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Thesis abstract

Advanced trapping of light in resonant dielectric metastructures for nonlinear optics

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In the past two decades new frontiers emerged in the rapidly expanding field of nanophotonics that have revolutionised the conventional approaches to the manipulation of electromagnetic radiation at the nanoscale. The remarkable progress in the engineering of efficient nanostructured devices for functional flat optics and nonlinear photonics was achieved by using resonant dielectric metastructures operating through the excitation of Mie resonances and their collective configurations. Further progress in the subwavelength localisation of light in Mie-resonant nanostructures and enhancement of their optical nonlinearities remained hampered by the leaky nature of optical modes. The last decade marked the series of intense studies of optical resonances with a giant quality factor, bound states in the continuum (BICs), aimed to resolve this issue. The unique electromagnetic properties of BICs were examined as a versatile tool to tailor the optical response of photonic nanostructures, yet their physical nature and the feasibility of realisation in the form of high-quality quasi-BIC resonances in planar and compact metadevices remain largely unexplored. Moreover, it remains unknown in many aspects how BICs can be utilised for the engineering of resonant nonlinear metasurfaces and nanoantennas for efficient frequency conversion and the observation of strong nonlinearities.

In this thesis, we are focused on the comprehensive analysis of fundamental physical properties of optical quasi-BICs in resonant dielectric metastructures and exploration of their practical feasibility for strong light confinement and nonlinear applications. We outline the general framework for design and optimisation of nanostructured devices supporting quasi-BICs in the visible and infrared range for the maximisation of the local fields and associated enhancement of optical nonlinearities. More specifically, we focus on planar metasurfaces with broken-symmetry meta-atoms, and individual subwavelength resonators with a compact footprint, for which we test the utility of the developed concepts. Ultimately, we target the challenge of engineering of nonlinear dielectric metastructures with outstanding nonlinear performances, which may lead to new breakthroughs in the realisation of efficient nonlinear frequency converters, low-threshold nanolasers, and compact quantum sources.

In Chapter 1, we overview the recent developments in the fields of nanophotonics, dielectric meta-optics, and optical BICs. We outline the motivation and structure of the thesis.

In Chapter 2, we propose the concept of light localisation in dielectric metasurfaces composed of meta-atoms with a broken in-plane inversion symmetry by using quasi-

BIC resonances. We show that the optical response of broken-symmetry metasurfaces can be tailored precisely by changing the asymmetry of the unit cell that induces the controllable change of the quasi-BIC quality factor. With this unified concept we explain the results of numerous earlier studies reporting on sharp Fano resonances, dark modes, metamaterial-induced electromagnetic transparency, trapped resonances in asymmetric plasmonic and dielectric metasurfaces observed in various spectral ranges, from the visible to radio frequencies. We further explore the importance of parasitic losses originating due to fabrication imperfections in metasurfaces on the value of the field enhancement. We outline the criteria for the maximisation of the local fields in realistic metasurfaces with imperfections by adjusting the structure geometry to satisfy the optimal coupling regime. Using these findings, we propose a universal framework for designing dielectric metasurfaces supporting sharp resonances with a specific operating wavelength and linewidth on demand.

Chapter 3 is focused on the analysis and experimental demonstration of nonlinear optical effects in broken-symmetry dielectric metasurfaces supporting quasi-BICs in the near-IR and mid-IR wavelength range. We generalise the optimal coupling criteria for the nonlinear regime for maximisation of harmonic generation efficiency for low pump intensities. We design Si metasurfaces for third- and high-harmonic generation and prove experimentally that in the optimal coupling regime the conversion efficiency is maximised. Using the developed optimal coupling model, we demonstrate the enhancement of optical nonlinearities of two-dimensional Van der Waals materials integrated with Si metasurfaces supporting quasi-BICs. For strong field excitation, we demonstrate that Si metasurfaces tuned to the quasi-BIC resonance generate high-harmonic signal with the harmonic order up to the eleventh. We demonstrate pronounced self-action effects for ultrashort sub-picosecond pulse excitation of quasi-BICs in the near- and mid-IR and explain them in the model of resonantly enhanced photoionisation of Si.

In Chapter 4, we propose the new mechanism of light trapping in isolated subwavelength dielectric resonators by the formation of quasi-BICs due to the destructive interference of several Mie modes in the far field. For a dielectric disk with a variable aspect ratio, we demonstrate that quasi-BICs are manifested as high-Q resonances formed at an avoided resonance crossing of Mie mode dispersion branches. We study the near- and far-field properties of quasi-BICs and show that the cancellation of radiative losses is related to the suppression of the dominant multipolar component of the field. We explore the manifestation of quasi-BICs in the scattering spectra and outline the connection between the maximisation of the mode Q factor and the peculiarities of the scattering features. We show that the quasi-BICs can realised in subwavelength dielectric resonators with refractive index more than 2 in various spectral ranges from the visible to microwaves. The findings are verified in proof-of-principle experiments in the near-IR and radiofrequency range.

In Chapter 5, we examine the efficiency of harmonic generation from individual dielectric nanoresonators supporting quasi-BICs and outline the criteria for the maximisation of conversion efficiency by optimising the mode structure, pump spatial

and temporal profile, and the environment design. We propose the theoretical model of second-harmonic generation for nanostructures resonant at the pump and harmonic frequency beyond the phase matching and derive an analytical closed-form expression for the emitted harmonic power. We verify the developed model experimentally and show a record-high measured conversion efficiency of the optimized nonlinear nanoantenna. Chapter 6 summarises the results and concludes the thesis.

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