Numerical Investigation of Power Tunability in Two-Section QD Superluminescent Diodes

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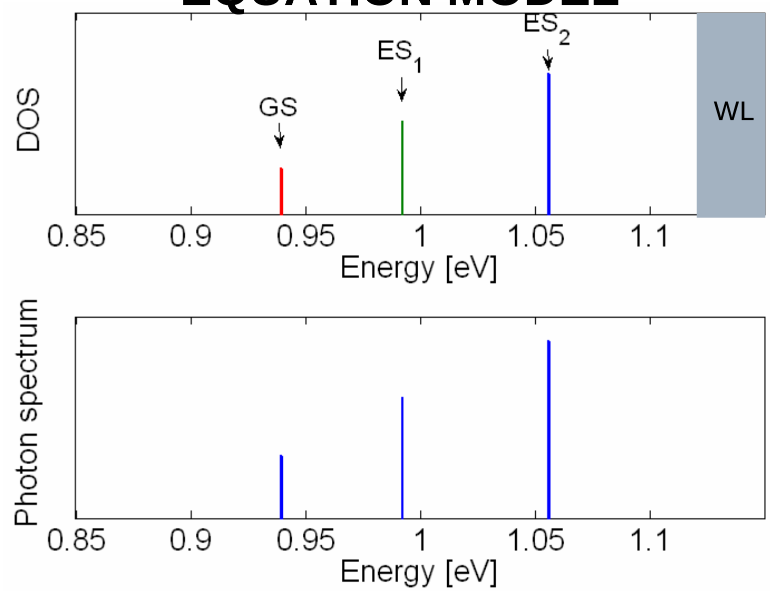
Summary

1. A simplified model for QD Super Luminescent Diodes (SLD)
2. Single section SLD: simulated and experimental results
3. How to increase the output power:
    - 2 sections SLD
    - tapered active region
    - saturable absorber
4. Conclusions

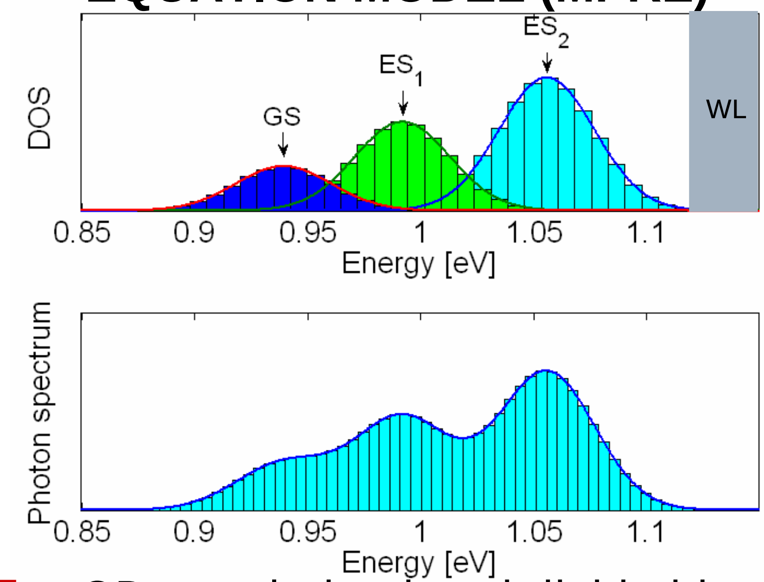
Existing Models

SIMPLE RATE EQUATION MODEL



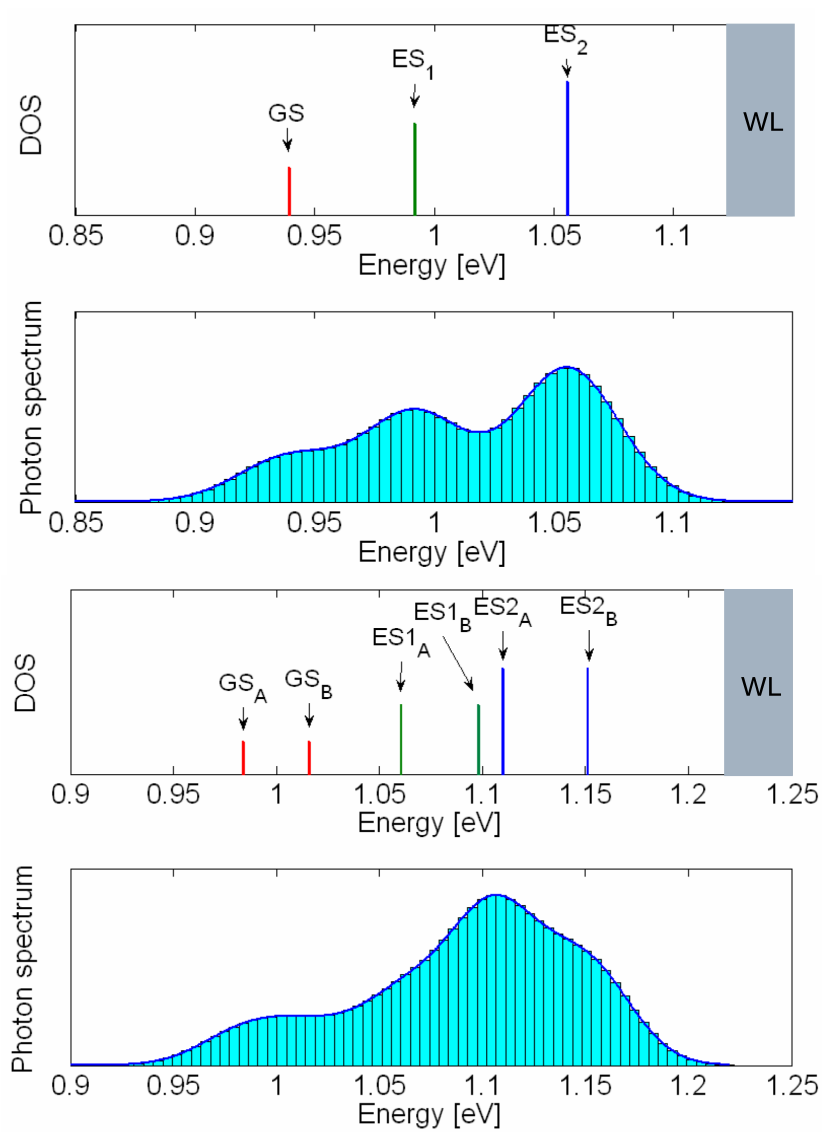
- A single rate equation for each confined QD state and for the corresponding emissions.
- **No information on the emission spectrum**, only on total optical power emitted from GS and ES
- **Very low computational cost**

MULTI POPULATION RATE EQUATION MODEL (MPRE)



- QD population is subdivided in many subpopulations to represent QD size dispersion
- The photon population is represented with a spectrally resolved model
- **High accuracy** in modeling of QD based devices
- **High computational cost**

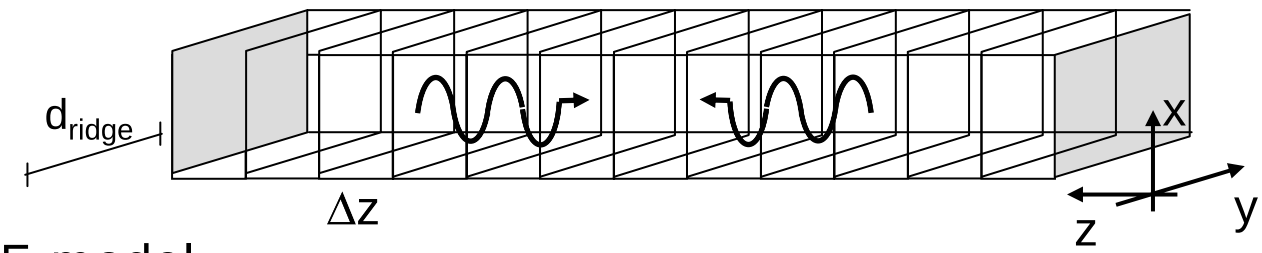
Our simplified model



- Carrier dynamics in QD states is modeled by a small set of rate equations, one for each continuous distribution of GS , ES1 and ES2 QD states and one for the carrier reservoir respectively.
- Inhomogeneous broadening of the QD energy levels is taken into account in the gain and spontaneous emission rate calculation
- Spectrally resolved model is used to represent ASE
- Reduced computational cost respect to MPRE

- Chirp is modeled considering a set of rate equations for each group of QD

Our simplified model: photons



TRAVELLING WAVE model

$$\pm v_g \frac{dS^{\pm}(z,\hbar\omega_i)}{dz} = \frac{1}{2} R_{sp}(z,\hbar\omega_i) + v_g\left[g(z,\hbar\omega_i) - \alpha_i - K_{pl}N_{wl}(z)\right]S^{\pm}(z,\hbar\omega_i)$$

$$g(z,\hbar\omega_i) = \sum_l \sum_m \xi \Gamma_l g_{0,l,k}(2\rho_{l,k} - 1) G(\hbar\omega_i - \hbar\omega_{l,k}) - \alpha_i - K_{pl}N_{wl}(z)$$

$$R_{sp}(z,\hbar\omega_i) = \sum_{l,k}\left(\frac{8\pi n^2}{h\lambda_{l.k}^2} g_{0,l,k}\right) G(\hbar\omega_i - \hbar\omega_{l,k}) N_k^l(z)\rho_k^l(z)$$

$G(\hbar\omega_i - \hbar\omega_{l,k})$ = Distribution function used to model the inhomogenous broadening of the QD energy spectrum due to dot-size dispersion

l = 1, 2, … number of QD layer groups

k = ES2, ES1, GS

Our simplified model: numerical solution

Initial conditions

$$\frac{d\underline{N}_0}{dt} = f\left(\underline{N}_0, \underline{S}(\underline{\lambda}) = 0\right) = 0$$

Stationary solution of the rate equations without photons

$\underline{N} = \underline{N}_0$

Photons propagation:

$$S^{\pm}(z \pm \Delta z, \lambda_i) = S^{\pm}(z, \lambda_i) e^{g(z, \underline{N}, \lambda_i)\Delta z} + \frac{1}{2}\beta_{sp} R_{sp}(z \pm \Delta z, \lambda_i)$$

$\underline{S}^{\pm}(\underline{z})$

Convergence

$$\left\| \underline{S}_{new} - \underline{S}_{old} \right\| < \varepsilon$$

Rate equations:

$$\frac{d\underline{N}(\underline{z})}{dt} = f\left(\underline{N}(\underline{z}), \underline{S}(\underline{\lambda})\right) = 0$$

Stationary solution with photons

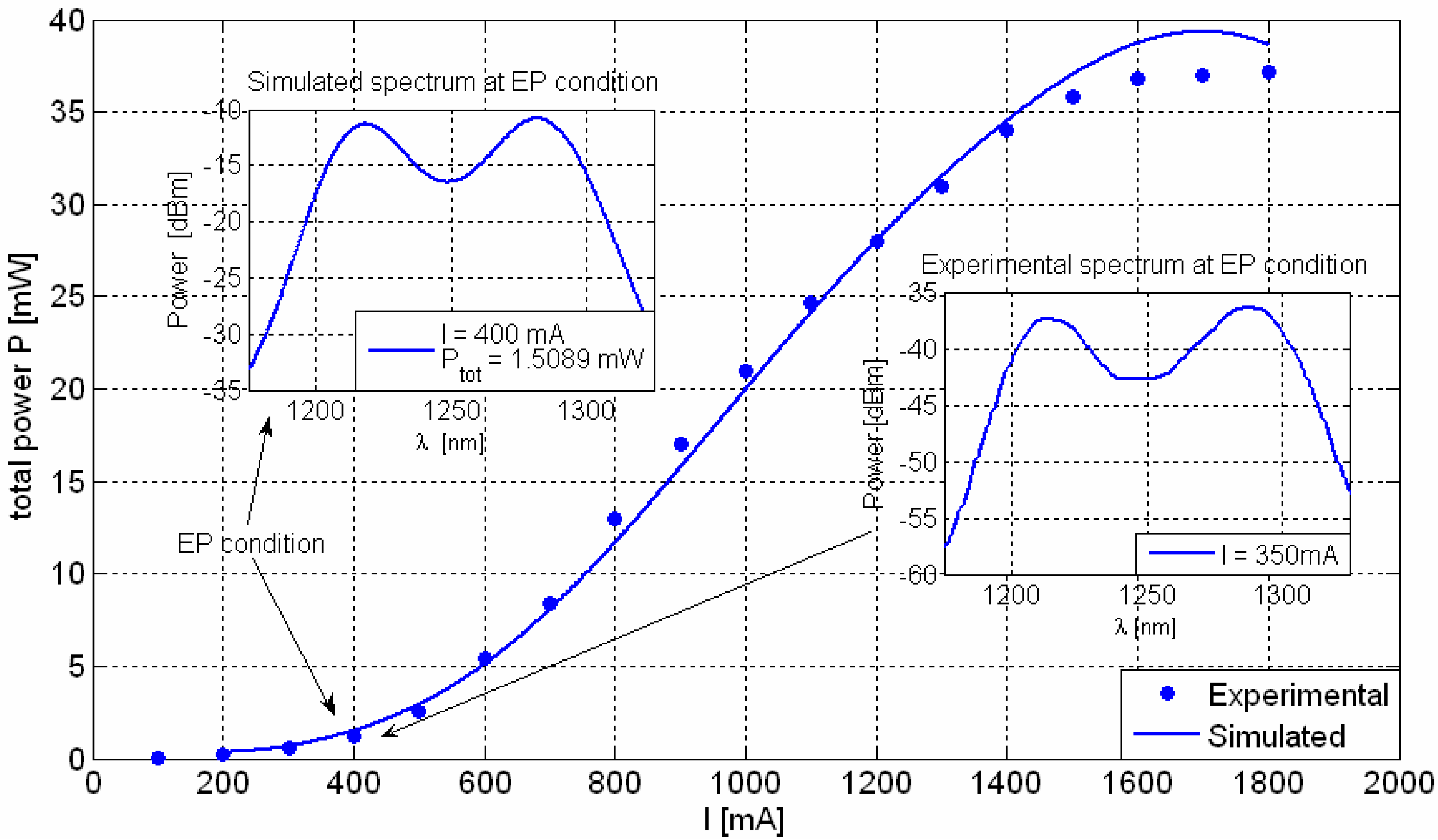
$\underline{N}$

Final Stationary Solution:

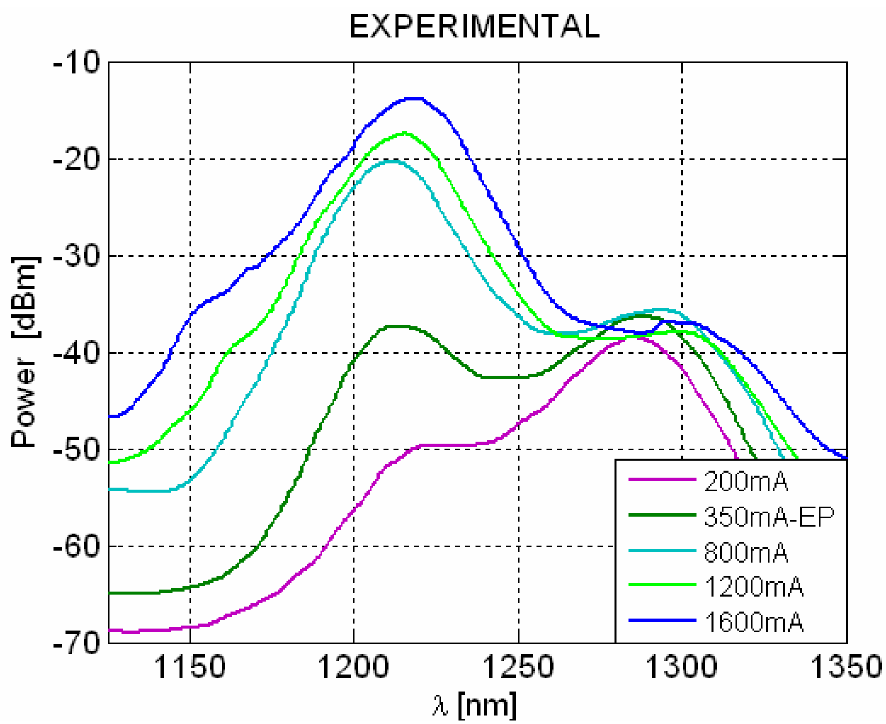
$$\begin{Bmatrix} \underline{N}(\underline{z}) \\ \underline{S}^{\pm}(\underline{z}, \underline{\lambda}) \end{Bmatrix}$$

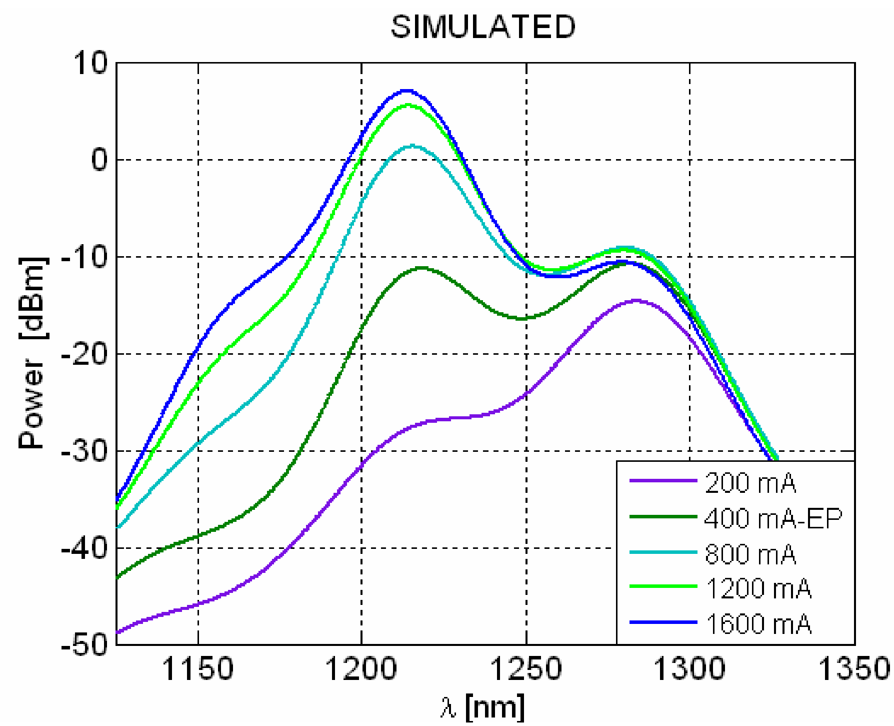
6-mm long and 4-μm wide single contact SLD with 6 QD layers

- 6QD layers of InAs/$In_{0.35}Ga_{0.65}$As Dwell (GS @1290nm)
- 7° tilted and anti-reflection coated facets



6-mm long and 4-μm wide single section SLD with 6 QD layers

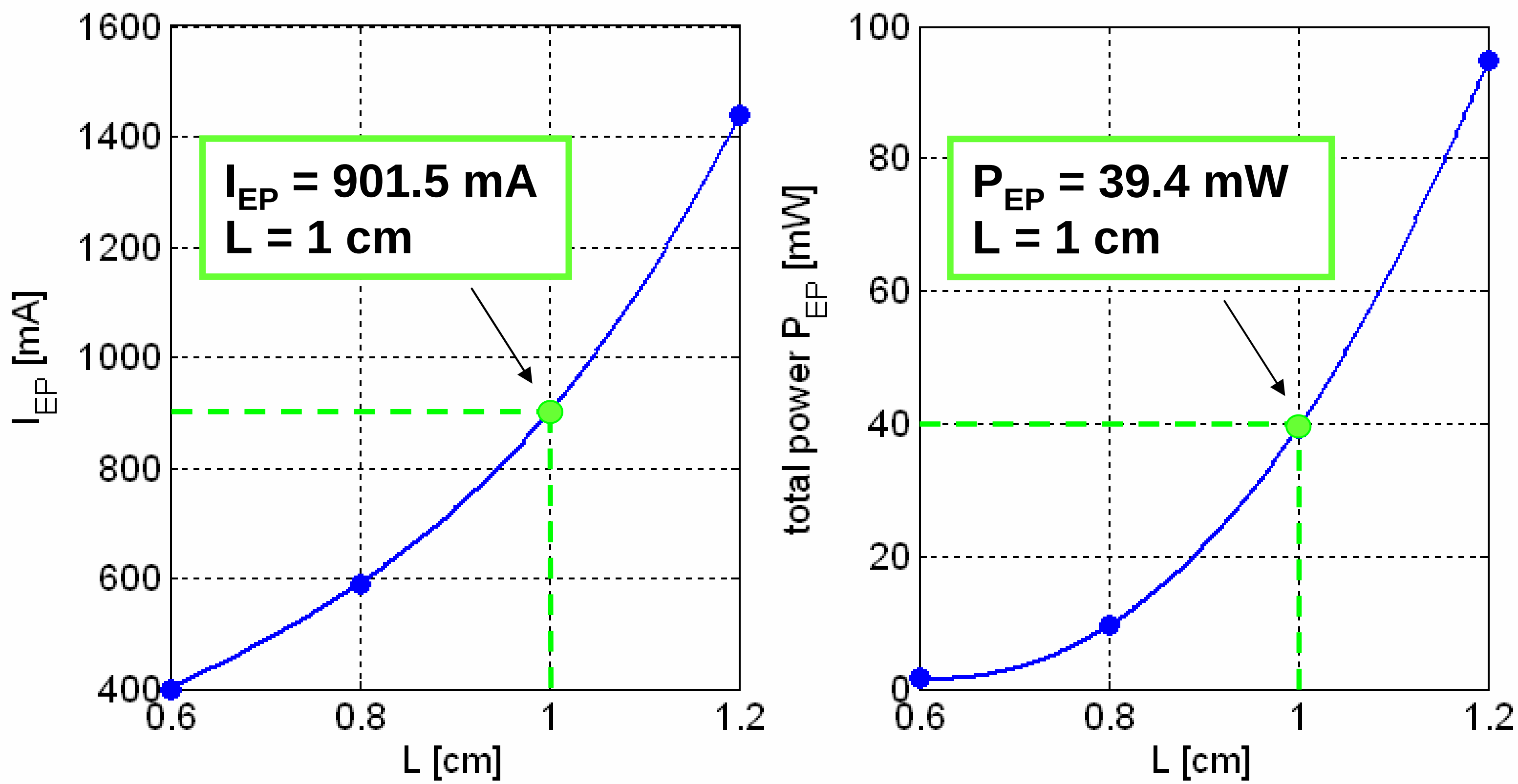




EP condition	Experimental	Simulated
Output power P_{EP}	1.1 mW	1.5 mW
Injected Current I_{EP}	350 mA	400 mA
-3 dB bandwidth	~100 nm	~95 nm
Central dip	~ 5.5 dB	~5.5 dB

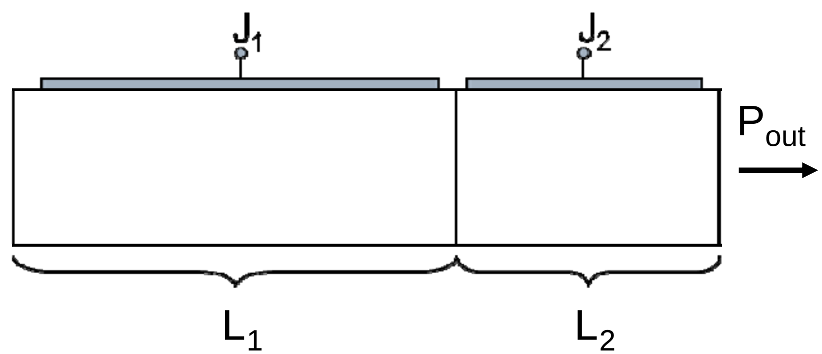
EP condition vs. device length

- Output power at EP condition increases exponentially with the device length, since GS saturates at low power

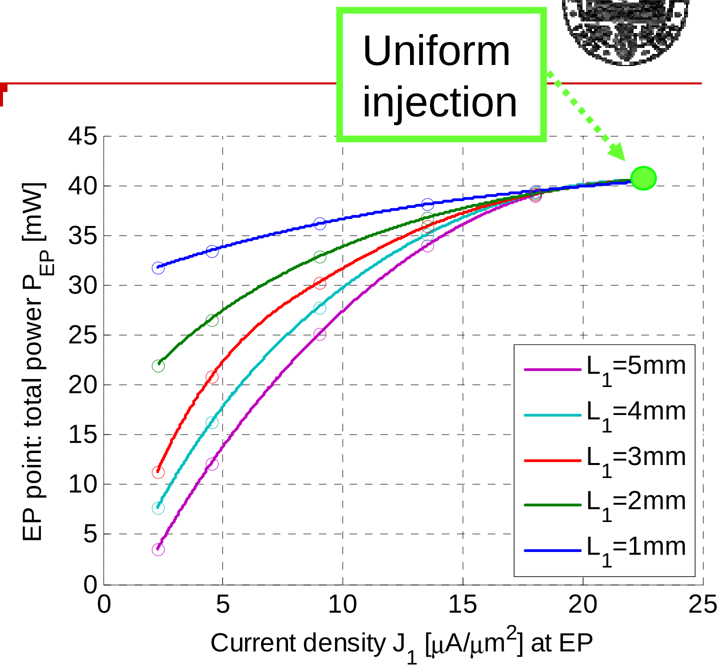


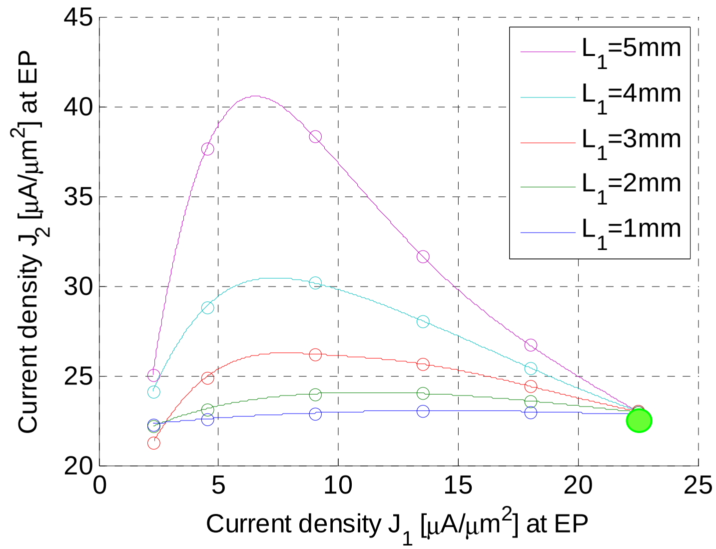
Power tunability in two-sections SLD

- We consider a 1cm long device and use two contacts with different lengths L_1 and L_2



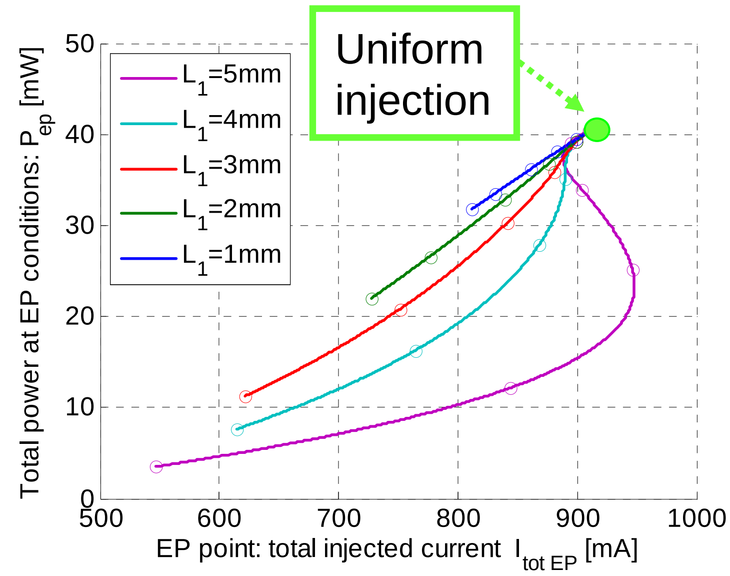
- We choose the values of J_1 and search for EP condition changing J_2
- The device exhibits a tunability of the EP point

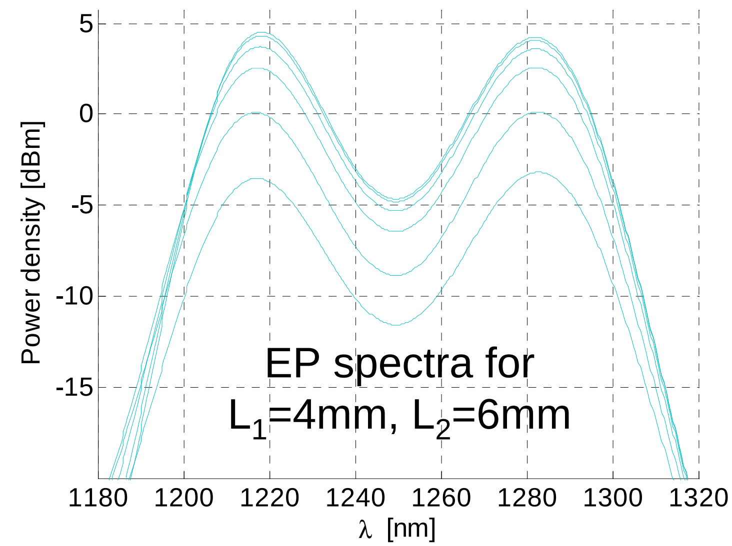




Power tunability in two-sections SLD

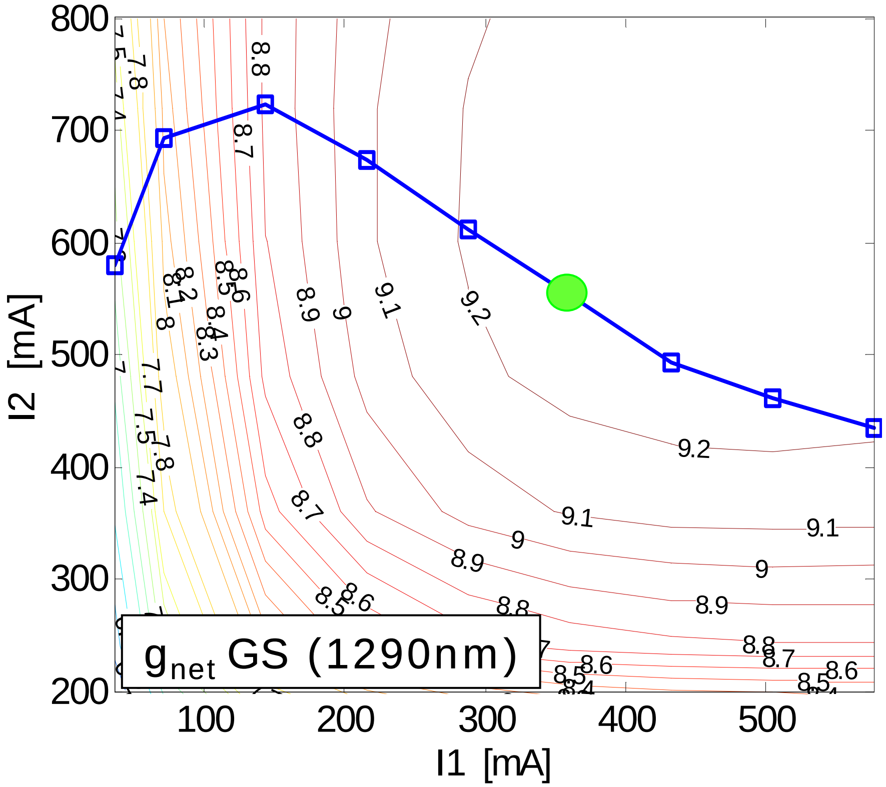
- Tunability range depends on the ratio L_1/L_2
  - it is maximum (5-40mW) when $L_1=L_2$
- Unfortunately this is the condition that requires the higher total current to obtain a certain EP power. Therefore:
  - high tunability-> high dissipation in the device
- A reasonable choice:
  - $L_1=4mm$, $L_2=6mm$
- The dip and bandwidth in the power spectrum are almost constant

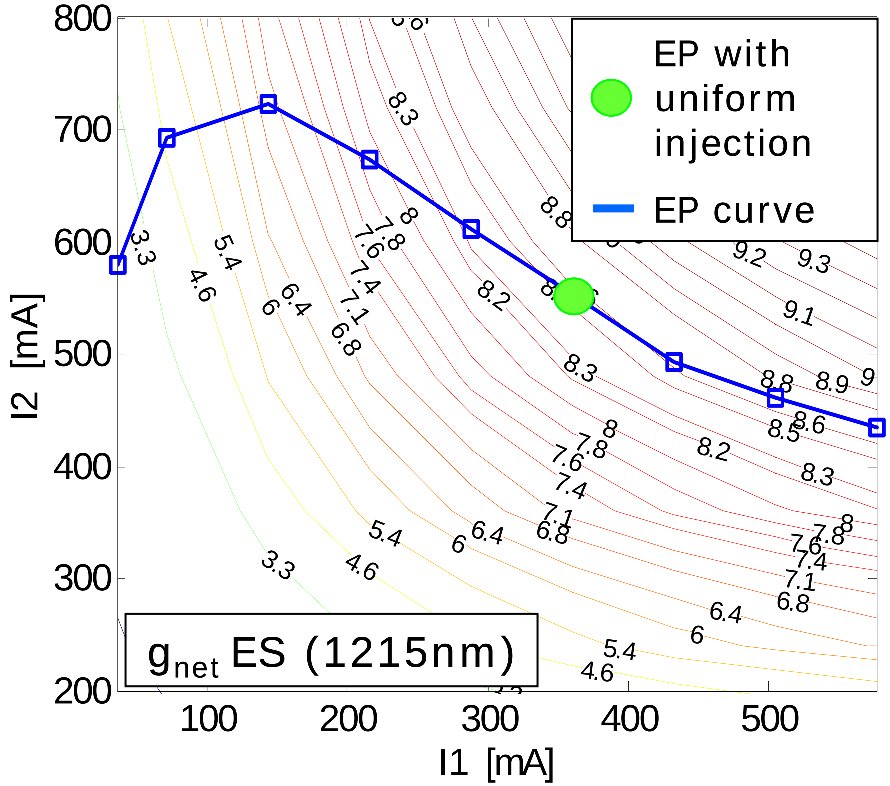




Power tunability in two-sections SLD: g_{net} maps

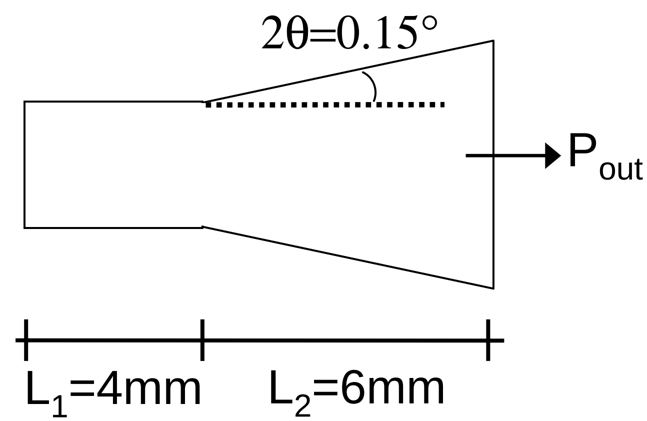
- The maximum EP power is always obtained at uniform injection
- We report the net modal gain averaged along the cavity at the GS and ES peak wavelengths as a function of control currents
- In this device GS gain at uniform injection is already saturated → no possible power improvement using two contacts

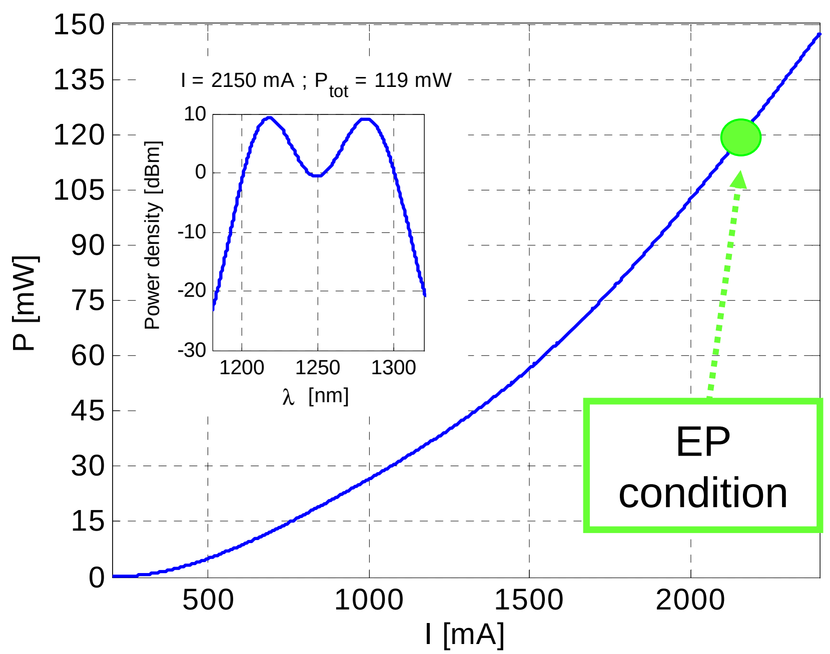


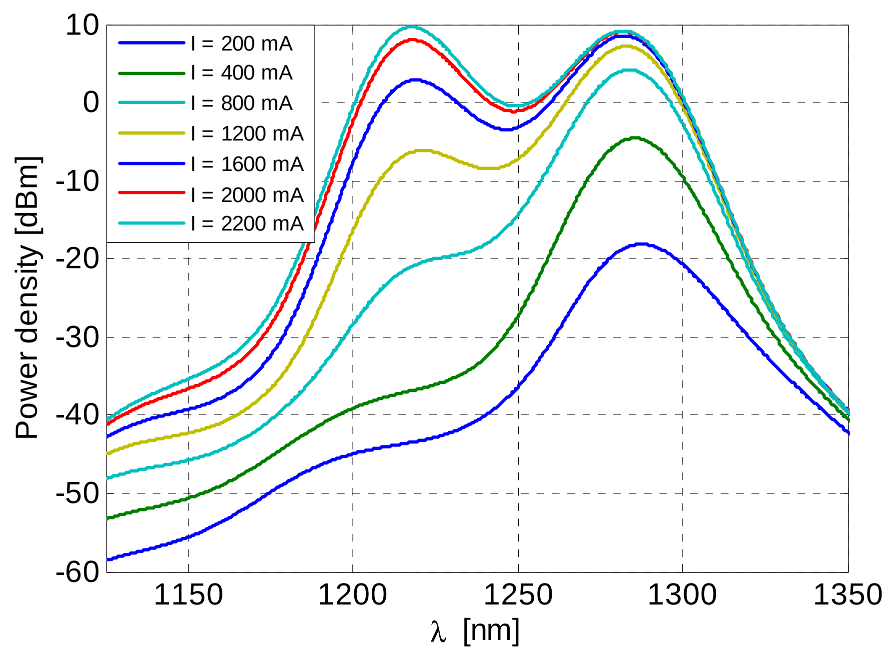


Simulations of tapered 6 QD layers SLDs

- In order to increase the power at EP condition we studied a flared structure with 4mm constant width waveguide and 6mm tapered region
- The output power is highly increased thanks to the higher optical confinement factor and to the larger active region area

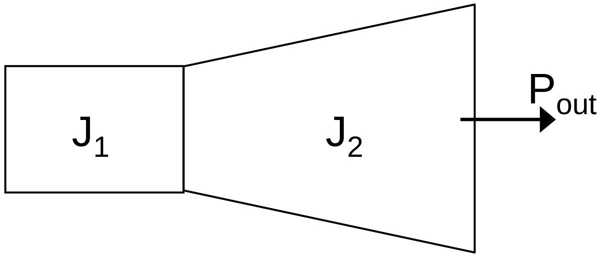


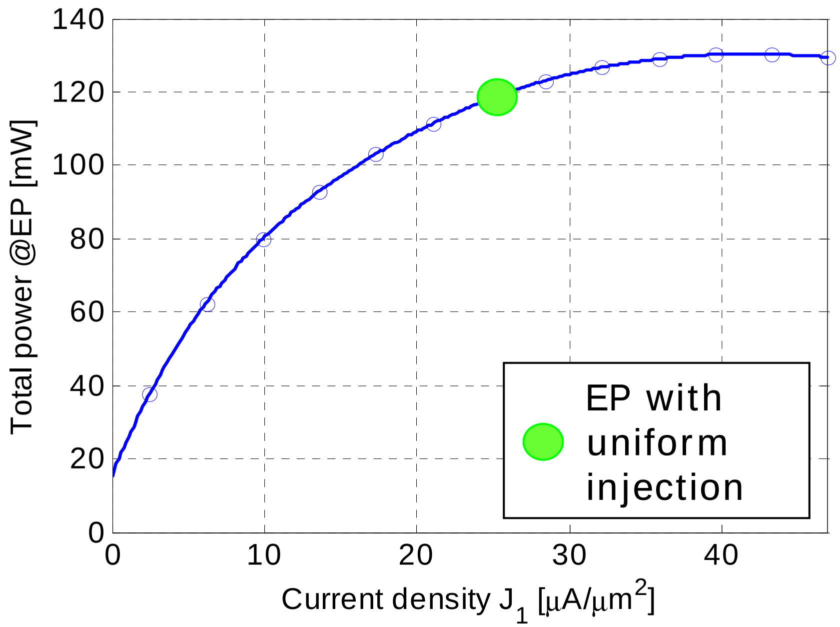


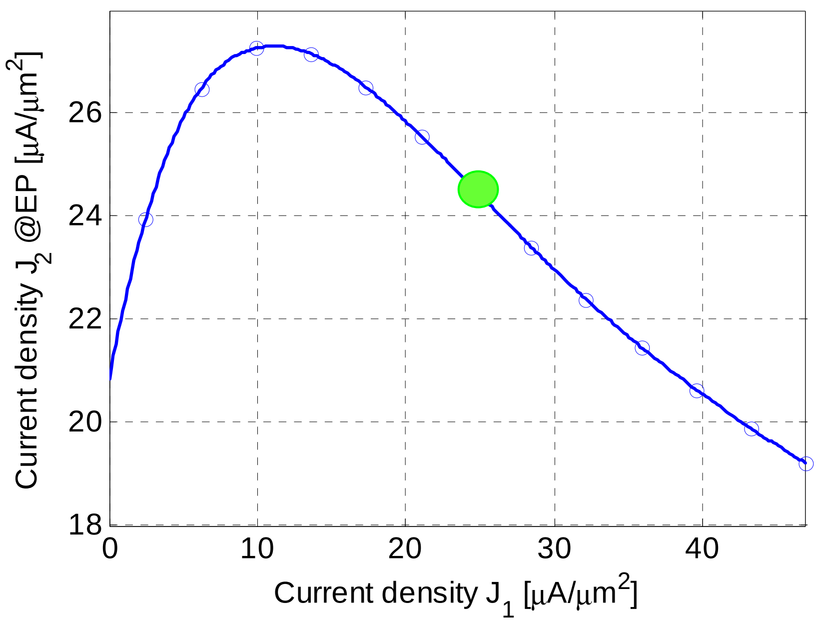


Power tunability in two section SLD with flared waveguide

- We investigate the power tunability of this layout using the same approach used for the uniform waveguide SLD
- Tunability is improved (20-130mW)
- The maximum reacheable power is also improved respect to the case with uniform injection

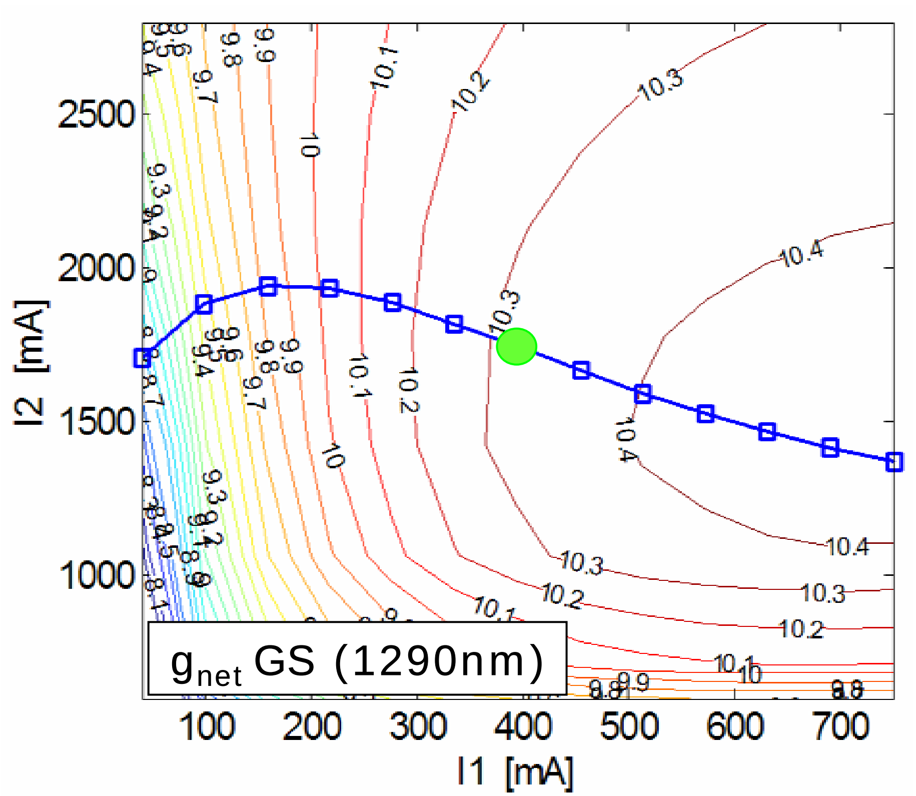


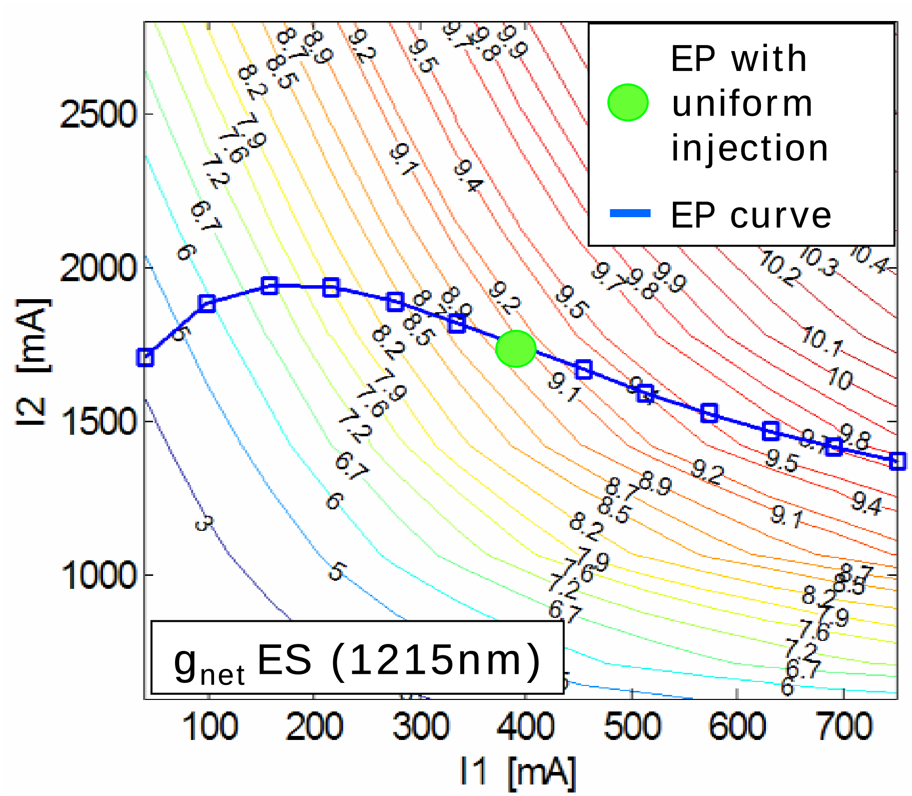




Power tunability in 2 section SLD with flared waveguide: g_{net} map

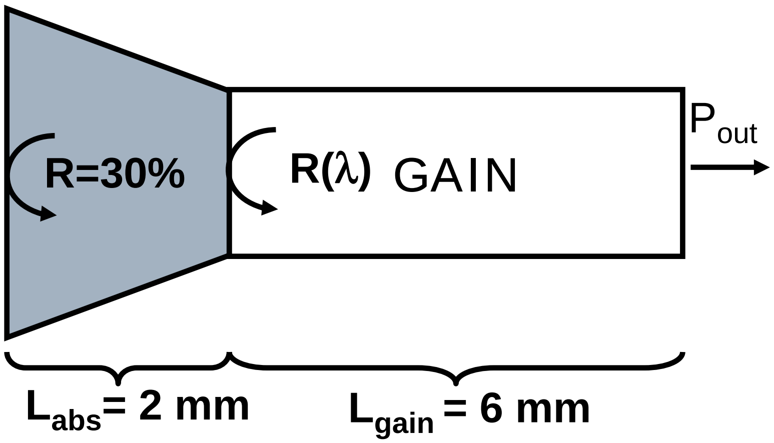
- The power increase is possible since the GS mean net modal gain in not saturated yet at uniform injection
- This is due to the higher saturated net modal gain in section 2 (flared) respect to the one in section 1 (uniform waveguide)

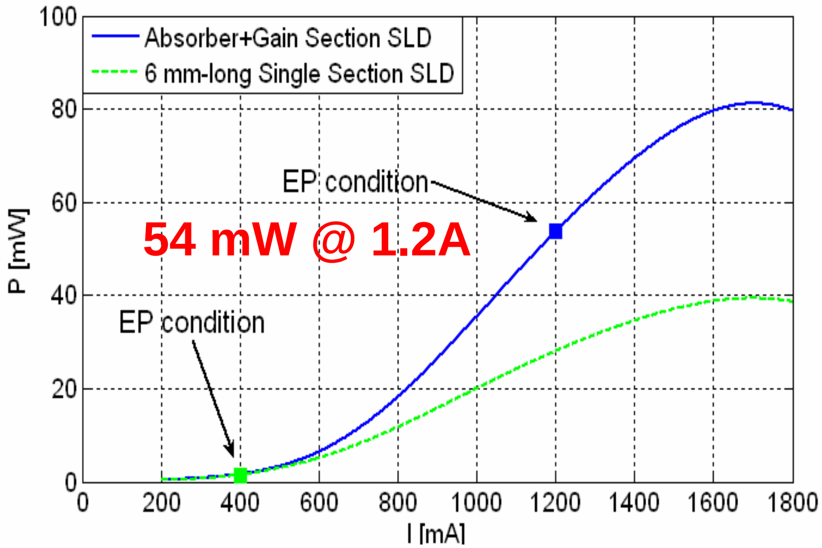




SLD with improved output power using a saturable absorber

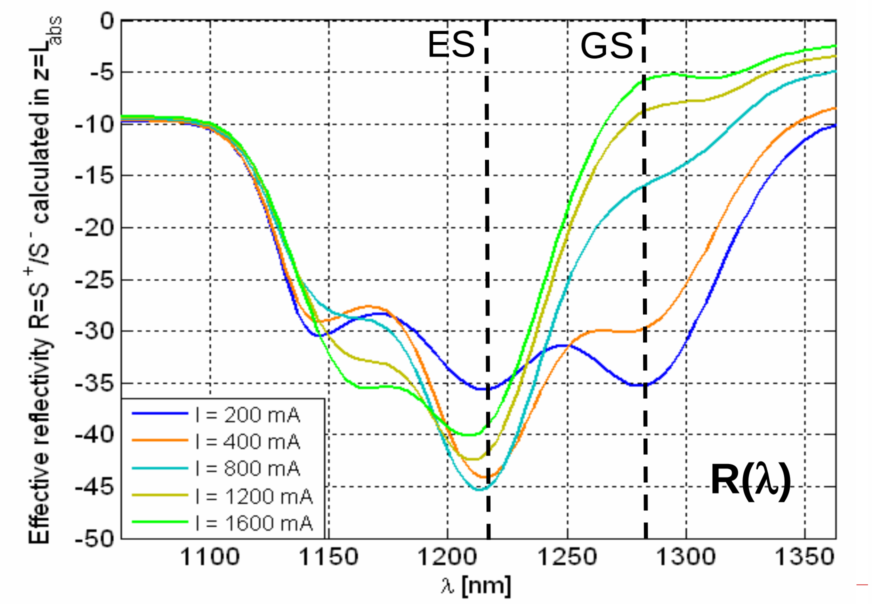
- We tried to equalize the emissions from GS and ES at higher output power
- We coupled the 6mm uniform waveguide gain region with a 2mm tapered absorbing section with a cleaved terminal facet
- EP is now obtained at 1.2A: output power is about 40 times higher than in the case without absorber!

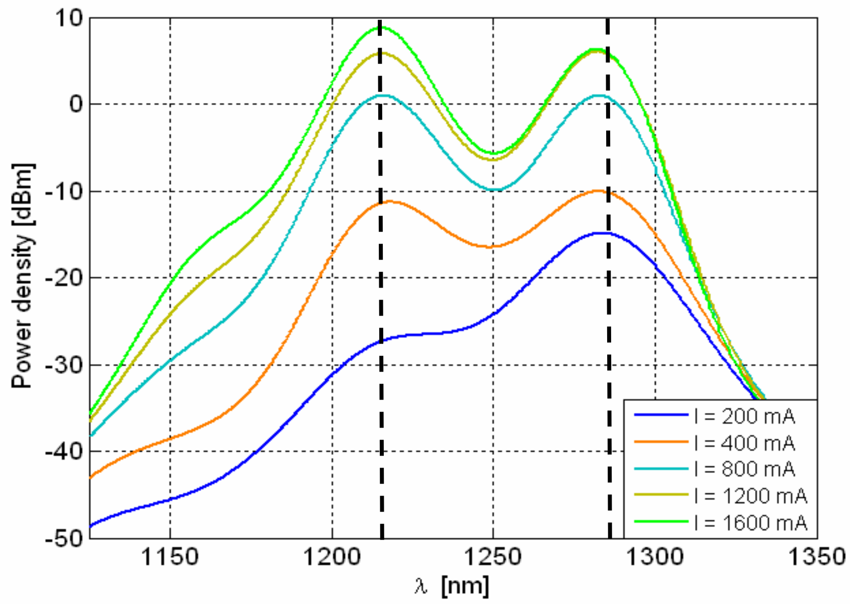




SLD with improved output power using a saturable absorber

- ES left propagating photons which reach the absorber section are strongly absorbed contributing therefore to the GS population inversion in the absorber (photon recycling)
- GS photons can therefore be further amplified also in the absorbing section
- We can thus obtain a strongly wavelength dependent equivalent reflectivity at the interface between gain and absorbing sections: as expected, reflectivity is much lower for ES than for GS
- EP condition is obtained for a wide range of current (800-1200mA)





Conclusions

- We proposed an alternative model to describe SLD power spectra in a computationally efficient way.
- We applied the model to the analysis of SLDs with 6 identical QD layers. Simulations show a good agreement with experimental results.
- We investigated the power tunability range of 2 sections devices with uniform and flared waveguides
- We showed that the use of a flared active section can increase the power tunability range and the maximum available power
- We analyzed the effects of a saturable absorber region coupled to the gain section: increased output power and EP tunability

Acknowledgments

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