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Scattering Properties of Orbital Angular Momentum Beams

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EXECUTIVE SUMMARY

This document satisfies the closeout requirements for NRL base program 1V24: Scattering Properties of Orbital Angular Momentum Beams. It provides an overview of the technical objectives of the program, technical progress, and dissemination of research findings through publications and presentations.

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SCATTERING PROPERTIES OF ORBITAL ANGULAR MOMENTUM BEAMS

1. OBJECTIVE

The optical scattering properties of particles depends on the intensity and the phase profile of the laser beams. Therefore, the scattering properties of Orbital Angular Momentum OAM laser beams are quite different from conventionally used Gaussian laser beams. These differences will be exploited to measure the intrinsic properties of individual particles and to mitigate scattering effects in dense media.

2. INTRODUCTION

In this paper we present our experimental and theoretical work in investigating OAM light interactions with single particles. We pursued two theoretical approaches to calculate the scattering effects of laser beams carrying OAM. The first approach uses Commercial Multiphysics Simulation Package COMSOL (CMSPC) to derive scattering phase and intensity from varying order OAM beams in the near-field. The second approach applies a Fourier optical method to decompose the input beam into an angular spectrum of plane waves and a coherent sum of the scattering fields in the far-field.

3. THEORETICAL APPROACHES

3.1 Near-field Scattering:

We study the scattering of incident OAM light in the near-field to shed insight into the phase and magnitude variations. The scattering field is studied for varying mode orders in an observation volume

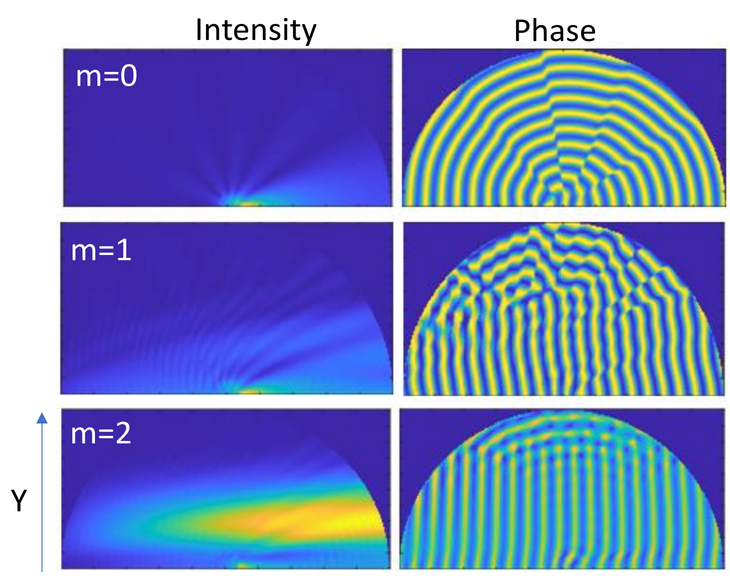

Figure 1. The intensity and phase of the near-field scattering in the XY plane for laser beams of modes 0, 1 and 2. The intensity nulls corresponds to phase discontinuities

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large enough to observe the full extent of the near-field variations. For beam propagating along X-axis and polarized along the Z-axis, the phase and intensity in the scattering plane (XY) is demonstrated in Fig.1 for modes of 0 (Gaussian), 1 and 2 for a particle with size parameter 5.9 (λ= 532 nm and particle diameter =1 µm) and index of refraction n=1.31. The familiar Mie scattering pattern is observed in the intensity for m=0 and corresponding discontinuity in the phase is observed. For higher order modes the intensity pattern get more complicated with more fine structure in the intensity and the phase patterns exhibit linear phase discontinuities in contrast to the spherical modulation observed for the Gaussian.

3.2 Far-field Scattering:

The second approach applies a Fourier optical method to decompose the input beam into an angular spectrum of plane waves and a coherent sum of the scattering fields in the far-field [1, 2]. The scattering intensity is presented as a function of scattering angle in the perpendicular and parallel planes in Fig. 2. Here, a 5 µm diameter particle (n=1.59) is illuminated by a 532 nm light beam with a beam waist of 5 µm, for m = 0 (a Gaussian beam) and 5 (nonzero orbital angular momentum). Of interest is the fact that the forward and backward scattering in the m = 5 case is greatly reduced relative to the m = 0 case. Such scattering calculated are used to validate our experimental measurements.

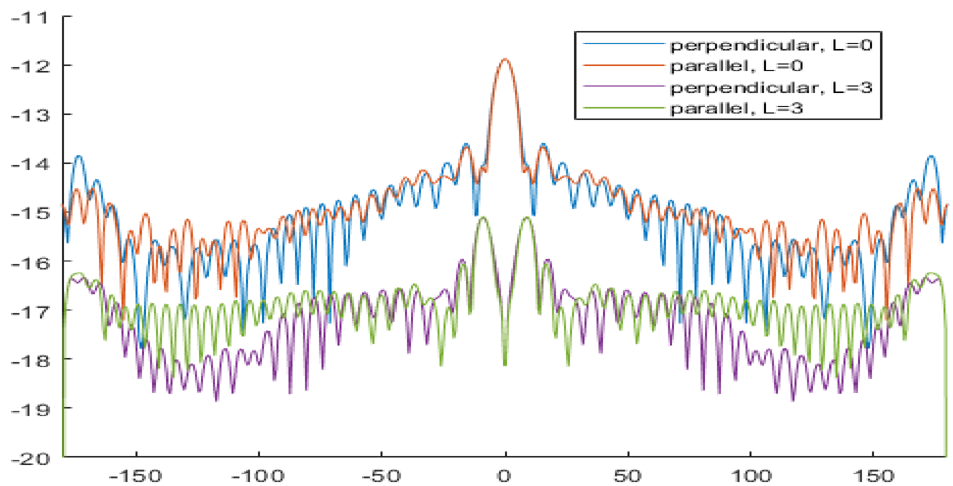

Figure 2. A line plot of the scattered intensities of a 5 µm diameter polystyrene bead under illumination by Laguerre-Gauss beams of different charges and polarizations, as a function of polar angle. Log scale, arbitrary normalization factor.

4. EXPERIMENTAL APPROACH

We use a 532 nm laser beam for our experimental investigations and study the scattering properties of suspended micron sized spherical particles in a linear electrodynamic quadrupole (LEQ) trap [3]. We study the angle-resolved scattering signal in a scattering plane in each of the forward, back and side scattering geometries by using line or 2D cameras. We generate OAM beams of varying modes and collect the angular scattering signal for varying sizes of commercially available particles of varying materials. The particle travels up the beam, resulting in continuous angular scattering measurements in the scattering detectors [2]. The optical Setup is shown in Fig. 3.

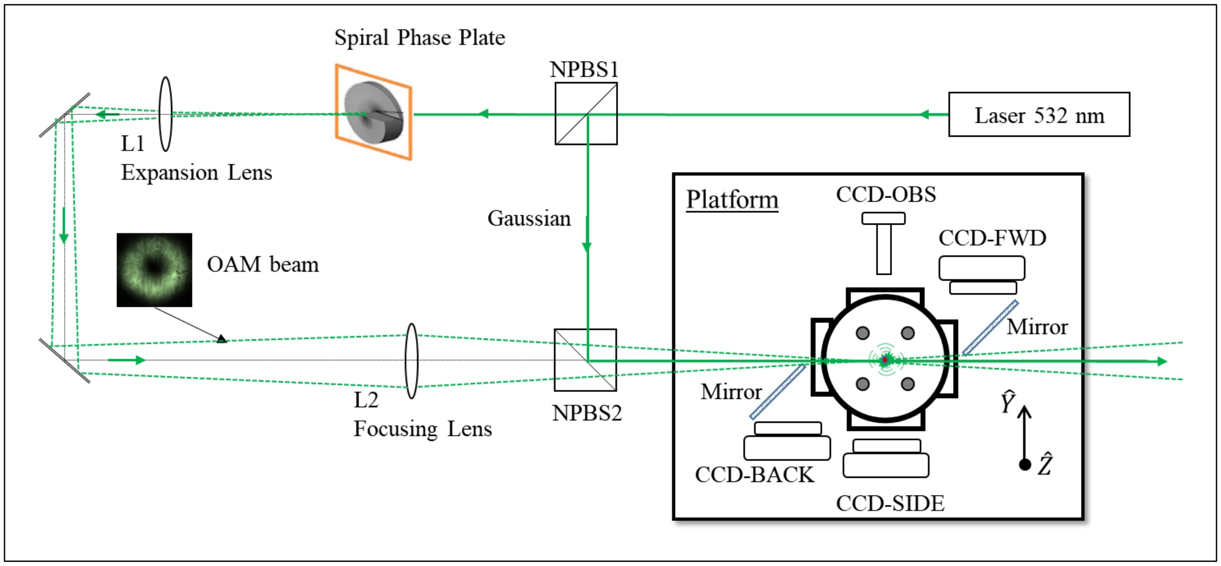

Figure 3. Optical layout of the experimental setup to measure elastic scattering from single particles held in a quadrupole trap. The 532 nm laser beam is divided into two arms, one that is used to create an OAM beam and one that preserves the original Gaussian beam. After passing through the nonpolarizing beam splitter, NPBS1, the light in the OAM arm passes through a phase plate creating a vortex beam with a Gaussian intensity distribution. The lenses L1 and L2 are used to first expand the beam for a wide aperture of the L2 lens so that the OAM beam can be focused to a diameter of less than 10 um near the point of intersecting the particle in the LEQ. The Gaussian beam is directed such that it is collinear with the OAM beam using the two nonpolarizing beam splitters to intersect the particle at the same point as the OAM beam. During the experiment each beam is used independently by placing appropriate beam blocks. The Gaussian beam is used to generate reference data for each particle before the OAM beam scattering is recorded. This data is used for determining accurate size of the particle and to calibrate the scattering angle positions across the pixel arrays on the three angular light recording CCDs.

5. Results

We have conducted scattering measurements for varying size polymers beads, including 5 µm, 10 µm, 15 µm and 20 µm. For OAM beam of small diameters < 40 microns, three distinct scattering patterns are observed as the particle transits through the bottom, middle and top of the donut pattern beam profile. The scattering pattern is markedly different from that of Mie scattering, showing that scattering from OAM beams are indeed different than that of Gaussian and plane waves. Results from a 20 µm polystyrene latex sphere transiting through the beam is shown in Fig. 4 for beams of mode 0 (Gaussian) and 3 from the forward scattering detector. The scattering intensity is recorded as the particle travels through the beam with particle position on the vertical axis and angles (not calibrated) on the horizontal axis and the color scale representing intensity. The plot on the left shows that the Gaussian beam diameter is around 30 µm. The detector records scattering angles >5°, therefore the forward scattering at 0° is not recorded, but the four lobes adjacent to the forward scattering peak are shown that are inline with Mie scattering calculations. For m=3 mode the scattering is shown as the particle is passing through the stronger two ring regions and the weaker center region. The plot shows that the beam diameter is around 70 µm. The scattering pattern from the top ring and bottom portions of the ring show angular placement in respect with each other. This is validated by our far-field scattering calculations, and shown to correlate to the handedness of the OAM mode. We are able to show that when the particle is in the center of the beam the scattering pattern varies greatly from that of plane waves and approaches plane wave scattering as the particle approaches the ring part of the beam. At the center of the beam, the scattering at

0° and 180° is minimized with the maximum scattering occurring at larger angles, which is proportional to the mode order.

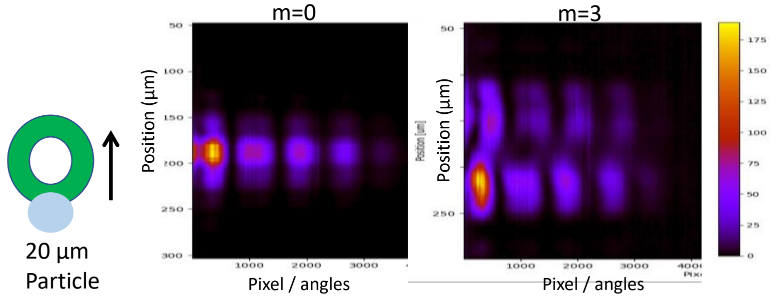

Figure 4. The cartoon on the left shows the travel of the particle through and OAM beam with donut intensity. The two graphs show the scattering intensity recorded as the particle transit the beam from bottom to top for laser beams of mode 0 (Gaussian) and 3. The particle position is plotted on the vertical axis and the scattering angle in the horizontal axis. The intensity map shows the strength of the scattering intensity.

6. Summary

We have developed a capability to measure scattering from single particles moving through laser beams with OAM. In parallel we developed two theoretical modelling technique to calculate the near-field and far-field scattering from OAM beams of varying modes. The Fourier decomposition based scattering technique is very robust and computationally efficient. Our measured and theoretical scattering results from single particles show that the scattering pattern varies drastically compared with conventional Mie scattering from plane waves with the scattering maxima shifting to larger angles that varies with the mode of the laser beam. The intensity at the forward and back scattering angles are greatly reduced. Furthermore, the scattering from the top and bottom of the donut beam profile is shifted in angular space relative to the center which correlates with the handedness of the beam.

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DISSEMINATIONS

Conference Proceedings

Matthew B. Hart, Vasanthi Sivaprakasam, Ryan Lindle, Shawn Divitt and Abbie Watnik, “Scattering of light with orbital angular momentum from single particles,” Proc. SPIE 12543, Ocean Sensing and Monitoring XV, 1254305, June 2023; doi: 10.1117/12.2664089.

Svetlana Avramov-Zamurovic, Nathaniel A. Ferlic, Owen O'Malley, Matthew B. Hart, Shawn Divitt, Vasanthi Sivaprakasam, K. Peter Judd, Martin Lavery, Linda J. Mullen, Matthew Kalensky, Jonathon Wells, Samuel Mellon, "Systematic propagation and scattering studies of light that carries orbital angular momentum," OPTRO, 11th International symposium on Optronics in Defense and Security, Jan 2024. Submitted for Publication.

Journal Publications

Svetlana Avramov-Zamurovic, Matthew B. Hart, Vasanthi Sivaprakasam and John E. McCarthy, "Laser beam carrying orbital angular momentum scattering from an ice particle: near-field intensity and phase numerical study," in preparation to submission to Journal of Quantitative Spectroscopy and Radiative Transfer (Dec 2023).

Shawn Divitt, Matthew B. Hart and Vasanthi Sivaprakasam, "Fourier decomposition-based OAM scattering far-field calculation for single particles," manuscript in preparation.

Invited Talks

Vasanthi Sivaprakasam, "Scattering Media Interactions with Orbital Angular Momentum Laser Beams," Optica Imaging Congress, Propagation through and Characterization of Atmospheric Oceanic Phenomena, Optica, Boston MA, Aug 2023.

Matthew B. Hart, Vasanthi Sivaprakasam, "Methodology to Study the Physical Properties of Single Particles with Applications to Benefit Aerosol Sensing and Improved Laser Propagation Through Turbid Media," Office of the Under Secretary of Defense - Basic Research Forum Series, Virtual Presentation, Feb 2023.

Conference Presentations

Svetlana Avramov-Zamurovic, Nathaniel A. Ferlic, Owen O'Malley, Matthew B. Hart, Shawn Divitt, Vasanthi Sivaprakasam, K. Peter Judd, Martin Lavery, Linda J. Mullen, Matthew Kalensky, Jonathon Wells, Samuel Mellon, "Systematic propagation and scattering studies of light that carries orbital angular momentum," OPTRO, 11th International symposium on Optronics in Defense and Security, Jan 2024.

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Vasanthi Sivaprakasam, Matthew B. Hart, Ryan Lindle, Paul S. Winkler and Abbie Watnik, "Elastic Light Scattering Measurements from Orbital Angular Momentum Laser Beams," Single Particle Light Scattering from Light Beams with Orbital Angular Momentum," Laser Applications to Chemical, Security and Environmental Analysis, Vancouver CA, July 2022.

Matthew B. Hart, Vasanthi Sivaprakasam, Ryan Lindle, Wenbo Sun and Abbie Watnik, "Single Particle Light Scattering from Light Beams with Orbital Angular Momentum," 39th Annual Conference of the American Association for Aerosol Research, Virtual Conference, October 2021.