Optical Vortices: Scattering through Random Media

A THESIS

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by

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Under the Supervision of

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DEPARTMENT OF PHYSICS

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UDAIPUR

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To

My Parents

Amma-Nanna

DECLARATION

I, **Mr. Salla Gangi Reddy**, *S/o Mr. Venkata Subba Reddy, resident of Room No. C-103, PRL Students Hostel, Navrangpura, Ahmedabad, 380009, hereby declare that the research work incorporated in the present thesis entitled,* **"Optical Vortices: Scattering through Random Media"** *is my own work and is original. This work (in part or in full) has not been submitted to any University for the award of a Degree or a Diploma. I have properly acknowledged the material collected from secondary sources wherever required. I solely own the responsibility for the originality of the entire content.*

Date:

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CERTIFICATE

I feel great pleasure in certifying that the thesis entitled, **"Optical Vortices: Scattering through Random Media"** embodies a record of the results of investigations carried out by Mr. Salla Gangi Reddy under my guidance. He has completed the following requirements as per Ph.D regulations of the University.

(a) Course work as per the university rules.

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I am satisfied with the analysis, interpretation of results and conclusions drawn. I recommend the submission of the thesis.

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Head of the Department

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ABSTRACT

Optical vortices, whirlpools of light, are phase singularities in the light field. These vortex beams have helical wave front and their Poynting vector rotates around the propagation axis. They carry an orbital angular momentum of $m\hbar$, m being the topological charge or order defined as the number of helices in one wave length. Such beams have an azimuthal phase dependence of $\exp(im\phi)$, where $\phi = tan^{-1}(y/x)$ is the azimuthal angle. Vortex beams can be generated by a number of methods. Few of them are an astigmatic mode converter, computer generated holography and spiral phase plates. However, vortices of first order naturally exist in the speckles that can be formed by the scattering of a coherent light beam through a rough surface. Speckles are due to the mutual interference of a number of scattered wave fronts from inhomogeneities of the random medium. It would be very interesting to study the speckles generated by the optical vortices as they themselves contain vortices. This thesis concerns with the study of optical vortices and their scattering through random media.

The spatial intensity profile of optical vortices has been studied using two novel and measurable parameters, inner and outer radii along with their propagation through free space. We show that the propagation characteristics depend only on width of the host Gaussian beam and its intensity profile at the source plane. We have also studied the divergence of vortex beams, considering it as the rate of change of inner and outer radii with the propagation distance (z), and found that it varies with the order in the same way as that of the inner and outer radii at $z = 0$. The corresponding experimental and theoretical results have been presented.

We have embedded a pair of vortices with different topological charges in a Gaussian beam and studied their evolution through an astigmatic optical system, a tilted lens. The propagation dynamics is explained by a closed-form analytical expression. Furthermore, we show that a careful examination of the intensity distribution at a predicted position, past the lens, can determine the charge present in the beam. To the best of our knowledge, our method is the first non-interferometric technique to measure the charge of an arbitrary vortex pair. Our theoretical results are well supported by experimental observations.

We have experimentally generated higher order optical vortices and scattered them through a ground glass plate resulting in speckle formation. Intensity autocorrelation measurements of speckles show that their size decreases with increase in the order of the vortex. It implies increase in angular diameter of the vortices with their order. The characterization of vortices in terms of the annular bright ring also helps us to understand these observations. We

have generated the ring shaped beams from the speckles generated by the scattering of LG and BG beams. We also show that these ring-shaped beams have the same vorticity as the incident beam falling on the rough scattering surface. The vorticity is measured through a novel method that uses a non separable state of polarization and orbital angular momentum of light. The observed vorticity is found to be independent of the amount of scattered light collected. Therefore, vortices can be used as information carriers even in the presence of scattering media. The experimental results are well supported by the theoretical results.

We have generated perfect optical vortices (POV), whose intensity distribution are independent of the order, using Fourier transform of Bessel–Gauss (BG) beams and scatter them through a rough surface. We show that the size of produced speckles is independent of the order and their Fourier transform gives the random non-diffracting fields. The invariant size of speckles over the free space propagation verifies their non-diffracting or non-diverging nature. The size of speckles can be easily controlled by changing the axicon parameter, used to generate the BG beams.

Keywords : Optical vortices, Scattering, Random media, Speckles, Astigmatic system, Perfect optical vortices.

List of Abbreviations

OAM	Orbital Angular Momentum
HG	Hermite Gaussian
LG	Laguerre Gaussian
CGH	Computer Generated Hologram or Holography
SPP	Spiral Phase Plate
VL	Vortex Lens
GGP	Ground Glass Plate
POV	Perfect Optical Vortex
BG	Bessel-Gauss
SLM	Spatial Light Modulator
PMT	Photomultiplier Tube
GSM	Gaussian Schell Model
LGSM	Laguerre Gaussian Schell Model
BGSM	Bessel Gaussian Schell Model
RGG	Rotating Ground Glass
CCD	Charge Couple Device
FWHM	Full Width Half Maxima

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LIST OF PUBLICATIONS

Publications contributing to this thesis :

1. *Experimental generation of ring shaped beams with random sources*,
   Salla Gangi Reddy, Ashok Kumar, Shashi Prabhakar, and R. P. Singh, Optics Letters **38**, 21, 4441-4444 (2013).

2. *Higher order optical vortices and formation of speckles*,
   Salla Gangi Reddy, Shashi Prabhakar, Ashok Kumar, J. Banerji, and R. P. Singh, Optics Letters **39**, 15, 4364-4367 (2014).

3. *Propagation of an arbitrary vortex pair through an astigmatic optical system and determination of its topological charge*,
   Salla Gangi Reddy, Shashi Prabhakar, A. Aadhi, J. Banerji, and R. P. Singh, Journal of the Optical Society of America A **31**, 6, 1295-1302 (2014).

4. *Recovering the vorticity of a light beam after scattering*,
   Salla Gangi Reddy, Chithrabhanu P, Shashi Prabhakar, Ali Anwar, and R. P. Singh, Applied Physics Letters, **107**, 021104 (2015).

5. *Divergence of the optical vortex beams*,
   Salla Gangi Reddy, Chithrabhanu P, Ali Anwar, Shashi Prabhakar, J. Banerji, and R. P. Singh, To be published in Applied Optics (2015).

6. *Perfect optical vortices and the non-diffracting speckles*,
   Salla Gangi Reddy, Chithrabhanu P, Aadhi A, Pravin Vaity, Shashi Prabhakar, and R. P. Singh, Submitted to Optics Letters (Under Revision).

Other publications :

1. *Measuring the Mueller matrix of an arbitrary optical element with a universal SU (2) polarization gadget* ,
   Salla Gangi Reddy, Shashi Prabhakar, A. Aadhi, A Kumar, M. Shah, R. P. Singh, R. Simon, Journal of the Optical Society of America A **31**, 3, 610-615 (2014).

2. *Spatial distribution of spontaneous parametric down-converted photons for higher order optical vortices*,
   Shashi Prabhakar, **Salla Gangi Reddy**, A. Aadhi, Ashok Kumar, P. Chithrabhanu, G. K. Samanta, and R. P. Singh, Optics Communications **326**, 64-69 (2014).

3. *Scattering of non-separable states of light*,
   Chithrabhanu P, **Salla Gangi Reddy**, Ali Anwar, Aadhi A, Shashi Prabhakar, and R. P. Singh, Optics Communications **355**, 301-305 (2015).

4. *Three particle hyper entanglement: Teleportation and quantum key distribution*,
   P. Chithrabhanu, A. aadhi, **Salla Gangi Reddy**, Shashi Prabhakar, G. K. Samanta, G. Paul, and R. P. Singh, To be published in Quantum Information Processing (2015).

5. *Violation of Bell's inequality for phase singular beams*,
   Shashi Prbhakar, **Salla Gangi Reddy**, A. Aadhi, P. Chithrabhanu, and R. P. Singh, Submitted to Physical Review A (Under Revision).

6. *Scattering of phase singular beams: A model for experimental results*,
   Salla Gangi Reddy, Shashi Prabhakar, J. Banerji, and R. P. Singh, To be submitted to Physical Review A.

7. *Two component polarization gadget*,
   Salla Gangi Reddy, Shashi Prabhakar, P. Chithrabhanu, R. P. Singh, and R. Simon, To be submitted to Journal of Biomedical optics.

Conference papers :

1. Shashi Prabhakar, Ashok Kumar, **Salla Gangi Reddy,** A. Aadhi, and R. P. Singh, *Determination of order of vortex from intensity distribution,* International Conference on Trends in Optics and Photonics, University of Calcutta, Koltata, India, pp. 115-119, December 7-9, 2011.

2. R. P. Singh, Pravin Vaity, Ashok Kumar, **Salla Gangi Reddy,** and A. Aadhi, *Dynamics of fractional charge optical vortices,* International Conference on Trends in Optics and Photonics, University of Calcutta, Koltata, India, pp. 217-220, December 7-9, 2011.

3. P. Vaity, Ashok Kumar, **Salla Gangi Reddy,** A. Aadhi, P. Chithrabhanu, and R. P. Singh, *Determining orbital angular momentum of light using simple convex lens,* in International Conference on Fibre Optics and Photonics, OSA Technical Digest (online) (Optical Society of America, 2012), paper MPo.4.

4. S. Prabhakar, **Salla Gangi Reddy,** A. Aadhi, Ashok Kumar, G. Samanta, and R. P. Singh, *Spatial distribution of Spontaneous Parametric Down-Converted Photons,*

in International Conference on Fibre Optics and Photonics, OSA Technical Digest (online) (Optical Society of America, 2012), paper T1C.2.

5. **Salla Gangi Reddy,** S. Prabhakar, A. Aadhi, Ashok Kumar, M. Shah, R. P. Singh, and R. Simon, *Determination of Mueller matrix of an optical element with Simon-Mukunda gadget,* in International Conference on Fibre Optics and Photonics, OSA Technical Digest (online) (Optical Society of America, 2012), paper M1B.2 (**Best Paper Award**).

6. **Salla Gangi Reddy,** Ashok Kumar, Shashi Prabhakar, and R. P. Singh, **Revival of the dark core in scattered optical vortices,** presented at SPIE optics and photonics during August 25-29, 2013 at San Diego, California, USA.

7. **Salla Gangi Reddy,** Shashi Prabhakar, Ashok Kumar, and R. P. Singh, *Spatial Intensity Distribution of optical vortex beams,* presented at Workshop in recent advances in Photonics during December 17-18, 2013 at IIT Delhi, New Delhi, India (**Best Paper Award**).

8. **Salla Gangi Reddy,** Shashi Prabhakar, Ashok Kumar, J. Banerji, and R. P. Singh, *Variation of speckle size with the order of an optical vortex,* presented at International conference on Optics and Optoelectronics during March 05-08, 2014 at IRDE Dehradun, India.

9. **Salla Gangi Reddy,** Ashok Kumar, J. Banerji, Shashi Prabhakar, and R. P. Singh, *Optical vortices through a ground glass,* presented at International conference on Optics and Optoelectronics during March 05-08, 2014 at IRDE Dehradun, India.

10. Chithrabhanu P, Aadhi A, **Salla Gangi Reddy,** Shashi Prabhakar, G. K. Samanta, and R. P. Singh, *A novel entangled source for higher dimensional quantum teleportation and QKD,* presented at International conference on Optics and Optoelectronics during March 05-08, 2014 at IRDE Dehradun, India (**Best Paper Award**).

11. **Salla Gangi Reddy,** Shashi Prabhakar, Ali Anwar, J. Banerji, and R. P. Singh, *Propagation of an arbitrary vortex pair through an astigmatic optical system,* presented at National Laser Symposium during December 03-06, 2014 at Sri Venkateswara University, Tirupathi, India.

12. Chithrabhanu, **Salla Gangi Reddy,** Aadhi A, Shashi Prabhakar, Ali Anwar, and R. P. Singh, *Scattering of non-separable light beams,* presented at National Laser Symposium during December 03-06, 2014 at Sri Venkateswara University, Tirupathi, India.

13. A. Aadhi, Chithrabhanu, **Salla Gangi Reddy,** Shashi Prabhakar, Jabir MV, G. K. Samanta, and R. P. Singh, *Measurement of Berry Phase by non-interferometric method,* presented at National Laser Symposium during December 03-06, 2014 at Sri Venkateswara University, Tirupathi, India.

14. **Salla Gangi Reddy,** Shashi Prabhakar, Ali Anwar, J. Banerji, and R. P. Singh, *Modelling of scattered optical vortices,* presented at Photonics 2014 during December 13-16, 2014 at IIT Kharagpur, India.

15. **Salla Gangi Reddy,** Chithrabhanu, Shashi Prabhakar, Ali Anwar, and R. P. Singh, *Revival of the vorticity in scattered optical vortices,* presented at Photonics 2014 during December 13-16, 2014 at IIT Kharagpur, India.

16. Chithrabhanu, A. Aadhi, **Salla Gangi Reddy,** Shashi Prabhakar, Ali Anwar, and R. P. Singh, *Construction of OAM Poincare sphere with both coherent and partially coherent light beams,* presented at Photonics 2014 during December 13-16, 2014 at IIT Kharagpur, India.

17. Shashi Prabhakar, **Salla Gangi Reddy,** Chithrabhanu, A. Aadhi, G. K. Samanta, and R. P. Singh, *Violation of Bells inequality with phase singular beams,* presented at Photonics 2014 during December 13-16, 2014 at IIT Kharagpur, India. to be presented at Photonics 2014 going to be held on December 13-16, 2014 at IIT Kharagpur, India (**Best Paper Award**).

18. **Salla Gangi Reddy,** Chithrabhanu, Shashi Prabhakar, Ali Anwar, and R. P. Singh, *Divergence of the optical vortex beams with measurable parameters,* presented at International conference on optics and photonics (ICOP 2015) during February 20-22, 2015 at Calcutta University, Kolkata, India.

19. Chithrabhanu, **Salla Gangi Reddy,** Ali Anwar, Aadhi A, Shashi Prabhakar, and R. P. Singh, *Generalized orbital angular momentum Poincaré sphere,* presented at International conference on optics and photonics (ICOP 2015) during February 20-22, 2015 at Calcutta University, Kolkata, India.

20. Aadhi A, Chithrabhanu, **Salla Gangi Reddy,** Apurv Chaitanya, G. K. Samanta, and R. P. Singh, *Superposition of polarization singularity,* presented at International conference on optics and photonics (ICOP 2015) during February 20-22, 2015 at Calcutta University, Kolkata, India.

21. **Salla Gangi Reddy,** Chithrabhanu, Shashi Prabhakar, Ali Anwar, and R. P. Singh, *Perfect optical vortices: Response to an astigmatic optical system,* to be presented at Third international conference on optical angular momentum (ICOAM 2015) going to be held on August 4-7, 2015 at City college of New York, New York, USA.

22. Chithrabhanu P, **Salla Gangi Reddy,** Ali Anwar, Aadhi A, Shashi Prabhakar, and R. P. Singh, *Scattering of light beams with non-separable polarization and orbital angular momentum states,* to be presented at Third international conference on optical angular momentum (ICOAM 2015) going to be held on August 4-7, 2015 at City college of New York, New York, USA.

23. Aadhi A, Chithrabhanu P, **Salla Gangi Reddy,** Apurv Chaitanya, G. K. Samanta, and R. P. Singh, *Non-interferometric method to measure the Pancharatnam phase using a non-separable light beam,* to be presented at Third international conference on optical angular momentum (ICOAM 2015) going to be held on August 4-7, 2015 at City college of New York, New York, USA.

24. Aadhi A, Chithrabhanu P, **Salla Gangi Reddy,** Apurv Chaitanya, G. K. Samanta, and R. P. Singh, *Spatial superposition of vector vortex beams,* to be presented at Third international conference on optical angular momentum (ICOAM 2015) going to be held on August 4-7, 2015 at City college of New York, New York, USA.

25. **Salla Gangi Reddy,** Chithrabhanu, Shashi Prabhakar, J. Banerji, and R. P. Singh, *Correlations in scattered optical vortices,* to be presented at Correlation optics 2015 going to be held on September 14-18, 2015 at University of Chernivtsi, Chernivtsi, Ukraine (**Invited talk**).

Publications attached with the thesis

1. *Higher order optical vortices and formation of speckles*,
   Salla Gangi reddy, Shashi Prabhakar, Ashok Kumar, J. Banerji, and R. P. Singh, Optics Letters **39**, 15, 4364-4367 (2014).

2. *Propagation of an arbitrary vortex pair through an astigmatic optical system and determination of its topological charge*,
   Salla Gangi Reddy, Shashi Prabhakar, A. Aadhi, J. Banerji, and R. P. Singh, Journal of the Optical Society of America A **31**, 6, 1295-1302 (2014).

3. *Recovering the vorticity of a light beam after scattering*,
   Salla Gangi Reddy, Chithrabhanu P, Shashi Prabhakar, Ali Anwar, and R. P. Singh, Applied Physics Letters, **107**, 021104 (2015).