Laser : introduction

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Plan

A. Laser introduction – fonctionnement, dynamique et bruits

B. Spectroscopie de haute résolution, mesure de fréquence

C. Refroidissement et piégeage I

D. Refroidissement et piégeage II

E. Horloges atomiques et GPS

F. Exposés

F. Exposés

Exposés de 20 minutes

- Principe de fonctionnement
- Présentation d'une application
- Points forts – points faibles

Sujets

- Spectroscopie attoseconde
- Le laser à électrons libres
- Le laser Mégajoule
- Contrôle cohérent
- Virgo – détection d'ondes gravitationnelles
- Oscillateur paramétrique optique
- Chat de Schrödinger

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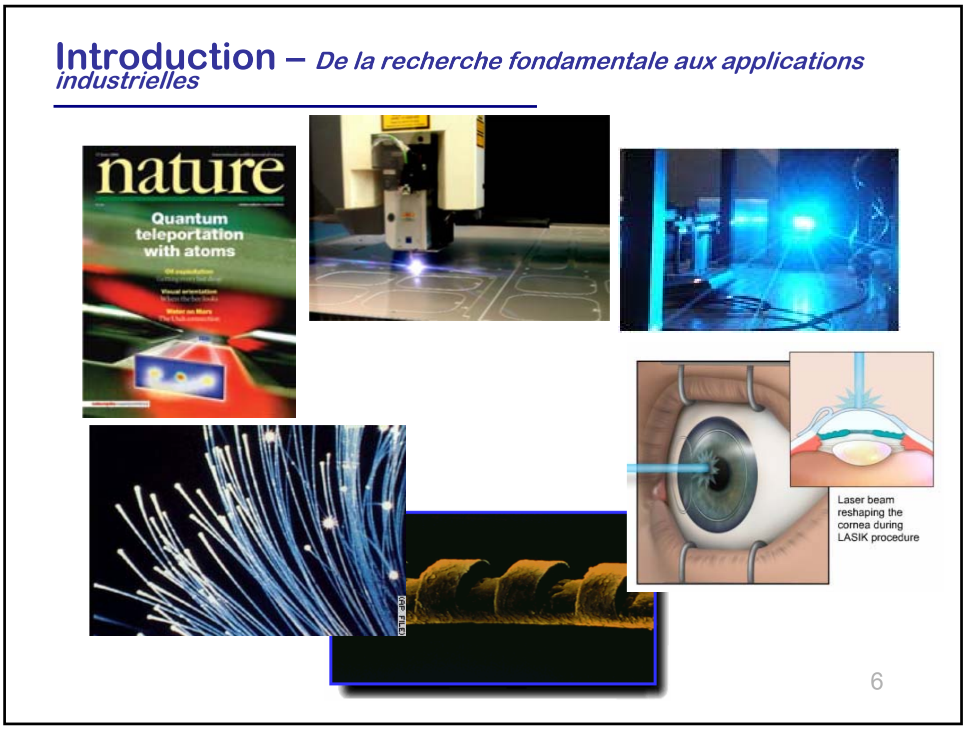
References

- Anthony E. Siegman, « Lasers », University Science Books, Mill Valley, California 1986
- W. Demtröder, « Laser spectroscopy », Springer Verlag, Berlin 1986
- D. Meschede, "Optics, Light and Lasers", Wiley-VCH, Weinheim 2004
- AL Schawlow and C.H. Townes, « Infrared and Optical Masers », Phys. Rev. 112, 1940 (1958)
- C.E. Wieman and L. Hollberg, « Using diode lasers for atomic physics », Rev. Sci. Instrum. **62**, 1-20 (1991)
- J.L. Hall, « Nobel lecture: Defining and measuring optical frequencies », Rev. Mod. Physics **78**,1279-1295 (2006)
- Ch. Chardonnet, « Laser monofréquence et stabilisation » dans *Les lasers et leurs applications scientifiques et médicales*, école d'été Cargèse, EDP Sciences 1996

Le laser

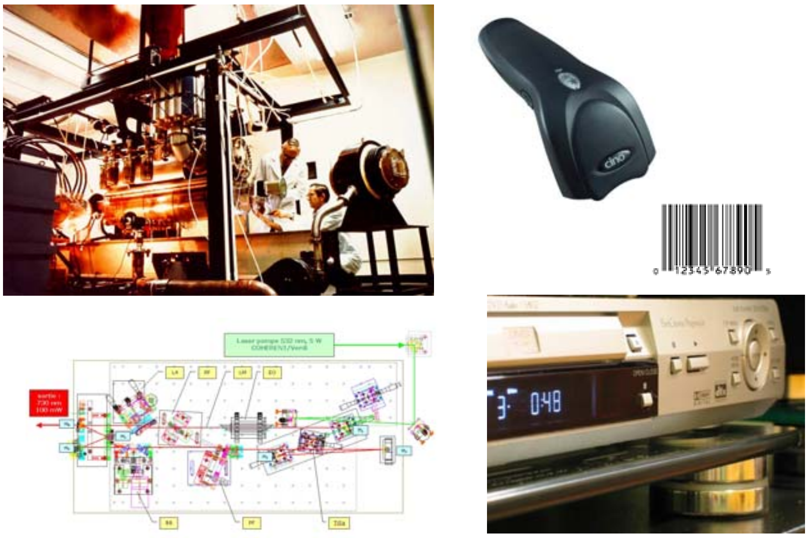
de la mémoire à la lecture optique…



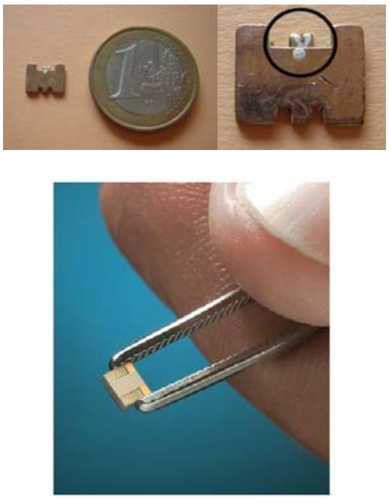
Introduction – *De la recherche fondamentale aux applications industrielles*

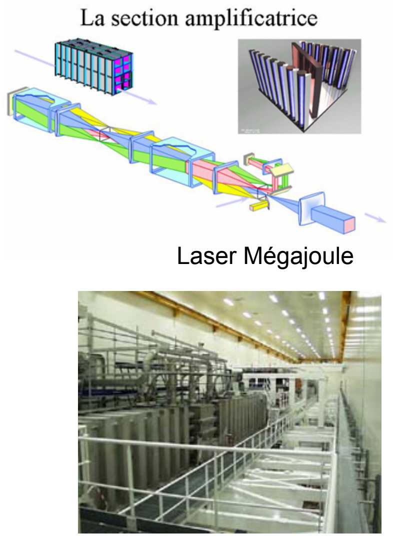
Laser beam reshaping the cornea during LASIK procedure

Introduction – *Du prototype aux applications « grand public »*



Introduction – *Du plus petit au plus grand*





Introduction - *Historique*

Étapes dans la conception et la réalisation du laser

1905 : Einstein : émission stimulée

≈1950 : Schawlow et Townes :
Utilisation d'une cavité Fabry-Perot
1958: Schawlow et Townes : Maser
à Ammoniac

1960 Maiman : Laser à Rubis

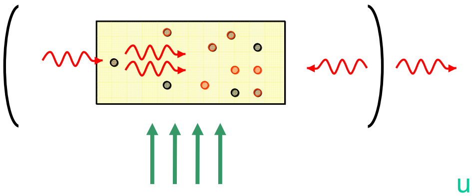
1970 : Laser à semi-conducteurs

Le laser

Light **A**mplification by **S**timulated **E**mission of **R**adiation

Émission stimulée

Cavité (rétroaction)



Pompage (électrique, optique ...)
→ Inversion de population
→ milieu amplificateur

un gain supérieur aux pertes
$g(\omega) > T+A$

Caractéristiques du laser

- Concentration dans l'espace
- Concentration en direction
- Concentration dans le spectre

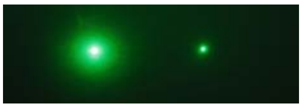
Caractéristiques du laser

concentration dans l'espace

Éclairement: puissance par unité de surface [W/cm^2]

- incandescence 60W à 1m : 0.5mW/cm^2

- soleil 0.1 W/cm^2
- pointeur laser 1mW à 1m: 30 W/cm^2



- laser 100 mW focalisé (50μm) à 1m: 300 W/cm^2

Caractéristiques du laser

- Concentration en direction

La divergence d'un faisceau laser de diamètre D est

$$\theta \square \frac{\lambda}{D} = 10^{-6}$$

Télémetrie laser

faisceau laser: laser Nd:YAG doublé (1064nm, 532 nm),

- impulsions de 200ps, 10 tirs par seconde, energie 200mJ+200mJ,
- diamètre sur la lune ~2,5 km,
- diamètre théorique 1,3 km (sans perturbations par l'atmosphere).

Caractéristiques du laser

- Concentration en fréquence
- Energie concentré dans un mode

Nombre de photon par mode

- Laser N = 10^{10}- 10^{20} photons/mode
- Source thermique

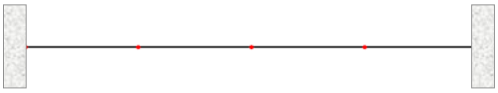
$$N = \frac{1}{\exp\left\{\frac{\hbar\omega}{k_B T}\right\} - 1} \square \exp\left\{-\frac{\hbar\omega}{k_B T}\right\}$$

0.1 photon/mode à 633 nm à 300K

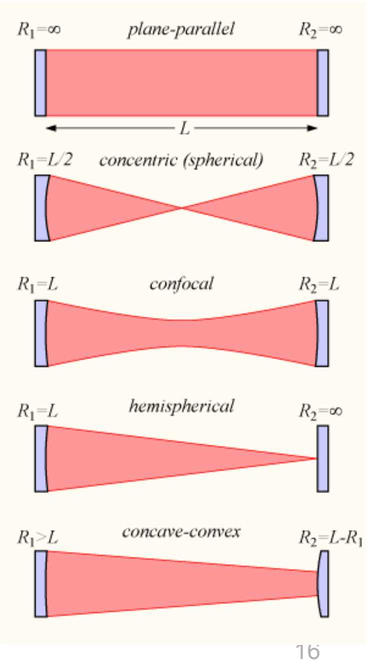
Sécurité laser

Risques
dermatologiques
et
ophtalmologiques

La cavité optique



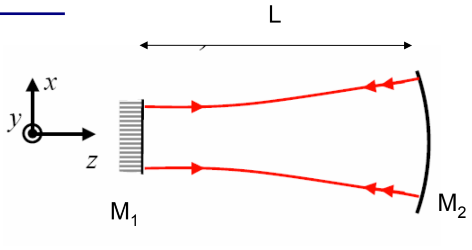
- onde stationnaire
- composé d'au moins deux miroirs
- reglé à mieux que $\lambda/2$
- la qualité de la cavité dépend du coefficient de reflexion des miroirs



La cavité optique

Condition de stabilité

$$0<\left(1-\frac{L}{R_1}\right)\left(1-\frac{L}{R_2}\right)<1$$



Modes de Hermite-Gauss

$$u_{m,n,p}(x,y,z)=A\exp\left\{-\frac{x^2+y^2}{w(z)^2}\right\}H_m\left(\frac{x\sqrt{2}}{w(z)}\right)H_p\left(\frac{y\sqrt{2}}{w(z)}\right)\cos\left(\frac{\omega_p}{c}z+\Phi(z)\right)$$

Polynômes d'Hermite
$H_0(u)=1$
$H_1(u)=2u$
$H_2(u)=4u^2-2$

Inversion de population

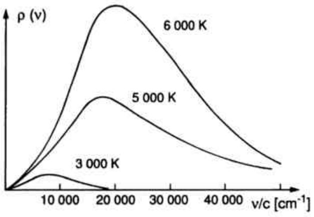


Fig. 2.2. Spectral distribution of the energy density $\rho_\nu(\nu)$ for different temperatures

$$\rho(\upsilon)\,d\upsilon=\frac{8\pi\upsilon^2}{c^3}\cdot\frac{h\upsilon}{e^{-h\upsilon kT}-1}\,d\upsilon$$

Loi de Planck

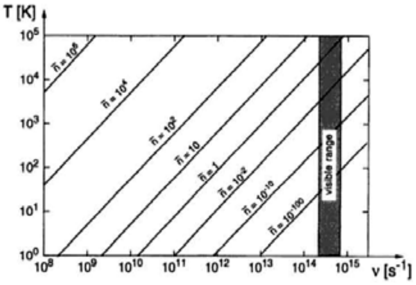
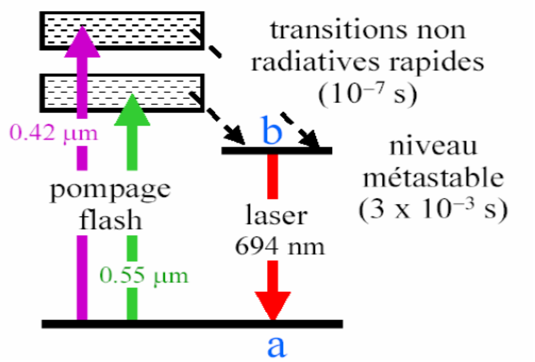


Fig. 2.5. Average number of photons per mode in a thermal radiation field as a function of temperature T and frequency ν

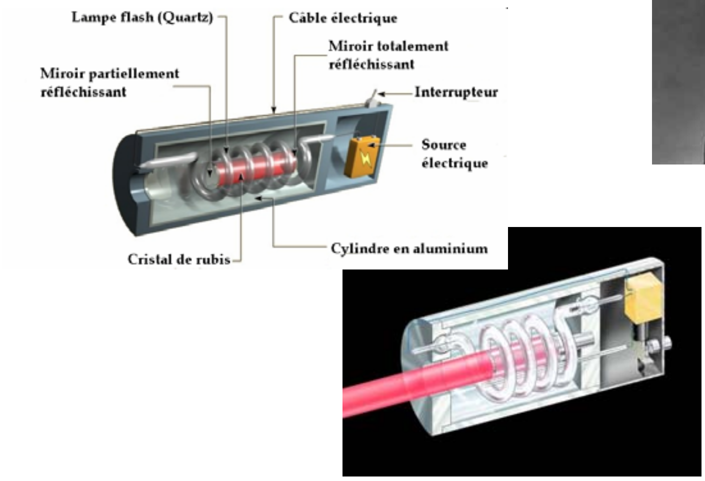
Systèmes à 3 niveaux

Rubis : ion Cr^{3+} en substitution de Al^{3+} dans matrice d'alumine

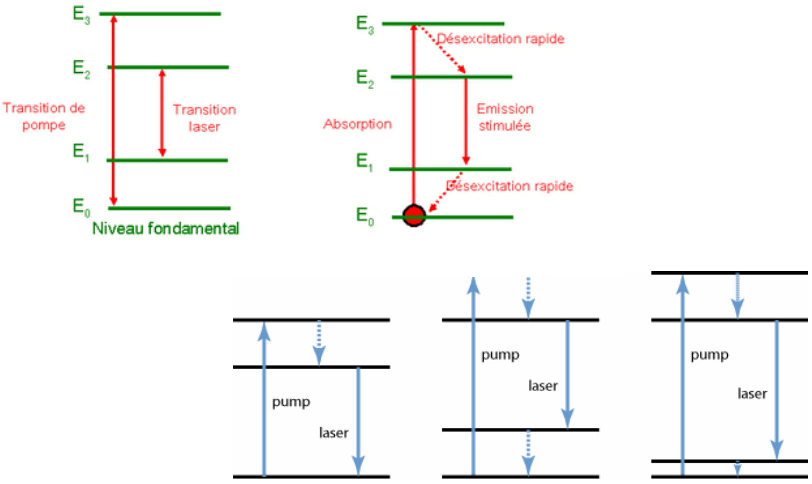


Theodore Maiman

Hughes Research Labs , mai 1960

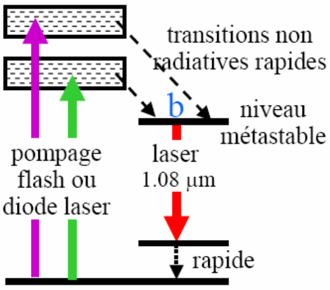


Système à 4 niveaux



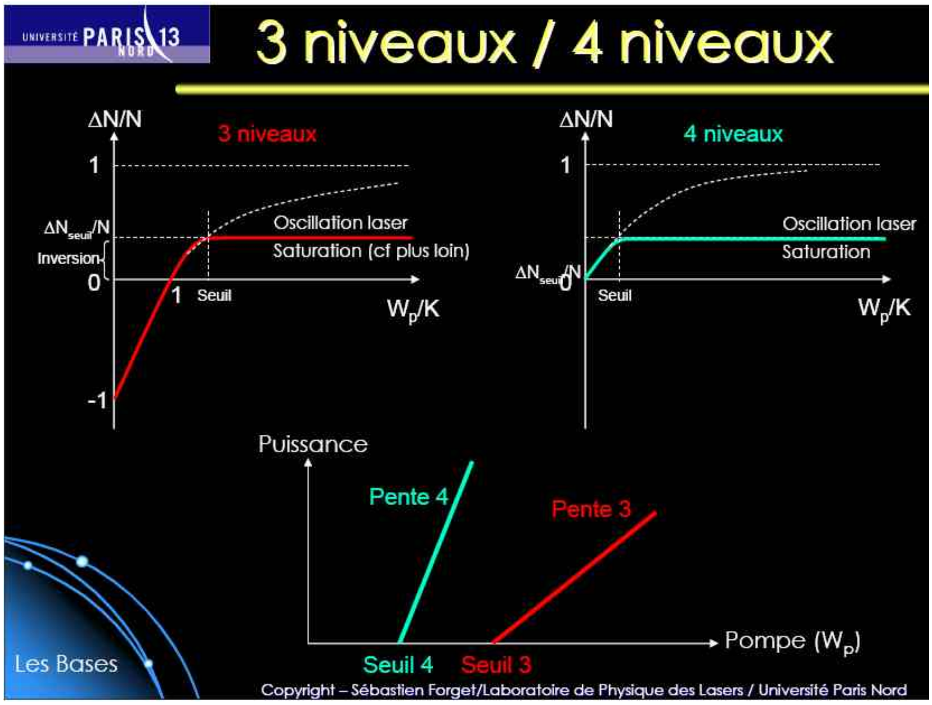
Système à 4 niveaux

Néodyme YAG (ou verre)



« Facile » à doubler

⇒ vert à 540 nm



3 niveaux / 4 niveaux

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Elements d’un laser

- Filtre de Lyot
- Diode optique
- Etalon (fin ou epais)
- Prisme (correction d’astigmatisme)
- Output coupler
- Milieu amplificater
- Tweeter

Bruits fondamentaux et largeur de raie

Laser noise

- Two groups of origins

  * **quantum noise,** in particular associated with spontaneous emission in the gain medium

  * **technical noise,** arising e.g. from excess noise of the pump source, from vibrations of the laser cavity, or from temperature fluctuations

- Laser noise is an issue in many applications. Some examples are:

  * High precision optical measurements, e.g. in frequency metrology, precision spectroscopy or interferometry, require low intensity and phase noise.
  * The achievable data transmission rates of optical fiber communications systems are usually limited by noise of lasers and amplifiers.

Laser noise

Noise in **cw lasers:**

- Frequency
- phase (linewidth), limits of temporal coherence
- amplitude/intensity

multimode laser : mode partition noise (few modes, higher-order transverse modes)

in **pulsed and mode-locked lasers**

- timing jitter
- pulse energy
- pulse duration
- chirp
- phase
- supermode noise in harmonic mode locking

beam pointing fluctuations.

There may be **coupling** between the different parameters

Noise contributions

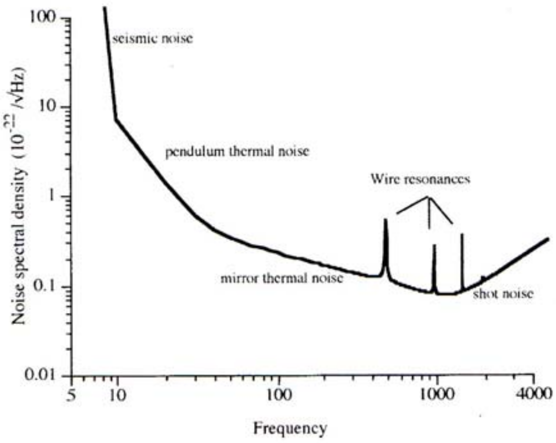

Figure 1. Fundamental noise limits for an hypothetical long baseline laser interferometer (including the effects of support wire resonances). It has been assumed that the effects of quantum light pressure are negligible at the predicted power level.

Laser noise analysis

Characterization of noise

- colour
- stationarity
- statistical properties
- periodicity

Measures

- Intensity noise: measurements e.g. with photodiodes or photomultiplier tubes
- Phase noise: beating with reference laser; heterodyne measurement with unbalanced Mach-Zehnder interferometer
- Timing jitter of mode-locked lasers: various measurement schemes exist - high demands for low jitter levels!

Quantum noise

•While the noise performance of electronic systems is often limited by thermal noise, **quantum-mechanical effects often set the limits for optical systems**.

(high optical frequencies, the photon energy in the optical domain is much higher than the thermal energy k_BT *at room temperature.)*

In QM, the electric field of a light beam is described by quantum-mechanical operators, and the outcome of optical measurements does not simply reflect the expectations values of these operators, but is also subject to **quantum fluctuations.**

Light with unusual quantum noise properties is called nonclassical light and occurs e.g. in the form of **squeezed light**.

Quantum noise is often a limiting factor for the performance of optoelectronic devices. However, it can occasionally be useful, e.g. in quantum cryptography.

vacuum fluctuations can get into the cavity e.g. through the output coupler mirror, but also at any other location where optical losses occur.

•S. Reynaud and A. Heidmann, "A semiclassical linear input output transformation for quantum fluctuations", Opt. Commun. 71 (3-4), 209 (1989)

Fundamental limits (QNL)

Schawlow-Townes linewidth : linewidth of a single-frequency laser with quantum noise only

Even before the first laser was experimentally demonstrated, A. L. Schawlow and C. H. Townes calculated the fundamental (quantum) limit for the linewidth of a laser. This lead to the famous Schawlow-Townes formula:

$$\Delta\nu_L = \frac{\pi h\nu\left(\Delta\nu_c\right)^2}{P_{out}}$$

with the photon energy $h\nu$, the cavity bandwidth $\Delta\nu_c$ (full width at half maximum), and the output power P_{out}. It has been assumed that there are no parasitic cavity losses. (Compared with the original formula, a factor 4 has been removed because of a different definition of the cavity bandwidth.)

References [1] A. L. Schawlow and C. H. Townes, "Infrared and optical masers", Phys. Rev. 112 (6), 1940 (1958)

Fundamental limits (QNL)

Carefully constructed solid state lasers can have very small linewidths in the region of a few kHz, which is still significantly above their Schawlow-Townes limit. The linewidth of semiconductor lasers is also normally much larger than according to the formula; this is caused by amplitude-to-phase coupling effects, quantified by the linewidth enhancement factor.

Example for Schwalow-Townes-linewidth

- HeNe: 633 nm (5.10^{14} Hz), $\Delta\nu_c$= 1MHz, P=1mW : $\Delta\nu_L$ **=5.10^{-4} Hz**
- Ar^+-laser : 6.10^{14} Hz, $\Delta\nu_c$= 3MHz, P=1W : $\Delta\nu_L$ **=5.10^{-5} Hz**

Today, $\Delta\nu_L$ = 10 kHz « easily », $\Delta\nu_L$ = 1Hz with a lot of work

Phase noise

Noise in oscillator systems characterized by

- **long-term frequency stability:** usually on min, h, given in □f/f (for a given period/bandwidth (*see next chapter)*

- and **short-term frequency stability:** random or periodic fluctuations over periods less than a second
  - due to **quantum noise**, in particular spontaneous emission of the gain medium into the cavity modes, but also quantum noise associated with optical losses. In addition, there can be **technical noise** influences, e.g. due to vibrations of the cavity mirrors or to temperature fluctuations.
  - leads to a **finite linewidth** of the laser output. The same applies to the frequency components of the output of a mode-locked laser,

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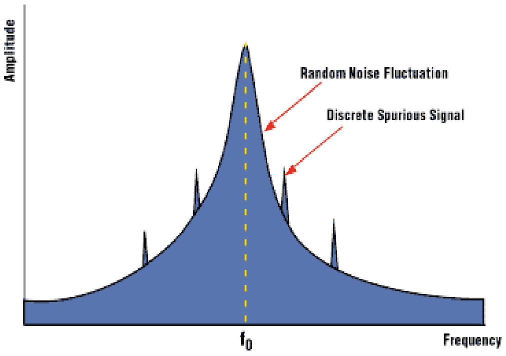
Phase noise



The ideal oscillator : $V(t)=V_0\sin(□t)$

the instantaneous output of a fluctuating oscillator: $V(t)=V_0[1+A(t)]\sin(□t+q(t))$

q(t) discrete : spurious signal, discrete components

q(t) random : line broadening

Phase noise - *sources*

- dephasing in the laser amplifier medium
- dephasing at the mirrors (δL)

$$\delta\varphi_m = \frac{2\omega_0 \delta L}{c} = \frac{2\delta L}{\lambda}$$

with ω_0 the unmodulated laser oscillation frequency

- axial phase shift: the Guoy effect (up to 2 Rayleigh ranges off the waist)
- coupling of intensity noise to phase noise, e.g. via nonlinearities
- build-up

Phase noise

Phase noise can be quantified by the power spectral density of the phase deviations. Phase noise is measured in the frequency domain, and is expressed as a ratio of signal power to noise power measured in a 1 Hz bandwidth at a given offset from the desired signal. This power spectral density often diverges for zero frequency.

Example

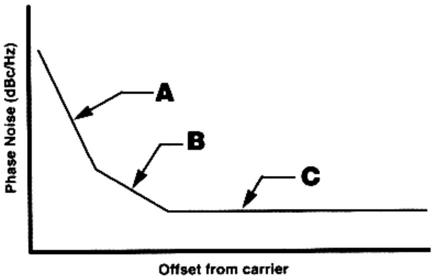


Figure 1

A: flicker; B: 1/f; C: white/broadband noise

Frequency noise

Frequency noise is noise of the instantaneous frequency of an oscillating signal. The instantaneous frequency is defined as

$$\nu(t) = \frac{1}{2\pi}\frac{d\phi}{dt}$$

The power spectral density of frequency noise is directly related to that of the phase noise:

$$S_\nu(f) = f^2 S_\phi(f)$$

This means that e.g. white frequency noise corresponds to phase noise with a power spectral density proportional to $1/f^2$. (example: a single-frequency laser which is only subject to quantum noise and exhibits the Schawlow-Townes linewidth)

Numerical processing of frequency noise rather than phase noise can have technical advantages in certain situations.

Laser noise - reduction

- Laser noise can be reduced in many ways. Basically one has the following options:

* reducing **quantum noise** e.g. by increasing the intracavity power level and by minimizing losses

* reducing **technical noise** influences (e.g. by building a stable laser cavity, by temperature stabilization of the setup, or by using a low-noise pump source)

* **optimizing laser parameters** so that the laser reacts less strongly to noise influences

* using **active** or **passive** stabilization schemes

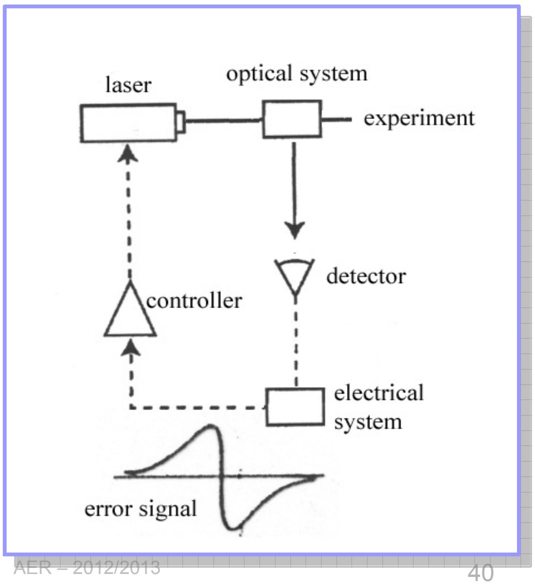
Stabilisation en fréquence

- Causes
  - variations de température
  - fluctuations de courant
  - vibrations mécaniques
  - effet Doppler

pré-requis

- Pourquoi stabiliser ?
  - mesures interférométriques
  - oscillateurs ultra-précis (horloges)
  - stabilité de l'environnement expérimental (repétabilité)

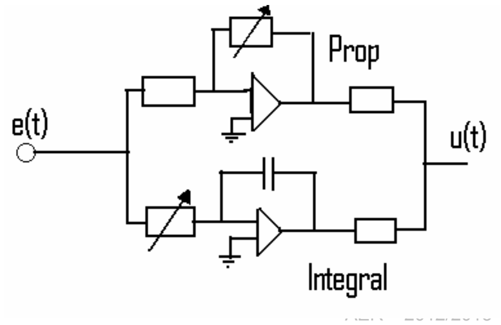
Schéma de principe



Système de contrôle

- A proportional integral control loop has a voltage function of:

$$u(t)=k_p\left[e(t)+\frac{1}{T_i}\int_0^t e(\tau)\,d\tau\right]$$



It amplifies the signal proportionally and adds the average signal of the integration time

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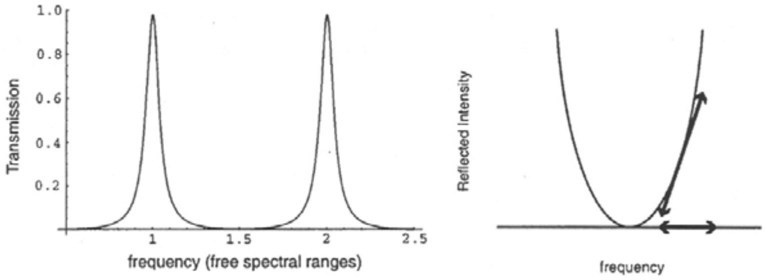
Noise reduction - *frequency*



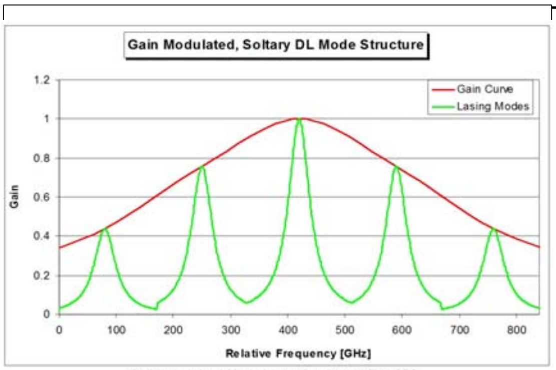
Frequency stabilisation can be done by actively controlling the laseroutput of a Fabry-Perot cavity to an amount of reflected intensity.

Disadvantage is that, in this case, output intensity changes cause the same signal as frequency instabilities.

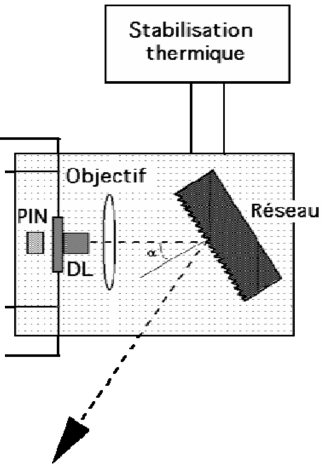
Solution: Modulate the signal, make a derivative of the profile and create an error signal around a zero offset.

Stabilisation en fréquence

- par feedback optique *sur un reseau*



Solitary modes AM modulated by gain profile of DL.



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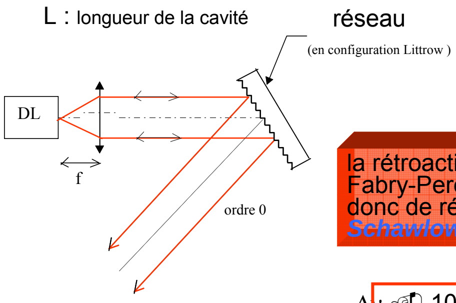
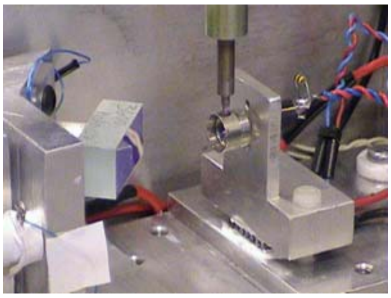
stabilisation en fréquence :
réduction des fluctuations de fréquence du laser

réduction de la largeur de raie
par une **rétroaction optique**





la rétroaction optique par un réseau, une cavité Fabry-Perot …. permet d'allonger la cavité et donc de réduire la largeur de raie (limite de ***Schawlow-Townes)***

Δν 📫 100 kHz (fluctuations mécaniques)

ces diodes laser sont dites « en cavité étendue »

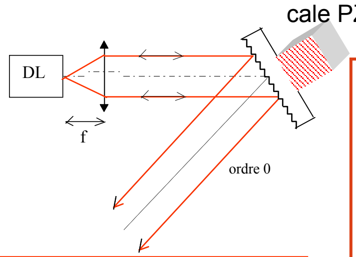
stabilisation en fréquence :
réduction des fluctuations de fréquence du laser

réduction de la largeur de raie par une **rétroaction électronique**

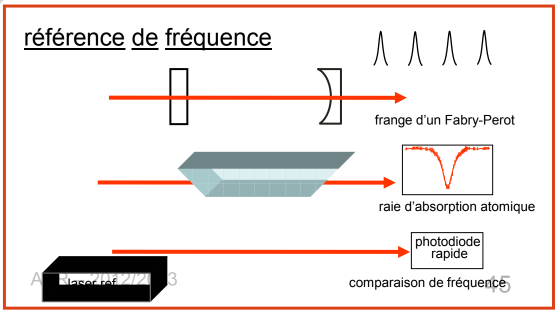
sur - la longueur de la cavité étendue (cale PZT)
- le courant d'alimentation de la jonction

corrections BF

corrections HF



largeur de raie instantanée
$\Delta\nu < 1\text{kHz}$
stabilité …celle de la référence


référence de fréquence

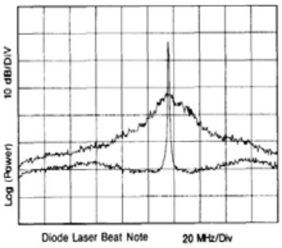
frange d'un Fabry-Perot

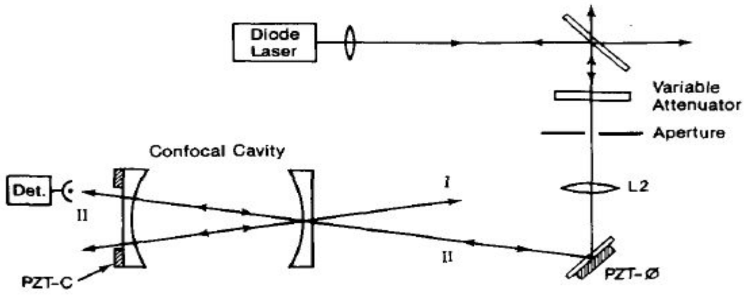
raie d'absorption atomique

comparaison de fréquence

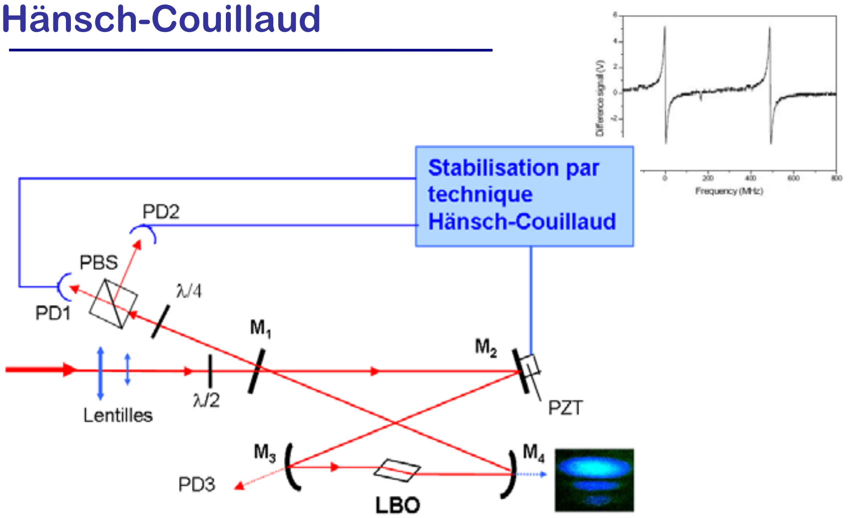
Stabilisation en fréquence

- par feedback optique *sur une cavité*





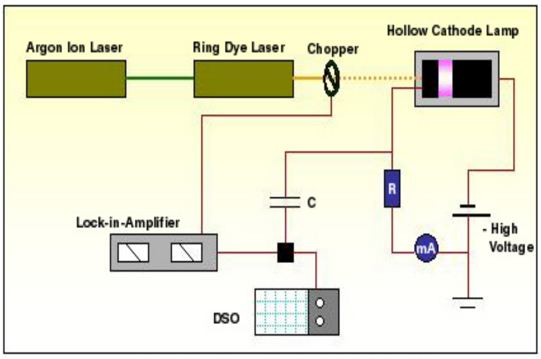
Hänsch-Couillaud



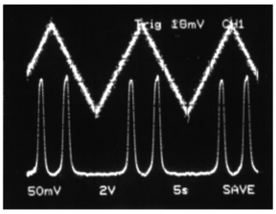
T.W. Hänsch, B. Couillaud, « Laser frequency stabilization by polarization spectroscopy of a reflecting reference cavity », Optics Communications **35**, pp. 441-444 (1980)

Stabilisation en fréquence – *sur une transition atomique*

- Par effet optogalvanique
  - Variation du courant de décharge

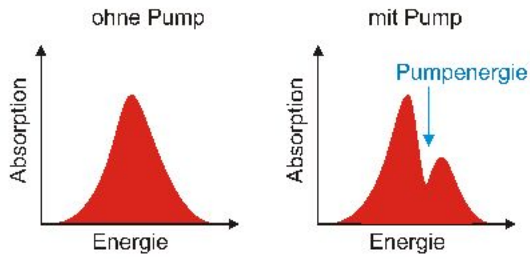


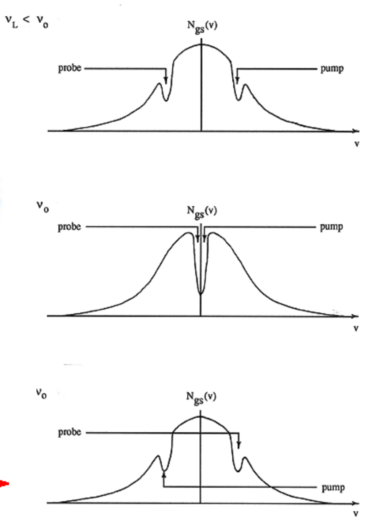
Experimental set-up for optogalvanic studies

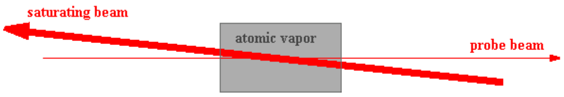


Stabilisation en fréquence – *sur une transition atomique*

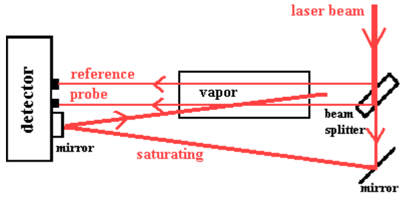
- Techniques « Doppler-free » par « spectral h burning » modification de la courbe de gain (faiscau pompe-faisceau sonde)

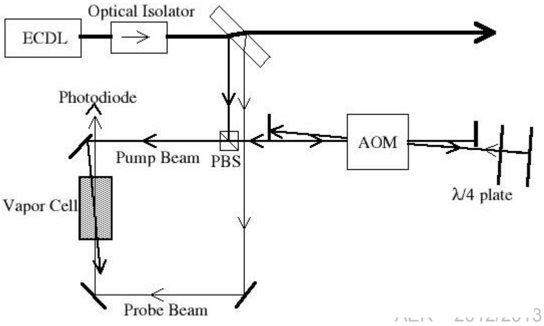


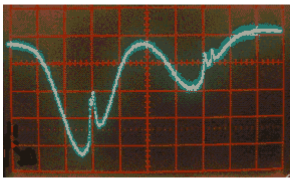




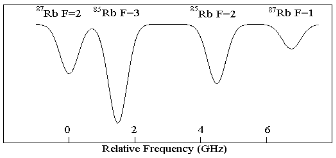
Absorption saturée







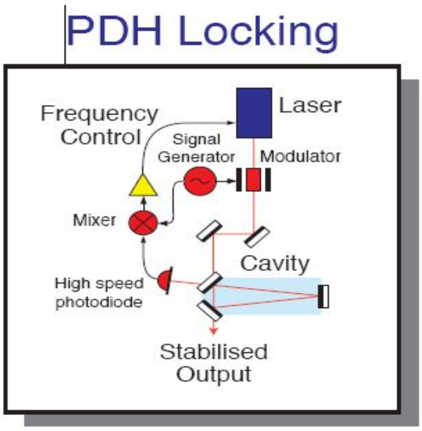
$5S_{1/2}$ to $5P_{3/2}$ transitions in ^{85}Rb and ^{87}Rb, the hyperfine structure is resolved.



Pound Drever Hall

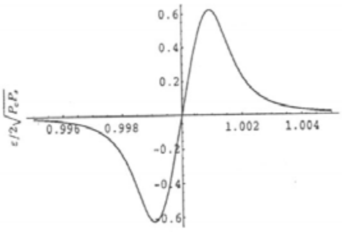
- creating an error signal by frequency modulation

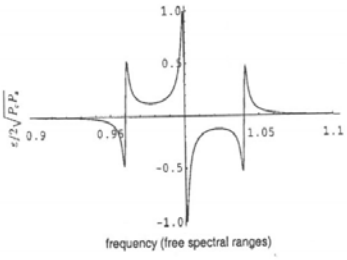
R. W. P. Drever, J. L. Hall et al., "Laser phase and frequency stabilization using an optical resonator", Appl. Phys. B 31, 97 (1983)



Pound-Drever-Hall

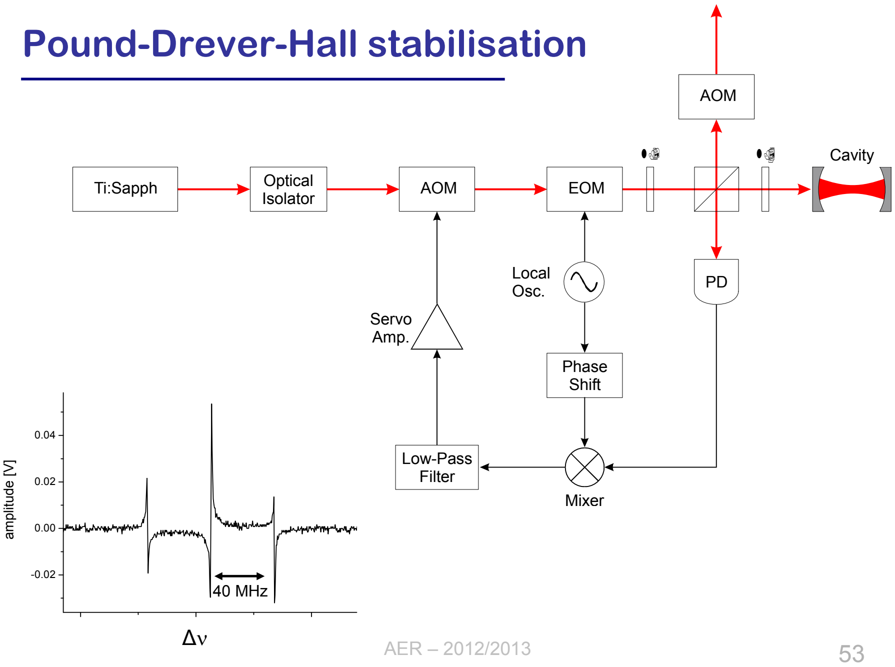
- Modulating the carrier signal sin(ϖ) with a sin(Ω) of the Pockels cell creates two sidebands sin(ϖ+Ω') and sin(ϖ-Ω').
- Multiplying this with the original sin(Ω) term in the mixer yields two terms: cos(Ω+Ω') and cos(Ω-Ω').
- cos(Ω-Ω') is a DC signal and is transmitted through the low pass filter



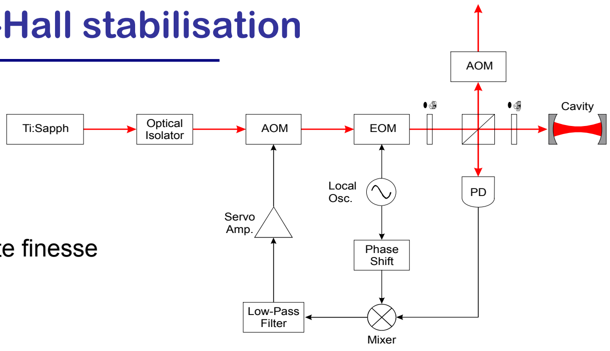


Pente porteuse ≠ pente bandes latérales

Pound-Drever-Hall stabilisation



Pound-Drever-Hall stabilisation



Sur une cavité très haute finesse
$\mathcal{F}$ > 100 000

perturbations:

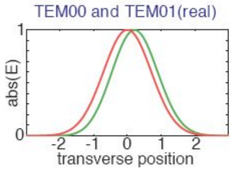
perturbations mécaniques (verticales) ≈ MHz/g

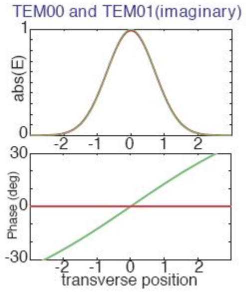
fluctuations thermiques : dans le visible 1mK → $\delta L/L \approx 10^{-12}$ (500 Hz)

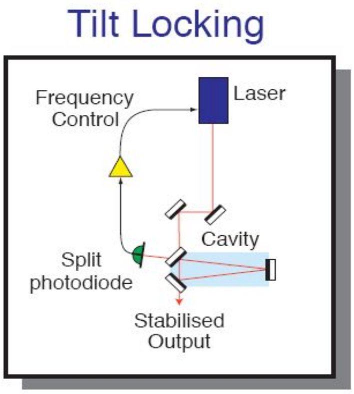
variation de la pression: n - 1 ≈ 3 x10^{-9} P
10% de 10^5 Pa → Ghz

pression de radiation: 1W → 7x10^{-9} N ==> $\delta L/L = 2\times10^{-16}$

Tilt locking

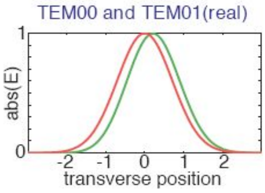


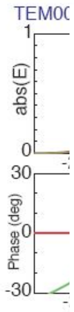


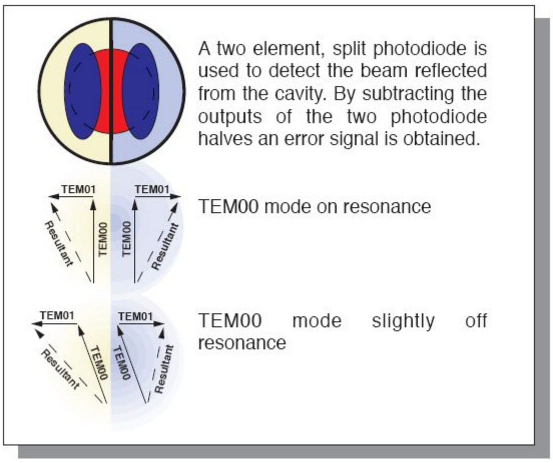


SLAGMOLEN B. J. J.; SHADDOCK D. A. ; GRAY M. B.; MCCLELLAND D. E. ;
IEEE journal of quantum electronics **38**, pp. 1521-1528 (2002)

Tilt locking







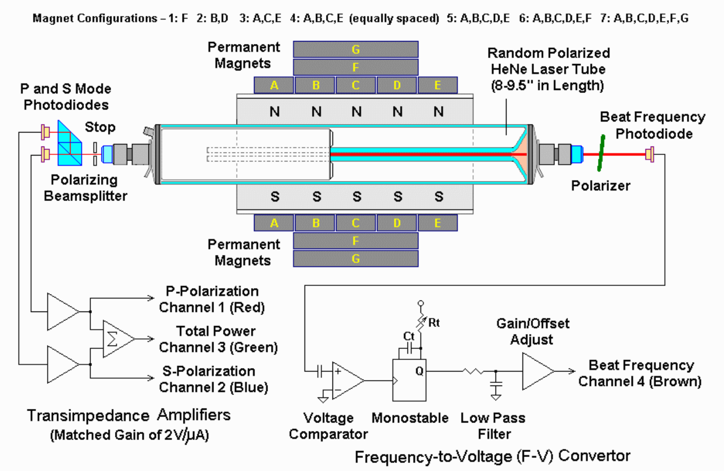
A two element, split photodiode is used to detect the beam reflected from the cavity. By subtracting the outputs of the two photodiode halves an error signal is obtained.

TEM00 mode on resonance

TEM00 mode slightly off resonance

Exemples

- HeNe stabilisé par effet Zeeman



Setup for Transverse Zeeman HeNe Laser Experiments

Bruit d' intensité

Intensity noise (amplitude noise)

Noise of the optical intensity or power of a laser beam

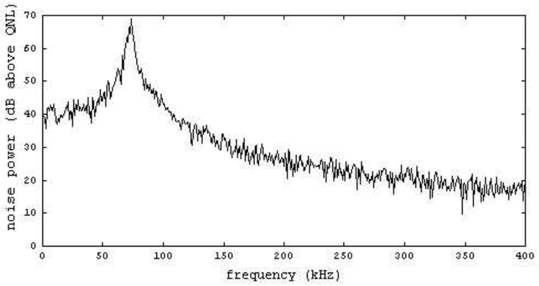
due to quantum noise (in laser gain and cavity losses) **AND**
technical noise (excess noise of pump source, vibrations of cavity mirrors, thermal fluctutations in the gain medium

Intensity noise can be **measured** e.g. by recording the measured intensity as a function of time (e.g. with a photodiode and an electronic spectrum analyzer)

Intensity noise can be quantified in the following ways:

* with an rms (root-mean-square) value (usually relative to the average power) for a certain measurement bandwidth
* as a power spectral density S(f), usually of the power relative to the average power (relative intensity noise, RIN)

Intensity noise



Intensity noise spectrum of a solid state laser. The noise level is given in decibels above the shot noise limit. There is a peak at 74 kHz, resulting from relaxation oscillations. Increased low-frequency noise is caused by excess noise of the pump source.

low-limit: shot noise. At least at high noise frequencies, well above the relaxation oscillation frequency, this noise level is approached by many lasers. However, for so-called squeezed states of light, the intensity noise can be below the shot noise, at the cost of increased phase noise.

Intensity noise

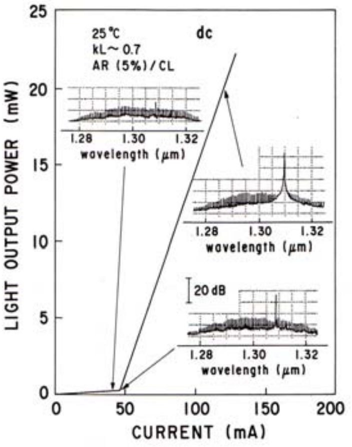
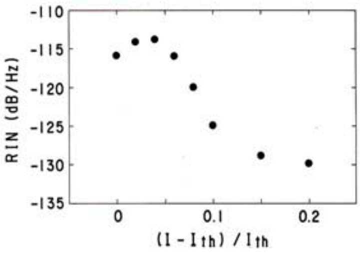


Figure 2.12 Change in emission spectra before and after lasing in a DFB laser.



ure 2.15 Intensity noise versus injection current.

Intensity noise also depends on the operation conditions; in particular, it often becomes weaker at high pump powers, where relaxation oscillations are strongly damped.

Laser TiSa doublé en fréquence