

Investigation of optically trapped lanthanide ions doped nanoparticles

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Thesis submitted in fulfilment of the requirements for
the degree of

Doctor of Philosophy

under the supervision of Dr. Fan Wang, Prof. Dayong Jin,
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3/11/2021

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.

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Acknowledgements

First and foremost, I would like to express my deep and sincere gratitude to my supervisors. I am particularly grateful to the following: Prof. Jin for offering the opportunity to pursue a PhD on such a great research topic; Dr Wang for the patient advises and guidance in the experiment designs and modelling simulations; and Dr Peter Reece in optical engineering. I also appreciate Dr Peter Qian Su for his mentoring on the subject of biological engineering. I would like to thank each of them for their constructive criticisms and helpful discussions on my PhD thesis. Their research attitudes always inspire me to work happily and professionally.

I would like to address a special thanks to Dr Laixu Gao, David Zhiguang Zhou and Chao Mi for the optical system design, Dr Chaohao Chen and Mr Lei Ding for the optical system setup and experiment design, Mr Baolei Liu for helping develop the image process algorithm and Mr Yongtao Liu for helping with the energy level simulations. I would like to acknowledge Mrs Xiangjun Di, Mr Dejiang Wang and Mr Baoming Wang for their help with the cell culture involved in this thesis. I also appreciate Dr Jiayan Liao and Dr Shihui Wen for the high-quality upconversion nanoparticle synthesis.

I would like to mention all the members of the IBMD (past and present), who provided technical support or suggestions and assistance regarding the experiments. I enjoy working with these lovely people and appreciate their help whenever I encountered any experimental difficulties. I would like to thank all the friends I have who live outside the realm of research during my four years in Sydney.

I would like to thank my family members for their continuous support and love throughout my life. In particular I thank my wife Yiqiao Wang, for her understanding and incalculable contribution to our little family.

Finally, I would like to acknowledge the Australian Government Research Training Program and the China Scholarship Council Scholarship for providing me with a scholarship and research opportunities.

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 nanoprobe. The advantages of different types of optical tweezers and nanoprobe 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