Latest Improvements on RGB Superluminescent LEDs

Nicolai Matuschek, Antonino Castiglia, Marco Malinverni, Christian Mounir, Marco Rossetti, and Marcus Duelk
EXALOS AG, Wagistrasse 21, CH-8952 Schlieren, Switzerland
Tel.: +41-43-444 60 90, Fax: +41-43-444 60 99, E-mail: matuschek@exalos.com

***Abstract* – Superluminescent light-emitting diodes (SLEDs) at the three primary colors red, green and blue (RGB) are interesting light sources for display applications. High electro-optical and luminous efficiency are among the key requirements for such light sources. In this paper, we report about the latest efficiency improvements of red SLEDs at 635 nm, blue SLEDs at 450 nm and green SLEDs at 510 nm. Modeling and design of the waveguide structure and its doping profile as well as of the active region will enable further improvements in the near future.**

I. INTRODUCTION

SLEDs combine the directionality of laser diodes (LDs) with the spectral width of LEDs. Their beam-like output enables efficient coupling to single-mode fibers or waveguide devices. Therefore, these light sources are preferred over LDs in applications where short coherence lengths or low speckle noise are required. Visible SLEDs with red, green and blue (RGB) emission wavelengths are interesting light sources for display applications and architectures based on scanning MEMS mirrors, liquid crystal on silicon (LCOS) devices or holographic spatial modulators. Here, high electro-optical efficiency and high luminous efficiency are crucial for realizing compact and battery-driven RGB light engines for such projection systems.

SLEDs exhibit, similar to LDs, a threshold current above which efficient light generation is occurring. At the threshold current, SLEDs transit from spontaneous emission to a regime of amplified spontaneous emission (ASE). Improvements in electro-optical efficiency are, therefore, implemented by lowering the ASE threshold current or by increasing the slope efficiency, which can be realized by maximizing the injection efficiency, lowering the internal losses or by increasing the optical confinement of the waveguide mode. Furthermore, reducing the forward voltage will results in lower power dissipation and, hence, in higher wall-plug efficiency (WPE) values. Additionally, the luminous efficiency can be improved by optimizing the emission wavelength and moving it into a region where the human eye has a higher sensitivity.

In this paper, we present the latest results on efficiency improvements of RGB SLEDs, including a new 635-nm device with 75% higher luminous flux compared to the 650-nm SLED previously presented, optimized blue SLEDs at 450 nm with lower drive currents and lower forward voltages as well as new green SLEDs at 505-510 nm with 70% higher luminous flux compared to 490-500-nm SLEDs presented a few months before. Moving the emission wavelength of these green light sources further up to 520 nm will improve the luminous efficiency by additional 38% compared to 510 nm.

II. RGB SUPERLUMINESCENT LEDS

A. Red SLEDs

Highly efficient SLEDs for the red spectral region are based on AlGaInP alloys similar to edge-emitting LDs. Light emission at 630-650 nm is achieved by sandwiching strained multi-quantum wells (MQWs) in between Al(Ga)InP cladding layers.

Based on full 3D simulations of the electro-optical performance, we have recently proposed different ways for shifting the emission wavelength down to 625 nm [1]. The simulator has been calibrated using measurement results obtained from fabricated SLEDs operating at 650 nm [2]. It was found that for our current epitaxial layer structure the highest luminous flux values can be obtained for wavelengths around 635 nm. This is achieved by properly adjusting the material composition of the QWs (and not their thickness) and by using a reflective SLED (R-SLED) geometry [3].

The proposal has been realized by growing an SLED structures operating at 650 nm and another at 635 nm. The results are shown in Fig. 1. Obviously, the measured curves (solid lines) agree quite well with what has been predicted from simulations (dotted lines). Secondly, and as expected [1], the *L-I* curves obtained from the 635-nm SLED chip are a bit inferior compared to the *L-I* curves for the 650-nm chip. However, the corresponding luminous flux values at 70 mA are 1.2 lm (650 nm) and 2.1 lm (635 nm) and, therefore, 75% larger for the structure operating at the lower wavelength.

The dashed lines in Fig. 1 show the result of a 2-parameter fit using the analytical model presented in [3]. The logarithmic dependence of the modal gain according to $g_{\mathrm{mod}} = g_0 \cdot \ln(J / J_{\mathrm{tr}})$ is used as an input function for the calculation of the SLED's output power. Here, we use the modal

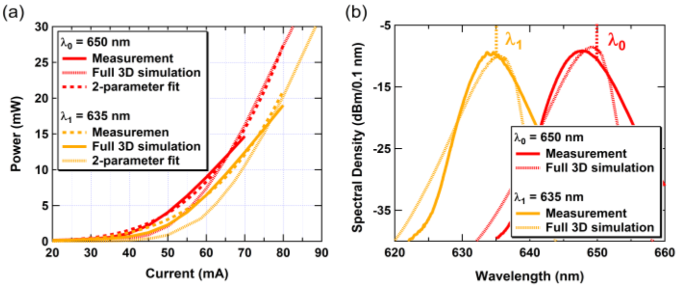

Fig. 1. (a) *L-I* characteristics of red SLED chips obtained under CW operation at 25°C with center wavelengths at 650 nm and 635 nm. The solid lines show the measurement results and the dotted lines what has been predicted by the simulator [1]. The dashed lines show a 2-parameter fit to the measured *L-I* curves, as described in the text. (b) Corresponding ASE spectra obtained for an injection current of 70 mA. The 3-dB bandwidth is 5-6 nm FWHM.

gain constant g_0 and the transparency current density J_{tr} as open parameters for fitting the measured *L-I* characteristics. All other parameters, which enter into the model (e.g., chip dimensions, facet reflectivity, internal loss coefficient, etc.) are known. The extraction of the two fitting parameters allows for the reconstruction of the modal (and material) gain as a function of the current density (see Sec. C).

B. Blue and green SLEDs

Both blue and green SLED structures are based on III-nitride compound semiconductors. In 2009, EXALOS introduced the industry's first blue-violet (420-nm) SLEDs [4]. Meanwhile, true-blue SLEDs at 450 nm (see Fig. 2 (a)) are now commercially available. Realizing longer emission wavelengths for such GaN-based edge-emitting devices is challenging. Nonetheless, using improved growth conditions for the active region, the waveguide and cladding layers, first SLEDs operating in the cyan-to-green wavelength region (490-500 nm) were introduced a few months ago. Latest improvements have now resulted in true-green SLEDs operating at wavelengths of 505-510 nm (see, Fig. 2 (b)).

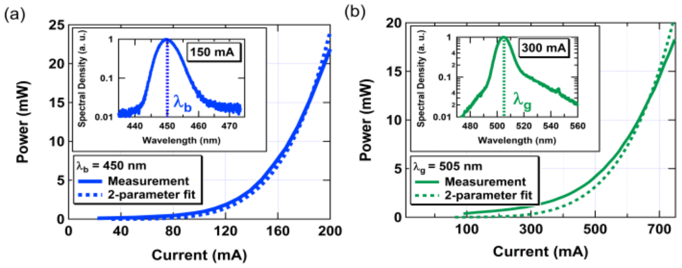

Fig. 2. *L-I* characteristics of a blue SLED chip at 450 nm (a) and a green SLED chip at 505 nm (b) obtained under pulsed operation. The solid lines show the measurement results and the dashed line the results of a 2-parameter fit. The insets show typical ASE spectra with 3-dB bandwidths of 6-10 nm FWHM.

The active region of these devices is realized with strained InGaN QWs. The main challenge for longer-wavelength blue SLEDs is due to the reduced modal gain at increasing wavelength because of the reduced refractive index contrast between the waveguide and the cladding region. The resulting lower optical confinement factor leads to a higher internal loss coefficient caused by increasing free-carrier absorption. In our presentation, we will discuss this performance trade-off in more detail based on numerical results obtained from a full-vectorial Maxwell solver [5].

Increasing the emission wavelength to 500 nm and beyond, requires an increase in the Indium concentration of the InGaN MQW layers from typically 15% for blue SLEDs to values above 20% for green SLEDs. Such high Indium contents have a negative impact on the device performance caused by the higher lattice mismatch. This leads to a reduction of the critical QW thickness and, thus, to a reduced gain, higher defect formation as well as higher internal electric fields on substrates with polar orientation (c-plane). Consequently, the modal gain for green SLED structures is rather low and higher injection currents are needed to reach the ASE regime. As shown in Fig. 2 (b), the onset of ASE is reached at 300-400 mA and output powers of 15 mW or more are obtained for currents of 700 mA.

Improved epitaxial layer designs based on full 3D-simulation of the electro-optical device performance may allow for green SLED structures with reduced ASE threshold and higher slope efficiencies at longer emission wavelengths of 510-520 nm.

C. Modal gain characteristics

Using the 2-parameter fitting model, we are able to extract the logarithmic modal gain dependence from measured *L-I* characteristics. Fig. 3 shows the modal gain curves for the SLEDs discussed in this paper. Moreover, the solid curve shows the result obtained from a direct measurement of a 440-nm SLED device. A comparison with the extracted curve from the 450-nm chip shows that the 2-parameter fitting model yields reasonable results. Obviously, red, blue, and green SLEDs operate in completely different regimes with respect to the modal gain. The modal gain for red SLEDs is very high. For blue SLEDs it is significantly smaller, and for green SLEDs it is another 50% smaller at the same current density compared to blue SLEDs. This explains why the typical operating current is very different for the three different colors.

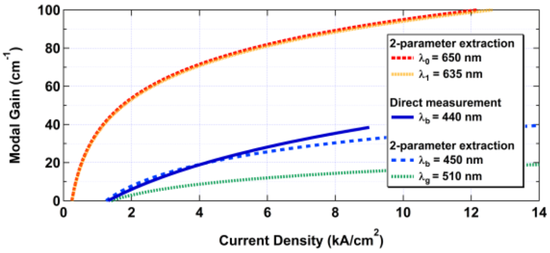

Fig. 3. Modal gain curves extracted from the 2-parameter fitting model for the four *L-I* curves discussed above. The solid line shows the modal gain curve obtained from a direct measurement of a blue SLED operating at 440 nm with similar epitaxial layer structure as the 450-nm structure discussed in this paper.

III. SUMMARY

We have presented our latest results on RGB SLEDs with improved electro-optical performance. The luminous flux of red SLEDs has been improved by 75% by shifting the wavelength down to 635 nm. A major improvement has been achieved for green SLEDs by shifting their emission wavelength close to 510 nm. This is the longest emission wavelength of GaN-based SLEDs reported today. The improvements are driven by numerical simulations of the device performance using different simulation tools including a full 3D-simulator, a vectorial Maxwell solver, and analytical models.

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