

Stable Continuous-Wave Perovskite Lasers by Harvesting Triplet Excitons

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Abstract

Intrinsic spin statistics fundamentally hinder continuous-wave lasing in solution-processed organic–inorganic perovskites because triplet excitons cause singlet–triplet annihilation. By embedding P2F8 quasi-2D perovskite in a Fabry–Pérot cavity, we achieve strong light–matter coupling, producing a lower polariton branch that overcomes the energy barrier for triplet harvesting and opens a rapid radiative pathway. In vacuum, the triplet lifetime shortens from 1312 ± 135 ns to 75 ± 8 ns, suppressing annihilation. This enables room-temperature CW lasing with a threshold of 0.45 W cm^{-2} , Q factor of 4,583, beam divergence of 0.156° , and 95% intensity retention after 3,600 s. The same mechanism is validated in CsPbBr_3 and CsFAMA-IBr perovskites, providing a general route to convert triplet excitons from a loss channel into a gain resource.

INTRODUCTION

Solution-processed organic–inorganic semiconductors are promising for developing electrically pumped lasers^{1,2} because of their excellent photophysical properties. These attributes distinguish this new class of light emitters as leading candidates for next-generation on-chip optical sources². Rapid progress has been made in recent years, including the development of low-threshold CW lasers^{3,4} and even indirectly electrically injected dual-cavity lasers^{2,5}, representing important steps toward electrically pumped lasers. However, they suffer from an intrinsic spin-statistical bottleneck, which governs the formation of long-lived triplet excitons over singlet states at a 3:1 ratio^{6,7}. The continuous accumulation of long-lived triplet states triggers severe singlet–triplet annihilation (STA), quenching optical gain and even causing rapid lasing death under CW pumping⁸. Eliminating triplet losses is thus a core prerequisite for electrical pumping^{8,9}.

Halide perovskites are among the most promising gain materials because of their robust optical gain, high quantum yields, wavelength tunability and facile solution processing, making them competitive across optoelectronics^{10–14}. Owing to their high exciton binding energy¹⁵, quasi-2D perovskites can form stable excitons in quantum-confined perovskites at room temperature. This feature results in fast radiative excitonic recombination rates and hence higher photoluminescence quantum yield (PLQY) even at low carrier density¹⁵. Notably, stable room-temperature CW lasers have been demonstrated in quasi-2D perovskites, an important step toward the realization of electrically pumped laser diodes⁸.

To mitigate the performance decay from triplet accumulation, various strategies have been developed for managing triplet excitons, including indirect electrical pumping via dual-cavity architectures^{2,16}, heavy-atom-assisted acceleration of reverse intersystem crossing (RISC)^{17,18}, and the incorporation of triplet quenchers^{7,8,19} or thermally activated delayed fluorescence (TADF) sensitizers^{20,21}. As an example, $\text{PEA}_2(\text{CH}_3\text{NH}_3)_{n-1}\text{Pb}_n\text{Br}_{3n+1}$ ¹⁵, with a pure phase $n = 8$ perovskite, which is typically referred to as P2F8, shows high optical gain and bound excitonic recombination, making it promising for use as a laser gain material. Oxygen-assisted triplet quenching enables CW lasing in P2F8, but this approach fails

in vacuum or nitrogen, as required for device encapsulation⁸. Indirect electrical pumping via dual-cavity structures avoids the triplet state but increases device complexity¹⁶. This bottleneck similarly limits organic and quantum-dot lasers. Polariton lasing via strong light–matter coupling has been pursued for coherent emission, but polariton devices still suffer from triplet-mediated annihilation losses and decoherence under continuous excitation. Unlike those prior efforts targeting polariton-mode coherent emission, here we employ strong light-matter coupling not to realize polariton lasing itself, but as a photophysical tool to mitigate triplet-related losses.

Here, we address the intrinsic triplet bottleneck by exploiting a lower-polariton (LP) channel formed via strong light–matter coupling in a high-Q DBR cavity. The resulting LP branch reshapes the exciton energy-level distribution. Importantly, such energy rearrangement alone cannot overcome spin-selection constraints, and intrinsic perovskite spin-orbit coupling (SOC) enables spin mixing²² to mediate population transfer toward singlet-derived polaritonic states^{22,23}. This provides an ultrafast radiative channel for triplet depopulation. The triplet lifetime is shortened from 1312 ± 135 ns to 75 ± 8 ns under vacuum. Under vacuum, room-temperature CW perovskite DBR lasers operate with a threshold of 0.45 W cm^{-2} , a Q-factor of 4583, and a beam divergence of 0.156° , retaining 95% of their intensity after 3600 seconds of continuous operation. We further validate the generality of this mechanism in CsPbBr₃ and CsFAMA-IBr (Cs_{0.05}(FA_{0.95}MA_{0.05})_{0.95}Pb(I_{0.95}Br_{0.05})₃) perovskites, where the triplet lifetimes are compressed from 5.4 μ s and 11.0 μ s to 365 ns and 473 ns, respectively. Harvesting triplet excitons via the lower polariton branch provides a general strategy for advancing direct electrically pumped lasers.

RESULTS AND DISCUSSION

Our triplet-management mechanism is based on exciton–polaritons formed under strong light–matter coupling (Fig. 1a). In bare P2F8 films, the lowest singlet state, S₁ (≈ 2.348 eV), lies only 20 meV above the triplet state, T₁ (≈ 2.328 eV). Despite this small singlet–triplet energy gap, the structural reorganization associated with T₁-to-S₁ conversion introduces a substantial activation barrier, resulting in long-lived triplets. They therefore accumulate under CW excitation and deplete the singlet population through singlet–triplet annihilation (STA). This loss process becomes particularly severe under vacuum, where oxygen-mediated triplet quenching is absent and ultimately results in lasing death. A phase-pure quasi-2D P2F8 perovskite, (PEA₂(CH₃NH₃)_{n-1}Pb_nBr_{3n+1})₁₆, was prepared using a solvent-sieving strategy²⁴ (Fig. 1b, c). Because the triplet level of the PEA ligand lies above the perovskite T₁ state, triplet

transfer to the ligand is energetically unfavorable and provides no competitive relaxation pathway. Triplet depopulation under vacuum is therefore dominated by slow intrinsic relaxation, which is consistent with the suppressed decay expected in the Marcus inverted regime. When oxygen is present as a quencher⁸, long-lived triplet accumulation disappears. The polariton-mediated triplet-harvesting mechanism was initially established in a broadband Ag-mirror Fabry–Pérot cavity and subsequently transferred to a high-Q DBR cavity for laser operation. When the cavity photon mode (Cav) is tuned to resonate with the exciton, fitting of the dispersion curve for P2F8 in Ag-FP cavity yields a mean exciton energy $E_{\text{ex}} = 2.351$

± 0.004 eV (Extended Data Table 1). This value closely matches the singlet state energy $S_1 \approx 2.348$ eV of P2F8 but deviates significantly from the triplet state energy $T_1 \approx 2.328$ eV⁸. The coupling strength (Extended Data Fig. 1) exceeds the system's losses, and the coherent interaction shows anti-crossing and generates a new light–matter hybrid state known as the exciton–polariton state²⁵, with the system splitting into two polariton states: the upper polariton (UP) and the lower polariton (LP)²⁶. To further confirm the role of triplet accumulation in gain quenching, a P2F8 DFB laser under nitrogen and oxygen conditions was also investigated (Extended Data Fig. 2). With the injection of nitrogen into the P2F8 DFB laser (Extended Data Fig. 2), the lasing emission disappeared, which is the so-called lasing death. However, when the inert gas is removed from the DFB and it operates under oxygen conditions, the laser reappears (Fig. 1d–f).

Angle-resolved measurements further confirm the distinct dispersion of these hybrid states (Fig. 1g–h). Strong light–matter coupling affects the semiconductor band structure and electron distribution^{27,28}. The LP branch provides an ultrafast radiative route for triplet harvesting. In the strongly coupled cavity, this SOC-assisted spin mixing enables population transfer from dark triplet excitons toward the singlet-character lower-polariton state, providing a triplet-harvesting pathway²². From coupled-oscillator fitting, an exciton fraction of 23.42% was obtained for 0° polaritons (Fig. 1i).

Having established the detuning-dependent polariton characteristics and triplet-harvesting mechanism in Ag-mirror cavities, we next transferred this mechanism to a high-Q DBR cavity for laser operation. Angle-resolved measurements further confirm the dispersion of these hybrid states across different exciton–photon detuning energies (Fig. 2a–b and Extended Data Table 2). The lower-energy LP state enables the long-lived triplet excitons to be harvested through the SOC^{22,29}. In the weakly hybridized reference device shown in Fig. 2c, no clear ant crossing or strongly mixed lower-polariton branch is observed, and the optical response predominantly follows the bare-cavity mode. Below the polariton condensation threshold (P_{th_EPC}), the polariton emission follows the profile of the LP dispersion over a wide range of angles (Fig. 2d). Under a CW pump density above P_{th_EPC} , the polaritons condense into the ground state, yielding a much narrower energetic and angular distribution at the bottom of the LP branch (Fig. 2f–g). Angle-resolved spectroscopy at varying CW pump densities reveals that the characteristic lower-polariton dispersion remains observable throughout the investigated excitation range, indicating that the system retains strong light–matter coupling under these conditions with a Hopfield exciton fraction of 30.1% (Fig. 2h). To probe triplet dynamics, picosecond transient measurements (Fig. 2i) reveal an ultrafast lower-polariton radiative channel³⁰ with a lifetime of 10.23 ps.

To investigate triplet-state dynamics, we performed nanosecond transient absorption spectroscopy on perovskite oxygen triplet quenching (Fig. 3a), STA-affected bare perovskite (Fig. 3b), weak coupling (Fig. 3c) and four P2F8 in Ag-mirror FP cavities (Fig. 3d–e and Extended Data Fig. 4). For Ag-mirror FP cavity ($\Omega = 336$ meV), an additional bleaching feature centered at approximately 607 nm is observed in the transient absorption spectrum (Fig. 3e, f), which is consistent with the signature identified in the angle-

resolved reflectivity measurements (Fig. 1h). A common bleaching feature centered at ~533 nm is observed across all the samples (Extended Data Fig. 4).

We adopted a 5 μ s time window to test the perovskite with STA and the four P2F8 in Ag-FP cavities because the lifetime of triplet excitons was reported to exceed 1 μ s. As illustrated in Fig. 3a–f and Extended Data Fig. 4a–b, the transient absorption spectra reveal a consistent blue bleaching peak at approximately 533 nm across all the samples, including the film and the cavity with various Rabi splitting (72 meV~460 meV). As summarized in Extended Data Table 3, triexponential fitting was implemented to deconvolve the transient bleaching dynamics into three physically meaningful decay channels with characteristic lifetimes τ_1 , τ_2 and τ_3 . Specifically, τ_1 corresponds to ultrafast radiative recombination of spatially localized bound multiexcitons constructed from singlet excitons, τ_2 originates from monomolecular radiative recombination of free band-edge singlet excitons, and the longest-lived component τ_3 is assigned to triplet exciton recombination. The assignment of τ_3 to triplet-exciton population decay is supported by its microsecond-scale lifetime and its selective acceleration upon exposure to molecular oxygen, a well-established triplet quencher. Consistently, CW lasing disappears after replacing oxygen with nitrogen and recovers upon re-exposure to oxygen, linking the oxygen-sensitive triplet reservoir to gain quenching. The perovskite with the STA yields a triplet-exciton lifetime of 1312 ± 135 ns under vacuum. This energetic configuration is consistent with a strongly suppressed triplet-to-singlet transfer pathway. This energetic shift induced by the LP branch (2.04 eV, ~288 meV below T_1) moves the system from the inverted regime into the normal Marcus regime, driving the exponential factor from a strongly suppressed value in the inverted regime toward unity according to the Marcus rate expression. This condition was theoretically predicted as a route to overcome the inherent dilution of polariton-mediated triplet harvesting but remained experimentally unrealized because their organic test molecule resided in the normal Marcus regime²². Our perovskite system naturally satisfies the inverted-regime condition, providing the first experimental verification of this predicted mechanism. Across the four P2F8 in Ag FP cavities, the long-lived triplet-associated decay time τ_3 does not vary monotonically with vacuum Rabi splitting. P2F8 in Ag FP ($\Omega = 336$ meV), has the shortest τ_3 of 75 ± 8 ns, compared with 183 ± 16 ns for P2F8 in Ag FP ($\Omega = 410$ meV), 205 ± 18 ns for P2F8 in Ag FP ($\Omega = 460$ meV), and 298 ± 16 ns for P2F8 in Ag FP ($\Omega = 72$ meV) under vacuum. The nonmonotonic dependence of τ_3 on Rabi splitting is consistent with that of Marcus-type transfer, where the rate is maximized when the triplet–LP energy offset matches the effective reorganization energy²². Strong coupling creates a lower-energy LP acceptor channel, converting the otherwise activation-limited triplet-to-singlet transfer into an energetically downhill process. The minimum τ_3 observed for P2F8 in Ag FP ($\Omega = 336$ meV) is therefore consistent with a favorable polaritonic energy shift for triplet harvesting. Under vacuum, τ_3 is approximately ninefold shorter than that of the oxygen-quenched control (686 ± 10 ns) (Extended Data Fig. 4c and Extended Data Table 4).

We further extracted transient absorption bleach profiles recorded at a delay of 1.8 ns from Figs. 3b and 3e. The trace collected for the P2F8 in Ag-FP ($\Omega = 336$ meV) shows two distinct bleach features centered at 533 nm and 607 nm, whereas the P2F8 in vacuum perovskite reference displays only a single bleach

signal at 533 nm. An additional bleaching feature emerges at ~607 nm exclusively in the strongly coupled cavity. Its spectral position (~2.04 eV) coincides with the LP energy independently determined from the angle-resolved reflectivity, supporting its assignment to the lower-polariton state. To elucidate the complex carrier recombination pathways, the decay kinetics monitored for the ~533 nm bleach feature were analyzed using a triexponential model. The fitting parameters are summarized in Extended Data Table 3. After incorporation into the microcavity, the triplet exciton fraction (A_3) decreases from 11.2% (perovskite with STA) to 5.7% (P2F8 in Ag-FP ($\Omega = 336$ meV)). The A_2 component increases from 37.7% in P2F8 in vacuum to 54.2% in P2F8 in Ag FP ($\Omega = 336$ meV), whereas the triplet-associated A_3 component decreases from 11.2% to 5.7%. Similarly, the total singlet-associated amplitude, $A_1 + A_2$, increases from 88.8% to 94.3%.

Nanosecond transient absorption (TA) spectroscopy provides evidence that accelerated triplet depopulation is associated with the LP channel. The extracted τ_3 values allow a direct comparison of triplet dynamics across the sample series (Extended Data Table 4). The results of a set of control experiments in which different competing quenching pathways were separated are shown in Fig. 3h. Neither extrinsic quenching induced by oxygen exposure nor the weakly coupled microcavity reference can replicate the pronounced triplet-decay acceleration seen in P2F8 in Ag FP ($\Omega = 336$ meV). The close match between the triplet kinetics of the P2F8 in vacuum film and the weakly coupled cavity rules out trivial cavity-associated artifacts. Large-magnitude triplet-lifetime shortening occurs only within P2F8 in Ag FP ($\Omega = 336$ meV). We turn to the pump-fluence-dependent TA measurements in Fig. 3i to further elucidate the density-dependent decay mechanisms for our two sets of samples (Extended Data Table 5). Increasing the excitation fluence accelerates triplet decay for both the P2F8 in vacuum reference film and P2F8 in Ag FP ($\Omega = 336$ meV). For bare P2F8 in vacuum films, faster decay arises from triplet-triplet annihilation. In the strongly coupled P2F8 in Ag FP ($\Omega = 336$ meV), by contrast, accelerated triplet depopulation stems from more efficient triplet-to-polariton harvesting at higher excitation density. To establish the generality of this polariton triplet harvesting scheme, as shown in Extended Data Figs. 5–6, we further investigated CsPbBr_3 and $\text{Cs}_{0.05}(\text{FA}_{0.95}\text{MA}_{0.05})_{0.95}\text{Pb}(\text{I}_{0.95}\text{Br}_{0.05})_3$ cavities. The CsPbBr_3 film, which suffers from severe singlet-triplet annihilation (CSTA), displays an intrinsic triplet exciton lifetime of 5400 ± 791 ns, which is compressed to 365 ± 53 ns upon strong coupling, redirecting triplet excitons into the lower polariton branch via polariton-enhanced triplet harvesting. With respect to the CsFAMA-IBr film with severe singlet-triplet annihilation (FSTA), the triplet lifetime reaches 10961 ± 606 ns and is shortened to 473 ± 71 ns via LP modulation (Extended Data Table 6). The analogous kinetic behavior observed in the P2F8 system is reproduced across both material platforms, demonstrating that polariton-facilitated triplet depletion constitutes a broadly applicable strategy to manipulate triplet excitons. While Ag-mirror cavities provide an ideal platform for elucidating polariton-mediated triplet management, practical laser operation requires a cavity with high optical feedback and low loss. Therefore, we fabricated a high-Q DBR cavity to convert the recovered optical gain into stable CW lasing.

In this device, a 148 nm-thick PMMA layer was spin-coated onto the P2F8 flake, which encapsulated the fragile perovskite to retain its intrinsic optical quality and integrate with the perovskite film to sustain

Fabry–Pérot oscillations (Fig. 4a). The evolution of the emission spectra measured at 0° with CW pump densities ranging from 0.02 to 1.5 W cm⁻² is shown in Fig. 4b. The integrated emission intensity from the ground-state emission window as a function of the CW pump density on a log-log scale is shown in Fig. 4c. Below the photon lasing threshold ($P_{th_laser} \sim 0.45$ W cm⁻²), a sublinear light-in–light-out dependence is observed. With the CW pump density exceeding P_{th_laser} , a superlinear increase is observed.

Remarkably, the light-in versus light-out curve under CW pumping closely resembles that under pulsed laser excitation (Extended Data Fig. 7). However, the slightly slower emission saturation with increasing CW power than with pulsed excitation can be attributed to a lower reservoir density. The fabricated P2F8 in DBR FP laser yields a Q factor of 4583 (Fig. 4d). The stimulated emission lifetime is 48 ± 0.5 ps, which is drastically shorter than the 1020 ± 11 ps below the threshold of the P2F8 in DBR FP laser (Fig. 4e).

These performance characteristics are

consistent with the polariton-mediated triplet management established in Fig. 3. The operational stability of the P2F8 in DBR FP laser was evaluated under uninterrupted continuous-wave excitation at 1.2 times the lasing threshold. Three independently fabricated devices were tested under vacuum conditions without repositioning the excitation spot, and their emission intensities were normalized to the respective initial values. All three devices retained approximately 95% of their initial emission intensity after 3,600 s of continuous operation, with no appreciable shift in the lasing peak (Fig. 4f). The sample temperature was actively maintained at 20 °C. Well-defined spatial coherence can be visualized from the near-field images of the P2F8 in DBR FP laser, as shown in Extended Data Fig. 8a. After crossing the threshold, a high-brightness spot emerged, whereas dim and diffuse emission was observed below the threshold. A clear, well-defined output beam projected at 30 cm (Extended Data Fig. 8b) confirms the spatial coherence of the laser emission. The emission is linearly polarized, with a degree of polarization of 81% (Extended Data Fig. 8c). After storage in air for 300 days, the device retained its characteristic narrow lasing emission under CW excitation (Extended Data Fig. 9). The temporal coherence properties of the emission from the microcavities were examined using a Michelson interferometer. The first-order coherence function $g^1(\tau)$ (Extended Data Fig. 10) is given by the visibility of the interference fringes. At zero-time delay ($\tau = 0$ ps) above the threshold, the collected interference pattern shows a maximum fringe visibility contrast of 68%. A far-field pattern with a fundamental Gaussian beam mode was also characterized under lasing conditions, as shown in Extended Data Fig. 11, with a transverse (FWHM) divergence angle of $\sim 0.156^\circ$. The emission wavelength was finely tuned from 547.93 nm to 553.00 nm by adjusting the PMMA spacer thickness, with the range limited by the P2F8 gain bandwidth (Extended Data Fig. 12 and Extended Data Table 7). In contrast, a reference DFB laser without triplet harvesting degrades by nearly 90% under identical conditions because of uncontrolled STA⁸.

The polariton-assisted triplet depopulation time is only 75 ± 8 ns, substantially shorter than that in bare P2F8 films, thereby limiting the build-up of the triplet reservoir and the resulting loss of optical gain. To separate this triplet-harvesting effect from passive cavity confinement, we compared devices with matched Q factors (Fig. 4g–i). For this analysis, we used a Q-matched device rather than the optimized device described above. Triplet harvesting reduced the CW lasing threshold from 18.88 W cm⁻² in the

triplet-quenched reference laser to 3.45 W cm^{-2} , corresponding to a 5.47-fold reduction. Because the two devices provide comparable passive optical confinement, this reduction can be linked directly to the suppression of triplet accumulation and the consequent recovery of optical gain. We next examined the nature of the coherent emission to distinguish polariton Bose–Einstein condensation from conventional photon-mode lasing. Under pulsed excitation, four independent measurements yielded a threshold of $0.04 \mu\text{J cm}^{-2}$, above which sharp, narrow emission peaks emerged. However, under pulsed excitation, the polariton condensation threshold is approximately $0.24 \mu\text{J cm}^{-2}$ (Extended Data Fig. 13), whereas under CW excitation, it is approximately 1.2 W cm^{-2} (Fig. 2f). These observations indicate that coherent emission arises from conventional photon lasing rather than polariton condensation. In this work, the strongly coupled exciton polaritonic state formed plays a major role in efficiently managing triplet excitons. The device performance demonstrates that polariton-mediated triplet exciton management not only enables CW lasing but also yields a pulsed laser with a very low threshold and high spectral purity.

All of these devices are fabricated using pure-phase perovskite. To verify the generalizability of this polariton-facilitated triplet-harvesting strategy, we implemented an identical strong-coupling architecture within mixed-phase quasi-2D perovskite films. The resulting microcavities sustain robust CW lasing, featuring a lasing threshold of 2.1 W cm^{-2} and a quality factor of 1100 (Extended Data Figs. 14–16). These observations validate that the underlying photophysical mechanism is not exclusive to the single-phase P2F8 material system. The observation of similarly accelerated triplet depletion in compositionally distinct perovskites further suggests that this strategy is not restricted to P2F8. More broadly, strong light–matter coupling provides a route to regulate long-lived, gain-quenching, excited-state reservoirs in continuously driven semiconductors. Together, these orthogonal measurements establish an experimental link between polariton-assisted triplet depletion and the recovery of optical gain in continuously driven perovskite microcavities. The selective oxygen sensitivity of the long-lived transient, together with the reversible loss and recovery of lasing under nitrogen and oxygen, supports its assignment to a gain-quenching triplet reservoir. Whereas weakly coupled cavities retain triplet kinetics comparable to those of bare films, strong coupling accelerates the depletion of this reservoir by approximately 17.5-fold. This accelerated depletion suppresses singlet–triplet annihilation and recovers optical gain, enabling stable CW lasing under vacuum.

CONCLUSION

In summary, strong coupling between the singlet exciton and the cavity photon mode opens a rapid triplet-harvesting pathway through exciton–polariton formation in quasi-2D perovskites. The resulting dynamics are consistent with spin–orbit-coupling-assisted transfer into the polariton manifold. By limiting triplet accumulation and the associated singlet–triplet annihilation, this pathway prevents the lasing death observed in the reference system and sustains CW lasing under vacuum for more than 3,600 s. At room temperature and under vacuum, the DBR laser operates with a threshold of 0.45 W cm^{-2} , a Q factor of 4,583 and a beam divergence of approximately 0.156° . Comparable polariton-induced shortening of the triplet lifetime was observed for CsPbBr_3 and CsFAMA-Ibr . Because this approach

requires neither tailored molecular energy-level alignment nor external triplet scavengers, it offers a potentially general route toward electrically pumped perovskite lasers.

METHODS

Device fabrication

DBR mirrors with an alternating $\text{Ta}_2\text{O}_5/\text{SiO}_2$ structure had a reflectivity exceeding 99.99% at the central wavelength of 550 nm. The high reflection ($R > 99.99\%$) range of the DBR mirrors covers the entire photoluminescence (PL) band, and simultaneously, the high transmittance ($T > 95.0\%$) remains in the range of 343 to 400 nm for efficient excitation of the perovskites by a 343 nm pumping laser. The quartz substrate has a thickness of 1 mm. The PL spectrum of the quasi-2D heterostructure perovskite thin film is in the high-transmittance region of the transmittance spectrum of the DBR. The DBR mirrors were successively cleaned with deionized water in the ultrasonic cleaning machine. An appropriate amount of P2F8 solution was dropped on the upper surface of the DBR mirror, after which the toluene was allowed to evaporate. Subsequently, a total PMMA spacer thickness of ~ 148 nm (~ 74 nm on each side) was spin-coated on the exfoliated P2F8 flake to cover the fragile perovskites, preserving their intrinsic optical quality, and merged with the perovskite layer to support Fabry–Pérot oscillation. After that, another DBR, which was covered with a layer of PMMA, was used as the top DBR to form the VCSEL. The two DBRs are aligned, and uniform pressure (5 MPa) is applied to the custom-made planar pressing device through two polytetrafluoroethylene (PTFE) gaskets (diameter of 1.5 cm and thickness of 2 mm). The pressure is exerted using a custom-built press equipped with a pressure sensor; the pressure is increased by adjusting a knob and applying a force of 884 N onto a circular gasket with a diameter of 1.5 cm, which yields a pressure of 5 MPa (calculated on the basis of the force and the gasket's contact area). The VCSEL was sealed by applying optical epoxy resin to the edges of the DBR mirrors. Finally, the VCSEL was pressed and exposed to UV light for 24 h.

P2F8 thin film properties

The PL of the perovskites (Fig. 1c) was obtained with a TPL300 microscopic fluorescence spectrometer (Dalian Time-Tech spectra) that had a spatial resolution of 1 μm . A 405 nm continuous wave laser (PIL1-040-40FC, NKT Photonics) with a CW pump density of 4 W cm^{-2} was used as a pumping source. The absorption spectra of the perovskite films were obtained at room temperature by using an R1-A-UV (Fuxiang Instruments, Shanghai) and were collected using a PG2000-PRO-EX spectrometer. The XRD data were acquired on a DX-2700 diffractometer (Dandong Haoyuan) by using a sampling time of 0.1 s. Optical images of the perovskite and PMMA nanoplatelets were recorded using an optical microscope (LV150, Nikon). The atomic force microscopy image and nanoplatelet thickness were then measured using an FM-Nanoview 1000 AFM (FSM Precision).

Lasing and Spectra Measurements

A 325 nm CW solid-state laser (OBIS LX 325) and a frequency-tripled, femtosecond laser (343 nm, 60 kHz repetition rate, 230 fs pulse width; Carbide, Light Conversion) were used to pump the lasers. Transmission measurements revealed that the DBR mirrors exhibited a transmittance of approximately 96% at both pump wavelengths (325 and 343 nm). We used an objective lens (20×, numerical aperture = 0.4) to focus the pump beam to a 90-μm-diameter spot (325 nm, CW) and an 80-μm-diameter spot (343 nm, pulse), which corresponds to the width where the intensity falls to $1/e^2$ of its peak value on the intensity profile. All the experiments were conducted at room temperature under vacuum conditions. Individual spectra were recorded using a spectrometer with a resolution of 0.04 nm (Horiba iHR550), and emission images were collected using a high quantum efficiency air-cooled sCMOS camera (Dhyana95, Tucsen).

Polarization characteristics of the device

The polarization characteristics were measured using the same excitation setup described above. We used a focal lens ($f = 20$ cm) to focus the pump beam to a 90-μm-diameter spot. Individual spectra were recorded using a spectrometer with a resolution of 0.25 nm (PG2000Pro, Ideaoptics). All the experiments were conducted at room temperature under vacuum conditions. Polarization control was achieved using Thorlabs polarization devices, including a mounted wire grid polarizer (WP25M-UB1, Ø25.0 mm, 300 nm–3.2 μm) and super achromatic wave plates (SAQWP05M-1700 for quarter-wave retardance over 325–1100 nm).

Optical Spectroscopy Characterization

The momentum space and real-space spectroscopy measurements are collected by a custom-built time-resolved/steady-state photoluminescence setup in the Fourier imaging configuration. All angle-resolved spectroscopic characterization was performed under laser excitation. Angle-resolved reflectance spectra were acquired with a 100× high-numerical-aperture microscope objective ($NA = 0.7$), providing an angular detection window of $\pm 44.4^\circ$, with pumping delivered by a 400 nm pulsed laser. For angle-resolved transmission measurements, an objective with an $NA = 0.4$ was adopted to cover an angular range of $\pm 25^\circ$, where the excitation sources included a 343 nm pulsed laser and a 325 nm CW laser. The signal was recorded using a spectrometer with a resolution of 0.04 nm (Horiba iHR550) with a 1200 gr/mm grating and a 256×1024 pixel liquid-nitrogen-cooled charge-coupled device (CCD).

Nanosecond Transient Absorption Spectroscopy

Nanosecond transient absorption spectroscopy was performed by using a femtosecond laser (Ultrafast Transient Absorption Setup, TA100, Dalian Chuangrui Spectroscopy) operating at 380 nm and a repetition rate of 1 kHz as the pump source and probed with a broadband white-light continuum (450–650 nm). The nanosecond-resolved measurements had a temporal resolution of 1.8 ns. Measurements were performed at normal incidence with the cavity mode resonant with the P2F8 exciton. Polarization of the probe pulse was set to TE mode. The measurements were performed at room temperature. The signals were recorded using low-energy ($7.28 \mu\text{J cm}^{-2}/\text{pulse}$) pumping pulses.

Ultrafast transient-reflectivity spectroscopy and time-resolved photoluminescence measurements

Ultrafast lower-polariton dynamics were measured using a custom-built microscopic *k*-space transient-reflectivity setup with a temporal resolution of approximately 200 fs. The sample was excited at near-normal incidence using a pulse laser (1 kHz repetition rate, with an approximately 200 fs pulse width). A delayed broadband white-light continuum was used as the probe, and the reflected signal was collected in a Fourier-imaging configuration. Emission excited by a 343 nm pulsed laser (60 kHz) was time resolved using a TCSPC module (PicoQuant, PicoHarp 300) and a SPAD detector (MPD, PD-100-CTE), with an instrument response function of 40 ps (FWHM).

Numerical Calculations

COMSOL Multiphysics was employed to simulate the effective refractive index and photon resonant modes of the DBR laser, where PMMA serves to tune the optical cavity length.

Declarations

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Data availability

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

References

1. Whitworth, G. L., Dalmases, M., Taghipour, N. & Konstantatos, G. Solution-processed PbS quantum dot infrared laser with room-temperature tunable emission in the optical telecommunications window. *Nat. Photon.* **15**, 738-742 (2021).
2. Zou, C. *et al.* Electrically driven lasing from a dual-cavity perovskite device. *Nature* **645**, 369-374 (2025).
3. Zou, C. *et al.* Continuous-wave perovskite polariton lasers. *Sci. Adv.* **11**, eadr8826 (2025).

4. Song, B. *et al.* Chiral Exciton-Polariton Continuous-Wave Perovskite Laser. *Adv. Mater.***38**, e15301 (2026).
5. Pushkarev, A. P. *et al.* Nonepitaxial perovskite polariton laser diode operating under direct current. *Nature***656**, 80-85 (2026).
6. Zhou, H. *et al.* Exciplex-enabled high-efficiency, fully stretchable OLEDs. *Nature***649**, 604-611 (2026).
7. Qin, C. *et al.* Triplet management for efficient perovskite light-emitting diodes. *Nat. Photon.***14**, 70-75 (2020).
8. Qin, C. *et al.* Stable room-temperature continuous-wave lasing in quasi-2D perovskite films. *Nature***585**, 53-57 (2020).
9. Wang, K. *et al.* Perovskite lasers: From optical pumping to electrical pumping. *FlexMat***3**, 101-116 (2026).
10. Goldberg, I. *et al.* Toward Thin-Film Laser Diodes with Metal Halide Perovskites. *Adv. Mater.***36**, 2314193 (2024).
11. Li, Y. *et al.* Phase-pure 2D tin halide perovskite thin flakes for stable lasing. *Sci. Adv.***9**, eadh0517 (2023).
12. Wang, X. *et al.* Quasi-2D Dion-Jacobson phase perovskites as a promising material platform for stable and high-performance lasers. *Sci. Adv.***9**, eadj3476 (2023).
13. Li, G. *et al.* Room-Temperature Single-Mode Plasmonic Perovskite Nanolasers with Sub-Picosecond Pulses. *Adv. Funct. Mater.***34**, 2405559 (2024).
14. Su, R. *et al.* Perovskite semiconductors for room-temperature exciton-polaritonics. *Nat. Mater.***20**, 1315-1324 (2021).
15. Li, G. *et al.* Localized Bound Multiexcitons in Engineered Quasi-2D Perovskites Grains at Room Temperature for Efficient Lasers. *Adv. Mater.***35**, 2211591 (2023).
16. Yoshida, K. *et al.* Electrically driven organic laser using integrated OLED pumping. *Nature***621**, 746-752 (2023).
17. Liu, Y., Li, C., Ren, Z., Yan, S. & Bryce, M. R. All-organic thermally activated delayed fluorescence materials for organic light-emitting diodes. *Nat. Rev. Mater.***3**, 18020 (2018).
18. Kim, H. S. *et al.* Enhancement of Reverse Intersystem Crossing in Charge-Transfer Molecule through Internal Heavy Atom Effect. *Adv. Funct. Mater.***31**, 2104646 (2021).
19. Mai, V. T. N. *et al.* Solid cyclooctatetraene-based triplet quencher demonstrating excellent suppression of singlet–triplet annihilation in optical and electrical excitation. *Nat. Commun.***11**, 5623 (2020).
20. Bickerdike, A. *et al.* Reverse Intersystem Crossing and Exciton Harvesting: A Pathway to Low Threshold in Multi-Resonant TADF Electrically Pumped Organic Semiconductor Lasers. *Adv. Opt. Mater.***14**, e01796 (2026).
21. Stavrou, K., Franca, L. G., Danos, A. & Monkman, A. P. Key requirements for ultraefficient sensitization in hyperfluorescence organic light-emitting diodes. *Nat. Photon.***18**, 554-561 (2024).

22. Eizner, E., Martínez-Martínez, L. A., Yuen-Zhou, J. & Kéna-Cohen, S. Inverting singlet and triplet excited states using strong light-matter coupling. *Sci. Adv.***5**, eaax4482 (2019).
23. Yu, Y., Mallick, S., Wang, M. & Börjesson, K. Barrier-free reverse-intersystem crossing in organic molecules by strong light-matter coupling. *Nat. Commun.***12**, 3255 (2021).
24. Zhao, W. *et al.* Phase-purity engineering in quasi-2D perovskites for amplified spontaneous emission. *Sci. China Mater.***69**, 3847-3855 (2026).
25. Kasprzak, J. *et al.* Bose–Einstein condensation of exciton polaritons. *Nature***443**, 409-414 (2006).
26. Gomez-Dominguez, M., Kumar, E. J., Koch, K. A., Srimath Kandada, A. R. & Correa-Baena, J.-P. Materials and Cavity Design Principles for Exciton-Polariton Condensates. *ACS Nano***19**, 10579-10588 (2025).
27. Ardizzone, V. *et al.* Polariton Bose–Einstein condensate from a bound state in the continuum. *Nature***605**, 447-452 (2022).
28. Liu, H., Latini, S., Lu, I. T., Shin, D. & Rubio, A. Modifying electronic and structural properties of 2D van der Waals materials via cavity quantum vacuum fluctuations: A first-principles QEDFT study. *Opt. Mater. Express***15**(9), 2105-2118 (2025).
29. Polak, D. *et al.* Manipulating molecules with strong coupling: harvesting triplet excitons in organic exciton microcavities. *Chem. Sci.***11**, 343-354, doi:10.1039/c9sc04950a (2020).
30. Laitz, M. *et al.* Uncovering temperature-dependent exciton-polariton relaxation mechanisms in hybrid organic–inorganic perovskites. *Nat. Commun.***14**, 2426 (2023).

Figures

40° for microcavities with Rabi splitting, $\Omega = 410$ meV (**g**) and $\Omega = 336$ meV (**h**). The straight line represents the exciton dispersion, the solid parabolic curve represents the cavity–photon dispersion, and the dashed curve represents the lower polariton (LP) branch (see Methods, coupled oscillator model). **i**, Hopfield coefficients of the 0° polariton extracted from the angle-resolved reflection spectrum in Fig. 1**h** using a coupled-oscillator model, showing an excitonic fraction ($|X|^2$) of 23.42% and a photonic fraction ($|C|^2$) of 76.58%; see Methods “Calculation of Hopfield coefficients”.

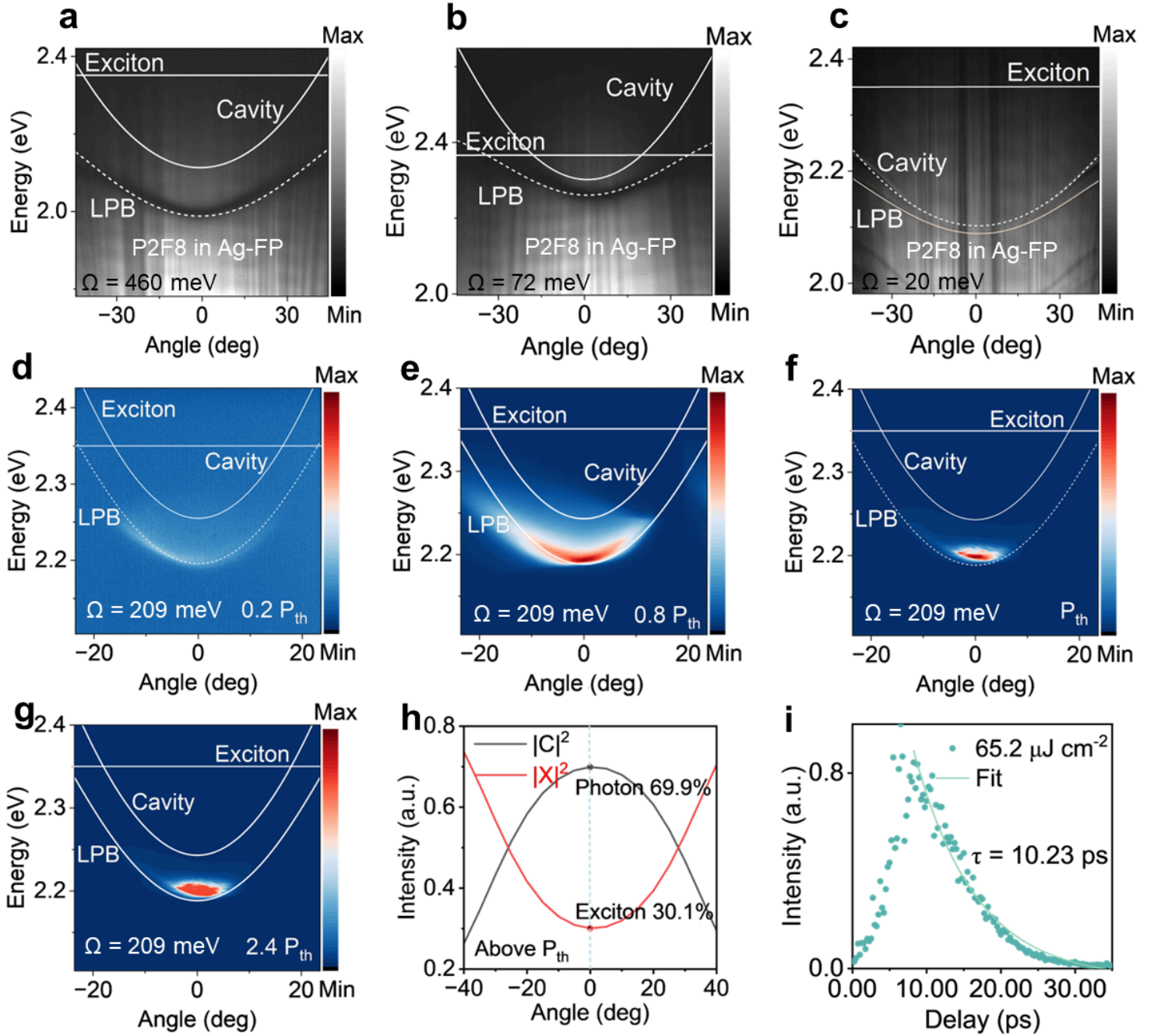


Figure 2

Signature of strong coupling in microcavities. **a–c**, Angle-resolved reflection spectra of P2F8 in Ag-mirror FP cavity with different Rabi splitting, $\Omega = 460$ meV (**a**) and $\Omega = 72$ meV (**b**). The straight line represents

the exciton dispersion, the solid parabolic curve represents the cavity-photon dispersion, and the dashed curve represents the lower polariton (LP) branch. **c**, Angle-resolved reflection spectrum of P2F8 in Ag-mirror FP cavity (weak-coupling), showing zero-detuning polariton loss of $(\Gamma_c + \Gamma_x)/2 = 55.90$ meV and a Rabi splitting of 20 meV. The Rabi splitting is substantially smaller than the loss, indicating weak exciton–photon hybridization under this strongly detuned condition. **d–g**, Angle-resolved transmission spectra of P2F8 in the DBR FP cavity (strong-coupling) recorded from -25° to 25° at different CW pump densities. The DBR microcavity architecture is shown in Fig. 4a. **(d)** $P = 0.2 P_{\text{th_EPC}}$, **(e)** $P = 0.8 P_{\text{th_EPC}}$, **(f)** $P = P_{\text{th_EPC}}$, **(g)** $P = 2.4 P_{\text{th_EPC}}$. The straight line represents the exciton dispersion, the solid parabolic curve represents the cavity–photon dispersion, and the dashed curve represents the lower polariton (LP) branch. **h**, Hopfield coefficients of the 0° lower polariton extracted from Fig. 2g, yielding an excitonic fraction of 30.1% and a photonic fraction of 69.9% (see Methods, Calculation of Hopfield coefficients). **i**, Transient reflectivity dynamics of P2F8 in the DBR FP cavity (strong-coupling) laser under 400 nm pulsed excitation at a pump fluence of $65.2 \mu\text{J cm}^{-2}$, with a fitted decay lifetime of 10.23 ps.

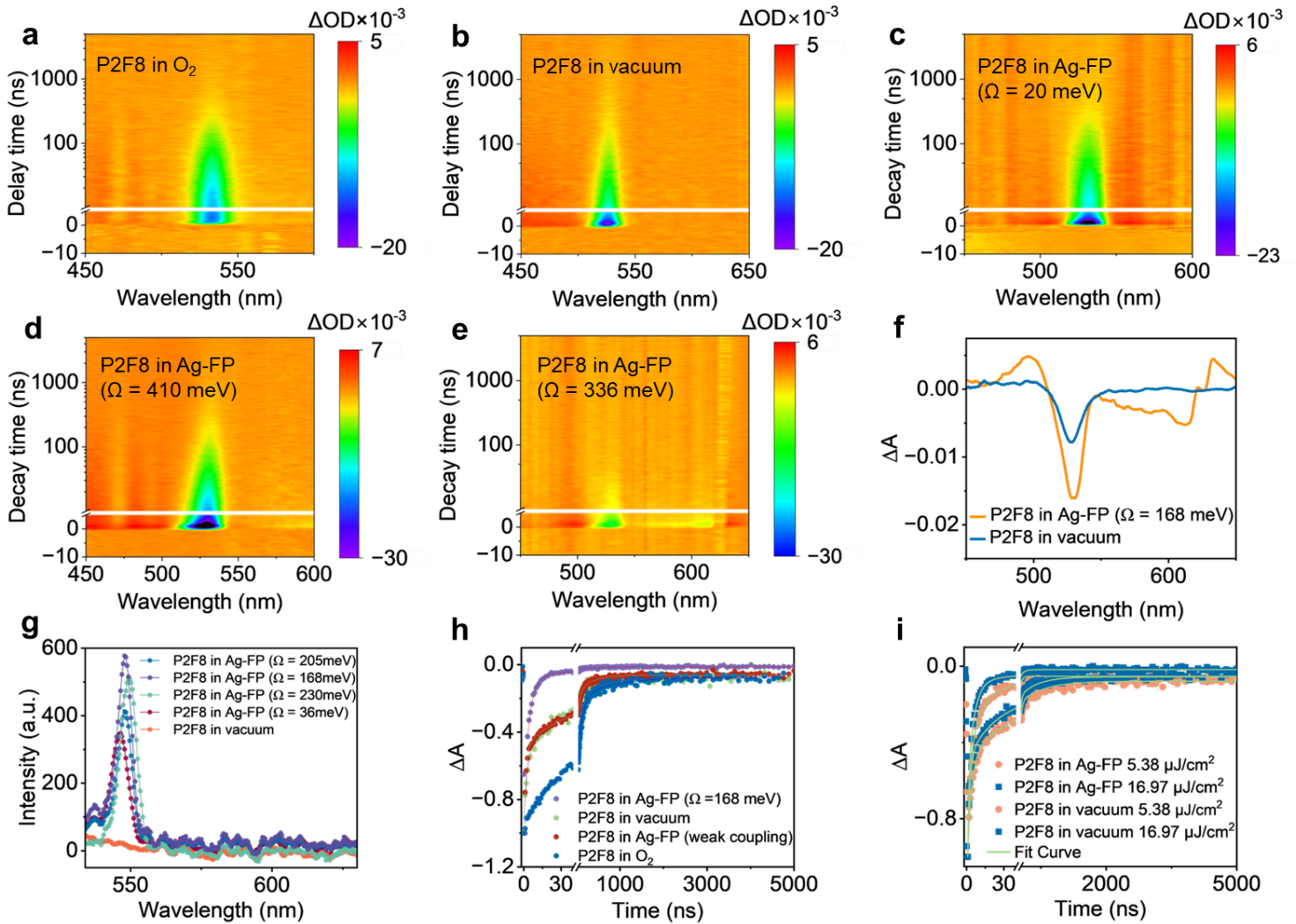


Figure 3

Triplet-state dynamics in Ag-mirror FP cavities. Ag-mirror microcavities were used because the limited optical transmission of the DBR structure prevents reliable transmission-mode transient absorption measurements. **a–e**, Nanosecond transient absorption contour plot obtained by transmission-mode pump–probe spectroscopy: P2F8 in oxygen (**a**), P2F8 in vacuum (**b**), and P2F8 in Ag-mirror FP cavity ($\Omega = 20$ meV) (**c**), P2F8 in Ag-mirror FP cavity ($\Omega = 410$ meV and $\Omega = 336$ meV) (**d–e**). **f**, Transient absorption spectra showing a prominent bleaching feature centered at ~ 533 nm and an additional lower-polariton-associated bleaching feature at ~ 607 nm in the strongly coupled cavity. **g**, PL spectra of the perovskite with STA and four microcavities with different Rabi splitting (Ω). **h**, Triplet-exciton decay kinetics monitored at approximately 533 nm under 380 nm excitation, together with triexponential fits for P2F8 in oxygen, P2F8 in vacuum, and P2F8 in Ag-mirror FP cavity (weak-coupling) and P2F8 in Ag-mirror FP cavity (strong-coupling). **i**, Pump fluence-dependent transient absorption kinetics of P2F8 in vacuum and P2F8 in Ag-mirror FP ($\Omega = 336$ meV) under 380 nm excitation.

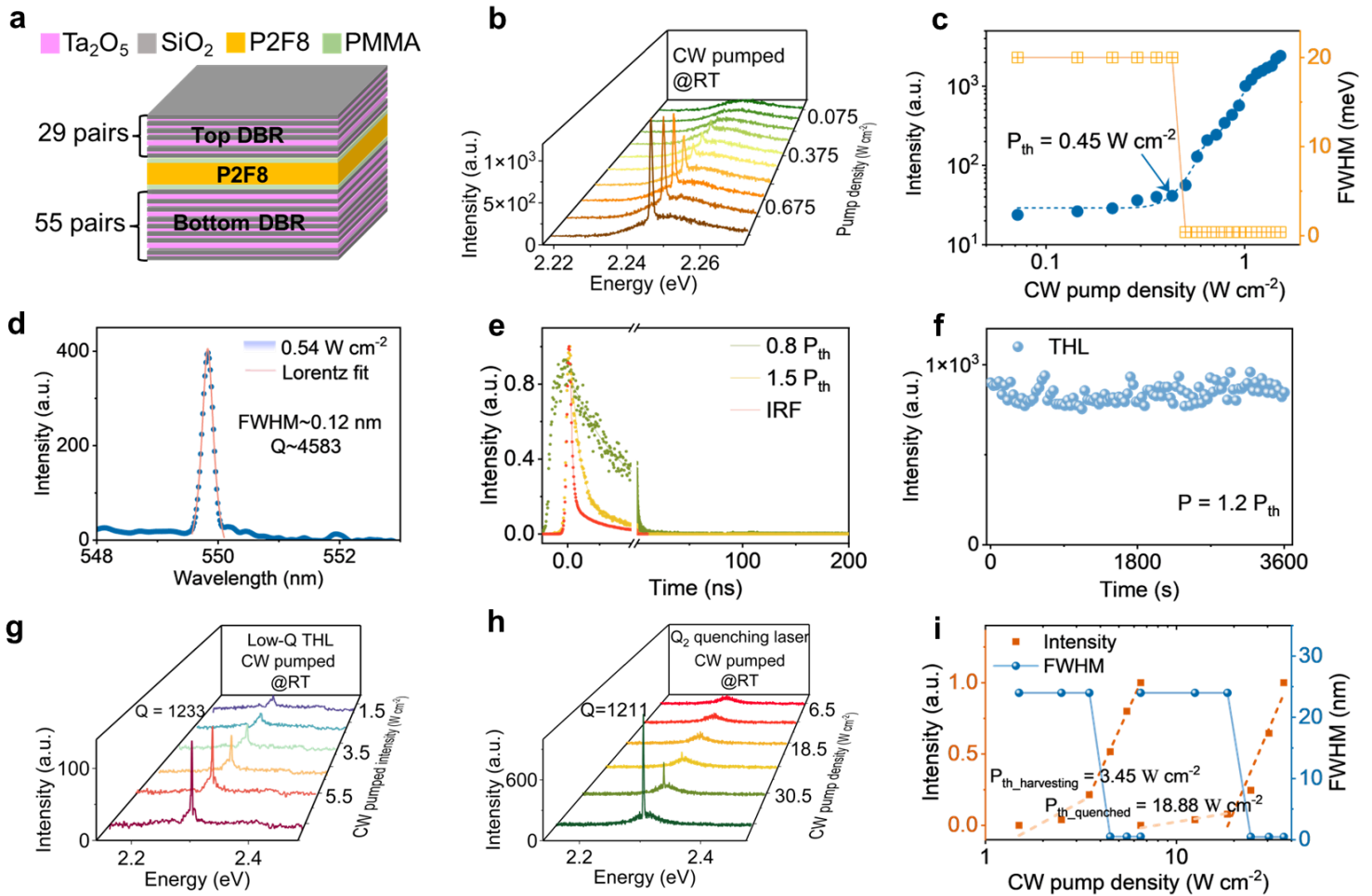


Figure 4

Characteristics and contrast of the P2F8 in DBR FP laser. **a**, Schematic representation of the P2F8 in DBR FP laser. The pure-phase P2F8 film is sandwiched between two DBR mirrors. A PMMA layer is deposited between each DBR mirror and the emissive layer to prevent direct contact between the P2F8 film and the DBR mirrors. **b**, Evolution of the emission spectra under CW excitation at different pump densities of the

P2F8 in DBR FP laser. **c**, CW-pumped laser emission intensity and FWHM as a function of the pump density of the P2F8 in DBR FP laser under vacuum. **d**, Lorentzian fitting yields a cavity linewidth of 0.12 nm, corresponding to an optical quality factor $Q \approx 4583$. **e**, Time-resolved PL traces below the threshold of the P2F8 in DBR FP laser, the instrument response function and above the threshold of the P2F8 in DBR FP laser. **f**, Long-term CW operational stability of the P2F8 in DBR FP cavity (strong-coupling) laser measured at $1.2 P_{th}$. **g–h**, Spectrum evolution under different CW pump densities of the P2F8 in DBR FP cavity (strong-coupling) laser (the low-Q DBR laser architecture is shown in Fig. 4a) and P2F8 in DFB cavity laser (the device architecture of the DFB laser is shown in Extended Data Fig. 2.). **i**, CW-pumped laser emission intensity and FWHM as a function of the pump density of the P2F8 in DBR FP cavity (strong-coupling) laser and the P2F8 in DFB cavity laser.

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