# RGB Organic Electroluminescent Devices with High Color Purity and Directionality

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## Abstract

***We are introducing an innovative organic semiconductor electroluminescent device capable of emitting red, green or blue light (RGB) with high directionality with divergence angles of 0.7° (red), 0.8° (green) and 1.5° (blue), and high color purity with spectral full-width at half-maximum (FWHM) of 1.9 nm (red), 1.6 nm (green) and 1.7 nm (blue). This achievement was realized through design techniques aimed at enhancing gain via meticulous recombination zone control and complemented by the reduction of the optical losses. These results demonstrate the simultaneous achievement of a narrow spectrum and high directionality in RGB organic electroluminescent devices. Our ongoing focus is on further improving these specifications to advance toward a fully functional RGB microdisplay for augmented reality devices***.

## Author Keywords

Organic semiconductor laser diode; OLED; microdisplay; directional light; monochromatic light; optical gain; optical loss.

## 1. Introduction

Display technologies have rapidly expanded into new applications, particularly in extended reality (XR) devices. However, the market is still in its early stages, with limited adoption due to challenges such as the lack of compelling content, bulky and uncomfortable equipment, and high costs. The XR market is poised for significant growth once value, comfort, and cost challenges are resolved, creating new opportunities beyond conventional display technologies.

In particular, augmented reality (AR) glasses are prone to become the primary device for digital interactions, potentially replacing smartphones. However, to achieve widespread adoption, AR glasses must evolve into lightweight, user-friendly devices that resemble regular eyewear. An AR system is primarily composed of two essential components: the microdisplay (also referred to as the light engine) and the optical combiner. The microdisplay generates the digital image or virtual content, while the optical combiner seamlessly overlays this image onto the user's view of the physical environment, creating an immersive augmented reality experience (1).

As for microdisplays, micro-light emitting diode (micro-LED) and micro-organic light emitting diode (micro-OLED) displays stand out. Both are gaining attention due to their potential for smaller form factors and higher contrast ratio, making them good candidates for the next generation of AR systems. While micro-LEDs are known for their high efficiency, their performance diminishes as pixel sizes decrease, presenting significant challenges for small-pixel applications. In contrast, micro-OLEDs emerge as a promising alternative for tiny pixels (2). However, as pixel density increases, OLEDs can experience crosstalk where signals meant for one pixel interfere with adjacent ones. These challenges make it difficult and costly to develop high-resolution small-pixel displays, pushing the need for constant innovation in materials, manufacturing, and design (3).

Another key element in an AR system is the optical combiner, with several types available. Recent developments emphasize grating-based waveguides due to their compactness. However, a significant hurdle with waveguide combiners is improving brightness and light efficiency, as they currently achieve only around 1% efficiency in light transmission (4), (5).

Many efforts are deployed to improve the microdisplay luminance efficiency to compensate for the low transmission efficiency of the waveguide combiner. Among the solutions to improve luminance efficiency is the optimization of OLED materials and device design, such as using a tandem OLED structure (6), microlenses (7), corrugation or nanostructures under the anode (8) or employing nanoparticles on top of the cathode (9) to improve the light outcoupling.

Another promising approach is to narrow the angular and spectral emission of the micro-display pixels — in other words, to produce directional and monochromatic light — to boost the coupling and outcoupling efficiency in grating-based waveguides. OLEDs, with their broad spectral and angular emissions, often face challenges when it comes to efficiently coupling light into these waveguides (1). By using directional and monochromatic light, the coupling efficiency of the grating can be significantly improved. Directional light ensures that the optimal angle is maintained when striking the grating, reducing scattering and maximizing light entry. Monochromatic light, composed of a single wavelength, aligns more precisely with the grating's design, further improving efficiency. This approach also minimizes the need for bulky lenses, paving the way for more compact, slimmer, and lighter AR designs, while also potentially reducing manufacturing costs.

In this context, KOALA Tech. is advancing the development and specifications of organic semiconductor laser diodes (OSLDs) previously reported (10). In our previous article, we demonstrated an organic electroluminescent device emitting a blue light with narrow emission spectrum (FWHM = 2.5 nm, hereafter referred to as $\Delta\lambda$) and high directionality (FWHM = 1.1°, hereafter referred to as $\Delta\theta$) (11). These characteristics—narrow spectral width and high directionality—are key indicators often associated with laser emission.

In this report, we present the properties of a newly optimized blue OSLD, along with our first developments in green and red OSLDs. The blue OSLD device structure was optimized by balancing optical and electrical properties, allowing us to maintain the color purity ($\Delta\lambda$ = 1.8 nm) and the directionality ($\Delta\theta$ = 1.8°) while improving the operational lifetime (LT50) from 3 hours to 11 hours. The green and red OSLDs showed comparable color purity with $\Delta\lambda$ values of 1.6 nm and 1.9 nm and high directionality with $\Delta\theta$ values of 0.8° and 0.7°, respectively. Both devices exhibited LT50 values exceeding 20 hours. With the successful demonstration of blue, green, and red OSLDs, we have achieved a high directional electroluminescence with a wide color gamut, covering the full RGB spectrum. As we continue refining our

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technology, our focus remains on further enhancing the specifications of these devices, with the goal of developing a fully functional RGB OSLD microdisplay.

## 2. Device structure and concept

Unlike traditional organic light sources such as OLEDs, which emit light with a broad spectrum in multiple directions, an OSLD is a type of organic electroluminescent device that emits light with a narrow spectrum and high directionality under electrical driving.
The OSLD structure presented in this work consists of hole injection and transport layers (HIL, HTL), a gain organic material as an emitting material (EML), electron transport and injection layers (ETL, EIL), and a top electrode, all sequentially deposited over a $SiO_2$ grating fabricated on a semi-transparent bottom electrode. This entire assembly forms the distributed feedback (DFB) cavity.

Figure 1 shows a cross-sectional scanning electron microscopy (SEM) image along with an illustration of the operational principle of a DFB-OSLD designed to emit light in the blue region with a grating period of 260 nm. In this device structure, electrons are injected from the top electrode, while holes are injected from the spaces between the grating where HIL contacts the bottom electrode. Electrons and holes recombine in the EML to form excitons. These excitons subsequently recombine to generate photons. Some photons are lost due to optical absorption by the surrounding materials. The remaining photons propagate within the cavity and are subject to optical feedback. The light outcoupling occurs from the surface in a second-order DFB cavity.

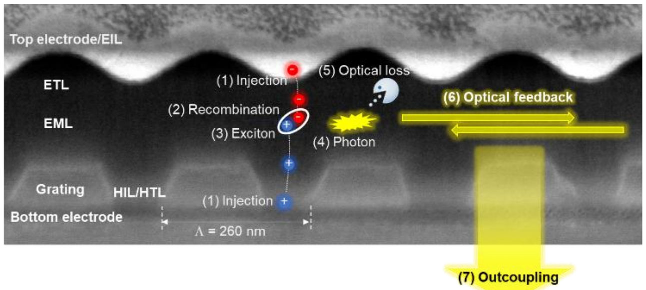

**Figure 1.** Cross-sectional SEM image of the DFB-OSLD along with an illustration of its operational principle for blue light emission, featuring a grating period of 260 nm. The figure highlights the main steps involved: (1) charge injection, 2) charge recombination, (3) exciton formation, (4) photon generation, (5) optical losses, (6) optical feedback, and (7) surface light outcoupling.

A DFB cavity enables prolonged interaction between the light and the organic gain material. These cavities are compact, easily integrated into planar organic thin films, and offer precise spectral selection by adjusting the grating period. Thus, the blue, green and red OSLD can be achieved by varying the grating period to adjust the emission wavelength to the gain material's spectrum. The resonant wavelength satisfies the Bragg condition, i.e., $m\,\lambda_{Bragg} = 2\,n_{eff}\,\Lambda$, where m is the order of diffraction, $\lambda_{Bragg}$ is the Bragg wavelength in the cavity, $n_{eff}$ is the effective refractive index of the waveguide and $\Lambda$ is the grating period.

## 3. Experiments

The OLEDs were fabricated by evaporating organic materials and a cathode onto a glass substrate with a semi-transparent bottom anode. The OSLD was fabricated similarly to the OLED but onto a $SiO_2$ grating, which was fabricated on top of the semi-transparent anode keeping an opening to the electrode to enable charge injection while forming a DFB resonator. The grating was fabricated by sputtering $SiO_2$ onto the semi-transparent anode, followed by patterning the $SiO_2$ with electron beam lithography and subsequent engraving through reactive ions etching. After device fabrication, the OLED and OSLD devices were encapsulated inside a nitrogen-filled glove box using glass lids and UV-cured epoxy.

For the electrical driving of the device, a DC power supply was used to apply voltage to the device and the electroluminescent spectra were measured using a spectrophotometer (PMA50, Hamamatsu Photonics) positioned normal to the substrate. The current density-voltage (J-V) characteristics of the OLEDs and OSLDs were evaluated using a source meter (Keithley 2400, Keithley Instruments Inc.). The luminance (L) and external quantum efficiency (EQE) was measured by an absolute EQE measurement system utilizing an integration sphere (C9920-12, Hamamatsu Photonics) with a photonic multichannel analyzer (PMA-12, Hamamatsu Photonics).

## 4. Results and discussion

In this section, we will discuss the characteristics of the optimized blue OSLD. Furthermore, we will demonstrate the realization of the green and red OSLDs for the first time. Fig. 2 shows the schematic illustration of RGB-OSLDs.

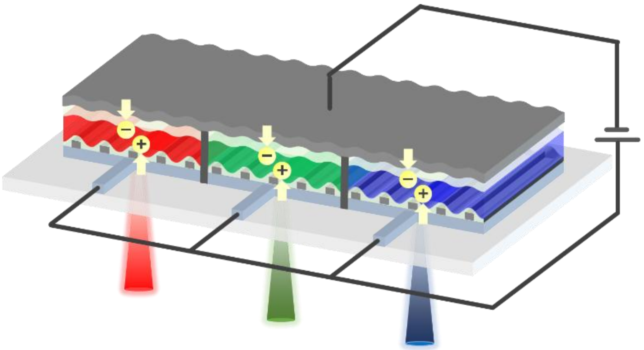

**Figure 2.** Schematic illustration of RGB OSLDs.

Previously, the blue OSLD was designed to maximize the exciton density into a specific region of the EML, i.e. localizing the recombination zone (RZ) near the ETL interface for better gain efficiency. At this RZ position, the metallic cathode absorption losses increase significantly. Thus, we used the ETL as an optical buffer to minimize electrode absorption, which improved optical properties but led to reduced electrical performance (11). In this work, we further improved the blue OSLD by selecting EML and ETL materials with more balanced optical and electrical properties, to reduce the optical loss as well as to enhance the electrical characteristics of the device. Based on the advancements made in blue OSLDs, we also realized red and green devices.

The electroluminescent spectra and angular profiles of the RGB OLEDs and OSLDs are shown in Fig. 3, with specifications summarized in Table 1. As shown in Fig. 3 (a, b, c), the RGB OSLDs exhibit high color purity, with $\Delta\lambda$ value under 2 nm, significantly lower than their corresponding OLEDs, which have $\Delta\lambda$ value above 50 nm. Similarly, Fig. 3 (d, e, f) demonstrates that the RGB OSLDs presented a high directionality, with $\Delta\theta$ values below 2°, much lower than their corresponding OLED with $\Delta\theta$ values around 140°. Furthermore, the EQE values at 500 cd/m$^2$ for the RGB OSLDs are 1.4-1.7 times higher than those for their respective RGB OLEDs (see Table 1), indicating a significant enhancement in EQE for the OSLDs compared to that of the

OLEDs. Notably, as mentioned in Table 1, the blue OSLD showed more than a threefold increase in operational lifetime (LT50 = 11 hours) compared to previous results (LT50 = 3 hours). Meanwhile, the green and red OSLD presented even higher stability, with LT50 values exceedingly 20 hours. These results show promising levels of color purity and directionality, they represent preliminary versions that require further optimization to achieve comparable performance to the blue OSLD. Ongoing optimizations are aimed at further enhancing the specifications of RGB OSLDs.

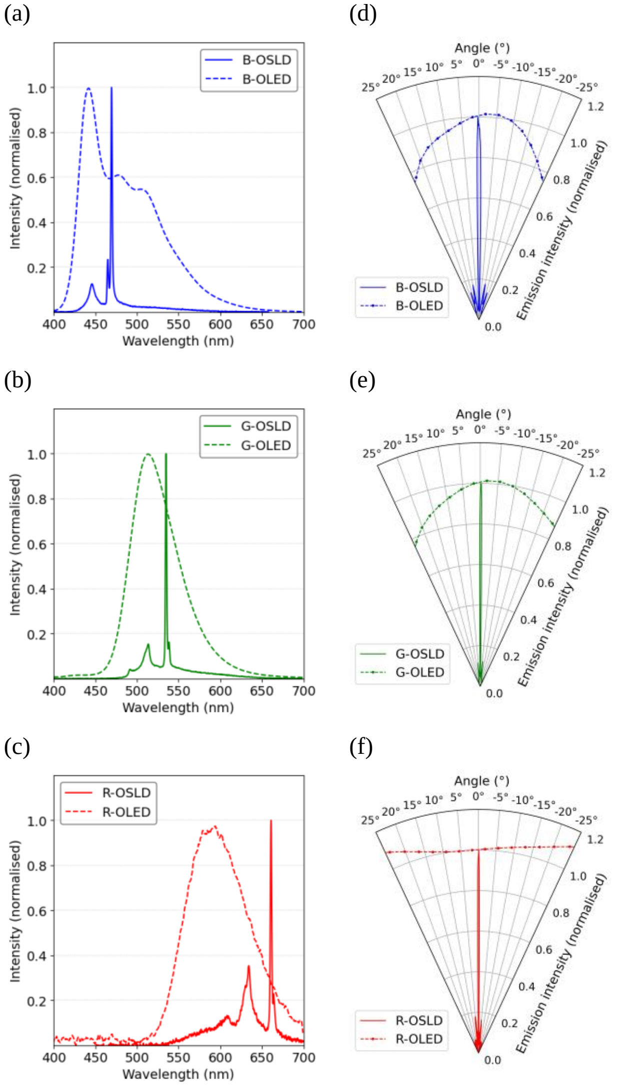

**Figure 3.** Electroluminescence spectra of (a) blue, (b) green and (c) red, along with angular emission profile of (d) blue, (e) green and (f) red OLEDs and OSLDs at 500 cd/m$^2$.

**Table 1.** Specifications at 500 cd/m$^2$ of RGB OSLDs and OLEDs.

| **Colors** | **Red** | | **Green** | | **Blue** | |
|---|---|---|---|---|---|---|
| **Devices** | **OLED** | **OSLD** | **OLED** | **OSLD** | **OLED** | **OSLD** |
| **λ (nm)** | 590 | 660 | 515 | 535 | 440 | 470 |
| **Δλ (nm)** | 80 | 1.9 | 60 | 1.6 | 70 | 1.7 |
| **Δθ (°)** | 140 | 0.7 | 140 | 0.8 | 140 | 1.5 |
| **EQE (%)** | 0.7 | 1.2 | 2.0 | 2.9 | 1.5 | 2.6 |
| **LT50 (H)** | > 20 | | > 20 | | 11 | |

A compact demo system was prepared to showcase the RGB OSLDs (Fig. 4). This demo system integrates RGB OSLDs with a power supply and a spectrophotometer connected via an optical fiber. This demonstration marks a significant milestone as we unveil the world’s first RGB OSLDs having high color purity as well as high directionality.

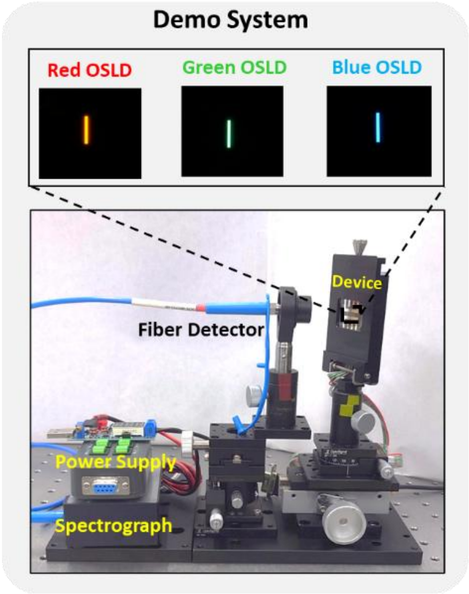

**Figure 4**. RGB OSLDs demo system.

## 5. Conclusion

In summary, we have successfully developed novel RGB OSLDs with high color purity (Δλ < 2 nm) and high directionality (Δθ < 2°). These features make them promising candidates for RGB microdisplay applications. The blue OSLD was optimized by selecting EML and ETL materials with more balanced optical and electrical properties resulting in a higher operational lifetime of 11 hours. Furthermore, we realized the first red and green OSLD which also demonstrates high color purity, directionality, and an operational lifetime exceeding 20 hours. Ongoing optimizations aim to further enhance the performance of RGB OSLDs, making them more suitable for microdisplay applications.

## 6. Impact of the research

This research could potentially offer a significant advancement in improving the efficiency of light coupling in grating-based waveguides for augmented reality (AR) displays. By developing RGB organic semiconductor lasers with enhanced color purity and directionality, it might help address the challenges posed by the broad spectral and angular emissions of traditional OLEDs. If successful, this approach could lead to better coupling efficiency, reduced scattering, and the elimination of bulky lenses, contributing to more compact and cost-effective AR designs.

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