Introduction of semiconductor laser

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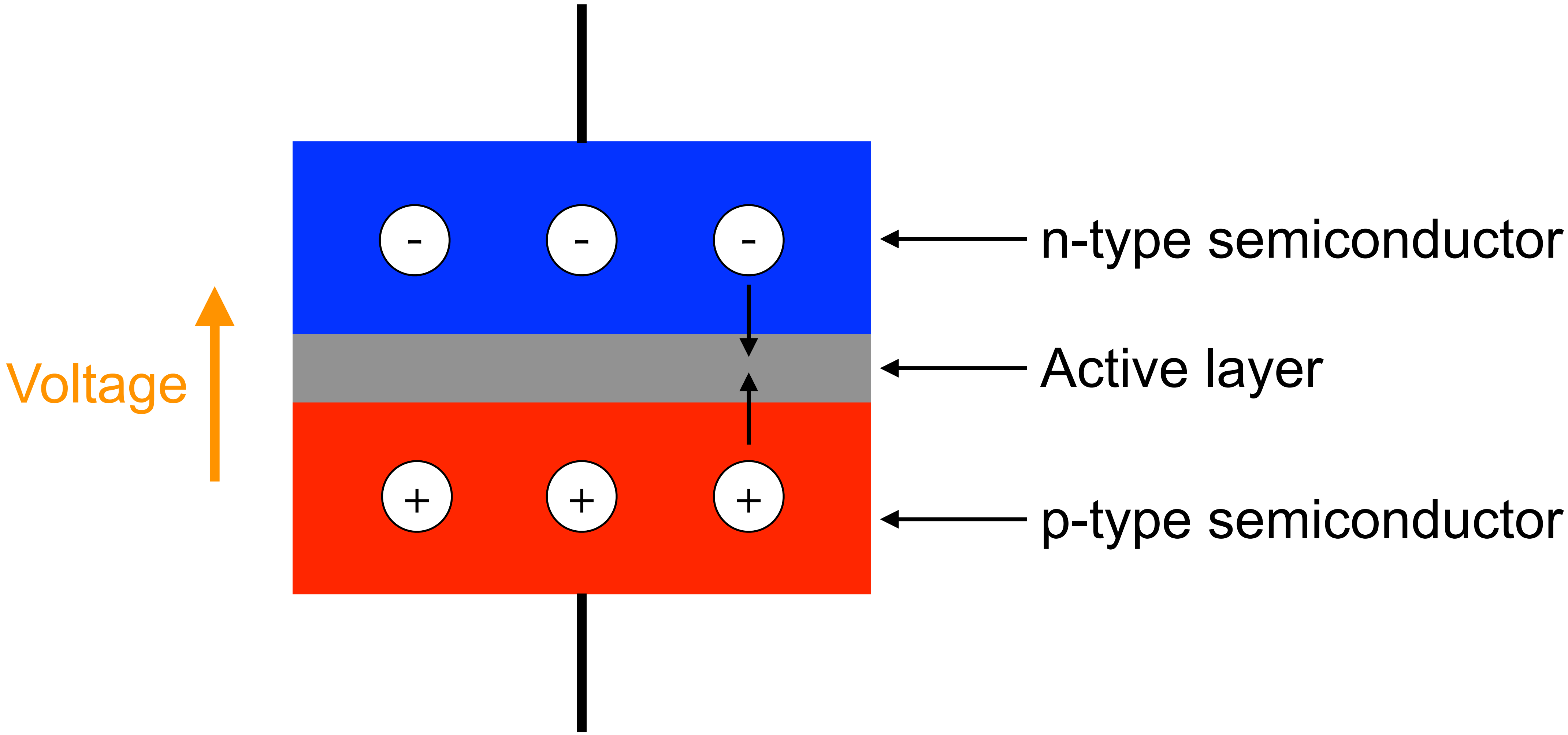
Contents

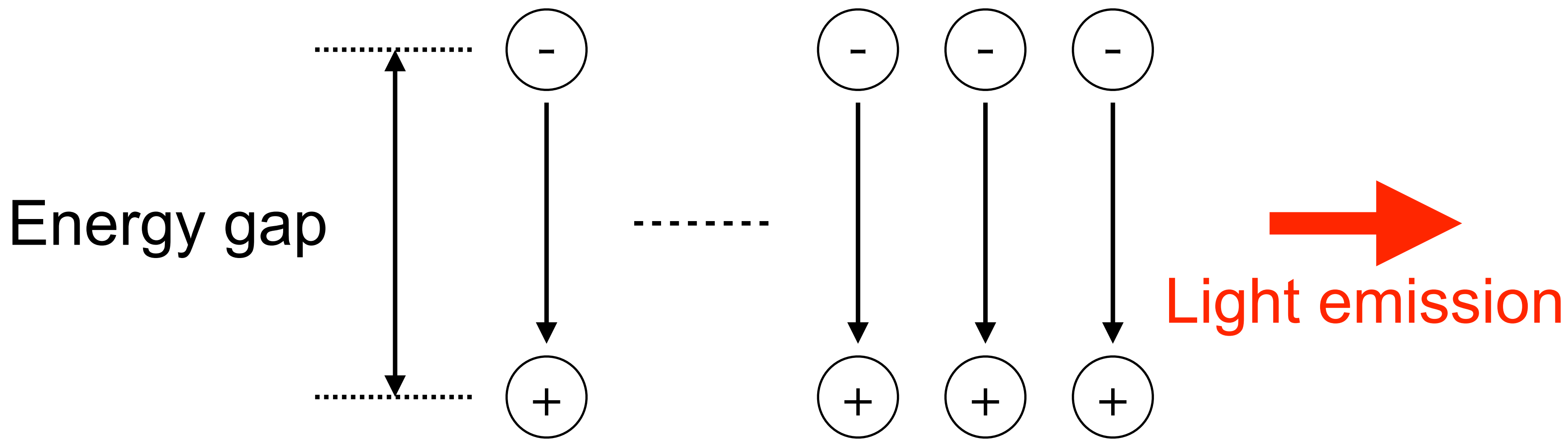
- Principle of semiconductor laser
- Types of ECDL
  - Diffraction grating
  - Interference filter
- Introduction of various noises
- Summary

What is semiconductor laser ?

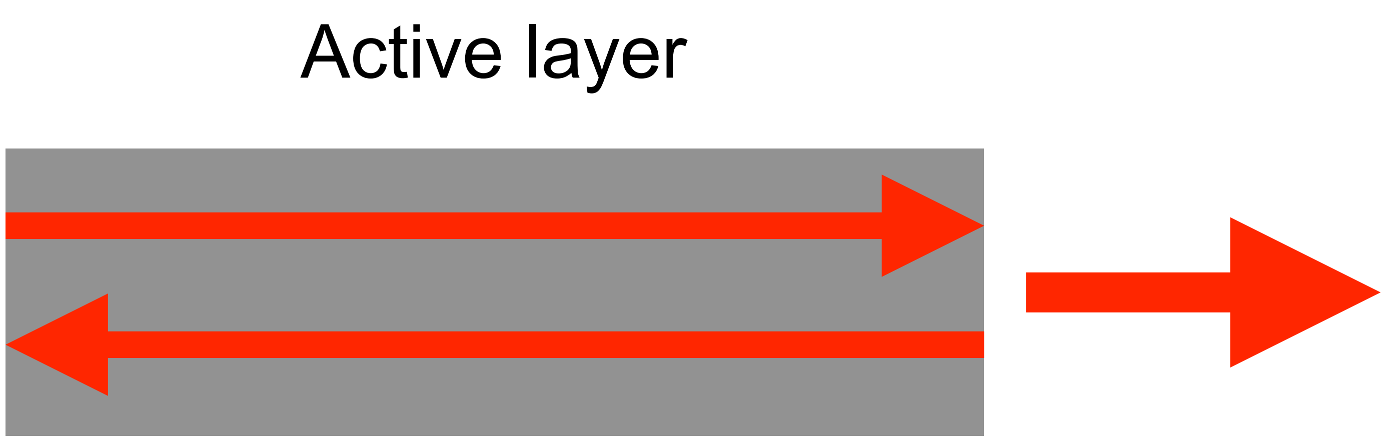


In the active layer, a phenomenon called recombination occurs in which high-energy-level electrons from the n-type semiconductor combine with holes, releasing energy and producing light

What is semiconductor laser ?



The light generated inside the active layer causes other electrons to recombine one after another, amplifying the light.
⟹ This phenomenon is called stimulated emission.



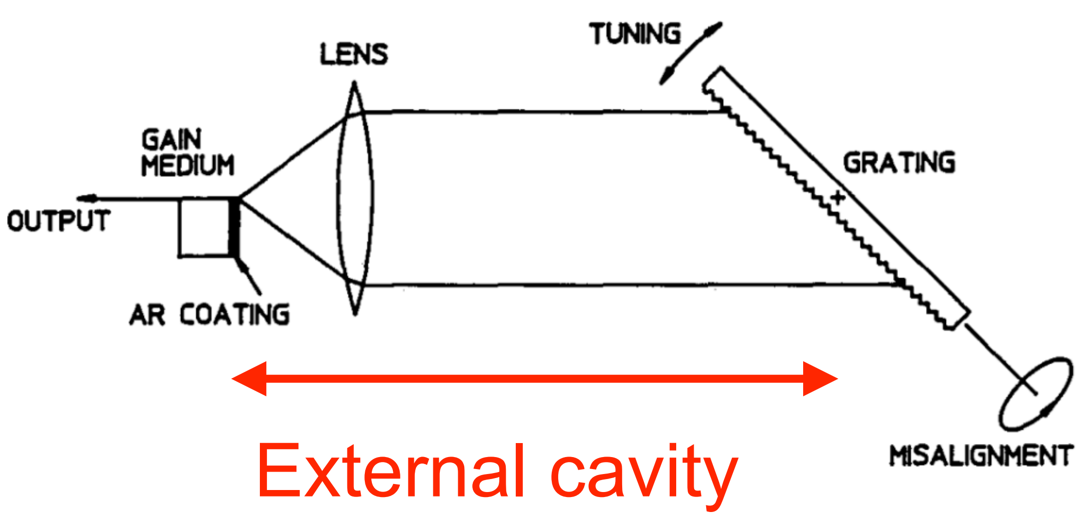
Light produced by stimulated emission is amplified inside the active layer.

Types of ECDL

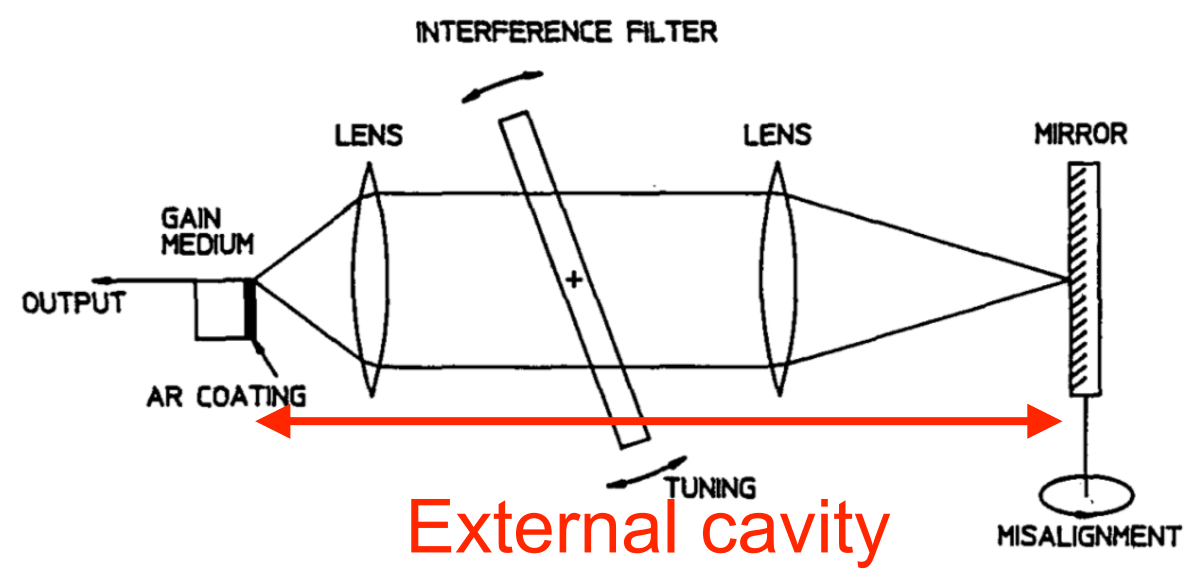
Applications in many fields such as atomic physics, metrology and telecommunication require single mode operation with narrow linewidth and good tunability.

⟹ It is achieved by incorporating the laser diode into an external cavity.

ECDL with diffraction grating



ECDL with interference filter

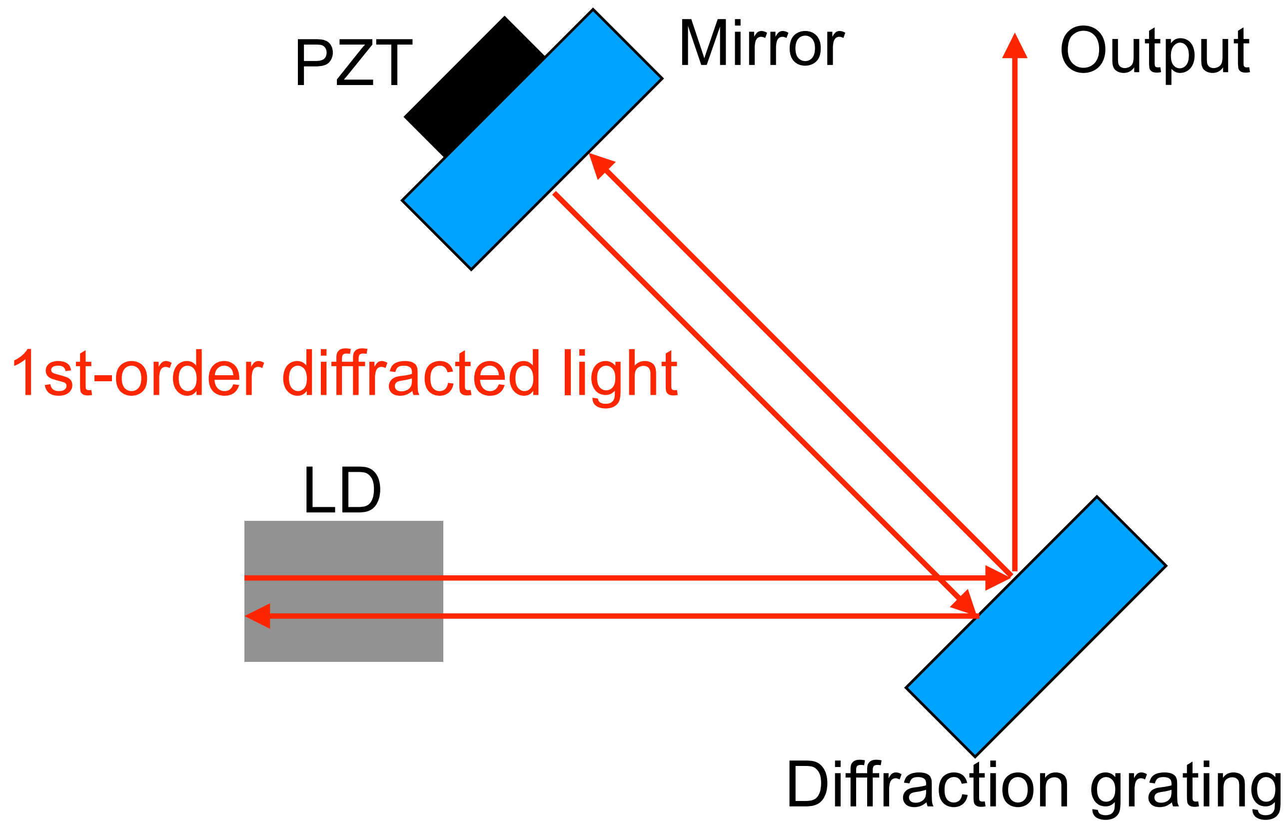


P. Zorabedian and W. R. Trutna, Jr., Opt. Lett. 13 (1988).

ECDL with diffraction grating

Requirement of ECDL with diffraction grating

- Precise alignment
- Sensitive to acoustic and mechanical disturbances



Littman configuration

The 1st-order diffracted light from the diffraction grating is reflected by a mirror to select wavelength. The light is fed back into the semiconductor laser.

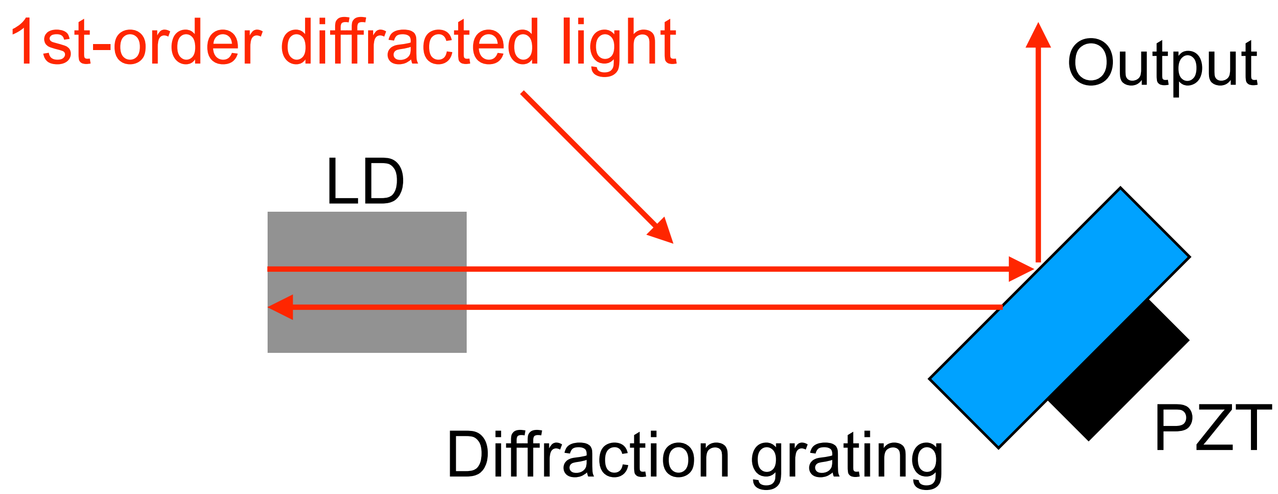
Advantage

Obtain narrow linewidth because of longer cavity length

Disadvantage

Limit laser output because of twice diffraction

ECDL with diffraction grating



Littrow configuration

The 1st-order diffracted light from the diffraction grating is directly fed back to the semiconductor laser

The 0th-order diffracted light is extracted as a laser.

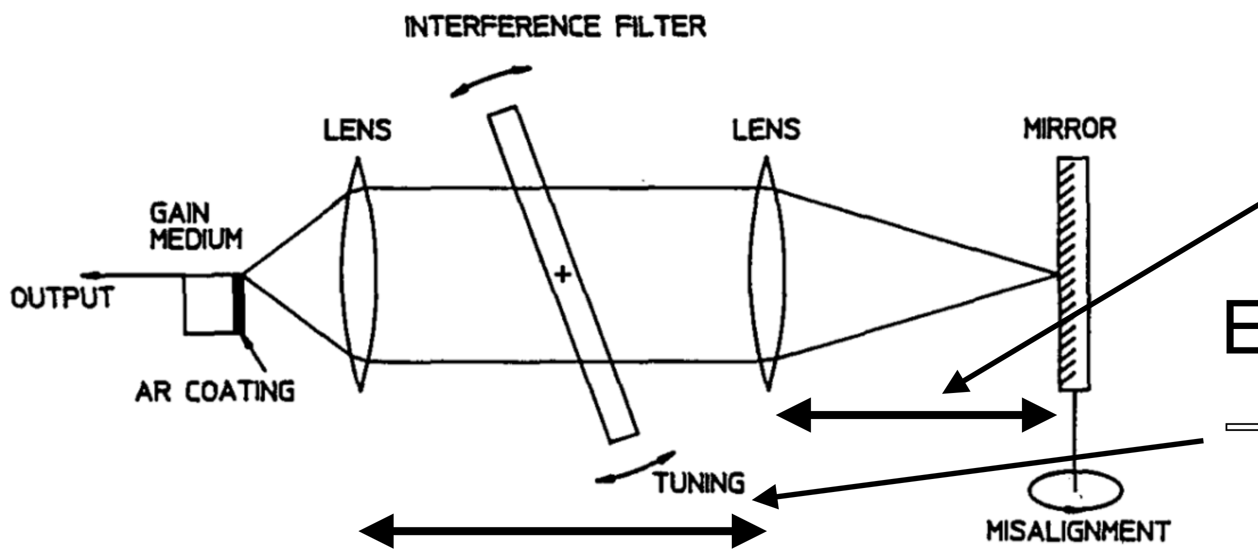
Advantage

Obtain higher laser output than Littman configuration

Disadvantage

Harder to obtain narrow linewidth than Littman configuration

ECDL with interference filter (IF)



P. Zorabedian and W. R. Trutna, Jr., Opt. Lett. 13 (1988).

Equal to focal length of the lens

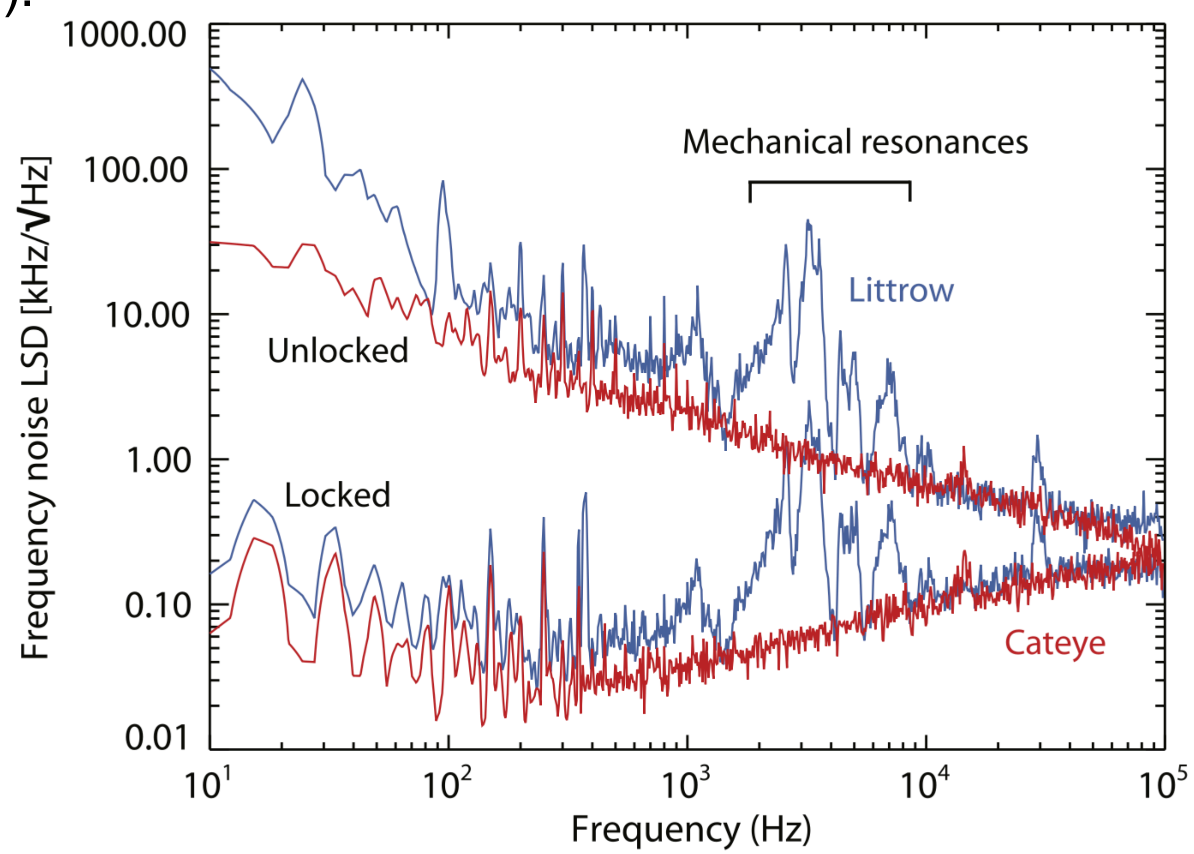
⟹ Independent of the mirror tilt

Equal to the sum of the focal length

⟹ Insensitive to displacements

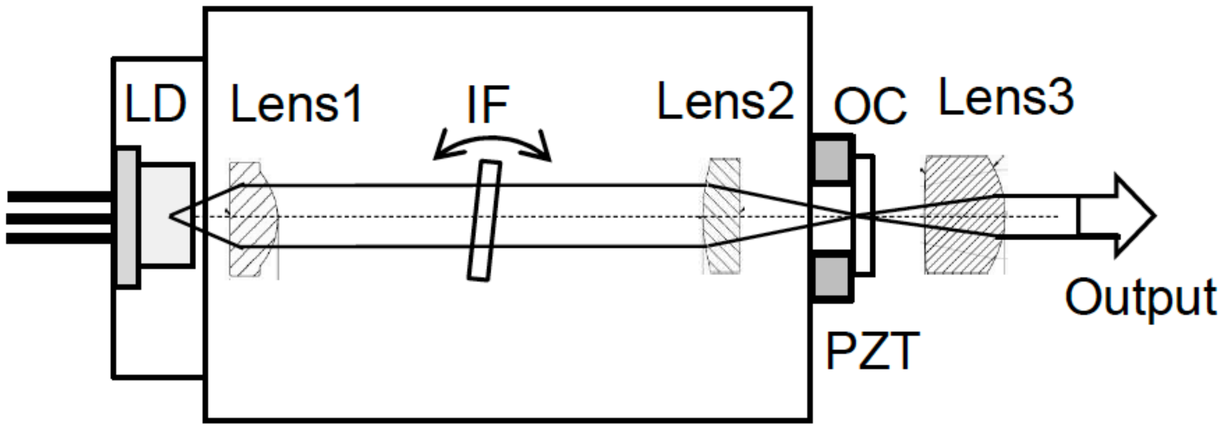
- Wavelength selection by rotating IF
- Cat's eye structure

⟹ Better robustness



Daniel J. Thompson and Robert E. Scholten, Rev. Sci. Instrum. **83**, 023107 (2012).

Wavelength selection



$$T_{total} = G_D T_D T_{cavity} T_{filter}$$

G_D: semiconductor gain of the laser diode

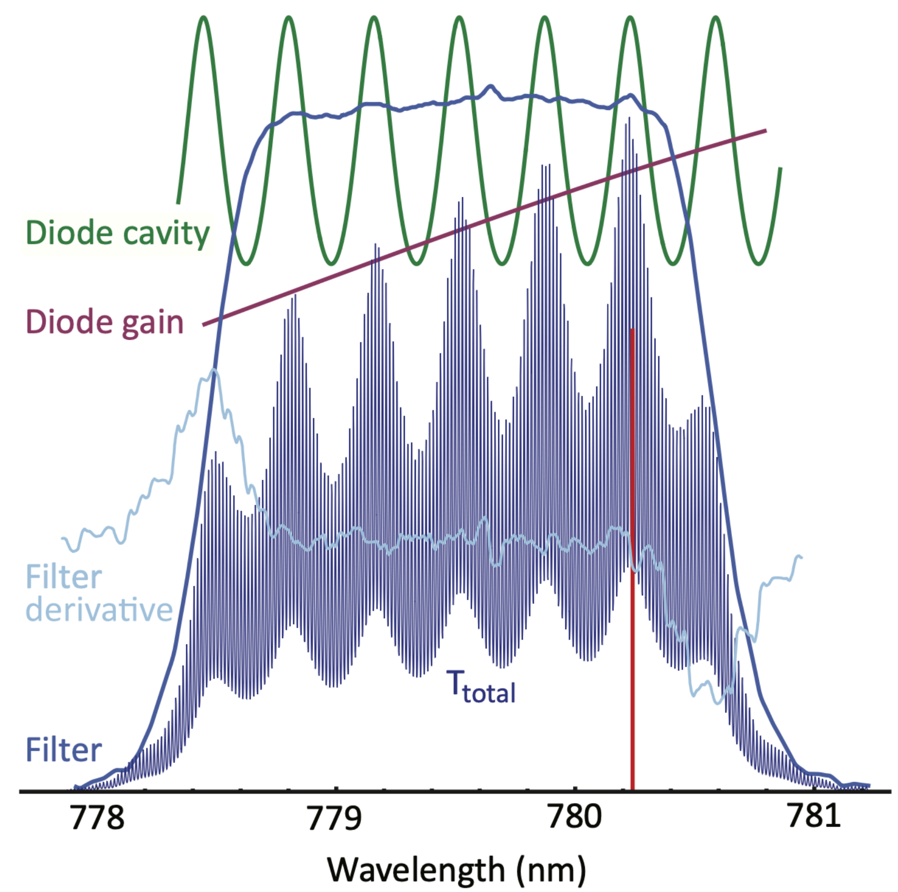
T_D: transmission of the laser diode

T_{cavity}: transmission of external cavity

T_{filter}: transmission of an IF

$$T_D, T_{cavity} = \frac{1}{1 + \mathscr{F} \sin^2(\delta(\nu)/2)} \qquad \mathscr{F} = \frac{4\sqrt{r_1 r_2}}{(1 - \sqrt{r_1 r_2})^2}$$

The mode that maximizes T_{total} is selected



Daniel J. Thompson and Robert E. Scholten, Rev. Sci. Instrum. **83**, 023107 (2012).

Wavelength selection

Wavelength vs rotation angle of IF

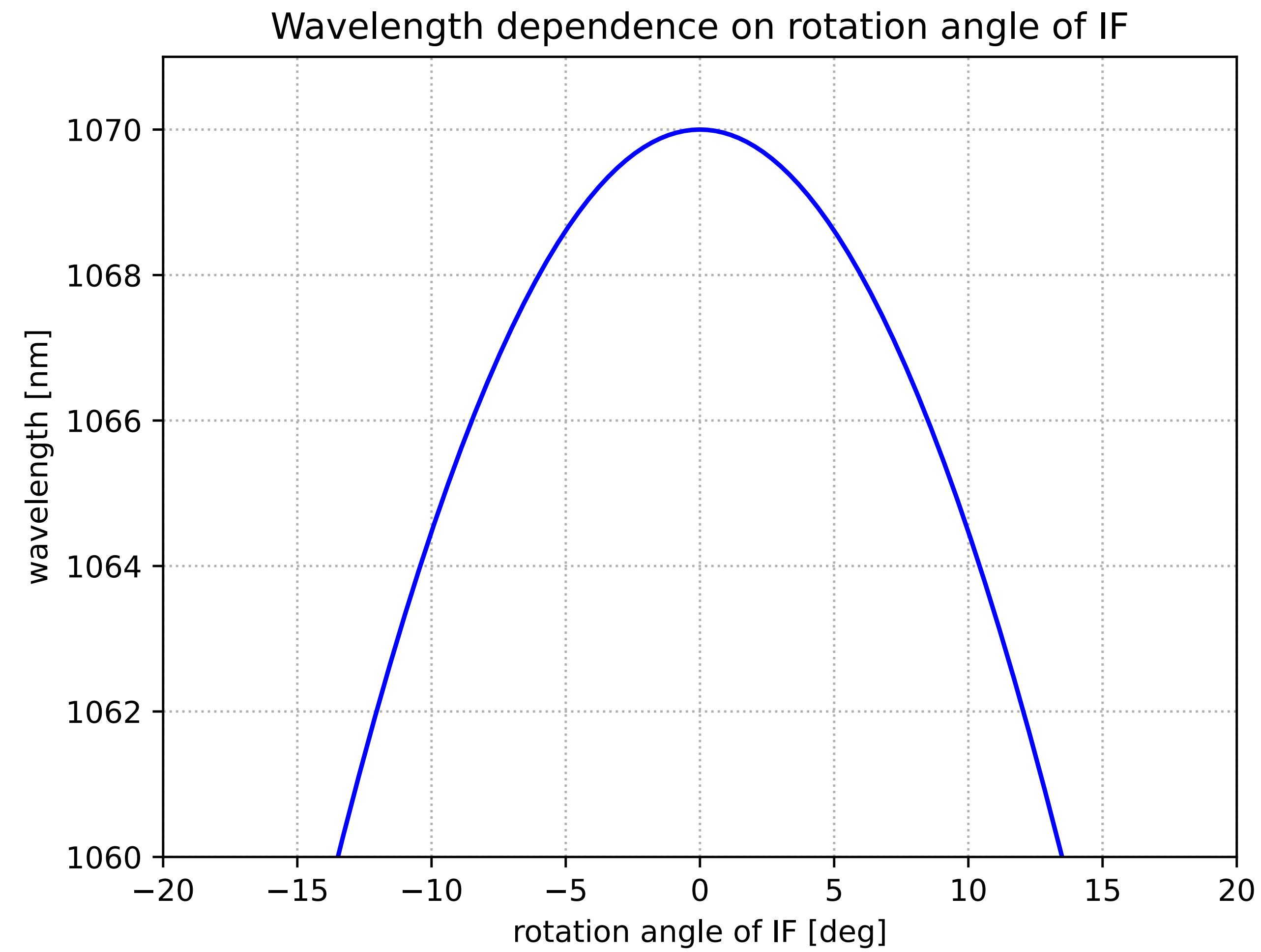
$$\lambda(\theta) = \lambda_0 \sqrt{1 - \left(\frac{\sin\theta}{n_{eff}}\right)^2}$$

When $\theta = 0$ deg, $\lambda_0 = 1070$ nm

When $\theta = 6$ deg, $\lambda = 1068$ nm

↓

$$n_{eff} = 1.71$$



IF is calculated to transmit more than 90% of the intensity at the nominal wavelength at 6 degree incidence

Sensitivity of the optical feedback

The dependence of the threshold current I_{th} on external feedback

$$I_{th} = C\left[\alpha + \frac{\ln(R_0 R_{ext})}{2}\right]$$

The amount of optical feedback

$$R_{ext} = R_{ext}^0 \exp\left[-\delta^2\left(\frac{\pi w_0}{\lambda}\right)^2\right]$$

$$\frac{d^2 I_{th}}{d\delta^2} = C\left(\frac{\pi w_0}{\lambda}\right)^2$$

<u>ECDL with diffraction grating</u>

The quantity $(d^2 I_{th}/d\delta^2)^{-1/2}$ is proportional to w_0^{-1} (alignment stability)

The grating resolution is proportional to w_0

⇒ Trade-off exists between alignment stability and resolution

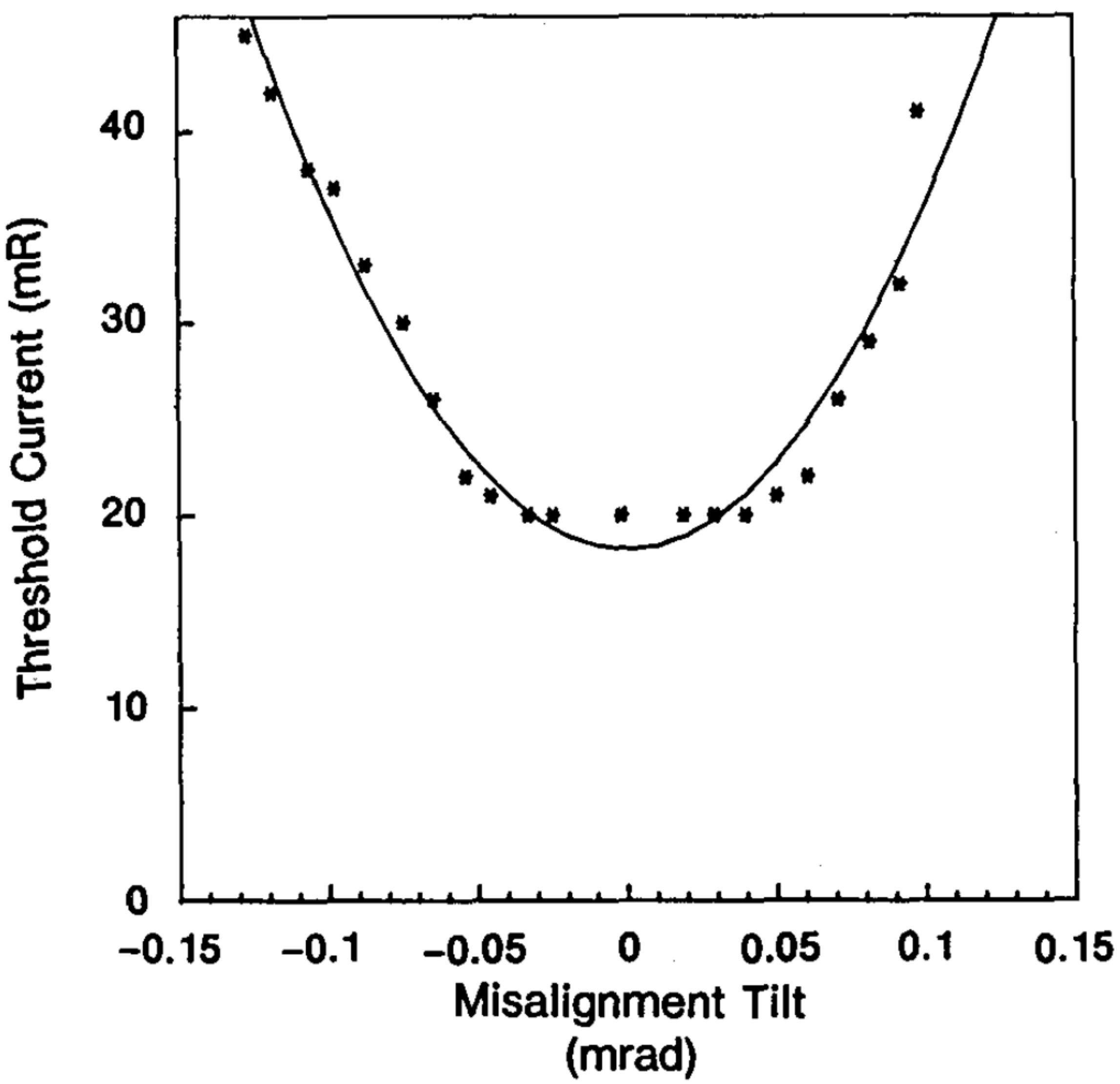
<u>ECDL with IF</u>

The separation of the wavelength selection and optical feedback allow to choose a more favorable value for beam waist.

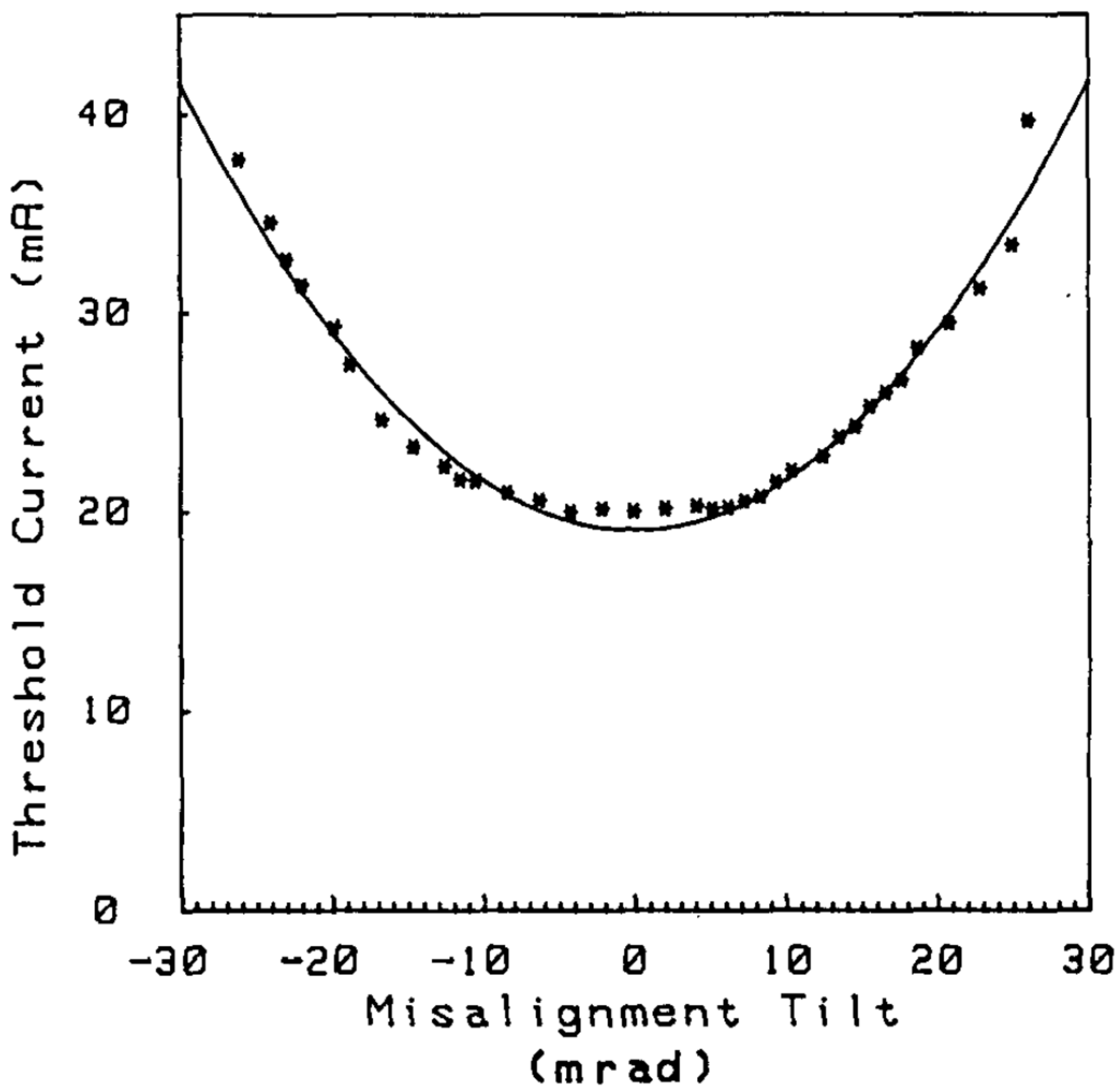
⇒ The misalignment sensitivities is greatly reduced.

Sensitivity of the threshold current

P. Zorabedian and W. R. Trutna, Jr., Opt. Lett. 13 (1988).



The grating misalignment in the ECDL with diffraction grating



The mirror misalignment in the ECDL with IF

↓

ECDL with IF has greater alignment tolerance

Intensity noise

Relative intensity noise (RIN)

$$\text{RIN} = \frac{P_{in} + P_{ds} + P_{dt}}{P_0}$$

P_0: output power from semiconductor laser

P_{in}: power due to fluctuation

P_{ds}: shot noise (PD)

P_{dt}: thermal noise (PD)

<u>Measurement</u>

Detect output light from laser in PD, dividing DC and AC component

If P_0 is large, RIN becomes

$$\text{RIN} = \frac{P_{in}}{P_0}$$

If P_0 is small, RIN includes PD noise

Quantum noise

Quantum noise: essential noise sources

Natural emission electric field generated by electronic transition

$$E_m \exp[i\omega_m(t - t_m)]$$

Natural emission power generated by multiple electronic transition

$$\sum_m \sum_n E_m E_n^* \exp\left[i(\omega_m - \omega_n)t\right]$$

$\omega_m - \omega_n$ is beat note ranging from DC to microwave

$\Longrightarrow$ almost constant white noise

↓ Laser gain amplify this component

Quantum noise

Mode hopping noise

Mode competition phenomena

With mode hopping ⇒ mode hopping noise

Without mode hopping ⇒ optical feedback noise

Fluctuation of current or temperture, reinjection of light into LD
⇒ Noise in low frequency region is sharply multiplied

⇒ Mode hopping noise (interaction between laser modes)

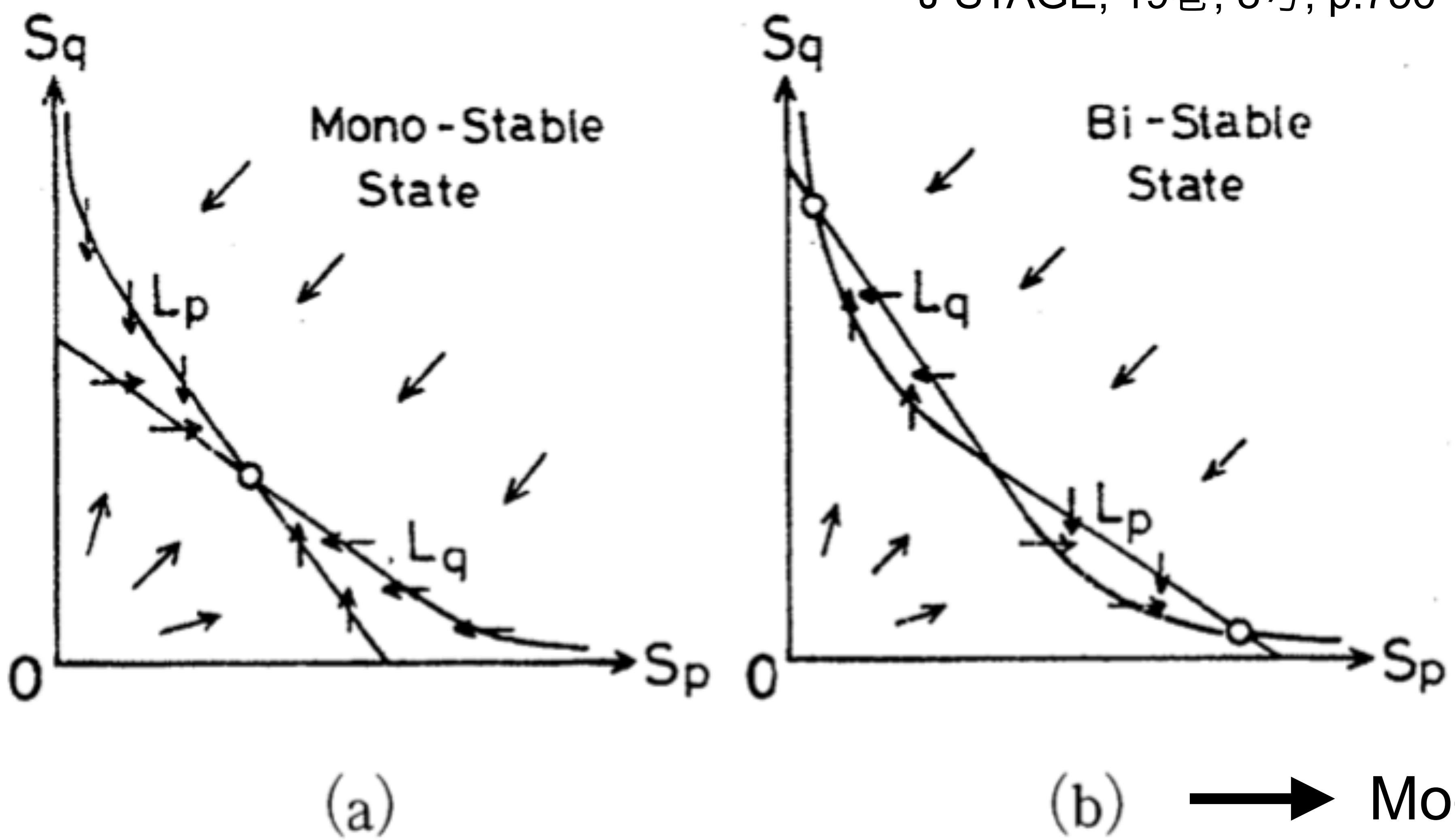
The variation of the photon number $S_{p/q}$ in mode p,q

$$\frac{dS_{p/q}}{dt} = \left[A_{p/q} - BS_{p/q} - DS_{q/p} - G_{th(p/q)}\right] S_{p/q} + C\frac{NV}{\tau_s} + F_{p/q}(t)V$$

Mode hopping noise

Steady state $\frac{dS_{p/q}}{dt} = 0$

山田実, 飯山宏一: 半導体レーザーの雑音測定, J-STAGE, 19巻, 8号, p.756-766 (1991).



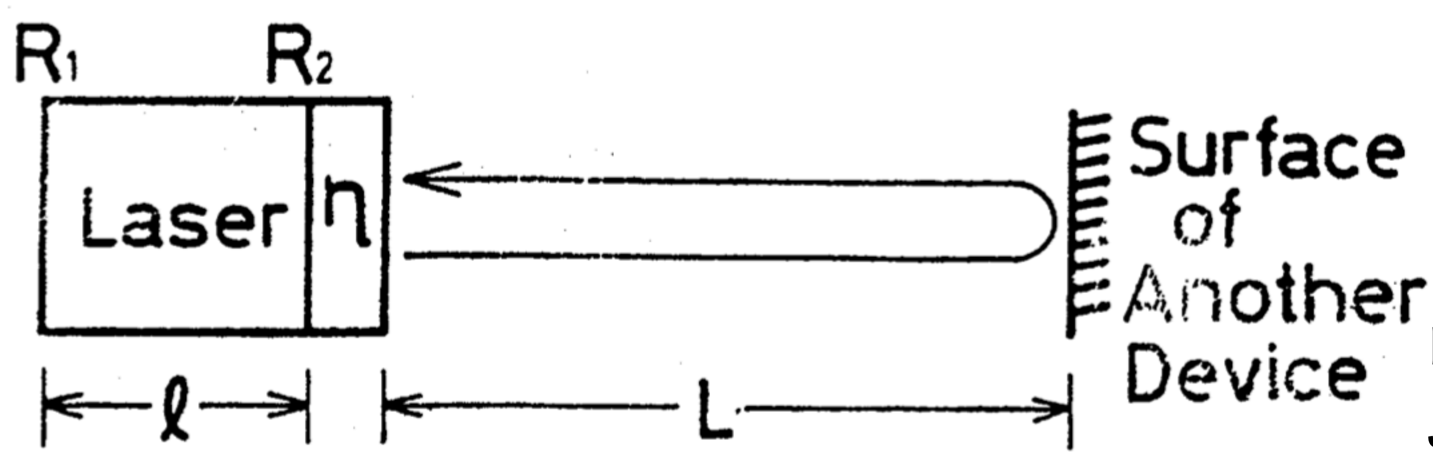
(a) $I/I_{th} < 1.1$

(b) $I/I_{th} \geq 1.1$ → Mode hopping

Variation of injection current and temperature ⇨ $A_{p/q}$

Reinjection of light into LD ⇨ $G_{th(p/q)}$

Optical feedback noise



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The ratio of optical feedback to output light is over 10^{-4}

⇒ Optical feedback causes the electron density inside the laser to fluctuate irregularly

The ratio of optical feedback to output light is under 10^{-6}

⇒ Interaction between external cavity mode and oscillation mode

↓

It is important to isolate the output light and optical feedback

Frequency noise

Fluctuation of optical phase by natural emission light and refractive index fluctuation

Frequency noise power spectrum density

$$Q_{FM}(f) = \frac{(\delta f)_{ST}}{\pi}\left[1 + \frac{\alpha^2 f_R^2}{\left(f_R^2 - f^2\right)^2 + (\gamma_e/2\pi)^2 f^2}\right]$$

⟹ spectrum has resonant peak at f_R

Schawlow-Townes equation

$$(\delta f)_{ST} = \frac{h\nu n_{sp}}{8\pi\tau_p^2 P}\left(\frac{c}{n_r L}\right)^2$$

⟹ The larger P is, the smaller frequency noise is

Summary

- Using ECDL is good way to obtain narrow linewidth
- ECDL with IF is more stable than ECDL with diffraction grating
- Many noises may occur to Nakagawa ECDL

⇨ Deal with issues flexibly