Abstract

Photonic bound states in the continuum (BIC) in the metasurfaces are explored as a route to achieve extreme optical confinement. This thesis leverages mode coupling, structural symmetry, and design engineering to realize high-Q resonances in nanophotonic metasurface designs, supported by theoretical analysis and numerical simulations. The fundamental theory of BICs in dielectric resonators highlights the basics of symmetry-protected BICs (SPBICs) and accidental BICs (ABICs), their analysis through multipolar decomposition, and eigenmode analysis. The metasurface made from symmetric split-ring resonators (SRRs) supports multiple BIC resonances for both linear polarizations, which are converted to sharp quasi-BIC (QBIC) Fano resonances when out-of-plane asymmetry is introduced. When such metasurfaces are coated with two-dimensional material such as Graphene, the SRRs allow dynamic and controlled optical switching by applying suitable electrostatic gating. Numerical simulations reveal the modulation of coupling in specific BIC modes via the Graphene Fermi potential, yielding high-contrast transmission switching. Furthermore, mode coupling engineering in the SRRs shows hybridization of a bright mode with two quasi-BIC dark modes, which produces dual electromagnetically induced transparency (EIT)-like resonances with a giant group index, enabling slow-light propagation. The high group delay (~ 1 ns) and smaller delay-bandwidth products illustrate the potential of BIC-induced slow light for optical buffering applications. Another interesting design of a dielectric metasurface has been proposed and investigated, where hollow air channels are etched into a nanodisk. Such architecture supports both multiple symmetry-protected and accidental BICs (ultrahigh Q ~ 3.8×10^4) for linear polarized light. Under oblique incidence of circularly polarized light, the designed metasurface yields a maximal extrinsic chiroptical response, achieving near-perfect circular dichroism (CD ~ 99%). This represents a high optical chirality with ultra-high Q-factor, useful for enantio-sensitive detection and chiral sensing. In a related design, an absorptive metasurface is studied by introducing a thin MXene layer on a BIC-supporting metasurface. The quasi-BIC resonance, coupled with the loss of MXene, reaches near-critical coupling, yielding a sharp absorption peak that can enhance light–matter interaction for sensing and photodetection applications. Finally, the thesis work demonstrates the versatility of all-dielectric metasurfaces by integrating a metasurface onto an optical fiber tip. The fiber metatip device functions as a flat beam-steering metalens, efficiently deflecting and focusing light over a 60 nm telecom band. Two-dimensional beam steering with continuous angle tuning is achieved, pointing to advanced applications in Light Detection and Ranging (LiDAR) and optical interconnects, and can be combined with the physics of BIC in future scope.

In a nutshell, the thesis provides a comprehensive study of BICs in dielectric metasurfaces, from semi-analytical analysis and simulation to the design engineering for ultra-high Q-factor resonances. The key points include multi-resonant high-Q resonances, dynamic BIC amplitude modulation for optical switching, BIC-driven slow light and EIT analogues, BIC-induced giant chiroptical response, enhanced light absorption for sensing due to BIC, and integration of metasurface with optical fiber for beam steering. These contributions significantly broaden the scope of BIC physics in nanophotonics, opening new avenues for high-performance applications in linear, nonlinear, and quantum domains for advanced photonic systems.

Keywords: Bound States in the Continuum, EIT, MXene, Circular Dichroism, Cartesian Multipole Decomposition