Research article

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Low-threshold and narrow-linewidth perovskite microlasers pumped by a localized waveguide source

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Abstract: For the widely used vertically pumped (VP) method with a free-space beam, very little pump power is absorbed by the gain materials in microlasers because of the large spatial mismatch of areas between laser modes and free-space pump beams together with small thicknesses of gain materials, resulting in a high pump power threshold. Here, an in-plane-waveguide-pump (IPWP) method with a localized waveguide source is proposed to reduce pump power threshold of perovskite microlasers. Owing to reduced spatial mismatch of areas between laser modes and localized waveguide sources as well as increased absorption distances, the pump power threshold of the IPWP method is decreased to approximately 6% that of the VP method. Moreover, under the same multiple of the pump power threshold, the laser linewidth in the IPWP method is narrowed to approximately 70% that in the VP method. By using the IPWP method, selective pumping two adjacent (separation 2 or 3 μm) parallel-located perovskite microlasers is experimentally demonstrated, and no crosstalk is observed. This IPWP method may have applications in low-energy and high-density microlasers and photonic integrated circuits.

1 Introduction

Acting as an important component of photonic integrated circuits (PICs), on-chip microlasers have attracted enormous attention in recent years [1–16]. Various on-chip microlasers were demonstrated in experiments, including Fabry–Perot (FP) lasers [2–7], whispering-gallery mode (WGM) lasers [8–12], distributed-feedback (DFB) lasers [13, 14], and photonic crystal (PC) lasers [15, 16], etc. Generally, these microlasers were vertically pumped (VP) by a focused pump beam from free space. To pump whole structures of microlasers, the spot sizes of the pump beam were usually much greater than the sizes (or lasing area) of microlasers [3, 4, 7, 9, 14]. In this case, only a small ratio of the pump beam illuminated the lasing area in microlaser structures. For example, when a lead halide perovskite nanowire with a width of $W \approx 600 \text{ nm}$ and a length of $L \approx 10 \mu\text{m}$ was vertically pumped by a pump spot with a diameter of $D \approx 30 \mu\text{m}$, a FP microlaser was achieved [3]. Only a very small ratio $[\sigma V = WL/(\pi D^2/4)\beta = 0.6 \times 10/(\pi \times 30^2/4) \times 1.86 \approx 1.6\%]$ of the pump beam is irradiated onto the nanowire. Here, β is the correction coefficient after considering the Gaussian distribution of the pump spot. Under a pump spot with a size of $D_1 \times D_2 \approx 3.15 \times 0.07 \approx 0.22 \text{ mm}^2$, a colloidal quantum dot (CQD) DFB laser with a width of $W \approx 2 \mu\text{m}$ and length of $L \approx 100 \mu\text{m}$ was realized [14]. It is estimated that only $\sigma V = WL/(\pi D_1 D_2/4)\beta = 2 \times 100/(\pi \times 3150 \times 70/4) \times 2.0 \approx 0.2\%$ of the pump beam is illuminated onto the DFB laser. When a colloidal quantum dot (CQD) waveguide-ring resonator (WRR) lasers with a radius of $R_c \approx 7.5 \mu\text{m}$ was vertically pumped by a pump spot with a radius of $R_p \approx 40 \mu\text{m}$, a WGM microlaser was experimentally demonstrated [9]. The modal size of a WGM in the WRR resonator is $\sim 480 \text{ nm}$, so the ratio of the pump beam impinging on the lasing area is only approximately

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$$\sigma V = \pi[R_c^2 - (R_c - 0.479)^2] / (\pi R_p^2) \beta = \{\pi \times [7.5^2 - (7.5 - 0.480)^2] / [\pi \times 40^2] \times 1.9 \approx 0.8\%.$$

Besides, to maintain a single transverse mode, the thickness of the gain medium of the microlaser is usually smaller than lasing wavelengths [2, 3, 6–9, 11, 12, 14] or even less than a nanometer (~ 0.7 nm) [16]. For such a small thickness together with a small ratio of the pump beam illuminated the lasing area, the pump beam cannot be efficiently absorbed by gain materials, and most of the pump power directly transmits microlaser structures in the VP method. For example, in a FP microlaser by using a lead halide perovskite nanowire with a thickness of $t \approx 300$ nm [3], only $\mu = \{\sigma V[1 - \exp(-\alpha H)] = 1.6\% \times [1 - \exp(-5 \times 0.3)]\} \approx 1.2\%$ of the pump power was absorbed by the nanowire laser. For a CQD DFB laser with a CQD gain film (thickness $t \approx 50$ nm) [14], only $\mu = \{\sigma V[1 - \exp(-\alpha t)] = 0.2\% \times [1 - \exp(-0.5 \times 0.05)]\} \approx 0.01\%$ of the pump power was absorbed by the microlaser. For a CQD WGM laser with a thickness $t \approx 300$ nm [9], approximately $\mu = \{\sigma V[1 - \exp(-\alpha t)] = 0.8\% \times [1 - \exp(-0.5 \times 0.3)]\} \approx 0.1\%$ of the pump power was absorbed by the WGM laser.

Due to large spatial mismatch of areas between laser modes and vertical pump beams together with small thicknesses of gain materials, a very small proportion ($\leq 1.2\%$) of the pump power is absorbed by lasing modes in microlasers. This phenomenon greatly increases pump power thresholds (the pump power at the position of the kink in the linear fitting of the light input–light output curve) [17–19]. Moreover, for the VP method with large pump spots, the pump beam will also affect other functional devices next to microlasers [16]. In order to eliminate this influence of the large pump spot, the distance between two adjacent devices should be much larger than the diameter of the pump spot ($\sim$ several tens of microns), which severely decreases the integration densities for the PICs. In the previous studies on integration of multiple microlasers on a single chip, the distances between two adjacent lasers are usually ~ 10 μm or more [20–22], and multiple microlasers were simultaneously pumped.

2 Results and discussion

2.1 Theoretical calculations

In the letter, we propose to use a localized waveguide source instead of a free-space beam to in-plane pump on-chip perovskite microlasers. Due to the excellent optical properties including low density of defect states (10^9 – 10^{10} cm^{-3}) [23–26], long diffusion length (> 1 μm) [27–29], long carrier lifetime [3], and tunable band gap

[23, 27, 30], the lead halide perovskites have emerged as promising gain materials for microlasers [3, 21, 31–41]. The proposed in-plane-waveguide-pump (IPWP) method can not only greatly improve the absorption efficiency of the pump power by the gain materials, but also reduce the crosstalk between adjacent devices. Due to a good lateral confinement of waveguide modes, the waveguide mode size and the cross section of a perovskite microlaser match better than that in the VP method. In addition, the absorption distance of the gain material (CsPbBr_3) in a perovskite microlaser is converted from the thickness ($<$ lasing wavelength) to the length (~ 10 times lasing wavelength) of the gain material. As a result, the absorption distance in the IPWP method is greater than 10 times that in the VP method. The absorption efficiency of the pump power by the gain material (CsPbBr_3) in a microlaser is greatly improved up to $\sim 56\%$, which is more than 40 times that ($< 1.2\%$) in the previous works [3, 9, 14]. As a result, compared with the VP method, the pump power threshold of the IPWP method is decreased by an order of magnitude. Moreover, under the same multiple of the pump power threshold (P/P_{th}), the laser linewidth $\Delta\lambda_l$ by using the IPWP method is smaller than that $\Delta\lambda_v$ in the VP method ($\Delta\lambda_l/\Delta\lambda_v \approx 0.7$). By using the IPWP method, two adjacent (separation 2 μm) perovskite microlasers are selective pumped experimentally, and the crosstalk is avoided.

The IPWP method is schematically shown in Figure 1, where a high-index gain dielectric strip (width of W , length of L , and thickness of H) is placed on a dielectric waveguide (width of w and height of h). This high-index dielectric strip can serve as both the gain material and the optical cavity for a microlaser [42, 43]. The pump light propagates along the dielectric waveguide, and the waveguide source is evanescently coupled to the gain dielectric strip, as shown in Figure 1.

The cross-section schematic of the dielectric waveguide is demonstrated in Figure 2(a). Here, the dielectric waveguide is a poly(methyl methacrylate) (PMMA) strip, which is placed on a MgF_2 substrate. The simulated field distribution ($|E|^2$) and electric field vectors of the fundamental transverse electric (TE_0) waveguide mode supported by the PMMA waveguide at the pump wavelength of $\lambda_p = 450$ nm are depicted in Figure 2(b). In the simulation with Comsol, the lateral width and height of the PMMA waveguide are $w = 2$ μm and $h = 380$ nm, respectively. In the simulation, the refractive indices of air, PMMA waveguide, and MgF_2 substrate are set to be $n_{\text{air}} = 1.00$, $n_{\text{wav}} = 1.50$, and $n_{\text{sub}} = 1.38$, respectively. The effective refractive index of the TE_0 waveguide mode is $n_{\text{eff}} = 1.43$, and the electric field is well confined in the PMMA waveguide, as shown in Figure 2(b).

Figure 1: Schematic of the IPWP method with a localized waveguide source. Inset is the zoomed-in view of a high-index gain dielectric strip.

Figure 2: IPWP method.

(a) Cross-section schematic of the PMMA waveguide. (b) Field distribution $|E|^2$ of the TE_0 waveguide mode supported by the PMMA waveguide at $\lambda = 450$ nm. (c) Relationship between the absorption efficiency μ_I and the absorption coefficient α of the gain dielectric strip with different lengths (L) in the IPWP method. (d) The ratio of the absorption efficiencies of the IPWP method and VP method versus the absorption coefficients of gain dielectric strips with different lengths of gain dielectric strips. (e) Field distribution $|E|^2$ at $\lambda = 450$ nm in the IPWP method with $\alpha = 3 \mu\text{m}^{-1}$.

For the IPWP method, the absorption efficiency μ_I of the pump beam is:

$$\mu_I = \eta_I (1 - e^{-\alpha L}) \quad (1)$$

where, η_I is the coupling efficiency of the pump beam from the PMMA waveguide to the gain dielectric strip, and α is

the absorption coefficient of the gain dielectric strip. In the following, η_I is obtained by a finite element method (FEM) of Comsol Multiphysics, and it is on the order of 10%.

For the commonly used VP method, the absorption efficiency μ_V of the pump beam by the gain dielectric strip is:

$$\mu_V = \sigma_V (1 - e^{-\alpha H}) \quad (2)$$

where, $\sigma_V = \beta S_I / S_p = \beta W L / (\pi D^2 / 4)$ is a ratio of the area of a gain dielectric strip to the pump spot ($S_p = \pi D^2 / 4$). Based on the discussion in Introduction, σ_V is approximately 1%.

According to Equations (1) and (2), the ratio (γ) of absorption efficiencies of the pump power in the IPWP method (μ_I) to the VP method (μ_V) is:

$$\gamma = \frac{\mu_I}{\mu_V} = \frac{\eta_I (1 - e^{-\alpha L})}{\sigma_V (1 - e^{-\alpha H})} \quad (3)$$

When $\gamma > 1$, the absorption efficiency of the pump beam of the microlaser in the IPWP method is greater than that of the VP method. Since η_I (~10%) is much greater than σ_V (~1%) and the length (L) of the gain dielectric strip is usually greater than the thickness (H) of the gain dielectric strip, the IPWP method has greater advantages over the VP method. As the thickness of the gain dielectric strip H is very small ($H \ll 1/\alpha$), the advantage of the IPWP method becomes more prominent.

To validate the above analysis, γ is calculated for different lengths (L) and absorption coefficients (α) of the gain dielectric strip. The thickness of the high-index gain dielectric strip and the height of the PMMA waveguide are $H = 300$ nm and $h = 380$ nm, respectively. The widths of the PMMA waveguide (w) and the gain dielectric strip (W) are both $W = w = 2 \mu\text{m}$. We first simulate the absorption efficiencies μ_I in the IPWP method, and the results are displayed in Figure 2(c). Since the widths of the gain dielectric strip and the PMMA waveguide are the same, the three-dimensional model is simplified into a two-dimensional model in the simulation. The real part of the refractive index of the gain dielectric strip is $n_g \approx 2.52$ [42]. The absorption efficiency μ_I in the gain dielectric strip increases with the increase of α , and the longer dielectric strip has larger absorption efficiency μ_I , which is in consistent with Equation (1). There is an optimal length of the microlasers for the IPWP method, and the detail can be found in Section 1 in Supplementary Material.

The ratios $\gamma = \mu_I / \mu_V$ versus the absorption coefficients α for different lengths L of the gain dielectric strip are shown in Figure 2(d). Here, the thickness of the gain dielectric strip and the height of the PMMA waveguide are $H = 300$ nm and $h = 380$ nm, respectively. The widths of the PMMA waveguide (w) and the gain dielectric strip (W) are both

$W = w = 2 \mu\text{m}$. The diameter of the pump spot in the VP method is $\sim 21 \mu\text{m}$. It is observed that the IPWP method is superior ($\gamma > 1$) to the VP method for $L = 3, 5, 7$ and $10 \mu\text{m}$. Besides, the ratio γ increases with the decrease of the absorption coefficient (α) of the gain dielectric strip, which also agrees well with Equation (3). The electric intensity distribution ($|E|^2$) in a coupling structure with a PMMA waveguide and a gain dielectric strip ($L \approx 7 \mu\text{m}$ and $\alpha = 3 \mu\text{m}^{-1}$) in the IPWP method is shown in Figure 2(e), and the absorption efficiency in the IPWP method is approximately $\mu_1 \approx 56\%$. The absorption efficiency is more than 40 times that ($\leq 1.2\%$) in the previous works [3, 9, 14].

2.2 Lasing from a perovskite microplate

In experiments, CsPbBr_3 perovskite microplates synthesized with a chemical vapor deposition (CVD) method [42] are used as the high-index gain dielectric strip. A transfer-printing approach (angle accuracy of $1.3 \pm 0.7^\circ$) is used to transfer a CsPbBr_3 microplate on a PMMA waveguide (see Methods). The dark-field optical image of a sample is depicted in Figure 3(a). The width of the perovskite microlaser is smaller than that of the PMMA waveguide. When the width of the perovskite microlaser is much greater than that of the PMMA waveguide, the pump beam can only pump part of the perovskite microplate partly. Here, the width, thickness, and length of the perovskite microplate are $W \approx 1.1 \mu\text{m}$, $H \approx 300 \text{ nm}$, and $L \approx 7.0 \mu\text{m}$, respectively. The width, height, and length of the PMMA waveguide are $w = 2 \mu\text{m}$, $h = 380 \text{ nm}$, and $l = 50 \mu\text{m}$, respectively. In order to couple the pump beam into the PMMA waveguide and decouple the lasing signals from the CsPbBr_3 microplate to the free space, two gratings with periods of $p = 400 \text{ nm}$ are fabricated on both ends of the PMMA waveguide. According to the conditions of the constructive interference, the coupling efficiency of the grating is optimal when the grating period satisfies the following equation:

$$n_{\text{eff}1} p/2 + n_{\text{air}} p/2 = m\lambda \quad (4)$$

where $n_{\text{eff}1}$ is the effective refractive index of the fundamental mode in the air-PMMA- MgF_2 multilayer slab waveguide, p is the grating period, n_{air} is the refractive index of the air, m is an integer, and λ is the wavelength. To obtain a high coupling efficiency of the pump beam, the gratings are optimized for the pumping wavelength. The perovskite microplate and PMMA waveguide are almost parallel. When a pump beam (wavelength of 450 nm , pulse width of 20 ps , repetition rate of 1 kHz , and spot size of $\sim 24 \times 15 \mu\text{m}^2$) vertically pump the CsPbBr_3 microplate, the lasing behavior is observed. The lasing wavelength, pump

power threshold, and the linewidth are $\lambda = 535.1 \text{ nm}$, $P_{th} \approx 0.15 \mu\text{W}$ (pump power threshold), and $\Delta\lambda_V = 0.27 \text{ nm}$, respectively. The pump threshold and the linewidth are comparable with previous literature reports [44]. Details of the demonstration of the lasing action in a perovskite microplate by the VP method can be found in Section 2 of Supplementary Material, and the detailed measurement process can be seen in Methods.

Next, a TE-polarized (electric field vectors along y -axis direction) is focused at one grating of a PMMA waveguide. The pump spot size is approximately $4.5 \times 8.4 \mu\text{m}^2$. The

Figure 3: Lasing actions of a perovskite microplate pumped by the IPWP method.

(a) Dark-field optical image of the integrated structure composed of a perovskite microplate and a PMMA waveguide. The scale bar is $10 \mu\text{m}$. (b) Emission spectra of a perovskite microplate pumped by the IPWP method at different pump powers in the PMMA waveguide. (c) Dependence of the peak intensities and linewidths on the pump powers of the lasing peak at $\lambda = 535.1 \text{ nm}$. (d) Linewidths of the lasing peak centered at $\lambda = 535.1 \text{ nm}$ with different P/P_{th} . (e) Optical images of a perovskite microplate at $1.5P_{th}$ with the exposure time of 10 ms (top panel) and 500 ms (bottom panel), respectively. (f) Spectra measured at the perovskite microplate (position A), left grating (position B), and right grating (position C) under a pump power of $1.5P_{th}$.

pump power in the PMMA waveguide is $P = P_0\eta_g$. Here, P_0 is the power of the pump beam in the free space, and η_g is the coupling efficiency of the grating. The coupling efficiency of the grating at $\lambda = 450$ nm are experimentally measured to be about $\eta_g \approx 0.016$ (see Section 3 of Supplementary Material). The measured emission spectra from a perovskite microplate at different pump powers in the waveguide pumped by the IPWP method are demonstrated in Figure 3(b). With the increase of pump powers, several narrow lasing peaks appear over the broadband PL spectrum. Here, the perovskite microlaser is a multimode lasers. The single-mode lasers can be achieved when the length of perovskite microplate is short enough, and a single-mode laser with the length of $L \approx 5.8$ μm has been demonstrated in Figure S4 in Supplementary Material. Figure 3(c) summarizes peak intensities (black circle symbols) and linewidths (red square symbols) of the lasing peak at $\lambda = 535.1$ nm under different pump powers in the waveguide. The clear pump threshold and the narrowing of linewidths (from 20 to 0.19 nm) reveal the lasing action in the perovskite microplate. The measured pump power threshold of the perovskite microplate in the IPWP method are $P_{\text{thI}} = P_0\eta_g = 0.56 \times 0.016 \approx 8.9 \times 10^{-3}$ μW . Thus, the pump power threshold of the IPWP method is only approximately 6% that of the VP method (~ 0.15 μW), revealing that the IPWP method increases the absorption efficiency of the pump beam by more than 16 times. The similar decrease of the pump power threshold is also observed on other samples (see Section 4 of Supplementary Material). If the pump beam is coupled to the perovskite microplate through the fiber taper, η_g can be increased from ~ 0.016 to $\sim 97\%$ [45, 46]. In addition, when the perovskite microplate is placed beside the PMMA waveguide in an end-to-end configuration [5], η_g will become higher.

Above the pump threshold, the linewidths of the lasing peak centered at $\lambda = 535.1$ nm as a function of the multiple of the pump power threshold (P/P_{th}) for the IPWP method and VP method are depicted by the black square symbols and red circle symbols in Figure 3(d), respectively. It is observed that the laser linewidths in the IPWP method is narrower than that in the VP method at the same P/P_{th} . In the IPWP method, the linewidth of the lasing peak at $\lambda = 535.10$ nm (at $1.5P_{\text{thI}}$) is about $\Delta\lambda_I = 0.19$ nm, which is 70% that (at $1.5P_{\text{thV}}$) of the VP method ($\Delta\lambda_V = 0.27$ nm). The corresponding quality factor $Q_I = \lambda/\Delta\lambda_I \approx 2816$, which is ~ 1.4 times that of the VP method for the lasing peak centered at $\lambda = 535.1$ nm. This phenomenon may be attributed to that the heat of the whole structure induced by the pump power in the IPWP method is more localized, making the heat

dissipating more quickly to the environment in the IPWP method [16]. The simulations of the heat dissipations in the perovskite microlasers are depicted in Section 5 in Supplementary Material.

Figure 3(e) shows optical images of a perovskite microplate with different exposure times at $1.5P_{\text{th}}$. The bright scattered spots can be observed at the perovskite microplate and both ends of the PMMA waveguide. Moreover, under a pump power of $P = 1.5P_{\text{th}}$, the same lasing wavelengths in the spectra measured at an end of the perovskite microplate (position A) and gratings (position B and C in Figure 3(f)) confirm that the lasing signals from the perovskite microplate are coupled to the PMMA waveguide. By integrating the intensities of the scattered spot at one end of the perovskite microplate (I_e) and that at the grating (I_g), the intensity ratio (I_e/I_g) is measured to be approximately $I_e/I_g \approx 28.6$. The collecting efficiency (η_c) of the lasing emissions ($NA = 0.5$) scattered by the perovskite microplate to the free space is obtained by using COMSOL Multiphysics, and it is approximately $\eta_c \approx 6.1\%$. The coupling efficiency (η_g) of the grating at the lasing wavelength ($\lambda \approx 535$ nm) is numerically simulated to be approximately $\eta_g \approx 1.9\%$. Due to the fabrication deviation and imperfect, the coupling efficiency becomes smaller in the experiment. Then, the coupling efficiency of the laser to the PMMA waveguide is $\eta = (I_g/\eta_g)/(I_e/\eta_c) = (I_g/I_e) \times (\eta_c/\eta_g) \approx 11.0\%$. It is observed that the spectrum of the IPWP method (Figure 3(b)) has one more lasing peak ($\lambda = 535.6$ nm) than that of the VP method (see Section 2 in Supplementary Material). The appearance of this lasing mode is attributed to the nonuniform pumping intensity in the in-plane-waveguide-pump method (Figure S7 in Supplementary Material). The absorption power density distributions of the pump light in the same perovskite microplate (see Section 6 in Supplementary Material) are different under these two pump methods, resulting in establishing different lasing modes [35, 47–49] and different wavelength separation between lasing modes. Then, we change the relative position of the pump spot and the grating while keeping the pump spot size and the pump power in the free space unchanged, and the emission intensities of the perovskite microplate are measured. The optical images of the perovskite microplate at different positions along the x -axis and y -axis are depicted in Figure 4(a) and (b), respectively. It is clearly observed that the emission intensity of the perovskite microplate decreases when the pump spot moves away from the grating ($x = 0$ μm and $y = 0$ μm). Moreover, the emission intensities of the perovskite microplate at different relative positions of the pump spot and the grating along the x -axis and

y -axis are shown in Figure 4(c) and (d), respectively. When the pump spot deviates from the grating by more than $3.7\ \mu\text{m}$ in the x -axis direction ($x < -3.3\ \mu\text{m}$ and $x > 3.7\ \mu\text{m}$), the intensity of the perovskite microplate will reduce to less than 0.1 times that at the origin position ($x = 0\ \mu\text{m}$, $y = 0\ \mu\text{m}$), as depicted by the blue dashed line in Figure 4(c). Similarly, when the sample is moved beyond the range between $y = -5.6\ \mu\text{m}$ and $y = 7.9\ \mu\text{m}$, the emission intensities of the perovskite microplate will decrease to less than 0.1 times the intensity at the origin position ($x = 0\ \mu\text{m}$, $y = 0\ \mu\text{m}$), as depicted by the blue dashed line in Figure 4(d). Therefore, the lasing actions of the perovskite microplate results from the IPWP method.

Figure 4: Verification of the IPWP method.

(a) Optical images of a perovskite microplate at $x = -2.7\ \mu\text{m}$ (top panel), $x = 0\ \mu\text{m}$ (middle panel), and $x = 3.2\ \mu\text{m}$ (bottom panel), respectively. The yellow dashed line is the reference line for the sample position. The blue dashed ellipses indicate the pump spots. (b) Optical images of the perovskite microplate at $y = 7.6\ \mu\text{m}$ (top panel), $y = 0\ \mu\text{m}$ (middle panel) and $y = -4.1\ \mu\text{m}$ (bottom panel), respectively. The yellow dashed line is the reference line for the sample position. The blue dashed ellipses indicate the pump spots. Emission intensities of the perovskite microplate at different positions when the sample is moved along the x -axis direction (c) and y -axis direction (d). The blue horizontal dashed lines denote the emission intensity, which is 0.1 times the intensity at origin position.

2.3 Selective pumping on-chip perovskite microlasers

Furthermore, two adjacent (2 or $3\ \mu\text{m}$) PMMA waveguides are fabricated by electron beam lithography (EBL). Then, we place two perovskite microplates on the two PMMA waveguides by using the transfer-printing approach. The schematic and structural parameters of two close PMMA waveguides are depicted in Figure 5(a). Here, the curved part in each PMMA waveguide has the cosine-arc shape [50], and it is expressed as:

$$y = H_1 \times [x/W_1 - \sin(2\pi x/W_1)/(2\pi)] \quad (5)$$

where H_1 and W_1 denote the width and length of the curved part, respectively. The grating A and B are fabricated to couple the free-space pump beam into PMMA waveguides. Besides, the lasing signals in PMMA waveguides can be scattered to free space by the grating C and D . Figure 5(b) is the dark-field optical image of the fabricated structure. Here, the separation of the PMMA waveguides is $S = 3\ \mu\text{m}$, and the lateral width and height of the PMMA waveguide is $w = 3\ \mu\text{m}$ and $h = 380\ \text{nm}$, respectively. Moreover, the lengths of the straight waveguides on the left and right ends of the each PMMA waveguide are $l_1 = 10\ \mu\text{m}$ and $l_2 = 25\ \mu\text{m}$, respectively. The width and length of the curved part are $W_1 = 30\ \mu\text{m}$ and $H_1 = 8\ \mu\text{m}$, respectively. When a TE-polarized laser beam ($\lambda = 450\ \text{nm}$) with the pump power of $P = 1.5P_{\text{th}} = 2.9\ \mu\text{W}$ is focused on the grating A , the scattered spots are observed on the perovskite microplate a and the grating C , as depicted in Figure 5(c). The lasing wavelengths in the spectra (in Figure 5(e)) measured at the perovskite microplate a and the grating C are the same, confirming that the lasing signals from the perovskite microplate a are coupled to the upper PMMA waveguide. Similarly, when the pump beam is focused at grating B under $P = 1.5P_{\text{th}} = 1.4\ \mu\text{W}$, the scattered spots can be observed at the perovskite microplate b and the grating D , as shown in Figure 5(d). Furthermore, the similar spectra measured at the perovskite microplate b and the grating D confirm that the lasing signals of the perovskite microplate b are coupled to the PMMA waveguide, as depicted in Figure 5(f). Therefore, by using the proposed IPWP method, selective pumping on-chip perovskite microlasers with close spacing ($S = 3\ \mu\text{m}$) is realized. Besides, the more adjacent ($S = 2\ \mu\text{m}$) perovskite microlasers are selective pumped experimentally (see Section 7 of Supplementary Material).

Figure 5: Selective pumping on-chip microlasers.

(a) Schematic and structural parameters of two adjacent PMMA waveguides. (b) Dark-field optical image of a fabricated structure including two identical PMMA waveguides and two perovskite microplates. The scale bar is 20 μm . Optical images of the fabricated structure when the pump beam is focused on the grating A (c) and grating B (d). The scale bar is 20 μm . The blue dashed ellipses indicate the pump spot. Inset is the zoomed-in image of the decoupling grating. Besides, the exposure time of the inset in right panel is 25 times longer than that of the optical image in left panel. (e) Measured emission spectra at the perovskite microplate *a* and the grating C. (f) Measured emission spectra from the perovskite microplate *b* and the grating D.

3 Conclusion

In summary, the IPWP method was proposed to decrease the pump power threshold of the perovskite microlasers and increase the integration density of microlasers in PICs. In the proposed IPWP method, a localized waveguide source was used instead of a free-space beam, and the mismatch between the area of the laser mode and that of the localized waveguide source was smaller than that in the VP method. Besides, the absorption distance was converted from the thickness to length of gain materials in perovskite microlasers. The absorption efficiency of the pump power was increased to $\sim 56\%$, which was more than 40 times that ($\leq 1.2\%$) in the previous works by using the VP method. Experimentally, the pump power threshold of the IPWP method was decreased to approximately 6% that of the VP method. Moreover, the laser linewidth in the IPWP method was narrowed to approximately 70% that in the VP method under the same multiple of the pump power threshold. Besides, selective pumping one of two closely located (separation 2 or 3 μm) perovskite microlasers was experimentally demonstrated, indicating that the IPWP

method had no influence on surrounding photonic devices adjacent to perovskite microlasers. Therefore, the IPWP method might find important applications in low-energy and high-density microlasers.

4 Methods

4.1 Synthesis of the perovskite microplate

The CsPbBr_3 microplates are synthesized with a chemical vapor deposition (CVD) method on the PDMS substrate [42]. The perovskite microlasers can be stable in the air for more than two weeks. The stability can be improved by coating Al_2O_3 layer [42] and hexagonal boron nitride flakes [43] on the perovskite microlasers.

4.2 Fabrication

The fabrication of the coupling structure in IPWP method included two main steps. In the first step, a PMMA film (AR-P 672.045, Allresist) with the thickness of 380 nm was exposed to the electron beam at a current about 23 pA (Raith e-LINE plus). Then, the PMMA waveguide were obtained. In the second step, a transfer-printing approach method was used to transfer the CsPbBr_3 microplate on the PMMA waveguide. A polydimethylsiloxane (PDMS) stamp with the size of $\sim 1.5 \times 1.5 \times 160 \mu\text{m}$ was used. Then, the PMMA waveguide was imaged on a complementary metal oxide semiconductor (CMOS) camera through a microscope in the dark field mode. Next, the target perovskite microplate adheres to the PDMS stamp was aligned with a PMMA waveguide under the microscope. Then, the PDMS stamp was gradually pressed onto the surface of the PMMA waveguide. When the entire perovskite microplate was in touch with the PMMA waveguide, the PDMS stamp was lifted, and the perovskite microplate was printed on the PMMA waveguide. Here, the perovskite microplates can also be placed at the end of PMMA waveguides. When the perovskite microplates are placed at the end of PMMA waveguides, the coupling efficiencies between the perovskite microplates and the PMMA waveguides are related to the gap between themselves. There is a little difficult to precisely control the gap in the fabrication.

4.3 Measurement

All the lasing measurements in the perovskite microplate were carried out at room temperature by a home-made microscope system. A piezo-actuated stage is utilized to finely adjust position of the sample. The wavelength, repetition rate, and pulse width of the picosecond pump laser were 450 nm, 1 kHz, and 20 ps, respectively. The pump beam (electric field vectors parallel to the y-axis) was focused by an objective (Olympus 20 $\times$, $NA = 0.4$) from the back side of the MgF_2 substrate. The lasing signals from the perovskite microplate and the gratings of the PMMA waveguide were collected by an objective (Olympus 100 $\times$, $NA 0.8$) from the other side of the MgF_2 substrate. After passing through two long-pass filters, the collected lasing signals were focused by two lens with the focal length of $f_1 = 15 \text{ cm}$ and $f_2 = 5 \text{ cm}$, and divided into two paths by a beam splitter. The lasing signals of one path were imaged on a CMOS camera. Besides, the lasing signals in another path

are received by a coupled fiber connected to the spectrograph (with a resolution of 0.03 nm) for the spectrum measurement. In order to spatially select the lasing emissions from the perovskite microplate, a pinhole with a diameter about 300 μm was placed on the image plane between the two lenses. The detail for measurement of the absorption coefficient of the perovskite microplate can be seen in Section 8 in Supplementary Material.

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Optimal length of the micro-lasers for the IPWP method, lasing emissions from a perovskite microplate pumped by the VP method, coupling efficiency of the gratings, lasing in another sample, thermal dissipation processes of the perovskite microplates in the VP method and the IPWP method, absorption power density distributions in the perovskite microplate with different pump methods, selective pumping either of two closer ($S = 2 \mu\text{m}$) perovskite microplate, absorption coefficient of the perovskite microplate.