Lasers for Instrumentation

SUMMARY

- the lasers as an oscillator
- light-matter interaction
- optical gain
- types of lasers for instrumentation
- the He-Ne, basics; frequency stabilization
- semiconductor laser, basics; narrow-line types

Laser for Instrumentation

Table I - Classes of optoelectronic instruments and the lasers they use

Application	Typical Laser	Main Characteristic
• ALIGNMENT, POINTING and TRACKING	He-Ne and semiconductor	collimation, beam quality
• DIAMETER SENSOR and PARTICLE SIZING	He-Ne	collimation, beam quality
• TELEMETERS		
- geodimeter (d>1 km)	solid state (Nd, etc.)	high peak-power (Q-switched)
- topograph (d<1 km)	GaAs diode	high-frequency modulation
• INTERFEROMETERS for dimensional metrology	He-Ne	temporal coherence, 6-digit wavelength-accuracy
• Doppler VELOCIMETERS	He-Ne, Ar	spatial coherence, beam quality
• ESPI vibration analyzers	He-Ne, Ar	spatial coherence, beam quality
• FOG gyroscopes and Fiber Optics Sensors	GaAlAs diode and SLED	high radiance, controlled temporal coherence

Lasers for Instrumentation: HeNe

• He-Ne laser: one of the first types mass=produced, since 1961. In production ≈300,000 units are sold per year, second only to DL.

• Lines of He-Ne; most common is the red at λ=632.8 nm, then the green λ=543 nm and a few IR at λ=1.15 μm, 1.52 μm and 3.39 μm.

• The medium is a gas mixture, at a few-torr pressure. Ne is the active atom with a number of energy levels

• By electrical discharge, He atoms are excited by electrons and transfer to Ne atoms by collision.

• The capillary tube is carefully sealed to attain a loss of <0.01 torr/year, and the glass wall is thick (≈5 mm) to limit He leakage.

• He-Ne medium provides low-gain, typ. γ=0.5-1%/cm.Optical gain per pass is just ≈1.1-1.2 in a tube of L=20-cm length.

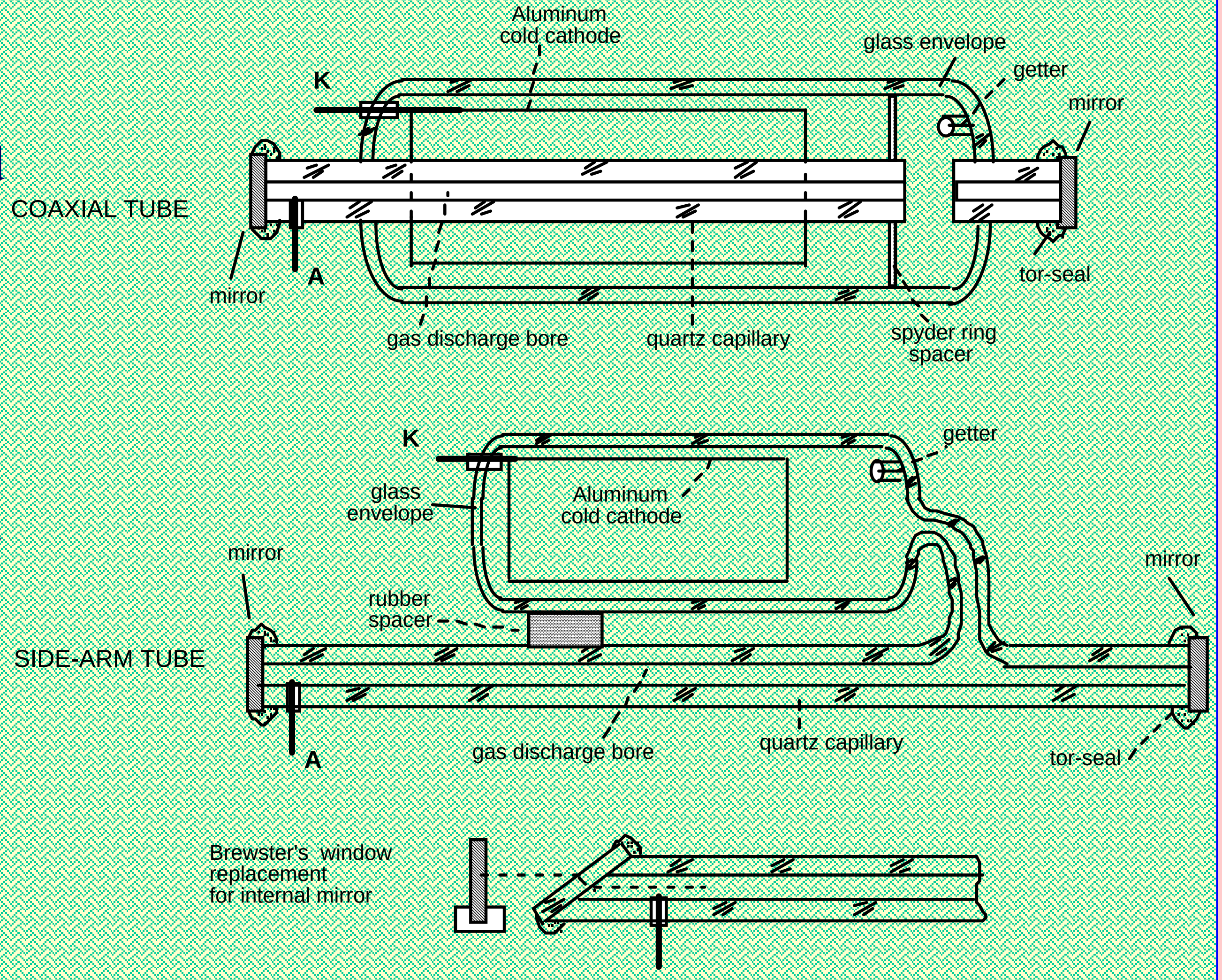
• Mirrors reflectivity: one 99.99%, the output mirror 0.95 typ.Their radius of curvature is: one ∞, the other >L, typ 1-m.

• MTTF or useful lifetime may be in excess of 10Mhour, if sealing has been made properly

Lasers for Instrumentation: HeNe (2)

• End surfaces of the capillary tube are worked flat and parallel to accommodate the mirrors or the Brewster-angle windows, in units with internal or external mirrors.

• In the two cases output is unpolarized (random polarized) and linearly polarized (in the plane of incidence)



Lasers for Instrumentation: HeNe (3)

• Active medium is the amplifying function of the oscillator, whereas mirror cavity is the counterpart of the feedback loop and ensures a positive, narrow-band feedback.

•As a Fabry-Perot resonator, the mirror cavity is frequency-selective. Resonances, or TEM_{00N} modes, are at multiple of $\lambda/2$: $N(\lambda/2) = L$

Frequency spacing is $\Delta\nu = \nu_{N+1} - \nu_N = c/2L$.

• TEM_{00} modes have a field distribution $E(r) = E_0 \exp -r^2/w_0^2$,

• Parameter w_0 of the Gaussian is the laser beam *spot-size*

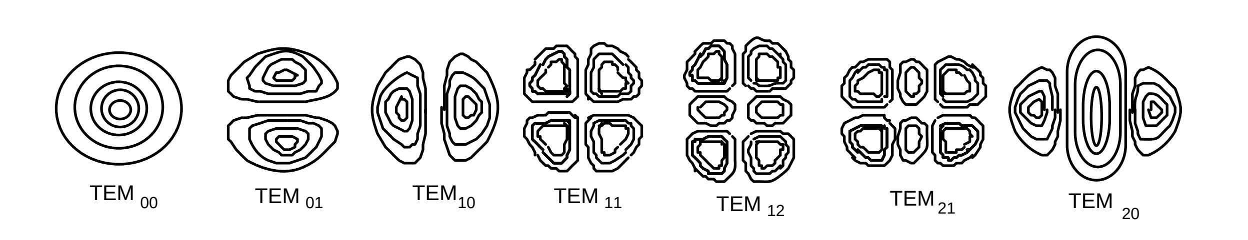
[At $r = w_0$, field amplitude E drops off to $1/e=0.37$ and power density `($\approx E^2$) drops off to $1/e^2=0.13$ of the maximum. Also, integrating $E^2(r)$ on r, we find that $1-1/e^2=0.86$ of the total beam power is contained within w_0].

Lasers for Instrumentation: HeNe (4)

• Each TEM_{00} mode is accompanied by transversal modes TEM_{pqN} with a distribution $E_{pq}(r, \phi) = E_0\ \Pi_p(r/w_0)\ \cos(q\ \phi)\ \exp -r^2/w_0^2$, where Π_p is a polinomial of order p.

• The main spatial dependence is again a Gaussian, but because of the polynomial, the distribution is broader and has zeros in it.

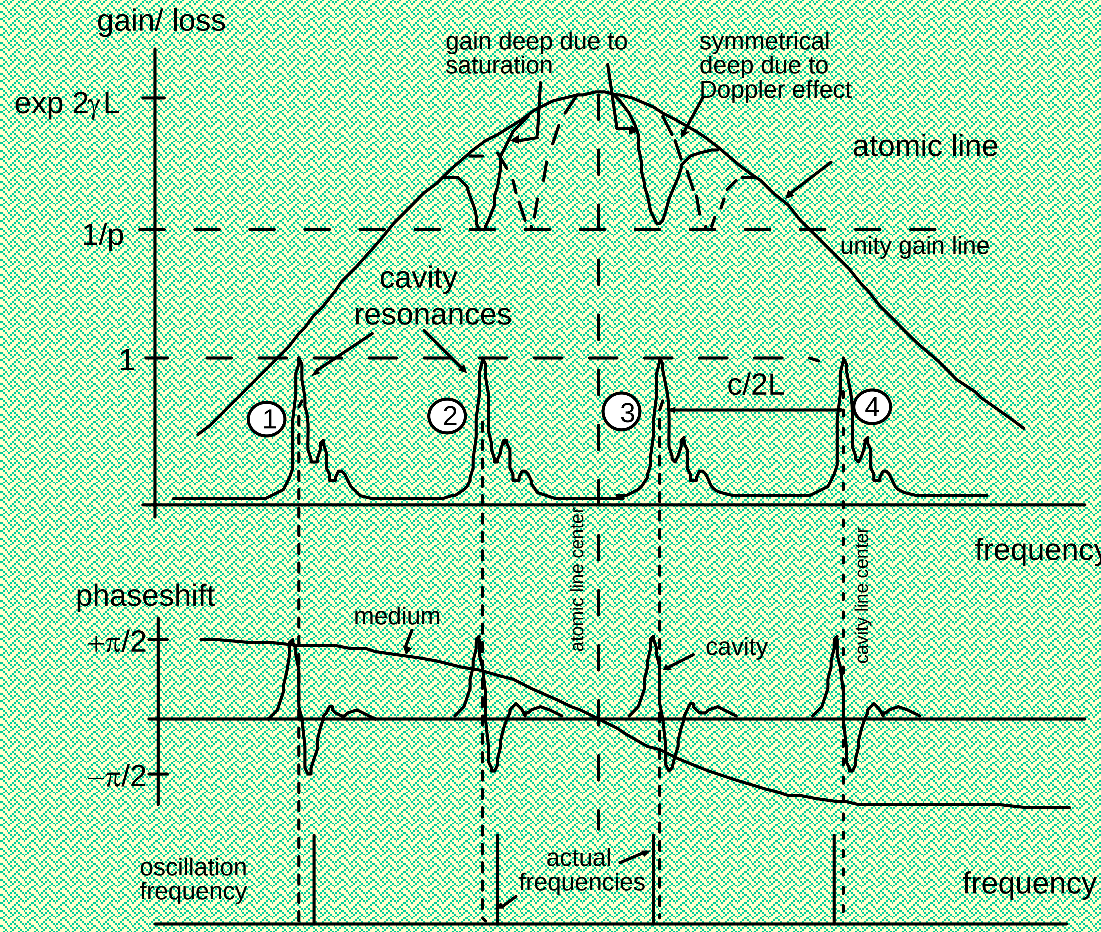
• Transversal modes have a spot size, again defined as the radius containing 86% of the beam power, larger than the fundamental longitudinal mode w_0 and increasing with mode order.



Field distributions of lowest-order transversal modes TEM_{pq}

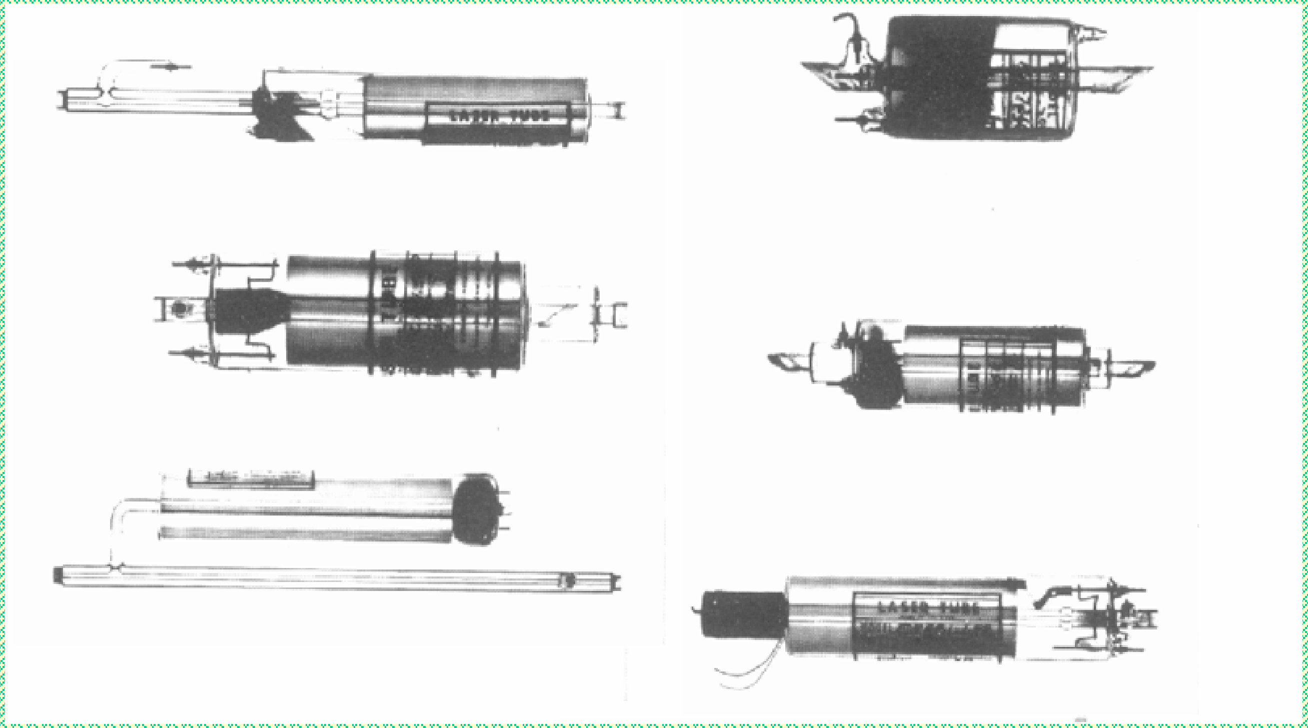
Lasers for Instrumentation: HeNe (6)

- In a He-Ne, the atomic line ($\Delta\nu_{at}$ =1.5 GHz) provides optical gain.
- Resonance of the mirror cavity add a much tight selectivity.
- When gain exp2γL is large and overcomes losses 1/p (dotted line), the laser breaks into oscillation
- The pattern of cavity modes determines the oscillating frequencies.
- Modes falling within the gain>loss can oscillate (hre modes 2 and 3)



Lasers for Instrumentation: HeNe (7)

Typical He-Ne laser tubes for instrumentation: left, with internal mirrors cemented to the capillary right, with Brewster's windows and external mirrors. Left bottom: a side-arm tube; other units are coaxial tubes.



Lasers for Instrumentation: HeNe (9)

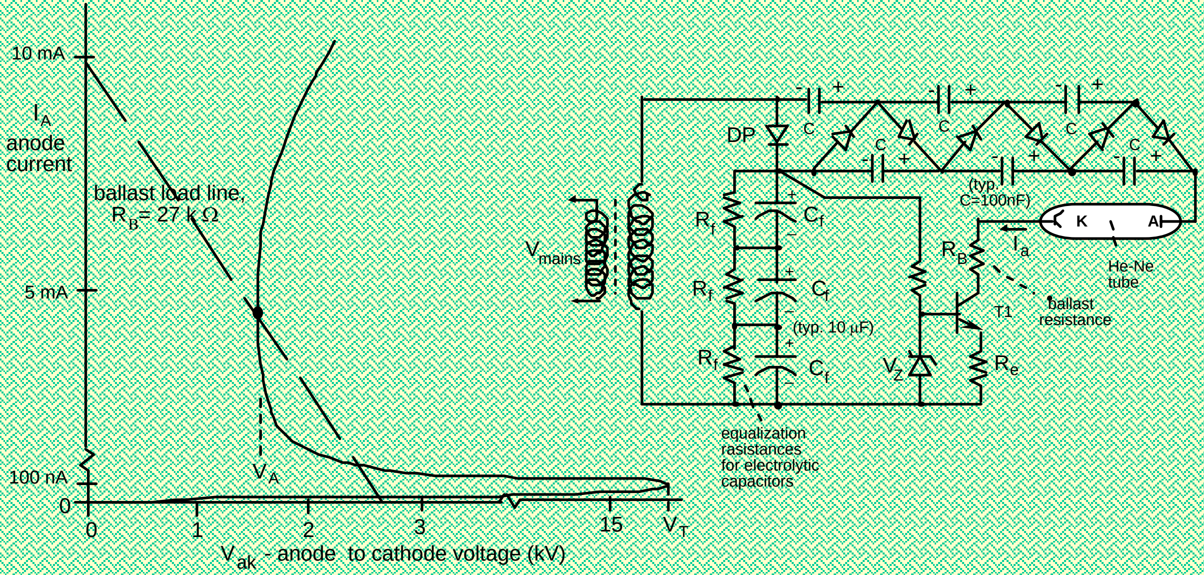
• Cold cathodes (a large Al-tube) are used in He-Ne lasers, to save power

• The I-V characteristic of the He-Ne tube is a low-pressure gas discharge with a low (≈nA) initial current.

• A voltage V_T =+15..20 kV to switch-on discharge and get I_a ≈5..10 mA through it. Voltage is then lowered (typ. V_A=1.5 kV) to sustain the gas discharge.

• The sequence is provided by the circuit , where DP gives the V_A on-voltage, and diodes arranged in a Marx-pump circuit give the initial trigger V_T. When current is low a high voltage is supplied, then current through cleares the diodes.

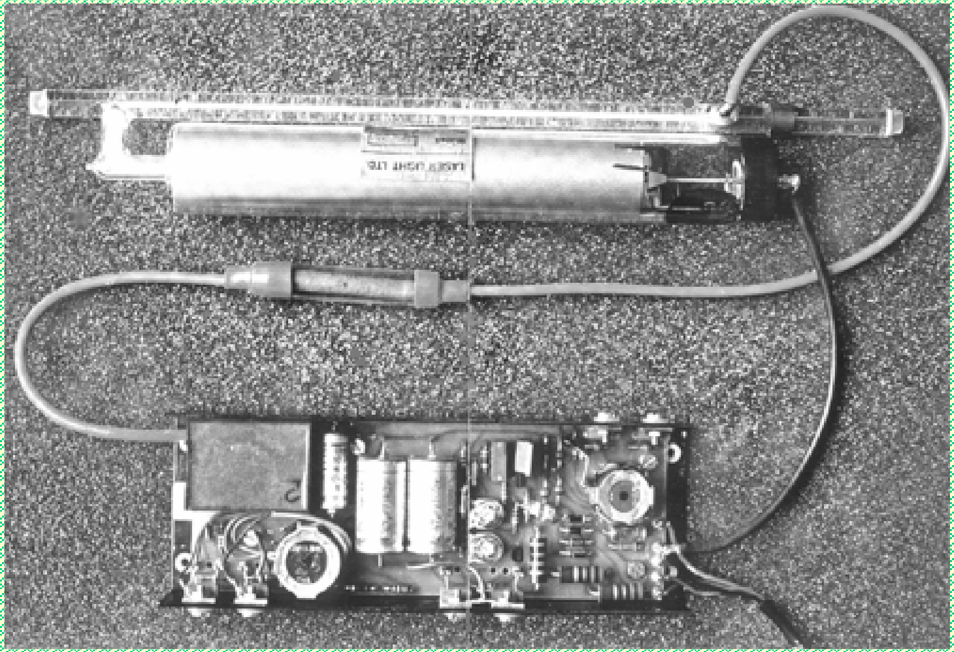
• To prevent ripple from affecting power, T1 is added to constant-current feed the discharge (I_a=V_Z/R_e), thus stabilizing laser power.



Lasers for Instrumentation: HeNe (10)

• Ballast R_B (≈10-50kΩ) in series to tube avoids spurious oscillations due to the negative resistance of the discharge.

• A dc/ac converter may be included in the supply module for battery operation of the source in portable instruments.



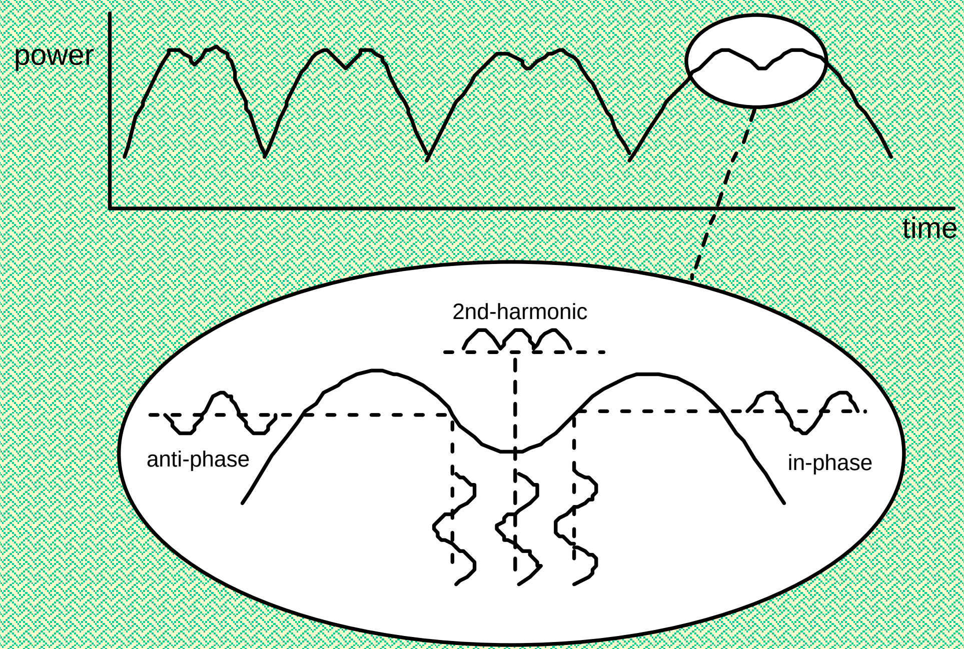
Typical He-Ne side-arm laser, complete with supply and drive circuit

Frequency stabilization: Lamb's dip

• For frequency stabilization, three basic functions are:
- a frequency reference (i.e., a frequency marking)
- a mechanism for generating a signal-error
- an actuator to change the frequency (through the cavity length)

• The reference determines how good the ultimate frequency stability is.

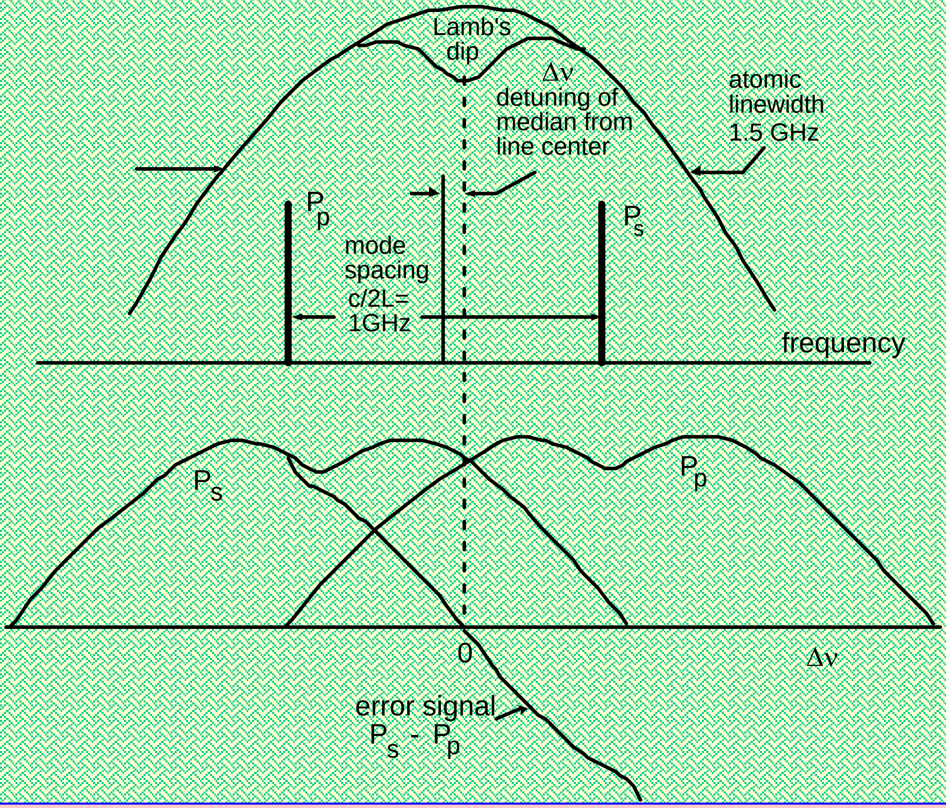
• Once the reference is chosen, we need a signal for frequency error:
- Lamb's dip
- Two-mode cross-polarized
- Zeeman splitting
- Iodine (external cell) signature



• With the *Lamb's dip reference*, we look at the mode power P_m as frequency f_m sweeps under the atomic line. It works well in the single-mode regime, as obtained with a ≈15-20 cm cavity length

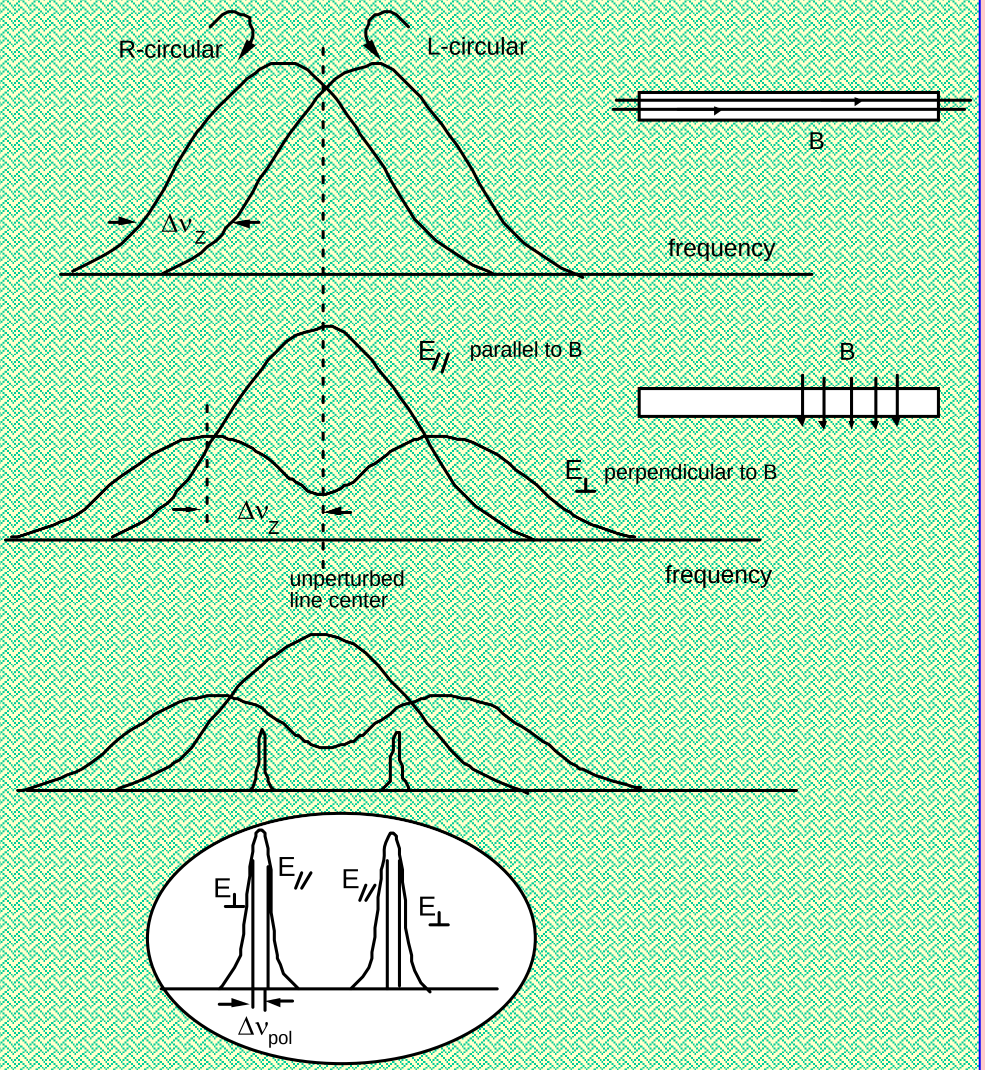
Frequency stabilization: two-mode cross-polarization

• the *two-mode*, *crossed-polarization regime* is another technique, based on spatial-hole burning. Oscillation establishes a standing wave pattern in the medium, subtracting energy to modes attempting to oscillate with the same polarization. The result is that, when two adjacent longitudinal modes oscillate simultaneously, they run in orthogonal states of polarization. Internal-mirror laser-tube are better because they start with no preferred polarization. If P_s and P_p are the powers they carry, we find replicas of the $P_m(\Delta\nu)$ curves for each of them, and difference P_s-P_p is adequate as an error signal to perform stabilization.



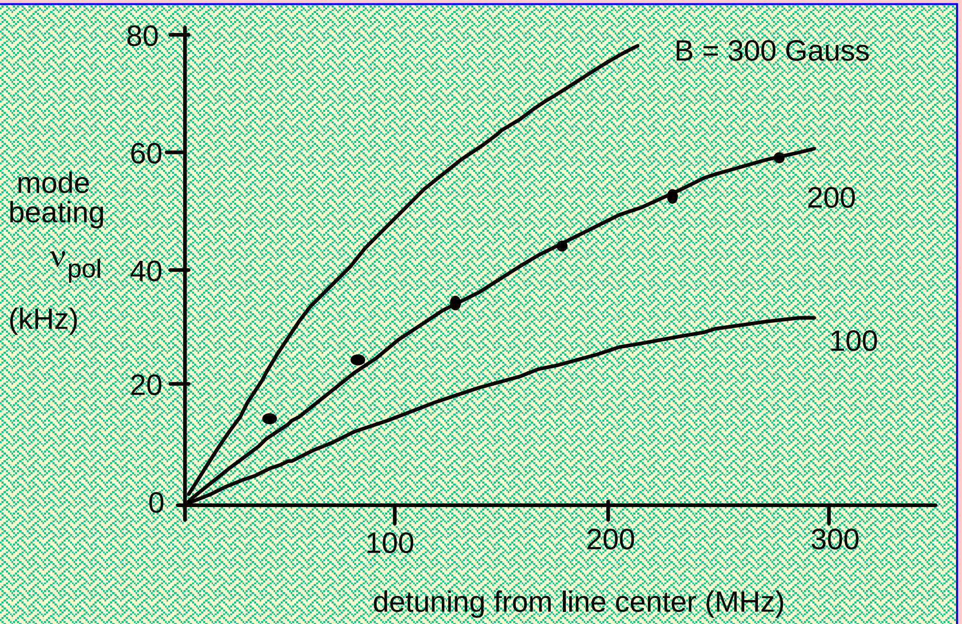
Frequency stabilization: Zeeman splitting

- *Zeeman splitting* of atomic line, for a magnetic field parallel (top) and perpendicular (center) to the tube axis.
- Mode pulling makes the two modes oscillate at a difference, typ. $\Delta\nu_{pol}$=50-200 kHz, dependent on detuning. This $\Delta\nu_{pol}$ is the error signal for cavity control, and can be recovered by a photodiode and a polarizer combination detecting mode beating at the rear mirror.
- After a F-V conversion, the error signal is ready for the actuator.
- Both longitudinal and transversal Zeeman effects can be used in practice.

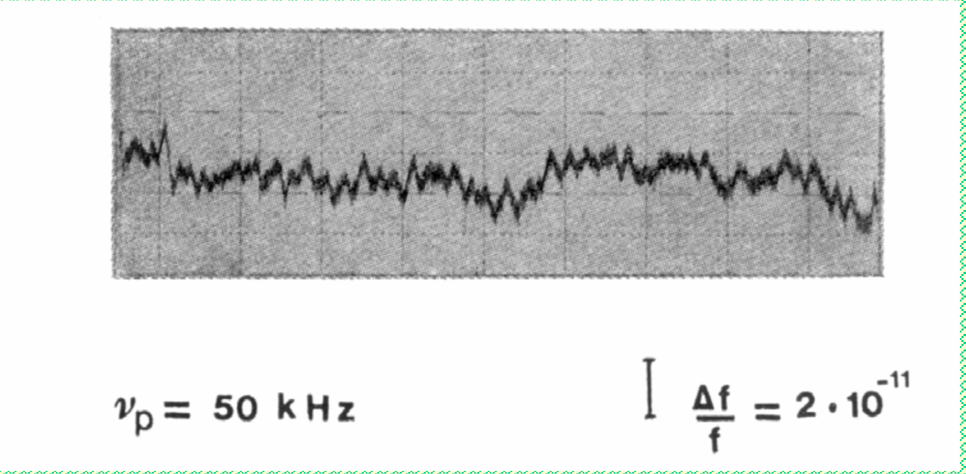


Frequency stabilization: Zeeman splitting (2)

The frequency difference between linearly polarized orthogonal modes in a He-Ne Zeeman laser with a transverse magnetic field, as a function of detuning and for several applied magnetic fields. Lines: theory; points: experimental values for B=200 Gauss.



Typical stability of frequency difference in a He-Ne Zeeman laser with transverse magnetic field, on a time scale of 1 hour.



from: 'Electro-Optical Instrumentation' by S.Donati, 2004,

Frequency stabilization: Iodine cell

With the *iodine (external cell) stabilization method*, we take advantage of the several lines of absorption that the $^{127}I_2$ vapor has under the Ne atomic line [5]. These lines are due to the hyperfine structure of iodine and are very narrow dips, typically ≈100 kHz wide.
We can probe the $^{127}I_2$ cell with the laser beam sweeping its frequency by means of the actuator. If we use the same modulation technique explained for the Lamb's dip method, we can lock the frequency at one of the fine dips. Frequency stability down to ≈100 Hz have been reported with external cell, the best achievable and of relevance for metrology. Despite that, the absorption cell method is seldom used for industrial interferometers, because the so many lines falling under the atomic line require a sophisticated control strategy to lock on a particular one, adding complexity to the final source layout.

Frequency stabilization: actuation

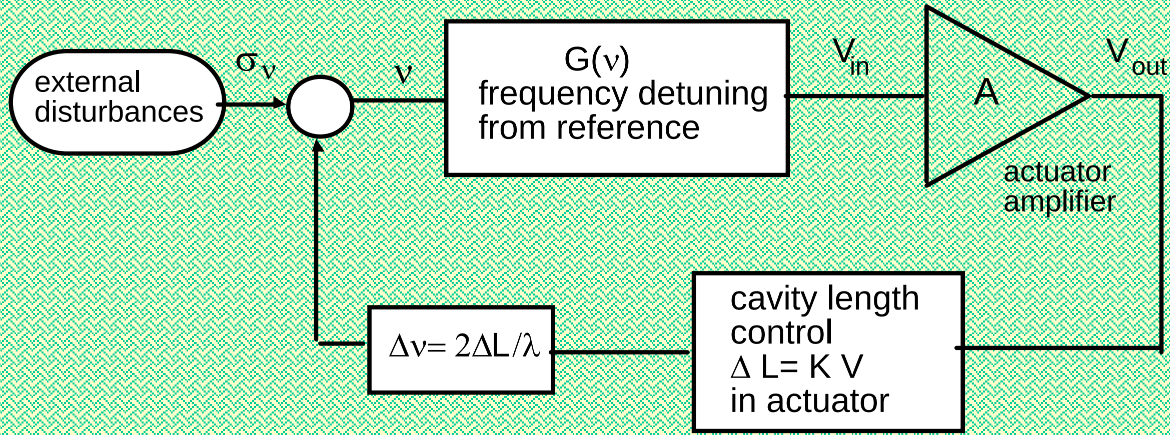
•The methods most used for actuation of the cavity length are:
(i) thermal expansion of the capillary tube, best for internal mirrors lasers
(ii) piezoelectric movement of the mirror, best for external mirrors lasers

•Thermal expansion is accomplished by Joule-dissipation in a resistive-wire (typ. Ni-Cr) directly wound on the capillary-tube length. With a few Watts of dissipated power is enough to ensure a ≈100-λ expansion, with response time τ=20-50 ms typ. enough for slow drifts and thermal transients.

• Piezo actuation is implemented by mounting a mirrors on a PZT piezo element. A few-mm thick ceramic disk will provide a few μm movement with a ≈1000 V supply on a capacitance (typ. 1000 pF) to the drive amplifier. Few-μm are enough for frequency stabilization when we have an Invar bearing structure, or put the structure in a thermostat. If not, we have to wait for thermal equilibrium (typ. 30 min, in a normal He-Ne tube).

• The advantage of the piezo respect to thermal actuation is the fast response time, down to 1..10μs.

Frequency stabilization: analysis of feedback loop



The block-scheme describes the functions of the feedback control loop:

- the error signal is converted into an electrical signal by G(ν),
- the power actuator has a voltage-gain A,
- the cavity-control makes a ΔL variation for unit voltage with a factor K.
- the ΔL change turns to Δν with a ratio $\Delta\nu/\Delta L=(c/2L)/(\lambda/2)=c/\lambda L$.

The loop-gain is accordingly $G_{loop}= G(\nu)AK(c/\lambda L)$. Thus a disturbance σ_ν of the frequency is reduced by a factor $1+G_{loop}$.

In the above examples, we have typ. $G_{loop}\approx 10^3\text{-}10^4$. The closed-loop rms frequency fluctuation is typ. 1-10MHz. The ultimate frequency stability is set by the quantum limit $\sigma_{\nu(limit)} =[2h\nu B/P]^{1/2}/\tau_c$, where P laser=cavity power, and $\tau_c =(1-r_1r_2)c/2L$ =photon decay time in the cavity. Values for $\sigma_{\nu(limit)}$ are down to few Hertz for P≈1mW, but seldom approached in practice.