Coupling-Assisted Quasi-Bound States in the Continuum in Heterogeneous Metasurfaces

Wei Huang, Songyi Liu, Dehui Zeng, Quanlong Yang, Wentao Zhang, Shan Yin, and Jiaguang Han

Abstract—In this paper, we present a Bound states in the continuum (BIC) metamaterial in heterogeneous structures based on the coupled mode theory. We find the more general physical parameters to represent BIC, which are the resonant frequencies and corresponding phases of metamaterial structures. Therefore, BIC metamaterial comes from the equal value of the resonant frequencies and phases of metamaterial structures which are not only for homogeneous structures. Meanwhile, if one of the metamaterial structure’s resonant frequency and phase vary by varying geometry, we can obtain the quasi-BIC instead of the broken symmetry of homogeneous structures. In this paper, we provide the BIC and quasi-BIC with one example of two heterogeneous structures which are cut wire (CW) and Split-Ring Resonator (SRR) and it widely extends the metamaterial BIC beyond common sense. Furthermore, we demonstrate the simulation results and experimental results to proof our idea.

Index Terms—Metasurfaces, quasi-bound states in the continuum, metamaterials.

I. INTRODUCTION

BOUND states in the continuum (BIC) is initially proposed in quantum mechanics [1], which trapped or guided modes with their frequencies in the frequency intervals of radiation modes in the optical system [2], [3], [4], [5]. Based on this idea, most recently, the concept of BIC has already been introduced into the metamaterial structure, which can offer the ultra-high Q resonance [6], [7], [8], [9], [10], [11], [12], [13]. In real world applications, BIC or quasi-BIC peaks can be used for high sensitivity sensing in biomedical detection, due to the high Q factor of quasi-BIC. Therefore, it will largely increase the sensitivity of THz detection [14], [15], [16]. Based on the metamaterial BIC, there are many practical applications for photonic systems, such as lasers [17], [18], sensors [19], [20], high-sensitive medical devices [21], [22] and filters [23]. Due to its wide applications, the BIC has been attracted many research interests.

The reason for causing metamaterial BIC in metamaterial can be illustrated in many perspectives, such as topological theory [24], [25], Fano resonance theory [26], [27], and the multi-poles theory [28], [29]. However, topological theory gives the effective Hamiltonian of system to analyse BIC, but the effective Hamiltonian is not directly relative to geometrical parameters of the metamaterial structure. Fano resonance theory gives the fitting number q (Fano asymmetry parameter) which is not a physical and fundamental parameter for the metamaterial. The multi-poles theory can explain BIC metamaterial by employing toroidal dipole. Another good explanation of the metamaterial BIC employs the coupled mode theory. With the standing point of coupled mode theory, if two radiation fields of metamaterial structures have the same phase and resonant frequency of a single metamaterial structure, the far field of two lossy fields have destructive interference with each other. When we slightly vary one of metamaterial structure, the far field of two lossy fields can not cause destructive interference, but provides high Q Fano-shape resonance instead, so-called broken symmetry of quasi-BIC. The most intuitive choice and common sense for BIC metamaterial are made of two uniform structures and quasi-BIC comes from the broken symmetry of homogeneous structures, which can obtain the high Q resonance.

The coupled mode theory (CMT) is a prosperous and universal theory that is widely used in many systems [30], [31], [32], [33], [34], [35], [36], [37]. In the metamaterial BIC, firstly applying the coupled mode theory of one bright mode and one dark to illustrate the quasi-BIC [12]. After the coupled mode theory with two bight modes improves the prediction of metamaterial BIC [36]. Most recently, we further improved the coupled mode theory with two bight modes and phase information, which better fits theoretical calculations and simulations over other coupled mode theories [38]. Indeed, CMT can not perfectly calculate the whole transmission spectrums of coupling metamaterial. However, CMT can relatively obtain the accurate transmission spectrums based on the numerical technique, such as fitting,
and it is a good theory for understanding the basic mechanism of coupled metamaterial structures. BIC and quasi-BIC come from the coupling between two metamaterial structures. To sum up, CMT is a good and powerful theory for better understanding the basic physical mechanism of BIC and quasi-BIC.

The coupled mode theory implies the causing of BIC metamaterial is that resonance frequencies and phases of metamaterial structures are the same without limitation of the same metamaterial structures. Therefore, we can simply extend this deduction of establishing BIC metamaterial by employing two heterogeneous structures with the same value of resonant frequencies and corresponding phases. In other words, even for two heterogeneous metamaterial structures (for example, Cut Wire (CW) and Split-Ring Resonator (SRR)) which have the same resonant frequency and corresponding phase, we can obtain the BIC metamaterial with heterogeneous configuration. This finding will exceed the common sense of BIC metamaterial with homogeneous structures. Normally, previous researches only realize BIC metamaterial is caused by two homogeneous structures (or quasi-BIC caused by two slightly different structures). In this paper, we obtain the BIC (and quasi-BIC) with two heterogeneous metamaterial structures, as shown in Fig. 1 (CW and SRR) for the first time. We provide the CW and SRR with the same phase and resonant frequency (see Fig. 2(a)) for the BIC case as shown in Fig. 2(b). Furthermore, we slightly vary the structure of CW to change the phase and resonant frequency of CW (see Fig. 3(a) and (b)), to obtain the corresponding quasi-BIC. Subsequently, we continuously vary the length of CW to find the corresponding Q-value of quasi-BIC, and we give the fitting function, as shown in Fig. 4.

The paper is organized as follows. In Section II, we firstly introduce the coupled mode theory for metamaterial BIC. Section III employs the coupled mode theory to predict the BIC with the same phase and resonant frequency of CW and SRR. After that, we slightly change the phase and resonant frequencies of CW, which provides a different Q-value of quasi-BIC. In addition, we give the experimental results to demonstrate our device. In Section IV, we provide the further discussions on our design. Finally, we conclude in Section V.

II. COUPLED MODE THEORY

The coupled mode theory with two bright modes and phase information can be described as following [38],

\[
\begin{bmatrix}
  w - w_a - i\gamma_a & \Omega \\
  \Omega & w - w_b - i\gamma_b
\end{bmatrix}
\begin{bmatrix}
a \\
b
\end{bmatrix}
= \begin{bmatrix}
\sqrt{\gamma_a}E \\
\sqrt{\gamma_b}E
\end{bmatrix},
\]

where \(|a|^2\) and \(|b|^2\) as the energies in each metamaterial structure. \(\omega\) is the frequency of input THz wave. \(\omega_a\) and \(\omega_b\) represent the eigen-frequencies of the coupling. \(\Omega\) is the coupling strength with loss, due to the loss of transferring energy from one metamaterial structure to another. And \(\gamma_a\) and \(\gamma_b\) are the loss terms of the coupling, \(\phi\) is the phase information. \(E\) is the amplitude of external exciting THz wave. The relationships between those parameters of coupling and the parameters of corresponding metamaterial structures are given by,

\[
\begin{align*}
\omega_a &= \omega_1; \omega_b = \omega_2 \\
\gamma_a &= \gamma_1; \gamma_b = (\gamma_1 - \gamma_2)/2; \\
\phi &= \phi_1 - \phi_2; \\
\Omega &= g - i\sqrt{\gamma_a \gamma_b}e^{i\phi},
\end{align*}
\]

where \(\omega_1\) and \(\omega_2\) are the resonant frequency of the corresponding metamaterial structures. \(g\) is the coupling strength between two metamaterial structures. \(\gamma_1\) and \(\gamma_2\) are the loss of related metamaterial structures. \(\phi_1\) and \(\phi_2\) are the phases at resonant frequencies of corresponding metamaterial structures.

Subsequently, we can obtain the energy amplitudes \(a, b\) of each metamaterial structure by solving the (1), as shown,

\[
\begin{align*}
a &= \frac{((w - w_b - i\gamma_b)\sqrt{\gamma_a} - \Omega\sqrt{\gamma_b}e^{i\phi})E}{(w - w_b - i\gamma_b)(w - w_a - i\gamma_a) - \Omega^2}; \\
b &= \frac{((w - w_a - i\gamma_a)\sqrt{\gamma_b} - \Omega\sqrt{\gamma_a}E)}{(w - w_b - i\gamma_b)(w - w_a - i\gamma_a) - \Omega^2}.
\end{align*}
\]

Then we calculate the effective electric susceptibility which is the linear superposition with energy amplitudes \(|a|^2\) and \(|b|^2\), the effective electric susceptibility of the metamaterial can be written as [40]

\[
\chi_{\text{eff}} = \frac{\sqrt{\gamma_a}a + \sqrt{\gamma_b}b}{\epsilon_0 E}.
\]

Finally, we obtain the transmission spectrum with \(T \approx 1 - \text{Im}(\chi_{\text{eff}})\) [12], as shown in the (6). Hence, we can predict the transmission spectrum of the structure [38], to obtain the BIC and Q-value of quasi-BIC.

\[
T \approx 1 - \text{Im}
\frac{(w - w_a - i\gamma_a)\sqrt{\gamma_b}e^{i\phi} + ((w - w_b - i\gamma_b)\gamma_a - 2\Omega\sqrt{\gamma_a\gamma_b}e^{i\phi})}{(w - w_b - i\gamma_b)(w - w_a - i\gamma_a) - \Omega^2}.
\]

III. BIC WITH TWO DIFFERENT STRUCTURES

Based on the prediction of our theory, we carefully select the structures of CW and SRR to obtain the BIC or quasi-BIC. We do the full-wave simulations with scanning a large set of geometrical parameters of CW and SRR. By scanning line width,
length of CW and line width, gap and the side length of SRR, we try our best to obtain the geometrical parameters of CW and SRR to get matched phase and resonant frequency of CW and SRR. In other to easier demonstration, we fix the structure parameters of SRR, where the gap of SRR is 4 \( \mu m \); width of SRR is 4 \( \mu m \) and the side length of SRR is 60 \( \mu m \). Besides, the width of CW is fixed 20 \( \mu m \) with the length \( L \) of CW, as shown in Fig. 1. Therefore, we just required to change the length \( L \) of CW to vary the phase and resonant frequency of CW, to obtain the BIC or quasi-BIC.

For the BIC case, we select the length \( L_0 \) of CW as 85.5 \( \mu m \), where the resonant frequency of CW is 0.6097 THz and the corresponding phase at the resonant frequency is 26.125 degrees. Besides, the resonant frequency of SRR is 0.6095 THz and corresponding phase at resonant frequency is 26.051 degrees, as shown in Fig. 2(a). Thus, according to our theory, this configuration generates the ultra-high Q resonance or we can call it BIC. The transmission spectrum of CW and SRR coupling demonstrates in Fig. 2(b). From the results, coupling between two entirely different structures performs the transmission spectrum as the single resonance. Thus, the Q-value at BIC frequency reveals the infinite.

Based on coupled mode theory, if we slightly change the length \( L \) which varies the resonant frequencies and the corresponding phases of CW, the resonant frequencies and corresponding phases of CW and SRR are not match. Therefore, the Fano resonant shapes will appear in the transmission spectrum, so-called quasi-BIC cases. In order to demonstrate the correct prediction of our theory, we propose the full-wave simulations, our theory and experiments by varying the length of CW from \( L = 67 \mu m \) to 110 \( \mu m \), as shown in Fig. 3. The first column and second column of Fig. 3 demonstrate our designed structure of units cells and our experimental devices, respectively. The third, fourth, and fifth columns are the full-wave simulations, our theory and corresponding experimental results, respectively. In Fig. 3, our theoretical results can be well-fitted to our full-wave simulations. Meanwhile, our experimental results are also well consistent with our theoretical and full-wave simulated results, compared with the resonance frequencies in our simulations, theoretical and experimental results. As we can obtain that when we slightly change the length \( L \), the Fano resonant shapes appear in the transmission spectrum as shown in Fig. 3 except (b), because Fig. 3(b) is the BIC case (\( L_0 = 85.5 \mu m \)) which the resonant frequency and corresponding phase of CW are very closed to SRR, as shown in Fig. 2.

**IV. Discussion**

From the results of Fig. 3, our experimental results are well satisfied with full-wave simulation and theoretical results. Therefore, we can conclude that our simulated and theoretical results have perfect confidence and we can employ our simulated and theoretical results to obtain more features of our device.

In order to better demonstrate the BIC with different structures, we vary the length of CW \( L \) from 66 \( \mu m \) to 107 \( \mu m \), which crosses the same phase and resonant frequency of CW and SRR (\( L_0 = 85.5 \mu m \)). Therefore, the coupled mode theory can easily predict that the highest Q-value appears when the same phase and resonant frequency of CW and SRR, such as the \( L_0 = 85.5 \mu m \). Consequently, when the length of CW is \( L_0 = 85.5 \mu m \), we can predict that \( L_0 = 85.5 \mu m \) is the BIC point. As we can see from the Fig. 4, it is effortless to see that the Q-values of quasi-BIC are higher, when the length of CW \( L \) is closer to 85.5 \( \mu m \) (BIC point). The fitting functions are given in black line and red line in Fig. 4. Our results in Fig. 4 is consistent with our theory and analysis. Hence, our theory can predict and have a very good fitting with BIC or quasi-BIC with CW and SRR, which is the entirely new metamaterial structure for BIC. In the theory, Q-value becomes infinite which represents a perfect cavity configuration. However, the metal of metamaterial has the intrinsic loss and this loss can not be destructive interference by BIC. Therefore, this physical limitation restricts to obtain very high Q-values of quasi-BIC metamaterial in simulations and experiments. However, we can predict the BIC point by using Fig. 4 and the contour plot shown in Fig. 5. Besides, CMT can predict the infinite quality factor of a BIC system. Based on our theory, if two structures are exactly the same, the resonant frequency and corresponding phase of two structures are the
Fig. 3. The transmission spectrum of coupling between CW and SRR with varying the length of CW (a) $L = 67 \, \text{µm}$, (b) $L = 85.5 \, \text{µm}$, (c) $L = 92 \, \text{µm}$, (d) $L = 93 \, \text{µm}$, (e) $L = 94 \, \text{µm}$, (f) $L = 97 \, \text{µm}$, (g) $L = 110 \, \text{µm}$. 
same. Subsequently, we substitute the same resonant frequency and corresponding phase into the CMT. After calculation, we can obtain that the transmission spectrums remain one resonant peak and there is no peak at BIC frequency. Therefore, we can consider that there is no loss at BIC frequency, in other words, there is no peak at BIC frequency with infinite Q value.

In order to demonstrate the BIC point, we give the contour plot with varying the length of CW and frequencies. The colour bar of the contour plot is the amplitude of transmission spectrum, as shown in Fig. 5. As we can see that, there is no crossing of the Fano resonance (quasi-BIC) and therefore, it is the type I BIC [41, 42], which comes from the Fano resonance and we can further confirm that the BIC point is $L = 85.5 \, \mu\text{m}$ which is consistent with Fig. 4. From the standing point of metamaterial structures' electric fields, we give two situations of quasi-BIC ($L = 95 \, \mu\text{m}$) and BIC ($L_0 = 85.5 \, \mu\text{m}$), as shown in Fig. 6. In Fig. 6(a), the electric fields of metamaterial structures are configuration of anti-directions dipoles with quasi-BIC at Fano resonant frequency. The electric fields of metamaterial structures are configuration of same direction dipoles with BIC point at BIC frequency ($f = 0.575 \, \text{THz}$). These configurations of electric fields are consistent with type I BIC which is shown in Fig. 5.

The maximum Q values of the quasi-BIC peaks obtained by simulation and experimental measurements are 193 and 25, respectively. The restriction of Q factor in the simulation is that it is hard to find the geometrical parameters of CW and SRR to get matched phase and resonant frequency of CW and SRR. Besides, BIC only can cancel interference of radiation loss of two structures, but it can not avoid the intrinsic loss, due to the loss of metal. The restriction of Q factor in the experiment comes from the fabrication error of our metamaterial and also the limitations of the sensitivity of our THz-TD system. Therefore, our Q values of quasi-BIC can not be comparable to others very high Q designs, such as the quasi-BIC based on topological metamaterial [43, 44] and all-dielectric THz metamaterial BIC systems [16, 45, 46, 47, 48]. Due to the reflection index matching of structures and substrate, it will produce higher Q factors of BIC. However, all-dielectric THz metamaterial device requires higher manufacturing technology. Furthermore, the generation of all-dielectric BIC can be considered due to the coupling of electric dipole and toroid dipole. Therefore, the BICs of those papers can also be described by employing CMT. In those papers, the coupling does not come from metamaterial structures and coupling comes from the electric dipole and toroid dipole of the resonant. Therefore, those papers will not change our main results and findings. Our paper’s motivation is not to produce a very high Q quasi-BIC. In fact, The motivation of our paper extends the concept of BIC based on CMT. The common sense of BIC is made of two exactly the same structures. However, in our paper, we demonstrate that the quasi-BIC can come from two heterogeneous metasurfaces (for example, CW and SRR) which is the novelty of our paper. Our experiment only demonstrates correction of our theoretical prediction.
In order to demonstrate the universality of our theory, we further demonstrate the BIC and quasi-BIC based on two heterogeneous structures (U shape and SRR) in the full-wave simulations. The specific geometrical parameters of U shape and SRR are shown in Fig. 7(a). We carefully scan the length of U shape \( L \) to obtain the resonant frequency and corresponding phase which are very close to the resonant frequency and corresponding phase of SRR. When the length of U shape is \( L = 85.4 \) \( \mu \)m, the resonant frequencies and corresponding phases of U shape and SRR are nearly the same, as shown in Fig. 7(b) and (c) respectively. Based on our theory, it brings the BIC due to the coupling between U shape and SRR (see Fig. 7(d)). Furthermore, we slightly change the length of U shape to vary the resonance frequency and phase and therefore it brings the quasi-BIC instead, as shown in Fig. 8. As we can see from Fig. 8, the Q-factors of quasi-BIC are increased with more close to the equivalent of resonant frequencies and corresponding phases of U shape and SRR (\( L = 85.4 \) \( \mu \)m), which is exact same results as the example of CW and SRR. Therefore, we demonstrate our theory is a general approach which can be applied to different structures.

There are two remarkable papers about coupling between split-ring and cut-wire \([49],[50]\). The first paper \([49]\) proposed the plasmon-induced transparency (PIT) based on the coupling between split-ring and cut-wire, and the split-ring is the dark mode in this paper. However, split-ring and cut-wire must be bright modes in our paper, otherwise, we can not build up the BIC. Another paper \([50]\) proposed the PIT based on the two bright modes of split-ring and cut-wire. The PIT is focus on the energy of one bright mode, which flows to another bright mode, due to coupling between two bright modes and thus, the bright mode can not excited by external field equivalently, which becomes transparency. The PIT causes the group delay of electromagnetic field \([50]\). The quasi-BIC in our paper is focus on the Q-factor changing of Fano peak (so called quasi-BIC peak) due to the coupling between the close resonance frequencies and corresponding phase. The basic physics behind quasi-BIC is the destructive interference of coupling between two metamaterial structures. Therefore, quasi-BIC should take the two metamaterial as one part together. To sum up, PIT and quasi-BIC are two different aspects for the same metamaterial device, which are focus on different phenomena for the same metamaterial device. Based on our discussion, the paper \([50]\) can be considered as the potential design of BIC, if the authors carefully design the geometrical parameters of split-ring and cut-wire and let the resonant frequencies and corresponding phases of split-ring and cut-wire are the same or very close. Our paper proposes a universal theory to construct BIC based on coupled mode theory (CMT). Therefore, the specific structures of metamaterial are not important in our paper. In our paper, we just employ two most commonly used metamaterial structures (CW and SRR or U shape and SRR) as the examples to demonstrate our idea. It is worth emphasizing that we employ the CW and SRR as the heterogeneous example to construct BIC and quasi-BIC in this paper. Still, our conclusions and results can be extended to arbitrary heterogeneous structures to build up the BIC and quasi-BIC, not only for CW and SRR or U shape and SRR.

It is worth to discuss the physics origin of metamaterial BIC. Metamaterials in the terahertz range are always excited by free-space beams, which means that the metamaterial structures always have the radiation to outside. Thus, there is no perfect
resonance in metamaterial. However, the original principle of BICs is that two leaky waves from modes or metamaterial structures interfere and are cancelled by each other (so called destructive interference). Thus, we do not try to design a perfect resonance in metamaterial to confine the EM waves and we should carefully design the two leaky metamaterial structures to make sure their destructive interference. In our paper, we should carefully design two leaky metamaterial structures (cut-wire and a split-ring resonator). CW and SRR should radiate EM waves based on their structures, but these two leaky radiated waves of CW and SRR can cancel interference with each other. Therefore, it does not have any radiation loss, if we consider CW and SRR together. The theory can extend to the example of U shape and SRR as well.

V. EXPERIMENTAL SETTING UP

For the structure fabricated, the sample is fabricated by a surface micromachining process. First, a high resistance silicon substrate is coated with a layer of negative photoresist and baked, and then illuminated with an ultraviolet lamp and mask to form a pattern. After that, a 200-nm-thick aluminum film is deposited by metal evaporation process. Finally, a lift-off process removes the photoresist and forms a metal pattern on the substrate. The microscope images of the fabricated samples are presented in Fig. 3.

The principle of the measurement system (all-fiber terahertz-TD system model TPF15 K produced by Terahertz Photonics Technology) is shown in following figure. A femtosecond laser beam with a central wavelength of 780 nm is divided into two beams by a beam splitter. An intense beam is focused on the conductive antenna to generate a linearly polarized THz pulse, which is focused on the front surface of the tissue sample and then passes through it and reaches the ZnTe crystal. The other weak beam is a probe pulse, passing through the optical delay line and splitter. The probe pulse and the THz pulse which contains the sample information collinearly get to the front surface of the ZnTe crystal. After the THz pulse and the reference signal converge, it passes through a quarter wave plate (QWP) and Wollaston prism (WP), and the photoelectric diodes (PDs) convert the optical signal into the electrical signal. Then the signal is amplified through the lock-in amplifier, and the spectral line information of the sample is obtained by comparing the metasurface sample with the original scan reference signal. Finally, THz spectrum containing the information of sample is obtained and displayed on the computer. During the experiment, we reduced the humidity in the test environment to 8% (theoretical 0%) with a dryer, the temperature was 27 °C, and the pulse cutoff time is 58 ps. The schematic figure of our experiment is shown in Fig. 9.

VI. CONCLUSION

In this paper, we propose the new configuration of metamaterial BIC with two heterogeneous structures (Cut Wire and Split-Ring Resonator). We firstly theoretically and experimentally demonstrate the BIC and quasi-BIC with two heterogeneous structures. Our theory implies that resonant frequencies and corresponding phases of metamaterial structures are more fundamental physical parameters of BIC. We give the simulation and experimental results to proof our idea. This finding will extend the boundary of metamaterial BIC and could be widely used in applications.

REFERENCES

[1] J. V. Neumann and E. P. Wigner, “Uber merkwürdige diskrete eigenwerte,” Phys. Zeitschr., vol. 30, pp. 465–467, 1929.
[2] C. W. Hsu et al., “Bound states in the continuum,” Nature Rev. Mater., vol. 1, no. 9, pp. 1–13, 2016.
[3] D. C. Marinica, A. G. Borisov, and S. V. Shabanov, “Bound states in the continuum in photonics,” Phys. Rev. Lett., vol. 100, no. 18, 2008, Art. no. 183902.
[4] Y. Plotnik et al., “Experimental observation of optical bound states in the continuum,” Phys. Rev. Lett., vol. 107, no. 18, 2011, Art. no. 183901.
[5] X. Gao et al., “Formation mechanism of guided resonances and bound states in the continuum in photonic crystal slabs,” Sci. Rep., vol. 6, no. 1, pp. 1–7, 2016.
[6] S. I. Azzam et al., “Formation of bound states in the continuum in hybrid plasmonic-photonic systems,” Phys. Rev. Lett., vol. 121, no. 25, 2018, Art. no. 253901.
[7] K. Koshelev et al., “Asymmetric metasurfaces with high-Q resonances governed by bound states in the continuum,” Phys. Rev. Lett., vol. 121, no. 19, 2018, Art. no. 193903.
[8] K. Koshelev, A. Bogdanov, and Y. Kivshar, “Meta-optics and bound states in the continuum,” Sci. Bull., vol. 64, no. 12, pp. 836–842, 2019.
[9] A. E. Miroshnichenko, S. Flach, and Y. S. Kivshar, “Fano resonances in nanoscale structures,” Rev. Modern Phys., vol. 82, no. 3, 2010, Art. no. 2257.
[10] A. S. Kaprionov et al., “Metasurface engineering through bound states in the continuum,” Phys. Rev. Appl. vol. 12, no. 1, 2019, Art. no. 014024.
[11] D. R. Abujetas et al., “Spectral and temporal evidence of robust photonic bound states in the continuum on terahertz metasurfaces,” Optica, vol. 6, no. 8, pp. 996–1001, 2019.
[12] L. Cong et al., “Fano resonances in terahertz metasurfaces: A figure of merit optimization,” Adv. Opt. Mater., vol. 3, no. 11, pp. 1537–1543, 2015.
[13] Y. Liang et al., “Bound states in the continuum in anisotropic plasmonic metamaterials,” Nano Lett., vol. 20, no. 9, pp. 6351–6356, 2020.
[14] L. Sun et al., “Implantable, degradable, therapeutic terahertz metamaterial devices,” Small, vol. 16, no. 17, 2020, Art. no. 2000294.
[15] Y. K. Srivastava et al., “Terahertz sensing of 7 nm dielectric film with bound states in the continuum metasurfaces,” Appl. Phys. Lett., vol. 115, no. 15, 2019, Art. no. 151105.
[16] T. C. W. Tan et al., “Active control of nanodielectric-induced THz quasi-BIC in flexible metasurfaces: A platform for modulation and sensing,” Adv. Mater., vol. 33, no. 27, 2021, Art. no. 2100836.
[17] A. Kodigala et al., “Lasing action from photonic bound states in continuum,” Nature, vol. 541, no. 7636, pp. 196–199, 2017.
[18] S. T. Ha et al., “Directional lasing in resonant semiconductor nanolens array,” Nature Nanotechnol., vol. 13, no. 11, pp. 1042–1047, 2018.
Wei Huang received the M.Sc. (with distinction) degree in quantum technology from the University of Leeds, Leeds, U.K., in 2013 and the Ph.D. degree from the Singapore University of Technology and Design, Singapore, with full scholarship in 2018. He is currently an Assistant Professor with the Guilin University Of Electronic Technology, Guilin, China. His research interests include quantum computing, quantum optics and applications of quantum optics in multiple (classical and quantum) systems. He was the recipient of Guangxi oversea 100 talent in 2018.

Songyi Liu received the master’s degree with the School of Optoelectronic Engineering, Guilin University of Science and Technology, Guilin, China. He is currently a Graduate Student. His research focuses on terahertz device.

Quanlong Yang received the Ph.D. degree from Tianjin University, Tianjin, China. In 2018. From 2019 to 2022, he was a Postdoc Research Fellow with the Australian National University, Canberra, ACT, Australia. He is currently an Associate Professor with Central South University, Changsha, China. His research interests include terahertz science and technology, all-dielectric metasurfaces, topological photonics, and nonlinear photonics.

Wentao Zhang received the master’s degree from the University of Electronic Science and Technology of China, Chengdu, China, in 2003 and the Ph.D. degree from Tongji University, Shanghai, China, in 2008. He is currently a Professor with the Guilin University of Electronic Technology, Guilin, China. His main research interests include photodetector technology, laser technology, and terahertz technology. He was awarded as a Guangxi Distinguished Expert in 2018.

Shan Yin received the B.S. degree in electronic science and technology from Minzu University, Beijing, China, in 2010, and the Ph.D. degree in optics from the Institute of Physics, Chinese Academy of Sciences, Beijing, in 2016. She is currently an Assistant Professor with the Guilin University of Electronic Technology, Guilin, China. Her research interests include surface plasmon polaritons, metamaterials, and functional devices in the terahertz regime.

Jianguang Han received B.Sc. degree in material physics from Beijing Normal University, Beijing, China, in 2000, and the Ph.D. degree in applied physics from the Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Beijing, in 2006. He is currently a Full Professor with Tianjin University, Tianjin, China. From 2006 to 2007, he was a Postdoctoral Researcher with Oklahoma State University, Stillwater, OK, USA. In 2007, he joined the National University of Singapore, Singapore, as a Lee Kuan Yew Research Fellow. His research interests include surface plasmon polaritons, metamaterials, and material studies in the terahertz regime.