Highly Efficient Superluminescent Light-Emitting Diodes (SLEDs) at 625-650 nm

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Abstract **– Superluminescent light-emitting diodes (SLEDs) are very attractive as compact, highly efficient light sources for various applications in the visible red spectral region. We simulate and discuss the electro-optical performance of SLEDs operating at center wavelengths of 625-650 nm. We show that for current SLED structures the optimum wavelength with respect to maximum luminous flux and power conversion efficiency is around 635 nm. Design improvements of the epitaxial layer structure offer the way to shorter wavelengths with higher luminous flux and efficiency values.**

I. Introduction

Superluminescent light emitting diodes (SLEDs) are an interesting alternative to laser diodes (LDs) for applications where short coherence lengths or low speckle noise are required. They combine the directionality typical of LDs with the spectral width of LEDs. Their beam-like output enables efficient coupling to external elements while keeping a broadband emission spectrum. These characteristics stem from amplifying the spontaneous emission by stimulated emission within a single or double pass in the waveguide [1]. Therefore, visible SLEDs targeting the red, blue, and green primary colors represent an ideal light source candidate for compact and efficient projection systems with low power consumption and for sequential lighting of DLP-based micro-displays.

For visible light, human eyes have highest sensitivity for wavelengths around 555 nm, see Fig. 1 (a). Obviously, for the red spectral region the sensitivity is rapidly decreasing with increasing wavelength. As an example, the luminous efficiency at 625 nm is almost 3 times greater compared to 650 nm. For typical applications, luminous flux values of about 10 lm are desired. Hence, for this spectral region light sources are required that deliver output powers between 40 mW and 120 mW (Fig. 1 (b)). As a consequence, red SLEDs should operate at wavelengths as short as possible.

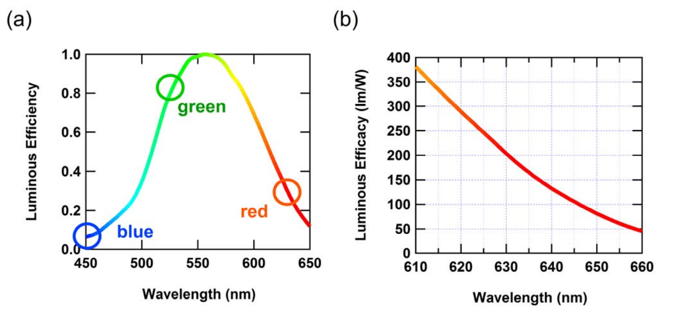

Fig. 1. Spectral dependence of the (a) luminous efficiency and (b) luminous efficacy for human eyes. The luminous efficacy is obtained from the luminous efficiency by multiplication with the scaling factor K_m = 683 lm/W, which is the maximum luminous efficacy at 555 nm.

While the development of blue and green SLEDs is based on the AlGaInN alloy system [2], highly efficient visible devices for the red spectral region are based on the AlGaInP alloy system. First SLEDs operating at wavelengths around 670 nm were demonstrated in 1993 [3] and SLEDs operating at 650 nm have been commercially available for the past few years [4]. Aiming for high-power SLEDs at shorter wavelengths faces an intrinsic problem of the AlGaInP material system, which follows from the small conduction-band offset between the active layers and cladding layers. As a result, thermally-induced carrier leakage from the active region to the cladding layer limits the achievable output power. The leakage effect increases significantly for shorter wavelengths due to the higher quasi-Fermi level in the active region. This is the reason why only few investigations have been published about high-power LD and SLED devices operating at wavelengths shorter than 640-650 nm.

Here, we present simulation results for the electro-optical performance of SLEDs down to 625 nm based on an existing SLED design realized for operation at 650 nm. It is shown that for the current epitaxial design the optimum wavelength for achieving highest luminous flux values is around 635 nm due to the compromise between increasing luminous efficacy and decreasing output power of the SLED chips. Moreover, we propose modifications of the epitaxial structure in order to improve the SLED's efficiency, and thus, to increase the luminous flux.

II. Epitaxial SLED Design and Chip Simulation

The electro-optical performance of the SLED chips has been simulated using a full 3D simulation software tool. The simulator has been calibrated using measurement results obtained from fabricated and commercially available SLED chips operating at wavelengths around 650 nm [4]. All simulations have been performed at a heat-sink temperature of 25°C.

The epitaxial layer structure consists of a strained multi-quantum well (MQW) AlGaInP active region design sandwiched between AlInAs cladding layers. The center wavelength has been tuned down to 625 nm in steps of 5 nm by decreasing the thickness of the QWs properly and keeping the material composition of the active-region layers constant. The

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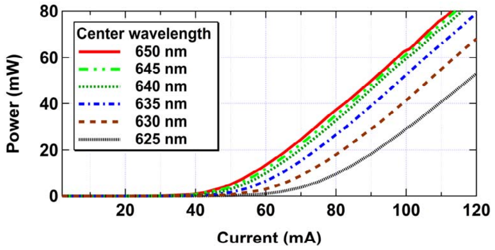

Fig. 2. *L-I* characteristics of SLED chips obtained at 25°C with center wavelengths tuned from 650 nm down to 625 nm.

(a) (b)

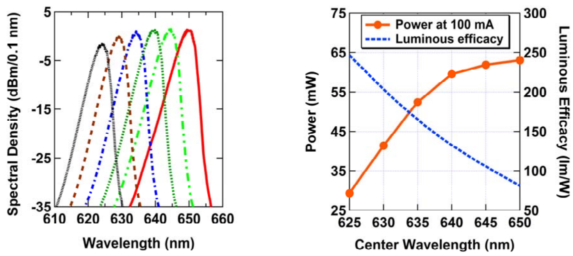

Fig. 3 (a) Amplified spontaneous emission (ASE) spectra and (b) ex-facet output power obtained at 25°C and an injection current of 100 mA. The luminous efficacy plotted on the right-hand scale shows the opposite trend with wavelength compared to the output power.

wavelength could be also tuned by the material composition. However, this changes the strain and depth of the QWs and makes the discussion of results more complicated.

In order to boost the output power and keep the chip lengths relatively short, we simulate reflective SLED structures as introduced and explained in [1]. Figure 2 shows *L-I* characteristics of these SLED structures at different center wavelengths. As can be clearly seen, the output power degrades strongly for wavelengths below 640 nm. Figure 3 (a) shows amplified spontaneous emission (ASE) spectra, $S(\lambda)$, extracted at an injection current of 100 mA for the different SLED designs. In Fig. 3 (b), corresponding output powers are plotted on the left-hand scale with the luminous efficacy shown on the right-hand scale. The opposite trends indicate that an optimum wavelength exists for which the luminous flux reaches a local maximum.

While the output power is obtained from the spectral density by integration according to

$$P = \int_0^\infty S(\lambda) d\lambda \tag{1}$$

the luminous flux has to be calculated according to

$$\Phi = K_m \cdot \int_0^\infty V(\lambda) S(\lambda) d\lambda, \tag{2}$$

with $V(\lambda)$ being the spectral luminous efficiency shown in Fig. 1 (a). The SLED's efficiency can be quantified by the power conversion efficiency, η_{conv}, which is defined as the luminous flux from the light source divided by the electrical input power, i. e. $\eta_{conv} = \Phi / P_{el}$. Figure 4 shows both the luminous flux and the power conversion efficiency obtained at an injection current of 100 mA for the simulated SLED structures. Obviously, the power conversion efficiency follows closely the luminous flux. Both curves show a local maximum around 635 nm with a

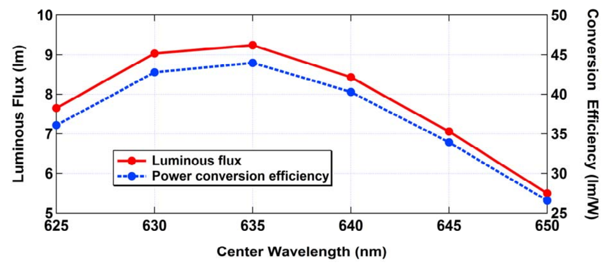

Fig. 4. Luminous flux and power conversion efficiency obtained for the different SLED chips at an injection current of 100 mA and a temperature of 25°C.

luminous flux greater than 9 lm and a power conversion efficiency of 44 lm/W.

The SLED's efficiency at shorter wavelengths could be improved by an optimization of the epitaxial layer design with respect to the optical and electrical confinement. One approach might be to simultaneously increase the number of QWs when decreasing the QW thickness. Another possibility might be based on changing the material composition of the active-region layers in order to optimize the strain management of the chip and reduce the carrier leakage to the cladding layer. This would allow the design of SLED structures to operate at shorter wavelengths, and thus, shifting the local maximum shown in Fig. 4 to shorter wavelengths with higher values for the luminous flux and the power conversion efficiency.

III. Summary

The electro-optical performance of SLED chips operating in the red spectral wavelength region from 625 nm to 650 nm has been investigated by full 3D simulation of various epitaxial designs. It is found that the output power degrades strongly for shorter wavelengths in contrast to the considerably increasing luminous efficiency. As a consequence, we find a local maximum for the luminous flux and power conversion efficiency at center wavelengths around 635 nm for current epitaxial SLED structures and device operation at a heat-sink temperature of 25°C. It is clear that, with improved SLED efficiency at shorter wavelengths, the optimum wavelength shifts further down yielding both greater luminous flux and power conversion efficiency values.

In further investigations, the dependency of the optimal wavelength on the heat-sink temperature will be analyzed in detail. It is reasonable to assume that the optimal wavelength increases with temperature because of the enhanced thermal leakage of carriers from the active region.

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