Optical Metasurfaces Based on Nano-scale Dielectric Resonators

by

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Contents

Abstract

This thesis summarises my PhD research towards applying nano-scale dielectric resonators (DRs) to optical metasurfaces for achieving various functionalities, high efficiency, and reconfigurability. Additionally, the thesis also provides brief introductions to dielectric resonator antennas, plasmonics, and a short review of optical metasurfaces. The major contributions are briefly summarised as follows:

In Chapter 3, resonance properties of cylindrical nano-scale DRs on metallic substrates are analysed. At optical frequencies, subwavelength DRs with metallic substrates can support horizontal magnetic dipole resonance, which can be used for efficient coupling of surface plasmons. However, two types of resonance breakdown can occur in such DRs, and the cause for both types are analysed in detail. Of particular interest is the negatively-matched resonance breakdown, which occurs when real parts of the permittivities of a DR and its metallic substrate are negatively matched. The negatively-matched resonance breakdown is undesired for optical metasurfaces and can be avoided by inserting a low-permittivity dielectric spacer between the DR and its metallic substrate.

In Chapter 4, unidirectional launching of surface plasmons based on non-uniform arrays of DRs is proposed and investigated. By comparing the principles of DR-based anomalous reflection and surface plasmon unidirectional launching, it is concluded that the optimal launching can be achieved by avoiding the first-order diffraction. The optimal launching condition is verified with numerical simulations and linear array theory.

In Chapter 5, a narrowband plasmonic absorber made of a uniform array of nano-scale DRs on metallic substrates is experimentally demonstrated at visible frequencies. It relies on the surface plasmon standing waves coupled by the locally resonant nano-scale DRs for the high absorption. The simulation and measurement results are presented and analysed with coupled mode theory.

In Chapter 6, a mechanically tunable DR metasurface is experimentally demonstrated at visible frequencies. The tunable metasurface is realised by embedding a uniform array of DRs into an elastomeric encapsulation. The transmission responses of the metasurface can be tuned when the encapsulation is deformed with an external strain.

Measurement results confirm the predictions of simulations and shows a remarkable tuning range. A Lagrangian model is developed to rigorously analyse the simulation and measurement results. Such a design provides a preliminary concept usable in reconfigurable optical devices, and after further development can also be potentially commercialised for smart contact lenses.

In Chapter 7, metasurfaces made of metal-loaded DR arrays are proposed to realise the functionality of selective thermal emission. Two metasurface designs are presented. The first design is based on a uniform array of square metal-loaded DRs, which are made of doped silicon. Theoretical and numerical analysis demonstrate stable emission peaking at nearly 8 μm across a wide temperature range. The second further-developed thermal emission metasurface is designed to have broadband emission from 8 to 13 μm atmosphere window range and low emission at all other wavelengths. In this way, it can realise the function of radiative cooling.

These studies along with corresponding simulations or experimental validations demonstrate various functionalities can be realised with DR metasurfaces at optical frequencies. Furthermore, these nanostructure designs suggest a promising route for achieving the next generation highly-efficient integrated optical systems based on nano-scale DRs.

Originality Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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Date

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Thesis Conventions

The following conventions have been adopted in this Thesis:

Typesetting

This document was compiled using LaTeX2e. TeXnicCenter was used as text editor interfaced to LaTeX2e. Inkscape 0.92.1 was used to produce schematic diagrams and other drawings.

Spelling

Australian English spelling conventions have been used, as defined in the Macquarie English Dictionary (A. Delbridge (Ed.), Macquarie Library, North Ryde, NSW, Australia, 2001).

Referencing

The Harvard style is used for referencing and citation in this thesis.

System of Units

The units comply with the international system of units recommended in an Australian Standard: AS ISO 1000-1998 (Standards Australia Committee ME/71, Quantities, Units and Conversions 1998).

Publications

Journals

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List of Figures

List of Tables