

Organic Laser Indirectly Pumped by an Integrated OLED

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Abstract

Realizing direct electrical pumping of organic lasers remains a long-standing challenge due to carriers and triplets preventing lasing by absorbing the emitted light and quenching singlets. Here, we address this grand challenge of organic optoelectronics by integrating a thin-film polymer distributed feedback laser onto the substrate of a pulsed blue OLED with record-high light output. The OLED optically excites the laser, inducing population inversion and enabling an electrically driven laser.

Author Keywords

Electrically Driven Polymer DFB Laser; Organic Light-Emitting Diode; Pulse Operation.

1. Introduction

Organic materials are attractive for laser gain media due to their wavelength tunability across the visible range [1] and compatibility with other semiconductor technologies for potentially low cost and sustainable fabrication processes. However, electrically driven organic lasers have been a significant challenge. The conventional approach injects current into the gain medium to create a population inversion (direct pumping, Figure 1(a)) [2]. However, the low charge mobility and the low thermal conductivity of organic materials makes it difficult to inject the high current density, $> \text{kA}/\text{cm}^2$, to generate sufficient excited states for lasing. Organic devices thermally degrade when driven at such high current density. Also, accumulation of high densities of charges due to the low charge mobility and triplet excitons formed by electrical excitation cause additional losses and quenching of the singlet excitons,

preventing laser action. Furthermore, the contacts absorb light, creating losses that also impede lasing.

To overcome the above problems, we adopt a different approach: spatially separating charge injection and light amplification. Electroluminescence from an OLED excites the gain medium and induces a population inversion (indirect pumping, see Figure 1(b)). By doing this, we avoid the effects of the charges and triplets, and losses from the contacts. To achieve the very high excitation density needed for laser action, this strategy requires development of a record-bright OLED and efficient integration with a low-threshold organic laser to efficiently transfer electroluminescence from the OLED to the gain medium to induce lasing.

2. Results and Discussion

Overview of Indirect Pumping of Organic Laser by Integrated OLED

First, we introduce the details of the indirectly pumped organic laser we developed in this work (see Figure 2, the details were described in ref. [3]). We selected TSBF as the OLED emitter and BBEHP-PPV as the laser gain medium of the distributed feedback (DFB) laser (see Figure 2(a)). BBEHP-PPV shows one of the lowest lasing thresholds among reported organic semiconductor lasers and its absorption spectrum overlaps well with the TSBF emission spectrum, enabling efficient absorption.

We designed the OLED to have a line-shaped pixel with an emission area of $130 \mu\text{m} \times 1 \text{mm}$ to enable a high current density while minimizing series resistance of the semi-transparent silver with micrometre-thick opaque aluminium electrodes. The long emission area is helpful to realize lasing from the DFB laser at

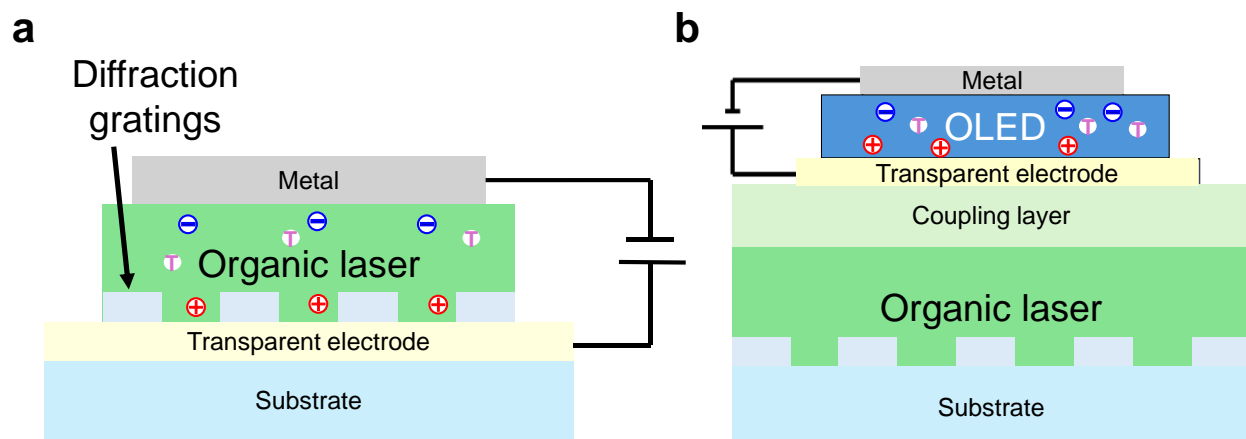


Figure 1. Schematic showing different approaches for electrically driven organic laser: (a) direct pumping and (b) indirect pumping. '+' and '-' represent positive and negative charges. 'T' represents triplets.

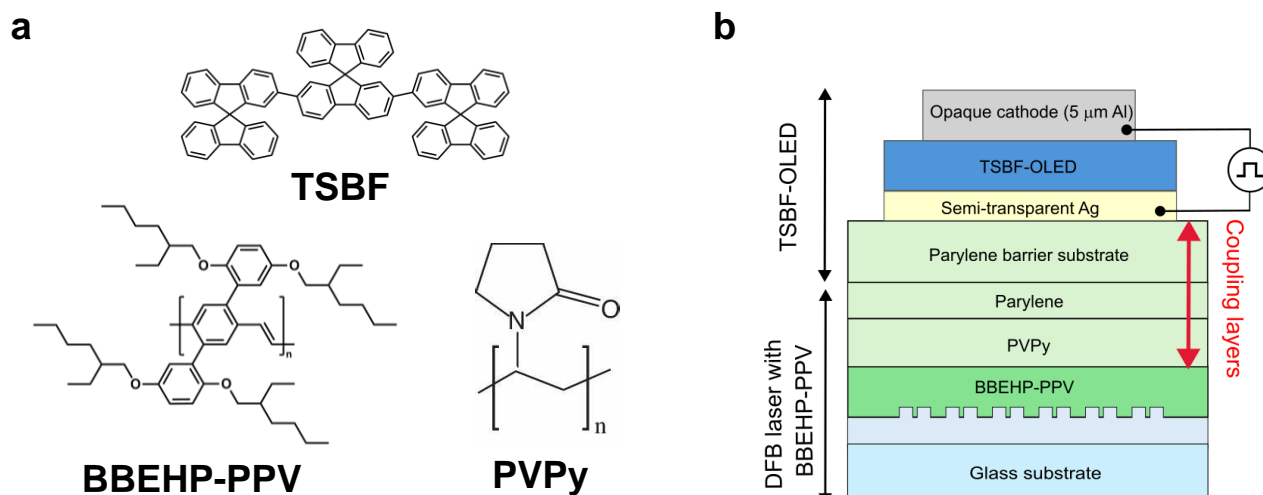


Figure 2. (a) Chemical structures of OLED emitter (TSBF), laser gain media (BBEHP-PPV), and cladding layer (PVPy). (b) Detailed structure of indirectly pumped organic laser developed in this work.

lower light intensity.

As OLED emission is usually divergent, the irradiance from the small OLED decreases quickly with propagation distance. Thus, the OLED and the organic laser should be integrated very closely. In optical simulations, we calculated that with a short separation distance of 7 μm, the peak irradiance is still more than 99% of the peak radiant exitance of the OLED. Thus, we fabricated our OLEDs on micrometre-thick parylene films with inorganic barrier layers of Al₂O₃/ZrO₂ as a substrate (Parylene barrier substrate). The inorganic layers are needed to protect the OLEDs from water and oxygen. We fabricated the organic laser separately, and then integrated the laser and the OLED together by physically attaching them. The organic laser has also micrometre-thick parylene layer on top of the cladding layer. We termed these parylene layers and the inorganic layers as “coupling layers” (see Figure 2). These coupling layers have high refractive index, >1.5, and so can more efficiently transfer light generated

internally in the OLED to the laser than a conventional coupling of light emitted through air by avoiding total internal reflection. We find that this increases the coupling of light from the OLED to the organic laser by a factor of 2.3 times from an outcoupling efficiency simulation of the OLED stack into air.

By driving with a pulsed current source with a half-width of around 6 ns to minimize device breakdown by Joule-heating and to inject a high current to achieve high light-output, the OLED can emit light into air with a maximum radiant exitance of 47 W/cm² at a peak current density of 6.7 kA/cm² which is the highest light output reported among OLEDs so far. Under separate optical excitation with a 4 ns optical parametric oscillator (OPO) at a wavelength of 450 nm, the organic laser has a lasing threshold of 92 W/cm². By integrating the OLED with the laser, we expect the TSBF-OLED to generate sufficient light output to produce lasing in the BBEHP-PPV laser assisted by the enhancement in the outcoupling efficiency by the coupling layers.

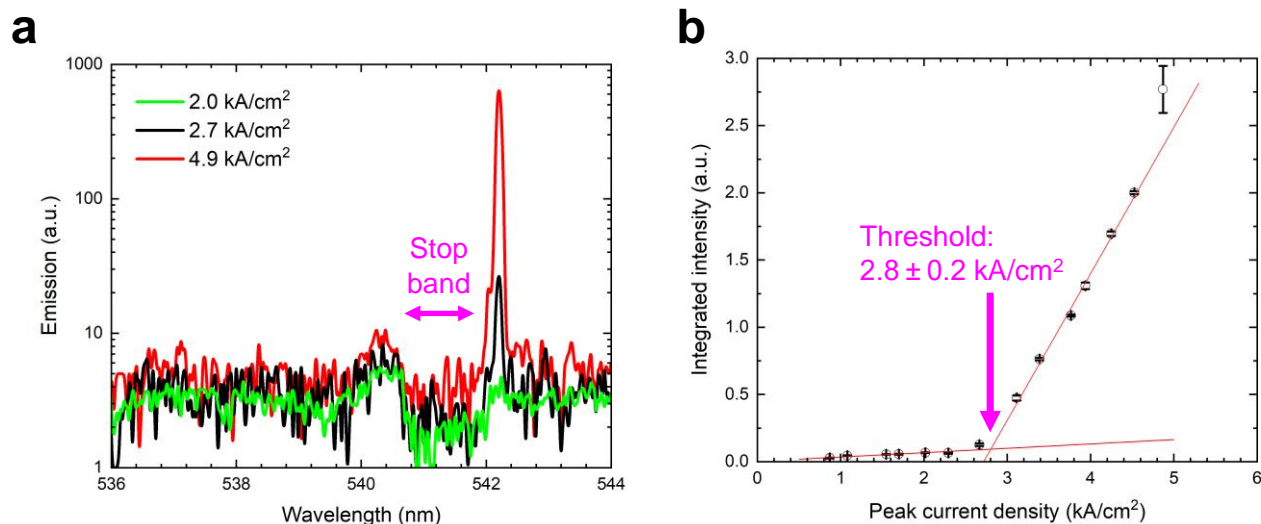


Figure 3. (a) Emission spectra from the integrated laser device (as shown in Figure 2 (b)) under different current pulses to the OLEDs. (b) Integrated emission intensity from the device as a function of peak current density.

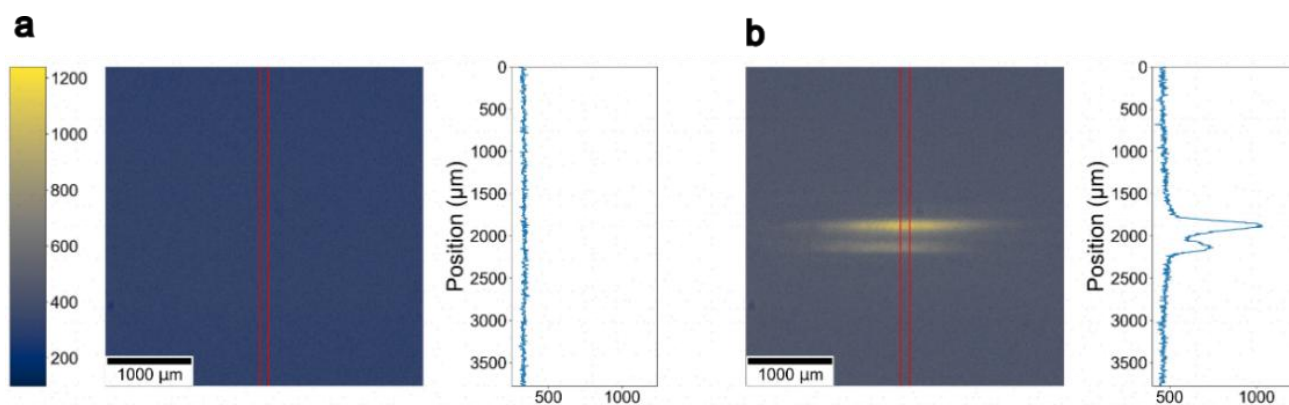


Figure 4. Far-field emission images and averaged line profile of the integrated laser measured at 6 cm: (a) below the lasing threshold and (b) above the lasing threshold

Characterization of Indirectly Pumped Organic Laser

We tested the integrated laser device by applying a current pulse to the OLED. Figure 3 (a) shows emission spectra from the laser at different current densities. When increasing the current density, a peak appears at the stop-band edge and becomes dominant. The full width at half maximum of the emission was 0.09 nm at 4.9 kA/cm², limited by the spectral resolution of our measurement system. Figure 3(b) shows integrated output intensity as a function of the current density of the OLEDs. The laser emission increases linearly at low current density, but the intensity abruptly increases above a threshold current density of 2.8 kA/cm².

We tested directionality of the laser by measuring the far-field spatial profile of its emission at 6 cm as shown in Figure 4. Below the laser threshold, the image does not show clear features but when the peak current was increased above laser threshold, a clear double-lobed beam was observed, which is a typical characteristic of a surface-emitting DFB laser with a one-dimensional feedback grating. We estimated the beam divergence of the laser by measuring the beam diameter at distances from 2 to 10 cm. The estimated beam divergence was 2.4 ± 0.2 mrad in the direction controlled by the grating, which is comparable to typical organic DFB lasers. These results clearly show the observed narrow emission from the integrated device is lasing [4]. To test the operational stability of the laser, we operated it at 1.7 times the threshold current density and observed laser emission sustained for 9.57×10^4 pulses.

3. Conclusion

We achieved an electrically driven organic laser by integrating a record-bright OLED with the laser cavity through micrometre-thick coupling layers, thereby allowing efficient transfer of electroluminescence from the OLED into the laser. This approach overcomes major difficulties in direct electrical injection organic lasers, whilst still providing a compact electrically driven visible laser. Our work provides strong evidence for lasing including

observation of a clear beam. Our integrated OLED-pumped laser is a new organic optoelectronics device with the potential to be integrated into, or alongside, OLED displays

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5. References

- [1] Chénais S, Forget S. Recent advances in solid-state organic lasers. *Polym Int* 2012;61:390–406. <https://doi.org/10.1002/pi.3173>.
- [2] Sandanayaka ASD, Matsushima T, Bencheikh F, Terakawa S, Potscavage WJ, Qin C, et al. Indication of current-injection lasing from an organic semiconductor. *Applied Physics Express* 2019;12. <https://doi.org/10.7567/1882-0786/ab1b90>.
- [3] Yoshida K, Gong J, Kanibolotsky AL, Skabara PJ, Turnbull GA, Samuel IDW. Electrically driven organic laser using integrated OLED pumping. *Nature* 2023;621:746–52. <https://doi.org/10.1038/s41586-023-06488-5>.
- [4] Samuel IDW, Namdas EB, Turnbull GA. How to recognize lasing. *Nat Photonics* 2009;3:546–9. <https://doi.org/10.1038/nphoton.2009.173>.