Efficient Metal-Halide Perovskite Micro Disc Lasers Integrated in a Silicon Nitride Photonic Platform

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Abstract: Metal-halide perovskites, low-cost solution processed semiconductors, have been successfully demonstrated in various optoelectronic devices, including optically pumped continuous wave lasers [1]. Straight forward deposition by spin coating [2] makes them an interesting choice for integrated micro/nano optoelectronics. We have recently demonstrated the first optically pumped perovskite lasers integrated into a silicon nitride photonics platform [3], where the perovskite was applied as the last step and remained unpatterned. Truly integrated device manufacturing, however, requires multilevel patterning with precise dimension control, overlay accuracy and high throughput. The chemical sensitivity of perovskites [4] typically prohibits using well-established lithography methods, and the few examples of perovskite patterning reported thus far do not fulfill all requirements of a versatile manufacturing technology. Here, we present for the first time integrated perovskite lasers manufactured by top-down patterning using processes routinely used in semiconductor manufacturing, including optical lithography and reactive ion etching (RIE). The resulting methylammonium lead iodide ($MAPbI_3$) perovskite disc lasers are integrated into a silicon nitride waveguide platform and show a low threshold of 5.57 μJcm^{-2}, outcompeting lasers made of unprocessed perovskite [3,5].

Micro discs with a radius of 6 µm were simulated and designed (**Fig. 1**). They support transverse magnetic (TM) (electric field normal to the disc plane) and transverse electric (TE) whispering gallery modes (WGMs) with free spectral range (FSR) of 3.15 nm and 3.26 nm, respectively. The edge of the disc is aligned with the silicon nitride bus waveguide located in the layer below, enabling out-coupling of WGMs to bus waveguide modes via a vertical directional coupler (**Fig. 2**). Due to a large mismatch of effective refractive indices between WGMs and bus waveguide modes, the vertical coupler gap was set to only 50 nm to ensure coupling efficiency of ~ 1%. After planarization, $MAPbI_3$ was deposited on the silicon nitride photonic chips by solvent engineering technique [2] and coated with a protective poly(methyl methacrylate) (PMMA) layer. Next, an AZ series photoresist was deposited, exposed with UV light and developed with tetramethylammonium hydroxide (TMAH) based developer. The pattern was transferred into the PMMA/$MAPbI_3$ stack by a single RIE step with an etch stop on the underlying SiO_2 layer. The photoresist was removed by a lift-off process. This procedure resulted in fully functional perovskite discs (**Fig. 3**). Finally, the samples were encapsulated with a 1 µm thick PMMA film to protect them from oxygen and moisture.

The perovskite micro discs were pumped by 120 fs / 250 kHz laser pulses (λ = 630 nm) focused with a 15 cm lens at an 58° incoming angle at room temperature and in ambient conditions. The output was collected from the end facet of the silicon nitride bus waveguide by an edge coupled single mode fiber with a fiber collimator at the other end. The collimated beam passed through a polarizer and entered a spectrometer. At low excitation a weak photoluminescence signal was observed (**Fig. 4**). When the pump fluence was increased above 5.57 μJcm^{-2} a single peak with a width 1.29 nm appeared in the spectrum accompanied by additional modes at higher excitations. The FSR was larger at shorter wavelengths indicating strong dispersion in the perovskite. The output intensity vs. pump fluence curve shows distinct threshold and saturation regimes, which is a clear indication of lasing (**Fig. 5**). The laser output is predominantly TM polarized, even though the TM to TE ratio is lower than ideally expected (3:1 vs. 6:3). This can be attributed to polarization cross talk in the vertical directional coupler occurring due to strong scattering induced by the polycrystalline morphology of the perovskite (**Fig. 6**).

We have developed a scalable fabrication technology for perovskite microscale devices, demonstrated through $MAPbI_3$ micro disc lasers with a low threshold of 5.57 μJcm^{-2}.This indicates that the processing does not strongly degrade the intrinsic material properties and opens up the possibility of fabricating a broad range of perovskite integrated devices. Since our technology is compatible with conventional semiconductor manufacturing tools it is a major step towards commercialization of low-cost solution processed perovskite based devices.

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[1] Y. Jia et al., Nat. Photonics, vol. 11, no. December, pp. 1–5, 2017. **[2]** N. J. Jeon *et al., Nat. Mater.*, vol. 13, no. July, pp. 1–7, 2014. **[3]** P. J. Cegielski *et al.*, *Opt. Express*, vol. 25, no. 12, p. 13199, Jun. 2017. **[4]** N. Zhang *et al.*, *Adv. Mater.*, vol. 29, no. 15, p. 1606205, Apr. 2017. **[5]**Q. Zhang, *et al., Nano Lett.*, vol. 14, no. 10, pp. 5995–6001, Oct. 2014.

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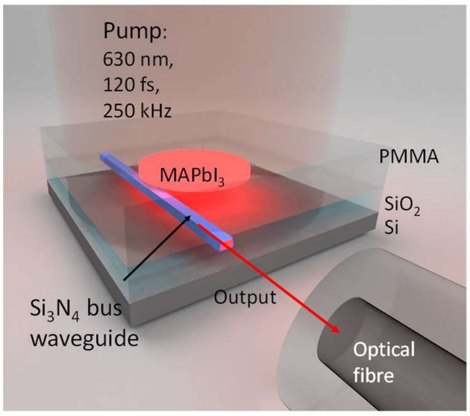

Fig. 1. Schematic of a $MAPbI_3$ disc laser integrated in a silicon nitride photonic chip. Light generated in the perovskite disc is vertically coupled to the Si_3N_4 bus waveguide. It is then collected from the end facet of the bus waveguide by an optical fiber.

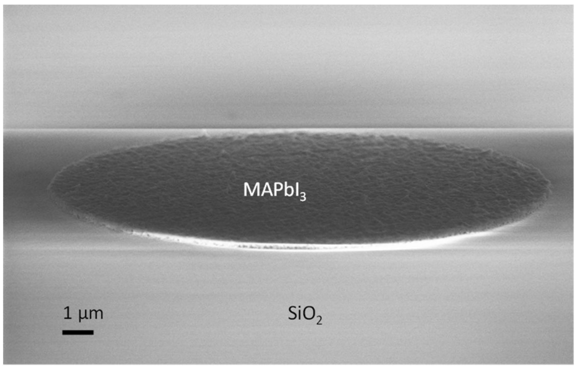

Fig. 3. SEM micrograph of a $MAPbI_3$ disc taken at 75 angle

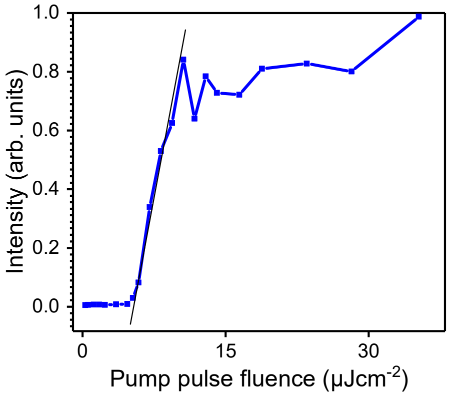

Fig. 5. Laser output peak intensity vs. pump pulse fluence of a laser with 6 µm radius. A clear threshold can be seen at 5.57 μJcm^{-2}, as well as a saturation above 12 μJcm^{-2}.

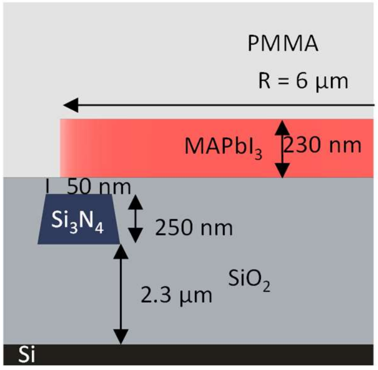

Fig. 2. Schematic of a cross-section of a $MAPbI_3$ disc laser.

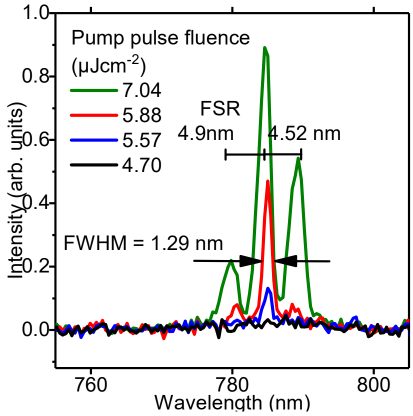

Fig. 4. Spectra of a disc laser with 6 µm radius pumped below the threshold (black) and above the threshold (colored lines).

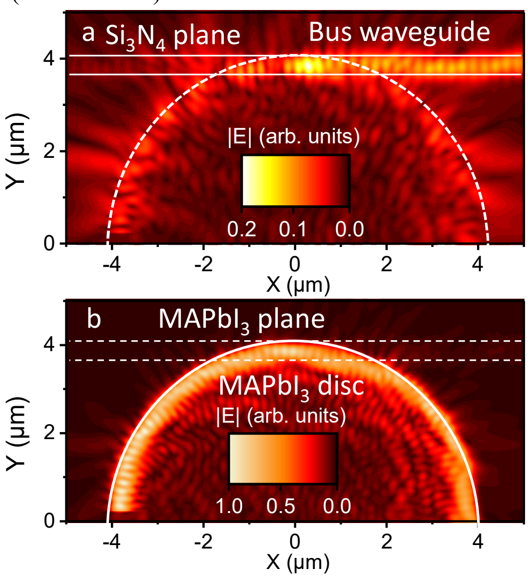

Fig. 6. FDTD simulation of TM WGM coupling to bus waveguide modes:. a) Despite the strong scattering ~1% of light couples to the waveguide mode. b) Scattering leads to losses and higher order mode excitation. Polarization of WGMs remained unchanged

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