Project Option 1: Design of Silicon Hybrid Laser (Due 5/13/2020, submit to bCourses)

Background: Silicon photonics has emerged as a universal platform of photonic integrated circuits. However, it is difficult to integrate lasers on Si as it is an indirect bandgap material. Recent, a "hybrid" approach has been proposed to add optical gain by bonding a thin III-V epitaxial film on Si waveguides. A hybrid laser has been realized by such approach [1]. The cross-section in the gain region is shown in the figure below. Light mainly resides in the Si waveguide, with evanescent tail extending to the gain region in III-V.

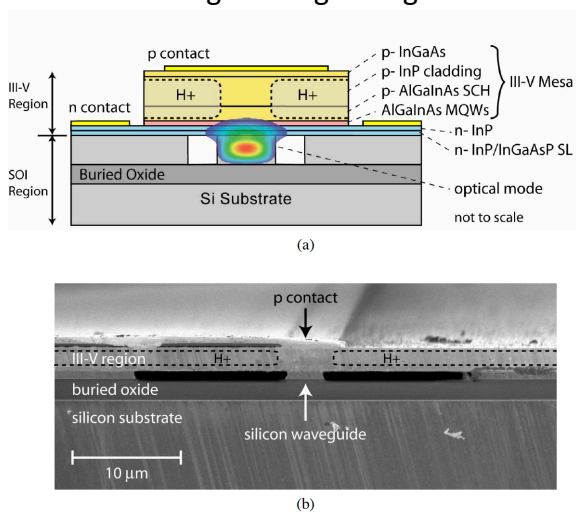

Figure 1 Concept of Si hybrid laser [1].

Project Goal: The goal of this project is to design a Si hybrid laser with low threshold and high output power. The schematic of the laser (top view) is shown in Figure 2. The red section is the gain region with III-V thin film bonded on Si waveguide, while the gray regions are passive silicon waveguide components. The layer structure of the passive and the active (gain) region is shown in Figure 3. The III-V epitaxial structure has been simplified for this project. It contains essentially a double heterostructure with a thin lower cladding layer to facilitate coupling with Si waveguides. To achieve smooth transition between the active and the passive waveguides, the III-V area is tapered to enable adiabatic transition of the optical mode. Loop mirrors on both sides of the laser provides optical feedback for the laser cavity. The following questions are meant to help you design the laser.

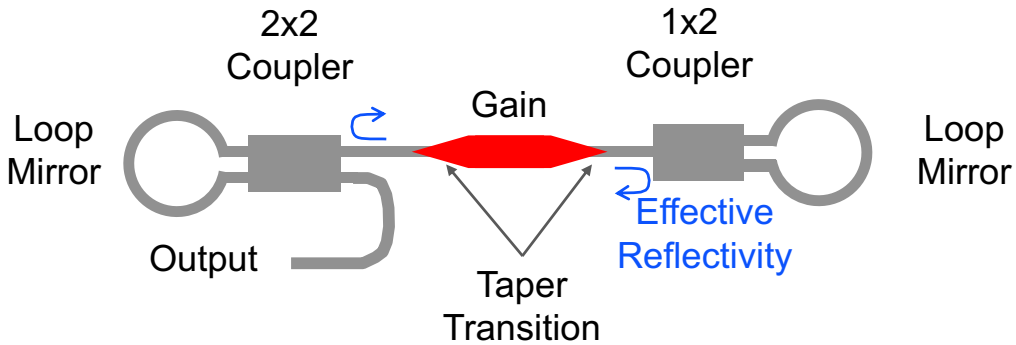

Figure 2. Schematic top-view layout of the Si hybrid laser to be designed in this project.

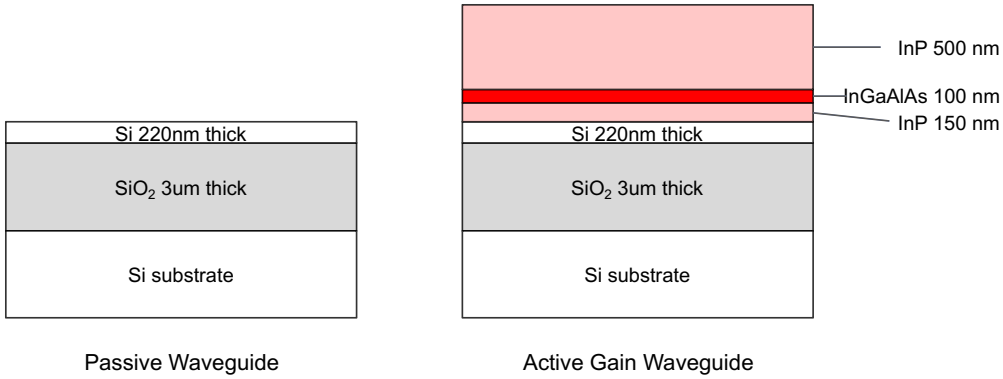

Figure 3. Cross-sectional view showing the layer structures of the passive and the active (gain) region.

1) The right reflector consists of a 1x2 coupler and a loop mirror. If all components are ideal, what is its reflectivity (seen before the 1x2 coupler)?
2) The left reflector consists of a 2x2 coupler and a loop mirror. If all components are ideal, what is its reflectivity (seen before the 2x2 coupler)? What is the percentage of power coupled to the output port? [*Hint: see Ref. [2] for an introduction to transmission matrix of a 2x2 coupler relating the output fields to the input fields. Note that the power coupled to the output port is a "loss" to the cavity, similar to the mirror loss of simple FP cavities.*]

For the problems/designs below, assume all silicon components have a loss of 1 cm^{-1}, and the gain section has an intrinsic loss of 5 cm^{-1}. The nominal width of the waveguide is 500 nm. The gain coefficient of the active material (InGaAlAs) can be modeled by $g(n) = g_0 ln(n/n_{tr})$, where $g_0 = 100$ cm^{-1}, $n_{tr} = 10^{18}$ cm^{-3} is the transparency carrier concentration, and n is the carrier concentration in the active region. The length of the gain section is 1 mm. The current density is related to the carrier concentration by $J(n) = qt(An + Bn^2 + Cn^3)$, where $A = 10^{-6}s^{-1}$ (SHR and surface recombination), $B = 10^{-10}cm^3s^{-1}$ (radiative recombination), $C = 10^{-28}cm^6s^{-1}$ (Auger recombination), q = 1.6x10^{-19} C is the electron charge, and t = 100 nm is the thickness of the gain layer (see Figure 3). The target wavelength is 1550 nm.

3) The width of the Si waveguide in the gain region will need to be wider than 500 nm in order to support a guided mode. Use FDTD or MODE to find the width for the Si waveguide in the gain region such that the TE mode has an index contrast of 0.01 with respect to InP. What is the confinement factor of the gain region of the laser for this Si waveguide width? Note this confinement includes both dimensions of the cross section (see Figure 1).
4) Derive the threshold condition using the simplified reflectivity in 1) and 2) and the propagation losses of active and passive waveguides. What is the expression of threshold gain?
5) If the gain section is 1 mm long, what is the threshold carrier concentration? What is the threshold current? What is the dominant recombination mechanism at threshold?
6) Design a 1x2 coupler using either directional coupler or a multi-mode interference (MMI) coupler. What is the excess optical loss determined by FDTD simulation? Excess loss is defined as the difference between the sum of the output power and the input power, usually expressed in dB.

7) Design a 2x2 coupler using either directional coupler or a multi-mode interference (MMI) coupler. What is the excess optical loss determined by FDTD simulation?
8) You can determine the radius of the loop mirror by requiring the bending loss to be less than 10% of the silicon propagation loss. What is the radius?
9) Design a taper coupler between the active and the passive sections to minimize reflection and maximize transmission. Simulate the coupler performance with FDTD and find the excess loss and the residue reflection. Note that the performance of taper is better with sharper tip. However, the sharpness of the tip is usually limited by the fabrication process. Assume the minimum tip width here is 200 nm.
10) Now include the non-ideal losses (excess loss of the couplers and tapers), what is the threshold current?
11) What is the quantum efficiency of the laser?
12) If the lateral dimensions of all Si components (waveguide width, etc.) turn out to be 10% larger, how does that impact the laser? How does the coupler's coupling ratio change? How does the output coupling ratio change? How does the threshold current change?

Reference:

[1] A. W. Fang, H. Park, O. Cohen, R. Jones, M. J. Paniccia, and J. E. Bowers, "Electrically pumped hybrid AlGaInAs-silicon evanescent laser," *Opt. Express*, vol. 14, no. 20, pp. 9203–9210, Oct. 2006, doi: 10.1364/OE.14.009203.

[2] A. Takagi, K. Jinguji, and M. Kawachi, "Wavelength characteristics of (2*2) optical channel-type directional couplers with symmetric or nonsymmetric coupling structures," *Journal of Lightwave Technology*, vol. 10, no. 6, pp. 735–746, Jun. 1992, doi: 10.1109/50.143072.

Material Properties of InP lattice matched $(Al_zGa_{1-z})_{0.47}In_{0.53}As$:

Property	Symbol	Equation	Remarks
Bandgap energy	E_g	$0.752 + 0.726z$	eV
Electron Effective Mass	m_e^*	$(0.043 + 0.031z)m_0$	
Heavy Hole Effective Mass	m_{hh}^*	$(0.465 - 0.0565z)m_0$	
Light Hole Effective Mass	m_{lh}^*	$(0.053 + 0.043z)m_0$	
SRH Coefficient	A	10^{-6}	s^{-1}
Radiative Recombination Coefficient	B	10^{-10}	cm^3s^{-1}
Auger Coefficient	C	10^{-28}	cm^6s^{-1}
Refractive Index	n	$3.6 - 0.51z + 0.12z^2$	$\lambda = 1550\ nm$
		$3.61 - 0.22z + 0.14z^2$	$\lambda = 1300\ nm$
Refractive Index of InP	n_{InP}	3.167	Use Lumerical material model