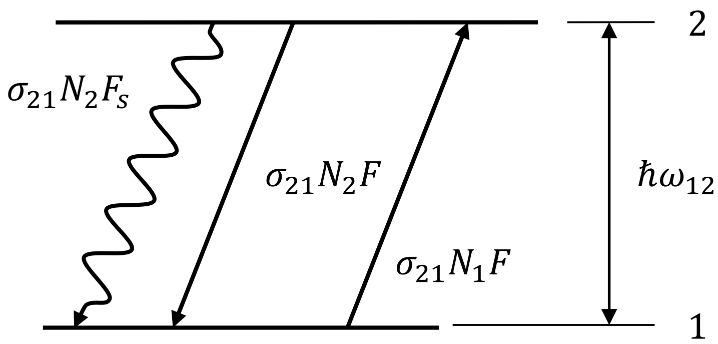
Lasers

lecture 6

Czesław Radzewicz

long pulse laser amplifier (a reminder)

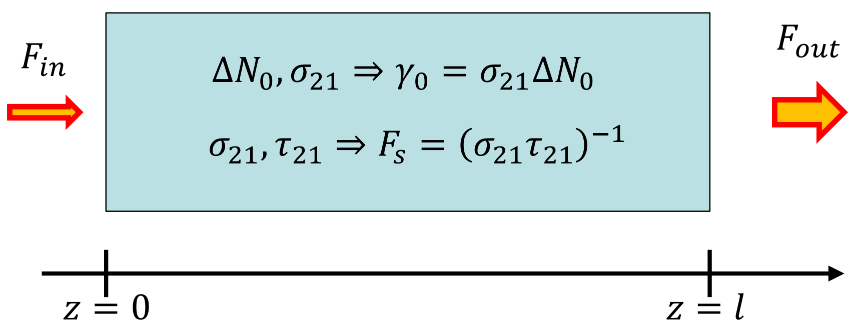


populations' dynamics:

$$\frac{dN_2}{dt} = -\frac{N_2}{\tau_{21}} + \sigma_{21} N_1 F - \sigma_{21} N_2 F + \cdots$$

$$\frac{dN_1}{dt} = \cdots$$

$$\Delta N = \cdots$$



photon flux:

$$\frac{\partial}{\partial z} F = \gamma F$$

- unsaturated amplifier:

$$\frac{\partial}{\partial z} F = \gamma_0 F \Rightarrow F(z) = F(0) \cdot e^{\gamma_0 z}$$

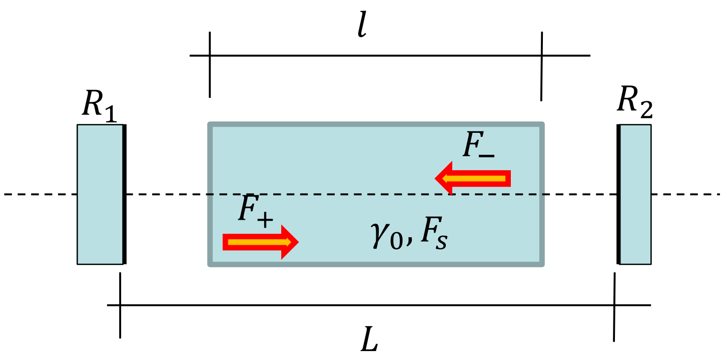
$$\Delta N(z) = \Delta N_0(z)$$

- saturated amplifier:

$$\frac{\partial}{\partial z} F = \frac{\gamma_0 F}{1 + F/F_s} \Rightarrow F(z) = \cdots$$

$$\Delta N(z) = \cdots$$

laser threshold



assumptions:

- stationary state
- stable optical resonator
- losses: (1) mirrors, (2) other
- constant intensity along and ⊥ resonator axis
- homogenous population inversion

small intensity:

photon flux change for a single round-trip:

$$F_-(l) = R_2 F_+(l)$$

$$F_-(0) = F_-(l) e^{\gamma_0 l} = R_2 F_+(l) e^{\gamma_0 l}$$

$$F_+(0) = R_1 F_-(0)$$

$$F_+(l') = F_+(0) e^{\gamma_0 l} = R_1 R_2 e^{2\gamma_0 l} F_+(l)$$

threshold condition (no losses):

$$R_1 R_2 e^{2\gamma_0 l} \geq 1$$

threshold unsaturated gain coeff.:

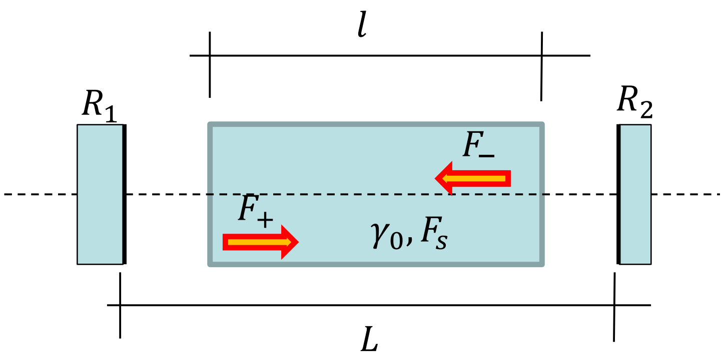
$$\gamma_0{}^t = -\frac{1}{2l} \ln(R_1 R_2)$$

To account for other losses we introduce additional attenuation coefficient inside the gain medium. For perfect mirrors ($R_1 = R_2 = 1$) we have after a round-trip the attenuation by a factor e^{2al}. Then, the full round-trip gain is $R_1 R_2 e^{2\gamma_0 l} e^{-2al}$ and the threshold condition reads

$$R_1 R_2 e^{2(\gamma_0 - a) l} \geq 1$$

which leads to $\boxed{\gamma_0{}^t = -\frac{1}{2l} \ln(R_1 R_2) + a.}$

numerical example:



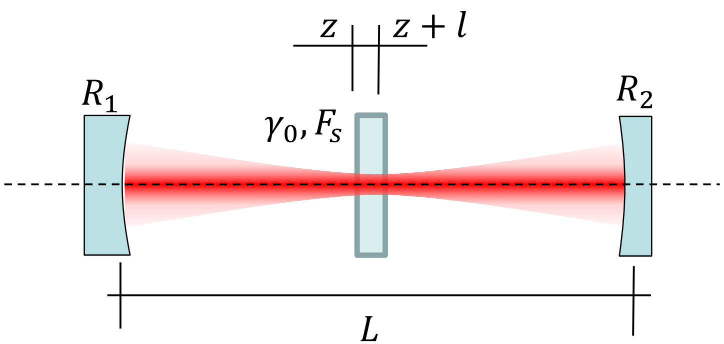
He-Ne laser :

- $l = 0.5\ \mathrm{m}, R_1 = 1, R_2 = 0.99, a \cong 0, \sigma \cong 10^{-13}\ \mathrm{cm}^2$
- ${\gamma_0}^t = \frac{1}{2l} \ln R_1 R_2 \cong 10^{-4}\ \mathrm{cm}^{-1}$
- threshold inversion: $\Delta N^t = \frac{{\gamma_0}^t}{\sigma} \cong 10^9\ \mathrm{cm}^{-3}$
- Ne atomic density $N_0 \cong 10^{17} \mathrm{cm}^3$
- very small inversion required: $\frac{\Delta N^t}{N_0} \cong 10^{-8}$

threshold condition – are the assumptions right?

assumptions:

- stationary state OK
- stable optical resonator OK
- losses: (1) mirrors, (2) other OK
- constant intensity along and ⊥ resonator axis NO
- homogenous population inversion ???



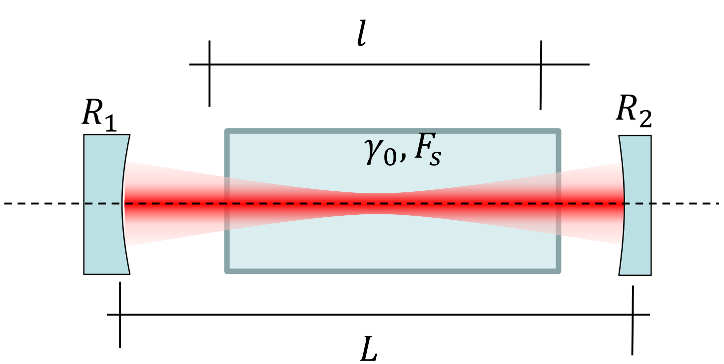
resonator mode $\Rightarrow F(x, y, z)$

gain coefficient distribution $\Rightarrow \gamma_0(x, y, z)$

- short amplifier

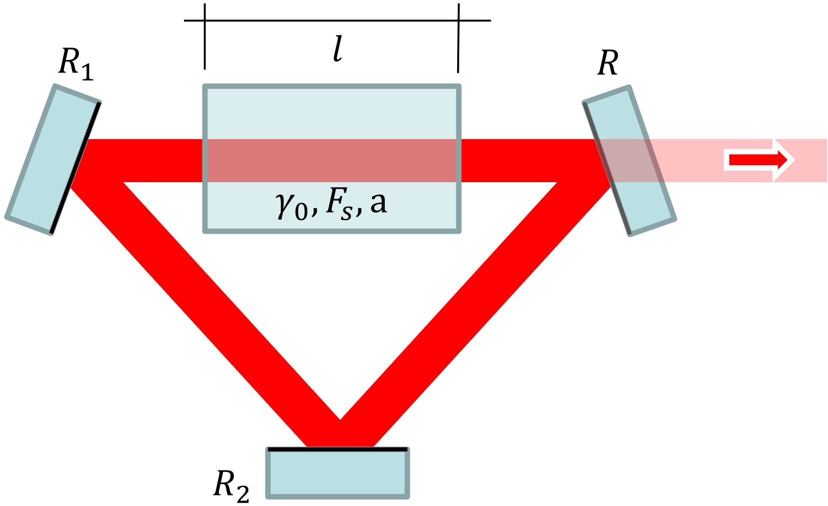
for TEM_{mn} the condition $z_0 \gg l$ is held, we neglect the mode change within the distance l:

$$F(x, y, z + l) \cong e^{\gamma_0(x,y,z)l} F(x, y, z)$$



- long amplifier; propagation and amplification cannot be untangled because the mode within the gain medium changes its size $\Rightarrow$ full 3D integration required

output intensity and power for a ring resonator, continuous wave (cw) operation



assumptions:
- resonator length L
- $R_1 = R_2 = 1, T = 1 - R$
- extra losses a
- lasing in one direction only
- constant intensity along and ⊥ resonator axis, cross-section area S
- homogenous population inversion
- homogenous line broadening, single-mode operation
- „closed" resonator $T \ll 1$

photon flux **inside** the resonator $F(z)$
stationary state $dF/dt = 0$

$$\gamma_0{}^t = -\frac{1}{l}\ln R + a \cong \frac{1}{l}(1 - \mathrm{R}) + \mathrm{a} = \frac{T}{l} + \mathrm{al}$$

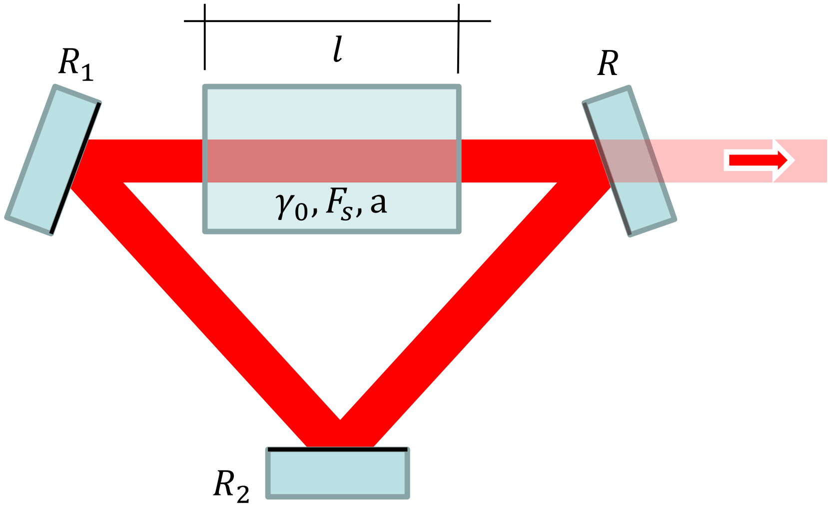
constant intensity along the resonator axis $F(z) = F_{int} \cong$ const gives

$$\gamma(z) = \frac{\gamma_0}{1 + F_{int}/F_s} = const$$

stationary state: $\gamma(z) = \gamma_0{}^t$

$$\frac{\gamma_0}{1 + F_{int}/F_s} = \frac{T}{l} + \mathrm{a} \Rightarrow F_{int} = F_s\left(\frac{\gamma_0 l}{T + al} - 1\right)$$

output intensity and power for a ring resonator, cw , 2



$$F_{int} = F_s\left(\frac{\gamma_0 l}{T + al} - 1\right)$$

new parameters: $g_0 \equiv \gamma_0 l,\ s_0 \equiv al$

$$F_{int} = F_s\left(\frac{g_0}{T + s_0} - 1\right)$$

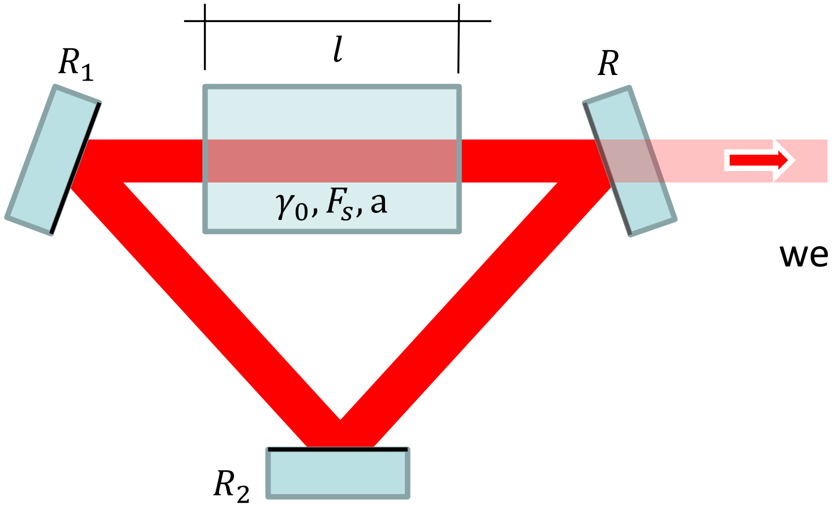
$$F_{out} = T \cdot F_{int} = TF_s\left(\frac{g_0}{T + s_0} - 1\right)$$

output power:

$$\boxed{P = TI_s\left(\frac{g_0}{T + s_0} - 1\right)S}$$

beam cross-section

optimal output coupler for a ring resonator and cw operation



$$P = TI_s\left(\frac{g_0}{T+s_0} - 1\right)S$$

we search for the maximum of P versus T:

$$\frac{dP}{dT} \propto \frac{g_0}{T+s_0} - 1 - \frac{g_0}{(T+s_0)^2} = 0$$

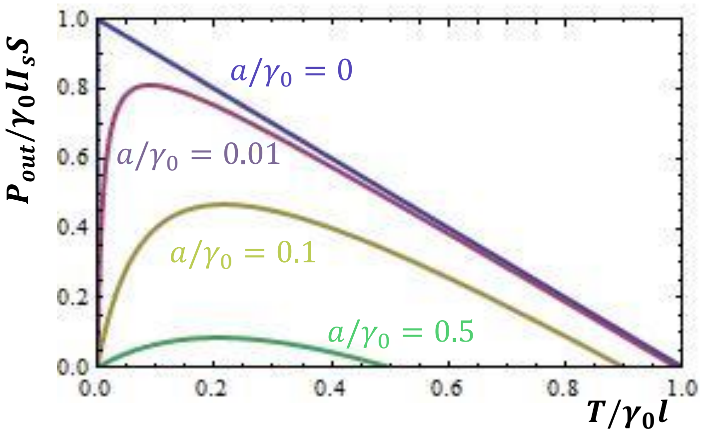
$$(T+s_0)^2 - g_0 s_0 = 0$$

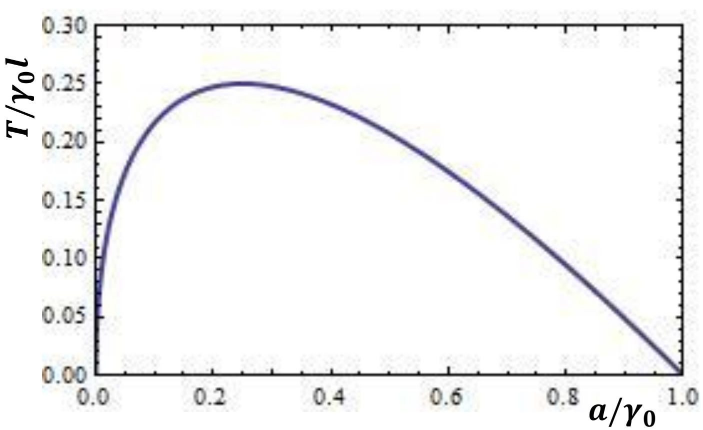
$$\boxed{T_{opt} = \sqrt{g_0 s_0} - s_0}$$

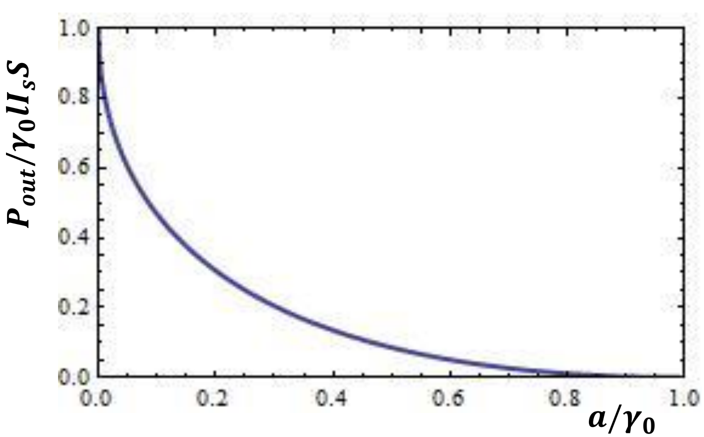
$$P_{out}{}^{opt} = (\sqrt{g_0 s_0} - s_0)I_s\left(\frac{g_0}{\sqrt{g_0 s_0}} - 1\right)S =$$

$$= I_s S(\sqrt{g_0} - \sqrt{s_0})^2 = I_s S \gamma_0 l \left(1 - \sqrt{\frac{a}{\gamma_0}}\right)^2$$

optimal output coupler for a ring resonator and cw operation – some graphs







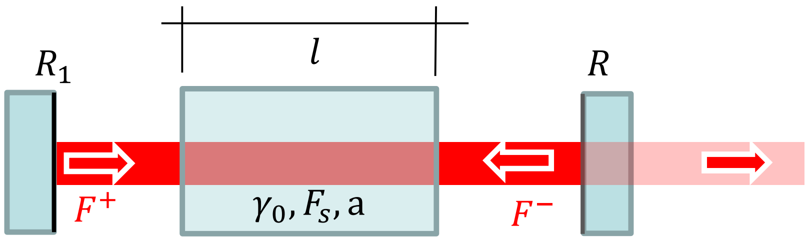
$$P = T I_s \left(\frac{\gamma_0 l}{T + a l} - 1 \right) S$$

$$T_{opt} = \sqrt{g_0 s_0} - s_0$$

$$P_{out}{}^{opt} = I_s S \gamma_0 l \left(1 - \sqrt{\frac{a}{\gamma_0}} \right)^2$$

any losses inside the resonator are very painful!

laser output power, cw, „closed" linear resonator



assumptions:

- resonator length L
- $R_1 = 1, T = 1 - R$
- extra losses a
- constant intensity along and ⊥ resonator axis, cross-section area S
- homogenous population inversion
- homogenous line broadening, single-mode operation
- „closed" resonator $T \ll 1$

2 photon fluxes inside the resonator $F^+(z)$ oraz $F^-(z)$

stationary state $dF^+/dt = dF^-/dt = 0$

$$\gamma_0{}^t = -\frac{1}{2l}\ln R + a \cong \frac{1}{2l}(1 - \mathrm{R}) + \mathrm{a} = \frac{T}{2l} + \mathrm{a}$$

$$F^+(z) = F^-(z) \cong \mathrm{const}$$

then $\gamma(z) = \gamma = \frac{\gamma_0}{1 + {(F^+ + F^-)}/{F_S}} = \frac{\gamma_0}{1 + {2F^+}/{F_S}}$

more algebra:

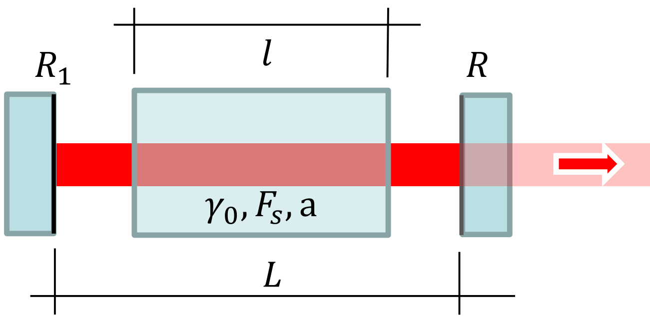
$$\frac{\gamma_0}{1 + 2F^+/F_s} = \frac{T}{2l} + \mathrm{a} \Rightarrow F^+ = \frac{1}{2}F_s\left(\frac{2\gamma_0 l}{T + 2al} - 1\right)$$

$$T_{opt} = 2\left(\sqrt{g_0 s_0} - s_0\right),$$

$$\boxed{P_{out}{}^{opt} = \frac{1}{2} I_s S \gamma_0 l \left(1 - \sqrt{\frac{a}{\gamma_0}}\right)^2}$$

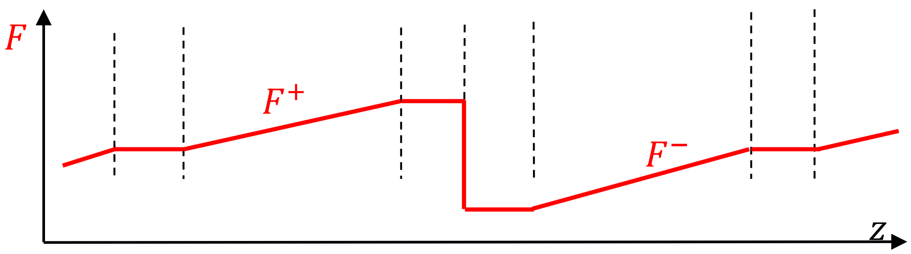
note: a standing wave inside the resonator

laser output power, cw, „open" linear resonator



assumptions:

- $R_1 = 1, T = 1 - R$
- extra losses a
- constant intensity in the plane ⊥ resonator axis, cross-section area S
- homogenous population inversion
- homogenous line broadening, single-mode operation



inside the gain medium

$$\frac{1}{F^+}\frac{dF^+}{dz} = \gamma(z) - a$$
$$\frac{1}{F^-}\frac{dF^-}{dz} = a - \gamma(z)$$

let's note that:

$\frac{d}{dz}(F^+F^-) = F^+F^-\left(\frac{1}{F^+}\frac{dF^+}{dz} + \frac{1}{F^-}\frac{dF^-}{dz}\right) = 0$ and thus $F^+F^- = C$
which means that

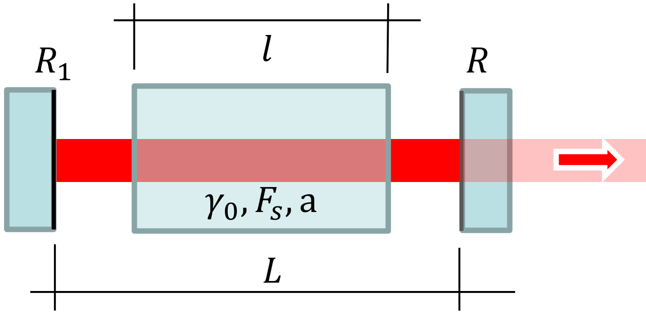
$$\frac{1}{F^+}\frac{dF^+}{dz} = \frac{\gamma_0}{1 + {(F^+ + F^-)}/{F_s}} - a = \frac{\gamma_0}{1 + {(F^+ + C/F^+)}/{F_s}} - a$$
$$\frac{1}{F^-}\frac{dF^-}{dz} = \frac{\gamma_0}{1 + {(F^- + C/F^-)}/{F_s}} - a$$

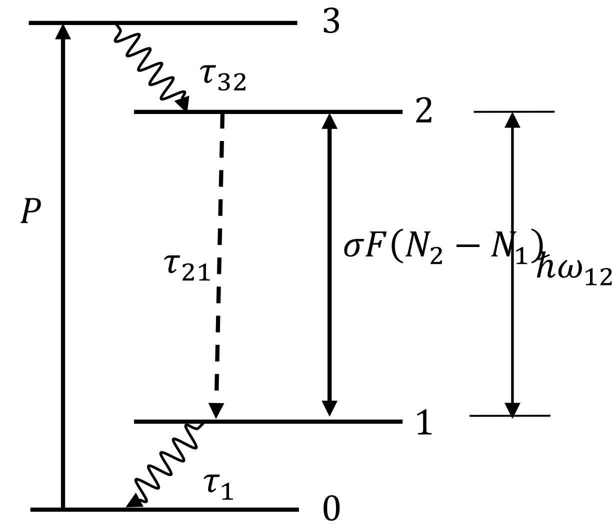
+ border conditions

algebra…

$$F_{out} = TF^+$$
$$F_{out} = \frac{1}{2}\frac{T\ln(1 - T - s_0)^{-1}}{T + s_0}\left[\frac{g_0}{\ln(1 - T - s_0)^{-1}} - 1\right]$$

laser output power vs pump power





we will consider a 4-level system pumped optically by another lasers beam. From lecture 4:

$$\Delta N_0 = \frac{P(\tau_{21} - \tau_1)}{1 + P(\tau_{21} + \tau_1)} N$$

for moderate pumping rate $P(\tau_{21} + \tau_1) \ll 1$ we have

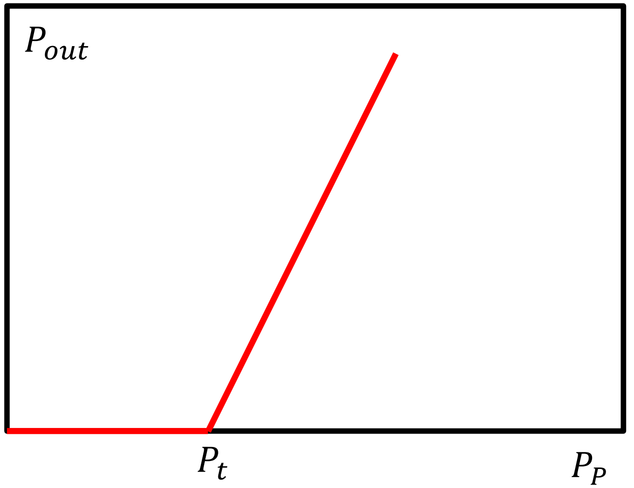
$$\gamma_0 = \sigma \Delta N_0 \propto P$$

the pump rate P is proportional to the power of the pump laser P_P

$$F_{out} = T \cdot F_{int} = T F_s \left(\frac{\gamma_0 l}{T + s_0} - 1 \right)$$

$$F_{out} = \kappa \left(\frac{P_P}{P_t} - 1 \right)$$

P_t - threshold power of the pump laser



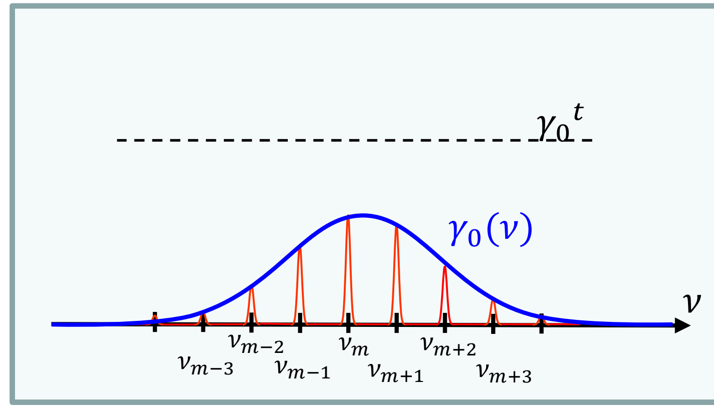
threshold power P_t
slope efficiency %

cw laser spectrum, homogenous line broadening

in a cw laser we have (always)

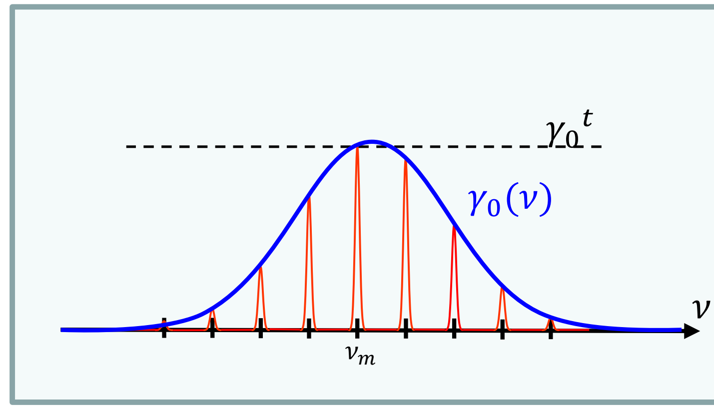
gain = losses

below the
laser threshold
$\gamma_0 < {\gamma_0}^t$



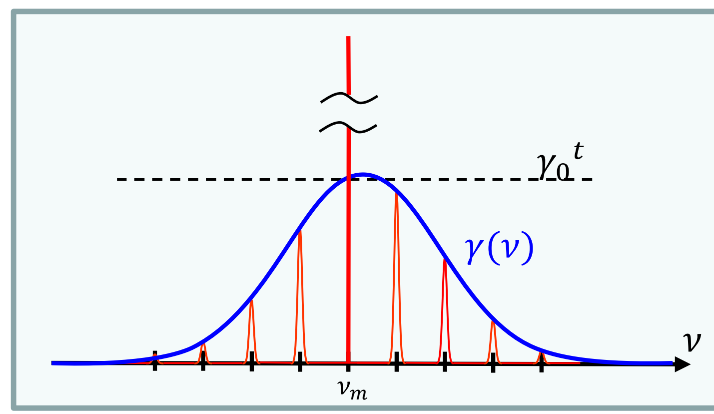
the gain is clamped at the threshold value for the mode which reached lasing first

laser threshold
$\gamma_0(\nu_m) = {\gamma_0}^t$

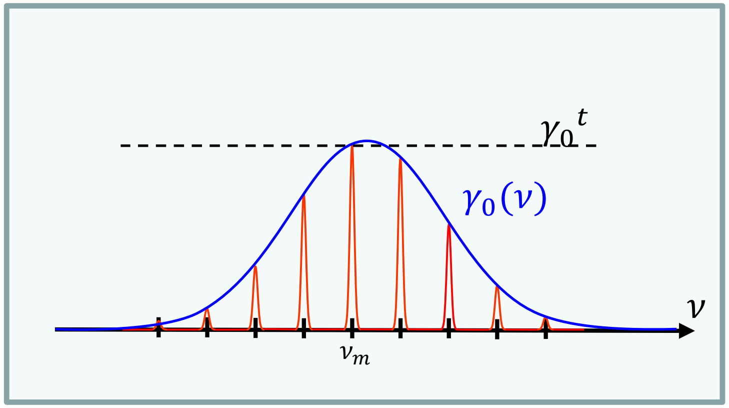


questions:
- is it really a single mode operation?
- what is the spectra width of the laser mode?

above the
laser threshold
$\gamma_0(\nu_m) = {\gamma_0}^t$



cw laser spectrum, inhomogenous line broadening

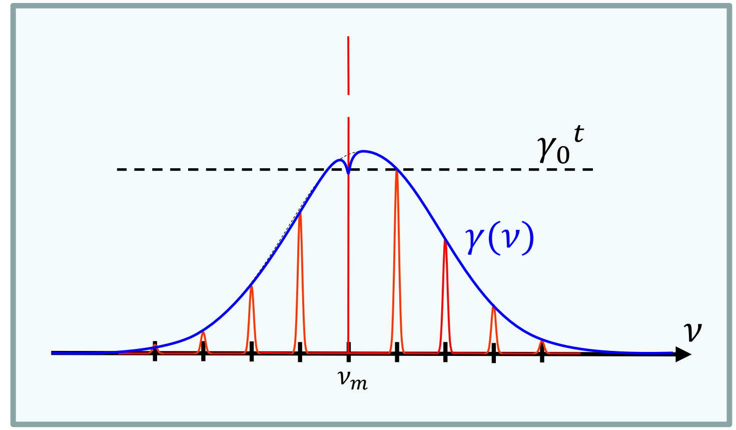


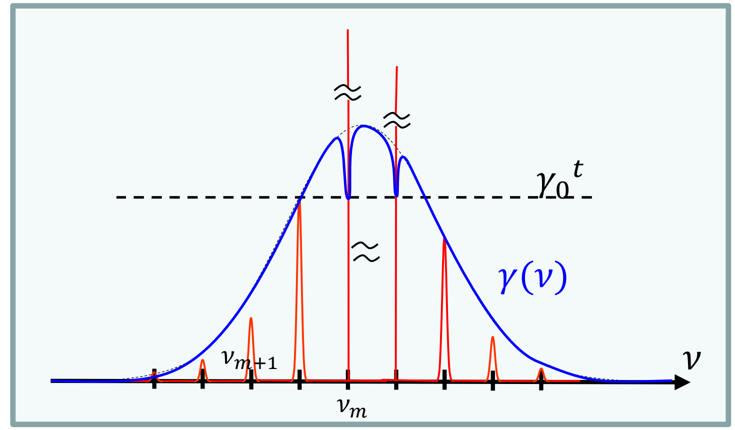
the values of gain coeeficient for different modes are not coupled

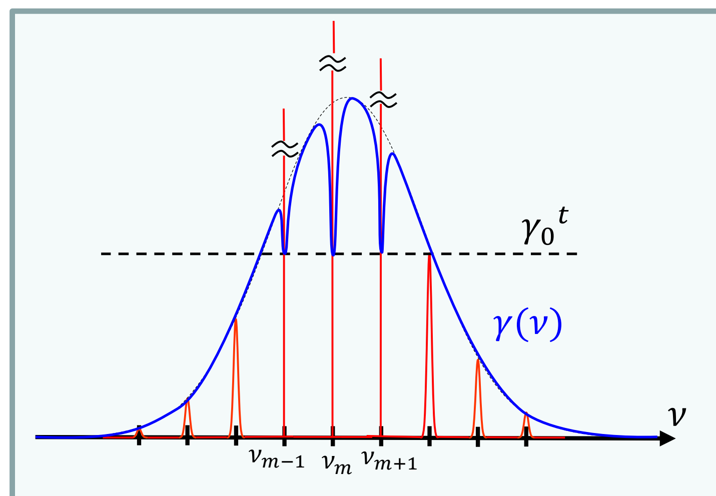
burning holes in the gain spectra profile

single mode operation:

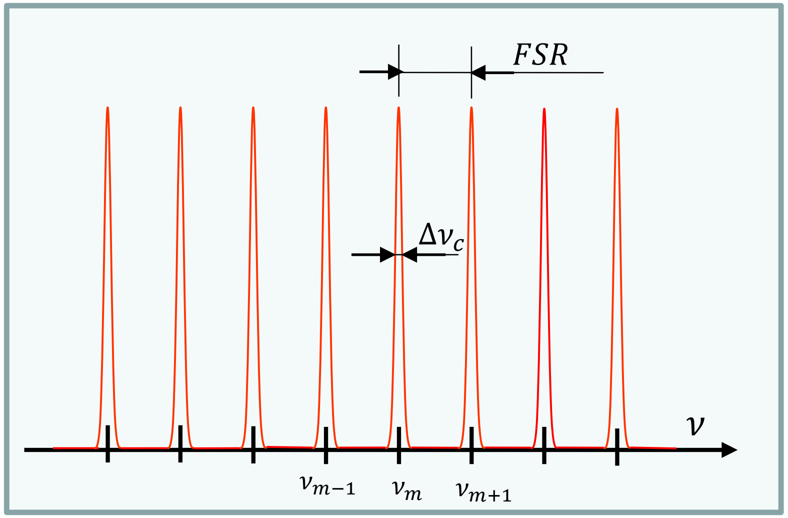
- short resonator – distance between modes larger than the gain bandwidth
- extra spectra selection – filters inside the cavity







spectral width of the laser mode – a simple picture



for a symmetrical Fabry-Perot cavity we have
$FSR = c/2L, \Delta\nu_c = FSR/\mathcal{F}, \mathcal{F} = \pi\sqrt{R}/(1-R)$
when the finesse of the cavity is high then $\mathcal{F} \cong \pi/(1-R)$

$$\Delta\nu_c = \frac{c(1-R)}{2\pi L} = \frac{1}{2\pi\tau_c}$$

with $\tau_c = \frac{2L}{c(1-R)}$ lifetime of the photon in the cavity

laser amplification relies on photon cloning which means that

$\tau_c \longrightarrow \infty$ and thus $\Delta\nu_c \longrightarrow 0$

but quantum cloning is not perfect!!! spontaneous emission leads to a finite spectral width of the laser mode.

spectral width of the laser mode – calculated result

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Infrared and Optical Masers

A. L. SCHAWLOW AND C. H. TOWNES*
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received August 26, 1958)

The extension of maser techniques to the infrared and optical region is considered. It is shown that by using a resonant cavity of centimeter dimensions, having many resonant modes, maser oscillation at these wavelengths can be achieved by pumping with reasonable amounts of incoherent light. For wavelengths much shorter than those of the ultraviolet region, maser-type amplification appears to be quite impractical. Although use of a multimode cavity is suggested, a single mode may be selected by making only the end walls highly reflecting, and defining a suitably small angular aperture. Then extremely monochromatic and coherent light is produced. The design principles are illustrated by reference to a system using potassium vapor.

$$\Delta\nu_{osc} = (4\pi h\nu/P)(\Delta\nu)^2$$

$$\boxed{\Delta\nu_{laser} = \frac{4\pi h\nu(\Delta\nu_c)^2}{P_{out}}}$$

with:

$\Delta\nu_c$ - spectra width (passive) of the cavity mode

P_{out} - laser output power

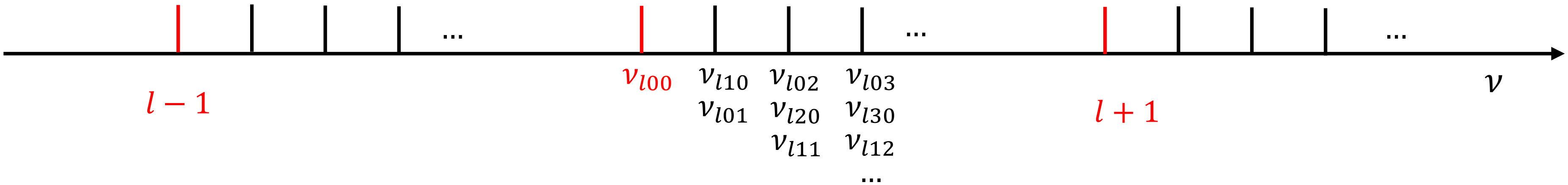
numbers: $\lambda = 1\mu m \Leftrightarrow \nu = 3\cdot10^{14}\text{Hz}, h \cong 6\cdot10^{-34}\text{J}\cdot\text{s}, L = 0.15\text{m}, R = 0.97 \Rightarrow \Delta\nu_c \cong 10^7\text{Hz}, P = 0.1\text{ W}$:

$$\Delta\nu_{laser} \cong \frac{3\cdot6\cdot10^{-34}\cdot3\cdot10^{14}\cdot10^{14}}{0.1} \cong 0.6\text{ mHz}$$

$$\frac{\Delta\nu_{laser}}{\nu_{laser}} \cong 2\cdot10^{-18}$$

single-mode operation of a cw laser

lecture 5:



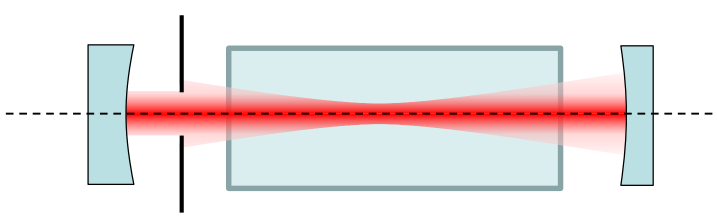
often we want to force the laser to operate in a single mode; preferably TEM_{l00}

✓ select transverse mode

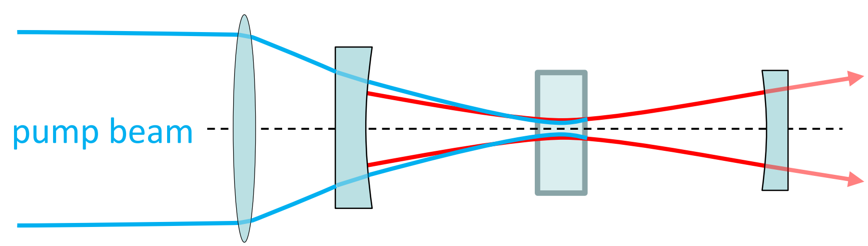
✓ select longitudinal mode

selection of the single transverse mode – lecture 5: diffraction losses are the smalest for the TEM_{l00} mode; we put an adjustable aperture in the laser cavity:

hard aperture



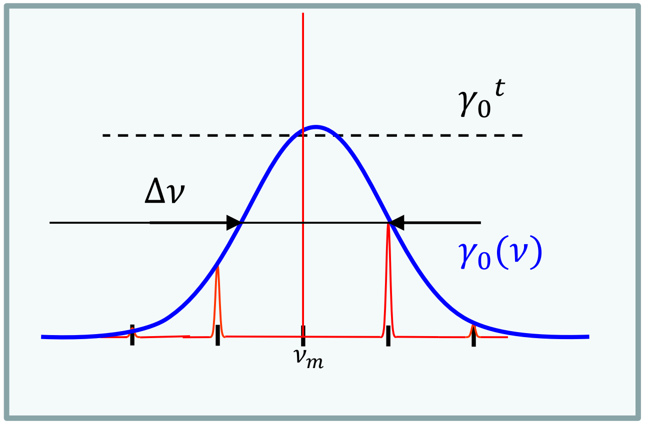
soft aperture



single-mode operation of a cw laser, 2

single longitudinal mode selection:

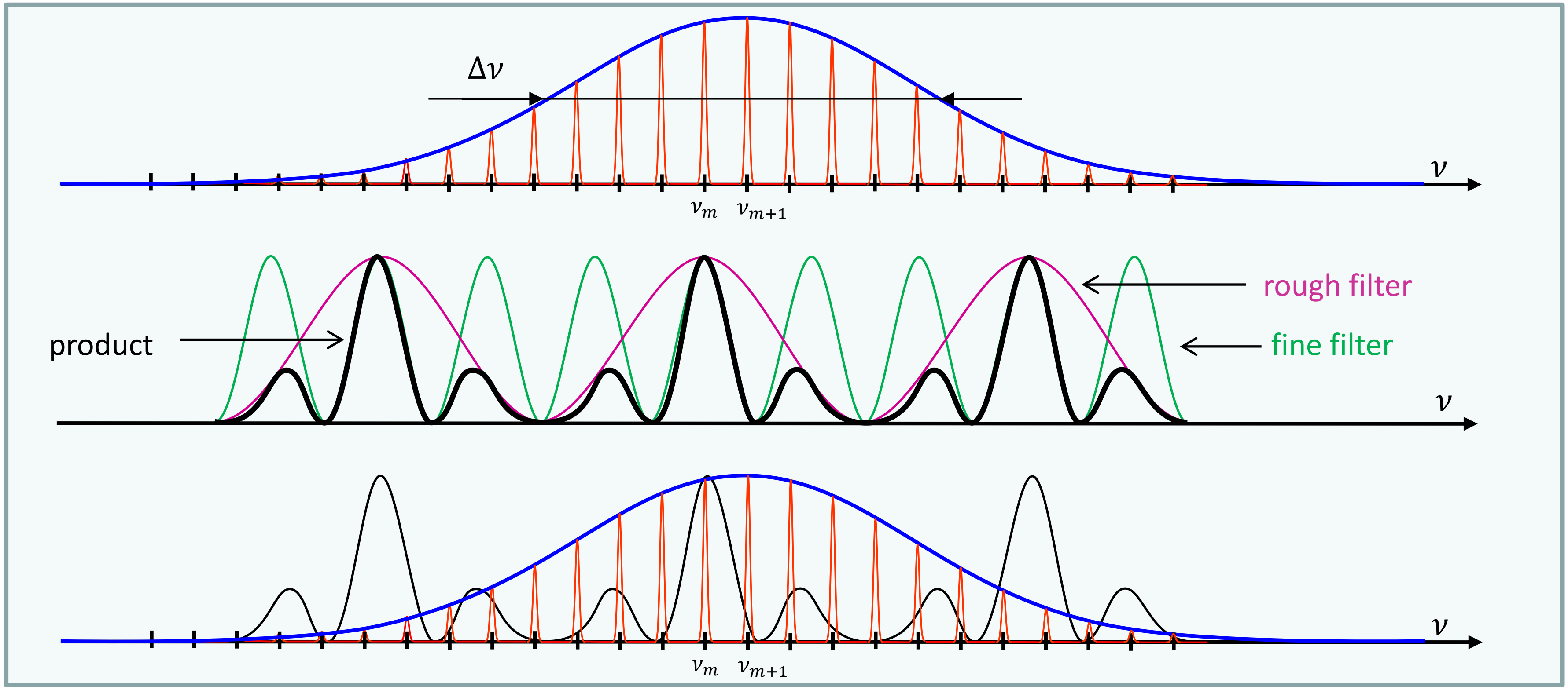
- short cavity - $\frac{c}{2L} \geq \Delta\nu$



examples:

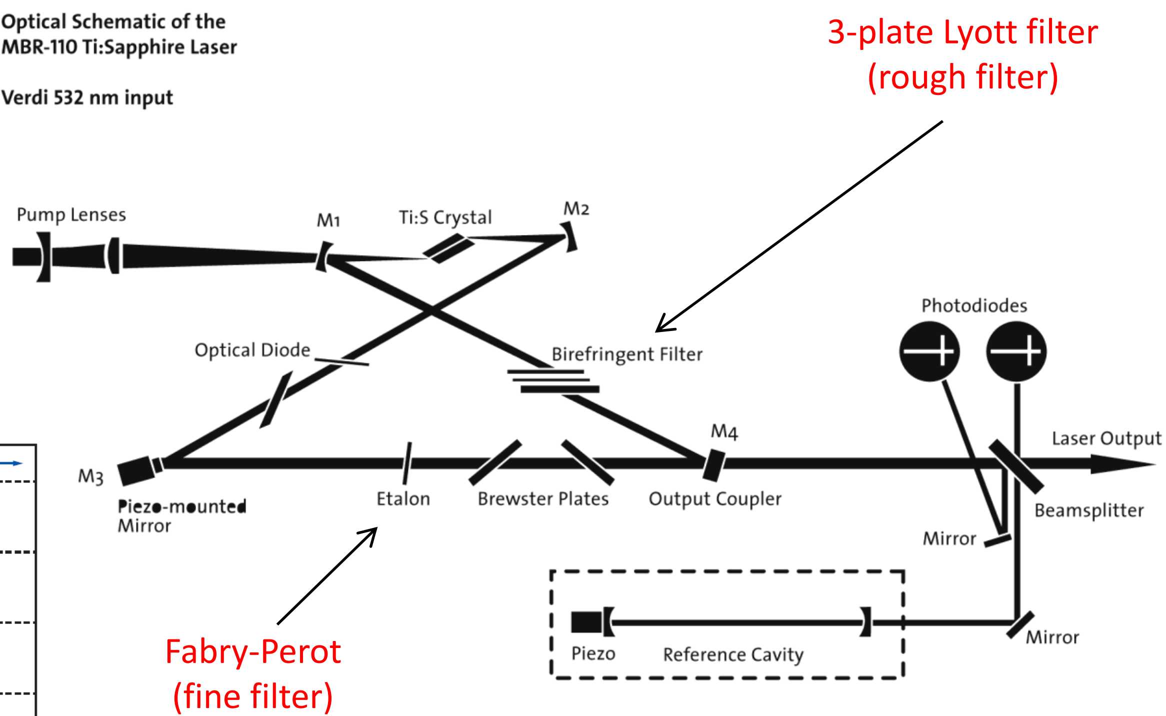
- short He-Ne, $\Delta\nu \cong 1.5\ \text{GHz}, L = 15\ \text{cm}\ \Rightarrow \frac{c}{2L} = 1\ \text{GHz}$
- VCSEL (Vertical-Cavity Surface-Emitting Laser) $L \approx \mu\text{m}$

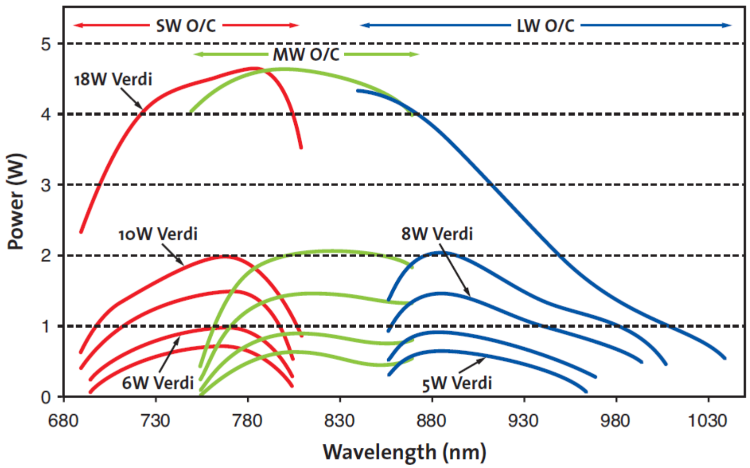
- long cavity - $\frac{c}{2L} \ll \Delta\nu$



single-mode operation of a cw laser, 3

single longitudinal mode selection in a long cavity. an example Ti:Sapphire laser MBR-110, Coherent, Inc. USA





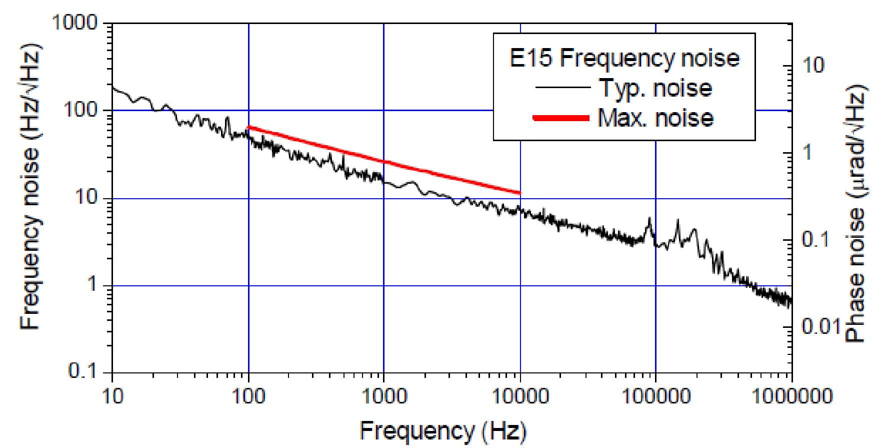
Relative Linewidth[3] (kHz)(rms)	<75
Typical Beam Divergence (half-angle)(mrad)	1.7
Typical Beam Radius[4] (mm)	0.25
Scan Range (GHz)	30
Spatial Mode	TEM00
Polarization	Horizontal
Amplitude Noise[5] (rms)	<1.5%
Tunability (nm)	700 to 1030 (high-power pump)
Laser Head Dimensions (L x W x H)	630 x 310 x 160 mm (25.2 x 12.4 x 6.4 in.)

single-mode operation of a cw laser, 4

single longitudinal mode selection in a long cavity – fiber Bragg grating. An example: fiber laser, model Koheras Basic, NKT Photonics, Denmark

Koheras BasiK™ Module	E15	C15
Center wavelength [nm] [1]	1535-1575, optionally other	1535-1575, optionally other
Laser emission	CW - inherently single frequency	CW - inherently single frequency
Beam quality	$M^2 < 1.05$	$M^2 < 1.05$
Output power [mW] [2]	up to 40	>10
Line width [kHz]	< 0.1 (Lorentzian)	< 50 (optionally <10)
Frequency stability [MHz] [3]	< 10	< 50
Frequency-noise [Hz/√Hz]	65@100Hz, 26@1kHz, 13@10kHz	-
Phase-noise [μrad/√Hz] 1m opt. path	2.0@100Hz, 0.8@1kHz, 0.4@10kHz	-
RIN peak [MHz]	app. 0.3	app. 0.9
RIN level [dBc/Hz]	<-100 @ peak/<-135 @ 10MHz	<-120 @ peak/<-140 @ 3MHz [4]

1. The center wavelength is selectable within the specified range.
2. Depends on the center wavelength.
3. Over 1 hour after warm-up and ambient temperature variation < 2 °C.



single-mode operation laser frequency stabilization

we need a reference frequency:

- relative, most often Fabry-Perot interferometer
- absolute, a transition in a atom or a molecule

Appl. Phys. B 31, 97–105 (1983)

Applied Physics B Photophysics and Laser Chemistry

Laser Phase and Frequency Stabilization Using an Optical Resonator

R. W. P. Drever

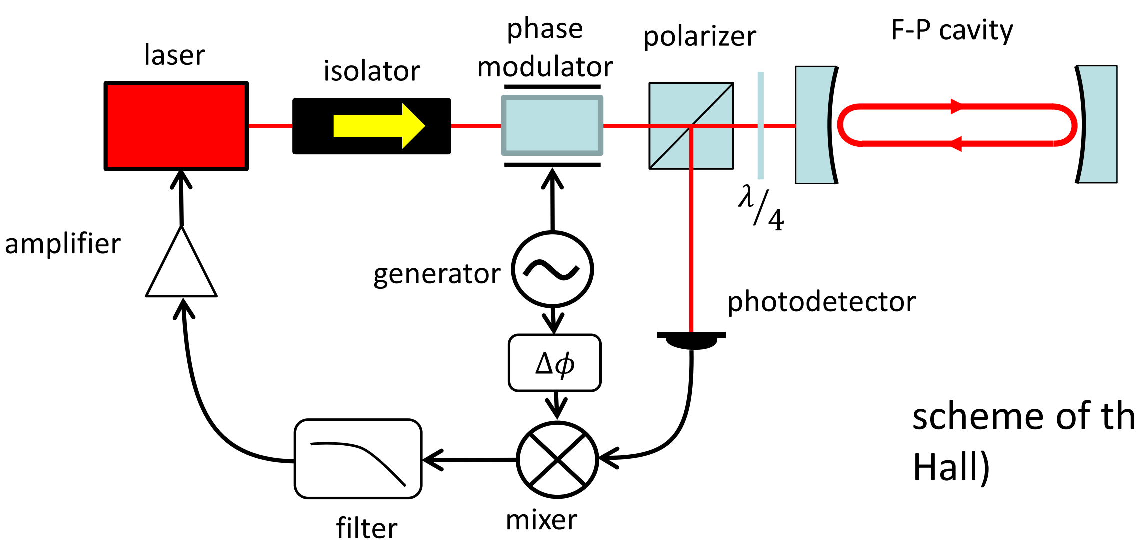
University of Glasgow and California Institute of Technology, Pasadena, CA 91125, USA

J. L. Hall* and F. V. Kowalski**

Joint Institute for Laboratory Astrophysics, National Bureau of Standards and University of Colorado, Boulder, CO 80309, USA

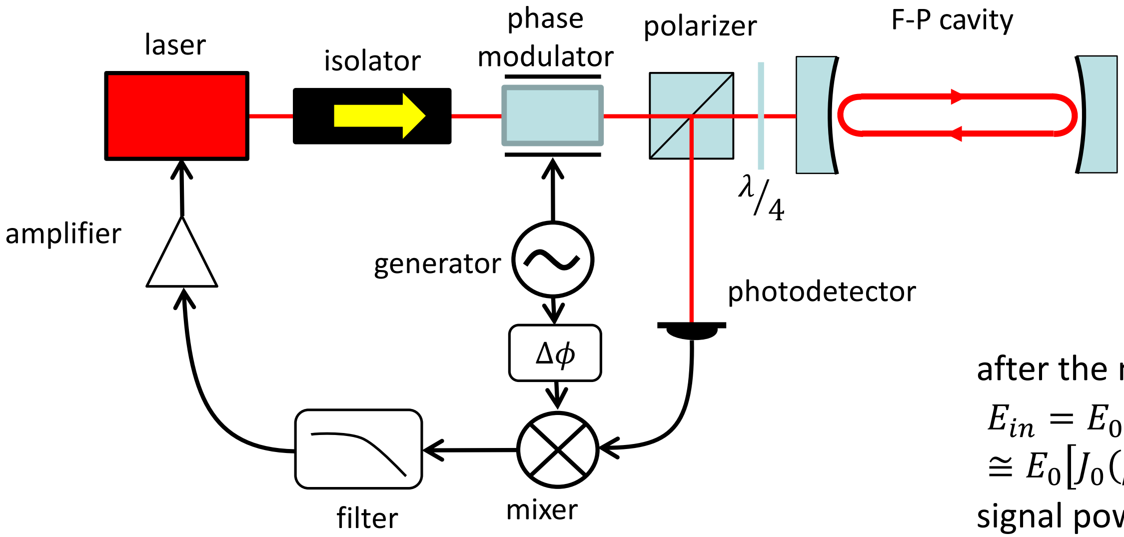
J. Hough, G. M. Ford, A. J. Munley, and H. Ward

Department of Natural Philosophy, University of Glasgow, Glasgow, Scotland G12800



scheme of the PHD system (Pond, Drever, Hall)

PHD lock



after the modulator

$E_{in} = E_0 e^{i(\omega t + \beta \sin\Omega t)}$

$\cong E_0\left[J_0(\beta)e^{i\omega t} + J_1(\beta)e^{i(\omega+\Omega)t} - J_1(\beta)e^{i(\omega-\Omega)t}\right]$

signal power: $P_C = {J_0}^2(\beta)\cdot P_0$, $P_S = {J_1}^2(\beta)\cdot P_0$

reflection from Fabry-Perot

$$F(\omega) = \frac{r\left(e^{i\phi}-1\right)}{1-r^2e^{i\phi}}, \qquad \phi = \frac{2\omega L}{c}, \qquad r = \left|\frac{E_r}{E_{in}}\right| - \text{reflection coefficient}$$

reflected wave

$E_{ref} = F(\omega)\cdot E_{in}$

signal from the photodetector = reflected power

$P_{ref} = \left|E_{ref}\right|^2 =$

…

$= P_C|F(\omega)|^2 + P_S\{|F(\omega+\Omega)|^2 + |F(\omega-\Omega)|^2\}$

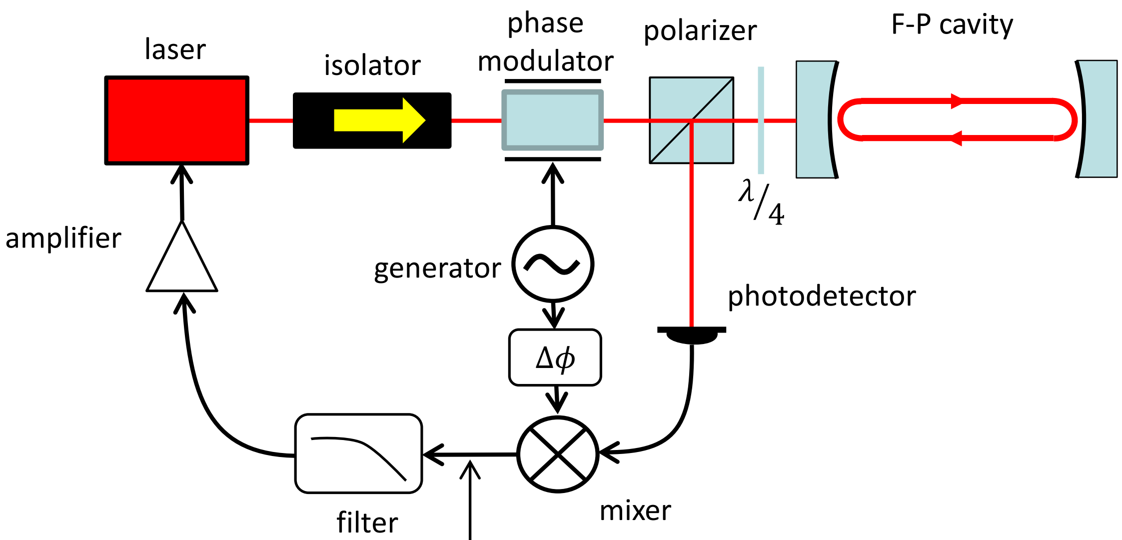
$+2\sqrt{P_C P_S}\{\mathrm{Re}[F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)]\cos\Omega t\}$

$+2\sqrt{P_C P_S}\{\mathrm{Im}[F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)]\sin\Omega t\} + \cdots$

mixer selects one quadrature

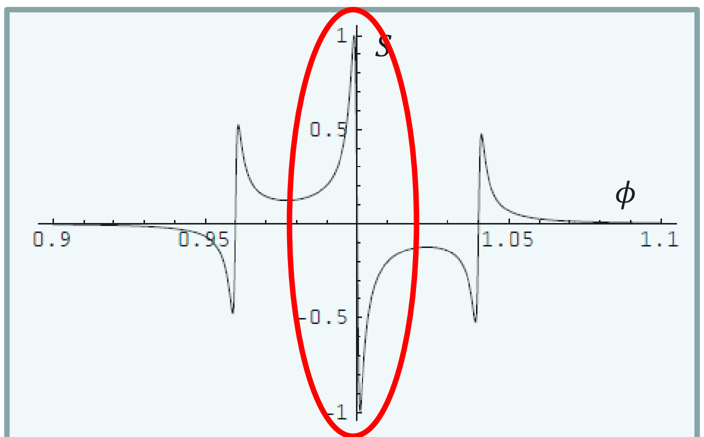
$$\mathrm{S} = 2\sqrt{P_C P_S}\,\mathrm{Im}[F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)]$$

PHD lock



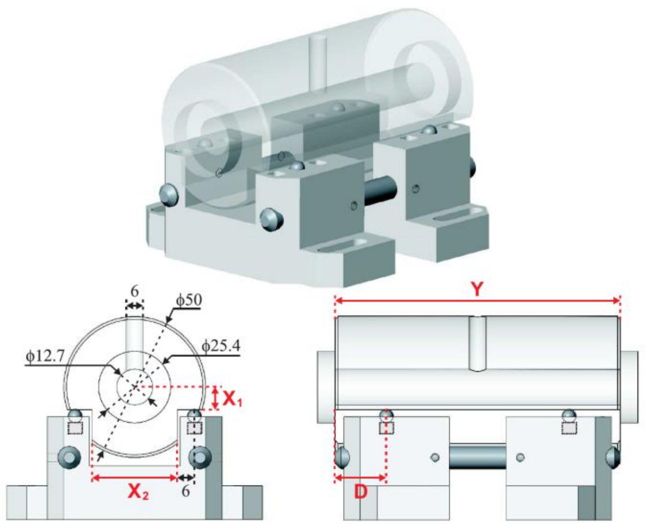
$$S \propto \mathrm{Im}[F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)]$$

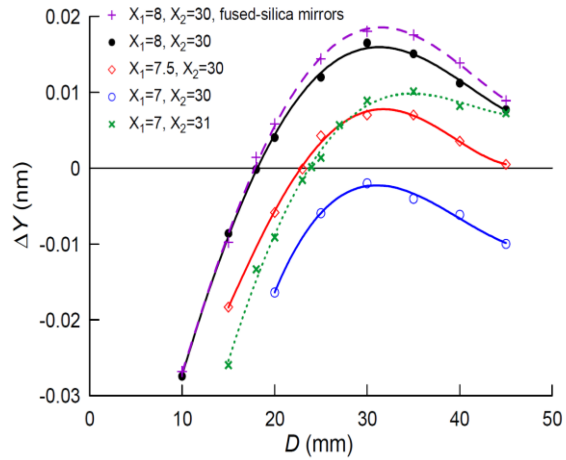
the dispersion line-width scales as $1/\mathcal{F}$

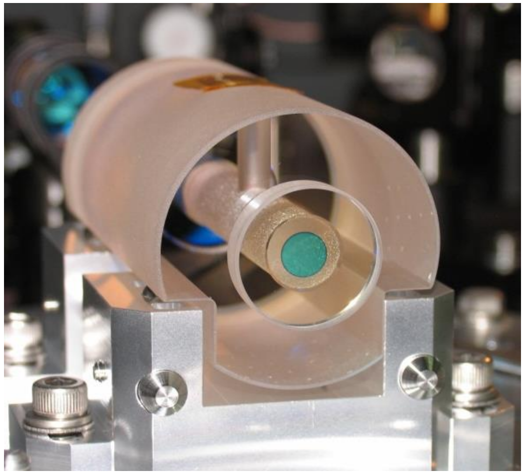


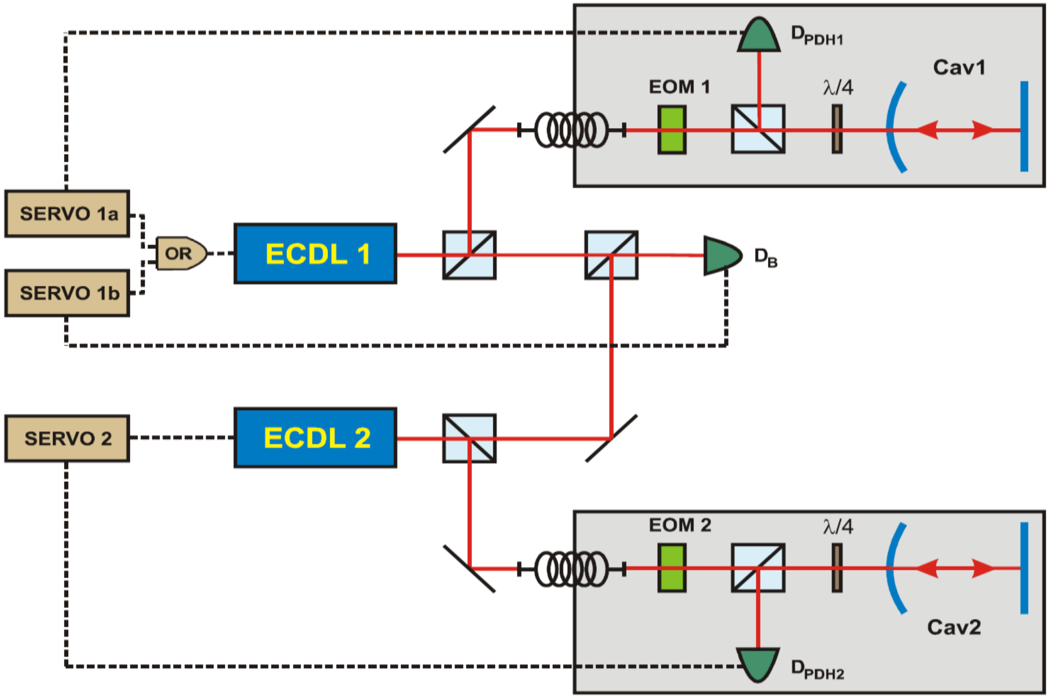
$\mathcal{F} = 100, \Omega = 0.04 \cdot FSR,$

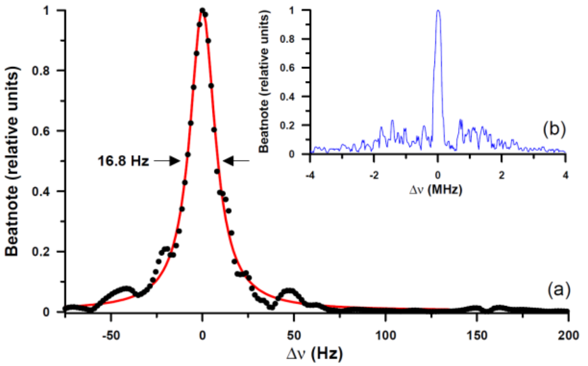
PHD lock in KL FAMO (Roman Ciuryło)











Ultra-stable single-frequency cw laser · low noise · 532 nm · up to 1 W

PROMETHEUS / DIABOLO · PRODUCT LINE

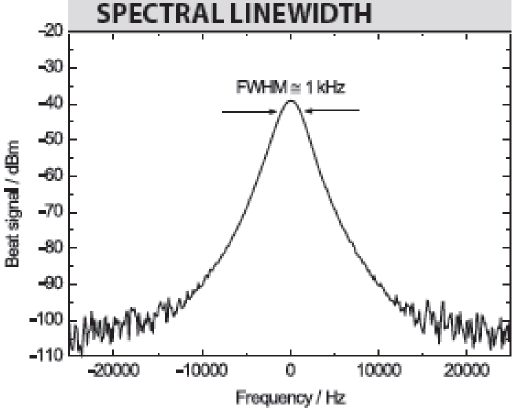
SPECIFICATIONS @ 532 nm

	PROMETHEUS	DIABOLO	Unit
Operational mode	Continuous wave	Continuous wave	
Spatial mode	TEM_{00} ($M^2 < 1.2$)	TEM_{00} ($M^2 < 1.1$)	
Beam roundness (at exit)	< 1.3	< 1.1	
Thermal tuning coefficient	-6	-6	GHz/K
Thermal tuning range	60	60	GHz/K
Thermal response bandwidth	1	1	Hz
PZT tuning coefficient	≅ 2	≅ 2	MHz/V
PZT tuning range	±200	±200	MHz
PZT response bandwidth	100	100 [5]	kHz
Emission spectrum	Single-frequency	Single-frequency	
Spectral linewidth (over 100 ms)	≅ 1	≅ 1	kHz
Coherence length	> 1	> 1	km
Frequency stability [6]	≅ 2	≅ 2	MHz/min
Relative intensity noise (RIN), f > 10 kHz	< -90	< -90	dB/Hz
RIN with Noise Eater (NE) option, f > 10 kHz	< -135	< -125 [7]	dB/Hz
Intensity noise without NE, 10 Hz to 2 MHz	< 0.1	< 0.1	% rms
Intensity noise with NE, 10 Hz to 2 MHz	< 0.06	< 0.06	% rms
Type of second harmonic generation	Non-resonant	Resonant [8]	
Modulation frequency for cavity stabilization	N/A	12 [9]	MHz
Laser head size, w · h · d	150 · 113 · 336	270 · 179 · 528	mm
Laser head weight	6.8	30	kg

[5] Small signals. [6] Measured Allan deviation at constant room temperature. [7] Sideband level attenuation at modulation frequency > 30dB. [8] Pound-Drever-Hall stabilization. [9] Other modulation frequencies on request. [10] Arbitrary units.

Prometeus (Innolight)

SPECTRAL LINEWIDTH

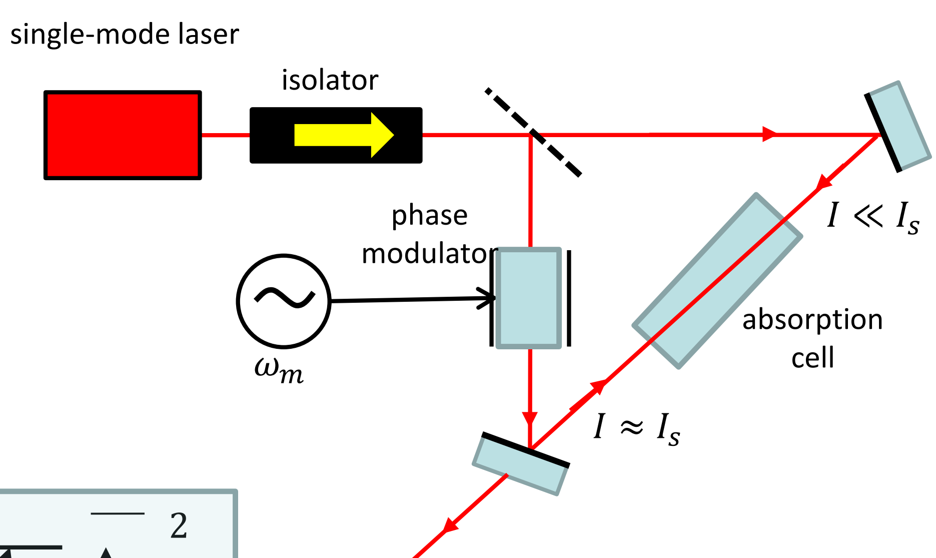


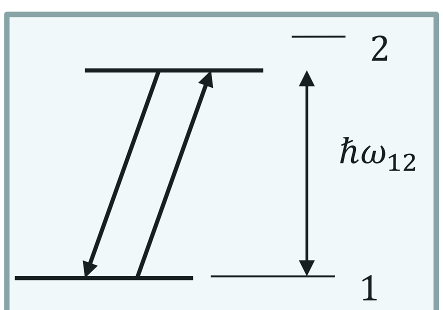
modulation transfer spectroscopy (MTS)

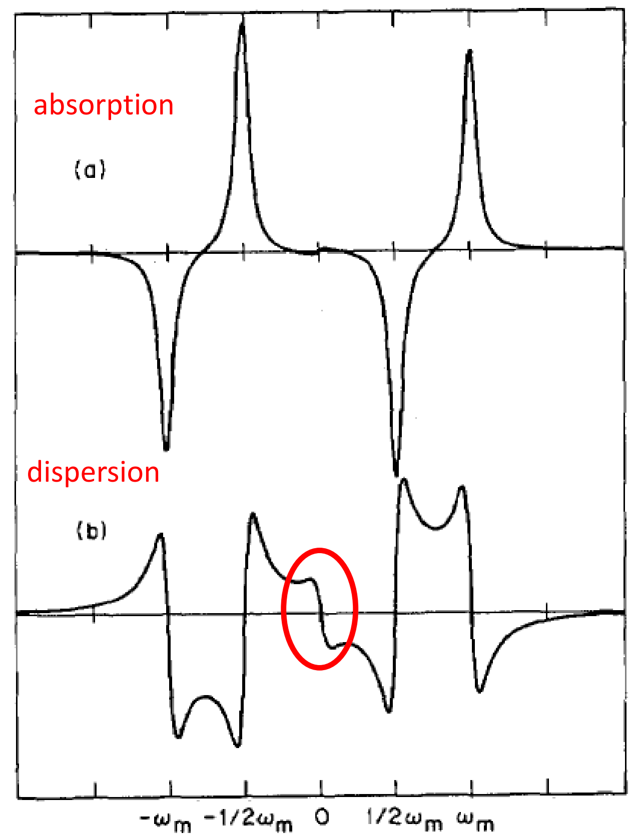
Modulation transfer processes in optical heterodyne saturation spectroscopy

Jon H. Shirley

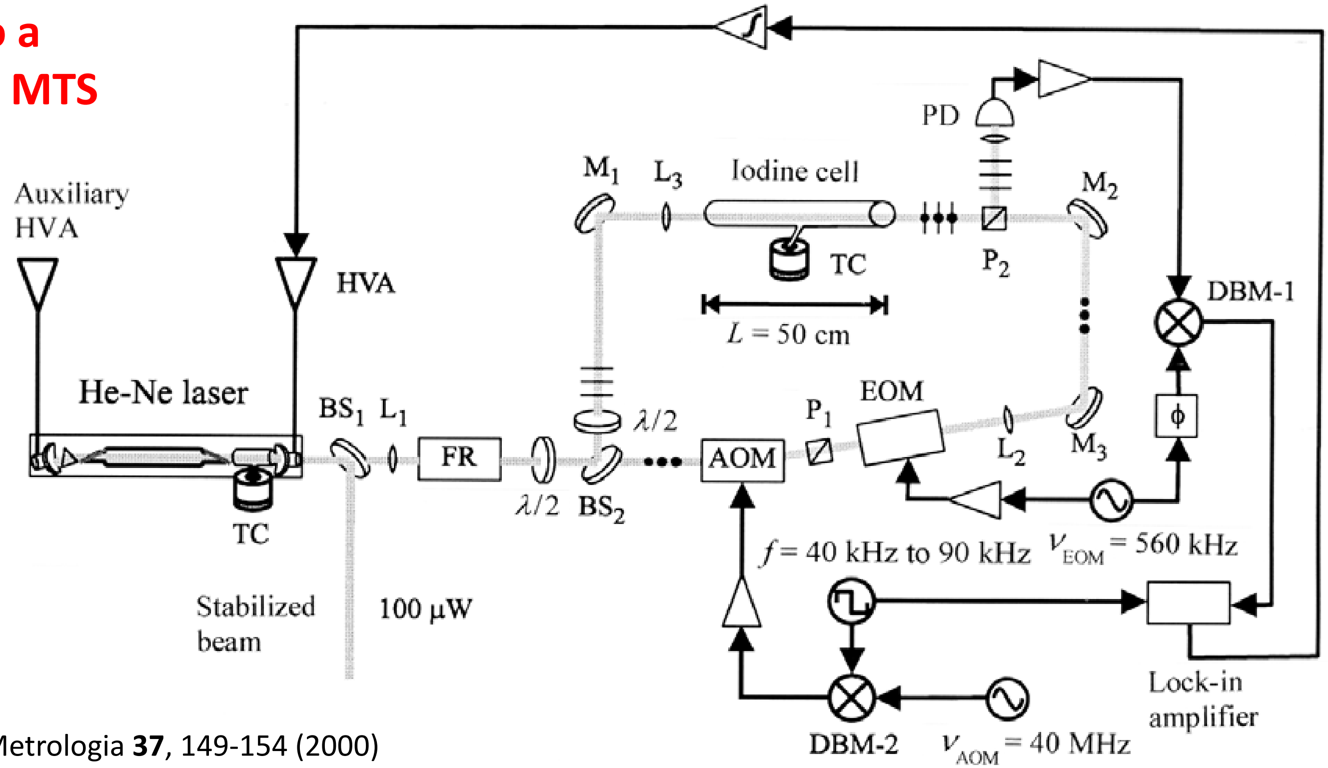
set-up



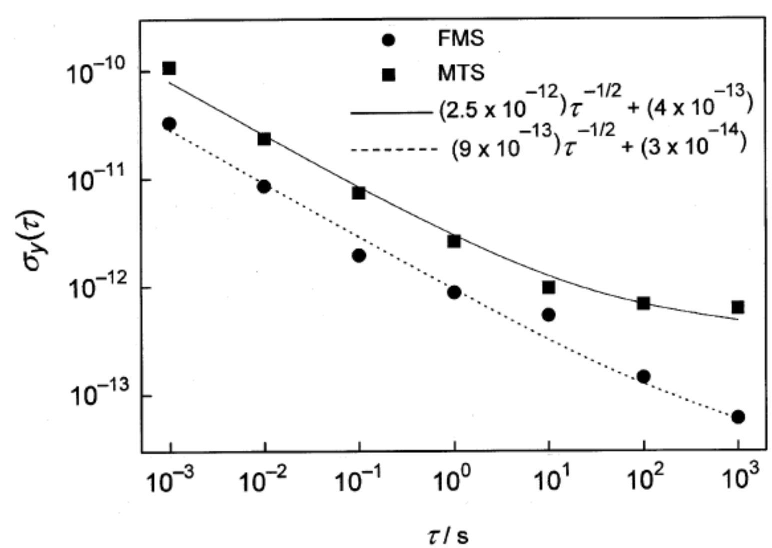


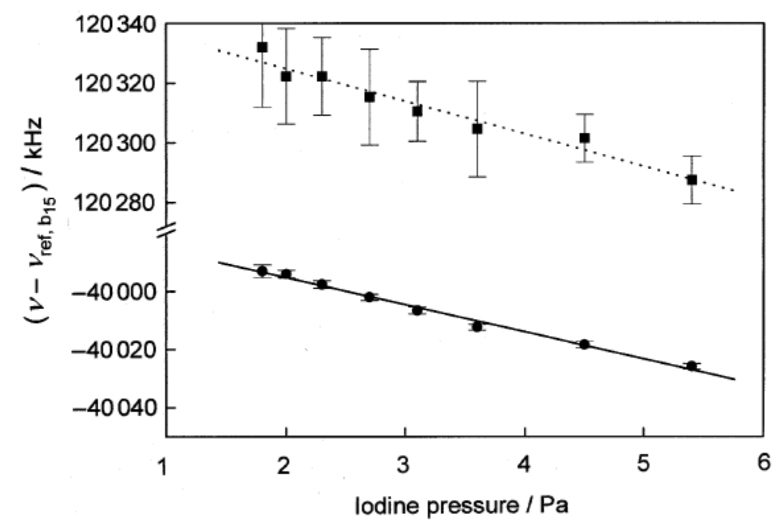


He-Ne laser stabilization to a molecular resonance using MTS



G. Galzerano, F. Bertinetto and E. Bava, Metrologia **37**, 149-154 (2000)

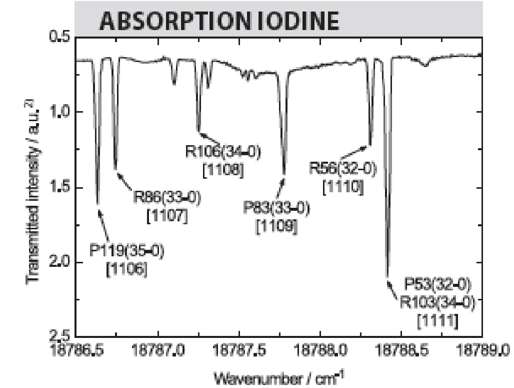


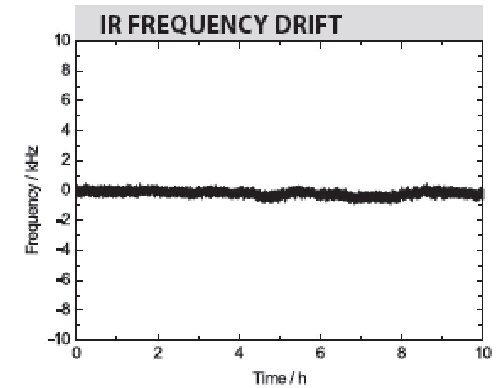


SPECIFICATIONS

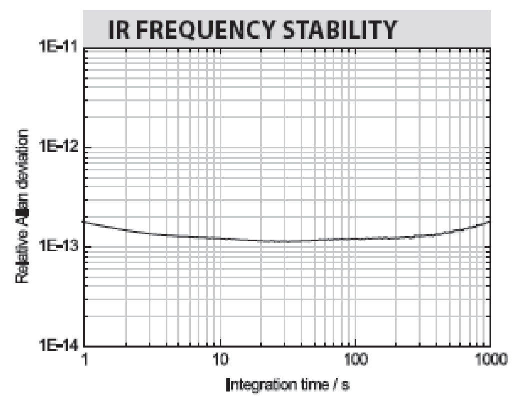
General:		Unit
Frequency range @ 532 nm	563.205-563.265	THz
Frequency stability @ 1064 nm	10^{-12} or better (relative Allan deviation, iodine transition R(56) 32-0, a10)	
Laser system	InnoLight Prometheus (separate data sheet)	
Operational mode	Continuous wave	
Spatial mode	TEM_{00} ($M^2 < 1.1$)	
Laser emission spectrum	Single-frequency	
Wavelength	532 and 1064	nm
Output power @ 532 nm	Depending on laser model	
Output power @ 1064 nm	> 500	mW
Optical setup size, w · h · d	614 · 224 · 513	mm
Optical setup weight	55	kg
Control electronics	Details on request	

[2] Arbitrary units





Prometeus, stabilization to I_2 molecular line



nature photonics

ARTICLES

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A sub-40-mHz-linewidth laser based on a silicon single-crystal optical cavity

T. Kessler[1], C. Hagemann[1], C. Grebing[1], T. Legero[1], U. Sterr[1], F. Riehle[1]*, M. J. Martin[2], L. Chen[2†] and J. Ye[2]*

State-of-the-art laser frequency stabilization by high-finesse optical cavities is limited fundamentally by thermal noise-induced cavity length fluctuations. We present a novel design to reduce this thermal noise limit by an order of magnitude as well as an experimental realization of this new cavity system, demonstrating the most stable oscillator of any kind to date for averaging times of 0.1–10 s. The cavity spacer and the mirror substrates are both constructed from single-crystal silicon and are operated at 124 K, where the silicon thermal expansion coefficient is zero and the mechanical loss is small. The cavity is supported in a vibration-insensitive configuration, which, together with the superior stiffness of the silicon crystal, reduces the vibration-related noise. With rigorous analysis of heterodyne beat signals among three independent stable lasers, the silicon system demonstrates a fractional frequency instability of 1×10^{-16} at short timescales and supports a laser linewidth of <40 mHz at 1.5 μm.

limit- thermal noise of the materials

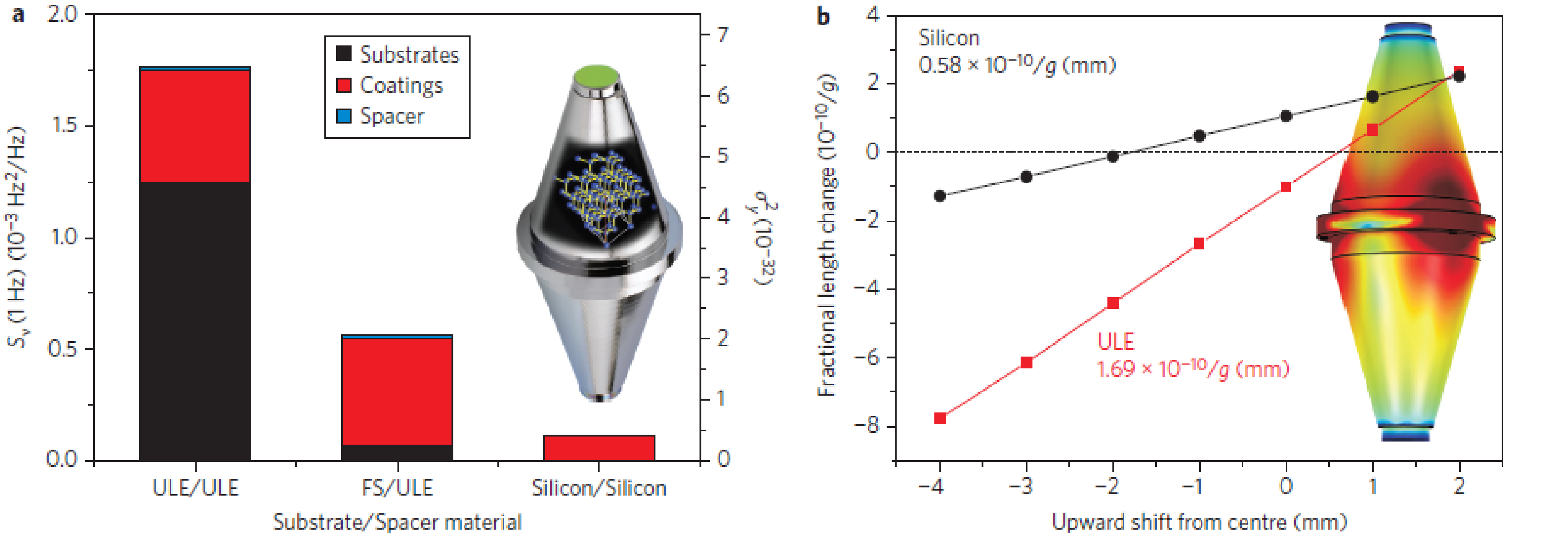

Figure 1 | Performance of a single-crystal silicon Fabry–Pérot interferometer. a, Estimation of frequency noise power spectral density arising from Brownian-motion thermal noise for various mirror substrate and spacer materials at their corresponding zero crossing temperatures. The nominal dimension of the optical cavity has a spacer length of 210 mm, spacer radius of 50 mm, central bore of 5 mm, radii of curvature of 1 m/∞ for the two mirrors. Right axis: corresponding Allan variance for fractional optical frequency instability (Allan variance is the square of Allan deviation presented in subsequent figures). **b**, FEM simulation of the vibration sensitivity of the vertical cavity design as a function of position of the central support ring from the symmetric plane, for ULE and single-crystal silicon as cavity materials. Inset: strain energy distribution for the silicon spacer.

construction and results

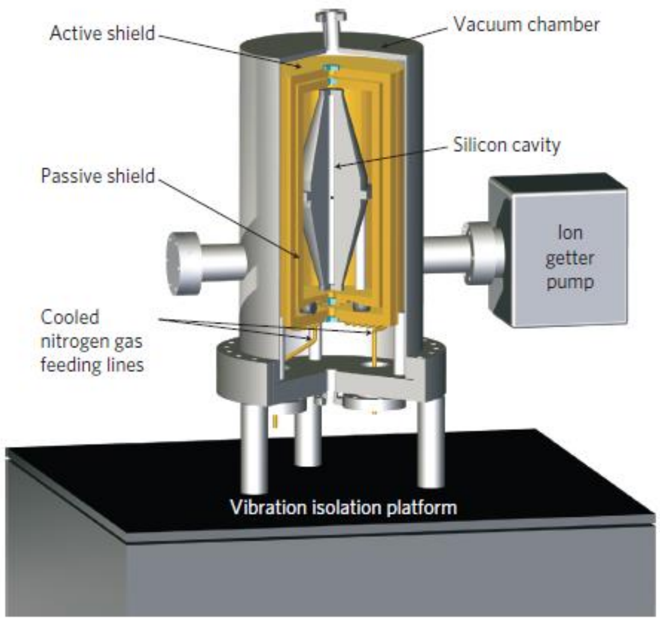

Figure 2 | Schematic of the vibration-reduced, nitrogen-gas-based cryostat, including the vacuum chamber and two heat shields centred around the silicon single-crystal cavity. The thermal time constant of the system is 10 days.

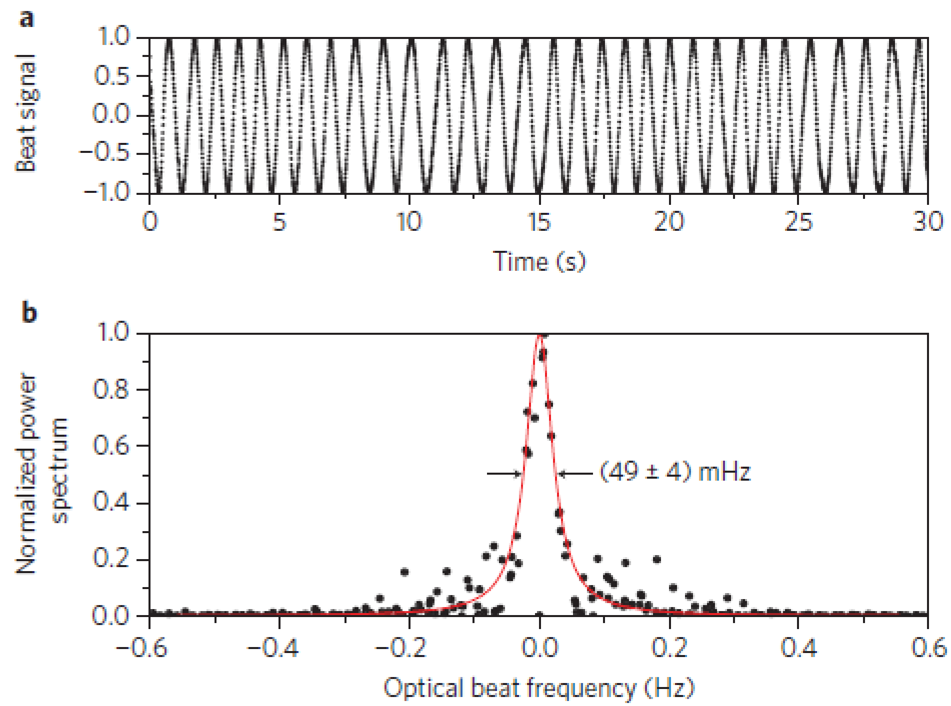

Figure 5 | Optical heterodyne beat between the silicon cavity system and REF. 2. a, Beat signal mixed down close to d.c. and recorded with a digital oscilloscope. **b**, Normalized fast Fourier transform of the beat signal recorded with a HP 3561A FFT analyser (37.5 mHz resolution bandwidth, Hanning window). A Lorentzian fit is indicated by the red line. The combined result of five consecutive recordings of the beat signal (black dots) is displayed here, demonstrating the robustness of this record-setting linewidth.