Modeling and Simulation of Reflecting SLEDs

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***Abstract*- Generally, for the modeling of superluminescent light emitting diodes (SLEDs) the occurrence of light reflection at the chip's facets is neglected for simplicity reasons. In this presentation we extent our recently developed model for ideal SLEDs and include the effect of arbitrarily strong facet reflections on the SLED performance. The generalized model allows directly the introduction of a new class of SLEDS, so-called reflecting SLEDs (R-SLEDs). Such devices consist of a front-facet side with negligible residual reflectivity, as it is the case for standard SLEDs, and a highly reflecting back-facet side. It is shown theoretically and verified by a comparison of simulation results with experimental data that R-SLEDs behave optically like standard SLEDs (without facet reflections) of doubled physical length, but electrically and thermally like SLEDs of single physical length. Hence, R-SLEDs are the ideal concept for strongly boosting the output power of SLEDs but keeping the chip length short.**

I. Introduction

Superluminescent light emitting diodes (SLEDs) are well-established broadband optical light sources for wavelengths ranging from the red to the near-infrared spectral region (650-1700 nm). They are used for various applications including fiber optic gyroscopes (FOGs), fiber optic current sensors (FOCS), optical coherence tomography (OCT), structural health monitoring with optical fiber sensors, speckle-free illumination, metrology systems or optical test equipment for fiber optical networks.

Our SLEDs are realized in an index-guided ridge-waveguide geometry similar to a Fabry-Perot-type laser diode (LD). They operate in the amplified spontaneous emission (ASE) regime, i. e. spontaneously emitted photons are amplified by stimulated emission within a single pass in the optical waveguide. However, in contrast to LDs, SLEDs do not exhibit an intrinsic resonant cavity, which would allow the build-up of longitudinal cavity modes. Hence, the output spectrum is smooth and continuous. The suppression of resonant cavity modes is achieved by tilting the waveguide by a few degrees and by applying anti-reflection coatings on the output facets of the SLED chip. Residual reflections at the facets of an SLED may result in an unwanted modulation (ripples) of the ASE output spectrum, or even worse, in a start-up of laser oscillation.

For the modeling and simulation of SLEDs residual facet reflections are normally ignored, as they are considered to lead only to a negligible disturbance of the system. On the other hand, the precise understanding of changes in the electro-optical performance of an SLED caused by finite facet reflections requires their inclusion in the modeling. In particular, the inclusion in the modeling is inevitable for the design of intentionally asymmetric SLED designs.

In this paper we present a theoretical model that includes the effect of arbitrarily strong facet reflections on both sides of the SLED chip. This approach leads directly to the introduction of a new class of SLEDs, so-called reflecting SLEDs (R-SLEDs) by making the facet design extremely asymmetric. An ideal R-SLED consists of a perfect back-side reflector with 100% reflectivity and a non-reflecting front-facet side without any residual reflection. We show theoretically and by a comparison of simulation results with experimental data that an ideal R-SLED behaves exactly like an ideal standard SLED of doubled length folded at its symmetry plane. This means that an R-SLED produces the same amount of output power at half injection current compared to a standard SLED of doubled length. Thus, R-SLEDs can be used for boosting the output power of SLEDs tremendously. Such devices are very good candidates for applications where high power with broadband emission is needed and requirements for low spectral ripple are not of primary concern.

II. Theory

We include the effect of finite facet reflections back into the chip by combining the theoretical approach presented in [1] for ideal standard SLEDs with the traveling-wave amplifier approach as given in [2, 3]. As a result, we find that the power out of the front-facet side of a reflecting SLED with chip length L can be written as

$$P_{\mathrm{f}} = P_0 \cdot \frac{1+G_0(L)R_{\mathrm{b}}}{1-G_0^2(L)R_{\mathrm{b}}R_{\mathrm{f}}}\left(G_0(L)-1\right)\cdot T_{\mathrm{f}}. \tag{1}$$

In (1), the power factor P_0 is the same as defined in [1], T_{f} denotes the transmittance at the front-facet side, and R_{f} and R_{b} are the effective mode reflectivities back into the waveguide at the chip's front- and back-facet side, respectively. $G_0(L)$ is the single pass gain at the gain maximum.

For an ideal standard SLED with $R_{\mathrm{f}} = R_{\mathrm{b}} = 0$ and $T_{\mathrm{f}} = 1$ it follows

$$P_{\mathrm{f}}^{\mathrm{SLED}} = P_0 \cdot \left(G_0(L)-1\right), \tag{2}$$

whereas we find for an R-SLED with perfectly reflecting back-side mirror and perfectly transmitting front-facet side ($R_{\mathrm{f}} = 0$ and $R_{\mathrm{b}} = T_{\mathrm{f}} = 1$)

$$P_{\mathrm{f}}^{\mathrm{R\text{-}SLED}} = P_0 \cdot \left(G_0(2L)-1\right), \tag{3}$$

Equation (3) for an R-SLED can be interpreted as follows when compared with (2). The perfect reflection of light at the back-facet mirror leads to a double pass amplification process

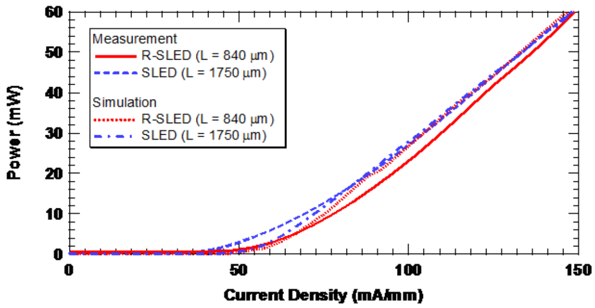

Fig. 1. Measured and simulated front-facet output power of an R-SLED chip with length 840 µm and of a standard SLED chip with length 1750 µm as function of current density. (The current density values are only scaled by the chip length, i. e. $J = I/L$. The width of the active area is the same for all devices, and thus, irrelevant for the considerations of this paper.)

of spontaneously emitted photons. Or in other words, an R-SLED of chip length L behaves optically like a standard SLED of the same type but with doubled physical chip length $2L$ folded at its symmetry plane. However, it should be noted, that with respect to current injection the chip is still a short chip of length L. This means that an R-SLED of length L emits the same amount of power out of the front facet as a standard SLED of length $2L$ at same current density value, J, i. e. at half value of the injection current I. Under this condition the spectral gain is the same, and thus, the ASE output spectra, too.

In conclusion, an ideal R-SLED shows the same electro-optical performance as a standard SLED but downsized in operating current and chip length by a factor of two. This demonstrates the enormous potential of R-SLEDs for the design of ultimate high-power SLEDs.

III. Simulation and Experimental Verification

In this section we want to verify the theoretical results by a comparison with experimental data as well as by a comparison of results obtained from a full 3D simulation of an R-SLED and an equivalent standard SLED.
As object of our study, we use an SLED and R-SLED from the same epi wafer operating in the wavelength region around 870 nm. The multi quantum-well epi structure of these chips is based on (Al)GaAs/(In)GaAs layers grown on a GaAs substrate. The simulator has been calibrated with respect to output power and shape of the ASE spectra using short standard SLED chips with various chip lengths between 500 µm and 850 µm. After the successful calibration the electro-optical performance of 840 µm long R-SLEDs is compared against the performance of 1750 µm long standard SLEDs. The measured R-SLED chips do not have a perfect back-side reflectivity of 1 but a partial reflectivity of only a few percent. Nevertheless, this is sufficiently high compared to the effective front-side reflectivity, which is orders of magnitude smaller ($<10^{-8}$). For the simulations we use the values of an ideal R-SLED in order to simplify the discussion.

Figure 1 shows that the measured and simulated front-facet output powers as function of current density for both types of SLEDs agree very well. Only the measured R-SLED power is a little bit smaller because of the imperfect back-side reflection.

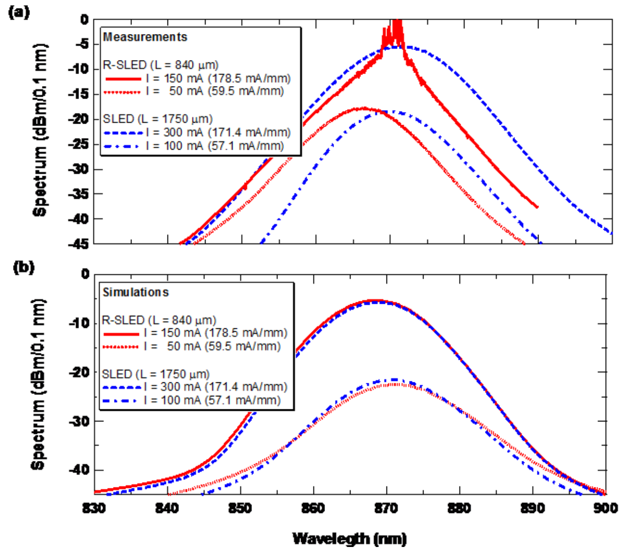

Fig. 2. (a) Measured and (b) simulated ASE output spectra of the same SLED chips as used for Fig. 1 at two different levels for the current density.

In Fig. 2 (a) measured ASE spectra and in (b) simulated ASE spectra are shown at two different levels for the current density. Obviously, the simulated spectra agree almost perfectly, whereas small deviations for the measured spectra can be observed. In particular, some spectral ripples can be seen in the center of the R-SLED's ASE spectrum measured at high current injection, which indicates that R-SLEDs are more susceptible to resonant cavity effects caused by the high reflectivity at the back-facet side.

The results presented in this section prove that an R-SLED behaves indeed like a standard SLED of doubled length at the same level of current density. In our talk we will show that the equivalence also holds for the internal SLED properties like, e. g., the longitudinal carrier density distribution and the optical intensity distribution.

IV. Summary

We have presented a generalized SLED model that includes the effect of arbitrary facet reflectivities on the electro-optical performance of SLED chips. Asymmetric chip designs with respect to the facet reflectivities lead to the concept of R-SLEDs. Such devices can be used to boost the SLED output power enormously or to shorten the chip length for a given level of output power. This opens the way to ultimate high-power SLEDs with broadband emission spectrum for applications, which are less stringent on the spectral noise performance.

References

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