# Investigation of optically trapped lanthanide ions doped nanoparticles

**by Xuchen Shan**

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**Doctor of Philosophy**

under the supervision of Dr. Fan Wang, Prof. Dayong Jin, Dr. Peter Reece

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# Certificate of Original Authorship

I, Xuchen Shan declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Mathematical and Physical Sciences, Faculty of Science, at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program and the China Scholarship Council Scholarship.

Signature: Production Note: Signature removed prior to publication.

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# Format of Thesis

This thesis has a conventional format and consists of seven chapters as illustrated by the flow chart below.

Chapter 1 is an introduction chapter about optical tweezers and nanoprobes. The advantages of different types of optical tweezers and nanoprobes are discussed in detail.

Chapter 2 provides detailed methods of optical trapping theory and laser beam control used in the results-based chapters.

Chapter 3 investigates the trap stiffness detecting method and highlights the principle and methodology for the PSD detecting and video tracking methods.

Chapter 4 describes the strategy to enhance the trap stiffness of optically trapped nanoparticles by doping lanthanide ions.

Chapter 5 focuses on the machine learning prediction demonstration results for UCNPs size prediction.

Chapter 6 is concerned with the nanomaterials video display by optimizing lanthanide ion-doped upconversion nanoparticles.

Chapter 7 summarizes the key research results of the projects undertaken and suggestions for future research work based on the current progress described in this thesis.

# List of Publications

## I. Journal Articles

1. _Nature Nanotechnology_ (2021) – **X. Shan**†, F. Wang†, D. Wang, S. Wen, C. Chen, X. Di, P. Nie, J. Liao, Y. Liu, L. Ding, P. J. Reece and D. Jin, "Optical tweezers beyond refractive index mismatch using highly doped nanoparticles", vol. 16, 5,2021
2. _Nanoscale_ (2020) – L. Gao, **X. Shan**, X. Xu, Y. Liu, B. Liu, S. Li, S. Wen, C. Ma, D. Jin and F. Wang" Video-rate upconverting display by optimizing lanthanide ions doped upconversion nanoparticles", vol. 12, 36, 2020
3. _Advanced Materials_ (2021) – C. Chen, B. Liu, Y. Liu, J. Liao, **X. Shan**, F. Wang and D. Jin. "Heterochromatic Nonlinear Optical Responses in Upconversion Nanoparticles for Super-Resolution Nanoscopy", vol. 33, 23, 2021
4. _Nature Communication_ (2018) – C. Chen†, F. Wang*†, S. Wen, Q. P. Su, M. C.L. Wu, Y. Liu, B. Wang, D. Li, **X. Shan**, M. Kianinia, I. Aharonovich, M. Toth, S. P. Jackson, P. Xi and D. Jin, "Multi-photon near-infrared emission saturation nanoscopy using upconversion nanoparticles", vol. 9(1), 4, 2018.
5. _Nano letters_ (2020) – B. Liu, C. Chen, X. Di, J. Liao, S. Wen, Q. P. Su, **X. Shan**, Z. Xu, L. A. Ju, C. Mi, F. Wang, and D. Jin, "Upconversion nonlinear structured illumination microscopy", vol. 20, 7, 2020
6. _Small_ (2020) – Y. Liu, F. Wang, H. Lu, G, Fang, S. Wen, C. Chen, **X. Shan**, X. Xu, L. Zhang, M. Stenzel and D. Jin, "Super-Resolution Mapping of Single Nanoparticles inside Tumor Spheroids", 1905572, 2020

## II. Conference Articles

7. _CLEO_ (2020) – B. Liu, **X. Shan**, J. Zhu, C. Chen, Y. Liu, F. Wang, D. McGloin, "Self-optimizing ghost imaging with a genetic algorithm", pp. 1-2, 2020.
8. _SPIE_ (2020) – Y. Liu, F. Wang, H. Lu, S. Wen, C. Chen, **X. Shan**, G. Fang and D. Jin, "Deep tissue super-resolution microscopy mapping single nanoparticles inside multicellular spheroids", vol. 11468, 2020.
9. _SPIE_ (2019) – C. Chen, F. Wang, S. Wen, Y. Liu, **X. Shan**, and D. Jin, "Upconversion nanoparticles assisted multi-photon fluorescence saturation microscopy", vol. 10891, 2019.

## III. Patents

10. L. Gao, F. Wang, **X. Shan**, S. Li, A two-dimensional display device based on up-conversion luminescent material, Patent Number: CN 211786516U
11. L. Gao, F. Wang, **X. Shan**, S. Li, Three-dimensional display device based on up-conversion luminescent material, Patent Number: CN 211786462U

([1,2,10,11] are closely related to my PhD program)

# Abbreviations

| | |
|---|---|
| UCNPs | upconversion nanoparticles |
| 3D | three dimensional |
| AOM | acoustic optical modulator |
| SLM | spatial light modulator |
| HOT | holographic optical tweezers |
| TEM | transmission electron microscopy |
| DNA | deoxyribonucleic acid |
| RNA | ribonucleic acid |
| PSD | position sensor detector |
| RI | refractive index |
| PVA | polyvinyl acetate |
| 2D | two-dimensional |
| DMD | digital micromirror device |
| AOD | acousto-optic deflector |
| FPGA | field-programmable gate array |
| LC | liquid crystal |
| LUT | look up table |
| TPA | two photon absorption |
| SPAD | single-photon avalanche diode |

| | |
|---|---|
| NP | nanoparticle |
| VTM | video tracking method |
| FPS | frame per second |
| PSF | point spread function |
| CMOS | complementary metal-oxide-semiconductor |
| CCD | charge-coupled device |
| VTA | video tracking analysis |
| STORM | stochastic optical reconstruction microscopy |
| DNN | deep neural networks |
| CM | Clausius-Mossotti |
| rCM | real part of the Clausius-Mossotti factor |
| iCM | imaginary part of the Clausius-Mossotti factor |
| EM | electromagnetic |
| NIR | near-infrared |
| CW | continuous wave |
| ROI | region of interest |

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# Abstract

Nanoscale optical force probe for optical tweezers provides a new non-contact force-sensing technology with a high spatial resolution, one that is to break the limitations in conventional methods. The developing of optical trapping nanosensor can map out interactive information in the nanoscale region in water. However, the low refractive index from functional nanoparticles results in a reduced magnitude of the scattering field, which complicated its optical force measurement, hindering the application of optical trapping on these particles.

Here, applying machine learning involved video tracking analysis on the optically trapped nanoparticle, we achieved the 3D optical trapping force measurement for nanoparticles with refractive index 1.5. Applying optical astigmatism modification, we achieved nanoscale 3D localizing of optically trapped upconversion nanoparticles (UCNPs) and thus the construction of 3D force. This work offers a unique solution to investigate the optical manipulation of low refractive index nanoparticles, also enables high resolution sensing for a range of environment variations. Based on the video tracking technology, we found that it applies a resonance effect that enhances the permittivity and polarizability of nanocrystals, leading to enhanced optical trapping forces by orders of magnitude. This effectively bypasses the requirement of refractive index mismatch at the nanoscale. The result shows that under resonance conditions, highly doped lanthanide ions in $NaYF_4$ nanocrystals makes the real part of the Clausius-Mossotti factor approaches its asymptotic limit.

Besides, we further use machine learning technology to analysing the point spread function of nanoparticles, to predict the size of the trapped luminescent nanoparticles in the water environment.

**Keywords**: upconversion nanoparticles, optical tweezers, video tracking, machine learning