

Last Lecture

1. **Spectroscopy using incoherent light:
case studies**

**Absorption, Reflection, PL, PLE, FTIR;
SWCNs, Conventional and HTc
superconductors**

2. **Laser fundamentals**

Today

1. **Laser fundamentals**
2. **Fundamentals of ultrafast optics and lasers**
The birth of ultrafast optics, femtosecond generation:
case studies, manipulating laser pulses
3. **Laser-based static spectroscopy**
Laser Raman/Raleigh, multi-photon nonlinear
Spectroscopy; manganites, SWCNs
4. **Time-resolved spectroscopy (Next week)**

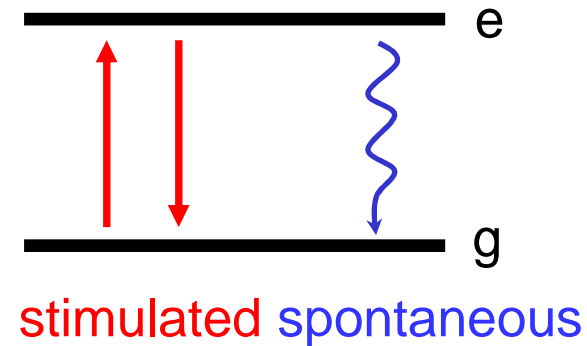
Optical Spectroscopy

1. Absorption, reflection, transmission, PL, PLE, FTIR...
2. Fundamental material properties

How Does Laser Work?

The model system: Titanium-doped Sapphire laser

Rate Equations Analysis



$$\frac{dN_e}{dt} = -\gamma_{eg}N_e - Kn_pN_e + Kn_pN_g = -\frac{dN_g}{dt}$$

$$\frac{dN_e}{dt} = -\gamma_{eg}N_e + Kn_p(N_g - N_e)$$

Rate Equation Analysis

Photon number varies:

$$\frac{dn_p}{dt} = -Kn_p (N_g - N_e) = -Kn_p \cdot \Delta N$$

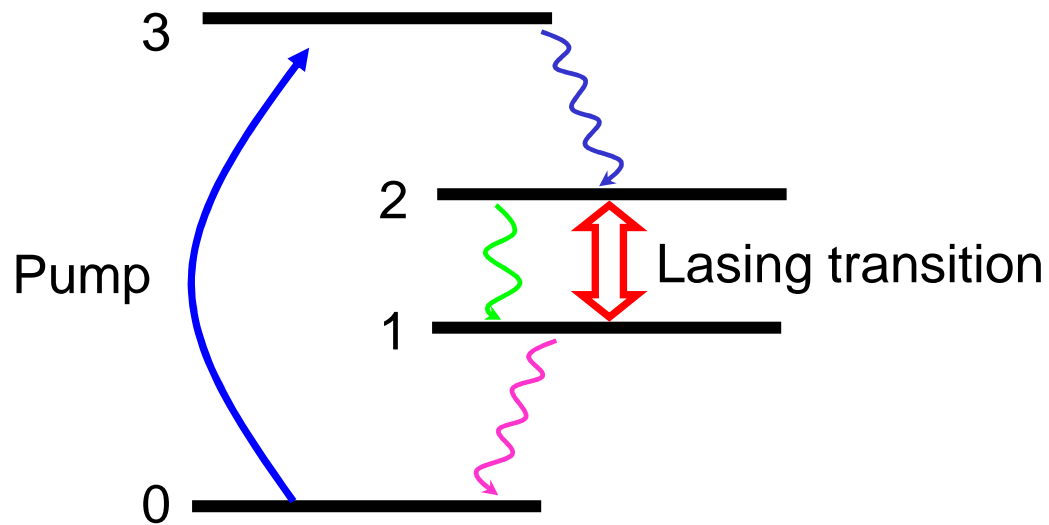
If $N_e > N_g$

A laser!

Wait, in thermal equilibrium:

$$N_e = e^{-\Delta E/kT} \cdot N_g < N_g$$

Four-level system



1 and 2:

Pumping rate for level 2: R_p

3:

stimulated transitions n_p

spontaneous decay γ_{21}

4:

spontaneous decay γ_{10}

$$\frac{dN_2}{dt} = R_p - \gamma_{21}N_2 + Kn_p(N_1 - N_2)$$

$$\frac{dN_1}{dt} = \gamma_{21}N_2 - Kn_p(N_1 - N_2) - \gamma_{10}N_1$$

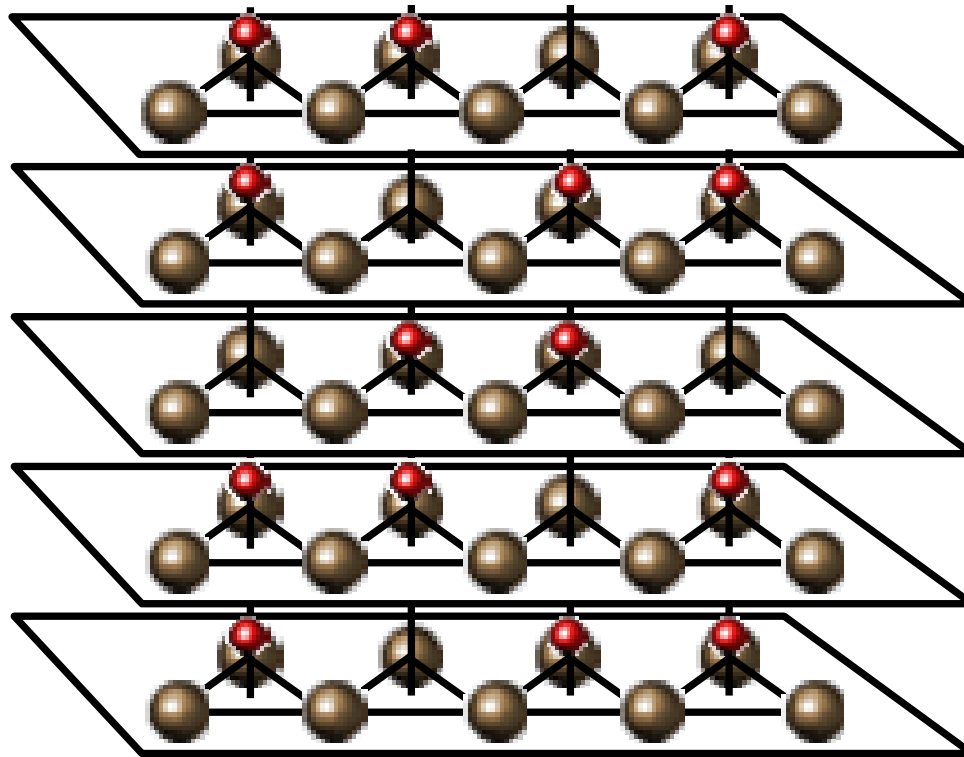
$$\frac{dN_0}{dt} = \gamma_{10}N_1 - R_p$$

Solving Four-level Model

Steady State $\Delta N \equiv N_1 - N_2 = \frac{R_p}{\gamma_{10}} \left[\frac{\gamma_{21} - \gamma_{10}}{\gamma_{21} + Kn_p} \right]$

Population inversion (i.e., $\Delta N < 0$) if $\gamma_{10} > \gamma_{21}$

Ti:sapphire – the Femtosecond Workhorse



Al_2O_3 lattice



oxygen
aluminum

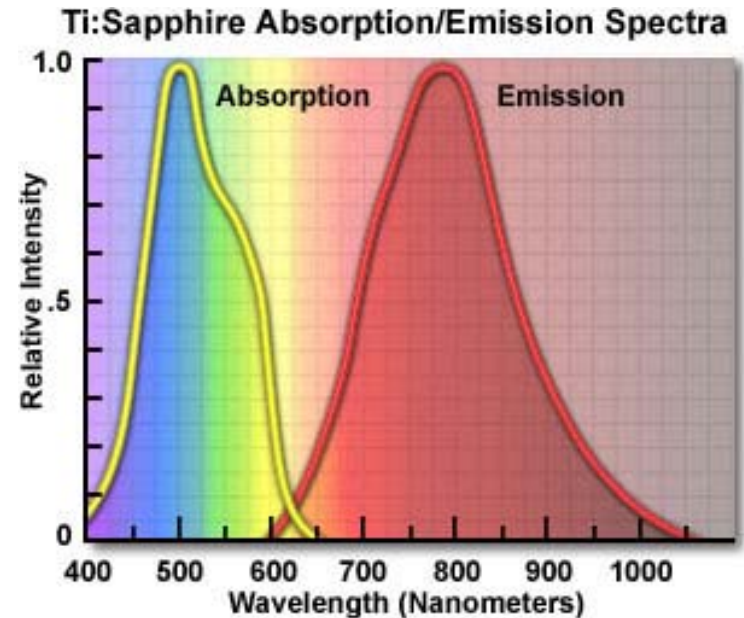
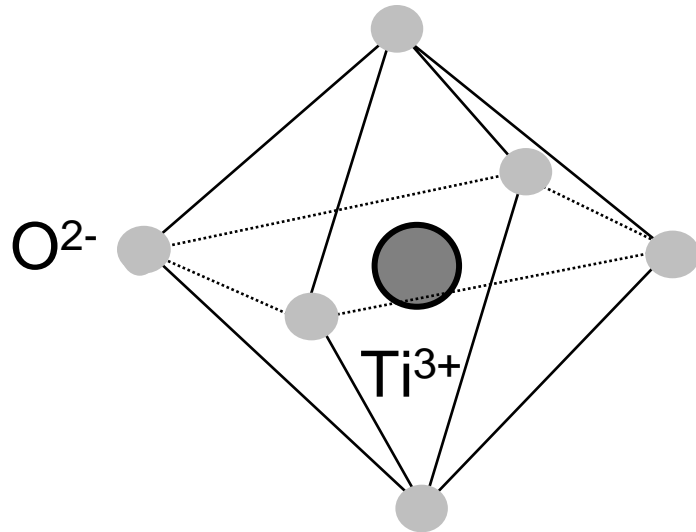


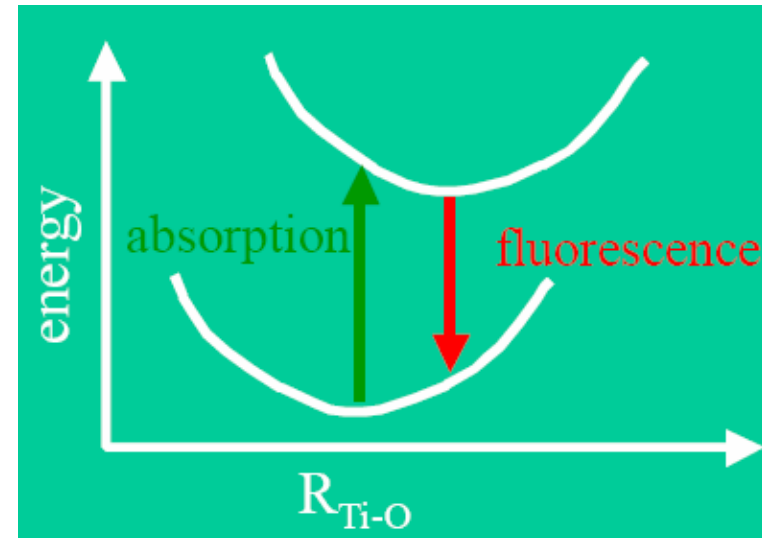
Figure 1

Four-level system
Broad gain spectrum

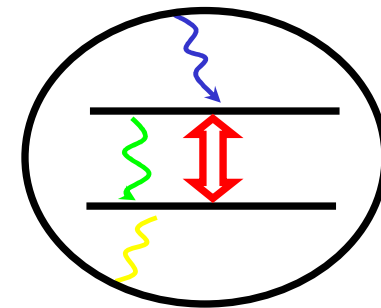
Ti:sapphire – “materials control technology”



3d¹, ~1.5 eV due to CF splitting
Superior thermal conductivity
Well-controlled doping



$$\tau_{10} = 3.2 \mu\text{s}$$



Example: a 5 mm Ti:sapphire crystal (0.5%), in a cavity with
5% output coupler

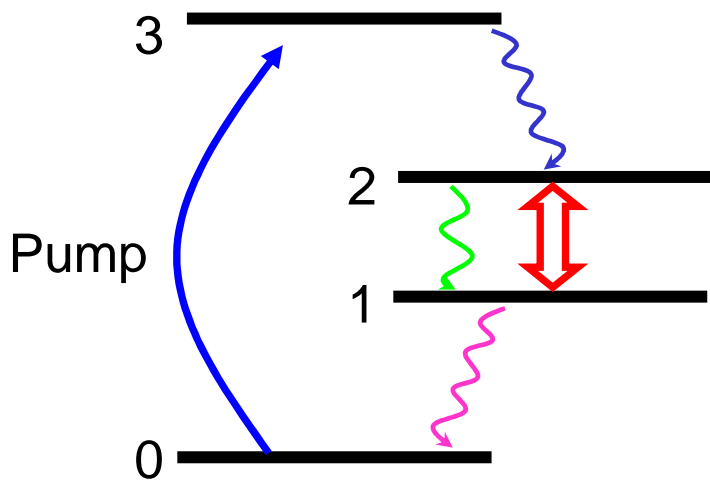
$$\Delta N_{th} \approx 2 \cdot 10^{17} \text{ cm}^{-3}$$

More Issues (I)...

Gain Saturation

$$\Delta N = \frac{R_p}{\gamma_{10}} \left[\frac{\gamma_{21} - \gamma_{10}}{\gamma_{21} + Kn_p} \right] = \left(\frac{\gamma_{21} - \gamma_{10}}{\gamma_{21} \gamma_{10}} \right) \cdot R_p \frac{1}{1 + W_{sig} \tau_{21}}$$

\uparrow ΔN_0 \uparrow \uparrow
 Kn_p $1/\gamma_{21}$



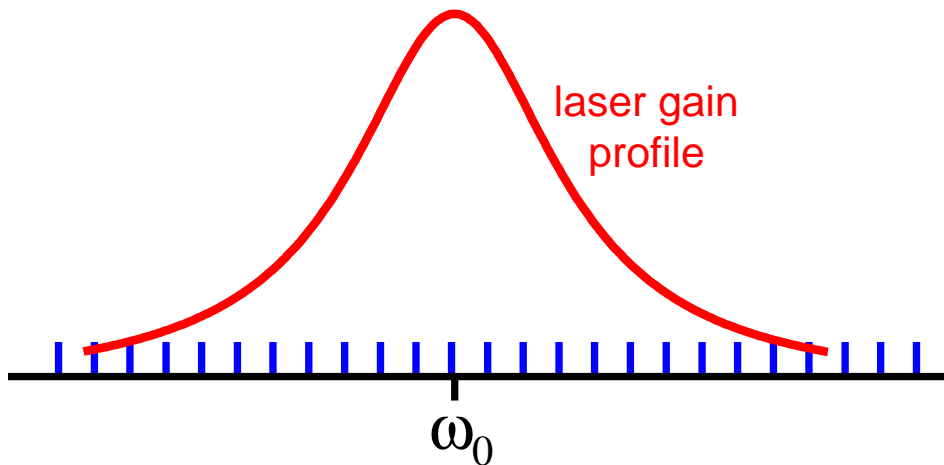
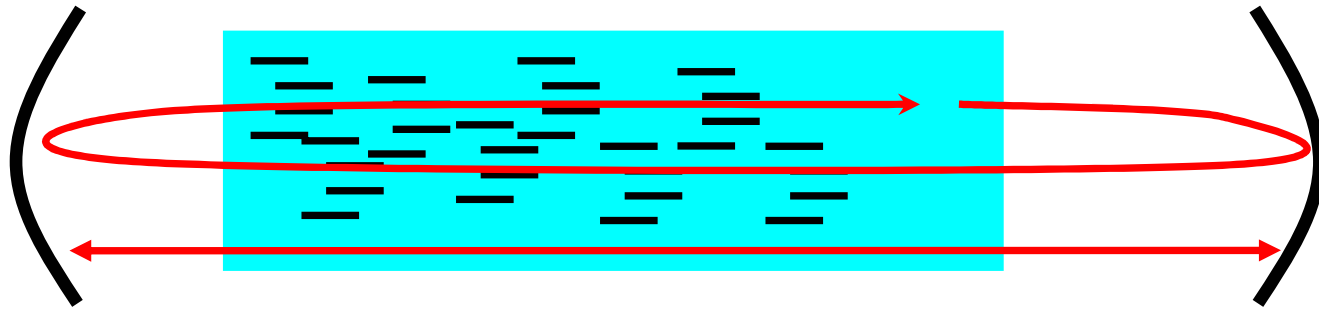
**Gain saturates when
signal intensity > 1/τ₂₁**

$$\Delta N = \frac{N_0}{1 + I/I_{sat}} \quad I_{sat} = \gamma_{21}/K = \hbar\omega/\tau_{21}\sigma$$

10⁵ to 10¹³ W/cm²

More Issues (II)...

Longitudinal modes



$$\frac{\text{angle}(E_{\text{after}})}{\text{angle}(E_{\text{before}})} = \exp(-i\omega L_{rt} / c) = 1$$

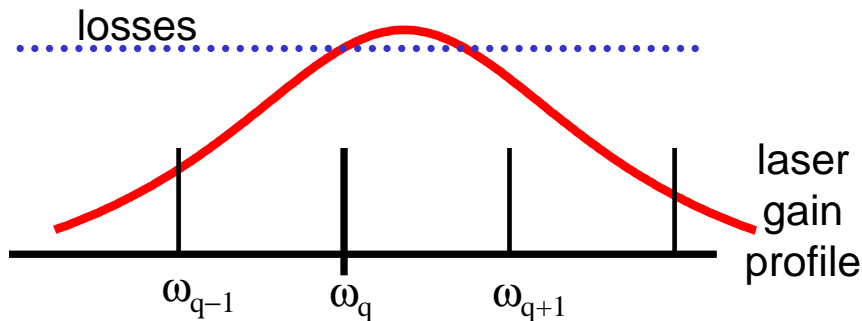
$$\rightarrow \omega_q = \frac{2\pi c}{L_{rt}} \cdot q \quad (q = \text{an integer})$$

$$\Delta\nu = c/2L_c \approx 100 \text{ MHz for a 1.5 meter cavity length}$$

More Issues (II)...

An ideal laser
(homogeneous Gain Medium)

$$g_0 \propto \Delta N_0 = \left(\frac{\gamma_{21} - \gamma_{10}}{\gamma_{21}\gamma_{10}} \right) \cdot R_p$$

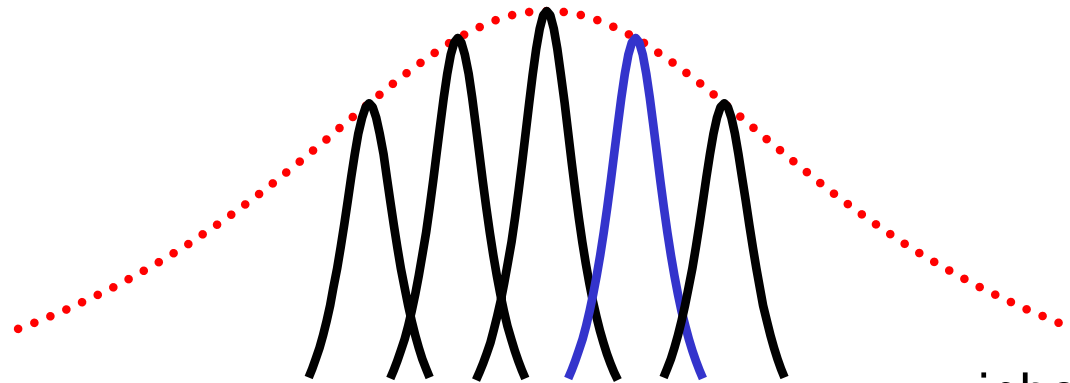


Q: Suppose the gain is increased further. Can it be increased so that the mode at ω_{q+1} oscillates cw?

A: In an ideal laser, NO!

More Issues (II)...

Inhomogeneous Gain Medium



homogeneous “packet”

$$dN(\omega_0) = Ng(\omega_0)d\omega_0$$

inhomogeneous
line

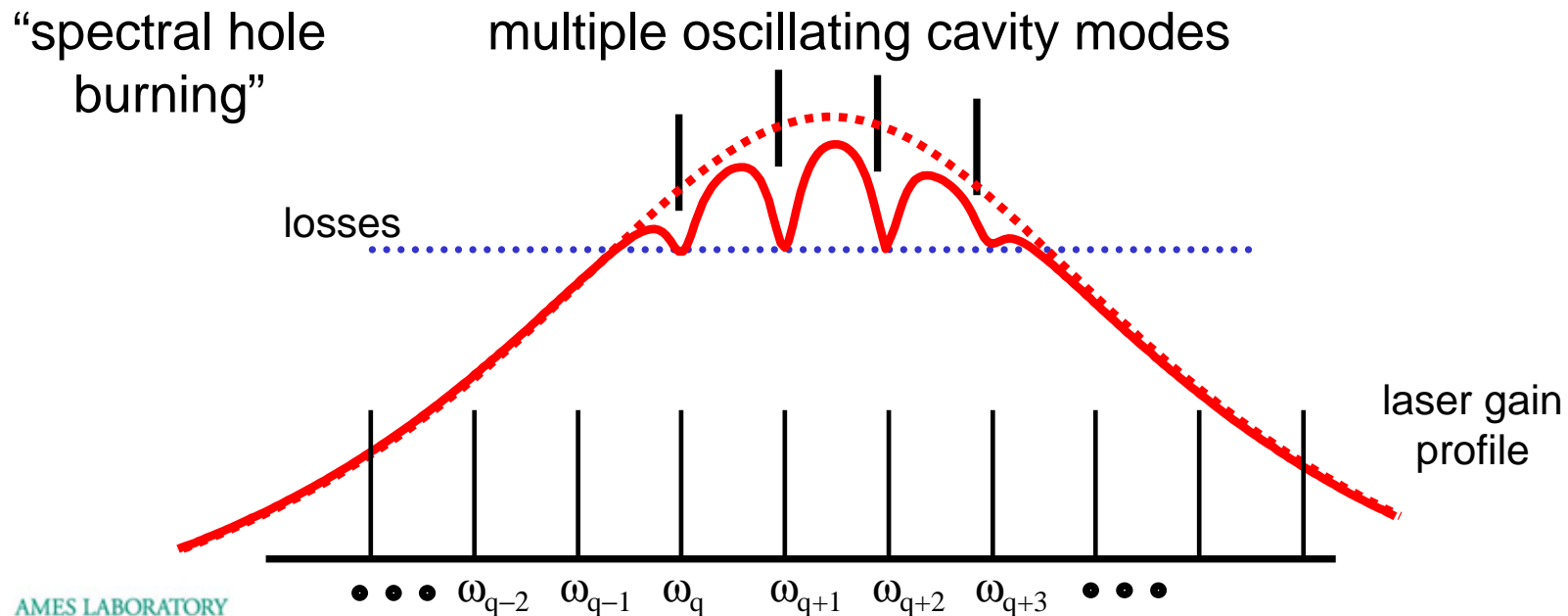
$$\Delta\omega \gg \gamma$$

$$\chi(\omega) = \int d\omega_0 \chi_h(\omega; \omega_0) \cdot e^{-4\ln(2)\left(\frac{\omega_0 - \bar{\omega}_0}{\Delta\omega}\right)^2}$$

More Issues (II)...

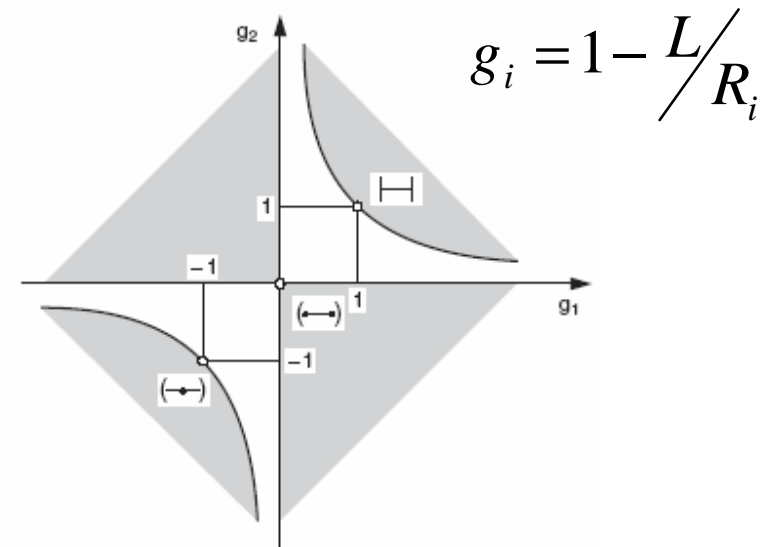
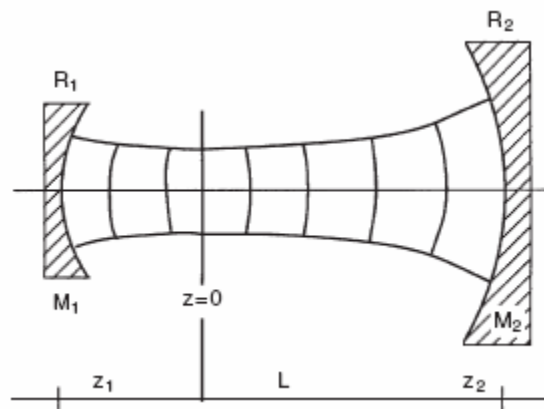
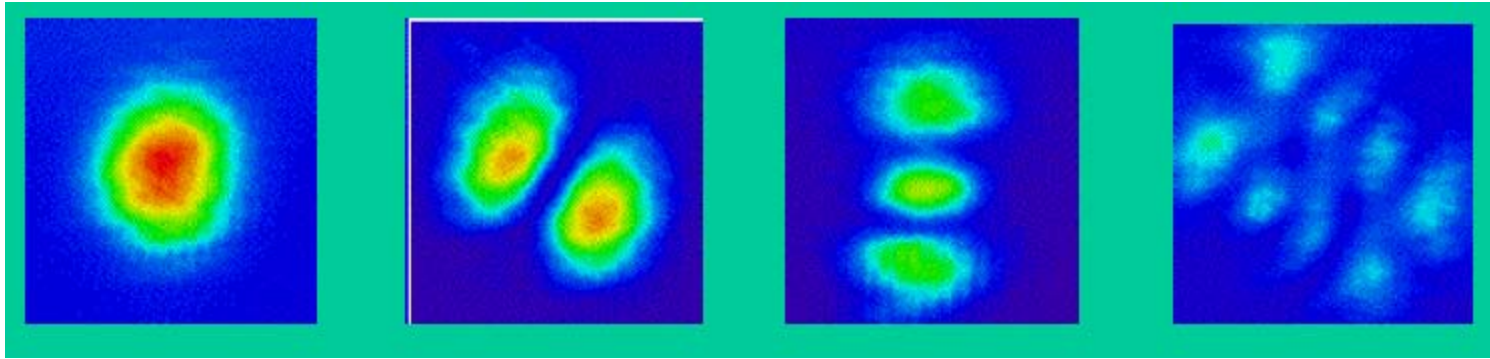
Q: Suppose the gain is increased above threshold in an inhomogeneously broadened laser. Can it be increased so that the mode at ω_{q+1} oscillates cw?

A: Yes! Each homogeneous packet saturates independently



More Issues (III)...

Transverse modes and stability zones



Lasers as spectroscopy light sources

1. **Static spectroscopy using CW lasers**
2. **Static spectroscopy using ultrashort pulsed lasers**