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Author(s)	Wang, Yue; Li, Xiaoming; Nalla, Venkatram; Zeng, Haibo; Sun, Handong
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1 **Solution-processed low threshold vertical cavity surface emitting lasers**
2 **from all-inorganic perovskite nanocrystals**

3 Yue Wang¹, Xiaoming Li^{2,3}, Venkatram Nalla⁴, Haibo zeng^{2*}, Handong Sun^{1,4*}

4 ¹Division of Physics and Applied Physics, School of Physical and Mathematical Sciences,
5 Nanyang Technological University, Singapore 637371, Singapore

6 ²Institute of Optoelectronics & Nanomaterials, College of Materials Science and Engineering
7 Nanjing University of Science and Technology Nanjing, 210094, China

8 ³State Key Laboratory of Mechanics and Control of Mechanical Structures, College of Materials
9 Science and Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210085,
10 China

11 ⁴Centre for Disruptive Photonic Technologies (CDPT), Nanyang Technological University,
12 Singapore 637371, Singapore

13 * Authors to whom correspondence should be addressed, electronic email: hdsun@ntu.edu.sg,
14 zeng.haibo@njust.edu.cn.

15 **Abstract:** Recently, all-inorganic cesium lead halide perovskite nanocrystals (IPNCs) (CsPbX₃,
16 X = Cl, Br, I) were discovered to possess superior optical gain properties appealing for solution-
17 processed cost-effective lasers. Yet, the potential of such materials has not been exploited for
18 practical laser devices, rendering the prospect as laser media elusive. Herein, we realized for the
19 first time the challenging but practically desirable vertical cavity surface emitting lasers (VCSELs)
20 based on the CsPbX₃ IPNCs, featuring low threshold (9 μJ/cm²), unidirectional output (beam
21 divergence of ~3.6°) and favorable stability. The lasing wavelength can be tuned across red, green
22 and blue region maintaining comparable thresholds, which is promising in developing single
23 source-pumped full-color visible lasers. It is fully demonstrated that the characteristics of the

24 VCSELS can be versatily engineered by independent adjustment of the cavity and solution
25 processable nanocrystals. Our results represent a significant leap towards practical laser sources
26 leveraging on the advantageous CsPbX₃ IPNCs.

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43 Solution-processed gain materials are being pursued with the promise to revolutionize the
44 vacuum-based epitaxial semiconductor lasers aiming at developing low-cost yet high-
45 performance laser source¹. Colloidal quantum dot (CQD) has been recognized as the ideal
46 candidate due to the tunable emission color, enhanced optical properties and facile solution
47 processibility²⁻⁴. Ever since the first demonstration of stimulated emission from metal-
48 chalcogenide CQDs in 2000², significant progress has been made in improving the lasing
49 performance^{5, 6}. However, the relatively low absorption cross-section and the high optical loss
50 due to carrier trapping and Auger recombination (AR) still hinder the advance of CQD-lasers,
51 especially in the short visible spectral range of blue and green^{7, 8}.

52 In the past years, the organic–inorganic halide perovskites, which have demonstrated
53 impressive photovoltaic performance^{9, 10}, were also discovered to be potential optical gain
54 media^{11, 12}. However, the commercial aspirations may be stifled by the inherent instability of
55 these hybrid perovskites^{11, 12}. More recently, the newly engineered all-inorganic cesium lead
56 halide (CsPbX₃ (X=Cl, Br and I)) perovskite nanocrystals are resurging as a superior optical gain
57 material because of the large optical absorption cross-section, large exciton binding energy, high
58 photoluminescence (PL) quantum yield and relatively low AR loss^{13, 14}. Importantly, these all-
59 inorganic perovskite nanocrystals (IPNCs) show much enhanced endurance to ambient
60 environment than the organic-inorganic analogues^{13, 15, 16}. Compared to traditional metal-
61 chalcogenide CQDs, these CsPbX₃ IPNCs feature in narrow emission spectra, simple fabrication
62 process, ease of color tunability by anion exchange, superior optical gain properties and so on¹⁷⁻²⁰.
63 As a result, these new emerging CsPbX₃ IPNCs can be envisioned as the promising solution
64 towards inexpensive laser sources in the future.

65 So far, lasers based on single CsPbX₃ nanowire have been reported^{21, 22}. Regarding lasers
66 made from the ensemble of inorganic perovskite nanocrystals, only whispering gallery mode and
67 random lasers which are among the easiest configurations for lasers have been demonstrated as a
68 proof of concept^{13, 14}. However, both of these laser types lack directionality, one of the most
69 important advantages of a laser. Moreover, all of the above lasing demonstrations fall in multi-
70 mode operation^{13, 14}. In laser physics and applications, obtaining single-mode lasing is crucial
71 since multi-mode operation will deteriorate the color purity and temporal stability by mode
72 oscillation^{23, 24}. Due to the typical large cavity length to provide sufficient gain for lasing action
73 and the relatively broad gain bandwidth of traditional lasing materials, achieving single-mode
74 lasing is still challenging^{23, 24} and remains unaccomplished for CsPbX₃ IPNCs.

75 Vertical cavity surface emitting laser (VCSEL) is an important and much desired laser type
76 which finds a broad range of applications like optical communication, high density optical storage,
77 laser display, parallel optical computing and signal processing because of its ability to form 2-
78 dimensional arrays, surface normal emission characteristics and high beam quality output
79 ensuring easy coupling into an optical fibre^{25,26}. For any given gain materials, VCSELs represent
80 the most tough laser configuration determined by the stringent criteria between gain and loss^{6,25}.
81 As such, most surface normal devices were previously developed from complicated epitaxial
82 growth of semiconductor heterostructures of many layers in which both bandgap alignment and
83 lattice mismatch are big concerns²⁷⁻³⁰. The unavailability of independently adjusting the cavity
84 and the active gain materials in an epitaxy based VCSEL makes material selection a constraint
85 and the device cost ineffective. Thus, alternative fabrication of VCSELs with simplified
86 processing is very appealing. Herein, we realized for the first time the high-performance VCSELs
87 from solution-processed CsPbX₃ IPNCs. A clear evolution from spontaneous emission to lasing
88 in the device upon optical pumping was manifested by the spectral narrowing, nonlinear increase
89 of the PL intensity, drastic reduction of PL lifetime and remarkable decrease of output beam
90 divergence. Both multi-mode and single-mode lasing operation have been achieved by tuning the
91 cavity length. Thanks to the superior optical gain properties of the CsPbBr₃ IPNCs and the good
92 match between the gain profile and the high reflectivity band of the distributed Bragg reflectors
93 (DBRs), the lasing threshold of the IPNC-VCSELs is so low that quasi-continuous wave (q-CW)
94 pumping is feasible. In contrast to traditional metal-chalcogenide CQD based lasers, where the
95 thresholds for the green and blue are typically much higher than that of the red⁶, these CsPbX₃
96 IPNC-VCSELs lase with comparable thresholds across the whole visible spectral range, which is
97 promising in achieving single source-pumped full-color lasers. Our results highlight the resurging
98 CsPbX₃ IPNCs in developing the challenging but practical lasers and shed light on the feasibility
99 of independent adjustment of cavity and gain materials for the IPNC-VCSELs, which represent a
100 great progress towards advanced laser sources based on the advantageous CsPbX₃ IPNCs.

101 **Results**

102 **Modification of spontaneous emission from CsPbBr₃ IPNCs by microcavity effect.** The
103 CsPbX₃ IPNCs adopted here were synthesized following the method reported by Protesescu et
104 al.¹⁷ with slight adjustment¹³. The absorption and emission spectra of the CsPbBr₃ IPNCs are
105 shown in Supplementary Fig. 1b, revealing the emission peak of ~504 nm with a narrow full-
106 width at half maximum (FWHM) of ~21 nm. The corresponding transmission electron
107 microscope (TEM) image (Supplementary Fig. 1a) displays the cubic shape with an edge length

108 of ~ 9 nm. To build the vertical microcavity, the commercially available dielectric DBRs
109 consisted of 25 pairs of $\text{SiO}_2/\text{TiO}_2$ quarter-wave layers were employed as the high-reflective
110 mirrors. Figure 1a displays the reflection spectrum of a DBR used here, which exhibits a stop-
111 band from 430 nm to 570 nm, matching the PL spectrum of CsPbBr_3 IPNCs (see broadband
112 reflection spectrum in Supplementary Fig. 2). The reflectivity was determined to be as high as
113 99.6% at ~ 500 nm. To sandwich the CsPbBr_3 IPNCs between two DBRs so as to form the
114 prototypical VCSEL, the highly concentrated CsPbBr_3 IPNCs solution was spin-coated onto the
115 top surface of a DBR, then, another DBR was brought upside-down in contact to the CsPbBr_3
116 IPNC film and finally fixed with glue. The schematic diagram (Fig. 1b), photograph
117 (Supplementary Fig. 3) and the corresponding reflection spectrum ((Supplementary Fig. 2) of the
118 final device are presented. Prior to the lasing investigation, the modification of spontaneous
119 emission from CsPbX_3 IPNCs by the optical microcavity was interrogated, which could reflect
120 the quality of the complete DBR resonator. Figure 1a shows the typical PL spectrum from the
121 CsPbBr_3 IPNCs inserted within the cavity collected at 0° with respect to the surface normal (see
122 Methods for details). In contrast to the PL spectrum from CsPbX_3 IPNCs spin-coated on a single
123 DBR substrate, the PL within the cavity manifests multiple interference peaks, visualizing the
124 presence of Fabry-Perot cavity effect. It is worth to note that the spiked emission is not laser but
125 spontaneous emission modified by interference effect, which is further demonstrated by the
126 following lifetime measurements (Fig. 2c). The resonant peaks can be assigned to mode numbers
127 indexed as 29-33 based on the equation³¹: $m\lambda = 2nL$, where m is the mode number, λ is the
128 emission wavelength, n is the refractive index of the CsPbX_3 IPNC film, L is the effective cavity
129 length. L is estimated to be $4 \mu\text{m}$ assuming $n=2^{13}$. By changing the thickness of the CsPbBr_3
130 IPNC film, the optical modes of the cavity and thus the PL spectrum can be tuned as exemplified
131 in Supplementary Fig. 4. The slight red-shift of the envelop of the emission comb relative to the
132 free-space emission spectrum can be attributed to the reabsorption effect due to the multipass of
133 the radiation inside the cavity²⁴. Furthermore, the spatial distribution of the radiation and the
134 angle (θ) dependent PL spectrum from the device were examined by angle-resolved PL
135 measurement (see Methods for details). It is found that the optical mode wavelengths gradually
136 shift to blue as the detection angle increases (Fig. 2a), which quantitatively follows the equation:
137 $m\lambda = 2nL\sqrt{n^2 - \sin^2\theta}$ (Supplementary Fig. 5). Such behavior states nothing but that the
138 radiation propagation angle inside the cavity and the detection angle are correlated by Snell's law
139 (see detailed deviations in Supporting Information)^{1,31}, further confirming that the discrete peaks
140 originate from the Fabry-Perot interference. Notably, the radiation from the microcavity is much
141 narrowed in space with respect to that from free-space CsPbBr_3 IPNCs (Fig. 2b), indicating that

142 spatially confined emission is obtained by the microcavity effect, which may shed light on
143 developing CsPbX₃ IPNC-based light emitting diodes with directional radiation. Finally, the
144 carrier dynamics of CsPbBr₃ IPNCs within/without microcavity was inspected by a streak camera
145 system (Fig. 2c) (see the corresponding spectrograms in Supplementary Fig. 6). It is found that
146 the PL decay curve within microcavity is almost identical to that in free space. A reduction of PL
147 lifetime due to Purcell effect is not observed which can be attributed to the long cavity length and
148 that the cavity mode only confined in one dimension³².

149 **Vertical cavity surface emitting lasers from CsPbBr₃ IPNCs.** The stimulated emission from
150 the close-packed thin film of the CsPbBr₃ IPNCs was first studied by stripe pumping
151 configuration^{13, 33} to exam the optical gain. As increasing the pumping density, the development
152 of stimulated emission revealed by a much narrowed emission peak (FWHM: ~6.5 nm) can
153 readily occur from our sample with a threshold of ~18 μJ/cm² (Supplementary Fig. 7). Such a
154 low-threshold optical gain from CsPbBr₃ IPNCs in combination with the favorable coupling
155 between the emission and the cavity modes motivates us to pursue CsPbBr₃ IPNC-based VCESLs.
156 In doing so, the pump laser beam (400 nm, 100 fs) was focused by a circular lens (focus length: 5
157 cm) onto the device vertically, and the PL signal was collected from the surface normal of the
158 cavity. A 30% reflection by the DBR for pump wavelength was extracted and counted in
159 determining the final pump intensity. Figure 3a displays the evolution of PL spectra from the
160 device as a function of pump intensity. Under relatively low pump intensities (< 11 μJ/cm²), the
161 PL spectra are dictated by spontaneous emission shaped by the cavity mode. With the increase of
162 pump intensity, one of the discrete peaks with wavelength close to the stimulated emission
163 spectra grows much faster than the others, which is accompanied by dramatic narrowing of the
164 line-width down to ~0.6 nm. Figures 3b and c depict the change of PL intensity and the FWHM
165 of the peaks corresponding to mode numbers from 29 to 33, respectively. The abrupt increase of
166 the PL intensity and sudden decrease of the line-width of a particular peak indicate the
167 achievement of lasing action^{1, 34, 35}. The lasing threshold (P_{th}) is derived to be as low as 11 μJ/cm²,
168 which is much lower than that of the CdSe/CdZnS CQDs (65 μJ/cm²), under similar conditions⁶.
169 Importantly, due to the much larger free spectral range (FSR) of ~16 nm determined by the short
170 cavity length than the stimulated emission line-width (6.5 nm), single-mode lasing operation was
171 achieved. It should be noted that although the lasing peak locates at the blue side of the emission
172 comb, it is actually on the red side of the spontaneous emission maximum of CsPbBr₃ IPNCs
173 (Supplementary Fig. 8), in agreement with that the optical transition of the laser originates from
174 the biexciton recombination^{13, 36, 37}.

175 To further verify the development of lasing, the PL dynamics as a function of pump intensity
176 was investigated. Under pump intensity ($0.1 P_{th}$) of much lower than the threshold, the PL decay
177 resembles the spontaneous emission trace. With the increase of pump intensity ($0.8 P_{th}$)
178 approaching the threshold, a much faster decay channel, corresponding to the Auger
179 recombination, appears. As the pump intensity ($1.3 P_{th}$) surpasses the threshold, the PL decay
180 suddenly collapses to <50 ps, limited by the temporal resolution of the streak camera system,
181 indicating the onset of lasing action³⁸.

182 Coherence and directionality are two basic features of a laser but are rarely examined in
183 CQDs based lasers. Herein the directionality of the output radiation above and below the
184 threshold is assessed by a CCD camera located 15 mm away from the laser device (inset in Fig.
185 3a) as well as angle-resolved PL measurement (Supplementary Fig. 9). We can see that when the
186 pump intensity ($1.3 P_{th}$) exceeds the threshold, the divergence of the output signal remarkably
187 decreases from 15° for spontaneous emission below P_{th} to 3.6° , thus a directional emission was
188 obtained in our IPNC-VCSEL. Moreover, a clear interference pattern (Supplementary Fig. 10a)
189 can be observed by using the conventional Michelson interference experiment^{39,40}. From the plot
190 of the visibility ($V = \frac{I_{max}-I_{min}}{I_{max}+I_{min}}$, where I_{max} and I_{min} represent the intensities at the fringe maxima
191 and minimum) as a function of detuning time or optical path difference^{39,40}, the coherence time (τ)
192 of ~ 1 ps can be derived (Supplementary Fig. 10c).

193 Finally, we test the stability of the device by monitoring the lasing peak intensity versus time
194 at pump intensity of $1.5 P_{th}$ (pulse-width: 100 fs; repetition rate: 1KHz) (Supplementary Fig. 11).
195 Thanks to the robustness of the CsPbBr₃ IPNCs, the output signal can maintain 80% of its initial
196 value for more than one hour, which far excels the CdSe/CdZnS CQD-lasers⁶.

197 Inspired by the excellent laser performance under femtosecond laser pump, it is highly
198 promising to explore our IPNC-VCSEL pumped in the q-CW regime by a compact nanosecond
199 laser^{7,41}, which would be more practical and cost-effective. A ns laser pump is called the q-CW
200 just because the pump duration is much longer than that of the effective gain (~ 35 ps)⁴². Figure 4a
201 shows the pump intensity dependent PL spectra pumped by a Q-switched nanosecond laser
202 (pulse-width: 5 ns; repetition rate: 20 Hz; wavelength: 400 nm). The onset of lasing action is
203 unambiguously evidenced by the spectral narrowing and nonlinear increase of the PL intensity
204 with respect to the pump intensity (inset in Fig. 4a) with a low threshold of $900 \mu\text{J}/\text{cm}^2$. To the
205 best of our knowledge, this is the first demonstration of CQD-VCSEL operating in q-CW regime,
206 which represents a significant step towards continuous wave and electrical pumping. The lasing

207 stability under nanosecond pumping is also examined (Supplementary Fig. 11). It is found that
208 the lasing can last over one hour with losing only 50% of initial peak intensity. The faster
209 decrease of the lasing intensity compared to that under femtosecond pump suggests the more
210 serious thermal issue for long pump pulse duration³⁶. So the effective thermal management (heat
211 roll-off) shall be one of the major issues to address for future work toward stable CW operation³⁶,
212 ⁴³.

213 Furthermore, we demonstrate that multi-mode lasing operation can be produced in our
214 IPNC-VCSELS via tuning the *FSR* to be smaller than the stimulated emission bandwidth which is
215 enabled by increasing the effective cavity length (*L*) or film thickness of CsPbBr₃ IPNCs. Figure
216 4b illustrates the typical double mode lasing from the IPNC-VCSEL with *FSR* of ~6.2 nm and *L*
217 of ~10.3 μm. Due to the longer cavity path and thus the larger round-trip gain, the lasing threshold
218 further reduces to ~9.0 μJ/cm² (inset in Fig. 4b).

219 **Full-color VCSELS from CsPbX₃ IPNCs with comparable thresholds.** For traditional metal-
220 chalcogenide CQDs, the lasing wavelength is generally tuned by changing the dot size because of
221 the band gap limit^{2,6}. For example, smaller dot size is necessitated to obtain green and blue lasers
222 than that for red ones⁶. However, the optical loss including nonradiative AR and carrier trapping
223 becomes more serious and the absorption cross-section reduces as the dot decreases, making the
224 CQDs lase in short visible region challenging^{2,8}. Despite that lasing has been demonstrated from
225 CQDs across the full visible range⁶, the pump thresholds differ dramatically for red, green and
226 blue colors, which hinders the realization of integrated full-color lasers with single pumping
227 source⁴⁴. In contrast, the emission color of CsPbX₃ IPNCs can be facily tailored by composition
228 control^{17, 18}. By inserting the blue-emitting CsPb(Br/Cl)₃ IPNCs and red-emitting CsPb(I/Br)₃
229 IPNCs into the DBR resonators (for the red-emitting CsPb(I/Br)₃ IPNC-VCSEL, the DBR with
230 stop-band centered at 590 nm was employed (Supplementary Fig. 12)), we successfully achieved
231 IPNC-VCSELS across the full visible region (Fig. 5) (see full-range spectra in Supplementary Fig.
232 13 and Supplementary Fig. 14 for blue and red VCSELS, respectively). Notably, the lasing
233 thresholds for the red (19.0 μJ/cm²) and blue (25.5 μJ/cm²) are comparable to that of the green,
234 which indicates our CsPbX₃ IPNC-VCSELS may hold great promise for developing the single
235 source-pumped full-color visible and white lasers.

236 Discussion

237 We for the first time realized the tough yet practically desirable VCSELS based on the emerging
238 solution-processable CsPbX₃ IPNCs. The CsPbX₃ IPNC-VCSELS operate at a very low threshold,

239 so that the q-CW pumping is made feasible. Such a low lasing threshold can be mainly attributed
240 to the large absorption cross-section of the CsPbX₃ IPNCs, high PL quantum yield, relatively low
241 Auger loss and the good match between the gain profile and the stop-band of the DBRs^{13, 14}.
242 Especially, the absorption cross-section of the CsPbX₃ IPNCs was disclosed to be orders of
243 magnitude higher than those of the metal-chalcogenide CQDs^{13, 14, 42}, which allows for the
244 generation of excitons with denser concentration under the same pump density. Therefore, even
245 though the CsPbX₃ IPNC-VCSELs stem from the biexciton recombination^{13, 37}, the pump
246 thresholds for lasing still remain several times lower than that of the CdSe/CdZnS CQDs under
247 similar conditions which was claimed to lase in single exciton regime⁶. Another advantage of the
248 CsPbBr₃ IPNCs may be its cubic crystal shape. In general, dense packing of the nanocrystals in
249 the ensemble film is essential for high effective gain and thus a low lasing threshold. In this
250 regard, the cubic shape of CsPbBr₃ IPNCs is advantageous over the spherical ones of II-VI group
251 metal-chalcogenide CQDs. The directionality and coherence from the laser device was clearly
252 revealed. Taking advantage of the short cavity length and the narrow gain spectrum (~6.5 nm),
253 single-mode lasing was achieved, attractive for various application fields. Noticeably, it is facile
254 to independently choose the cavity characteristics and CsPbX₃ IPNCs for optimal match so that
255 red, green and blue VCSELs can be realized with comparable pump thresholds, which is
256 extremely difficult for epitaxial semiconductors and traditional metal-chalcogenide CQDs. We
257 envisage that further optimization of the CsPbX₃ IPNCs, such as engineering the core/alloyed-
258 shell heterostructure to mitigate the Auger and trapping loss⁴⁵, as well as adoption of proper
259 thermal management in the device³⁶ could further reduce the lasing threshold and may eventually
260 enable the continuous wave operation in the future.

261 **Methods**

262 **Synthesis of CsPbX₃ IPNCs.** Cs₂CO₃ (0.8 g), OA (oleic acid, 2.5 mL) and of ODE (octadecene,
263 30 mL) were mixed and kept in an argon atmosphere. The mixture was heated up to 130 °C for
264 one hour. After that, the mixture was further heated up to 150 °C for reaction and lasted for 0.5
265 hour. Then, the solution was cooled down to room temperature. On the other side, 10 mL ODE, 1
266 mL OA and 0.36 mmol of PbX₂ (X=Cl, Br and I) were put together and kept in an argon
267 atmosphere for one hour at temperature of 130 °C. Then, the solution was further heated up to
268 160 °C for reaction for 10 minutes. Finally, the Cs-precursor (1 mL) was quickly added into the

269 solution and cooled down by ice. More information about the synthesis of CsPbX₃ IPNCs can be
270 found in reference 13.

271 **Optical characterization.** To investigate the modification of spontaneous emission from CsPbX₃
272 IPNCs by microcavity effect, the same femtosecond laser source (excitation wavelength: 400 nm,
273 pulse-width: 100 fs, repetition rate: 1000 Hz) was employed as that used in the following lasing
274 studies to maintain consistency. The excitation intensity was kept very low (0.5 μJ/cm²), far less
275 than the threshold. We also have tried the continuous wave He-Cd laser as the excitation source,
276 where similar spiked emission was observed, further confirming the spiked emission is not laser.
277 The angle dependent PL signal was recorded as a function of detection direction by a home-built
278 fiber-optics system. In particular, the collection fiber with diameter of 200 μm was attached to a
279 50 mm diameter rotating stage with the sample mounted at its center. The distance between the
280 fiber and the sample is set as 15 mm. The other side of the fiber was coupled to a 320 mm
281 monochromator combined with a charge coupled device detector. For the lasing investigation, the
282 laser beam with wavelength of 400 nm generated by second harmonic generation from the seed
283 with wavelength of 800 nm was focused by a circular lens (focus length: 5 cm) onto the VCSEL
284 vertically, and the spot diameter on the sample was ~90 μm. The output signal was collected from
285 the other side of the VCSEL by the above-mentioned fiber-optics system.

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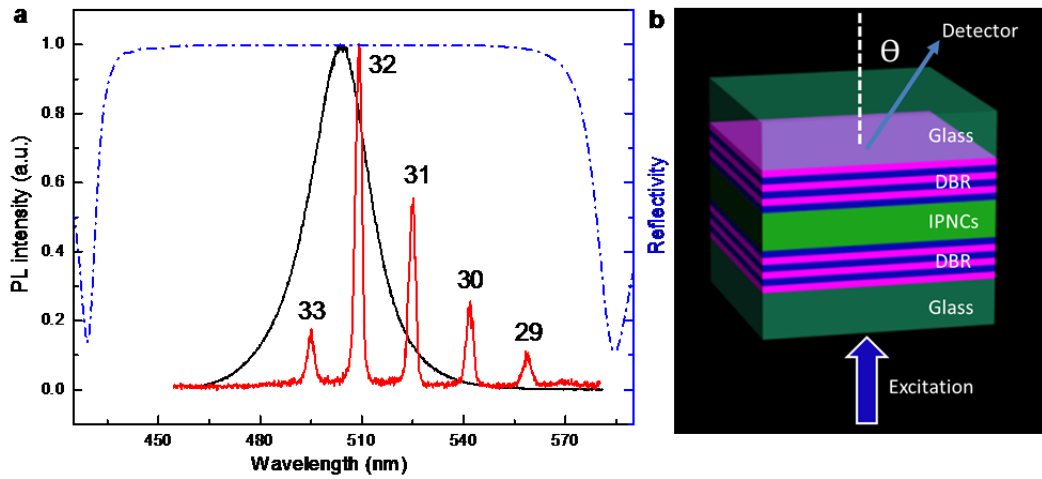
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292 **Figure 1 | Modification of spontaneous emission from CsPbBr₃ IPNCs by presence of**
 293 **microcavity. (a)** PL spectra from CsPbBr₃ IPNCs within (red line)/without (black line)
 294 microcavity under low excitation intensity of 0.5 μJ/cm². The blue dashed line represents the
 295 reflectivity of the adopted DBR. **(b)** Schematic configuration of the CsPbBr₃ IPNC-VCSEL.

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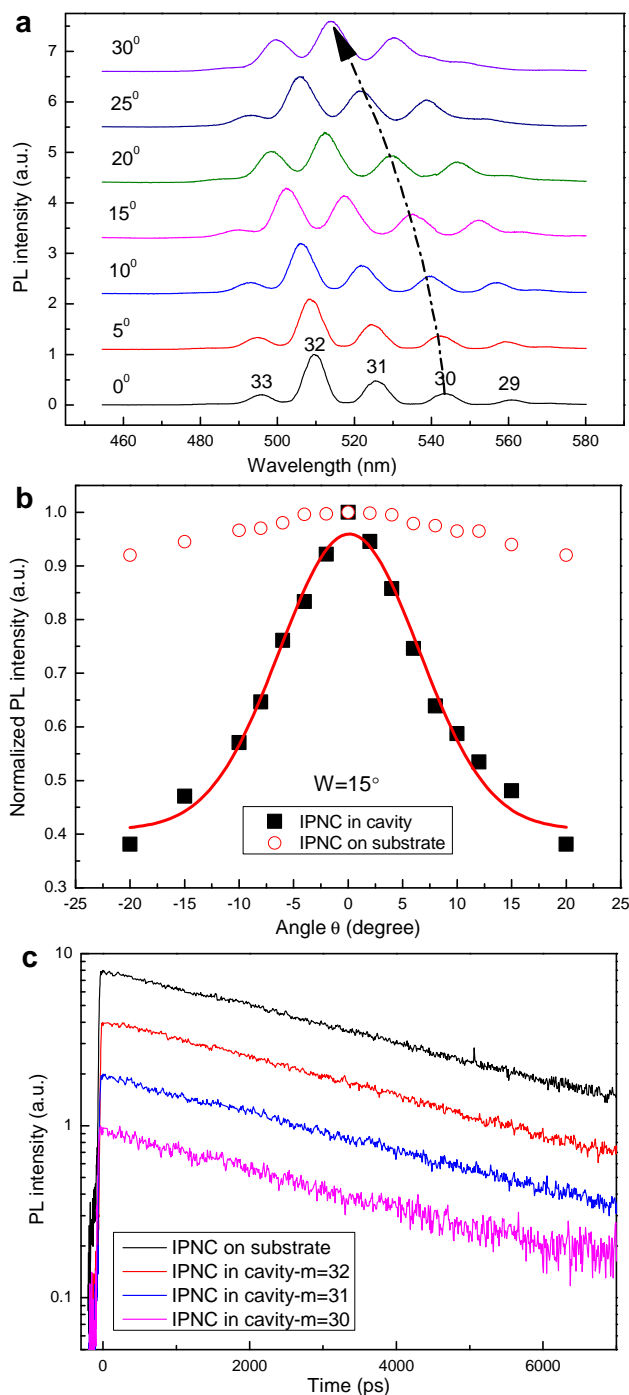
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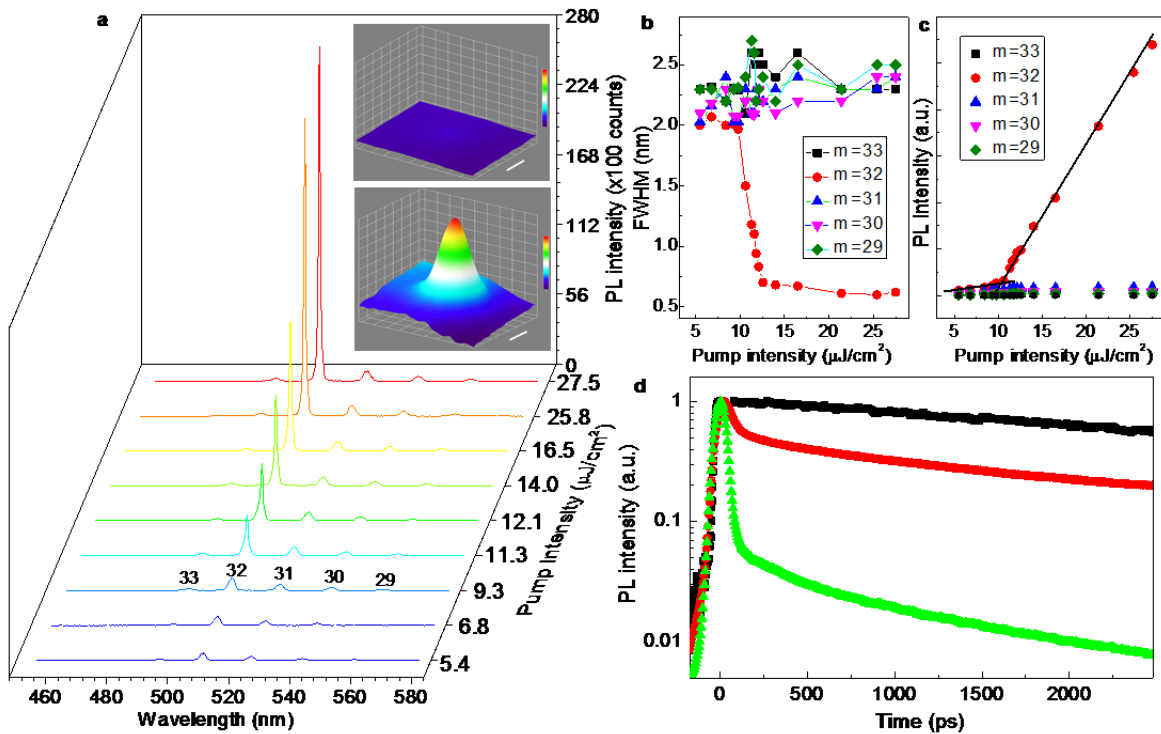
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307 **Figure 2| Angle-resolved PL from CsPbBr₃ IPNCs within microcavity and PL dynamics. (a)**
 308 **Detection angle dependent PL spectra from the CsPbBr₃ IPNCs within microcavity. (b)** Spatial
 309 **distribution of the irradiation from CsPbBr₃ IPNCs within/without microcavity. The PL signal**
 310 **greatly narrows with the presence of microcavity. The divergence is estimated to be 15° by**
 311 **Gaussian fitting (red line). (c)** PL decay curves of CsPbBr₃ IPNCs within microcavity (mode
 312 **number from 30 to 32) and that without microcavity.**



313 **Figure 3| Vertical cavity surface emitting lasers from CsPbBr₃ IPNCs. (a)** Pump intensity
 314 dependent PL spectra from the device. Inset shows the output beam profiles below (5.4 μJ/cm²)
 315 (upper one) and above (25.8 μJ/cm²) (bottom one) threshold. Scale bar is 1 mm. **(b)** Pump
 316 intensity dependent FWHM of the modes indexed from 29 to 33. **(c)** Pump intensity dependent
 317 PL intensity of the modes indexed from 29 to 33. **(d)** Pump intensity dependent PL decay curves
 318 of the device (0.1 P_{th} for the black curve, 0.8 P_{th} for the red curve and 1.3 P_{th} for the green curve)

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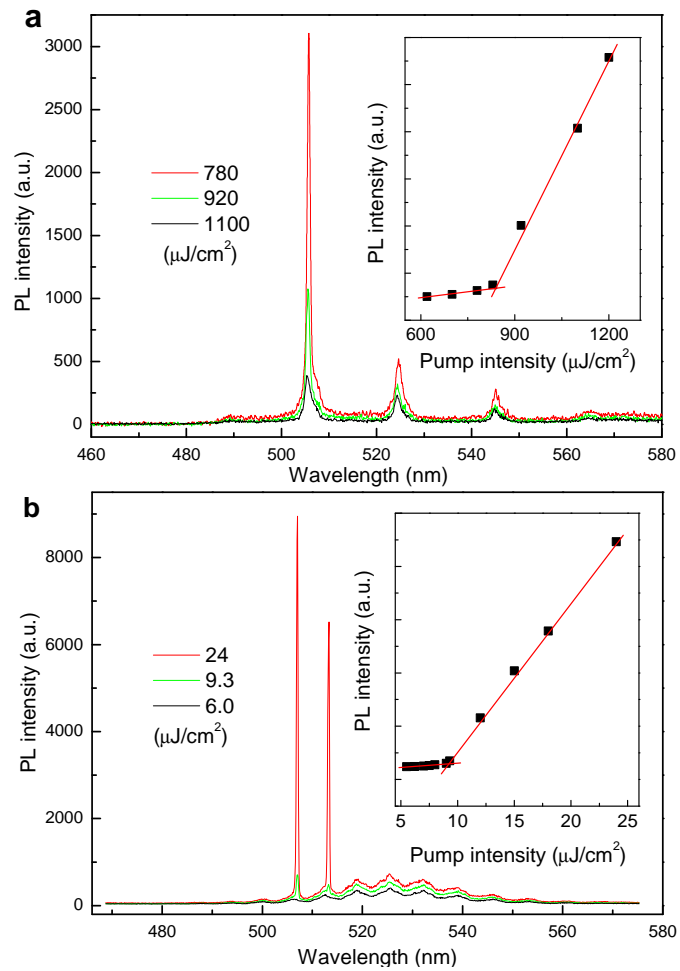
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328 **Figure 4| Lasing operation in quasi-continuous wave regime and multi-mode lasing. (a)**
 329 Nanosecond laser pumped PL spectra as a function of pump intensity. The inset shows the
 330 integrated PL intensity over the sharp peak versus pump intensity. **(b)** Multi-mode lasing from the
 331 CsPbBr₃ IPNC-VCSEL. The inset shows the integrated PL intensity over the sharp peaks versus
 332 pump intensity.

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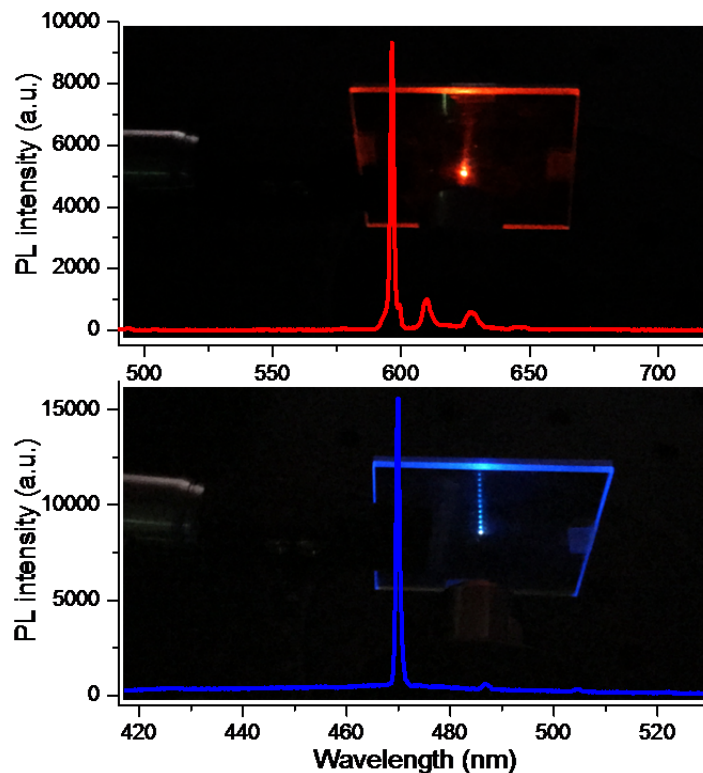
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339 **Figure 5| Red and blue vertical cavity surface emitting lasers from CsPbX₃ IPNCs.** Red and
 340 blue lasing spectra of vertical cavity surface emitting lasers from CsPb(I/Br)₃ and CsPb(Br/Cl)₃
 341 IPNCs under pump intensity of 30.5 and 38.2 $\mu\text{J}/\text{cm}^2$, respectively. The corresponding
 342 photograph of the device in operation is attached inside the plot.

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458 **Author contribution**

459 All authors contributed extensively to this work. Y.W. and V.N. conducted spectroscopic
460 experiment and analysis. Y.W. and H.S. conceived and fabricated the VCSEL structure. X.L. and
461 H.Z. synthesized the IPNC samples. H.S. and H.Z. supervised the project. Y.W., X.L., V.N., H.Z.,
462 and H.S. analyzed data and interpreted the results, and wrote the manuscript with input from all
463 authors.

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