OPTICS

Low-threshold nanolasers based on miniaturized bound states in the continuum

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The pursuit of compact lasers with low thresholds has imposed strict requirements on tight light confinements with minimized radiation losses. Bound states in the continuum (BICs) have been recently demonstrated as an effective mechanism to trap light. However, most reported BIC lasers are still bulky due to the absence of in-plane light confinement. Here, we combine BICs and photonic bandgaps to realize three-dimensional light confinements, as referred to miniaturized BICs (mini-BICs). We demonstrate highly compact active mini-BIC resonators with a record high-quality (Q) factor of up to 32,500, which enables single-mode lasing with the lowest threshold of 80 W/cm² among the reported BIC lasers. In addition, photon statistics measurements further confirm the occurrence of the stimulated emission in our devices. Our work reveals a path toward compact BIC lasers with ultralow power consumption and potentially boosts the applications in cavity quantum electrodynamics, nonlinear optics, and integrated photonics.

INTRODUCTION

Nanoscale coherent light generations via stimulated emissions have been the scientific frontier of nanophononics, topological photonics (1–3), non-Hermitian physics (4–6), and optics in random media (7, 8). From the viewpoint of technology, the scalable creations of miniaturized lasers with low-power consumption enable a variety of important applications across optical interconnects (9, 10), biosensing (11), and far-field beam synthesis (12, 13). To achieve lasing at the extreme subwavelength scale, plasmonic cavities are usually used; however, they unavoidably suffer from high ohmic losses associated with metals (14, 15). While at the wavelength scale, dielectric nanolasers have been realized with the assistance of high-quality (Q) cavities using total internal reflection or photonic bandgaps (PBGs) (16–19), such as microdisks or photonic crystal (PhC) defect cavities. However, because of the limited lasing volume, their emission power is still not quite sufficient in driving the applications, for instance, on-chip optical communications. Recently, several designs such as random laser (20, 21), topological laser (22, 23), and moiré lattice laser (24) had been proposed to achieve lasing behavior at a 10-wavelength scale to best compromise the footprint and power.

Trapping light is no doubt the first step toward nanoscale lasers. As an emerging mechanism, bound states in the continuum (BICs) have been demonstrated as a very powerful tool to suppress out-of-plane radiations and consequently boost the Q factors of planar optical resonators (25, 26). In addition, the vectorial nature of BICs enables emissions of structured light from chip-scale devices, leading to ultrafast switchable nanolasers (27) and multiplexed nanolasers carrying orbital angular momenta (28). In principle, ideal BICs with infinite Qs only exist in periodic and symmetric structures. Therefore, early demonstrations of BICs used relatively large sample sizes ranging from a few tens to hundreds of periodic unit cell to maintain the high-Q feature (29, 30). One of the successful efforts in promoting the Qs is to topologically merge a set of BICs into the so-called super-BIC regime (31), which markedly minimizes the radiation loss and therefore substantially reduces the thresholds of BIC lasers (32).

To make nanolasers suitable for practical applications with higher output powers, we look for the BICs in miniaturized sizes, namely, a 10-wavelength scale. For active devices, the benefits of shrinking the mode sizes lies on two folds: First, in the spontaneous emission regime, the small mode volumes can greatly enhance the strength of light-matter interactions at a single-photon level, enabling the explorations of cavity quantum electrodynamics (QED) effects in both weak and strong coupling regimes (33); second, in the stimulated emission regime, miniaturized mode volumes produce strong light trapping that significantly reduces the lasing thresholds (34). However, the symmetry breaking or truncating the infinite size, transiting ideal BICs to quasi ones (35, 36), unavoidably lowers down the Q factors accordingly and makes them less favorable for low-threshold lasing. Thus, it is highly desirable yet an on-going challenge to achieve miniaturized BICs (mini-BICs) with high-Q factors.

In this work, we simultaneously use the BICs to suppress the out-of-plane radiation and use the PBGs to minimize the in-plane optical dissipations for achieving high-Q optical resonators with small footprints. We fabricated active GaAs membranes supporting mini-BICs with Qs as high as ~32,500 and exploited high-density InAs quantum dots (QDs) as optical gain materials. Laser oscillations at telecom O band under both continuous wave (CW) and pulsed optical pumping were observed with a threshold down to 80 W/cm², which is nearly two orders of magnitude lower than the previous reported BIC lasers (32). We systematically compare the lasing and nonlasing behaviors by using time-resolved and photon statistics measurements, further revealing the phase transition from spontaneous to stimulated emission in our devices. This

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RESULTS

Our laser cavity is based on PhCs consisting of a suspended GaAs membrane with periodically etched air holes in a square lattice array, as schematically shown in Fig. 1A. Three layers of high-density (10^{11} cm^{-2}) InAs QDs are embedded in the center of GaAs membranes as optical gain materials at telecom O band. The details of the QD epitaxial wafer are presented in Fig. S1. To tightly localize the light in three dimensions, we explored a recent proposal of mini-BICs in which the out-of-plane radiation is suppressed by BICs, while the in-plane light confinement is achieved by PBGs (37). The BICs associated with the PhCs in regime A (lattice constant a) is surrounded by heterogeneous PhCs in region B (lattice constant b) with a gap size of g in between. The band diagram of the designed structure is shown in Fig. 1B, in which the transverse electric mode A (TE-A) mode of PhCs in region A sits in the bandgap of PhCs in region B. Therefore, region B serves as highly reflective mirrors to suppress the in-plane light leakage from the mini-BICs residing in region A and, thus, significantly improves the Q factor and reduces mode volume V. In addition, the finite size of the cavity region A quantizes the continuous TE-A band into discrete modes with a mode spacing of \( \delta k = \pi/L \), where \( L \) is the cavity length of region A. Each mode can thus be labeled by a pair of integers \((p, q)\), indicating that its momentum is mostly localized near \( \pi n/a \); \( \pi q/L \) in the first quadrant of the momentum space. In Fig. 1C, we plot the highly momentum-localized modes of \( M_{11}, M_{12}/M_{21}, \) and \( M_{22} \) in the first quadrant of momentum space, in which \( M_{12} \) and \( M_{21} \), are degenerated in frequency because of the 90° rotation symmetry of the structure (C4). The near-field mode distributions reveal that the mini-BICs are highly spatially localized in the cavity region enclosed by the PBG mirrors, while such momentum space localizations result in highly directional emissions toward specific angles, as presented in Fig. 1D.

Experimentally, the mini-BIC patterns were defined on the electron beam (E-beam) resist using a 100-kV E-beam writer and then transferred to the GaAs layer via a chloride-based dry etch process. The GaAs membranes were released by selectively wet etching a 1500-nm-thick AlGaAs sacrificial layer underneath. The full fabrication flow of the devices is presented in fig. S2. Sharp resonances corresponding to the cavity modes were identified by measuring microphotoluminescence (~PL) from the cavity area at room temperature. The details of the homemade ~PL setup are presented in figs. S3 and S4. For comparison, the ~PL of the QD ensemble, indicating the optical gain spectrum, was obtained from the area without any cavity structures. As presented in Fig. 2A, by choosing a proper lattice constant \( a = 445 \) nm with 17 periodicities, \( b = 463 \) nm with 15 periodicities, and \( g = 455 \) nm, cavity modes are spatially aligned with the gain spectrum to facilitate the lasing oscillations. The sharp resonances measured from the cavity area were further zoomed in Fig. 2B, where the optical characteristics such as resonant wavelength and mode spacing agreed very well with the simulations in Fig. 1. In addition, we performed the far-field characterizations of each mode (insets in Fig. 2B), further revealing the vectorial nature and momentum localization of the mini-BIC modes, as predicted in Fig. 1D. The cavity resonances as a function of the PhC lattice constant a are presented in fig. S5, indicating that the measured cavity modes are associated to BICs in the PhCs. The dependence of the Q factor measured at the transparent excitation power on the constant a of the \( M_{11} \) mode is presented in Fig. 2C. As shown in the simulations, the Qs of mini-BIC can be engineered by tailoring the topological charges of the BICs via tuning the lattice constant of etched air holes.

![Fig. 1. Design of mini-BIC lasers. (A) Schematic of mini-BIC laser device consisting of a suspended GaAs thin membrane with periodically etched air holes. The PhCs in regime A is surrounded by other heterogeneous photonic crystal (PhCs) in region B. Three layers of QDs are embedded in the center of the membrane as optical gain materials. Inset: Cross section of the etched membrane with three layers of QDs. (B) The band diagrams of PhCs in regime A (with infinite size). The continuous bands (TE-A; represented by the red line) associated with ideal PhCs in regime A was quantized into discrete modes above the light line and located in the bandgap of PhCs in region B (represented by the yellow area). (C) The momentum distribution of each mode, modes are labeled as \( M_{pq} \) according to their momentum peak positions in the first quadrant. (D) The near-field (6 μm by 6 μm) and far-field patterns (30° by 30°) of four modes \( M_{11} \) to \( M_{22} \).](image-url)

We measured the ~PL spectra of one cavity under CW excitation with different excitation powers, as presented in Fig. 3A. Sharp cavity modes on a broad emission background can be identified under low excitation powers. By increasing the excitation power, \( M_{11} \) mode dominated the emission spectrum, and its linewidth reduced significantly. The strong suppression of other cavity modes under high excitation powers is due to the mode competition in the lasing process. The intensity and linewidth of the cavity mode \( M_{11} \) as a function of the excitation power were plotted in Fig. 3C. A sharp increase in the input-output (IO) curve together with reduction of the cavity linewidth, commonly believed as signatures of lasing, was observed, suggesting the occurrence of lasing oscillation.

To reliably identify the lasing oscillation, we characterized photon statistics of the emitted photons by measuring the second-order coherence (38, 39), which can rigorously quantify the quantum nature of the phase transition from spontaneous emission to stimulated emission. In Fig. 3E, at very low excitation powers, the emission was in a thermal state but only exhibited a
slight bunching behavior in $g^2(0)$ because of the relatively short coherence time of the emitted photons. With further increase of the excitation powers, the coherence time had significantly prolonged, and therefore, appreciable photon bunching effects were observed. As long as the excitation power crossed the lasing threshold of 41 μW with a beam diameter of 8.11 μm (see fig. S4), corresponding to a power density of 80 W/cm², the thermal state evolved toward a coherent state, and the $g^2(0)$ gradually lowered down to 1 when far above threshold. The photon statistics evidence together with the IO curve and linewidth reduction unequivocally demonstrated the realization of lasing oscillation in our mini-BIC devices.

On the other hand, there have been increasing debates on using the kink feature upon IO curves as the single criterion of nanoscale lasing, especially when the device experiences cavity QED effects (40–42). To that end, we characterized a less-optimal mini-BIC device similarly and presented the experimental data in Fig. 3 (B, D, F, and H). The main difference between the lasing and less optimal device (nonlasing) is the spectral alignment between the cavity modes and gain media (see more details in fig. S6). This nonlasing device also exhibited a “threshold” feature upon the IO curve and a linewidth narrowing behavior, which are very similar to the lasing device shown in Fig. 3 (A and C). However, no signatures of phase transition from thermal emission to a coherent state were observed from the photon statistics measurements. As shown in Fig. 3F, the $g^2(0)$ raised monotonously with the increase of the
excitation power, which indicates that the device was operating as a nano–light-emitting diode (nano-LED) instead of a nanolaser.

It is expected that the nonlasing device can also exhibit nonlinear output intensities upon the excitation power. Such a fact has been observed in a coupled single QD cavity system without involving lasing oscillations, as a consequence of the nonresonant couplings between different excitonic states of QDs and the cavity mode (43). At low excitation powers, the intensity of the cavity mode followed the linearly increased emission of exciton state formed in the single QD. Under high excitation powers, the cavity mode showed a superlinear power dependence because of the nonresonant couplings to the biexciton states whose intensities grow nearly as twice as the exciton states. Such a mechanism could also be responsible for the nonlinear output intensities of the many QD-cavity-coupled system, as observed in Fig. 3D. The linewidth narrowing shown in Fig. 3D is easier to be understood, because the active cavity experienced more absorption from the gain material under low excitation powers. With the increase of excitation power, the excited states of QDs get populated, resulting in the reduction of the cavity linewidth.

To investigate the possibility of turning the nonlasing behavior to a lasing oscillation with higher peak powers and less thermal effects, we further performed pulsed excitation on the same devices. The CW lasing device also exhibited clear a nonlinear IO curve and linewidth reductions, as presented in fig. S7. The pulsed $g^2(0)$ clear exhibited the phase transition from a thermal state to a coherent state when increasing the excitation power, as shown in Fig. 4 (A and C). On the contrary, the nano-LED device showed “laser-like” behaviors in terms of nonlinear increase in the IO curve and linewidth reductions, but its photon statistics remained in a thermal state across all the excitation power, as shown in Fig. 4 (B and D). One of the advantages of pulsed excitation scheme is that we are able to directly measure the photon lifetime (44), which can serve as additional evidence to distinguish the fast stimulated emissions from the relatively slow spontaneous emission. The decay curves under different excitation powers for the laser and LED devices are presented in Fig. 4 (E and F), respectively. Their emissions lifetimes were shortened during the increasing of pulse power, as quantitatively presented in Fig. 4G. For the lasing device, the lifetime reduced more rapidly than those of the nano-LED until the measurement was beyond the time resolution of our photon detectors. Such fast decay rates above threshold are strong indications of stimulated emissions. The lifetime of photons emitted by the nano-LED device also decreased, which is

**Fig. 4. Characterizations of lasing and nonlasing devices under pulsed excitation.** (A and B) Second-order correlation function at zero delay time $g^2(0)$ as a function of the excitation power. The lasing device exhibited a clear phase transition from spontaneous emission [a thermal state with $g^2(0) > 1$] to stimulated emission [a coherent state with $g^2(0) = 1$] (A). The nonlasing device remained in a thermal state [$g^2(0) > 1$] through all the excitation powers (B). The shaded areas W, X, Y, and Z represent the excitation powers at which the $g^2$ trace are presented. (C and D) Autocorrelation traces taken at the pump power densities marked in (A) and (B). (E and F) The photon lifetime traces of lasing and nonlasing devices under different excitation powers. (G) The lifetimes of lasing and nonlasing devices as a function of the excitation power. The orange dashed line indicates the time resolution of our measurement system.
expected because of the different carrier relaxation dynamics under high excitation powers (45). However, the photon lifetime of nano-LED reduced rather slowly as compared to the lasing device and became saturated (not reaching the time resolution limit of our measurement) at high excitation powers, which is more preferably to ascribe to spontaneous emission.

**DISCUSSION**

We have demonstrated III-V semiconductor active mini-BIC resonators with a quality factor as high as ~32,500, which enables the realizations of lasing oscillations with a record-low threshold of 80 W/cm² that is nearly two orders of magnitude lower than the state-of-the-art BIC lasers (see Table S1 for comparison). Both CW and pulsed lasing were unequivocally realized by systematically measuring the device characteristics including μ-PL spectra, IO curves, emission linewidth, photon statistics, and photon lifetimes. Our investigations suggest that any claim of nanolasing with cavity QED effects should be very careful and further comparisons between more advanced theory and experiments are indispensable. Moving forward, the vectorial nature of mini-BICs could be exploited to build chip-scale lasers capable of emitting coherent structured light for high-capacity optical communication (46) and high-dimensional quantum information processing (47). It is also highly desirable to implement the electrical injections in active BIC devices, as successfully demonstrated for suspended PhC defect lasers (48) and on-substrate surface emitting laser with less thermal effect (49, 50). From the perspective of applications, the realization of mini-BIC laser may immediately boost the development of on-chip cavity QED (51) and the integrated nonlinear photonics (52) in which high-Q factors and small mode volumes are highly beneficial.

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