

Full length article

All-silicon active bound states in the continuum terahertz metamaterials

Yuwei Huang^a, Kelson Kaj^b, Zhiwei Yang^a, Erick Alvarado^c, Wenkuan Man^a, Yuan Zhang^b, Varun Ramaprasad^b, Richard D. Averitt^{b,c}, Xin Zhang^{a,*}

^a Department of Mechanical Engineering and Division of Materials Science and Engineering, Boston University, Boston, 02215, MA, USA

^b Department of Physics, University of California San Diego, La Jolla, 92093, CA, USA

^c Program in Materials Science and Engineering, University of California San Diego, La Jolla, 92093, CA, USA

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ABSTRACT

Bound states in the continuum (BIC) are a non-radiative state embedded in a continuous spectrum of radiating waves. BICs have emerged as a promising platform for opto-electronic phenomena that are dependent on high quality factors. However, the quality factor of metallic metamaterial-based BICs is limited due to ohmic loss, even at terahertz frequencies. As an alternative, we investigate active all-silicon BIC terahertz metamaterials. Quasi-BIC states can be realized either through structural symmetry breaking or by changing the incident angle of the terahertz waves, as verified with coupled mode theory (CMT). Samples fabricated using micromachining techniques were characterized using terahertz time domain spectroscopy revealing good agreement with simulations. Moreover, we investigated optical tuning of the quasi-BIC response using low-fluence ($<25 \mu\text{J}/\text{cm}^2$) excitation with 1.5 eV pulses. The dynamic response is consistent with full-wave electromagnetic simulations and indicate that all-silicon metamaterials are a viable active BIC platform with potential applications including terahertz sensing and terahertz nonlinear lightwave phenomena.

1. Introduction

High-quality factor (high-Q) resonators are in demand in photonic systems across the electromagnetic spectrum as enablers for a raft of potential applications. Narrow spectral widths enhance bio-/chemical sensing and filtering [1–8], while near-field localization facilitates strong light-matter interactions, which is important for lasing [9–15] and harmonic generation [16–21]. Recently, photonic bound states in the continuum (BIC), where a non-radiative state resides in a continuous spectrum of radiating waves, have emerged as a promising platform for achieving extremely high-Q resonances [22–27]. Ideal BIC structures remain experimentally elusive given their infinite quality factor (Q-factor) and impermeability to external influences. Nevertheless, by strategically introducing structural perturbations into the metasurface housing a BIC, a fascinating phenomenon emerges: quasi-BICs. Quasi-BICs reveal themselves in the far-field response as finite high-Q resonant modes, and are experimentally accessible [28]. The BIC concept was originally proposed in the context of quantum mechanics, but has since been extended to all wave-based phenomena [29–31].

Two main physical mechanisms are generally used to realize BICs. One approach is symmetry-protected BICs where a mode is trapped under given symmetry constraints [32,33]. It exists as a bound eigenmode embedded above the photonic light cone and is not detectable

in the far field [29]. Through external perturbation, the BIC can be transformed into a leaky Fano resonance with a finite Q-factor. The other approach to realize a BIC is parameter tuning (or “accidental”), referring to a structure with tailored structural parameters for cancellation of radiative channels [34]. Both BIC types are of importance for myriad light-matter applications [35,36]. Besides these two mechanisms, new design schemes have been found for the transform between BICs and quasi-BICs. This includes up-down mirror symmetry [37], twisted metalattices [38], and Brillouin zone folding [39,40].

Metamaterials (MM) and metasurfaces (MS) are widely employed in photonic structures to investigate BIC phenomena since the vast array of configurations provides considerable engineering flexibility. Previously, many instances of BIC and quasi-BIC MM/MS were realized using split ring resonator (SRR)-based structures [32,41–43]. However, ohmic loss is significant in metals, placing a limit on the magnitude of the Q-factor. Dielectric MM and MS complement traditional metallic-based MM and MS, allowing for higher Q-factors coupled with additional advantages such as increased temperature stability and better compatibility with CMOS processing [44–49]. Several dielectric MM and MS high-Q BIC structures have been demonstrated at terahertz frequencies [24,50,51], but the inclusion of a low-index substrate for supporting the MM and MS requires additional fabrication processing (e.g. bonding).

* Corresponding author.

E-mail addresses: raveritt@ucsd.edu (R.D. Averitt), xinz@bu.edu (X. Zhang).

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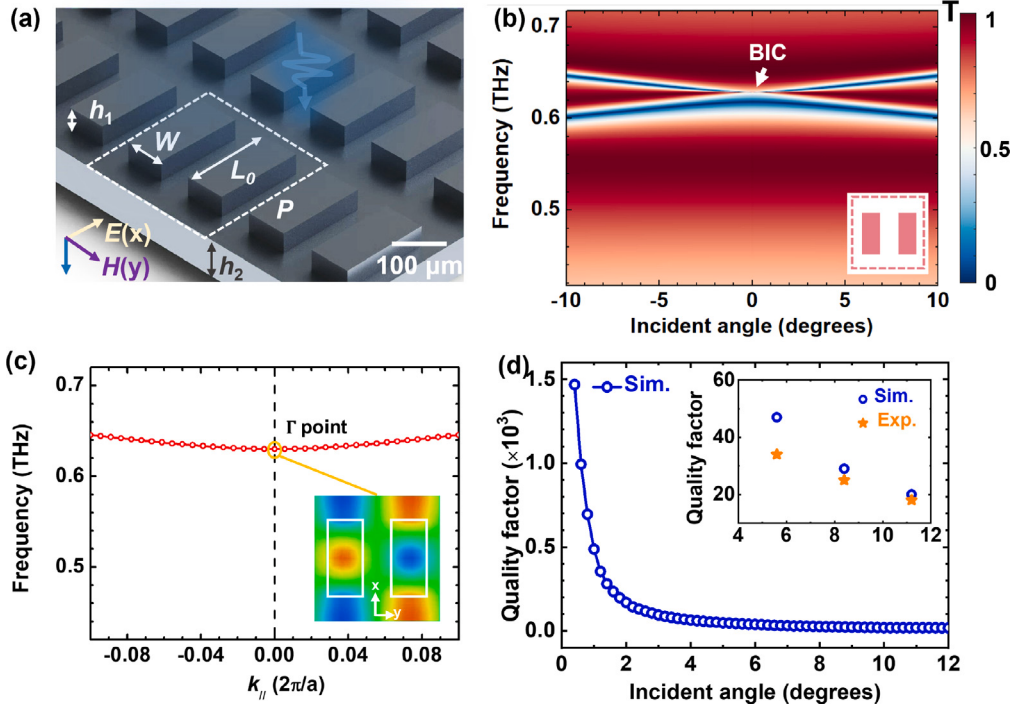


Fig. 1. (a) Design of the all-silicon active bound states in the continuum (BIC) terahertz metamaterial with periodicity $P = 250 \mu\text{m}$, $h_1 = 35 \mu\text{m}$, $h_2 = 65 \mu\text{m}$, $W = 70 \mu\text{m}$, $L_0 = 150 \mu\text{m}$. (b) Simulated angular dependence on the transmission spectra. (c) Dispersion diagram (ω vs. $k_{\parallel}$). (d) Dependence of Q factors from simulations on the incident angles. The inset shows the comparison of the Q factors from simulations and experimental results in Fig. 2.

As mentioned above, metallic BIC metamaterials exhibit significantly smaller Q-factors compared to dielectric BIC metamaterials, primarily due to ohmic loss [32]. In contrast, silicon metamaterials can, based on theoretical estimates, exhibit a Q factor on the order of 10^4 , comparable to other reported dielectric metamaterials [52]. Moreover, in the case of silicon, the ease of fabrication, integration, and compatibility with diverse technological platforms is important. In conjunction with potentially higher Q-factors, these advantages suggest that all-silicon metamaterials are promising for applications requiring superior performance and efficiency.

In this work, we propose and experimentally demonstrate an easily fabricated all-silicon symmetry-protected BIC MM with an overall thickness of $100 \mu\text{m}$ operating at terahertz frequencies. We also investigate the optical tunability of the THz transmission amplitude upon excitation by low-fluence ~ 100 fs optical pulses for dynamic control of the quasi-BIC resonance.

2. All-silicon BIC metamaterial

The design of our all-silicon BIC MM is shown in Fig. 1a. It consists of two symmetric rectangles, etched from a solid film of silicon (fabrication detail provided below and in the Experimental Section) to realize resonances in a single silicon sample without the need to adhere anything to a different index substrate. The overall periodicity of the MM is $P = 250 \mu\text{m}$ with a top layer $h_1 = 35 \mu\text{m}$ and a bottom layer $h_2 = 65 \mu\text{m}$. For the top layer, the length of the two bars $L_0 = 150 \mu\text{m}$ and the width $W = 70 \mu\text{m}$ while the distance between two bars is $55 \mu\text{m}$. The transmission terahertz response was simulated utilizing commercial full-wave simulations (CST Microwave Studio). Details of the simulations can be found in the Experimental Section.

The quasi-BIC mode of the all-Si structure in Fig. 1 can be tuned by changing the component of the in-plane wavevector $k_{\parallel}$, accomplished by varying the angle of incidence of the THz beam [53]. The dependence of the transmission amplitude profile for incident angles between 0 to 10 degrees is shown in Fig. 1b, while the dispersion diagram ω vs. $k_{\parallel}$ is plotted in Fig. 1c as determined from an eigenmode analysis.

The band diagram only shows the band corresponding to the BIC that we investigated between 0.6 to 0.7 THz. Both Fig. 1b and c show that the BIC resonance is at ~ 0.63 THz. The y-component of magnetic field distribution H_y from the eigenmode analysis is included in the inset of Fig. 1c. Fig. 1d shows the Q-factor dependence on incident angle, determined using the simulations from Fig. 1b. The exponential increase of the Q-factor as the incident angle approaches zero degrees is consistent with a BIC mode [53–56].

We fabricated the BIC MM sample to validate and compare with the simulated electromagnetic response. This was accomplished using bulk micromachining with fabrication comprised of photolithography, reactive ion etching (RIE), and deep reactive ion etching (DRIE) on a silicon-on-insulator (SOI) wafer [44]. The transmission response was measured using terahertz time domain spectroscopy (THz-TDS). Details of the fabrication and THz characterization can be found in the Experimental Section.

Fig. 2 compares the experimental and simulated transmission spectra of the BIC MM for several different angles of incidence. From the simulations in Fig. 2a–d, it is clear that increasing the angle of incidence from zero degrees leads to the appearance of a transmission peak, corresponding to the quasi-BIC state. As the figures show, the larger the incident angle, the wider the transmission peak (lower Q-factor) with a relatively non-dispersive resonance frequency near ~ 0.63 THz. The experiments in Fig. 2e–h nominally agree with the simulations, showing the same overall trend with angle and exhibiting similar frequencies for the transmission maxima and minima. The experimental transmission peak amplitudes are lower than simulations and can be attributed to the spectral resolution of the THz spectrometer (limited by etalon reflections) and transmission losses from the silicon that are not included in the idealized simulations. The Q-factors are determined through fitting with a Fano resonance lineshape:

$$T = |a_1 + ia_2 + \frac{b}{\omega - \omega_0 + i\gamma}|^2 \quad (1)$$

$$Q = \frac{\omega_0}{2\gamma} \quad (2)$$

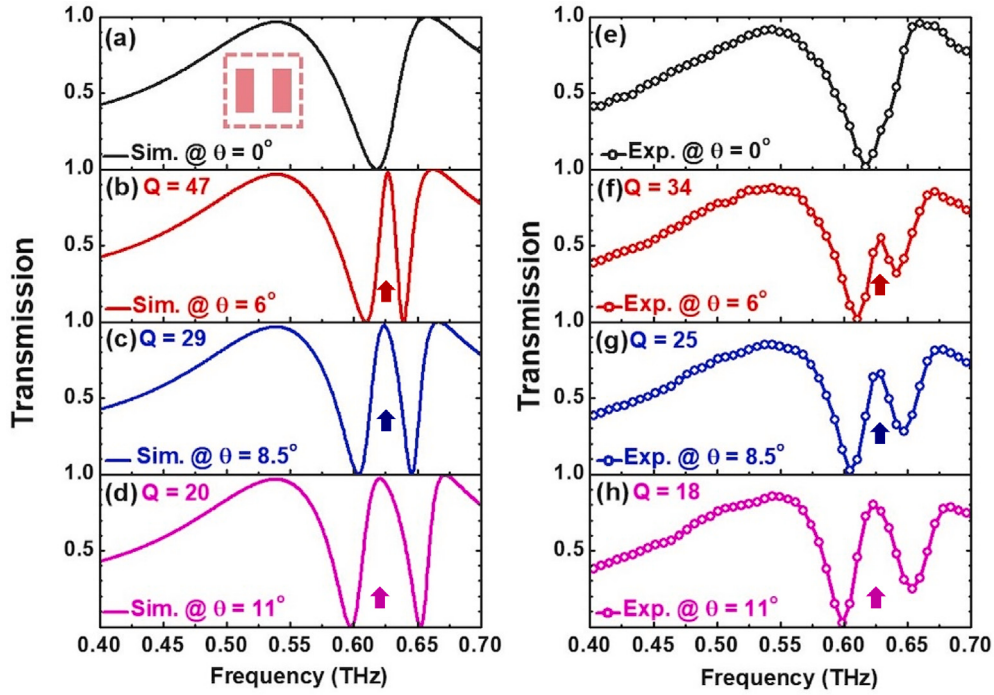


Fig. 2. (a) Comparison of transmission spectra for the all-silicon BIC metamaterial sample between simulations and experiments under different incident angles. (a)–(d) are simulations and (e)–(h) are experimental results.

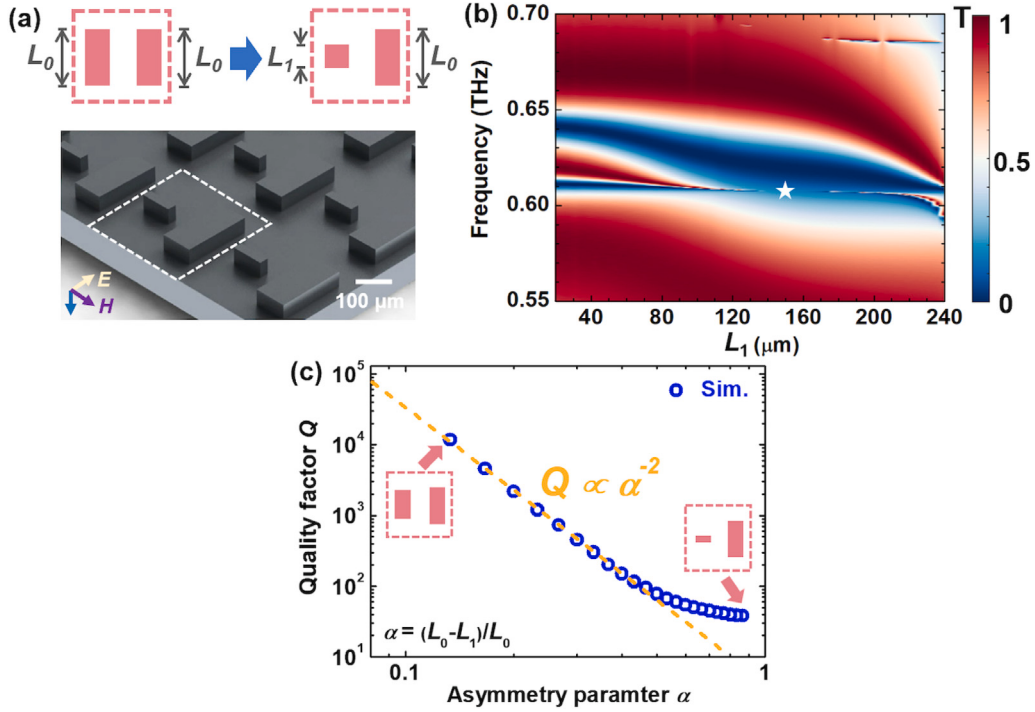


Fig. 3. (a) Design of the symmetry-protected BIC metamaterial with the left bar length L_0 is not equal to the right bar length L_1 . (b) Transmission profile of the metamaterial at $L_0 = 150 \mu\text{m}$ with varying dimension L_1 from $20 \mu\text{m}$ to $240 \mu\text{m}$. (c) Dependence of the calculated Q factors from simulations on the asymmetry parameter α . The description of α is indicated in the inset.

where T is the transmission, ω_0 is the resonance frequency, γ is the damping rate, a_1 , a_2 and b are constants and Q is the quality factor. Higher Q -factors can be achieved with smaller incident angles, i.e. below 5 degrees (Fig. 1d), but we only chose the incident angles larger than 5 degrees due to our limited measurement resolution.

3. Quasi-BIC through structural symmetry breaking

3.1. Design, simulations, and experiments

We now consider all-silicon high- Q quasi-BIC states with structural symmetry breaking. The design of the asymmetric structure is shown

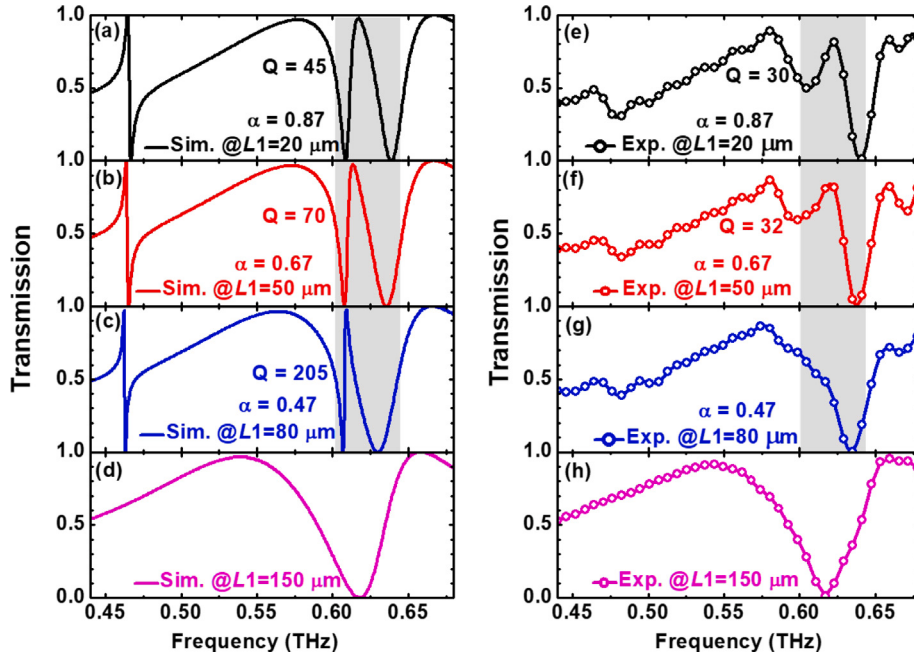


Fig. 4. Comparison between simulated and experimental transmission spectra of symmetry-broken all-silicon BIC metamaterial samples for varying values of $\alpha = 0.87, 0.67, 0.47$ and 0, respectively. (a)–(d) are simulations and (e)–(h) are experimental results.

in Fig. 3a where the length of one bar in the unit cell is decreased. As shown in the upper portion of Fig. 3a, L_0 is held constant at (150 μm) while the length of the left bar L_1 is changed. All other structural parameters including the thickness of both layers (h_1 and h_2) and periodicity (P) are kept constant. Fig. 3b plots the simulated transmission amplitude, varying L_1 from 20 μm to 240 μm . The simulations show that Fano resonances with finite Q-factors occur in the vicinity of the BIC state upon changing L_1 . The Q-factor is determined from the simulations as summarized in Fig. 3c as a function of the asymmetry parameter $\alpha = (L_0 - L_1)/L_0$. The asymmetry parameter describes the deviation of the structure from the symmetric BIC configuration. The relationship between the calculated Q-factor and α agrees with published work, proving the origin of the symmetry-protected BIC [52, 57].

In addition to the symmetric sample ($\alpha = 0$), samples were fabricated with $L_1 = 20 \mu\text{m}$ ($\alpha = 0.87$), $50 \mu\text{m}$ ($\alpha = 0.67$), and $80 \mu\text{m}$ ($\alpha = 0.47$). The transmission spectra were measured to compare with the simulations shown in Fig. 4a–d (the calculated Q-factors are included in the insets). The simulations reveal that there are two quasi-BIC resonances. The lower extreme Fano resonance occurs at ~ 0.45 THz, with the higher frequency resonance lying between 0.60–0.65 THz (similar to the resonance for the symmetric quasi-BIC discussed above). In what follows, we do not focus on the 0.45 THz resonance response as the Q-factor is too high to adequately resolve using our THz-TDS experiment (though, as shown in Fig. 4e–h, hints of this resonance and Fano-like lineshape are evident). Turning to the higher frequency resonance, Fig. 4e–h show the experimental results with the same designs as in the simulations. Similar to the transmission spectra of the symmetric BIC for different incident angles, transmission peaks appear at similar frequencies for the asymmetric configurations ($\alpha \neq 0$). The THz-TDS measurement results clearly identify the position of the quasi-BIC transmission peaks for $L_1 = 20 \mu\text{m}$ ($\alpha = 0.87$, Fig. 4e) and $L_1 = 50 \mu\text{m}$ ($\alpha = 0.67$, Fig. 4f). However, the transmission peak for $L_1 = 80 \mu\text{m}$ ($\alpha = 0.47$, Fig. 4g) is not observed as the Q-factor is too high to be resolved with our THz-TDS system. Nevertheless, the transition from the BIC state to quasi-BIC state with decreased Q-factors is evident for decreasing L_1 .

3.2. Temporal coupled mode theory analysis

To better understand the structural symmetry broken quasi-BIC response, the field distributions are analyzed at critical frequencies spanning the 0.60–0.65 THz spectral range. To be specific, there are three critical frequencies in the quasi-BIC transmission spectrum. This includes two transmission minima and one maximum, in contrast to the one minimum in the pure BIC state ($\alpha = 0$). The structure with $L_1 = 120 \mu\text{m}$ ($\alpha = 0.2$) is used as an example. As shown in Fig. 5c, two transmission dips occur at 0.607 THz and 0.625 THz while the peak appears at 0.608 THz. The y-component of the magnetic field (H_y) at these three frequencies is shown in Fig. 5e–g. We also plotted H_y at the transmission dip (0.62 THz) in the BIC state when $L_1 = 150 \mu\text{m}$ (Fig. 5d), as shown in Fig. 5h for comparison. Fig. 5g and h show similar H_y distributions, suggesting the same mode origin (i.e., transverse magnetic (TM) mode). Fig. 5e and f share some degree of similarity, though the magnetic field inside the two bars is in phase in Fig. 5e while being out of phase in Fig. 5f. We note that Fig. 5f is very close to the H_y distribution of the eigenmode in the inset of Fig. 1c although the field inside the left bar in Fig. 5f is not as strong as in Fig. 1c. Clearly, these two plots share the same mode origin. Therefore, we conclude that the quasi-BIC state with the transmission peak is attributed to the coupling between the degraded eigenmode of the intrinsic TM mode of the symmetric structure.

The electromagnetic response in Fig. 4 is similar to our previous research on metallic BICs [41]. That work utilized generalized temporal coupled mode theory (CMT) with the response arising from coupling between two modes (an LC mode and a dipole mode). Similarly, for all-Si quasi-BIC devices there is coupling between two modes. The general CMT model for a multi-resonant system with two coupled modes is given as [41]:

$$\frac{d}{dt} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = (j\Omega - \Gamma) \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} + K \begin{bmatrix} s_{1+} \\ s_{2+} \end{bmatrix} \quad (3)$$

$$\Omega = \begin{bmatrix} \omega_{01} & k \\ k & \omega_{02} \end{bmatrix}, \Gamma = \begin{bmatrix} \gamma_1 & \gamma_{12} \\ \gamma_{12} & \gamma_2 \end{bmatrix}, K = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} \quad (4)$$

where $[a_1, a_2]^T$ are the resonance amplitudes while ω_{01} and ω_{02} are the resonant frequencies of the two modes supported by the system.

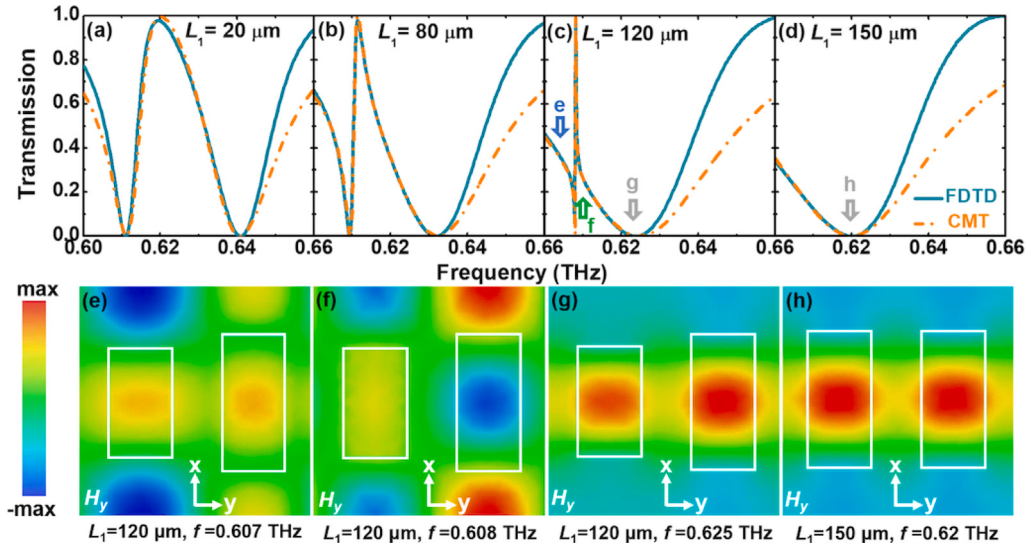


Fig. 5. Comparison of transmission spectra for the symmetry-protected BIC metamaterial samples between simulations and calculation from CMT with (a) $L_1 = 20 \mu\text{m}$, (b) $L_1 = 80 \mu\text{m}$, (c) $L_1 = 120 \mu\text{m}$, and (d) $L_1 = 150 \mu\text{m}$. (e)–(g) show the y-component magnetic field distributions (H_y) at 3 critical frequencies when $L_1 = 120 \mu\text{m}$ and (h) is the H_y at transmission dip (minimum) when $L_1 = 150 \mu\text{m}$.

γ_1 and γ_2 are the damping rates of the two modes, respectively. In this case, no ohmic loss is included since we utilize high-resistivity silicon. k represents the direct coupling rate between the two modes and $\gamma_{12} = \gamma_{21} = \sqrt{\gamma_1 \gamma_2}$ is the coupling coefficient generated by the damping due to the symmetry of the system. k_{ij} ($i, j \in \{1, 2\}$) is the coupling coefficient between the mode i and the mode j while s_{1+} (s_{2+}) is the input wave amplitude from the port 1(2). The outgoing waves from the excited resonance modes follow [41]:

$$\begin{bmatrix} s_{1-} \\ s_{2-} \end{bmatrix} = C \begin{bmatrix} s_{1+} \\ s_{2+} \end{bmatrix} + D \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \quad (5)$$

$$C = \begin{bmatrix} r_d & t_d \\ t_d & r_d \end{bmatrix}, D = \begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix} \quad (6)$$

where s_{1-} (s_{2-}) is the outgoing wave amplitude at port 1(2). r_d and t_d are the direct reflection and transmission coefficient between the ports without resonances. d_{ij} ($i, j \in \{1, 2\}$) is the coupling coefficient between the port j and the mode i . Based on energy conservation, $k_{11} = k_{12} = |d_{11}| = |d_{12}| = \sqrt{\gamma_1}$ and $k_{21} = k_{22} = |d_{21}| = |d_{22}| = \sqrt{\gamma_2}$. After solving the Eqs. (1) and (2), we obtain:

$$a_1(\omega) = \frac{jk - \gamma_{12}}{j(\omega - \omega_{01}) + \gamma_1} a_2(\omega) + \frac{\gamma_1}{j(\omega - \omega_{01}) + \gamma_1} s_{1+}(\omega) \quad (7)$$

$$a_2(\omega) = \frac{(jk - \gamma_{12})\sqrt{\gamma_1} + [j(\omega - \omega_{01}) + \gamma_1]\sqrt{\gamma_2}}{[j(\omega - \omega_{02}) + \gamma_2][j(\omega - \omega_{01}) + \gamma_1] - (jk - \gamma_{12})^2} s_{1+}(\omega) \quad (8)$$

Based on Eqs. (3) and (4), the outgoing wave amplitude at port 2 is:

$$s_{2-}(\omega) = t_d s_{1+}(\omega) - (\sqrt{\gamma_1} a_1(\omega) + \sqrt{\gamma_2} a_2(\omega)) \quad (9)$$

Thus, the transmission coefficient can be calculated by $t_{21}(\omega) = s_{2-}(\omega)/s_{1+}(\omega)$. In an ohmic lossless system, the decay rate is fully determined by the radiative loss, i.e. $\gamma_1 = \gamma_{r1}$, $\gamma_2 = \gamma_{r2}$. In contrast, in metallic metamaterials, the loss comes from radiative and ohmic contributions, i.e. $\gamma_{01} \neq 0$ and $\gamma_{02} \neq 0$. Quality factors are usually expressed in terms of the decay rates:

$$Q_1 = \omega_{01}/(2\gamma_1) \quad (10)$$

$$Q_2 = \omega_{02}/(2\gamma_2) \quad (11)$$

We used the above CMT equations to fit the simulations with $L_1 = 20 \mu\text{m}$ ($\alpha = 0.87$, Fig. 5a), $L_1 = 80 \mu\text{m}$ ($\alpha = 0.67$, Fig. 5b), $L_1 = 120 \mu\text{m}$ ($\alpha = 0.47$, Fig. 5c) and $L_1 = 150 \mu\text{m}$ (Fig. 5d), shown as the orange dashed lines in Fig. 5a–d. The values of the parameters

Table 1

Fitting parameters for the BIC MMs based on CMT.

L_1 (μm)	ω_{01} ($\times 2\pi$ THz)	Q_1	ω_{02} ($\times 2\pi$ THz)	Q_2	k ($\times 2\pi$ THz)
20	0.618	23	0.633	100	0.013
80	0.618	23	0.624	45	0.011
120	0.618	23	0.6148	23	0.0082
150	0.618	23	/	/	/

are listed in Table 1. Both ω_{01} and Q_1 remain unchanged while ω_{02} and Q_2 decrease with increased L_1 . Mode 1 can be understood as the intrinsic TM mode, disregarding the symmetry of the structure in our two-layer all-Si MM. Mode 2 is the eigenmode with no radiation when the structure is symmetric. When the symmetry of the structure is broken, the eigenmode couples with the intrinsic TM mode, resulting in Fano resonances with finite Q-factors, shown as the transmission peaks in Fig. 5a–c.

3.3. Dynamic optical response of all-silicon quasi-BIC

In addition to investigating the static electromagnetic response of the quasi-BIC states, optical-pump THz-probe spectroscopy (OPTP) was used to characterize the dynamic response when carriers are photoexcited in the silicon. The pump beam consisted of ~ 40 fs 800 nm near-infrared (NIR) pulses. Both the pump beam and THz probe beam were at near-normal incidence. Fig. 6a shows the transmission spectra of the quasi-BIC metamaterial in Fig. 4e ($L_1 = 20 \mu\text{m}$) for pump fluences ranging from 0.4 to 26 $\mu\text{J}/\text{cm}^2$. As the pump fluence increases, the transmission peak amplitude decreases with a relatively stable peak frequency (0.62 THz). Similar to the THz-TDS experimental results in Fig. 4, we are unable to capture the full transmission amplitude of the dip at 0.605 THz due to the limited experimental resolution.

In order to understand the decreased peak amplitude with increasing fluence (i.e., increased excitation density), simulations were performed. A penetration depth of 10 μm (for 800 nm excitation) was used for the simulations using carrier densities consistent with previous work [41,44,53]. Fig. 6b shows the simulation results for various carrier densities. Relatively good agreement is obtained between the experimental results and simulations despite that fact that the quasi-BIC transmission peak is less observable when the pump fluence increases to 2.6 $\mu\text{J}/\text{cm}^2$. It is clear that the quasi-BIC transmission peak gradually vanishes with increasing pump fluence.

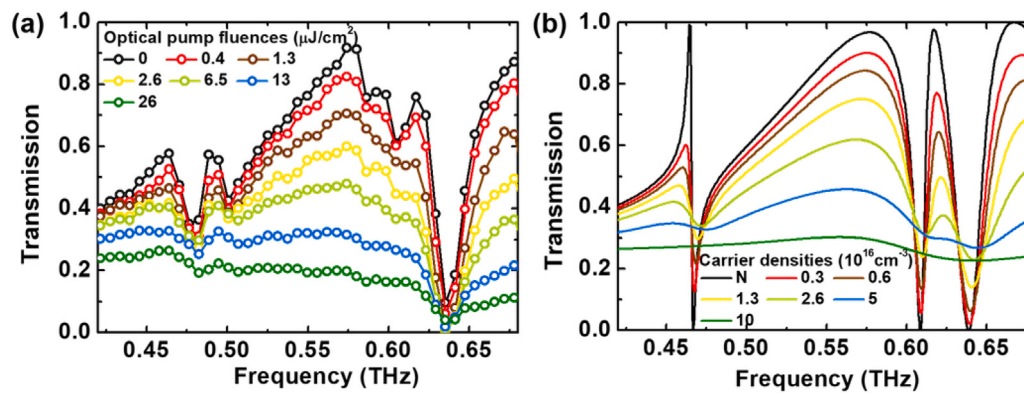


Fig. 6. (a) Experimental transmission spectra of the quasi-BIC metamaterial under different optical pump fluences. (b) Simulated transmission spectra for various carrier densities within 10 μm of the thick top layer.

4. Discussion and conclusion

We theoretically and experimentally investigated a design for all-silicon BIC and quasi-BIC metamaterials. By tuning the angle of incidence or breaking the structural symmetry, quasi-BIC states with finite Q-factors are realized. The change from the BIC state to quasi-BIC states is explained using coupled mode theory, where an eigenmode becomes a leaky mode when the symmetry of the structure is broken. This leads to coupling with an intrinsic TM mode, resulting in a Fano resonance. Optical pump excitation with low fluence pulses leads to a decrease in the quasi-BIC transmission peak providing a route for on-demand control of the quasi-BIC response.

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CRediT authorship contribution statement

Yuwei Huang: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Conceptualization. **Kelson Kaj:** Validation, Resources, Methodology, Investigation. **Zhiwei Yang:** Validation, Data curation. **Erick Alvarado:** Software, Data curation. **Wenkuan Man:** Validation, Methodology, Data curation. **Yuan Zhang:** Validation, Data curation. **Varun Ramaprasad:** Validation, Data curation. **Richard D. Averitt:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Xin Zhang:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.optlastec.2024.111176>.

References

- [1] A.A. Yanik, A.E. Cetin, M. Huang, A. Artar, S.H. Mousavi, A. Khanikaev, J.H. Connor, G. Shvets, H. Altug, Seeing protein monolayers with naked eye through plasmonic Fano resonances, *Proc. Natl. Acad. Sci.* 108 (29) (2011) 11784–11789.
- [2] B. Zhen, S.-L. Chua, J. Lee, A.W. Rodriguez, X. Liang, S.G. Johnson, J.D. Joannopoulos, M. Soljačić, O. Shapira, Enabling enhanced emission and low-threshold lasing of organic molecules using special Fano resonances of macroscopic photonic crystals, *Proc. Natl. Acad. Sci.* 110 (34) (2013) 13711–13716.
- [3] J.N. Anker, W.P. Hall, O. Lyandres, N.C. Shah, J. Zhao, R.P. Van Duyne, Biosensing with plasmonic nanosensors, *Nature Mater.* 7 (6) (2008) 442–453.
- [4] V. Kravets, F. Schedin, R. Jalil, L. Britnell, R. Gorbachev, D. Ansell, B. Thackray, K. Novoselov, A. Geim, A.V. Kabashin, et al., Singular phase nano-optics in plasmonic metamaterials for label-free single-molecule detection, *Nature Mater.* 12 (4) (2013) 304–309.
- [5] M.A. Al-Rawhani, C. Hu, C. Giagkoulovits, V.F. Annese, B.C. Cheah, J. Beeley, S. Velugotla, C. Accarino, J.P. Grant, S. Mitra, et al., Multimodal integrated sensor platform for rapid biomarker detection, *IEEE Trans. Biomed. Eng.* 67 (2) (2019) 614–623.
- [6] R. Singh, W. Cao, I. Al-Naib, L. Cong, W. Withayachumnankul, W. Zhang, Ultrasensitive terahertz sensing with high-Q Fano resonances in metasurfaces, *Appl. Phys. Lett.* 105 (17) (2014).
- [7] K.V. Sreekanth, Y. Alapan, M. Elkabbash, E. Ilker, M. Hinczewski, U.A. Gurkan, A. De Luca, G. Strangi, Extreme sensitivity biosensing platform based on hyperbolic metamaterials, *Nature Mater.* 15 (6) (2016) 621–627.
- [8] Z. Dong, L. Jin, S.D. Rezaei, H. Wang, Y. Chen, F. Tjptoharsono, J. Ho, S. Gorelik, R.J.H. Ng, Q. Ruan, et al., Schrödinger's red pixel by quasi-bound-states-in-the-continuum, *Sci. Adv.* 8 (8) (2022) eabm4512.
- [9] K. Hirose, Y. Liang, Y. Kurosaka, A. Watanabe, T. Sugiyama, S. Noda, Watt-class high-power, high-beam-quality photonic-crystal lasers, *Nat. Photonics* 8 (5) (2014) 406–411.
- [10] H. Matsubara, S. Yoshimoto, H. Saito, Y. Jianglin, Y. Tanaka, S. Noda, GaN photonic-crystal surface-emitting laser at blue-violet wavelengths, *Science* 319 (5862) (2008) 445–447.
- [11] E. Miyai, K. Sakai, T. Okano, W. Kunishi, D. Ohnishi, S. Noda, Lasers producing tailored beams, *Nature* 441 (7096) (2006) 946.
- [12] N.I. Zheludev, S. Prosvirnin, N. Papasimakis, V. Fedotov, Lasing spaser, *Nat. Photonics* 2 (6) (2008) 351–354.
- [13] W. Zhou, M. Dridi, J.Y. Suh, C.H. Kim, D.T. Co, M.R. Wasielewski, G.C. Schatz, T.W. Odom, Lasing action in strongly coupled plasmonic nanocavity arrays, *Nat. Nanotechnol.* 8 (7) (2013) 506–511.
- [14] J.Y. Suh, C.H. Kim, W. Zhou, M.D. Huntington, D.T. Co, M.R. Wasielewski, T.W. Odom, Plasmonic bowtie nanolaser arrays, *Nano Lett.* 12 (11) (2012) 5769–5774.
- [15] S.T. Ha, Y.H. Fu, N.K. Emani, Z. Pan, R.M. Bakker, R. Paniagua-Domínguez, A.I. Kuznetsov, Directional lasing in resonant semiconductor nanoantenna arrays, *Nature Nanotechnol.* 13 (11) (2018) 1042–1047.
- [16] Z. Liu, Y. Xu, Y. Lin, J. Xiang, T. Feng, Q. Cao, J. Li, S. Lan, J. Liu, High-Q quasibound states in the continuum for nonlinear metasurfaces, *Phys. Rev. Lett.* 123 (25) (2019) 253901.
- [17] K. Koshelev, Y. Tang, K. Li, D.-Y. Choi, G. Li, Y. Kivshar, Nonlinear metasurfaces governed by bound states in the continuum, *ACS Photonics* 6 (7) (2019) 1639–1644.
- [18] Z. Liu, J. Wang, B. Chen, Y. Wei, W. Liu, J. Liu, Giant enhancement of continuous wave second harmonic generation from few-layer GaSe coupled to high-Q quasi bound states in the continuum, *Nano Lett.* 21 (17) (2021) 7405–7410.
- [19] F. Ye, Y. Yu, X. Xi, X. Sun, Second-harmonic generation in etchless lithium niobate nanophotonic waveguides with bound states in the continuum, *Laser Photonics Rev.* 16 (3) (2022) 2100429.

- [20] G. Zograf, K. Koshelev, A. Zalogina, V. Korolev, R. Hollinger, D.-Y. Choi, M. Zuerch, C. Spielmann, B. Luther-Davies, D. Kartashov, et al., High-harmonic generation from resonant dielectric metasurfaces empowered by bound states in the continuum, *Acs Photonics* 9 (2) (2022) 567–574.
- [21] A.P. Anthur, H. Zhang, R. Paniagua-Domínguez, D.A. Kalashnikov, S.T. Ha, T.W. Maß, A.I. Kuznetsov, L. Krivitsky, Continuous wave second harmonic generation enabled by quasi-bound-states in the continuum on gallium phosphide metasurfaces, *Nano Lett.* 20 (12) (2020) 8745–8751.
- [22] C.W. Hsu, B. Zhen, A.D. Stone, J.D. Joannopoulos, M. Soljačić, Bound states in the continuum, *Nat. Rev. Mater.* 1 (9) (2016) 1–13.
- [23] S.I. Azzam, A.V. Kildishev, Photonic bound states in the continuum: from basics to applications, *Adv. Opt. Mater.* 9 (1) (2021) 2001469.
- [24] S. Han, L. Cong, Y.K. Srivastava, B. Qiang, M.V. Rybin, A. Kumar, R. Jain, W.X. Lim, V.G. Achanta, S.S. Prabhu, et al., All-dielectric active terahertz photonics driven by bound states in the continuum, *Adv. Mater.* 31 (37) (2019) 1901921.
- [25] L. Kühner, L. Sortino, R. Berté, J. Wang, H. Ren, S.A. Maier, Y. Kivshar, A. Tittl, Radial bound states in the continuum for polarization-invariant nanophotonics, *Nat. Commun.* 13 (1) (2022) 4992.
- [26] Y. Chen, H. Deng, X. Sha, W. Chen, R. Wang, Y.-H. Chen, D. Wu, J. Chu, Y.S. Kivshar, S. Xiao, et al., Observation of intrinsic chiral bound states in the continuum, *Nature* 613 (7944) (2023) 474–478.
- [27] M. Kang, Z. Zhang, T. Wu, X. Zhang, Q. Xu, A. Krasnok, J. Han, A. Alù, Coherent full polarization control based on bound states in the continuum, *Nat. Commun.* 13 (1) (2022) 4536.
- [28] M. Kang, L. Mao, S. Zhang, M. Xiao, H. Xu, C.T. Chan, Merging bound states in the continuum by harnessing higher-order topological charges, *Light: Sci. Appl.* 11 (1) (2022) 228.
- [29] C.W. Hsu, B. Zhen, J. Lee, S.-L. Chua, S.G. Johnson, J.D. Joannopoulos, M. Soljačić, Observation of trapped light within the radiation continuum, *Nature* 499 (7457) (2013) 188–191.
- [30] J. Gomis-Bresco, D. Artigas, L. Torner, Anisotropy-induced photonic bound states in the continuum, *Nat. Photonics* 11 (4) (2017) 232–236.
- [31] S.I. Azzam, V.M. Shalaev, A. Boltasseva, A.V. Kildishev, Formation of bound states in the continuum in hybrid plasmonic-photonic systems, *Phys. Rev. Lett.* 121 (25) (2018) 253901.
- [32] L. Cong, R. Singh, Symmetry-protected dual bound states in the continuum in metamaterials, *Adv. Opt. Mater.* 7 (13) (2019) 1900383.
- [33] S. Li, C. Zhou, T. Liu, S. Xiao, Symmetry-protected bound states in the continuum supported by all-dielectric metasurfaces, *Phys. Rev. A* 100 (6) (2019) 063803.
- [34] M. Sidorenko, O. Sergaeva, Z. Sadrieva, C. Roques-Carmes, P. Muraev, D. Maksimov, A. Bogdanov, Observation of an accidental bound state in the continuum in a chain of dielectric disks, *Phys. Rev. A* 15 (3) (2021) 034041.
- [35] E. Bulgakov, A. Sadreev, Robust bound state in the continuum in a nonlinear microcavity embedded in a photonic crystal waveguide, *Opt. Lett.* 39 (17) (2014) 5212–5215.
- [36] A.N. Poddubny, D.A. Smirnova, Nonlinear generation of quantum-entangled photons from high-Q states in dielectric nanoparticles, 2018, arXiv preprint arXiv:1808.04811.
- [37] W. Głowadzka, M. Wasiak, T. Czeszanowski, True-and quasi-bound states in the continuum in one-dimensional gratings with broken up-down mirror symmetry, *Nanophotonics* 10 (16) (2021) 3979–3993.
- [38] X. Zhang, T. Sang, C. Pian, Y. Wang, J. Wang, Dual-band polarization-independent high quality factor Fano resonances using a twisted tetrameric nanohole slab, *J. Opt. Soc. Am. B* 40 (7) (2023) 1652–1660.
- [39] W. Wang, Y.K. Srivastava, T.C. Tan, Z. Wang, R. Singh, Brillouin zone folding driven bound states in the continuum, *Nature Commun.* 14 (1) (2023) 2811.
- [40] T. Sang, Q. Mi, C. Yang, X. Zhang, Y. Wang, Y. Ren, T. Xu, Achieving asymmetry parameter-insensitive resonant modes through relative shift-induced quasi-bound states in the continuum, *Nanophotonics* (2024).
- [41] X. Zhao, C. Chen, K. Kaj, I. Hammock, Y. Huang, R.D. Averitt, X. Zhang, Terahertz investigation of bound states in the continuum of metallic metasurfaces, *Optica* 7 (11) (2020) 1548–1554.
- [42] T.C. Tan, E. Plum, R. Singh, Lattice-enhanced fano resonances from bound states in the continuum metasurfaces, *Adv. Opt. Mater.* 8 (6) (2020) 1901572.
- [43] X. Chen, W. Fan, H. Yan, Toroidal dipole bound states in the continuum metasurfaces for terahertz nanofilm sensing, *Opt. Express* 28 (11) (2020) 17102–17112.
- [44] Y. Huang, K. Kaj, C. Chen, Z. Yang, S.R. Ul Haque, Y. Zhang, X. Zhao, R.D. Averitt, X. Zhang, Broadband terahertz silicon membrane metasurface absorber, *ACS Photonics* 9 (4) (2022) 1150–1156.
- [45] S. Jahani, Z. Jacob, All-dielectric metamaterials, *Nat. Nanotechnol.* 11 (1) (2016) 23–36.
- [46] Y. Yang, I.I. Kravchenko, D.P. Briggs, J. Valentine, All-dielectric metasurface analogue of electromagnetically induced transparency, *Nat. Commun.* 5 (1) (2014) 1–7.
- [47] Y. Cheng, W. Cao, G. Wang, X. He, F. Lin, F. Liu, 3D Dirac semimetal supported thermal tunable terahertz hybrid plasmonic waveguides, *Opt. Express* 31 (11) (2023) 17201–17214.
- [48] X. He, F. Lin, F. Liu, W. Shi, 3D Dirac semimetals supported tunable terahertz BIC metamaterials, *Nanophotonics* 11 (21) (2022) 4705–4714.
- [49] G. Wang, W. Cao, X. He, 3D Dirac semimetal elliptical fiber supported THz tunable hybrid plasmonic waveguides, *IEEE J. Sel. Top. Quantum Electron.* (2023).
- [50] T. Ma, Q. Huang, H. He, Y. Zhao, X. Lin, Y. Lu, All-dielectric metamaterial analogue of electromagnetically induced transparency and its sensing application in terahertz range, *Opt. Express* 27 (12) (2019) 16624–16634.
- [51] S. Han, P. Pitchappa, W. Wang, Y.K. Srivastava, M.V. Rybin, R. Singh, Extended bound states in the continuum with symmetry-broken terahertz dielectric metasurfaces, *Adv. Opt. Mater.* 9 (7) (2021) 2002001.
- [52] K. Koshelev, A. Bogdanov, Y. Kivshar, Meta-optics and bound states in the continuum, *Sci. Bull.* 64 (12) (2019) 836–842.
- [53] K. Fan, I.V. Shadrivov, W.J. Padilla, Dynamic bound states in the continuum, *Optica* 6 (2) (2019) 169–173.
- [54] K. Koshelev, S. Lepeshov, M. Liu, A. Bogdanov, Y. Kivshar, Asymmetric metasurfaces with high-Q resonances governed by bound states in the continuum, *Phys. Rev. Lett.* 121 (19) (2018) 193903.
- [55] A.A. Kutuzova, M.V. Rybin, Quality factor scaling of resonances related to bound states in the continuum, *Phys. Rev. B* 107 (19) (2023) 195108.
- [56] Z. Dong, Z. Mahfoud, R. Paniagua-Domínguez, H. Wang, A.I. Fernández-Domínguez, S. Gorelik, S.T. Ha, F. Tjptoharsono, A.I. Kuznetsov, M. Bosman, et al., Nanoscale mapping of optically inaccessible bound-states-in-the-continuum, *Light: Sci. Appl.* 11 (1) (2022) 20.
- [57] K. Koshelev, G. Favraud, A. Bogdanov, Y. Kivshar, A. Fratalocchi, Nonradiating photonics with resonant dielectric nanostructures, *Nanophotonics* 8 (5) (2019) 725–745.

Further reading

- [58] X. Zhao, Y. Wang, J. Schallch, G. Duan, K. Cremin, J. Zhang, C. Chen, R.D. Averitt, X. Zhang, Optically modulated ultra-broadband all-silicon metamaterial terahertz absorbers, *ACS Photonics* 6 (4) (2019) 830–837.