Integrated semiconductor lasers

Fabrice Raineri

Maître de Conférences – Univ. Paris Diderot
Laboratoire de Photonique et de Nanostructures (CNRS-UPR20)
fabrice.raineri@lpn.cnrs.fr
Staff:
42 researchers and academic staff
40 technical staff
40 PhD students and post-doctoral fellows

Research in the fields of nanosciences, nanofabrication, photonics & devices from materials and technologies to basic science and applications

Mainly III-V semiconductors

From Nanoscience... ...To Telecom/Photonics oriented basic research
• Motivations and Issues
• How to go about semiconductor integrated lasers
• Integration technologies
Outline

• Motivations and Issues

• How to go about semiconductor integrated lasers

• Integration technologies
Motivations:

Photonics follows the steps of Microelectronics

From isolated components

To (complex) circuits
Motivations:

And with complexity comes functionality, possibilities!

Applications: sensing, biophotonics, telecom, datacom, computercom …

CHALLENGES

- Deliver the necessary passive and active functionalities: sources, low-loss waveguides, filters, switches, detectors…
- Harness wavelength division multiplexion
- Perform low power consumption and high speed: fJ activation energies, >10Gbits/s
- Small footprint for high density (10^4-10^5 of devices per mm^2): <100μm^2
- Integration with Si electronics and CMOS compatibility for cheap manufacturing
How do you go about integrated sources?

- Functionality is material dependant! Which unified optical platform?
- Coupling between the components: flip-chip, butt-coupling, evanescent wave?

→ Semiconductor-based planar waveguides platform

Ridge waveguides

Confinement by total internal reflection
Issues:

How do you go about integrated sources?

- Necessary change in design of the lasers: no cleaved facets!
  → Integrated mirrors, resonators

Distributed Bragg Reflectors (DBR)

Distributed FeedBack (DFB) resonators

Disk & ring resonators

Photonic crystals
Reflecting current trends in photonics, the presented talk will focus on the integration of semiconductor lasers, transitioning from conventional lasers to nanolasers. This approach emphasizes the development of novel integration technologies for improved efficiency and performance in optical devices.
Conventional lasers to nanolasers:

2 clear-cut goals:

→ Sources L~mm – $P_{out}$~mWs (conventional lasers)

→ Sources Footprint<100µm² – $P_{out}$~10µW (micro/nanolasers for dense integration and smart operation)
Conventional lasers to nanolasers: Materials

III-V SEMICONDUCTORS

- Tailored emission from UV to far IR
- High quantum efficiency

QDs
QWs
Conventional lasers: DBR and DFB

Both are based on Bragg gratings

Waveguide corrugated with periodic grating
Conventional lasers: DBR and DFB

*Both are based on Bragg gratings*

- Band-gap spectral width depends on index contrast (field overlap with grating)
- \( R_{\text{max}} \) depends on index contrast & grating length

\[ \rightarrow \text{DBR-based lasers uses the high reflectivity in the band-gap} \]

\[ \rightarrow \text{DFB lasers uses the mode edges} \]
Conventional lasers: DBR lasers

Passive DBR  Active zone  Passive DBR

typical length 0.5µm
Conventional lasers: DBR lasers

**Operation characteristics**

- Single mode
  Linewidth ~ MHz

- Threshold ~ few 10s of mA
  \[ P_{out} \approx 10-100\text{mW} \]

- Tunability: 5-10nm
Conventional lasers: DFB lasers

Perfectly periodic DFB can exhibit 2 laser modes whereas $\lambda/4$ shifted DFBs are single mode
Operation characteristics

- Linewidth < MHz
- Threshold ~ few 10s of mA
  \[ P_{\text{out}} \approx 10\text{-}100\text{mW} \]

Much simpler to fabricate as no material regrowth is necessary!
Microdisk & microring laser

Based on whispering gallery modes

Clockwise and Counterclockwise modes are degenerate

Confined vertically by TIR

Azimuthal mode (m)

\[ \lambda_m = \frac{2\pi R_n g}{m} \]
Optical losses:

- Highly dependant on R & vertical layer stack
- Surface roughness
- Ring Losses > Disks Losses

Low index contrast waveguide (InP/InGaAsP/InP): R>100µm

High index contrast waveguide (~\(\lambda/n\) thick Semiconductor slab): R>1µm

\[ Q = \omega/\tau \sim 10^5 \] with \(\tau\) photon lifetime

For R=1µm made in 255nm thick AlGaAs slab

Microdisk & microring lasers

Optical pumping (small disks)

- Free-Space Collection
  - $P_{\text{in}} \approx 1.1 \mu W$
  - $\eta \approx 0.1\%$

- Absorbed pump power $\approx 1 \mu W$

Electrical injection

- $\leq 0.2 \text{nm}$
- $0.43 \text{mA}$
- $0.35 \text{mA}$
- $0.20 \text{mA}$

$2 \mu m \text{ AlGaAs disk embedding QDs}$

$\rightarrow$ low threshold $\approx 1 \mu W$
$\rightarrow$ Weak emission

$\rightarrow$ low threshold $\approx 0.2 \text{mA}$
$\rightarrow$ Weak emission (collection by surface)
$\rightarrow$ 286K


Artificial materials with wavelength scale periodic modulation of refractive index


<table>
<thead>
<tr>
<th>1D</th>
<th>2D</th>
<th>3D</th>
</tr>
</thead>
<tbody>
<tr>
<td>multilayer film</td>
<td>square lattice of dielectric columns surrounded by air</td>
<td>spheres in a FCC configuration</td>
</tr>
<tr>
<td>AlGaAs/air waveguide</td>
<td>AlGaAs/air</td>
<td>inverted opals</td>
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Properties of the dispersion

2D Photonic band gap

\[ \frac{d\omega}{dk} = 0 \text{ possible!} \]

\[ \rightarrow \text{Control of the in-plane propagation} \]

\[ \rightarrow \text{Enhancement of light matter interaction} \]
2 Families of resonators

- **µ-cavity**
  - Etat de l’art $Q \sim 10^6 - V \sim (\lambda/n)^3$
  - Operation in waveguides

- **Band-edge resonator**
  - Etat de l’art $Q \sim 10^4 - V \sim 40(\lambda/n)^3$
  - Surface operation

*E. Kuramochi et al., APL 88 041112 (2006)*
PhC laser: How do you go about it?

Rate equations model

Photon density in the lasing mode

\[
\frac{dS}{dt} = \frac{N}{\text{rad}} S + \frac{v_g}{\text{p}} \left( N - N_{\text{tr}} \right) S
\]

Carrier density

\[
\frac{dN}{dt} = R - \frac{N}{\text{rad}} - \frac{N}{\text{Nrad}} - v_g \left( N - N_{\text{tr}} \right) S
\]

carrier lifetimes associated with radiative and non radiative recombinations

confinement factor
coupling of spontaneous emission into the lasing mode

photon lifetime
group velocity
differential gain
carrier density @ transparency
PhC laser: How do you go about it?

In the stationary regime $\rightarrow$ Laser characteristics curve

Laser threshold given by $\text{gain} = \text{losses}$ (classical definition)
PhC laser: How do you go about it?

In the stationary regime → Laser characteristics curve

Log-Log Scale

Laser threshold given by gain=losses (classical definition)
PhC laser: Static properties

What is special with PhC nanolasers?

- High Q and small modal volumes $\rightarrow$ threshold lowering (fJ!)

$$I_{th} = \frac{q}{p} \left( 1 + \frac{N_{tr} V}{p} \right) \frac{\rho}{1 + \frac{\rho}{N_{rad}}}$$

- $\beta$ coupling of spontaneous emission is close to 1!

$\rightarrow$ Spatial redistribution of spontaneous emission into the useful mode due to suppression of other modes (band gap), and Purcell effect
PhC laser: Static properties

What is special with PhC nanolasers?

• $\beta$ coupling of spontaneous emission is close to 1!

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Light-matter interaction in semiconductor materials

acceleration of spontaneous emission given by

$$F_p = \frac{G_{cav}}{G_{all}} = \frac{3}{4} \frac{Q}{V^{\frac{2}{3}}}$$

$$Q = \text{Max}(Q_{cav}, Q_{emitter})$$

$$\beta = \frac{F_p}{\gamma + F_p}$$
What is special with PhC nanolasers?

• $\beta$ coupling of spontaneous emission is close to 1!

$\rightarrow$ Threshold-less lasers?

![Graph showing photon number vs. injection current]


No! New definitions of threshold!
Identifying the laser threshold

Classical definition
Gain = losses

Quantum definition
Photon number in the useful mode $<n>=1$

Statistical definition
Second-order coherence $g^{(2)}(0)$

For some high-$\beta$ lasers, these two definitions do not coincide.

Experimental observation in 2D PhC cavity + QDs

- Measurements@ltn
  - 2nd order or higher order autocorrelation

\[
g^{(n)}(0) = \frac{\langle E(t)^n E^*(t)^n \rangle}{\langle E(t) E^*(t) \rangle^n}
\]

- Thermal light \( g^{(n)}(0) = \frac{1}{n!} \)
- Coherent state \( g^{(n)}(0) = 1 \)

\[
h^{(n)} = \frac{g^{(n)}(0) - 1}{n! - 1}
\]

\( n = 2, 3, 4 \)
PhC laser: Dynamics

Semiconductor lasers are class B lasers! (carrier lifetime > photon lifetime)

→ abrupt change in pump gives relaxation oscillations

Frequency and damping time depend strongly on $\beta$

→ response to a short pulse pump depends on photon lifetime, carrier lifetime and on $\beta$
What is special with PhC nanolasers?

• $\beta$ coupling of spontaneous emission is close to 1!

→ Very fast dynamics!

from G. Bjork et al, JQE 27, 2386-96 (1991)

→ 100GHz modulation possible!
Some experiments

950nm Nanocavity laser


Figure 8 (online color at: www.ipr-journal.org) Large-signal lasing response in QW-driven PC laser. (a) Response to excitation pulses at (i) 9 ± 0.5 and (ii) 15 ps. (b) Excitation pulse train created by etalon setup. Imperfect mirror arrangement causes an exponential decrease in pulse power and only the first three pulses exceed the photonic crystal lasing threshold. (c) Lasing response delay.
Some experiments

Band edge laser @1.55µm

Up-conversion gating technique

Electrical injection of PhC lasers

- Electrical injection is a major issue. The goal is to inject carriers and make them recombine within the cavity. The difficulties are:
  - PhCs are very sensitive to their environment. Contact on top of the cavity is difficult without destroying the cavity properties
  - The presence of the holes result in an increase electrical resistance

Only 3 groups demonstrated electrical injection of PhC lasers...
Electrical injection of PhC lasers

Smart design of the cavity and acrobatic fabrication…

Electrical injection of PhC lasers

Lateral PIN junction in GaAs based system B. Ellis et al, Nat. Photon. 5, 297-300 (2011)

same type of study by NTT on InP (2012)
• Motivations and Issues

• How to go about semiconductor integrated lasers

• Integration technologies
  → Telecom approach (regrowth technique)
  → Si Photonics
« God created Silicon for microelectronics, GaAs for optoelectronics and Carbon for life »

R.A. Suris, inventor of the DFB Laser
Integration technology: telecom approach

Integration of different optical components based on growth, selective area etching and regrowth (MOCVD)

→ passive/active integration enabled
Integration DBR lasers with SOAs, MZ modulators!
Integration technology: Si photonics for higher integration

**III-V semiconductors/Silicon hybrid structures**

*Combine the best of both materials for photonics*

**SILICON**

- Compatibility with μ-electronics
- Low cost production in CMOS fabs
- Ultracompact low loss optical circuitry using SOI (high index contrast)

*Ideal for passive devices*

**III-V SEMICONDUCTORS**

- Tailored emission from UV to far IR
- High quantum efficiency
- Material engineering for high nonlinearity

*Ideal for active devices*
• **Direct growth of III-V on Si:**

→ **issues:** lattice constants mismatch, thermal expansion coefficients mismatch

*Direct growth leads to defects detrimental to optical and electrical material properties*

**Research in progress to overcome the problems**

**Growth of nanostructures**


**Use of metamorphic or seed layers**


**Still no results comparable to structures grown on III-V!**
• Wafer bonding:

→ Many solutions: adhesive, molecular bonding, wafer fusion…

adhesive wafer bonding

After substrate removal

Presently the best solution!
2 clear-cut goals:

→ Sources for telecom/datacom applications: \( \lambda = 1.3\text{-}1.5\mu m \) – \( P_{\text{out}} \sim \text{mWs} \)

→ Sources for On-chip interconnects: \( \lambda = 1.3\text{-}1.5\mu m \) – \( P_{\text{out}} \sim 10\mu W \) – Footprint < 100\( \mu m^2 \) - Power efficient

The main different paths:

1- Hybrid III-V/Silicon Evanescent Lasers

2- Hybrid III-V/SOI lasers based on adiabatic evanescent coupling

3- III-V nano/micro lasers evanescently coupled to SOI waveguides: microdisks and photonic crystals
The III-V layer is in contact with SOI.

Hybrid mode mainly confined in the SOI.

Overlap with QWs ~ few %.

Many types of lasers demonstrated:

**Mode locked lasers**


**DFB lasers**


**Racetrack lasers**

Coupling efficiency determined by:

1. Phase matching between the original modes
2. Field overlap between the original modes

When phasematching:

$\mathbf{a_1 = 1}$

$\mathbf{a_2 = 0}$

Initial conditions

Maximum energy exchange vs. phase mismatch:

For example:
$\Delta n_{\text{eff}} = 10\%$ implies - 65% of energy exchanged
2- Hybrid III-V/SOI lasers based on adiabatic evanescent coupling @III-V Lab&LETI&Ghent

→ Mirrors in Si
→ III-V coupled through evanescent wave coupling
→ Engineering of the coupling zones

M. Lamponi et al, PTL 24, 1041 (2012)
III-V on SOI lasers

3- III-V nano/micro lasers evanescently coupled to SOI waveguides:

μcrodisks lasers

→ Whispering gallery modes for lasing
→ Coupled through evanescent wave
→ Footprint ~ 100μm²

III-V on SOI lasers

3- III-V nano/micro lasers evanescently coupled to SOI waveguides:

\[ \text{Photonic crystal lasers} \]

- Optically pumped
- Low threshold due to high Q/V
- Evanescent wave coupling measured >90%

**Convergence of μ-electronics & photonics**

Photonics can help to overcome the limits of electronics, in speed and power consumption, for intra or inter-chip communication


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**CHALLENGES**

- Deliver the necessary passive and active functionalities: low-loss waveguides, filters, sources, switches, detectors…
- Perform low power consumption and high speed: fJ activation energies, >10Gbits/s
- Small footprint for high density ($10^4$-$10^5$ of devices per mm$^2$): <100μm$^2$
- Integration with Si electronics and CMOS compatibility for cheap manufacturing

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*Are we there yet?*