Modeling of External Feedback in Semiconductor Lasers for Continuous-Variable Quantum Key Distribution Systems

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The simulation of semiconductor lasers with external feedback is of great significance due to their potential use in continuous-variable quantum key distribution (CV-QKD) systems. In these systems, it is essential to accomplish maximum powers in the range of milliwatts for single-mode operation. These laser powers can be achieved through a high coupling efficiency between the external cavity and the gain chip, which is calculated in this work with a mode overlap integral from the eigenmodes obtained by the eigenmode equation.

1 Introduction

Edge-emitting semiconductor lasers based on gallium arsenide (GaAs) are of a great interest for high and low power applications, such as free space communications, pumping high-power fiber or solid-state lasers and optical frequency conversion. Their potential use for continuous-variable quantum key distribution systems (CV-QKD) further increases the requirement to accurately model these systems [1, 2]. Edge-emitters offer a miniaturized and a low cost version of a laser system. For CV-QKD systems, an ultra narrow linewidth below 10 kHz as well as low noise near to the quantum noise limit is needed. The diode laser must therefore operate in continuous wave (CW) single-mode and at the same time a power of more than 10 mW is required. In this work, we use an external cavity with a waveguide and an integrated Bragg grating based on silicon nitride (SiN) to achieve both a narrow linewidth and a maximum power [3]. SiN is chosen for this task, as it is a low loss material. In the following, we refer to the edge emitter as the gain chip so that external cavity and gain chip form a Photonic Integrated Circuit (PIC). The gain chip emits a wavelength of about 808 nm. This work presents the calculation of the coupling efficiency between the gain chip and the external cavity to achieve a maximum output power of more than 10 mW. To model these we use our in-house implemented software SEMSIS.

2 Coupling efficiency

The external cavity has a taper at its back facet, see Fig. 1, so that the light from the gain chip can be guided with low loss into the waveguide. To increase the power output of the PIC, it is unavoidable to maximize the mode overlap between the fundamental mode of the gain chip with the fundamental mode of the taper facet,

$$\Gamma_{\mathrm{ov}} = \frac{\left|\int \phi^*(x,y)\psi(x,y)dxdy\right|^2}{\int |\phi(x,y)|^2 dxdy \int |\psi(x,y)|^2 dxdy}$$

where ϕ is the electric field of the fundamental eigenmode of the gain chip, ψ is the electric field of the fundamental eigenmode of the taper facet and Γ_{ov} the mode overlap.

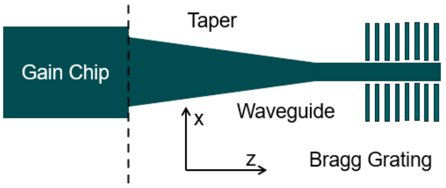

Fig. 1 *Schematic structure of the PIC consisting of a gain chip with external cavity.*

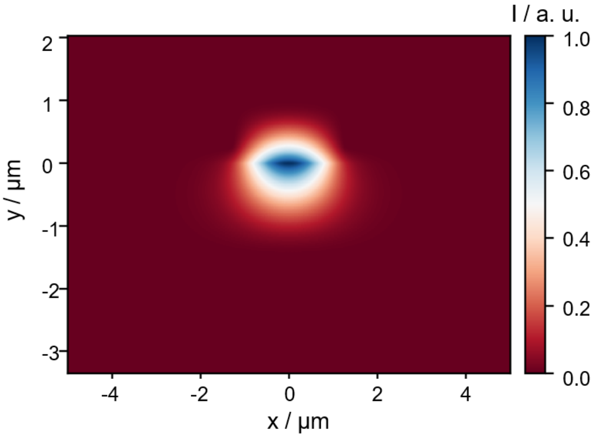

Fig. 2 *Fundamental eigenmode of the gain chip for a ridge width of 4.5 µm and an etch depth of 1.75 µm.*

The mode overlap is equivalent to the coupling efficiency [4], describing how much power of the gain chip couples into the external cavity. Therefore we calculate the eigenmodes with the eigenmode equa-

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tion for the gain chip and the taper facet for TE polarized light

$$\triangle\Phi(x,y) + k_0^2 n(x,y)^2\Phi(x,y) = k_{\mathrm{ref}}^2\Phi(x,y)$$

obtained from [5], where Φ is the electrical field of an eigenmode, k_0 the wavenumber, n the refractive index profile and $k_{\mathrm{ref}} = n_{\mathrm{ref}} k_0$ the reference wavenumber with n_{ref} the effective refractive index. The eigenmode equation is evaluated at the interface between gain chip and the taper section for the respective waveguide geometries (dashed line in Fig. 1). The eigenmodes of the gain chip are laterally confined by an etched ridge at the top of the gain chip. The first eigenmode of the gain chip is shown in Fig. 2 for a ridge width of 2.5 µm and an etch depth of 1.75 µm.

3 Results

To find optimal parameters for the height and width of the taper facet, we investigate their influence on the coupling efficiency. The maximum coupling efficiency follows a hyperbola (Fig. 3). A maximum of almost 95 % is achieved for a taper facet with a width and height of 2500 nm and 30 nm. Nonetheless, a taper heigth of 30 nm puts strains on the manufacturing tolerances. Hence, we focus on manufacturable geometries, which can be obtained by a width and height of 140 nm and 140 nm taper facet with an efficiency of about 80 %.

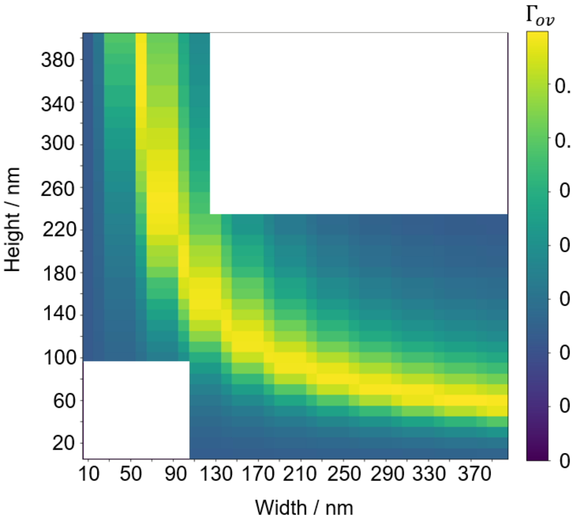

Fig. 3 *Coupling efficiency for a ridge width of the gain chip of 2.5 µm, an etch depth of 1.75 µm and a variation of the height and width of the taper facet. The white areas represent no calculated values.*

The coupling efficiency does not only apply to the coupling of the light from the gain chip into the external cavity (forward), but also backwards for the light coupling from the external cavity into the gain chip. The sepctrally narrow feedback from the external resonator ensures the single-frequency operation of the laser.

In this calculation for the coupling efficiency we neglect the bonding gap at the interface between the gain chip and the taper of the external resonator (Fig. 1) of about 1 µm, so we expect a slightly different coupling efficiency. Despite that, the Rayleigh length is a multiple of the bonding gap, so we conclude that the profile of the beam will not differ so much after the bonding gap.

4 Summary

We have shown by calculating the mode overlap that the coupling efficiency of a gain chip and a taper facet is at a theoretical maximum of about 80 % for manufacturable conditions. Therefore, 80 % of the power from the gain chip will couple into the external cavity and will be reflected from the Bragg grating in parts and couple back into the gain chip again. This value is expected to be the maximum coupling efficiency we can achieve, also in presence of a bonding gap.

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