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Ziming Wang,^{1,a)} Yinjuan Ren,^{2,a)} Yue Wang,^{1,b)} Zhiyuan Cu,¹ Xiaoming Li,¹ and Handong Sun^{3,4,5,b)}

AFFILIATIONS

¹MIIT Key Laboratory of Advanced Display Materials and Devices, Institute of Optoelectronics and Nanomaterials, College of Materials Science and Engineering, Nanjing University of Science and Technology, Nanjing 210094, China

²Department of Chemistry, National University of Singapore, 3 Science Drive 3, Singapore 117543, Singapore

³Division of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore 637371, Singapore

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

⁵MajuLab, CNRS-UCA-SU-NUS-NTU International Joint Research Unit, Singapore

^{a)}Contributions: Z. Wang and Y. Ren contributed equally to this work.

^{b)}Authors to whom correspondence should be addressed: ywang@njust.edu.cn and hdsun@ntu.edu.sg

ABSTRACT

Microlasers play an important role in the development of photonics and optoelectronics. As the rising star in the semiconductor family, all-inorganic lead halide perovskites (ILHPs) have been recognized as promising optical gain and lasing media. However, until now, achieving duplicable and single-mode microlasers remains a taunting challenge. Herein, we fabricated rectangular-shaped ILHP microsheets by the chemical vapor deposition method. The single-crystalline nature and the atomically smooth surfaces of the sample enable the achievement of lateral-cavity Fabry-Pérot (F-P) microlasers. Specifically, the lasing characteristics including the wavelength, mode spacing, and Q-factors can be well-reproduced along the axial direction of the individual microsheet. By regulating the width of the ILHP microsheet, the desirable single-longitudinal mode F-P microlaser was eventually achieved. Our results provide an enabling coherent light source for optics-related applications.

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Microlasers have attracted intense attention in numerous cutting-edge applications, such as on-chip coherent light sources, by virtue of their compact size and low power consumption.^{1–3} In the past few decades, impressive progress has been made in this field leveraging the conventional and emerging semiconductors (e.g., ZnO, GaN, and two-dimensional transition metal chalcogenides) in terms of miniaturizing the device size, lowering the pump threshold, and reducing the cost of device fabrication.^{4–8} Meanwhile, novel materials with improved optical gain properties and constructing microlasers with enhanced performance have always been pursued, which could provide possibilities in photonics and optoelectronics.^{9–12}

Recently, all-inorganic lead halide perovskites (ILHPs) have emerged as appealing optical gain materials thanks to the large absorption coefficient, highly defect tolerant property, and emission wavelength tunability across the whole visible regime.^{13–18} Until now, a variety of microlasers have been demonstrated from ILHP-based films, quantum dots (QDs), and single crystals.^{13–15} Different from the

polycrystalline films and QDs, which typically require additional cavities for developing laser devices, the bottom-up grown ILHP microcrystals have been demonstrated as attractive lasing candidates since the inerratic crystals with monocrystalline nature can serve as both the optical cavity and the active material, thus lowering down the complexity and cost of microlasers.^{15,19} Specifically, whispering gallery mode (WGM) microlasers have been realized from cubic ILHP microplates via total internal reflection around the periphery, and the pump threshold is found to be as low as $\sim 2.0 \mu\text{J cm}^{-2}$ owing to the superior gain properties of ILHPs and the advantageous optical confinement by the high-quality (Q) cavity.^{14,15} However, WGM lasers typically lack output directionality, which represents one of the most important merits of a laser, and hence, the collection and the ensuing exploitation of the WGM laser emission is relatively inefficient.¹³ On the other hand, Fabry-Pérot (F-P) microlasers showing directional output emission have been demonstrated from ILHP micro/nanowires.^{17,19–21} Due to the large axial F-P cavity length, the micro/nanowire lasers

typically show multimode lasing, while the desirable single-mode operation, which possesses the superb color purity and temporal stability, is still challenging.¹³ Furthermore, the lasing characteristics of the micro/nanowire lasers are closely related to the morphological factors, exemplified by the bending state as the micro/nanowires are extremely flexible, making the duplication of lasing features unfeasible.^{17,22} Until now, it remains a taunting challenge to achieve F-P microlasers with duplicable characteristics and single-mode output from ILHPs.

Herein, we fabricated the single-crystalline rectangular-shaped ILHP microsheets by the chemical vapor deposition (CVD) method and achieved the F-P microlasers enabled by the optical oscillation between the two lateral faces of the microcrystals. Specifically, we show that the lasing characteristics are duplicable at different positions along the longitudinal direction in the individual microsheet. The lasing mechanism is ascribed to the F-P oscillation based on the comprehensive optical characterization and numerical simulation. Notably, by regulating the width of the ILHP microsheet, we achieved the desirable single-longitudinal mode microlaser. Our results provide a route toward distinctive and functional microlasers based on the ILHPs.

The CsPbBr₃ microsheets were fabricated by the CVD method¹⁴ (see the detailed fabrication process in the Experimental Section, [supplementary material](#)). Figure 1(a) shows the typical optical microscopy image of the as-grown CsPbBr₃ samples on mica, and the representative scanning electron microscopy (SEM) image can be seen in Fig. S1. It is found that the CsPbBr₃ microsheets typically exhibit rectangular shapes with different aspect ratios. Due to the higher surface energy of corners compared to the edges, the adatoms tend to join the corners and lead to the formation of rectangular shapes.²³ The bright green color and the narrow photoluminescence (PL) spectrum with a full width at half maximum (FWHM) of ~ 19 nm [Fig. 1(a)] indicate the favorable optical properties of the samples. Figure S2 presents the atomic force microscopy (AFM) image of the CsPbBr₃ sample, where the small average roughness of < 1 nm indicates the atomically flat surface of the microsheets. The edge area was also investigated by the tilted SEM, which manifests the smooth lateral surface (Fig. S3). The X-ray diffraction (XRD) measurement of the sample discloses the cubic phase of the microsheets (Fig. S4), consistent with previous reports.²³ Furthermore, we performed energy dispersive X-ray spectroscopy (EDS) to access the elemental composition of the sample. The EDS mapping of the representative CsPbBr₃ microsheet is shown in Fig. 1(b), which reveals the uniform distribution of the constituent

elements of Cs, Pb, and Br. The elemental ratio of Cs, Pb, and Br was around 1:1:3, agreeing with the stoichiometric ratio of CsPbBr₃. All the above structural and composition measurements confirm the high quality of the CsPbBr₃ samples grown by the CVD method.

Leveraging on the smooth side surfaces of CsPbBr₃ microsheets, which may potentially serve as the reflective mirrors for cavity construction, and the superior optical gain property of ILHPs, it is highly possible to realize lateral cavity lasing from the CsPbBr₃ microcrystals. In this regard, we exploited the microphotoluminescence (μ -PL) system to investigate the lasing properties of the individual rectangular microsheet (see the details in the Experimental Section, [supplementary material](#)). Figure 2(a) shows the pump-fluence dependent PL spectra of a typical microsheet with a width of $21.3 \mu\text{m}$. Under low excitation fluences ($\leq 16 \mu\text{J}/\text{cm}^2$ or peak power density of $\sim 1.6 \times 10^8 \text{ W}/\text{cm}^2$), the PL is dominated by the spontaneous emission with a FWHM of ~ 19 nm. The corresponding fluorescence image shows the nearly homogeneous green color (excitation fluence: $7.2 \mu\text{J}/\text{cm}^2$) [inset in Fig. 2(a)]. With the gradual increase in excitation fluence, evenly spaced sharp spikes appear and the plot of the integrated PL intensity over the peak spectra region as a function of pump fluence exhibits the nonlinear increase behavior [Fig. 2(c)], indicating the achievement of lasing action with a low threshold (P_{th}) of $\sim 17 \mu\text{J}/\text{cm}^2$ or a peak power density of $\sim 1.7 \times 10^8 \text{ W}/\text{cm}^2$.²⁴ The fluorescence image under above-threshold pumping ($22 \mu\text{J}/\text{cm}^2$) manifests a pair of bright lateral edges [inset in Fig. 2(a)], which agrees with the F-P lasing behavior.²⁵ The trapezoidal far field emission pattern can be attributed to the uneven pumping condition. Specifically, more area in the downside part of the microsheet was pumped by the focused laser beam than that of the upside counterpart. This will lead to stronger light intensities emitted and scattered into free space from the bottom edge. To get more insight into the lasing mechanism, the free spectral range (FSR) of the lasing spectra was examined. In the case of the F-P cavity, the FSR is given by²⁵

$$\text{FSR} = \frac{\lambda^2}{2Ln_g}, \quad (1)$$

where λ is the lasing wavelength and L is the width of the microsheet or the cavity length. Accordingly, the group refractive index, n_g , is derived to be ~ 4.9 , which matches well with previous reports,^{14,15} further confirming the F-P lasing in this case. The corresponding F-P resonant oscillation in the horizontal plane in the CsPbBr₃ microsheet can be well retrieved by numerical simulation using the finite element method [inset in Fig. 2(a)] (see the details of the simulation method in the Experimental Section, [supplementary material](#)). Moreover, the PL dynamics from the individual ILHP microsheet was investigated by time-resolved μ -PL spectroscopy [Fig. 2(e)]. We can see that PL decay is relatively slow with a lifetime of ~ 550 ps at low pump fluence ($\sim 0.3 P_{\text{th}}$). With the increase in pump fluence ($\sim 0.8 P_{\text{th}}$), the PL decay becomes faster with a shortened lifetime of ~ 250 ps. Notably, as the pump fluence exceeds the threshold ($\sim 1.3 P_{\text{th}}$), the PL lifetime suddenly reduced to ~ 50 ps, which is ascribed to the occurrence of optical amplification and the lasing action.^{15,20} It is noted that the measured lifetime of ~ 50 ps under the lasing condition may be an underestimation, limited by the temporal response (~ 50 ps) of the streak camera system.

The Q-factor represents an important parameter that characterizes the performance of a laser device. In general, the Q-factor is

FIG. 1. (a) PL spectrum and fluorescence image of CsPbBr₃ microsheets grown by the chemical vapor deposition method. (b) SEM image and the corresponding energy dispersive X-ray spectroscopy spectra, revealing the compositions of Cs, Pb, and Br.

FIG. 2. (a) Pump-fluence dependent PL spectra of the CsPbBr₃ microsheet. The inset shows the PL images of above-threshold pumping (top), below-threshold (middle) pumping, and the simulated electric field distribution inside the lateral cavity (bottom). Scale bar: 20 μm . (b) Emission polarization of the lasing action. (c) Plot of the integrated PL intensity as a function of pump fluence. (d) A Gaussian fitting of the lasing mode. The FWHM is ~ 0.41 nm. (e) Pump fluence dependent PL decay from the individual CsPbBr₃ microsheet.

defined by $Q = \lambda / \Delta\lambda$, where λ and $\Delta\lambda$ are the lasing peak wavelength and the corresponding linewidth of the lasing peak, respectively.¹⁴ In our case, the linewidth of the resonant peak is determined to be ~ 0.41 nm [Fig. 2(d)]. Accordingly, the Q-factor of ~ 1300 was derived. Despite the fact that the higher Q-factor of ~ 5000 has been reported for WGM microlasers which suffer from the omnidirectional emission,¹⁵ the value of ~ 1300 is already quite high for the F-P lasing due to the inevitable radiative loss from the two end facets.^{13,26} The relatively high Q-factor observed in our case can be attributed to the large effective refractive index and the smooth surfaces of the ILHP microsheet which minimize the detrimental optical losses.¹⁴ We further studied the emission polarization of the lateral-cavity F-P microlaser. It is found that the laser output is dominated by the transverse-electric (TE)-polarized emission, where the electric field lies in the x direction [Fig. 2(b)]. The corresponding degree of polarization (DOP)²⁷ defined

by $\text{DOP} = \frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + I_{\perp}}$ is determined to be $\sim 71\%$. Such high DOP indicates the superior polarization purity of the laser emission, which is advantageous for a microlaser as a coherent light source.²⁷

Importantly, in contrast to the traditional semiconductor micro/nanowires possessing a small cross section area,^{20,27} the ILHP microsheet typically has a length of several tens to hundred micrometers. Therefore, different positions along the longitudinal direction in the microsheet could serve as individual lateral cavities. Moreover, since the cavity sizes are nearly identical by virtue of the rectangular geometry, the lasing characteristics are anticipated to be duplicable from the individual ILHP microsheet. To check the speculation, we tuned the position of the CsPbBr₃ microsheet with respect to the pumping laser beam by a three-dimensional (3D) translation stage [Fig. 3(a)]. As shown in Figs. 3(b)–3(d), when the laser beam moved along the axial direction, the lasing action indeed occurred from the different

FIG. 3. (a) Schematic illustration of the microphotoluminescence system used for the lasing measurement. (b)–(d) The PL images of the microsheet under the lasing condition pumped at different positions. Scale bar: 20 μm . (e) The lasing spectra of the perovskite microsheet pumped at different positions.

FIG. 4. (a) Lasing spectra of ILHP microsheets with different widths. The inset shows the corresponding PL images under the lasing condition. Scale bar: 20 μm. (b) Pump-fluence dependent PL spectra of the ILHP microsheet with a narrow width of 5.9 μm, manifesting the development of single-mode lasing. The inset shows the plot of integrated PL intensity over the peak spectral region vs the pump fluence. Scale bar: 5 μm.

positions of the microsheet. Notably, the lasing characteristics including the FSR, emission wavelength, and FWHM or Q-factor are nearly the same [Figs. 3(e) and S5]. For example, the deviation of the lasing peak wavelength lies within 0.2 nm, demonstrating the reproducibility of the laser emission. These results indicate that the lateral-cavity ILHP microlasers are promising for potential applications in integrated optics.

Furthermore, since the mode spacing is closely related to the cavity size [see Eq. (1)], the lasing spectra of the ILHP microlaser can be facilely manipulated by controlling the width of the rectangular microcrystals. Figure 4(a) shows the lasing spectra of CsPbBr₃ microsheets with different widths. The number of lasing peaks is found to decrease as the CsPbBr₃ microsheets narrow in width, and the plot of FSR as a function of $1/L$ follows a linear relationship (Fig. S6), which agrees with the attribute of the F-P longitudinal cavity modes.^{20,27} Notably, another important information on the approach toward the desirable single-mode lasing can be obtained from Eq. (1). Specifically speaking, when the size of the resonant cavity is sufficiently small such that the FSR exceeds the gain bandwidth, the single-longitudinal mode lasing would be achievable given that the optical gain from the active material was sufficient. Figure 4(b) displays the pump-fluence dependent PL spectra of the CsPbBr₃ microsheet with a narrow width of ~ 5.9 μm. Under low pump fluences, the PL spectra show the relatively broad spontaneous emission. As the pump fluence keeps increasing (≥ 24 μJ/cm²), a sharp peak appears and eventually dominates the PL spectra upon further rising the pump fluence. The integrated PL intensity of the stimulated peak exhibits its thresholdlike behavior [inset in Fig. 4(b)]. These results evidently confirm the development of single-mode lasing from the ILHP microsheets with a relatively low pump threshold of ~ 24 μJ/cm² or a peak power density of $\sim 2.4 \times 10^8$ W/cm². Thanks to the inorganic nature of the CsPbBr₃ microsheet, the single-mode lasing emission exhibits favorable photostability under the uninterrupted laser pumping (wavelength: 400 nm, repetition rate: 1000 Hz, and pump fluence: 28 μJ/cm²), where the lasing peak intensity can be readily maintained over more than 4×10^6 laser shots (~ 1.1 h) (Fig. S7).

In conclusion, we demonstrated the duplicable lateral-cavity supported F-P microlasers from the CVD-grown ILHP microsheets. The desirable single-mode lasing was achieved by reducing the width of the microsheet down to ~ 6 μm. The current lateral cavity microlaser outputs in two directions. In the future, one may selectively coat a highly reflective mirror on one end of the cavity, such that the unidirectional emission can be achieved, which would represent important

progress in perovskite F-P microlasers. Moreover, thanks to the duplicable lasing characteristics along the longitudinal direction of the microsheet, it is expected that isolated identical cavities can be fabricated by micronano processing technology, such as nanoimprint lithography^{28,29} and focused ion beam (FIB) treatment.³⁰ Note that the ILHP microsheets can be facilely transferred onto any on-demand substrate by the dry-processed technique thanks to the weak van der Waals interactions between ILHP microcrystals and mica.²³ Therefore, we envisage that these lateral-cavity ILHP microlasers would find widespread applications as favorable coherent light sources, especially for integrated optics.

See the [supplementary material](#) for the details of materials synthesis, SEM, XRD, and optical characterization of the inorganic perovskite lateral cavity microlasers.

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REFERENCES

- Y. Wang, V. D. Ta, K. S. Leck, B. H. I. Tan, Z. Wang, T. He, C.-D. Ohl, H. V. Demir, and H. Sun, "Robust whispering-gallery-mode microbubble lasers from colloidal quantum dots," *Nano Lett.* **17**, 2640–2646 (2017).
- J. Zhao, Y. Yan, Z. Gao, Y. Du, H. Dong, J. Yao, and Y. S. Zhao, "Full-color laser displays based on organic printed microlaser arrays," *Nat. Commun.* **10**, 870 (2019).
- S. Makarov, A. Furasova, E. Tiguntseva, A. Hemmetter, A. Berestennikov, A. Pushkarev, A. Zakhidov, and Y. Kivshar, "Halide-perovskite resonant nanophotonics," *Adv. Opt. Mater.* **7**, 1800784 (2019).
- S. Chen, W. Li, J. Wu, Q. Jiang, M. Tang, S. Shutts, S. N. Elliott, A. Sobiesierski, A. J. Seeds, I. Ross, P. M. Smowton, and H. Liu, "Electrically pumped continuous-wave III-V quantum dot lasers on silicon," *Nat. Photonics* **10**, 307 (2016).
- Y. Li, J. Zhang, D. Huang, H. Sun, F. Fan, J. Feng, Z. Wang, and C. Z. Ning, "Room-temperature continuous-wave lasing from monolayer molybdenum ditelluride integrated with a silicon nanobeam cavity," *Nat. Nanotechnol.* **12**, 987 (2017).
- X. Wu, Y. Wang, Q. Chen, Y.-C. Chen, X. Li, L. Tong, and X. Fan, "High-Q, low-mode-volume microsphere-integrated Fabry-Perot cavity for optofluidic lasing applications," *Photonics Res.* **7**, 50–60 (2019).

- ⁷A. Chen, H. Zhu, Y. Wu, D. Yang, J. Li, S. Yu, Z. Chen, Y. Ren, X. Gui, S. Wang, and Z. Tang, "Low-threshold whispering-gallery mode upconversion lasing via simultaneous six-photon absorption," *Adv. Opt. Mater.* **6**, 1800407 (2018).
- ⁸R. Chen, B. Ling, X. W. Sun, and H. D. Sun, "Room temperature excitonic whispering gallery mode lasing from high-quality hexagonal ZnO microdisks," *Adv. Mater.* **23**, 2199–2204 (2011).
- ⁹A. Zhizhchenko, S. Syubaev, A. Berestennikov, A. V. Yulin, A. Porfirev, A. Pushkarev, I. Shishkin, K. Golokhvast, A. A. Bogdanov, A. A. Zakhidov, A. A. Kuchmizhak, Y. S. Kivshar, and S. V. Makarov, "Single-mode lasing from imprinted halide-perovskite microdisks," *ACS Nano* **13**, 4140–4147 (2019).
- ¹⁰N. Zhang, Y. Fan, K. Wang, Z. Gu, Y. Wang, L. Ge, S. Xiao, and Q. Song, "All-optical control of lead halide perovskite microlasers," *Nat. Commun.* **10**, 1770 (2019).
- ¹¹H. Zhang, Q. Liao, Y. Wu, Z. Zhang, Q. Gao, P. Liu, M. Li, J. Yao, and H. Fu, "2D Ruddlesden-Popper perovskites microring laser array," *Adv. Mater.* **30**, 1706186 (2018).
- ¹²Z. Liu, J. Yang, J. Du, Z. Hu, T. Shi, Z. Zhang, Y. Liu, X. Tang, Y. Leng, and R. Li, "Robust subwavelength single-mode perovskite nanocuboid laser," *ACS Nano* **12**, 5923–5931 (2018).
- ¹³Y. Wang, X. Li, V. Nalla, H. Zeng, and H. Sun, "Solution-processed low threshold vertical cavity surface emitting lasers from all-inorganic perovskite nanocrystals," *Adv. Funct. Mater.* **27**, 1605088 (2017).
- ¹⁴Y. Wang, Z. Gu, Y. Ren, Z. Wang, B. Yao, Z. Dong, G. Adamo, H. Zeng, and H. Sun, "Perovskite-ion beam interactions: Toward controllable light emission and lasing," *ACS Appl. Mater. Interfaces* **11**, 15756–15763 (2019).
- ¹⁵Q. Zhang, R. Su, X. Liu, J. Xing, T. C. Sum, and Q. Xiong, "High-quality whispering-gallery-mode lasing from cesium lead halide perovskite nanoplatelets," *Adv. Funct. Mater.* **26**, 6238–6245 (2016).
- ¹⁶Z. Zheng, X. Wang, Y. Shen, Z. Luo, L. Li, L. Gan, Y. Ma, H. Li, A. Pan, and T. Zhai, "Space-confined synthesis of 2D all-inorganic CsPbI₃ perovskite nanosheets for multiphoton-pumped lasing," *Adv. Opt. Mater.* **6**, 1800879 (2019).
- ¹⁷X. Wang, M. Shoaib, X. Wang, X. Zhang, M. He, Z. Luo, W. Zheng, H. Li, T. Yang, X. Zhu, L. Ma, and A. Pan, "High-quality in-plane aligned CsPbX₃ perovskite nanowire lasers with composition-dependent strong exciton-photon coupling," *ACS Nano* **12**, 6170–6178 (2018).
- ¹⁸B. Tang, H. Dong, L. Sun, W. Zheng, Q. Wang, F. Sun, X. Jiang, A. Pan, and L. Zhang, "Single-mode lasers based on cesium lead halide perovskite submicron spheres," *ACS Nano* **11**, 10681–10688 (2017).
- ¹⁹A. P. Pushkarev, V. I. Korolev, D. I. Markina, F. E. Komissarenko, A. Naujokaitis, A. Drabavičius, V. Pakštas, M. Franckevičius, S. A. Khubezhov, D. A. Sannikov, A. V. Zasedatelev, P. G. Lagoudakis, A. A. Zakhidov, and S. V. Makarov, "A few-minute synthesis of CsPbBr₃ nanolasers with a high quality factor by spraying at ambient conditions," *ACS Appl. Mater. Interfaces* **11**, 1040–1048 (2019).
- ²⁰H. Zhou, S. Yuan, X. Wang, T. Xu, X. Wang, H. Li, W. Zheng, P. Fan, Y. Li, L. Sun, and A. Pan, "Vapor growth and tunable lasing of band gap engineered cesium lead halide perovskite micro/nanorods with triangular cross section," *ACS Nano* **11**, 1189–1195 (2017).
- ²¹S. W. Eaton, M. Lai, N. A. Gibson, A. B. Wong, L. Dou, J. Ma, L.-W. Wang, S. R. Leone, and P. Yang, "Lasing in robust cesium lead halide perovskite nanowires," *Proc. Natl. Acad. Sci. U. S. A.* **113**, 1993–1998 (2016).
- ²²K. Wang, S. Wang, S. Xiao, and Q. Song, "Recent advances in perovskite micro- and nanolasers," *Adv. Opt. Mater.* **6**, 1800278 (2018).
- ²³C. Huo, X. Liu, X. Song, Z. Wang, and H. Zeng, "Field-effect transistors based on van-der-Waals-grown and dry-transferred all-inorganic perovskite ultrathin platelets," *J. Phys. Chem. Lett.* **8**, 4785–4792 (2017).
- ²⁴Y. Wang, K. E. Fong, S. Yang, V. D. Ta, Y. Gao, Z. Wang, V. Nalla, H. V. Demir, and H. Sun, "Unraveling the ultralow threshold stimulated emission from CdZnS/ZnS quantum dot and enabling high-Q microlasers," *Laser Photonics Rev.* **9**, 507–516 (2015).
- ²⁵Y. Jiang, X. Wang, and A. Pan, "Properties of excitons and photogenerated charge carriers in metal halide perovskites," *Adv. Mater.* (published online).
- ²⁶Q. Liao, X. Jin, H. Zhang, Z. Xu, J. Yao, and H. Fu, "An organic microlaser array based on a lateral microcavity of a single J-aggregation microbelt," *Angew. Chem., Int. Ed.* **54**, 7037–7041 (2015).
- ²⁷H. Zhu, Y. Fu, F. Meng, X. Wu, Z. Gong, Q. Ding, M. V. Gustafsson, M. T. Trinh, S. Jin, and X. Y. Zhu, "Lead halide perovskite nanowire lasers with low lasing thresholds and high quality factors," *Nat. Mater.* **14**, 636 (2015).
- ²⁸Z. Li, J. Moon, A. Gharajeh, R. Haroldson, R. Hawkins, W. Hu, A. Zakhidov, and Q. Gu, "Room-temperature continuous-wave operation of organometal halide perovskite lasers," *ACS Nano* **12**, 10968–10976 (2018).
- ²⁹X. Yang, J. Wu, T. Liu, and R. Zhu, "Patterned perovskites for optoelectronic applications," *Small Methods* **2**, 1800110 (2018).
- ³⁰B. Gholipour, G. Adamo, D. Cortecchia, H. N. S. Krishnamoorthy, M. D. Birowosuto, N. I. Zheludev, and C. Soci, "Organometallic perovskite metasurfaces," *Adv. Mater.* **29**, 1604268 (2017).