# Tunable VCSELs

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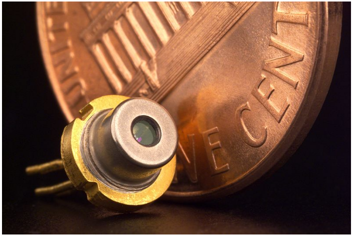
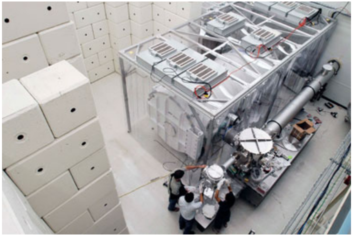
June 11, 2014

# What is a Laser ?

- A laser is a source of coherent light
- A laser may produce light with different colors
- There are very small and very huge lasers



Sub-diffraction nanolaser based on surface plasmon of amplification by stimulated emission for on-chip optical communications. The laser chip is as small that you can not see it with your eyes. [7]



Front end of a laser at the University of Texas with more than one quadrillion ($10^{15}$) watts (one petawatt) power [1].

LASER = Light Amplification by Stimulated Emission of Radiation

# Stimulated emission

- Not every device which uses stimulated emission is a laser
- A laser is a resonator
- Not every resonator is a laser
- A laser is a resonator where the gain due to stimulated emission cancels all losses

# Interaction between light and matter

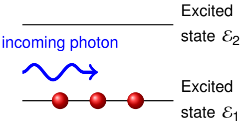
The most important interactions between light and matter are:

- (Stimulated) Absorption
- Stimulated Emission
- Spontaneous emission

# Simple explanation using a two level system (Absorption)

We assume that we have a material with two allowed energy levels $\mathcal{E}_1$ and $\mathcal{E}_2$. Electrons may sit on both levels.

Normally all the electrons will sit on the ground level. If a photon arrives an interaction between the electrons and the photon may happen.



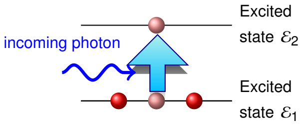
Excited state $\mathcal{E}_2$

incoming photon

Excited state $\mathcal{E}_1$

Before interaction

If the energy of the photon coincides with the energy difference $\mathcal{E}_{photon} = \mathcal{E}_2 - \mathcal{E}_1$ the photon may be absorbed by one electron and this electron will jump to the higher level.



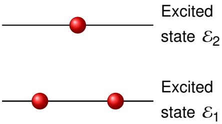
Excited state $\mathcal{E}_2$

incoming photon

Excited state $\mathcal{E}_1$

During interaction

After the interaction the photon disappears and its energy is taken by the electron. The electron stays in the mean on the higher level for some time (the electron lifetime) before falling down to the ground level.



Excited state $\mathcal{E}_2$

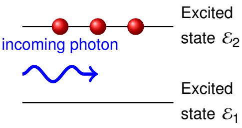
Excited state $\mathcal{E}_1$

After interaction

# Simple explanation using a two level system (Spontaneous Emission)

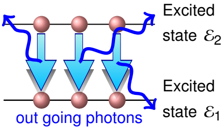
We assume that we have a material with two allowed energy levels $\mathcal{E}_1$ and $\mathcal{E}_2$
Electrons may sit on both levels. [1]

We assume now, that there are electrons on the higher level. This can be achieved e.g. by absorption or by electron means (semiconductor devices by filling up the conduction band).



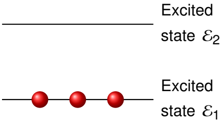
Before interaction

The electrons will not stay on the higher level, they will go to the stable ground state. This is done statistically where the mean life time on the upper level is called electron life time.



During interaction

The energy of the electrons is converted to photons which have the energy $\mathcal{E}_{photon} = h\nu = \mathcal{E}_2 - \mathcal{E}_1$.
All the photons may have an arbitrary direction and state of polarization. The outgoing light is called spontaneous emission.



After interaction

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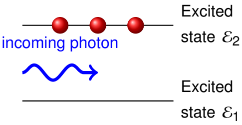
[1] h is the Planck constant $h = 1.05459\ 10^{-34}\ Ws^2$

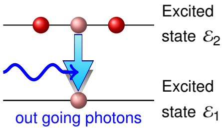
# Simple explanation using a two level system (Stimulated Emission)

We assume now again, that there are electrons on the higher level. If a photo arrives there may be again an interaction.



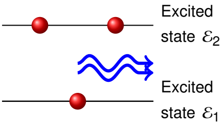
Before interaction

If the Energy of the photon coincides with the energy difference $\mathcal{E}_{photon} = \mathcal{E}_2 - \mathcal{E}_1$ the photon may stimulate an electron to jump doen to the lower level. The energy of this electron is converted into a photon.



During interaction

The result is that the electron will reside on the ground state and that we will have two outgoing photons with exact the same properties of the incoming photon such as frequency, polarization and direction. This is real amplification.



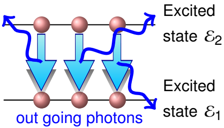
After interaction

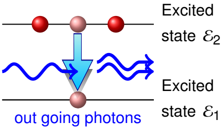
# Transition rates I

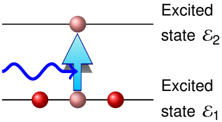
We assume that there is a system with two levels (ground and exited state), that there are electrons in both states and the system is in thermal equilibrium with the temperature $T$ and the electromagnetic energy density $u(\lambda)$.

All three interaction processes may happen at the same time

$N_{1,2}$ : Number of electrons per volume on level 1,2


Spontaneous emission

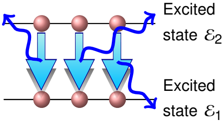

Stimulated emission


Absorption

# Transition rates II

$N_{1,2}$ : Number of electrons per volume on level 1,2

**Spontaneous emission**

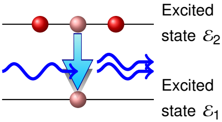


The mean number of transitions per volume for the spontaneous emission is given by the term

$$\frac{\partial}{\partial t}N_2 = -A_{21}N_2$$

It is proportional to the number of electrons on level 2.

**Stimulated emission**

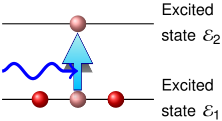


The mean number of photons per volume being emitted by stimulated emission is

$$\frac{\partial}{\partial t}S = B_{21}N_2S$$

It is proportional to the number of electrons on level 2 times the number of incoming photons S.

**Absorption**



The mean number of photons per volume being absorbed is given by

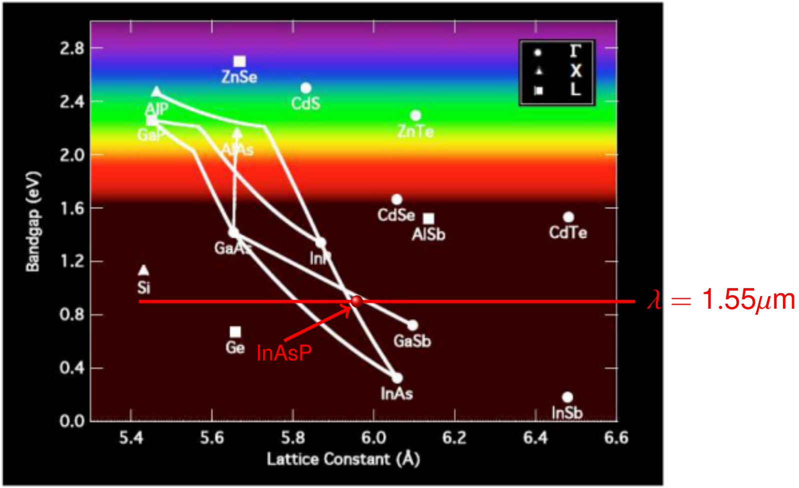
$$\frac{\partial}{\partial t}S = -B_{12}N_1S$$

It is proportional to the number of electrons on level 1 times the number of incoming photons S.

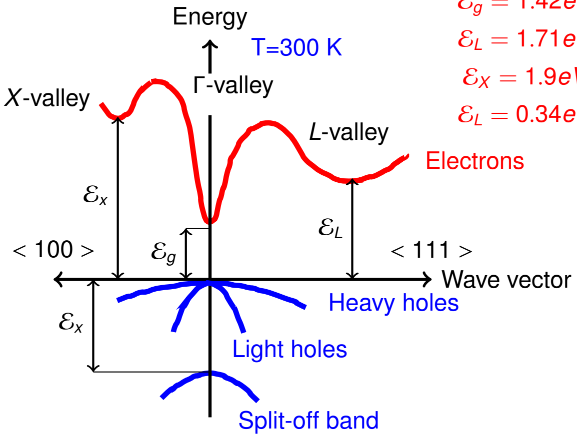
Therefore we have besides spontaneous emission as well absorption as stimulated emission.

Which process is larger , stimulated emission or absorption?

# Bandgap versus lattice constant



# Band diagram of semiconductors



$\mathcal{E}_g = 1.42eV$

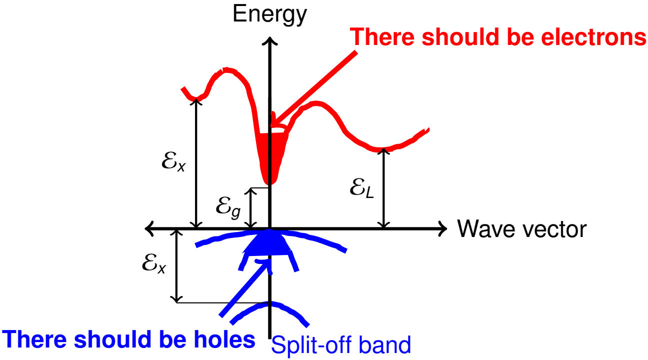
$\mathcal{E}_L = 1.71eV$

$\mathcal{E}_X = 1.9eV$

$\mathcal{E}_L = 0.34eV$

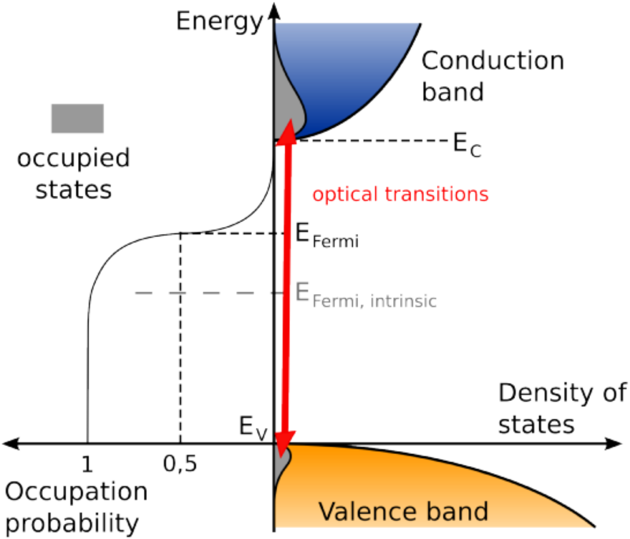
**Typical band-diagram of GaAs**

# Condition for gain



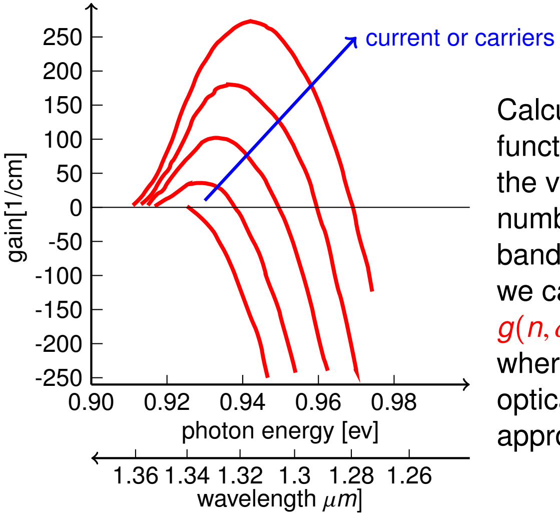
We assume that we have a material with two allowed energy levels $\mathcal{E}_1$ and $\mathcal{E}_2$ . Electrons may sit on both levels. But to get gain (larger stimulated emission than absorption) the number of carriers in the conduction band should be larger that that in the valence band.

# Carrier reservoir in semiconductors



Transitions are possible between arbitrary electrons in the conduction band and electrons in the valence band. The energy of emitted or absorbed photons equals to the energy difference of those bands. Since there are as well many energy states available in the conduction as in the valence band we have a broader spectrum of possible energies or optical frequencies.

# Gain coefficient



Calculated GaInAs gain as a function of energy and carriers in the valence band [8]. Since the number of carriers in the valence band is proportional to the current we can model the gain as follows:

$g(n, \omega) = g_0(\omega)(n - n_0)$

where the dependency of the optical frequency can be approximated by a parabola.

# Laser condition

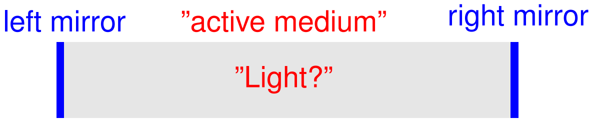
- The name Light Amplification by Stimulated Emission of Radiation is somehow misleading.
  (Also an optical amplifier uses stimulated emission.)
- A laser is additionally a resonator with an active material included
- Additionally a special condition has to hold:

**Laser Condition:**

**The amplification inside the resonator has to cancel all losses**

# What is a laser

- A laser is a (three dimensional) optical resonator



left mirror ”active medium” right mirror

”Light?”

What kind of picture should we use for representing light?

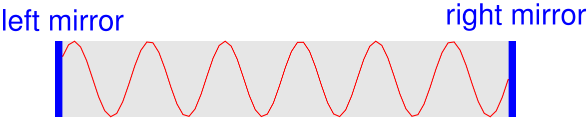
1. Light is a electromagnetic wave with very small wavelengths or very high frequencies, respectively ?
2. Light can be represented by small particles (photons) ?

The model to be used depends on the kind of experiment performed. For example if we do experiments where phenomena such as interference are essential we should use the wave picture. For experiments where absorption and amplification by stimulated emission are under investigation we have to use the quantum-mechanical particle picture.

# Evaluation of the field inside the resonator I

Since we have interference of the waves bouncing back and forth between both mirrors interference effects result. Therefore we have to use the wave picture.

Simple assumption: The mirrors are infinite large, that means we can assume plane waves propagating inside the cavity.



If we do not have any amplification or loss we have a standing wave with constant amplitude inside the cavity as shown above.

The only difference between well known electromagnetic waves and light is the wavelength. Therefore we can model the propagation of light using the Maxwell equations.

# Evaluation of the field inside the resonator II

Assumption for the properties of the material

- Stationary propagation : The propagation properties do not depend on time $\varepsilon_r \neq funktion(time)$.
- There are no free carriers or currents $\rho = 0, J = 0$.
- The material is isotropic
- The material has no magnetic properties $\mu_r = 1$
- We have a linear material $\underline{\vec{D}}(\omega) = \varepsilon_0 n^2(\omega)\underline{\vec{E}}(\omega)$

Using these assumption we have to solve the

**wave equation**

$$\Delta\underline{\vec{E}} + \omega^2\mu_0\varepsilon_0\underline{n}^2\underline{\vec{E}} = 0$$

For our simple geometry the solutions are plane waves.

# Evaluation of the field inside the resonator III

The solution of the equation gives the propagation of a dielectric plane wave in a homogeneous medium.
Ansatz: Plane wave travelling in k direction:

$$\underline{\vec{E}} = \underline{\vec{E}}_0 e^{-j\underline{\vec{k}}\cdot\underline{r}} = \underline{\vec{E}}_0 e^{-j(\underline{k}_x x + \underline{k}_y y + \underline{k}_z z)}$$

Inserting the ansatz in the wave equation:

$$|\underline{\vec{k}}|^2 = \underline{k}_x^2 + \underline{k}_y^2 + \underline{k}_z^2 = \omega^2 \mu_0 \varepsilon = \left(\frac{2\pi c}{\lambda}\right)^2 \mu_0 \varepsilon_0 \varepsilon_r = \left(\frac{2\pi}{\lambda}\right) \underline{n}^2$$

## wave equation

Planes of equal phase $\varphi = \mathcal{R}e\{\underline{\vec{k}} \cdot \underline{r}\}$ are perpendicular to the direction of propagation.

# Evaluation of the field inside the resonator IV

In our simple resonator model we have a plane wave.

## Plane wave propagating in z-direction

$$\underline{\vec{E}} = \underline{\vec{E}}_0 e^{-j\underline{k}z} = \underline{\vec{E}}_0 e^{-j\frac{2\pi}{\lambda}\underline{n}z} = \underline{\vec{E}}_0 e^{-j\frac{2\pi}{\lambda}(n'-jn'')z} = \underline{\vec{E}}_0 e^{-j\frac{2\pi}{\lambda}n'z-\frac{2\pi}{\lambda}n''z}$$
$$= \underline{\vec{E}}_0 e^{-j\beta z-\alpha z}$$

## Definition of propagation constant, attenuation and gain

propagation constant : $\beta(\omega) = \frac{2\pi}{\lambda} n'(\omega)$

attenuation : $\alpha(\omega) = \frac{2\pi}{\lambda} n''(\omega)$

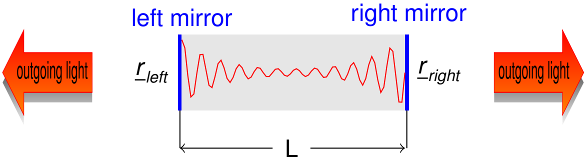
gain : $g(\omega) = -\frac{2\pi}{\lambda} n''(\omega)$

Gain and absorption can be modelled using the imaginary part of the refractive index.

# Laser condition II

A plane wave is propagating back and forth in a medium with gain $g$

$$(g = -k_0 n'' = \frac{2\pi}{\lambda_0} n'' \text{ and } n'' < 0).$$



**Laser condition**

A self reproducing field after one round trip :

$$\underline{r}_{left}(\omega)\underline{r}_{right}(\omega)e^{-j2\frac{2\pi}{\lambda}\underline{n}L} = 1$$

The gain has to exactly cancel all the losses.

# Discussion of the laser condition I

This equation gives us a good insight of the spectral behaviour of the lasers.

We separate the equation in absolute value and phase:

$$\underline{r}_{left}\underline{r}_{right}e^{-j22\pi f_{opt}\underline{n}L} = 1$$

$$\text{(Using } \underline{n} = n' - jn''\text{)} \quad \underline{r}_{left}\underline{r}_{right}e^{-j2\frac{2\pi}{\lambda}n'L}e^{-2\frac{2\pi}{\lambda_M}n''L} = 1$$

With the gain for the field $g_M = -\frac{2\pi}{\lambda_M}n''$ or the gain for the power $G_M = -\frac{4\pi}{\lambda_M}n''$ we get:

$$\angle\underline{r}_{left} + \angle\underline{r}_{right} - \frac{4\pi}{\lambda_M}n'L = -2\pi M \quad \text{condition for phase}$$

$$|\underline{r}_{left}||\underline{r}_{right}|e^{G_M L} = 1 \quad \text{condition for absolute value}$$

- The first equation gives us the optical frequencies (index M) of the lasing modes.
- The second equation gives us the value for the necessary gain to achieve lasing.

# Discussion of the laser condition II

Phase condition:

$$\angle \underline{r}_{left} + \angle \underline{r}_{right} - \frac{4\pi}{\lambda_M} n' L = -2\pi M$$

$$\angle \underline{r}_{left} + \angle \underline{r}_{right} - 2\pi f_{opt} \underbrace{\frac{2n' L}{c_0}}_{\tau} = -2\pi M$$

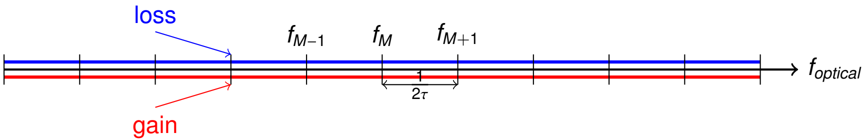
$\tau$ round trip time

$$f_M = \frac{1}{2\tau}\left(M - \frac{\angle r_{left}}{2\pi} - \frac{\angle r_{right}}{2\pi}\right)$$

- The lasing frequencies are equally spaced
- The lasing wavelengths are not equally spaced

$$\lambda_M = \lambda_{M+1} + \frac{\lambda_M^2}{\lambda_M + 2L}$$

# Discussion of laser condition III



$\tau$ round trip time

$$f_M = \frac{1}{2\tau}\left(M - \frac{\angle r_{left}}{2\pi} - \frac{\angle r_{right}}{2\pi}\right)$$
$$G_M = \frac{1}{L}\ln\left(\frac{1}{|r_{left}||r_{right}|}\right)$$

- The first equation defines the optical frequencies of the lasing modes
- The frequency spacing is constant and inversely proportional to the optical length $n'L$
- The second equation states that the effective gain has to cancel the losses due to the finite reflectivity of the mirrors
- The gain $G_M$ is the gain due to stimulated emission minus all additional losses inside the cavity for the mode with the index M

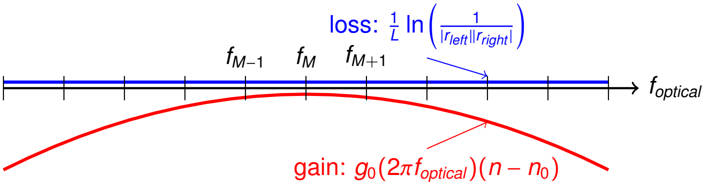
# Additional losses in a semiconductor laser

- scattering
- photons leaving the cavity passing both mirrors
- ...

**Up to now we made the following assumptions:**

- The additional losses of a Fabry Perot laser can be assumed to be frequency independent
- The gain is frequency independent

# Frequency dependent gain

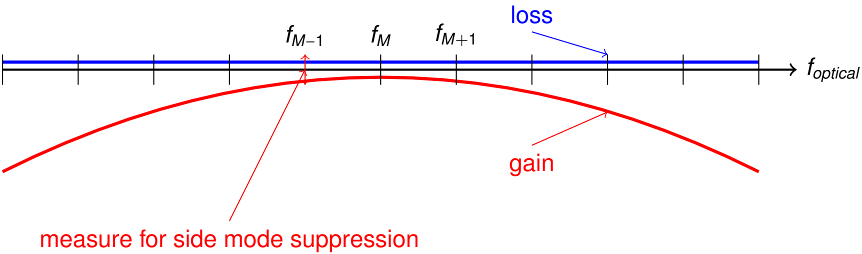


- The loss is still assumed to be constant. The reflection at an air semiconductor interface does not depend on frequency.
- The gain is frequency dependent.
- The frequencies $f_M$ are solutions of the laser condition (phase)
- The mode M where the difference between the losses and the gain is minimal will start to lase
- The difference between the gain and the loss at the other frequencies is a measure for the side mode suppression of the modes.

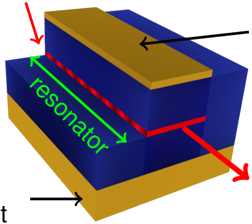
# Short summary

What did we learn?

- The frequency of the lasing mode is determined by the time $\tau$ of circulation of a photon (wave) in the resonator
- This time is proportional to the length times the refractive index divided by the speed of light in vacuum.
- We need sufficient gain to suppress the losses at the lasing frequencies
- For the other longitudinal modes the gain should be smaller (or the losses higher) to suppress the sidemodes



# Edge Emitter and VCSEL



active region with standing wave and waveguiding

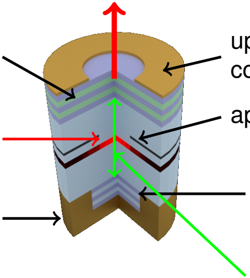
upper contact

resonator

outgoing light

lower contact

**Edge emitter**



outgoing light

upper Bragg mirror

upper contact

aperture

active region

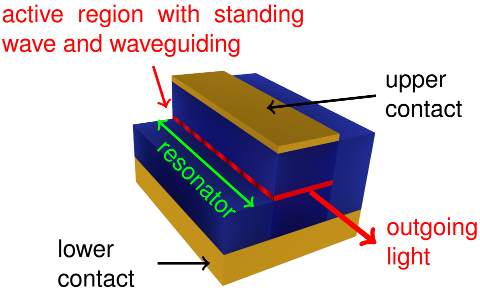
lower Bragg mirror

lower contact

resonator with standing wave

**Vertical Cavity Surface Emitting Laser**

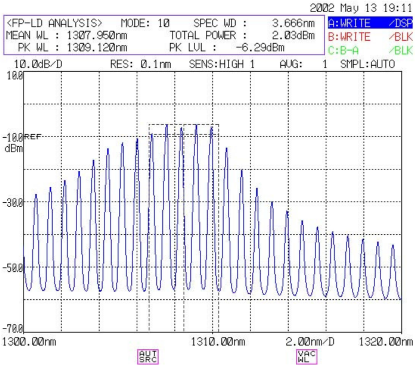
# Properties of edge emitter compared to VCSELs



**Edge emitter (Fabry Perot laser)**

- Long cavity with single mode dielectric waveguide (100$\mu m$ to 1$mm$);
- Several longitudinal modes
- Gain all along the resonator (high gain)
- Relative low reflection at semiconductor air interface (0.32%)

# Spectrum of Fabry Perot Laser



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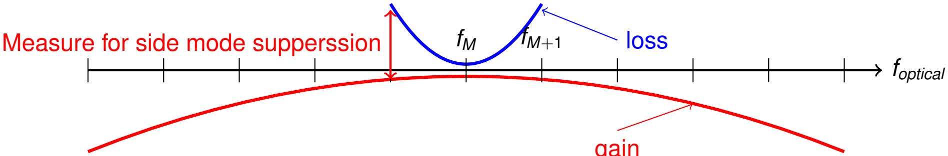
                                                 2002 May 13 19:11
<FP-LD ANALYSIS>  MODE: 10    SPEC WD :    3.666nm   A:WRITE   /DSP
MEAN WL : 1307.950nm      TOTAL POWER :    2.03dBm   B:WRITE   /BLK
  PK WL : 1309.120nm      PK LVL :   -6.29dBm        C:B-A     /BLK
  10.0dB/D       RES: 0.1nm   SENS:HIGH 1   AVG:   1  SMPL:AUTO
```

[2]

- The Fabry Perot laser has many longitudinal modes
- A longer Fabry Perot laser has more modes
- The number of modes is reduced due to mode competition
- some more effects !!!!

# Edge emitter (DBR Laser)

- For the higher longitudinal modes the gain should be smaller (or the losses higher) to suppress the sidemodes



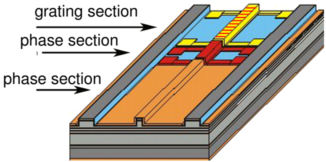
Measure for side mode supperssion

$f_M$ $f_{M+1}$

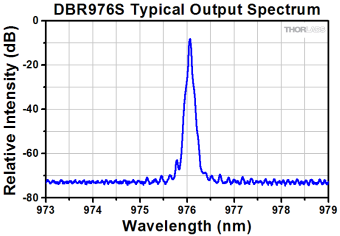
loss

$f_{optical}$

gain



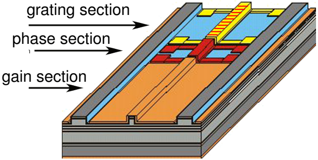
Typical **D**istributed **B**ragg **R**eflection laser



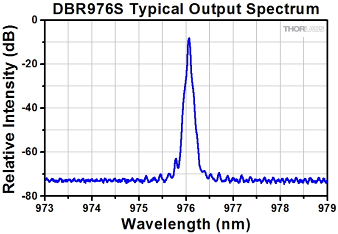
- If we have a mirror with a frequency dependent reflection we can enhance the sidemode suppression

# Edge emitter (DBR Laser)

Example for frequency dependent reflection



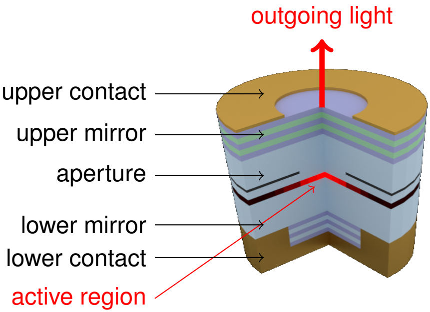
Typical



Distributed Bragg Reflection laser

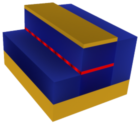
- The grating has a maximum reflection at the designed wavelength
- The phase section has to be adjusted that the round trip phase is a multiple of $2\pi$ at this wavelength

# Veritcal Cavity Surface Emitting Laser

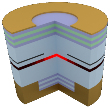


- Longitudinal single mode
- Circular beam with small divergence
- On wafer testing possible
- low fabrication and testing costs
- integrability into 1D and 2D arrays
- Low threshold and small power consumption
- High slope efficiency

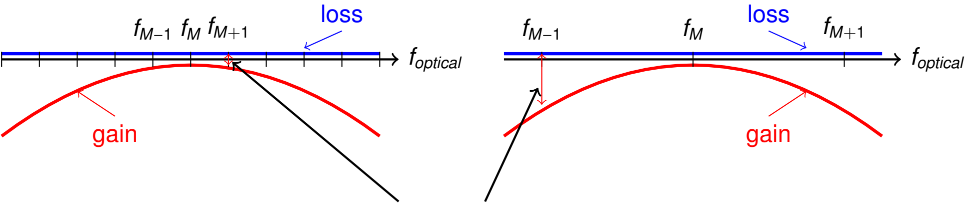
# Longitudinal modes of Edge Emitter and VCSEL



**Edge emitter**



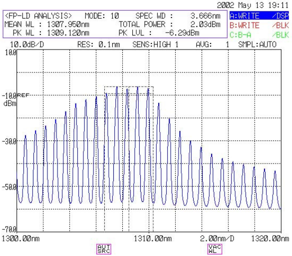
**VCSEL**



measure for side mode suppression

# Spectra of edge emitter and VCSEL (FP -laser)

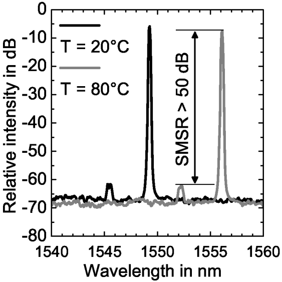
Spectrum of edge emitter
Fabry Perot laser



```
                                                      2002 May 13 19:11
<FP-LD ANALYSIS>   MODE: 10    SPEC WD :     3.666nm   A:WRITE   /DSP
MEAN WL : 1307.950nm      TOTAL POWER :     2.03dBm    B:WRITE   /BLK
  PK WL : 1309.120nm      PK LVL :   -6.29dBm          C:B-A     /BLK
 10.0dB/D        RES: 0.1nm   SENS:HIGH 1    AVG:    1  SMPL:AUTO
```

The edge emitter has many lateral modes [2]

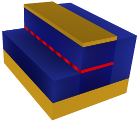
Spectrum of VCSEL



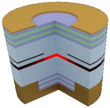
The VCSEL is longitudinally single mode [10]

# Lateral modes

- The laser is a three dimensional resonator
- Modes in all three directions may exist
- For many applications we want single mode behaviour

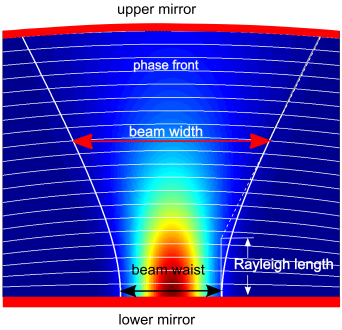


- The edge emitter has a waveguide
- Therefore the edge emitter is in lateral and transversal direction single mode



- The VCSEL has no wave guide
- The propagation of the light inside the cavity is as in free space
- An aperture enforces transversal single mode behaviour
- Gaussian beam propagation is a very good model for this situation

# Gaussian beam



- Higher lateral modes can be suppressed by an aperture
- The field inside the cavity can be approximated by a Gaussian beam
- The Gaussian beam id defined by its beam waist and Rayleigh length
- Close to the aperture the phase front is nearly plane
- Far away from the aperture we have a curved phase front

The cavity has to be carefully designed.

# Gaussian beam in a plane-plane resonator (large aperture)

- Nearly plane phase front
- Very pronounced standing wave

# Gaussian beam in a plane-pane resonator (small aperture)

- Plane phase front only at aperture
- Standing wave is somehow washed out

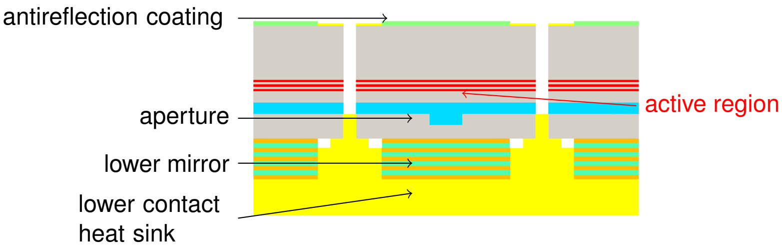
# Gaussian beam in a plane concave resonator (small aperture)

- Phase front has to fit the curvature of the mirror
- Standing wave with high intensity at its maxima
- The active region should be positioned at a maximum of the field
- The aperture should be positioned at a minimum of the field

# Tuning mechanism

- The frequency of the lasing modes is determine by the optical length $L_{opt} = n * L$
- The tuning is achieved by changing the physical length
- The maximum tuning range is limited
  - by the free spectral range (frequency spacing of the longitudinal modes)
  - by the bandwidth of the gain
  - by the bandwidth of the reflectivity of the mirrors

# Half VCSEL

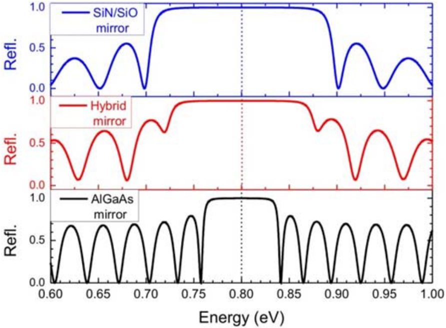


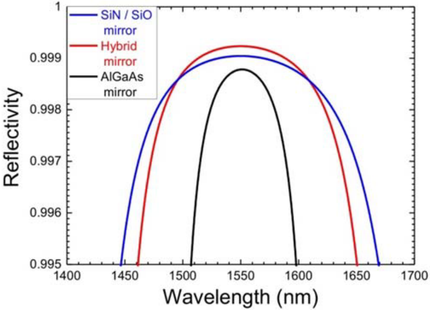
- starting point is the fabrication of a half VCSEL
- We need mirrors with a high reflectivity
- The solution is a Bragg mirror

# Bragg mirror

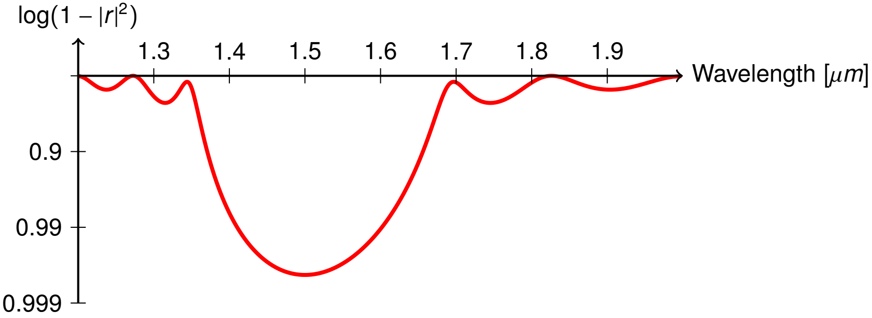
- The Bragg mirror consists of pairs of dielectric layers with the optical thicknes $n * d = \lambda/4$.
- The light reflected at the different interfaces superimposes in phase to achieve a very high reflectivity
- This high reflectivity is achieved at the nominal wavelength
- If the difference of the refractive indices is large the achievable reflectivity is large
- But the reflector has a limited bandwidth
- If the difference of the refractive indices is large the achievable bandwidth becomes larger

# Bragg mirrors



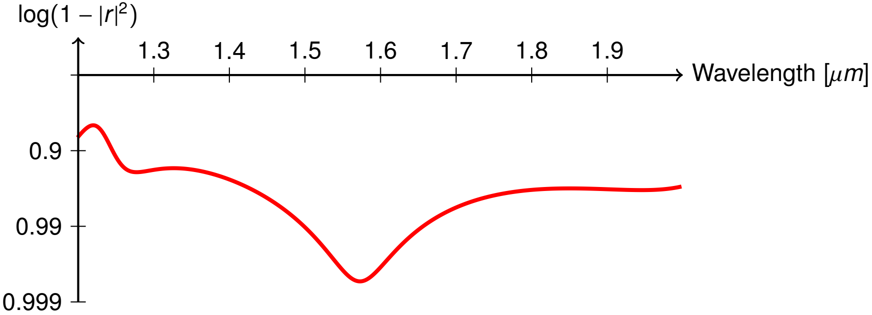


# Reflectivity of dielectric Bragg mirror



**Reflectivity of 11.5 pairs of SiN/SiO layers**

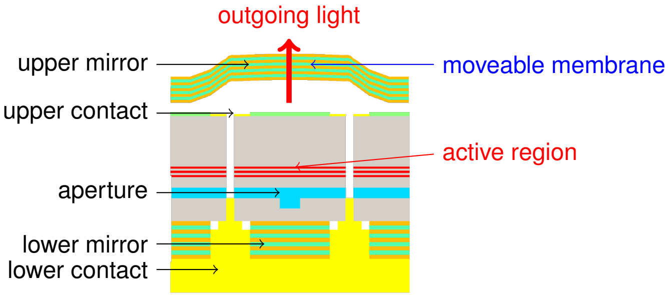
# Reflectivity of dielectric Bragg mirror and gold cladding



**Reflectivity of 6.5 pairs of AlF/ZnS layers and gold cladding**

A High reflectivity can be achieved

# Structure of tunable VCSEL



# Gaussian beam inside VCSEL

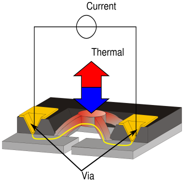
- Phase front has to fit the curvature of the mirror
- The active region should be positioned at a maximum of the field
- The aperture should be positioned at a minimum of the field

# Actuation principles (electrothermal actuation)

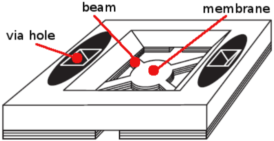
Two principles for the micromechanical tuning were used

- Electrothermal actuation
- Electrostatic actuation

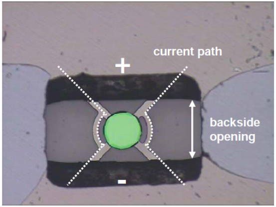
principle of thermal tuning



Schematic sketch of membrane



Dielectric membrane



## Principle of thermal actuation

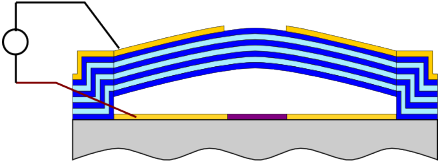
Due to current flow and resulting heat a prolongation of the beams of the membrane will result in a longer cavity and thus wavelength tuning

# Actuation principles (electrostatic actuation)

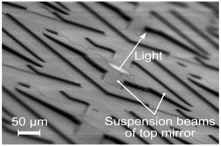
Two principles for the micromechanical tuning were used

- Electrothermal actuation
- Electrostatic actuation

principle of electrostatic tuning



Surface micromachined membrane

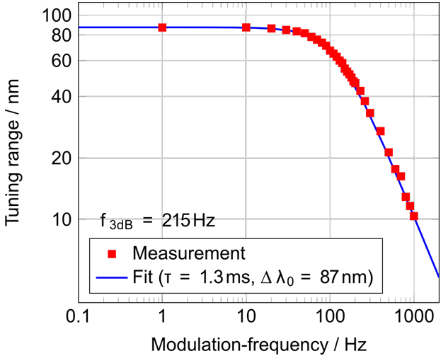


## Principle of electrostatic actuation

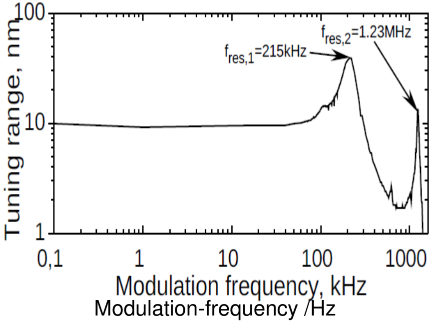
Due to the applied voltage an electrostatic force will move the membrane resulting in a shorter air-gap and thus in a wavelength tuning

# Tuning speed

Electrothermal tuning

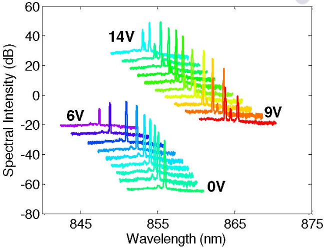


Electrostatic tuning



# Tuning Range

## How to define a tuning range

- 

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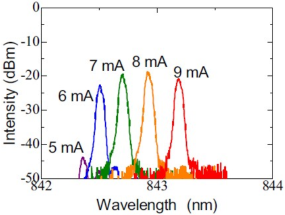
- 

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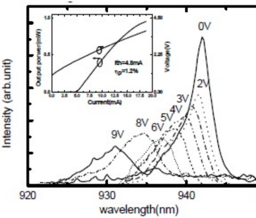
- 

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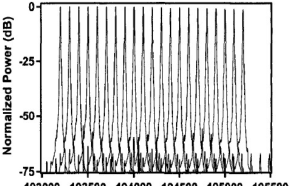
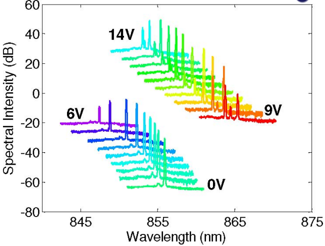
- 

# Tuning Range

How to define a tuning range

- 

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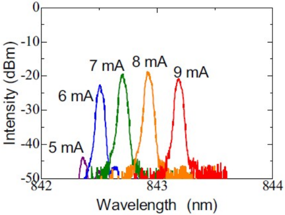
- 

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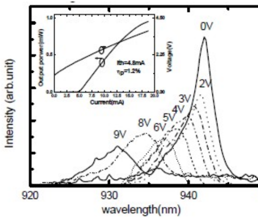
- 

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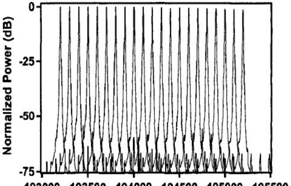
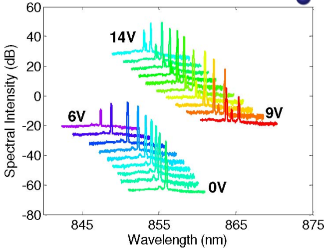


# Tuning Range

## How to define a tuning range

- 

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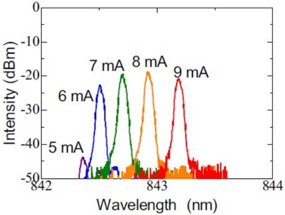
- 

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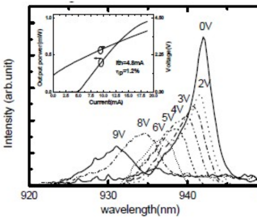
- 

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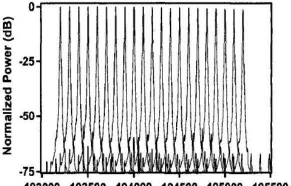
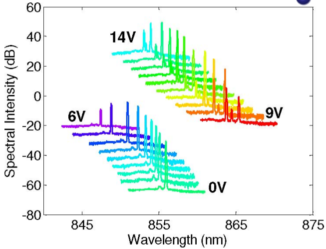


# Tuning Range

How to define a tuning range

- 

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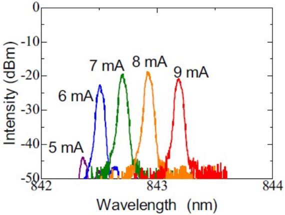
- 

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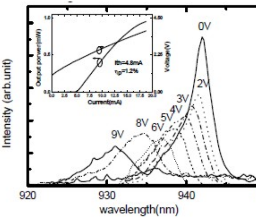
- 

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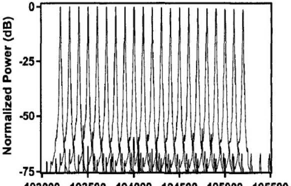


# Tuning Range

- The tuning range is defined by a frequency or wavelength range where the laser holds well defined specifications.
- These specifications depend on the application the laser is aiming for
- Therefore these specification should be defined in each publication on tunable lasers

# Specification for Tunable VCSELs

The following essential specifications for the VCSEL should be guaranteed for the whole tuning range

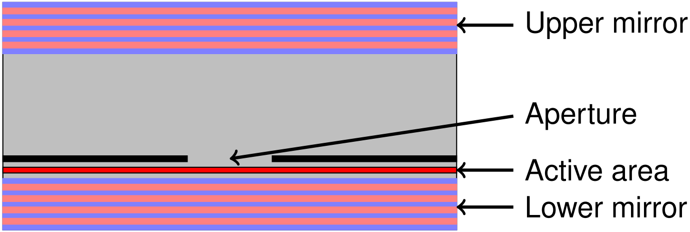
- Output power $> \; P_{min}$
- Tuning speed
- Power in higher longitudinal modes $< SMS_{long} * P_{mainMode}$
- Power in higher transversal modes $< SMS_{trans} * P_{mainMode}$
- Power in other polarization modes $< SMS_{pol} * P_{mainMode}$
- Linewidth of main mode $\Delta\nu < \Delta\nu_{min}$
- AM modulation bandwidth $< B_{max}$
- $\cdots$ depending on application

# Tunable VCSELs

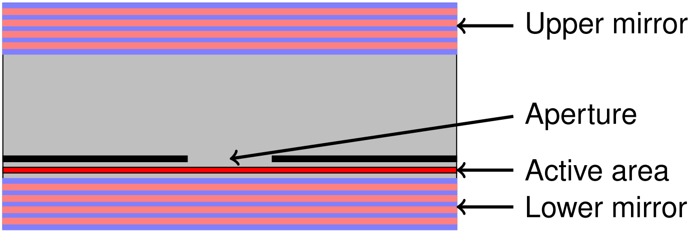
We distinguish between different types of tunable VCSELs

- Pumping Scheme
    - Optically pumped
    - Electrically pumped
- Tuning Mechanism
    - Electrostatical Actuation
    - Electrothermal Actuation

# Structure of a VCSEL

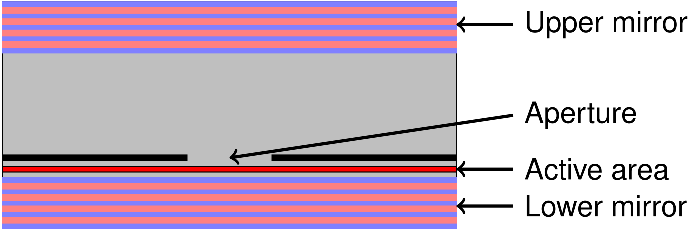


# Structure of a VCSEL



- Short cavity → Longitudinal single mode
- Very thin active region → small round trip gain
- Higher transversal modes have to be avoided
- Stable or well defined state of polarization has to be guaranteed

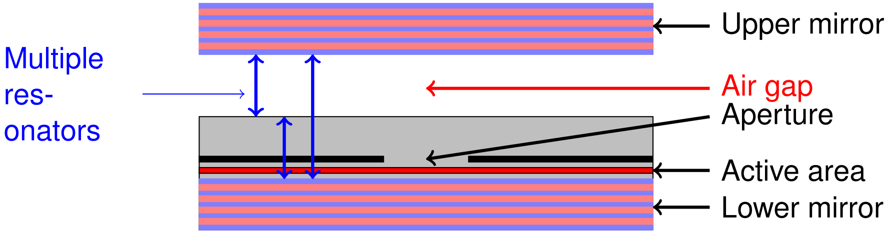
# Structure of a VCSEL



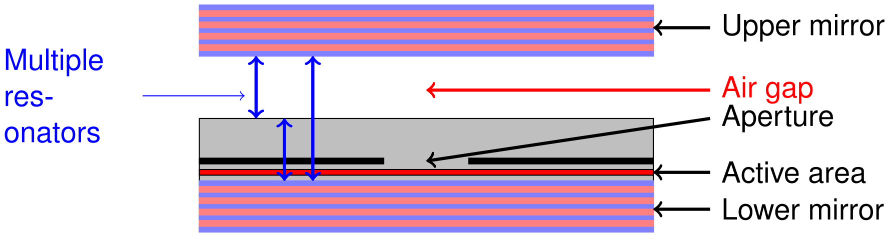
- Short cavity → Longitudinal single mode
- Very thin active region → small round trip gain
- Higher transversal modes have to be avoided
- Stable or well defined state of polarization has to be guaranteed

The VCSEL is very sensitive against additional losses

# Structure of a tunable VCSEL

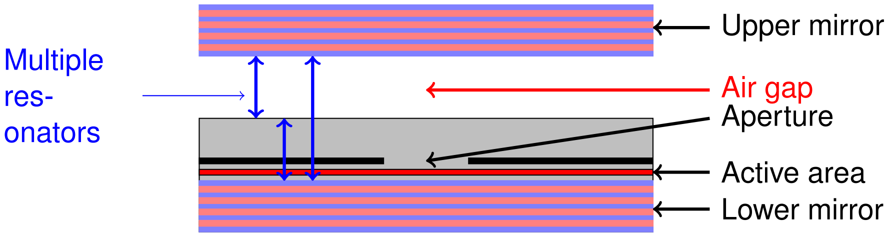


# Structure of a tunable VCSEL



The tunable VCSEL is a multi cavity laser

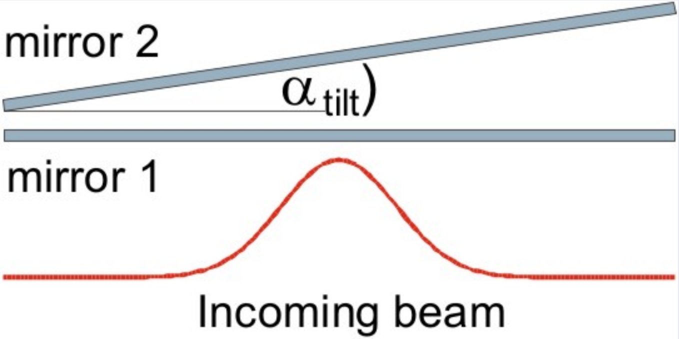
# Structure of a tunable VCSEL



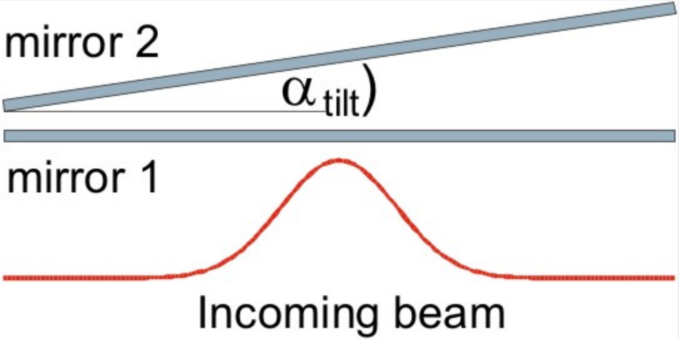
The tunable VCSEL is a multi cavity laser

The design of the multi cavity resonator is a trade off between tuning range and threshold current [6]

# Cavity losses



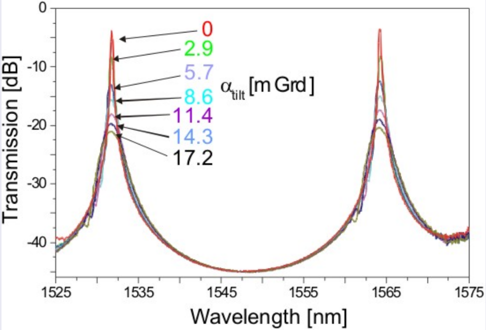
# Cavity losses



Two effects

- Polarisation dependence
- Walk off

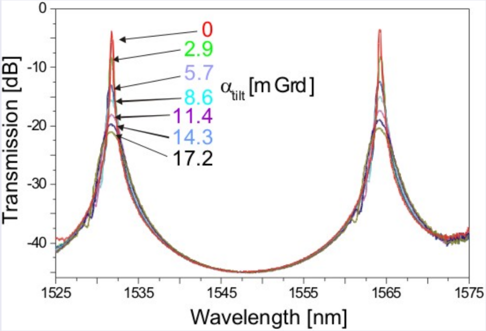
# Cavity losses (plane-plane resonator, measurement)



Single mode fiber- single mode fiber coupling
Reflexion 98.7 %

Length of resonator 36.9$\mu$m

# Cavity losses (plane-plane resonator, measurement)



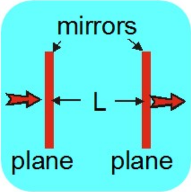
Single mode fiber- single mode fiber coupling
Reflexion 98.7 %

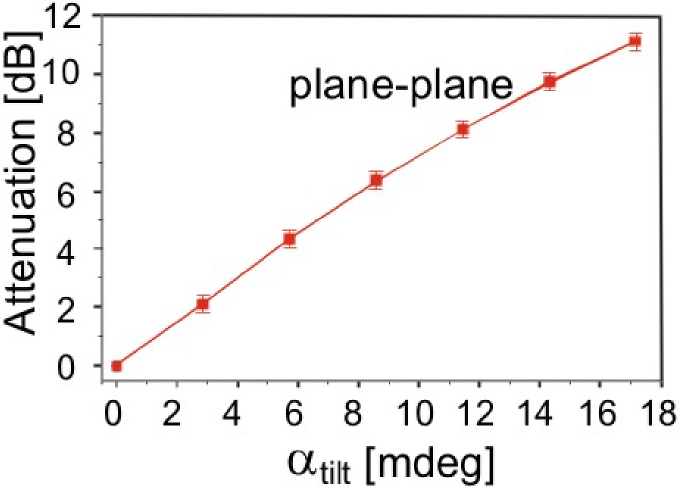
Length of resonator 36.9$\mu$m

- An angle of 3 mdegree results in a loss of 10 dB
- The result depends on the size of the beam

# Cavity losses, Theory and Experiment

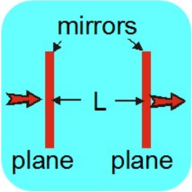
# Cavity losses, Theory and Experiment

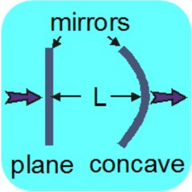


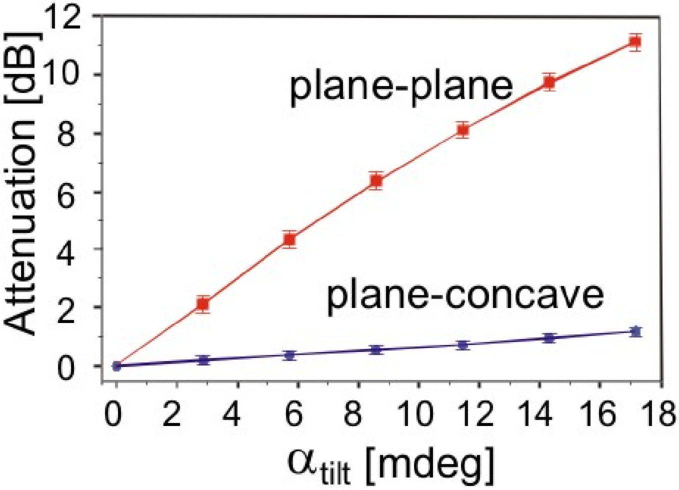


Gaussian beam ($w_0 = 45\mu$) - photo-diode coupling
Reflexion 99.5 %

# Cavity losses, Theory and Experiment

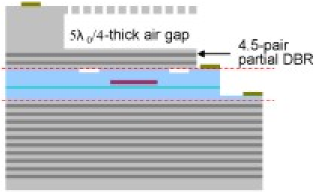






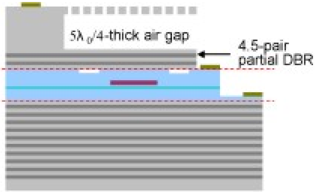
Gaussian beam ($w_0 = 45\mu$) - photo-diode coupling
Reflexion 99.5 %

# Selected Different approaches



[4]

# Selected Different approaches



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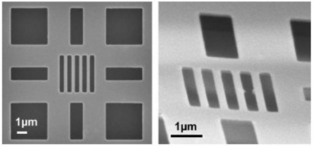
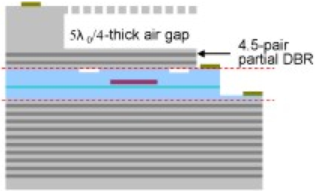


[3]

# Selected Different approaches



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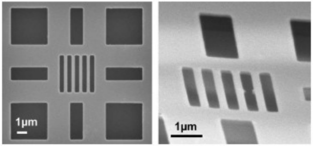

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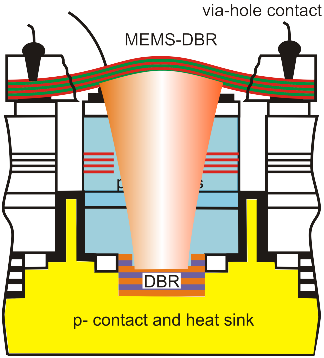
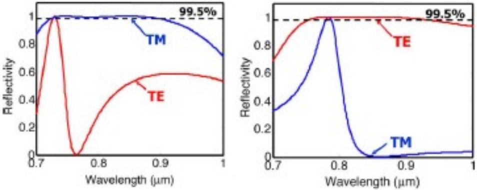


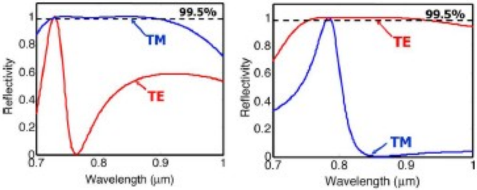
For all these devices we have to optimize the optical cavity very carefully

# Losses due to wavelength dependency of mirrors



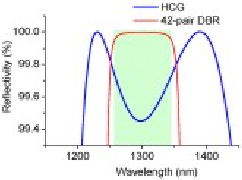
[3]

# Losses due to wavelength dependency of mirrors



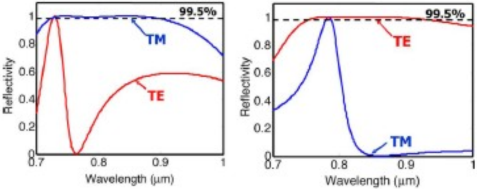
[3]

(a)



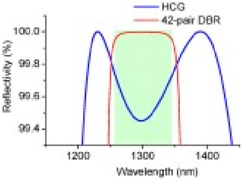
[4]

# Losses due to wavelength dependency of mirrors



[3]

(a)



[4]

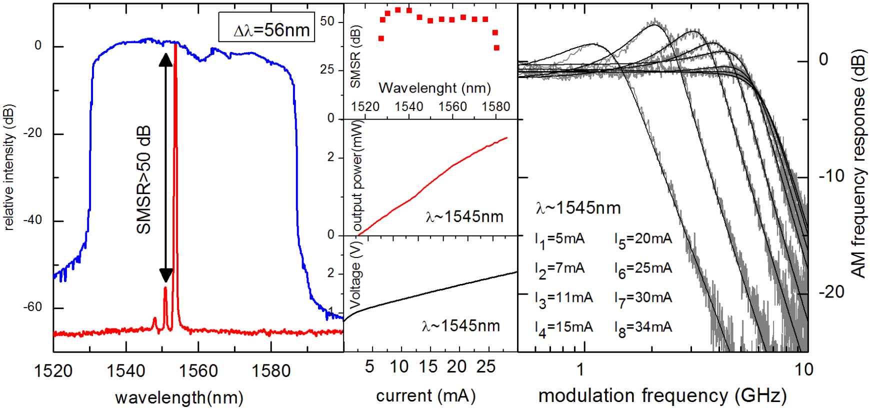
We have to ensure that the dependency on reflection factors on wavelength is not critical

# Fabrication technology

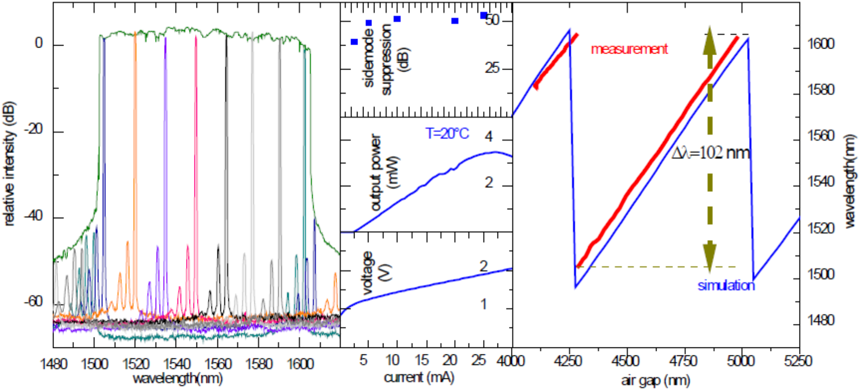
We used two different approaches

- Bulk micromachining (Two chip approach)
  - Fabrication of active part ("Half VCSEL") and membrane independently
  - Optimal technology for VCSEL fabrication and micromachining
  - Very flexible technology
  - Very difficult mounting procedure
- Surface micromachining (On wafer technology)
  - The surface micromachining of the membrane should not destroy the active part
  - No high temperatures are allowed
  - Simultaneous fabrication of many VCSELs
  - Lithografic accuracy

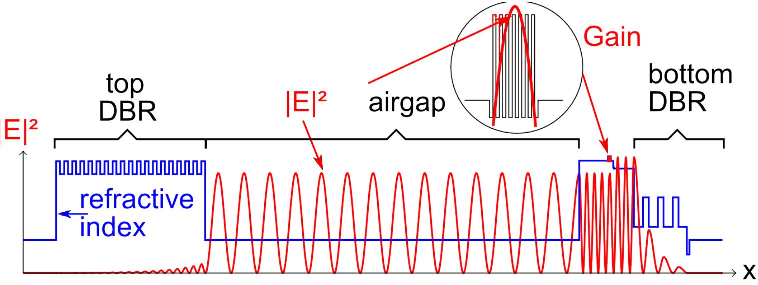
# Results for bulk-micromachined tunable VCSEL



# Results for surface-micromachined tunable VCSEL



# Field distribution of a tunable VCSEL



# Summary

- We have to be very careful with the tolerances designing tunable VCSEL
- The properties of the optical cavity should not change while tuning
- Best results were achieved up to now with plane concave cavities and lithographic accuracy for optically and electrically pumped VCSELs

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## Small Suggestion

Be careful comparing published data

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Be careful comparing published data

Thank you

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Be careful comparing published data

Thank you

Questions?

# Measured tuning of a 1.5 $\mu$ m VCSEL

In: (). URL: `https://newsline.llnl.gov/articles/2008/apr/04.11.08_texas.php`.

URL: `http://www.oemarket.com/catalog/product_info.php/optical-source-laser-1310nm-p-65`.

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