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Abstract: Light sources on the micro and nano-scale have been of great interest in recent years. Especially for data communication over centimeters densely integrated lasers are required. Ultra-small devices have been demonstrated [1]; the efficiency of such devices on the other hand is far behind values demonstrated for larger integrated laser concepts [2]. As a consequence the density of laser integration is currently limited by power consumption and cooling properties rather than the actual device footprint. In this work we will examine the challenges of increasing the efficiency of ultra-small laser concepts and present a design for a micron-scale laser promising record efficiencies.

1. Introduction

Extreme scaling of lasers naturally brings drawbacks, namely: increased series resistance, high threshold gains and inefficient coupling to photonic circuits. These factors contribute to low electro-optical efficiency (EOE) of nanoscale devices, which is defined as optical output-power P_{opt} over electrical power consumption P_{el}. In a simple model the EOE of an electrically pumped semiconductor laser depends on its series resistance R_s, differential quantum efficiency η, threshold current I_{th}, and the threshold diode voltage V_{th}, electron charge e and the optical transition energy E_{trans}.

$$EOE = P_{opt} / P_{el} = \eta \cdot E_{trans} / e \cdot (I - I_{th}) / (I^2 R_s + IV_{th}) \qquad (1)$$

Figure 1 illustrates the dependence of the EOE on these parameters. The parameters are set to η=0.8, I_{th}=350 µA and R_s=0.5 kΩ, and the EOE is plotted as a function of the output power (full line). The EOE is maximal with a value of 0.3 at an output power of 400 µW. For lower powers the EOE is limited by the threshold current as illustrated for R_s=0. For higher output power the threshold current is negligible compared to the current feeding the stimulated emission, and the EOE is limited by R_s. The maximum EOE is limited by the differential quantum efficiency efficiency, as illustrated for I_{th}=R_s=0. An improvement of the EOE can be achieved by increasing the differential efficiency, reducing the threshold current or reducing the series resistance. When designing a laser these parameters cannot be optimized independently. Consequently, careful tradeoffs need to be made, depending on the desired power output range. In the following we present the design of the micron scale photonic crystal beam laser depicted in Figure 2. The device promises an EOE in excess of 20% for a power range between 100-1000 µW.

2. Laser Design

The starting point of the design procedure is the choice of reflectors to form the laser cavity. A low modal gain is desired, which requires high reflectivities exceeding 90%. To achieve a high differential quantum efficiency when out-coupling the light through such good reflectors the scattering losses need to be minimized. We compared the characteristics of four waveguide compatible reflector designs using FDTD simulations [3]: (1) ring cavities, (2) metal mirrors with parallel out-coupling and distributed Bragg reflection in (3) waveguides with sidewall gratings and (4) photonic crystal beams. Only the photonic crystal beams show reflections R>90% at the same time as η>50% for a device footprint in the few µm² regime. On the basis of these results we designed and simulated the laser schematically depicted in Figure 2. The cavity is formed by a photonic crystal beam etched from a InGaAs /InP waveguide with a polymer (BCB) cladding. The top InP layer is heavily n-doped, while the bottom layer is p–doped forming the laser diode. Despite the high doping, Q factors on the order of 1000 can be reached. Our calculations show that the threshold gain can be reached for lower currents, when bulk InGaAs with a mode overlap of 0.55 is used as gain material instead of quantum wells. The p-contacts are placed to the sides of the device, where the contact layer is tapered towards the cavity to provide carrier confinement and reduce the threshold current, which we estimate at 340 µA. The n-side contact is moved to the back of the device to reduce optical absorption in the metal layers. Additionally, the contact area can be increased to reduce the serial resistance to R_s=480 Ω. At the front, the InGaAs waveguide is butt-coupled to a low-loss InP-membrane waveguide, providing efficient out-coupling with a differential quantum efficiency of η=0.77.

We envision the realization of such a device within the framework of the photonic platform IMOS [4], where a wide variety of passive components are readily available. In IMOS a thin III-V membrane is bonded to a Silicon or

CMOS carrier wafer using BCB. This technology allows processing before and after the bonding, which we use to isolate the electrical contacts. To realize the out-coupling at the front side of the laser, we are currently developing an active-passive regrowth process for such membranes. The fabrication of such devices will be very challenging. Nevertheless, if successful the laser should provide an output power in excess of 100 µW, with an EOE exceeding 20% and a device footprint smaller than 100 µm² including contacts.

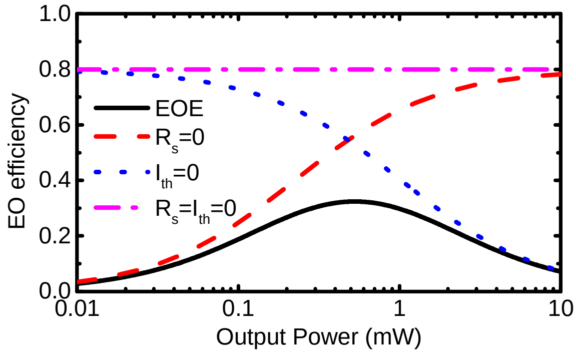

Figure 1 : Electro optical efficiency plotted as a function of output power.

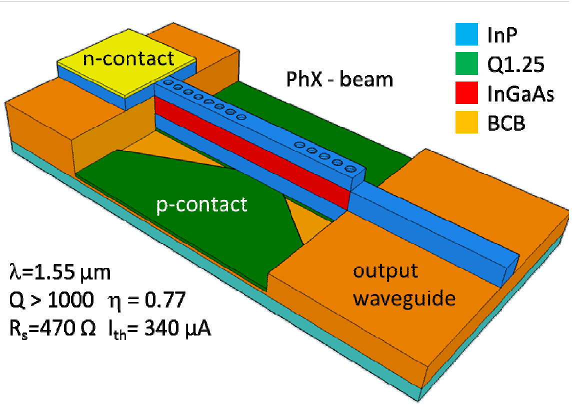

Figure 2 : Schematic of photonic crystal beam laser

4. Conclusion

The route towards densely integrated light sources lies in optimizing the efficiency of small lasers. Traditional cavity and coupling concepts are not easily scalable and substantial technological advances are necessary. In our studies we identified the photonic crystal beam as most promising candidate for micron-scale lasers. Within the framework of a III-V membrane photonic platform we designed a micron-scale laser based on photonic crystal beams, which should provide record efficiencies, provided the fabrication challenges can be overcome.

5. References

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