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Nonlinear imaging through magnetic dipole quasi-BIC ultra-thin resonators

Lei Xu[a*], Khosro Zangeneh Kamali[b], Lujun Huang[a], Mohsen Rahmani[b], Alexander Smirnov[c], Rocio Camacho-Morales[b], Yixuan Ma[d], Guoquan Zhang[d], Matt Woolley[a], Dragomir N. Neshev[b], and Andrey E. Miroshnichenko[a]

[a]School of Engineering and Information Technology, University of New South Wales, Canberra, ACT 2600, Australia
[b]Nonlinear Physics Centre, Research School of Physics and Engineering, The Australian National University, Canberra, ACT 2601 Australia
[c]Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod 603950, Russia
[d]The MOE Key Laboratory of Weak-Light Nonlinear Photonics, School of Physics and TEDA Applied Physics Insitute, Nankai University, Tianjin 300457, China

ABSTRACT

We propose an ultra-thin silicon metasurface supporting a high-quality leaky mode which is formed by partially breaking a bound-state-in-the-continuum (BIC) generated by the collective magnetic dipole (MD) resonance excited in the subdiffractive periodic systems. Such a quasi-BIC MD state leads to a robust near-field enhancement and a significant boost of the nonlinear process, resulting in measured 500-fold enhancement of third-harmonic emission in comparison to the conventional silicon disk metasurface. We further experimentally demonstrate the highly-efficient nonlinear image tuning via polarisation and wavelength control, opening the way for various applications in high-performance nonlinear metadevices including tunable laser, tunable displays, nonlinear imaging.

Keywords: Mie resonance, dielectric nanoresonators, bound state in the continuum

1. INTRODUCTION

Nonlinear nanophotonics is a rapidly developing research field benefiting applications such as chip-based light sources, nanolasers, optoelectronic devices, imaging, etc. High-index dielectric nanostructures have emerged as a promising tool to boost the nonlinear processes through efficient nanoscale light enhancement and manipulation based on the control over both optically-induced electric and magnetic Mie-type resonances.[1,2] MD resonance supported by dielectric nanostructures has been widely used to enhance the nonlinear frequency conversion due to the associated strong near-field enhancement and large mode volume. BICs, being originally predicted by von Neumann and Wigner in 1929,[3] have been extensively studied in different fields of wave physics including acoustics, microwaves and nanophotonics.[4] An ideal BIC manifests as itself via diverging Q-factor with complete suppression of the radiation of the state to the free space. By breaking the symmetry of the system which supports a symmetry-protected BIC, one can transform an ideal BIC to a quasi-BIC with finite Q-factor, which allows an energy exchange with the external modes and manifests itself as a sharp Fano resonance in the optical response spectrum.[5,6] Through the mechanism of BIC, one can control and tune the radiation damping rate and thus the width of the resonance. BIC-inspired mechanism provides a useful tool to engineer and tailor the line width and Q-factor flexibly and allows directly excite the quasi-BICs by free propagation plane waves, making it a novel platform for nanophotonics applications.

Here, by taking the advantages of both Mie resonators and BIC states, we design ultra-thin resonant silicon disk metasurface supporting high-quality quasi-BIC MD state leading to a strong near-field enhancement inside the nanoresonators. we further demonstrate highly-efficient dynamical nonlinear image tuning through designed quasi-BIC MD resonators.

E-mail: lei.xu@unsw.edu.au

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2. RESULTS AND DISCUSSION

Our designed metasurface is composed of silicon nanodisks supporting out-of-plane MD resonance which is a symmetry-protected BIC state.[1] The thickness and period of our metasurface are 53 nm and 840 nm, respectively. We introduce an off-centred hole to open a radiation channel and transform the ideal-BIC MD state into quasi-BIC MD state which can be excited directly under normal pump irradiation. The silicon metasurface is optimised to support a quasi-BIC MD state at a near-infrared wavelength around 1345 nm with spectral full-width-at-half-maximum (FWHM) around 12 nm, which matches the spectral width of our used laser to expect maximum coupling and nonlinear signal generation. We observed a pronounced asymmetric Fano line shape with a narrow

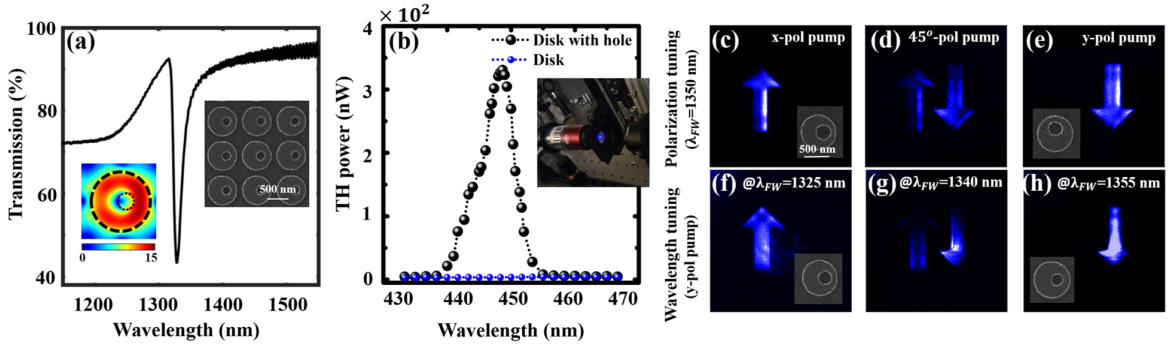

Figure 1. (a) Experimentally measured linear transmission spectrum. The inset shows the calculated electric near-field distribution in the x-y plane at the resonance (left) and the SEM image of the fabricated sample (right), respectively. (b) Experimentally measured THG spectra of the sample. The inset shows a photographic image of the TH emission from the sample. Nonlinear image tuning in the designed metasurfaces is demonstrated by polarisation (c-e) and wavelength tuning (f-h), respectively.

dip around $\lambda = 1345$ nm in the linear spectrum (Figure 1(a)), indicating the excitation of the quasi-BIC-MD state. Such state further leads to a significant 500-fold TH enhancement as compared with the silicon disk metasurface, as shown in Fig. 1(b). This leads to an estimated total TH conversion efficiency in the order of 10^{-5} under peak pump intensity only $I_0 = 1.0$ GW/cm^2. Such high-quality quasi-BIC MD states provide a powerful platform to efficiently control the nonlinear emission spatially. We further encode two images of arrow $\uparrow$ and $\downarrow$ into the metasurface, i.e., tuning the geometry of the nanodisks and holes to support resonances at different wavelength position or under different pump excitation polarisation conditions. The width and length of the arrow is about 20nm and 90nm, respectively. The quasi-BIC MD states supported by these two images can be seperately excited by varying the pump from x-polarization to y-polarization or by tuning the pump wavelength. Thus, one can read out the encoded image through the generated nonlinear signal (Fig. 1c-h). Our results offer unique opportunities for constructing nonlinear optical effects to achieve novel nonlinear photonic metadevices with multifunctionalities, such as tuneable displays, tuneable nanolasing, etc.

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