Bound states in the continuum-induced enhancement of evanescent field confinement

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Abstract. Here, the enhancement of electromagnetic field confinement in an all-dielectric metasurface is demonstrated. The enhanced confinement is achieved when the polarization singularity, corresponding to accidental bound states in the continuum, moves to the domain of evanescent fields (under the light line). Such a hybridization of the bound states and evanescent waves results in the 70-fold increase of the electric field enhancement on the top of the metasurface and boosting of the electric field localization.

1. Introduction
Metasurfaces and meta-gratings are one of the cornerstones of the modern photonics due to the high versatility of their physical and, specifically, optical properties. Since the very famous work by John Pendry in 2000 [1], the photonics of metasurfaces has got boost, and currently metasurfaces are utilized for signal modulation [2], information processing [3], color printing [4], surface-enhanced Raman scattering [5] and sensing [6]. Sensing by metasurfaces is of particular interest because of the capability of these nanostructures to confine and enhance optical fields as well as their high figure of merit [7]. Biosensing and single-molecule sensors based on metallic (plasmonic) metasurfaces have been demonstrated in several works [8], and the ability of surface plasmons to confine light makes them perspective for the practical applications. However, due to the high dissipative losses in metals in the optical range, this technology has not yet reached the industry [9].

Recently, new approaches which utilize high-Q modes in all-dielectric metasurfaces have been established [10]. The origin of such the high-Q modes has been discovered as bound states in the continuum (BIC) [11]. In theory, the Q-factors of BICs can be infinitely large, and the electric field enhancement can be respectively high [11]. Such a unique property of BIC originates from the physical symmetries of metasurfaces (parity and time) and results in cancelation of radiation in the far-field at the certain point of band diagram of the metasurface. At the same time, macroscopic dielectric structures in the waveguide regime, e.g. planar waveguides and optical fibers, are widely used in optical sensors.

Our work aims to combine unique properties of metasurface BICs and waveguides giving rise to the electromagnetic field confinement in the optical mode of a metasurface. By varying the geometrical parameters of the metasurface we achieve BIC transition under the light cone and boosting the field confinement of the waveguide mode. This approach is based on cancelation of certain Fourier term in electromagnetic field expansion of the metasurface mode.

2. Results and discussion
First, we consider a GaP meta-grating based on rectangular meta-atoms (see Fig. 1(a)) located at a quartz substrate. Notefully, such the mirror-symmetry shape of meta-atoms presumes both Π- and off-Π BICs.
We adjust the metasurface geometrical parameters to operate in near-IR spectral range. The refractive index of the metasurface is 3.143, the refractive index of the substrate is 1.452. The height (H) of the metasurface is set to 370 nm at the first calculation step. The metasurface is surrounded by air.

Figure 1. (a) A sketch of the metasurface operating in hybrid BIC-waveguide regime. (b) Band structure of the metasurface. H-parameter is tuned to tune the BIC under the light line of the air (yellow area).

Next, we calculate band structure of the metasurface using COMSOL Multiphysics (Fig. 1(b)). The green area corresponds to the radiation continuum above the light line of air. Yellow area is below the light line of air and above the quartz light line. Blue area designates the zone below the light line of quartz. The optical mode under consideration is distinguished by red. Initially, we observe the BIC in the green area simultaneously tracking the electric field distribution of the mode in the yellow area (Fig. 2(a)). It is clearly seen that, while the BIC is located in the radiation continuum of both air and quartz, the mode in the semi-waveguide regime gives 5-fold enhancement at the top of the metasurface and possesses long tails outside the rectangles.

Figure 2. Electric field distributions of the optical mode of the metasurface in semi-waveguide regime at (a) H = 370 nm and (b) H = 400 nm.

Finally, we vary the height of the metasurface (H) in order to tune the BIC location in the band diagram. After several optimization cycles, we have found that the increase of H from 370 nm to 400 nm moves BIC under the light line of the air (see Fig. 1(b), blue arrow). Such a band diagram transition
immediately reflects in the electric field distribution of the mode in semi-waveguide regime (Fig. 2(b)). It can be observed that the electric field enhancement in the hybrid BIC-waveguide regime is increased by 70 times, and the mode tails in the free space are shortened comparing with the Fig. 2(a). Other words, the electric field confinement of the waveguide mode gets boost after transition of BIC below the light line in the waveguiding area of the band diagram.

The presented electromagnetic confinement enhancement owes to the magnification and suppression of certain Fourier terms in the Fourier expansion of the electric field of the mode. The radiation cancelation in BIC is due to the suppression of zero Fourier term while the same term in the waveguide or semi-waveguide regime is partially responsible for the field confinement. Thus, after BIC transition below the light line, the waveguide mode obtains this expansion feature of BIC, and the zero terms gets canceled. In this case, the mode confinement is mostly determined by the first Fourier term which is characterized by the fast exponential decay of the field outside the metasurface.

3. Conclusion
To conclude, we have demonstrated the enhancement of electromagnetic field confinement in the all-dielectric metasurface. The confinement growth owes to the transition of BIC below the light line in the waveguiding area. We have shown that this transition results in 70-fold increase of the electric field and shortening of the mode tails.

References
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