Low-Threshold Bound State in the Continuum Lasers in Hybrid Lattice Resonance Metasurfaces

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Bound states in the continuum (BICs) have attracted considerable research attention due to their infinite quality factor ($Q$-factor) and extremely localized fields, which drastically enhances light–matter interactions and yields high potential in topological photonics and quantum optics. In this study, the room temperature directional lasing normal to a BIC metasurface is demonstrated with hybrid surface lattice resonances. Compared to the plasmonic nanolasers, the BIC metasurface lasers possess directional radiation and a larger emission volume. The high $Q$-factor resonance of BIC metasurface overcomes the limitation of a large mode volume in achieving low-threshold lasing. In addition, a design rule is proposed to prevent the occurrence of wavelength shift when the $Q$-factor changes; thus, the lasing thresholds for different BIC metasurfaces can be compared. In this work, the high localization ability of BICs is used to achieve the low lasing threshold (1.25 nJ) at the room temperature. The “light in–light out” diagram of the aforementioned laser based on simulations and experiments exhibits a large spontaneous emission coupling factor ($\beta = 0.9$) and the S-curve. The device developed in this study can be used in various applications, such as quantum emitters, optical sensing, nonlinear optics, and topological states engineering.

1. Introduction

In recent years, several studies have indicated that simple photonic structures possess bound states embedded into the continuum of scattering states.[1–3] Bound states in the continuum (BICs) were first demonstrated theoretically by von Neumann and Wigner in 1929.[4] These peculiar states possess the properties of lossless systems. Therefore, BICs have attracted considerable attention due to their strong localization property and infinite quality factor ($Q$-factor). The first experimental observation of the BIC effect was made by Henry et al. in a 1D grating;[5] however, the term BIC was not used in the paper of Henry et al. The aforementioned authors worked with quasi-BICs (Q-BICs) because the true BICs in the system were destroyed by the finiteness of the grating structure.[5] Subsequently,
a similar effect was observed in a 2D photonic crystal; however, no reference was made to BICs. After the publication of a review by Hsu et al. in 2016, researchers increasingly began to reference BICs. Because the fundamental mechanisms of metasurfaces and photonic crystals are similar, many studies have also observed BICs in metallic or dielectric metasurfaces. BICs can be switched to Q-BICs to generate radiation channels by breaking the geometric symmetry of metasurfaces. However, breaking the symmetry arbitrarily leads to an obvious shift in the resonance wavelength, which is unsuitable for a single gain material or BIC applications. The applications of BICs in many fields, especially topological photonics, have been widely discussed. By using a topological design to create BICs, different types of metasurfaces or photonic crystals can be used in various applications, such as photonic integrated circuits, sensors, nonlinear effect enhancements, and lasers. Optical BICs have attracted attention not only as resonators for lasing but also as sources of thermal emission. In particular, low-threshold lasers are suitable for BIC applications due to their infinite Q-factors. On the other hand, plasmonic nanolasers are also potential candidates for low-threshold lasers. They can shrink the lasing cavity to the nanometer scale and possess very low mode volume. Because of the low mode volume, the high Purcell factor low-threshold lasers can be achieved. However, the low emission volume, low output power, and nondirectional emission of nanolasers limit their applications. By contrast, BIC lasers can achieve a high Purcell factor and low-threshold characteristics even though they possess highly directional radiation and a high emission volume.

BIC metasurfaces possess an infinite Q-factor to compensate for their large mode volume. Moreover, BIC metasurfaces have a high Purcell factor, which enables them to be used for producing low-threshold lasers. Such designs endow lasers with a very high spontaneous emission coupling factor ($\beta$), which enables low-threshold lasing. Q-factor and threshold gain have major influences on the parameter $\beta$ of a laser. Studies have demonstrated laser applications of BICs through dark resonance of 2D periodic array nanostructures. However, most of these studies have not strictly demonstrated a low-threshold laser with a sufficiently high $\beta$ value to achieve a Q-factor resonance as high as that of a BIC. Because BICs have no emission channels, their output power is usually low. Thus, energy must be emitted from BICs, which are coupled to radiation channels. In the BIC lasers with periodic structures reported in previous studies, the emission direction is usually not in the normal direction (not at the $\Gamma$ point) because the Q-BICs are usually away from the $\Gamma$ point. Radiation channels (radiation losses) can be produced and the output power can be increased in the normal direction by breaking the geometric symmetry. However, if the geometric symmetry is arbitrarily broken, generating radiation channels systematically is difficult, and the wavelength of the BICs shifts. Hybrid surface lattice resonances (SLRs) in metasurfaces are suitable for studying the breaking of the geometric symmetry of BICs for the systematic generation of radiation channels.

In this study, Si$_3$N$_4$ metasurfaces with hybrid SLRs were used to investigate BICs with complete dark resonance modes. To determine the design rule and mechanism of BICs, simulations and experiments were performed with external and internal excitation. Dielectric metasurface low-threshold lasers with an extremely high coupling factor ($\beta = 0.9$) can be achieved using rhodamine 6G (R6G) and BICs with internal excitation and electric dipole lattice resonance (EDLR) at room temperature. Direct measurement results were obtained for the S-curve in the “light in–light out” diagram to analyze the spontaneous emission coupling factor, which can prevent confusion between amplified spontaneous emission (ASE) and lasing. A high $\beta$ value is helpful to prove the high Q-factor resonance, especially for the infinite Q-factor resonance of BICs. Such presentations are common for laser systems; however, these results have not been demonstrated with BIC lasers. Owing to the design of the EDLR, normal direction output (at the $\Gamma$ point) can also be achieved in this study. Moreover, the Q-factor of the lasing mode can be tuned by changing the particle size, which indicates that the threshold and output efficiency can be controlled by breaking the geometric symmetry. For further analysis of the laser threshold, the shift in the resonance wavelength during the change in Q-factor was prevented using the design rule of this study.

2. Design and Simulation

Numerous researchers have investigated the Fano resonance, especially for achieving high Q-factor resonance through topological design. When the Fano resonance occurs, constructive and destructive interferences create a Fano-shaped curve in the spectrum. When destructive and constructive interferences occur at the same wavelength, the clasp of the resonances generates a flat shape in the spectrum and possesses an infinite Q-factor. This state is called a BIC. To examine the characteristics of BICs, periodic structures are used to create high Q-factor resonances and a large performing area in experiments. Among the numerous periodic structure designs, nanoparticle arrays have been widely applied to create additional nanostructure resonances, which are also called SLRs. SLRs occur at wavelengths close to Rayleigh anomalies. When SLRs are generated, interference between waves radiated by each particle can create a strong resonance peak or dip in the spectrum. A high Q-factor Fano resonance can be achieved using two SLRs with a phase difference of $\pi$ to create BICs. Two antiphase SLRs can be generated by the hybrid lattice system, which has been demonstrated theoretically in the literature. In this study, hybrid SLRs were generated using Si$_3$N$_4$ nanobrick arrays because a high refractive index contrast and low material loss are essential for creating BICs.

Figure 1a displays the schematic of the Si$_3$N$_4$ hybrid lattice structure with active materials. In this study, EDLR was used to enhance photoluminescence because the electric field was localized outside the structure; thus, the active material covered the Si$_3$N$_4$ metasurface for the laser operation. Because the electric field polarization was along the y-direction, the phase variation is only presented along the x-direction at the wavelength of SLR, as displayed in Figure 1b. Figure 1b shows the phase distributions in a primitive unit cell when the wavelength is at lattice resonance, which is close to Rayleigh anomalies. To explain the mechanism of BICs, the phase difference between positions L, M, and R in Figure 1b must be determined. If particles of the hybrid lattice are placed at positions “L and M” or “R and M,” two independent SLRs can be created without any interference. By
contrast, if particles of the hybrid lattice are placed at positions L and R, two antiphase SLRs with strong destructive interference or Fano resonance are created. The aforementioned description is based on the assumption that a no near-field coupling effect exists between these two particles. By using the phase difference between different positions, BICs (completely dark resonance) can be created when two identical particles are present at positions L and R. Due to the infinite Q-factor of BICs, the electric field is localized in the plane of the nanobrick arrays. In the bottom of Figure 1b, the electric field intensity is decreased gradually by breaking the symmetry, which indicates that the resonance state is changed from BICs into Q-BICs. Figure 1c displays the variation trend of each particle. The asymmetry parameter ($\alpha$) can be obtained as follows

$$\alpha = \frac{a_b b_l - a_l b_b}{a_l b_l + a_b b_b} = \frac{S_l - S_R}{S_l + S_R}$$

The length and width of the left (right) nanobrick are denoted by $a_l$ ($a_b$) and $b_l$ ($b_b$), respectively. The range of $a_l$ ($a_b$) is from 270 nm (90 nm) to 180 nm (180 nm) and that of $b_l$ ($b_b$) is from 150 nm (50 nm) to 100 nm (100 nm). In the variation processes, both the $a_l/b_l$ ratio and $a_b/b_b$ ratio is 9.5. The value of $D_x$ is fixed at 200 nm, and the thickness of the Si$_3$N$_4$ nanobricks is 270 nm.

To compare the laser thresholds, the wavelengths of resonances must be the same while the asymmetry parameter is varied. To fix the resonance wavelengths for different asymmetry parameters, the size of left and right nanobricks are changed simultaneously for fixing the scattering cross-section (SCS) and preventing the shift of the resonance wavelength. Figure 2a displays different asymmetry designs. The type I design was used in this study. The type II and type III designs are general asymmetry designs that have been used in the references.[16,25,60–62] The resonant wavelength shift in the type I and III designs is larger than that in the type I due to the large variation in the SCSs of the type II and III designs when the asymmetry parameters are changed (Figure 2b). The SCS is the scattering cross-section of the structure that is influenced by the filling factor of each primitive unit cell. The filling factors of type III designs changes with the Q-factors; thus, a wavelength shift occurs for type III designs. For type II designs, although the filling factor is fixed, the resonance mode changes when the rotation angle is varied. Thus, the resonant SCS varies with changes in the Q-factor. According to the aforementioned discussion, the best method to fix the resonance wavelength is to prevent variations in the filling factor and resonant mode with the Q-factor. In the current study, we referred to type III designs and attempted to increase the size of one of the particles in the elementary cell when the other one was shrunk. Thus, type I designs maintain a constant filling factor and the fixed resonance mode to realize the changing of Q-factor without a shift in the resonance wavelength.

The simulated reflectance spectra obtained in color mapping are plotted in Figure 2c. In the simulation, the refractive index of the surrounding medium is 1.46 and the length of each primitive unit cell in the x-direction (y-direction) is 400 nm (300 nm). The wavelength of EDLR is fixed at $\approx$630 nm while $\alpha$ is changed. The insets in Figure 2c depict the electric field distributions for $\alpha$ = 0.8 and 0.05. The electric field intensity when $\alpha$ = 0.8 is weaker than when $\alpha$ = 0.05 because an $\alpha$ value of 0.05 is close to that of BICs. The color bars of the electric field in Figure 2c are depicted at a different scale because the intensity difference is too large. The field distributions for $\alpha$ = 0 are not displayed in Figure 2c because BICs cannot be excited through external excitation. This aspect is further discussed in the following section.

### 3. Characterization

The measured reflectance spectra and scanning electron microscopy (FEI Helios G3CX) images are displayed in Figure 2d (details in the Experimental Section). Structures A, B, and C represent designs with $\alpha$ = 0.73, 0.46, and 0, respectively. Reflectance spectra and images were collected using an optical microscope (BX51, Olympus) and a spectrometer (Kymera 193i, Andor) with a charge-coupled device (iVac 316 LCD-DD, Andor). To enable measurement close to normal incidence, a 5x objective lens (LMPLFLN 5X BD, numerical aperture (NA) = 0.13) was used to approximate 0° incidence. The simulated and experimental reflectance spectra are displayed in Figure 2c,d, respectively. Ripples (Figure 2d) were caused by the interference between the substrate and a cover slip containing dimethyl sulfoxide (DMSO). These interference ripples were different in each structure because the thickness of the DMSO varied between measurement positions. The reflectance did not reach unity in the experiment because of the loss resulting from the fabrication nonidealities ($\Gamma_F$ in Equation (S9) in the Supporting Information). The influence of the fabrication nonidealities can be described by the
Figure 2. a) Schematic of different designs for breaking the geometric symmetry. b) Normalized scattering cross-section (solid marker) and shift of wavelength (hollow marker) versus different asymmetry parameters for different symmetry breaking designs. c) Simulated reflectance spectra in color mapping. The insets display the near-field distribution for \( \alpha = 0.8 \) and 0.05. d) Measured reflectance spectra for \( \alpha = 0.73 \) (structure A), 0.46 (structure B), and 0 (structure C). The insets depict the optical reflection images and scanning electron microscopy images. The L-shaped marks in the optical images are fabricated to locate the semitransparent metasurface squares. The scale bar of optical image is 50 \( \mu \)m, and that of scanning electron microscope image is 500 nm.

equation derived from temporal coupled-mode theory (TCMT)\textsuperscript{[26,63–65]} Supporting Information). The variation in the \( Q \)-factor is illustrated in Figure 2d. The reflectance spectra exhibit sharp peaks when \( \alpha \) is close to 0. However, the feature of BICs (\( \alpha = 0 \)) cannot be observed in the reflectance spectrum. The reflectance spectra of structure C exhibited a BIC without reflectance peaks even when deviations of geometries occurred in its fabrication. This result was obtained because large-area measurement averaged out the ultrasharp reflection peaks, causing the disappearance of resonance. This phenomenon is clear when the \( Q \)-factor resonance is extremely high. However, even if a perfect symmetric structure (BIC) is achieved, the reflection signal cannot be observed because of the lossless property of the BIC. The optical images in Figure 2d depict the areas of the metasurfaces. The metasurfaces gradually become transparent in the reflection images when \( \alpha \) is close to 0. This is owing to BICs cannot be excited through external excitation. BICs can be excited through internal excitation; however, the resonance peak of BICs still cannot be observed due to the aforementioned reason.

Figure 3a,b displays the simulated spectra and electric field distributions for external and internal excitation, respectively. In the insets of Figure 3a, the electric field strength increases when \( \alpha \) decreases; however, the electric field strength becomes 0 when \( \alpha = 0 \). When imaging the BIC in an ideal cavity, external energy cannot arrive inside the ideal cavity; thus, the near-field distribution of \( \alpha = 0 \) does not exhibit any localized field. In Figure 3a,b, the reflectance spectra are depicted in the log scale, and the Fano shape displays the constructive and destructive interferences. These two types of interferences are close to each other when \( \alpha \) is close to 0. At the same time, the aforementioned two interferences overlap and display a flat spectrum without any feature. Figure 3b displays the spectra for internal excitation with dipole sources. The electric field intensity gradually increases even when \( \alpha = 0 \). The radiation loss spectra exhibit a similar result with external excitation because an ideal cavity can neither absorb any energy nor emit any energy outside the system. The relationship between the reflectance of resonance and the localized field intensity in Figure 3c can explain the mechanism of conversion from Q-BICs to BICs. These properties of BICs and Q-BICs can also be indicated by the decay time of the modes in the inset. In contrast to Q-BICs (\( \alpha = 0.1 \) and 0.2), BICs (\( \alpha = 0 \)) exhibit infinite decay time because of the property of lossless systems. The simulated near-field distribution of BICs (\( \alpha = 0 \)) and
Q-BICs ($\alpha = 0.1$) subjected to plane wave excitation and dipole excitation are illustrated in Figure 3d. In the case of plane wave excitation, BICs play the role of a transparent object without any coupling, whereas Q-BICs absorb energy and successfully generate resonance. In the case of dipole excitation, BICs trap all the energy without any radiation loss, whereas Q-BICs emit electromagnetic waves into free space.

To realize internal excitation in the BIC system, the gain material R6G was selected to cover the metasurface. Photoluminescence (PL) measurements were performed for the aforementioned material. The absorption peak of R6G was close to our laser excitation wavelength, which is beneficial for efficient laser pumping (Figure S1, Supporting Information). In addition, the resonance wavelength of our BIC system was designed to be red-shifted from the peak of the spontaneous emission (Figure S4, Supporting Information) to avoid the reabsorption of R6G in the lasing process.

The setup used for the reflectance measurement was also used to measure the PL and lasing spectra; however, the pumping source was replaced with a 532 nm pulse laser (MPL-III-532nm-1µJ-19101610, Changchun New Industries Optoelectronics Tech. Co.; details in the Experimental Section). Figure 4 illustrates the experimental PL results of three different samples. Figure 4a–c displays the PL spectra corresponding to structures A, B, and C in Figure 2, respectively, when the pumping power density is close to the lasing threshold. The insets illustrate the sizes of two nanobricks, and the symmetry parameter $\alpha$ decreases when the sizes of the two nanobricks are close to each other. Because the $Q$-factor increased with a decrease in $\alpha$, the full width at half maximum (FWHM) of the resonance peaks in the PL spectra below the threshold decreased when $\alpha$ was reduced. A decrease in the FWHM also demonstrates reduction of the number of radiation channels, which is in line with the lossless property of BICs. Figure 4d–f depicts the light-in–light-out (L–L) curves of structures A, B, and C, respectively. The insets depict the optical images and polarization intensity when the pumping power exceeds the threshold. The lasing threshold of BICs decreased from 10 to 1.3 nJ when $\alpha$ was reduced from 0.73 to 0 because the energy localized in the gain medium increased. Due to a decrease in the radiation loss, the output intensity decreased when $\alpha$ was decreased. The S-shaped L–L curve can be fitted by solving the following coupled rate equations for a laser system

\[
\frac{dn}{dt} = \eta P - A n - g_0(n - n_t) b
\]  

\[
\frac{db}{dt} = \Gamma \beta A n + \Gamma g_0(n - n_t) b - \gamma b
\]
where $n$ is the carrier density of R6G and $b$ is the photon density. The aforementioned equations are simplified, and only one SLR mode is considered in the BICs or Q-BICs. The parameter $\eta$ represents the injection efficiency of the carrier in R6G; $P$ is the pumping power density; $A = 1/\tau_r$, where $A$ is the average spontaneous emission rate of the R6G carrier and $\tau_r$ is the spontaneous lifetime of R6G; $g_0$ is the differential gain of R6G; $n_{tr}$ is the carrier density when the gain medium is transparent; and $\beta$ is the spontaneous emission coupling factor to be determined. Because Si$_3$N$_4$ is a lossless material in the visible range, the loss of SLR only comprises the radiation loss $\gamma$, which can be extracted from the linewidth of the reflectance spectra. The variable $\Gamma$ represents the confinement factor of SLR, which is calculated using a 3D mode solver. The following steady-state solution can be obtained when $dn/dt = 0$ and $db/dt = 0$

$$b = \frac{\Gamma \beta A n}{\gamma - \Gamma g_0 (n - n_{tr})}$$  \hspace{1cm} (4)

As displayed in Figure 4d–f, the calculated curves fitted well with the experimental L–L curves. Therefore, the $\beta$ factors for different metasurface lasers can be obtained by fitting the guided lines of L–L curves. The detailed calculation parameters for the dynamic rate equation are presented in Table S1 in the Supporting Information.

The variation in $\beta$ is also indicated by the intercept of the dashed and solid lines at the lowest pumping scale. The intercept difference between the dashed and solid lines presents the output difference below and above the threshold. The intercept difference was lower when the resonance was closer to that of BICs, which indicates that the laser was approaching low-threshold operation when BICs were formed. In principle, BICs are similar to perfect cavities because of the properties of lossless systems. According to the characteristics of lossless systems, the energy inside the BIC system cannot be radiated. Thus, the lasing signal of BIC should not be expected to be emitted. However, the lasing signal was detected in the experiment due to the artifacts produced during the fabrication process (Figure S2, Supporting Information) and the effects of noninfinite arrays [66] (Figure S3, Supporting Information). The defects in the structures can be observed in the optical images in Figure 4f. Piecemeal lasing areas indicate the size deviation of each nanobrick, which corresponds to the shift in the resonance wavelength of each nanobrick. Although deviations existed in each sample, the Q-factor of structure C was more affected by fabrication variation than the Q-factors of other structures were. High Q-factor resonances reduce the probability of overlap between different modes; thus, the resonances of the entire array become discrete and the lasing area of structure C is divided into multiple piecemeal lasing areas. The discrete lasing mode is illustrated in Figure S2 in the Supporting Information. By calculating the emission areas in Figure 4d–f,
the lasing areas of structures A, B, and C were determined to be 6000, 6000, and 1600 μm², respectively. Furthermore, the carrier density values of R6G at different pumping energy values were calculated by substituting the parameters in Table S1 in the Supporting Information into Equations (2) and (3) (Figure S5, Supporting Information).

The lasing area of structure C was considerably smaller than those of the other structures because of the artifacts produced during fabrication. A smaller lasing area results from a lower number of arrays. Figure S3 in the Supporting Information depicts the spectra of a nanobrick for different array numbers. Due to the limited number of arrays, BICs was not perfect and a radiation channel was formed. The polarization of emission is pure y-polarization, and the lasing optical images present x-direction parallel fringes. The polarization and parallel fringes are the evidence that the mode of stimulated emission is assisted by EDLR. Such EDLR assistance occurs because of the electric dipole oscillating in the y-direction. Therefore, an electric-magnetic wave is emitted in the x–z plane. The effect of the lattice only exists in the array of the x–z plane, and the influence of the array in y-direction is not obvious when the dipole is also in the y-direction.

Due to the very narrow resonance signal of BICs, lasing signals can be observed in the optical images of almost all the transparent samples. The oblique PL spectra were also measured to ensure that the lasing mode is assisted by EDLR (Figure S4, Supporting Information).

4. Conclusion

In this article, the characteristics of BIC metasurface lasers were demonstrated through simulations and experiments with Si3N4 metasurfaces with the R6G gain medium. Si3N4 metasurfaces with EDLRs were used to generate Fano resonance and create BICs through complete dark hybrid SLR. Nanolasers are a suitable candidate for use as general low-threshold lasers because of their low mode volume, which makes high β values relatively easy to achieve. However, the application of nanolasers is limited by their low emission volume, low output power, and nondirectional radiation. In the BIC laser developed in this study, the occurrence of complete dark hybrid SLR resulted in an infinite Q-factor and strong localized fields, which can compensate for the disadvantage of a large mode volume to achieve a high Purcell factor and β value (≈0.9). Such lasers with BIC metasurfaces, high β values, and low thresholds have not been studied. Because BICs are lossless states, external excitations cannot be used to generate resonance. To excite BICs, Si3N4 metasurfaces were covered with gain material, which can be treated as an internal excitation source. By using R6G, lasing was successfully achieved in the normal direction (at the Γ point) in the experiment. The threshold of the laser decreased gradually when the Q-factor was increased. Moreover, the low-threshold laser with BICs was experimentally demonstrated to have a large β value. The developed BIC laser had a low threshold of ≈1.25 nJ and a β value of ≈0.9 at room temperature. To analyze the lasing thresholds and radiation loss (emission efficiency) of different structures, their geometric symmetry was broken without causing a significant shift in the resonance wavelength. Although radiation loss can also be generated by truncating the array of the BIC structure, the rate of such loss is difficult to control and estimate. The results of this study provide a design rule for BIC metasurfaces with hybrid SLR to further design thresholdless or high-output-efficiency lasers. In addition to the emission volume and threshold, lattice resonance is highly dependent on the periodicity but not the geometry of a structure, which indicates that BIC metasurfaces with lattice resonance have a relatively high tolerance to fabrication inaccuracies of geometry. More importantly, our design can maintain laser polarization direction and far-field pattern during operation, which might be difficult for designs with asymmetric meta-atoms. In addition, this study reveals the optical interaction mechanisms of BICs when using internal and external excitations. The results of this study can be applied in high Q-factor lasers, optical sensing, and nonlinear optics enhancement integrated on a flat surface.

5. Experimental Section

Simulation of the External Excitation: Numerical FDTD was used to simulate the external excitation. Si3N4 bricks were placed in a unit cell. The simulation domain was corresponding to the period of each unit cell. Due to the array structure, boundary conditions in the x and y directions were the Bloch boundary condition. To eliminate the influence of structure, the optical refractive index of the surrounding medium was the same as quartz substrate (n = 1.47). To simulate the external excitation, the plane wave source was added at the top of the Si3N4 bricks array. The illuminating wave was propagating in the negative z-direction with a y-polarization electric field. To detect the reflectance (radiation loss), power flux monitors were placed at the top and the bottom of the Si3N4 bricks array. Note that, because the convergence condition in the FDTD (finite-difference time-domain) method is defined by the electric field intensity, the system that possesses vanishing radiation loss will take the longer time to run the simulation.

Simulation of the Internal Excitation: Similar to the simulation setting of external excitation, boundary conditions and power flux monitors were the same as the external excitation. Instead of the plane wave source, a dipole source was placed at the gap between each Si3N4 brick. Because the dipole was placed at the same plane of the Si3N4 metasurface, energy can be directly pumped in the mode. The electric field polarization direction of the dipole was in the y-direction. Similar to external excitation, the system that possesses vanishing radiation loss will take longer time to run the simulation. Importantly, the simulation does not converge when the structure supports a true BIC because the energy cannot be radiated or absorbed.

Fabrication: A plasma-enhanced chemical vapor deposition system (Oxford Plasmalab system 100) was used to deposit a Si3N4 thin film (thickness = 227 nm) on quartz substrate. Subsequently, a poly(methyl methacrylate) (PMMA)-A4 photoresist was spincoated on the Si3N4 thin film for the following lithography processes. Because the exposure equipment was an electron beam lithography (EBL) system, a conductive polymer (AR-PC 5090 by ALLRESIST) was spincoated on the PMMA photoresist to avoid charge accumulation. After exposure in EBL, rectangular nanohole arrays were formed. To create an etching mask, chromium layers (thickness ≈ 20 nm) were deposited on a patterned PMMA layer and then lifted off by acetone to generate a rectangular chromium array. To fabricate Si3N4 metasurfaces, an inductively coupled plasma etching system (EIS-700 by ELIONIX) was used for etching the Si3N4 layer. Finally, the chromium layer was removed through wet etching.

Measurement of the PL Spectra: In this study, R6G active material was used as the gain material. The R6G liquid was mixed with R6G powder and DMSO liquid, and the concentration of the R6G–DMSO liquid was approximated to 10 x 10^{-3} M. To surround the Si3N4 metasurfaces with R6G–DMSO liquid, R6G–DMSO was sandwiched between the Si3N4 metasurfaces and coverslips. A 532 nm pulse laser was used to pump and excite R6G. The repetition rate of the pulse laser was ≈4 kHz, and the pulse width was 1.24 ns. The PL information was collected using a confocal microspectrometer.
spectra were collected using an optical microscope (BX51, Olympus) and a spectrometer (JY Horiba iHR320, Andor) with a charge-coupled device (iVac 316 LDC-DD, Andor). A 5× objective lens (LMPF51 5X BD, NA = 0.13) was used to collect the signal from the normal direction.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

J.-H.Y. performed the sample fabrication, simulation, and optical characterization. D.N.M., P.S.P., and I.V.T. derived the theoretical equations of the initial optical characterizations. T.-C.L. provided the suggestion of laser characterization. T.-C.L. and C.-S.Y. joined the discussion. All the authors discussed the results and revised the manuscript.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

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