Towards densely integrated lasers for optical data communication

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Optical data links are employed at ever shorter distances, most recently with a few meters length in between cabinets in warehouse sized computer systems. A continuation of this trend to optical chip-to-chip and on-chip communication will require highly efficient and densely integrated optical devices. We will discuss general requirements to achieve such targets in nano- and micro- scale lasers integrated with a photonic membrane platform, where we focus on the optical cavity design and the electrical properties. Additionally, we will compare the advantages of laser concepts based on metallic-dielectric confinement, photonic crystal cavities and distributed feedback using sidewall gratings.

Introduction

Optically active devices on the micro and nano scale have been of great interest in recent years. The ultimate objective is on-chip communication using densely integrated directly modulated lasers at room temperature. Such devices have been demonstrated [1]; however, output powers in the hundred micro watt regime remain challenging as efficient cooling is needed. Currently, high density deployment in an on-chip scheme is not limited by the device footprint but rather by the high serial resistance of nano lasers and the associated heat generation. As an example, in a nano laser with an output power of 100 μW, a wall plug efficiency of 0.1, and a high performance water cooling mechanism, the device density is limited 1000/mm^2 [4]. High wall plug efficiency, low threshold currents and low serial resistance are, therefore, mandatory for densely integrated devices. Moreover, methods to couple the light source to a waveguide with a high efficiency have been proposed [1, 2], but not demonstrated to our knowledge.
In the first part of this paper, we discuss the requirements for an efficient electrically pumped micrometer laser in general terms of optical and electrical properties independently of a specific implementation.
In the second part, we describe three design approaches and compare their suitability to the requirements derived in the first part: sidewall grating, metallic-dielectric optical confinement [3] and 1D photonic crystal (PC). We also consider the fabrication complexity for each concept, and assess the potential to integrate it with a photonic membrane platform, InP Membrane On Silicon (IMOS), that would allow integration of photonic circuits with electronics.

Requirements for micro-nano scale lasers design

Miniaturization is essential for lasers in high density integrated photonic circuits (PICs). While it brings advantages as low device footprint and threshold current, it raises challenges due to the shortening of the gain section, which in turn, requires very efficient mirrors. This can be illustrated by considering a Fabry Perot cavity with mirror reflectivity R_{mirror}, length l and a modal gain g_{modal}. For a better understanding, we plot1-R_{mirror} on a logarithmic scale of such a cavity as a function of length for a range of modal gains between 10/cm and 500/cm. Values up to 1800/cm and 3000/cm are typically reached for QWs and bulk gain media respectively. As the length of a laser is reduced more perfect mirrors are required, for example R_{mirror}=0.98 is needed for lasers shorter than a micron (at g_{modal} 500/cm) which is very challenging to achieve. In the following we consider a five micrometer length laser and a modal gain of 500/cm. As shown in Figure 1a) a facet reflection of 90% is needed in this case.

To get an estimate of the threshold current as a function of device length we calculate the carrier recombination current in a 200 nm thick InGaAs active region. Here, we consider the Auger, radiative recombination and surface recombination (velocity) at threshold charge carrier density ρ_{th}. We can deduce the threshold carrier density from the differential gain using a logarithmic gain model for bulk InGaAs (g_0=3000, N_{tr}=1.1, N_s=5 [5]). In Figure 1b) the threshold current is plotted as a function of device length for different mirror reflectivities. At higher reflectivities the minimal threshold current is found for shorter cavity lengths. However, a minimum threshold current does not guarantee efficient laser operation, since one of the mirrors need to allow out-coupling of the laser light. A better figure of merit is the wall plug efficiency as discussed in the following.

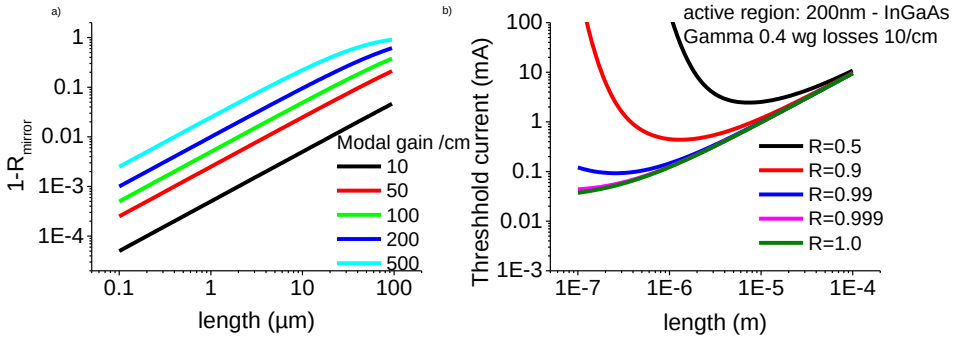


Figure: a) threshold current in mA versus device length in m b) facet reflectivity versus device length in µm.

The wall plug efficiency is the ratio of the optical output power over the total electrical power used by the device. A high WPE reduces the power consumption and reduces the amount of heat generated by the device leading to higher integration densities. In a simple model the WPE depends on the series resistance R_{ser}, differential efficiency η_d, threshold current I_{th}, current-independent series voltage V_s, and the ideal diode voltage V_d.

$$WPE = \frac{P_0}{P_{in}} = \frac{\eta_d \frac{h\nu}{q}(I - I_{th}) \cdot (I > I_{th})}{I^2 R_{ser} + IV_d + IV_s}$$

Figure 2 illustrates the dependence of the WPE on these parameters. In Figure 2a) the parameters are set to typical values for nano lasers (η=0.5, I_{th}=100 µA and R_{ser}=1KΩ), and the WPE is plotted as a function of the output power (black line). The WPE is maximal with a value of 0.2 at an output power of 100 µW. For lower powers the WPE is limited by the threshold current as illustrated by the green line, where the series resistance is set to 0. For higher output power the threshold current is negligible compared to the current feeding the stimulated emission, and the WPE is limited by the series resistance of the device (red line). The maximum WPE is limited by the differential efficiency, as illustrated by the blue line in fig 2a), where both I_{th} and R_{ser} are equal to zero. An improvement of the WPE can be achieved by increasing the differential efficiency (i.e. η=0.7 in figure 2b), reducing the threshold current (I_{th}=5µA in 2c) or reducing the series resistance (R_{ser}= 100 Ω in 2d). Note that the maximum efficiency shifts when changing these parameters, making the ideal optimization dependent on the desired power output range. In each case a high differential efficiency is desired.

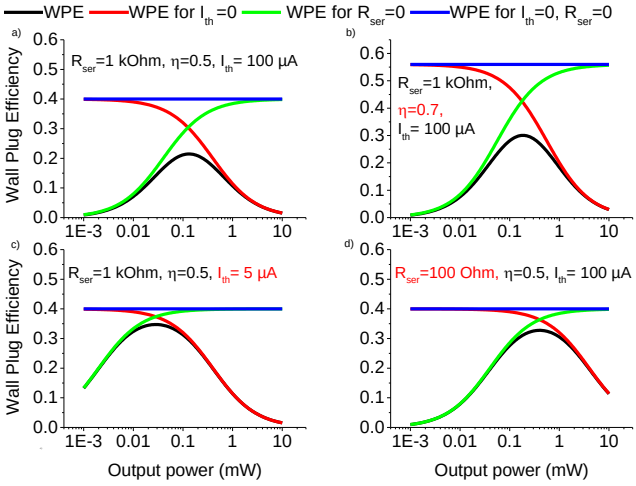
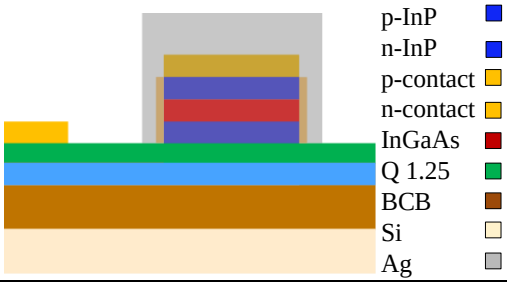


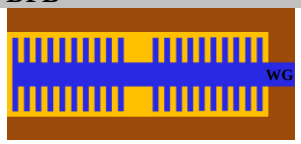
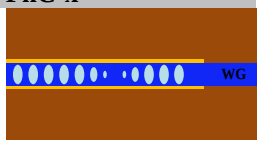
Figure: WPE vs. Output power in mW for a) R_{ser}= 1KΩ, η=0.5 and I_{th}=100 µA b) R_{ser}= 1KΩ, η=0.7 and I_{th}=100 µA c) R_{ser}= 1KΩ, η=0.5 and I_{th}=5 µA and d) R_{ser}= 100 Ω, η=0.5 and I_{th}=100 µA.

Conclusion: laser concepts summary

Table 1 summarizes the results obtained by 3D FDTD simulations. It shows the general layer stack in a cross sectional cut and the longitudinal view of each design. Some of the critical parameters that define advantages and drawbacks for each schematic are also shown.

Table 1. Summary of the main required parameters for different laser concepts

Layer stack cross section	
	

Laser concept	DFB	Metal wrapped	PhC-x
Longitudinal Cross section			
Differential efficiency	9%	20 %	Up to 40%
Facets reflectivity	70% at 20 periods	99 %	83% at 5 periods
Q factor	~240	~750	~650
Length	~15 μm	5μm	5μm

The first concept considered in Table 1 is the side wall grating laser. At least 20 grating periods are needed to reach reflections compatible with achievable material gains. This results in a large device length exceeding 15 μm. Furthermore, the η_d is around 9%, which severely limits the achievable WPE of the device. However, a DFB laser has the advantage of an accurate wavelength control, and is less complex to fabricate than the other schemes.

The main advantage of the metal wrapped cavity presented in column two is a high Q factor of 700 due to the 99% of reflection on a silver/silicon nitride (Ag/SiNx) facet. Furthermore, the length of the cavity can be squeezed to a 5μm length. Due to the metal mirrors, this design cannot be butt coupled to an output waveguide. Symmetric evanescent coupling to a parallel output waveguide results in a η_d up to 20%. Additionally, the design relies critically on low material losses achieved with high quality silver. Although the fabrication is at some extent challenging, there are currently techniques that tackles the critical fabrication steps of metallic-dielectric cavities [1, 6].

Finally, our most promising design is a photonic crystal nano-beam with a cavity length as short as 5μm and a Q factor of 650. Five periods are sufficient to achieve more than 83% of reflection. This concept shows good wavelength control and low threshold currents. Moreover, in this design it is possible to reduce the losses in the cavity by placing the ohmic contact to the side of the structure, leading to high η_d from 40% up to 60%, which would allow high WPE. This concept is challenging to fabricate. Due to the large surface to volume ratio it is critical to reduce surface recombination and avoid erosion of the conducting layers.

References

[1] K. Ding, M. Hill, Z.C. Liu, L. J. Yin, P.J van Veldhoven, and C.Z. Ning, "Record performance of electrical injection sub-wavelength metallic-cavity semiconductor lasers at room temperature," Optics Express, vol. 21, No. 4, 4728-4733, 2013.

[2] M. Kim, A. M. Lakhani, and M. C. Wu, "Efficient waveguide-coupling of metal-clad nanolaser cavities," Optics Express, Vol.19, No.23, 23504-23512, 2011.

[3] V. Dolores-Calzadilla, D. Heiss, A. Fiore, and M. Smit, "Waveguide-coupled nanolasers in III-V membranes on silicon," proceedings at ICTON IEEE, 978-1-4799-0683-3, 2013.

[4] D. Heiss, V. Dolores-Calzadilla, A. Fiore, and M. Smit, "Design of a waveguide-coupled nanolaser for photonic integration," in proceedings of the conference OSA IPR, Puerto Rico, 2013.

[5] L. A. Coldren, "Gain and current relations 4.6," in Diode lasers and photonic integrated circuits, John Wiley & Sons, New Jersey, pp.224-225,2012.

[6] M. T. Hill, and M. Marell, "Novel plasmon nanolasers," 15th OptoElectronics and Communications Conference (OECC2010) Technical Digest, Sapporo Convention Center, Japan,218-219, 2010.