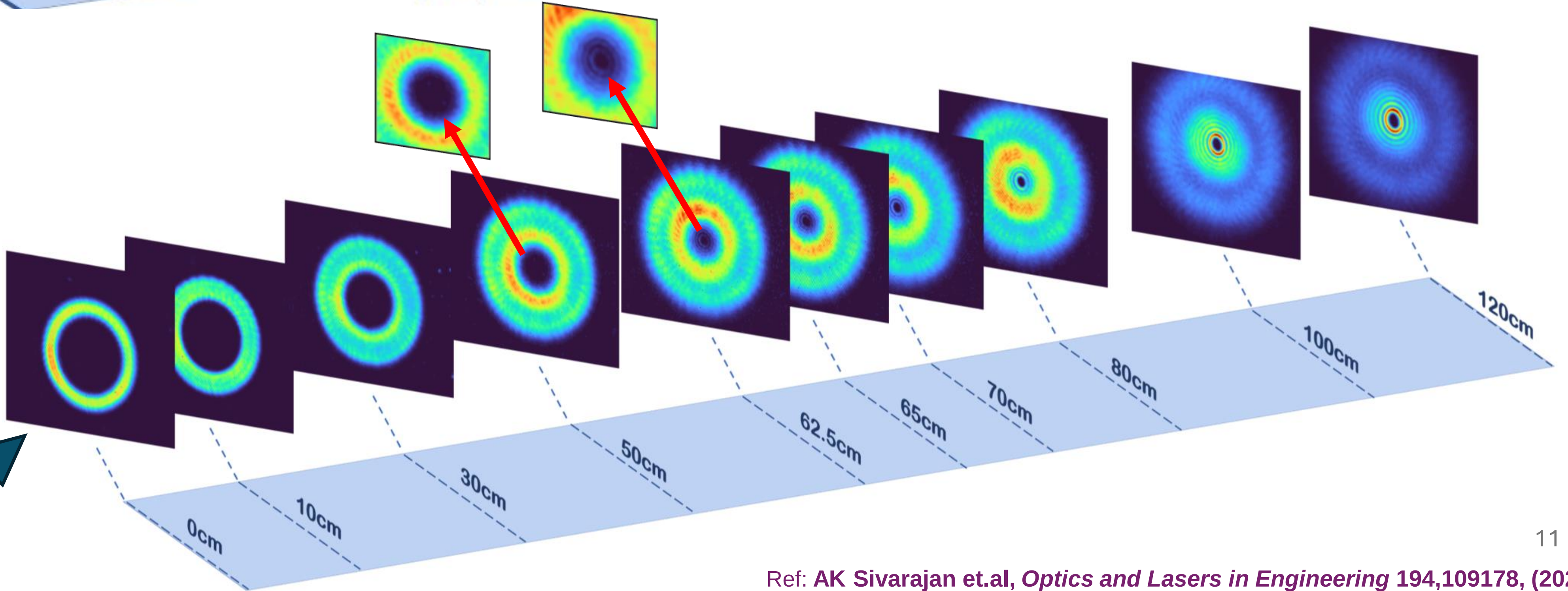
Experimentally captured images of the interference pattern for negative values of *l*

Propagation Characteristics



Conical POV

POV



Ref: **AK Sivarajan et.al, *Optics and Lasers in Engineering* 194,109178, (2025).**

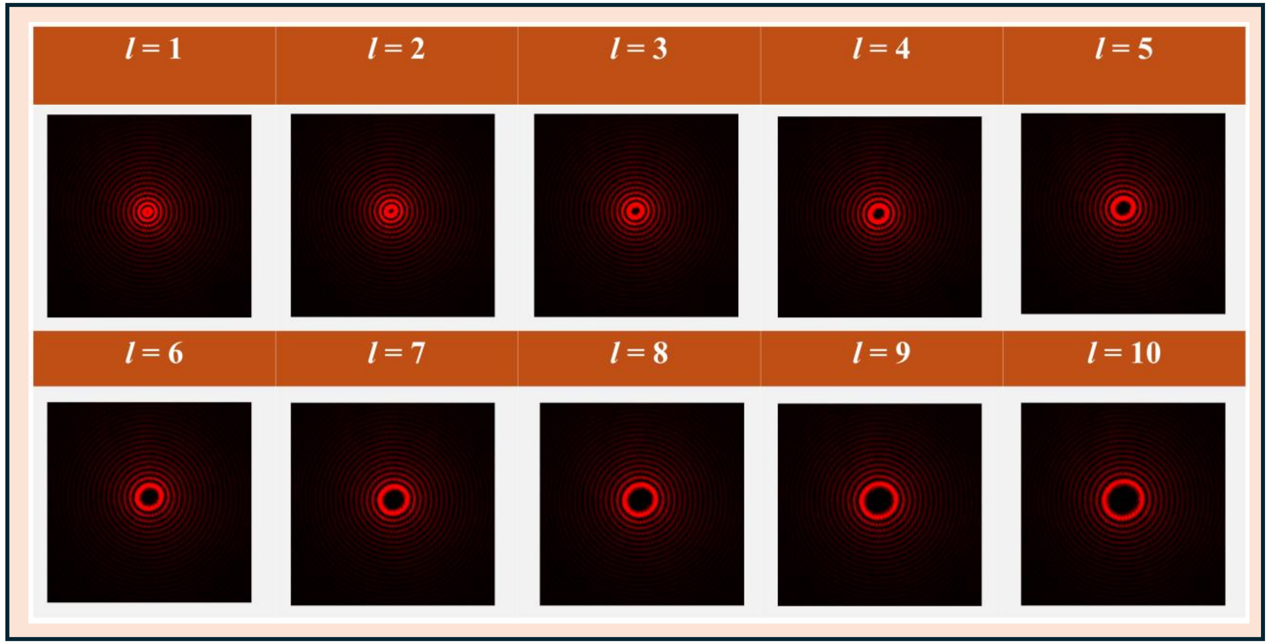
Propagation Characteristics

Conical POV

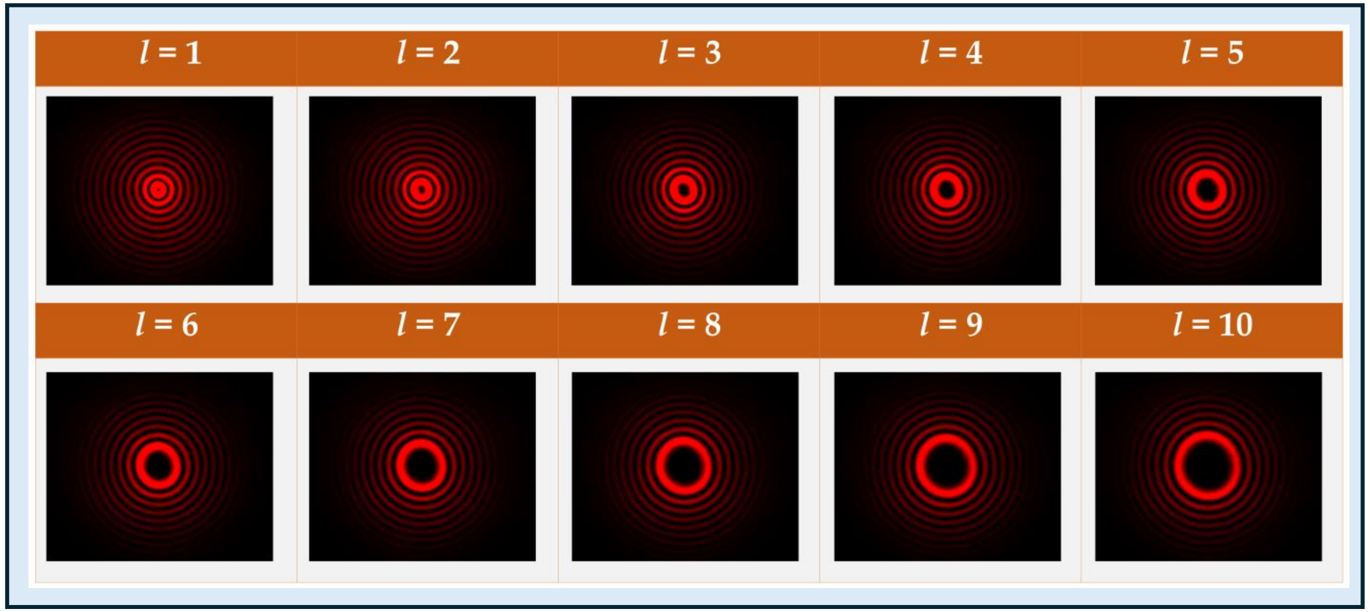
- During propagation, the beam **shrinks in size**.
- It **smoothly transforms** into a **Bessel–Gaussian (BG) like structure**.

POV

- Initially shows **diffraction**.
- **Small ring-like structures** arise from the central region.
- These rings **gradually transform into a BG-like structure**.



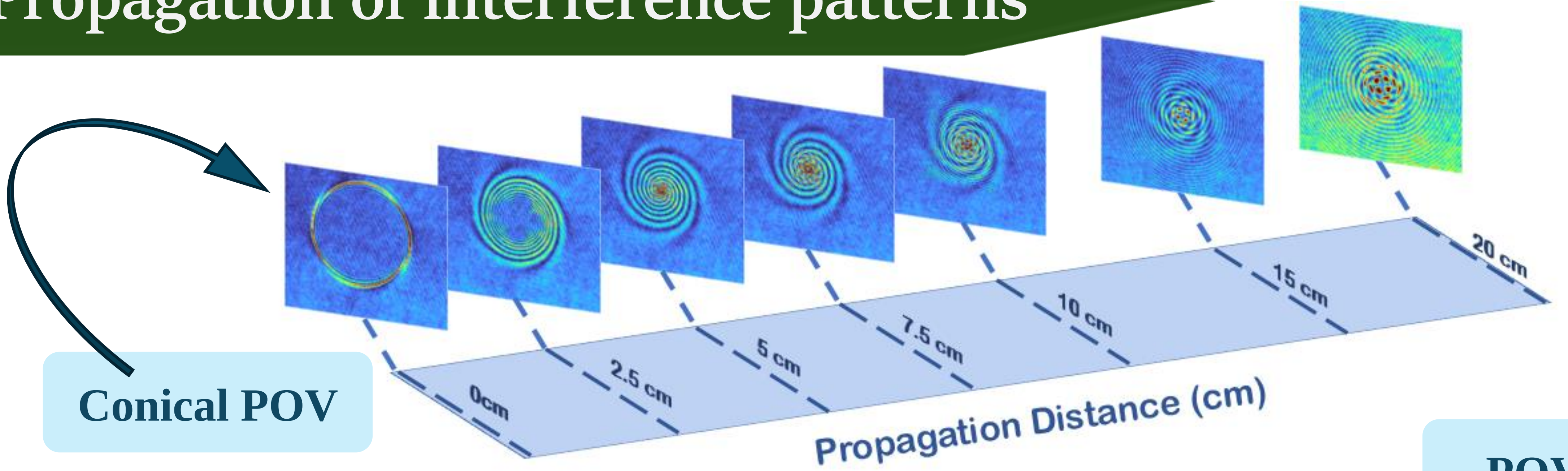
Experimentally captured images at a propagation distance of 50 cm, for *l* values 1 to 10.

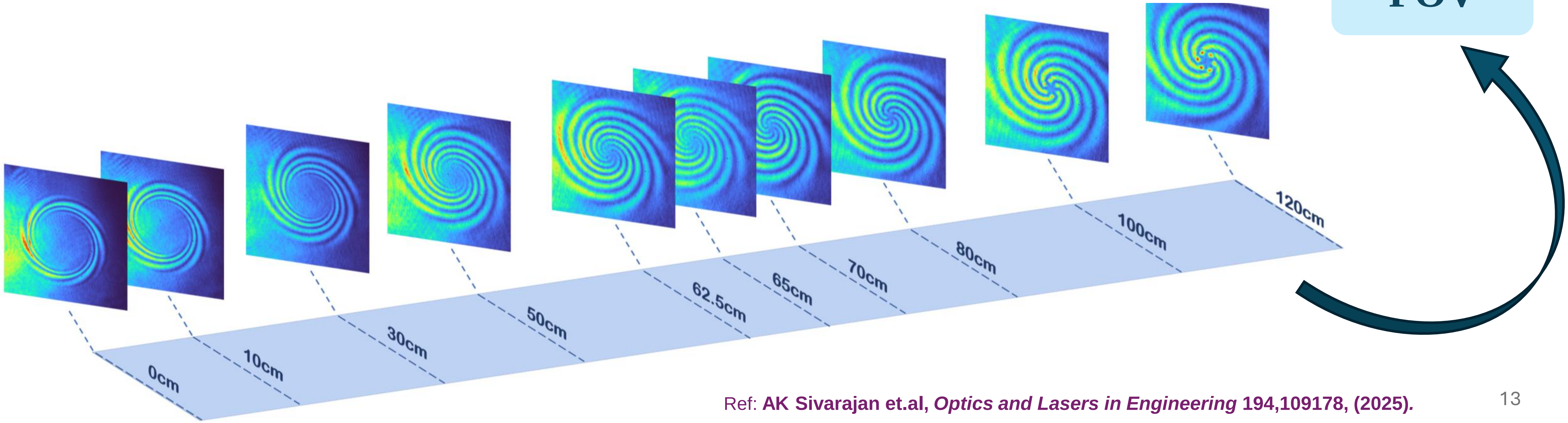


Experimentally captured images of POV beams at a propagation distance of 135 cm for varying *l* values

Ref: **AK Sivarajan et.al, *Optics and Lasers in Engineering* 194,109178, (2025).**

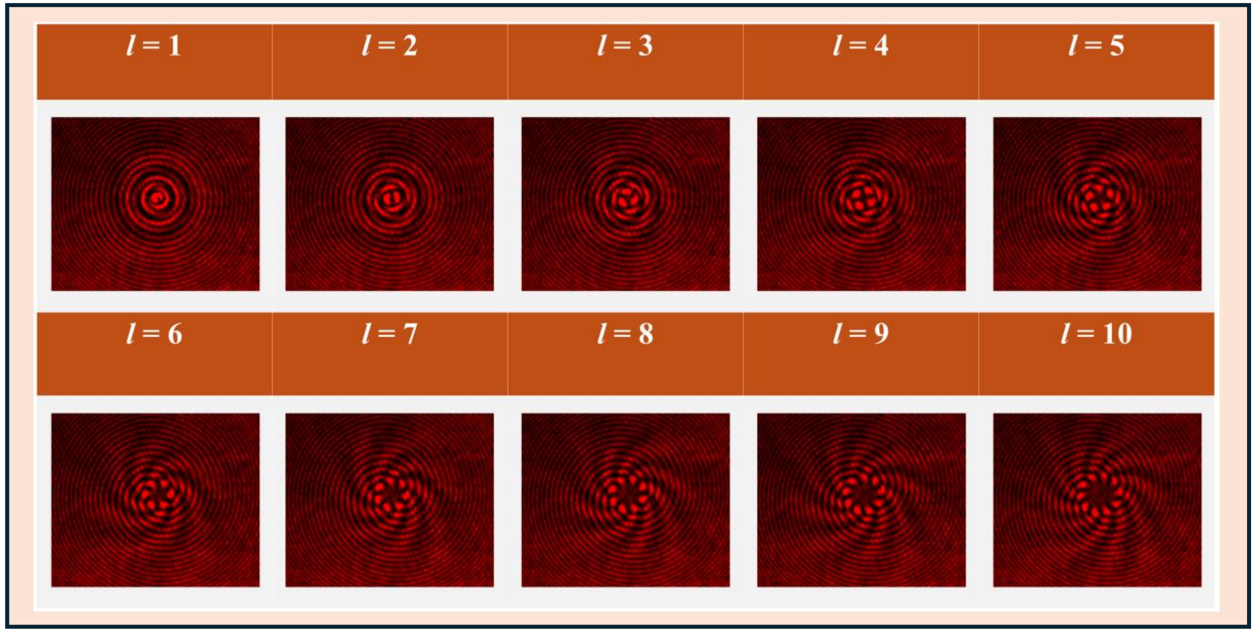
Propagation of interference patterns





Ref: AK Sivarajan et.al, *Optics and Lasers in Engineering* 194,109178, (2025).

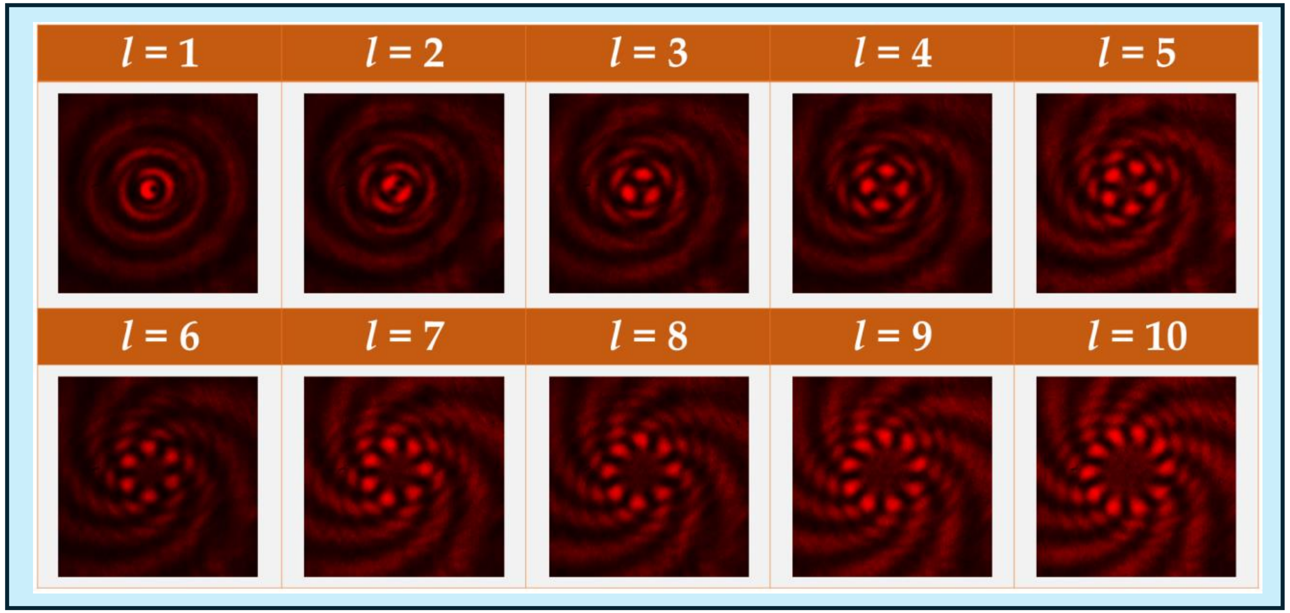
Propagation of interference patterns



Interference of BG beams with spherical beams produces **flower-like patterns**, similar to those observed with **Conical POV and POV beams**.

Experimentally captured images of interference patterns at a propagation distance of 50 cm, for *l* values 1 to 10.

Experimentally captured images of interference patterns at a propagation distance of 135 cm for varying *l* values



Double vortex POV beams

Both vortex with same charge

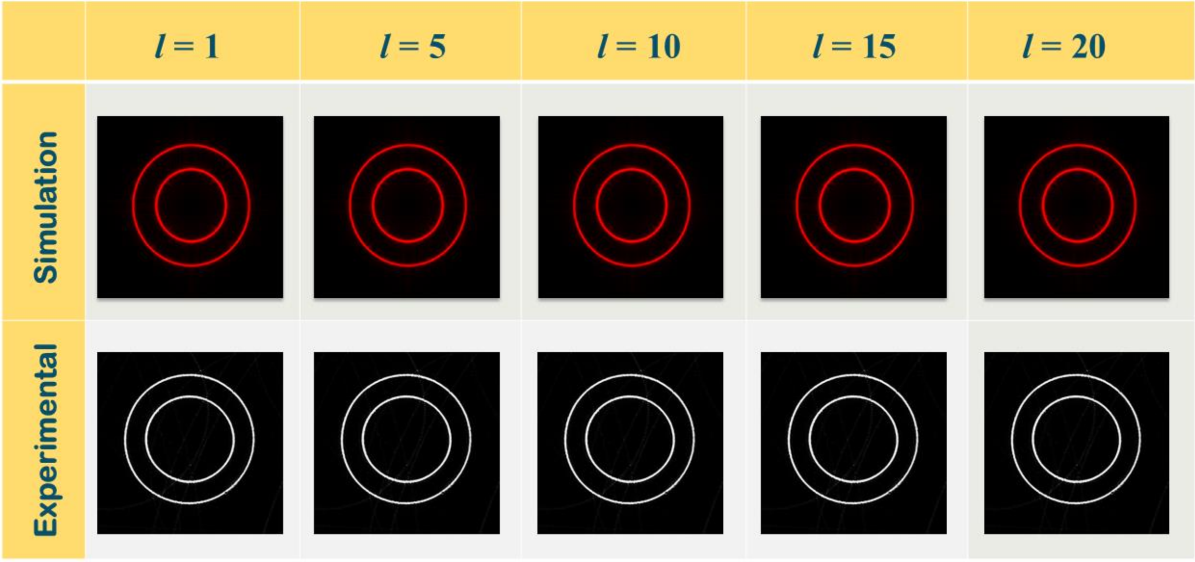
$$\Im\left[J_l(k_r r)exp(il\varphi) + exp(il\varphi)\, exp\left(-i\frac{r}{r_0}\right)\right] exp\left(\frac{-r^2}{w^2}\right)$$

Bessel Function Conical Function

Both vortex with opposite charge

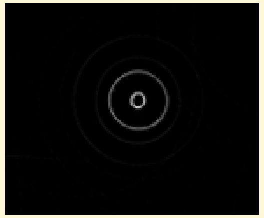
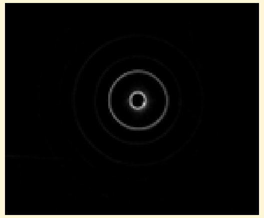
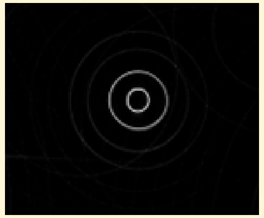
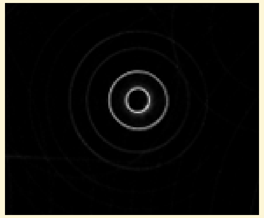
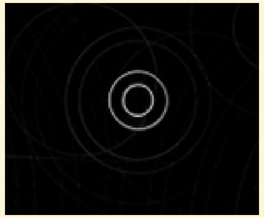
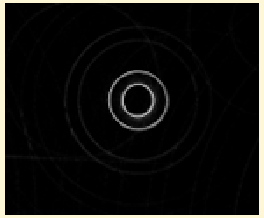
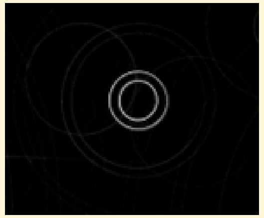
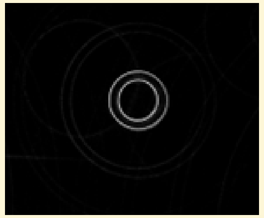
$$\Im\left[J_l(k_r r)exp(il\varphi) + exp(-il\varphi)\, exp\left(-i\frac{r}{r_0}\right)\right] exp\left(\frac{-r^2}{w^2}\right)$$

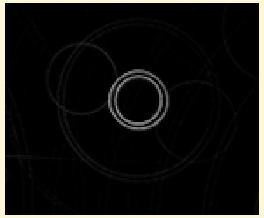
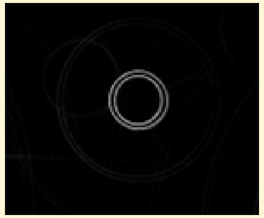
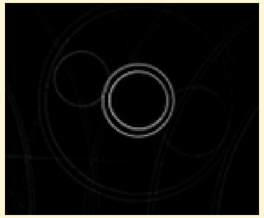
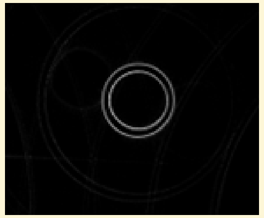
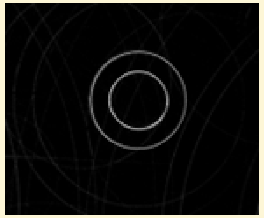
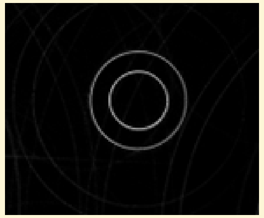
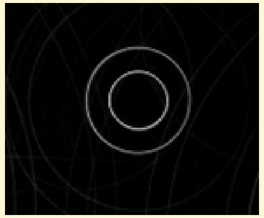
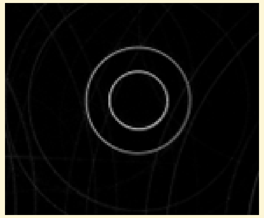
Bessel Function Conical Function



- Double vortex POV beams are generated by combining **Bessel function** and **Conical function.**
- One ring is generated using the **Fourier transform of the Bessel function**, and the other using the **Fourier transform of the Conical function**
- Both rings maintain a **ring radius independent of topological charge**.

Double vortex POV beams with different Bessel masks

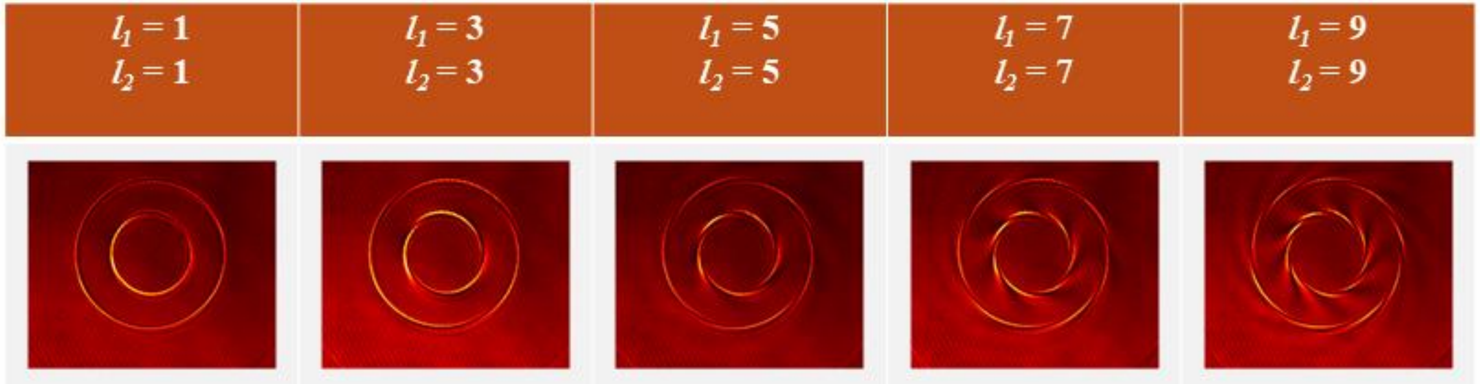
	l = 1	*l* = 10
a = 30		
a = 50		
a = 70		
a = 90		

	l = 1	*l* = 10
a = 110		
a = 170		
a = 230		
a = 250		

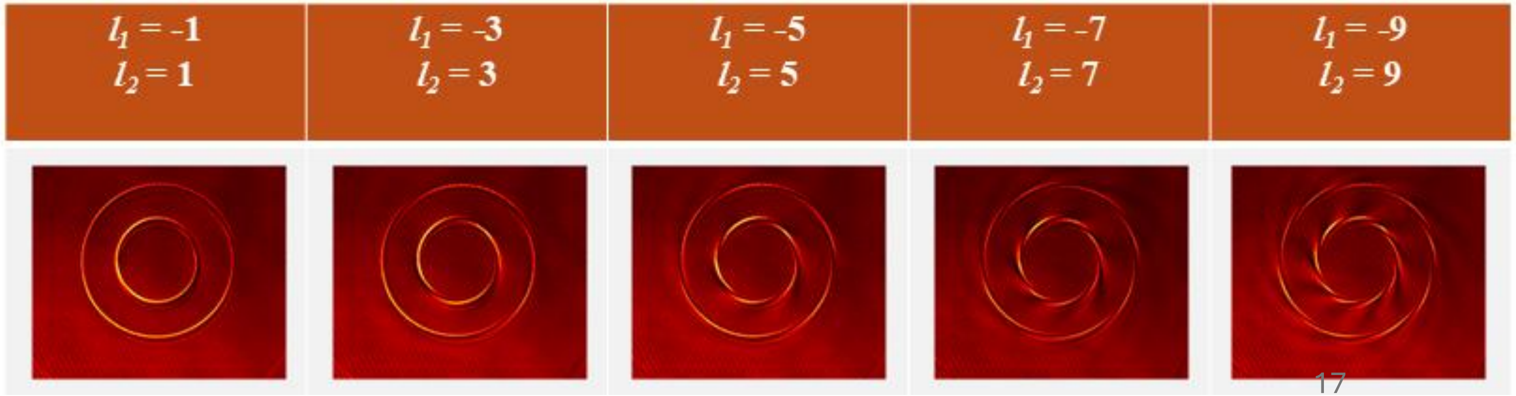
Experimentally captured images for different *l* values by controlling one of the vortex radius by the axicon parameter (a) keeping a constant r_0 value.

Identification of TC presence in Conical POV

- The double vortex POV beams were interfered with Gaussian beam using Mach-Zehnder interferometric setup.
- The interference pattern shows a **spiral-shaped structure**, with fringes spreading outward from the center.
- The **count of spiral fringes in each vortex,** directly indicates the **topological charge (TC)**.



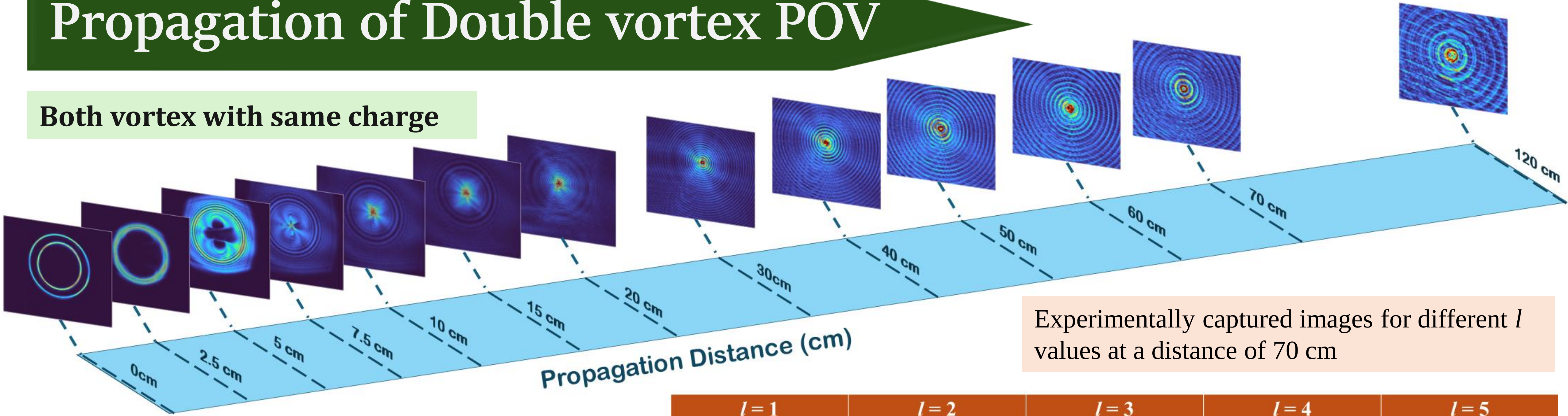
Experimentally captured interference pattern for positive *l* values



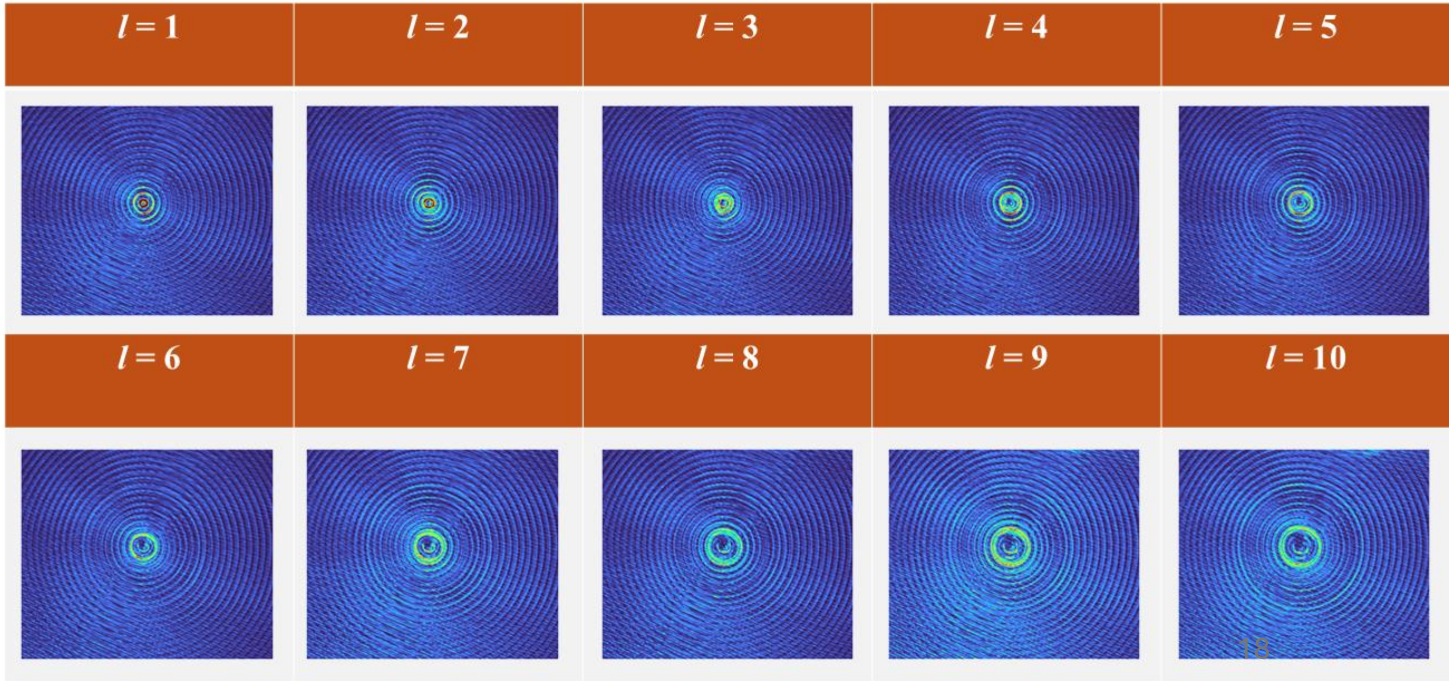
Experimentally captured images of the interference pattern for combination of positive and negative vortices

Propagation of Double vortex POV

Both vortex with same charge



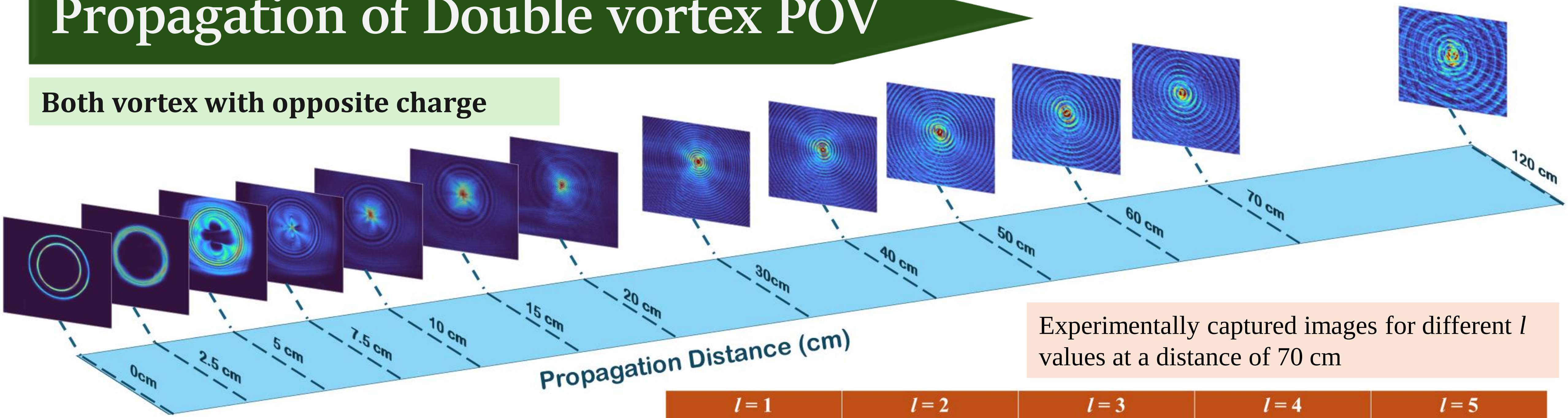
Experimentally captured images for different *l* values at a distance of 70 cm



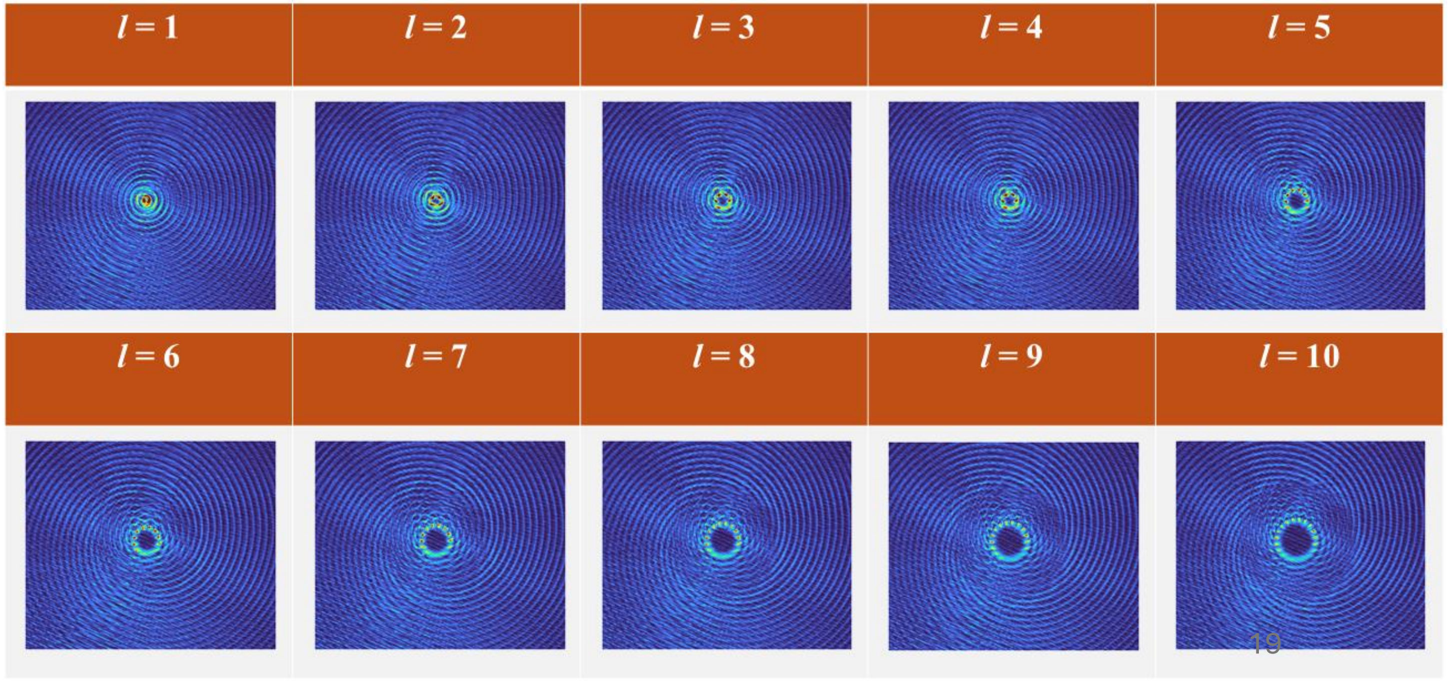
- During propagation, the vortex from the **Bessel function** gradually diffracts.
- After some distance, **small ring patterns** emerge from the center and transform into a **Bessel–Gaussian beam**.
- The **second vortex** shrinks directly and forms a **Bessel–Gaussian beam**.
- At around **50 cm**, two **Bessel–Gaussian beams** can be clearly observed propagating side by side, generated from different vortices.

Propagation of Double vortex POV

Both vortex with opposite charge



Experimentally captured images for different *l* values at a distance of 70 cm



- A similar phenomenon occurs here also, but interference appears when the beams overlap during propagation since both vortices carry **opposite charges**.
- The **number of lobes** in the pattern equals **2*l***.

Conclusions

- **Azimuthal phase modulation with a conical term** generates a Perfect Optical Vortex (POV) beam at the Fourier plane.
- These beams **naturally evolve into Bessel–Gaussian (BG) beams** during free-space propagation.
- During propagation, the **Conical POV beam shrinks in size** and transforms into a BG-like structure.
- The **experimentally captured intensity pattern at 50 cm** closely resembles a BG beam.
- A **Double Vortex POV beam** was successfully designed and experimentally generated using a combination of **Bessel and Conical functions**.
- The **propagation characteristics** were studied experimentally, showing that the beam exhibits **properties of both POV and Conical beams**.

Acknowledgements

- **SRM University – AP**
- **ANRF**

Optics group SRMAP


Dr Ravi Kumar


Dr Gangi Reddy Salla


Dr Sakshi Choudhary


Harsh Vardhan


Aswathi Sivarajan


V Ganesh


MD Haider Ansari

Thank You