# Light manipulation by plasmonic nanostructures

A thesis submitted for the degree
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Wei Liu

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# Declaration

This thesis is an account of research undertaken in the Nonlinear Physics Centre within the Research School of Physics and Engineering at the Australian National University between September 2009 and March 2013 while I was enrolled for the Doctor of Philosophy degree.

The research has been conducted under the supervision of A/Prof. Dragomir N. Neshev, Dr. Andrey E. Miroshnichenko, Dr. Ilya V. Shadrivov, A/Prof. Andrey A. Sukhorukov, and Prof. Yuri S. Kivshar. However, unless specifically stated otherwise, the material presented within this thesis is my own.

None of the work presented here has ever been submitted for any degree at this or any other institution of learning.

Wei Liu
July, 2013

# Publications and selected presentations

## Refereed journal articles

***The published results that are included in this thesis are typed in bold.***

1. **W. Liu, A. A. Sukhorukov, A. E. Miroshnichenko, C. G. Poulton, Z. Y. Xu, D. N. Neshev, and Yu. S. Kivshar, "Complete spectral gap in coupled dielectric waveguides embedded into metal," Appl. Phys. Lett. 97, 021106 (2010).**

2. **W. Liu, D. N. Neshev, A. E. Miroshnichenko, I. V. Shadrivov, and Yu. S. Kivshar, "Polychromatic nanofocusing of surface plasmon polaritons," Phys. Rev. B. 83, 073404 (2011).**

3. **W. Liu, D. N. Neshev, I. V. Shadrivov, A. E. Miroshnichenko, and Yu. S. Kivshar, "Plasmonic Airy beam manipulation in linear optical potentials," Opt. Lett. 36, 1164 (2011).**

4. A. R. Davoyan, W. Liu, A. E. Miroshnichenko, I. V. Shadrivov, S. I. Bozhevolnyi, and Yu. S. Kivshar, "Mode transformation in waveguiding plasmonic structures," Photon. Nano.: Fundam. Appl., **9**, 207(2011).

5. **W. Liu, D. N. Neshev, A. E. Miroshnichenko, I. V. Shadrivov, and Yu. S. Kivshar, "Bouncing plasmonic waves in half-parabolic potentials," Phys. Rev. A 84, 063805 (2011).**

6. **W. Liu, A. E. Miroshnichenko, D. N. Neshev, and Yu. S. Kivshar, "Broadband unidirectional scattering by core-shell nanoparticles," ACS Nano 6, 5489 (2012).**

7. **W. Liu, A. E. Miroshnichenko, D. N. Neshev, and Yu. S. Kivshar, "Polarization-independent Fano resonances arrays of core-shell nanoparticles," Phys. Rev. B 86 (R), 081407 (2012).**

8. **W. Liu, A. E. Miroshnichenko, R. F. Oulton, D. N. Neshev, O. Hess, and Yu. S. Kivshar, "Scattering of core-shell nanowires by the interference of electric and magnetic resonances," Opt. Lett. 38, 2621 (2013).**

9. B. Hopkins, W. Liu, A. E. Miroshnichenko, and Yu. S. Kivshar, "Optically-isotropic responses induced by discrete rotational symmetry of nanoparticle clusters," Nanoscale **5**, 6395 (2013).

## Articles in the special issue of Optics & Photonics News

***The December issues of Optics and Photonics News—the monthly magazine of The Optical Society of America—highlight the most exciting optics research that have emerged in the preceding* 12 *months all over the world.***

1. A. Minovich, A. E. Klein, W. Liu, A. Salandrino, N. Janunts, I.V. Shadrivov, A. E. Miroshnichenko, T. Pertsch, D. N. Neshev, D. N. Christodoulides, and Yu. S. Kivshar, "Airy plasmons: Bending light on a chip," Opt. Photon. News 12, 35 (2011).

2. A. E. Miroshnichenko, W. Liu, D. N. Neshev, Yu. S. Kivshar, A. I. Kuznetsov, Y. H. Fu, and B. Lukyanchuk, "Magnetic Light: Optical Magnetism of Dielectric Nanoparticles," Opt. Photon. News 12, 35 (2012).

## Selected presentations

1. W. Liu, A. A. Sukhorukov, A. E. Miroshnichenko, C. G. Poulton, Z. Y. Xu, D. N. Neshev, and Yu. S. Kivshar, "Complete spectral gap in coupled hollow metallic waveguides," The 19th Australian Institute of Physics Congress incorporating the 35th Australian Conference on Optical Fibre Technology 2010 (Melbourne Australia, December 2010).

2. W. Liu, D. N. Neshev, A. E. Miroshnichenko, I. V. Shadrivov, and Yu. S. Kivshar, "Polychromatic nanofocusing of surface plasmons," CLEO/Europe and EQEC 2011 Conference (Munich Germany, May 2011).

3. W. Liu, D. N. Neshev, A. E. Miroshnichenko, I. V. Shadrivov, and Yu. S. Kivshar, "Polychromatic nanofocusing of surface plasmons," Quantum Electronics and Laser Science Conference (Baltimore USA., May 2011).

4. W. Liu, D. N. Neshev, A. E. Miroshnichenko, I. V. Shadrivov, and Yu. S. Kivshar, "Polychromatic nanofocusing of surface plasmons," The Fifth International Conference on Nanophotonics 2011 (Shanghai China, May 2011).

5. W. Liu, D. N. Neshev, A. E. Miroshnichenko, I. V. Shadrivov, and Yu. S. Kivshar, "Plasmonic analogue of quantum paddle balls," 2011 IQEC/CLEO Pacific Rim Conference (Sydney, August 2011).

6. W. Liu, "Arching light on a chip", John Carver Seminar Series 2011 (Canberra Australia, October 2011, the most popular talk).

7. W. Liu, A. M. Miroshnichenko, D. N. Neshev, and Yu. S. Kivshar, "Polarization-independent Fano resonances in one dimensional arrays of core-shell nanospheres," Quantum Electronics and Laser Science Conference (San Jose USA., May 2012).

8. W. Liu, A. E. Miroshnichenko, D. N. Neshev, and Yu. S. Kivshar, "Polarization independent Fano resonances in one dimensional arrays of core-shell nanoparticles," The Sixth International Conference on Nanophotonics 2012 (Beijing China, May 2012).

9. W. Liu, "Nanoscale light manipulations through plasmonic potentials and magneto-electric resonances", ITI seminar, University of Southern Denmark (Odense Denmark, December 2012, invited by Prof. Sergey I. Bozhevolnyi).

# Acknowledgements

Since I started to write this thesis, I have been haunted, from time to time, by the strong feeling of being constrained by the rigid format requirement of the thesis, and thus of being deprived of my own right to express myself freely. As a student from mainland China, I am familiar with various theories of *Karl Marx* and naturally this feeling reminds me of his *Alienation Theory*. The major point of this theory is that the socially stratified society is like a big machine and as a mechanistic part of that machine, each person is alienated from his or her humanity, directed by the goals set by the big machine and deprived of the right to think him or herself. To some extent, as *Karl Marx* described, I feel I am alienated from my own thesis, and what is even worse, I am alienated from myself, working like a machine.

It is understandable that for scientific research there should be some rigid format requirement. Within the thesis however, I believe there should be a piece of land where we can express ourselves freely and write down whatever we like. The only such place I can find, throughout the whole thesis, is the section of acknowledgements. However when I have a look at the well accepted theses on the bookshelf of our department, and quite a few other ones approved by other universities all around the world, it is noticed that even this section is highly formatted, almost always starting with “Firstly I would like to thank ...”. There is nothing to blame in writing this section like this and actually in the first version I did so. But immediately after everything had been written down I realized that throughout the thesis which I should be able to claim my thesis, ironically I would not be able to find anything with an obvious stamp of my name. The even worse consequence of this kind of fixed format, I believe, is that it makes my sincere thanks extremely dry, and overshadows rather than illuminates the gratitude held at the bottom of my heart.

I would like to identify myself as an outgoing person and besides the supervisory panel, I have a lot of interactions with almost anyone else in our group and many researchers in other institutes. To abandon the well accepted format makes it much more difficult rather than simpler to write this section, as it is always easier to put the name of everyone after the expression “many thanks to”. Now the real challenge is how is it possible to enable all those people, to whom I am grateful, feel through the somehow cold sentences a warm and vibrating heart full of thanks?

The ancient Chinese philosopher *Laozi* told us from the first sentence of his book *Dao Te Ching* that “*The Way that can be described is not an everlasting*

*Way; the Name that can be named is not a perpetual name*". The Austrian-British philosopher *Ludwig Wittgenstein* expressed some similar belief by writing down "*My work consists of two parts: the one I have presented here plus all that I have not written. And it is precisely the second part that is the important one*". The core of what mentioned above, as far as I understand, is that the power of language is quite limited. I believe that there exists another version of Heisenberg's uncertainty principle: the more you want to reveal the bottom of your heart, the less words you should use. Maybe the best way to give my thanks to all the people who have been of great help, is not to write down long sentences full of their names, but to keep silent.

To make this section appear to be not too bizarre, I would like to write it down here a specific short story between me and *Dragomir Neshev*, who is the chair of the supervisory panel:

At the beginning of July 2012 I went to Imperial College London for a half year visit and approximately two months later I had to make a very urgent trip back to Canberra Australia due to some private personal crisis. After I explained briefly to *Dragomir* what the situation for me was, he said "*Wei, there are some things I can help you with while for others I can do nothing, but you can always count on me for full support!*"

At the same time *Andrey Miroshnichenko*, another member of the supervisory panel, also gave me a lot of consolation and encouragement. I am deeply pleased that throughout my PhD period I have been treated by the supervisory panel not as an employee or cheap labor, as is the case in many groups, but as a close friend. I will cherish all the time spent together with not only the people mentioned here, but also all of you, who have been of great help in terms of everything and to whom I am deeply grateful.

# Abstract

This thesis studies various effects based on the excitation of surfaces plasmons in various plasmonic nanostructures. We start the thesis with a general introduction of the field of plasmonics in Chapter 1. In this chapter we discuss both propagating surface plasmon polaritons (SPPs) and localized surface plasmons (LSPs), how to geometrize LSPs to make it related to SPPs through the Bohr condition, the features of subwavelength confinement and near-field enhancement, and wave guidance through coupled LSPs. Then after the discussion of the achievements and challenges in this field (Section 1.3), we will outline the basic structure of the thesis at the end of this chapter (Section 1.4).

In Chapter 2 we demonstrate a new mechanism to achieve complete spectral gap without periodicity along propagation direction based on the coupling of backward and forward modes supported by plasmonic nanostructures. We study the backward modes in single cylindrical plasmonic structures (Section 2.2) and focus on the two simplest cases: nanowires and nanocavities. Afterwards, we demonstrate how to achieve spectral gaps in coupled plasmonic nanocavities (Section 2.3). A polarization-dependent spectral gap is achieved firstly in two coupled nanocavities which support forward and backward modes respectively (Section 2.3.1). At the end we demonstrate a complete spectral gap, which is induced by the symmetry of a four-coupled-nanocavity system (Section 2.3.2).

In Chapter 3 we study beam shaping in plasmonic potentials. Based on the similarity between Schrödinger equation for matter waves and paraxial wave equation for photons, we introduce the concept of *plasmonic potentials* and demonstrate how to obtain different kinds of potentials for SPPs in various modulated metal-dielectric-metal (MDM) structures. We investigate firstly the parabolic potentials in quadratically modulated MDM and the beam manipulations in such potentials, including polychromatic nanofocusing in full parabolic potentials (Section 3.2.1), plasmonic analogue of quantum paddle balls in half parabolic potentials (Section 3.2.2), and adiabatic nanofocusing in tapered parabolic potentials (Section 3.2.3). In the following section (Section 3.3) we show the existence of linear plasmonic potentials in wedged MDM and efficient steering of the Airy beams in such potentials (Section 3.3.2) after a brief introduction on Airy beams in free space (Section 3.3.1).

In Chapter 4 we study scattering engineering by magneto-electric core-shell nanostructures with induced electric and magnetic resonances. The introduction part (Section 4.1) gives a brief overview on the scattering of solely electric dipole

(ED) or magnetic dipole (MD), and how the coexistence and interference of the ED and the MD can bring extra flexibility for scattering shaping. Afterwards, we discuss the scattering shaping by core-shell nanostructures through the interferences of electric and magnetic dipoles (Section 4.2), including two examples of broadband unidirectional scattering by core-shell nanospheres (Section 4.2.1) and efficient shaping of the scattering pattern for core-shell nanowires (Section 4.2.2). At the end of this chapter we demonstrate polarization-independent Fano resonances in arrays of core-shell nanospheres (Section 4.3.2).

At the end of this thesis in Chapter 5 we summarize the results and draw the conclusions. We also discuss the challenges and possible future developments of the field of plasmonics.

# Contents