Lecture 8: Laser oscillation

- Recall: No two-level laser (discuss “pump”, and semiconductor lasers)
- Recall: Three level lasers, gain saturation
- Single mode lasing
- Multi-mode lasing
- Reading: Verdeyen ch. 9
- Optional: Siegman ch. 12

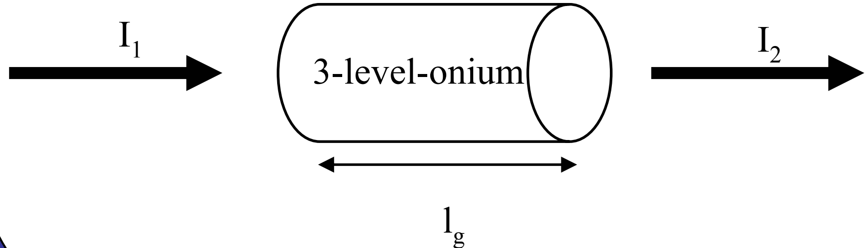
Gain saturation:

$$\frac{\partial I}{\partial z} = \gamma I_\nu \qquad \gamma = \sigma(\upsilon)(N_2 - N_1)$$

Physical interpretation of γ:
% gain/length

For a 3-level system, we found:

$$\gamma(I) = \frac{\gamma_0}{1 + I_\upsilon / I_s}$$



$$\ln \frac{I_2}{I_1} + \frac{I_2 - I_1}{I_s} = \gamma_0 l_g$$

In HW you will plot I_2 vs. I_1.

Homogenous broadening (e.g. lifetime broadening)

$$\gamma(I_\upsilon) = \frac{\gamma_0(\upsilon)}{1 + I_\upsilon / I_s}$$

$$\rightarrow \gamma(I_\upsilon) = \frac{\gamma_0(\upsilon)}{1 + \bar{g}(\upsilon) I_\upsilon / I_s}$$

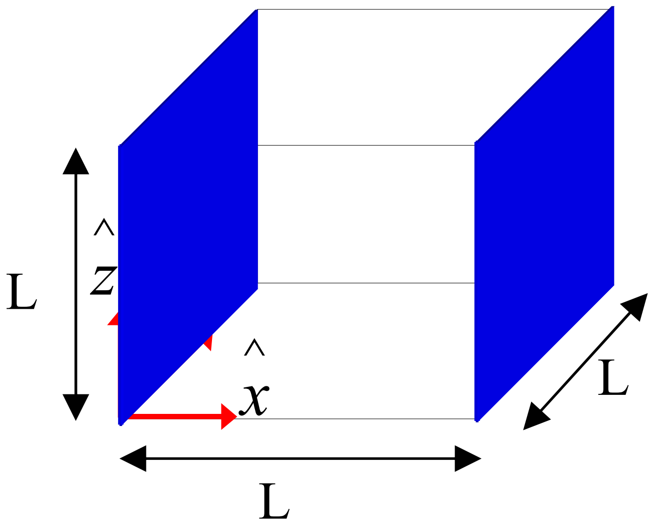
$\bar{g}(\upsilon)$ is the relative lineshape

$\bar{g}(\upsilon) = 1$ on resonance

Even if I is "off" resonance, it will tell tend to saturate the whole gain vs. frequency curve!

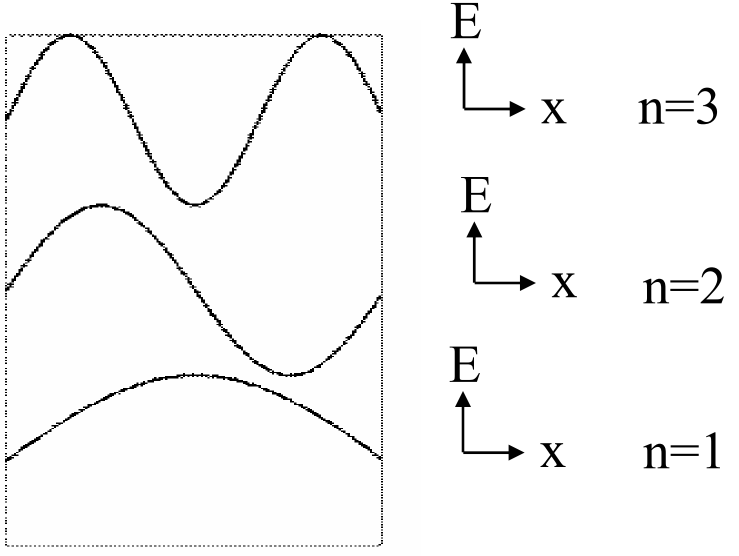
Draw this important point on the board.

Recall allowed modes for 2 mirror system



$$\vec{E}(\vec{r},t) = \mathrm{Re}\left[E_0 \hat{z} e^{i(k\hat{x}\cdot\vec{r} - \omega t)}\right] + \mathrm{Re}\left[E_0 \hat{z} e^{i(k\hat{x}\cdot\vec{r} + \omega t)}\right]$$

$$= -2E_{0imag}\hat{z}\sin(k_n x)\cos(\omega t)$$



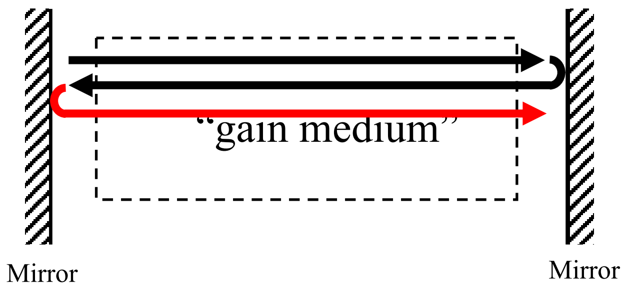
$$k_n = n\pi / L$$

$$\omega_n = ck_n = nc\pi / L$$

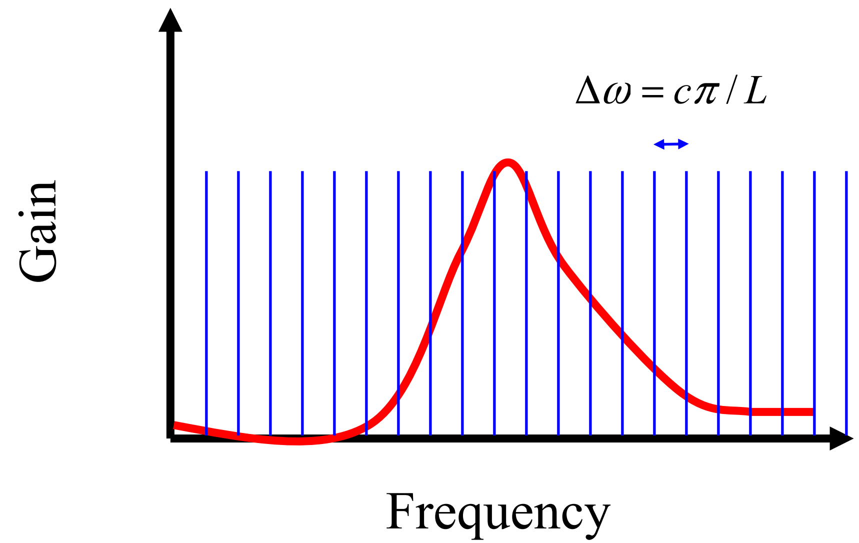
Note: amplitude E_0 can have any value.
Later we will find E_0 is quantized itself.

"Single vs. multi-mode lasing"

MULTI-MODE



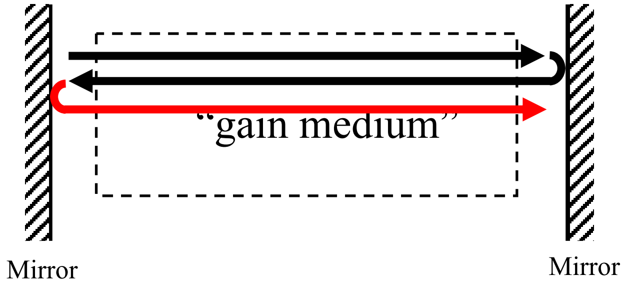
$$\omega_n = ck_n = nc\pi / L$$



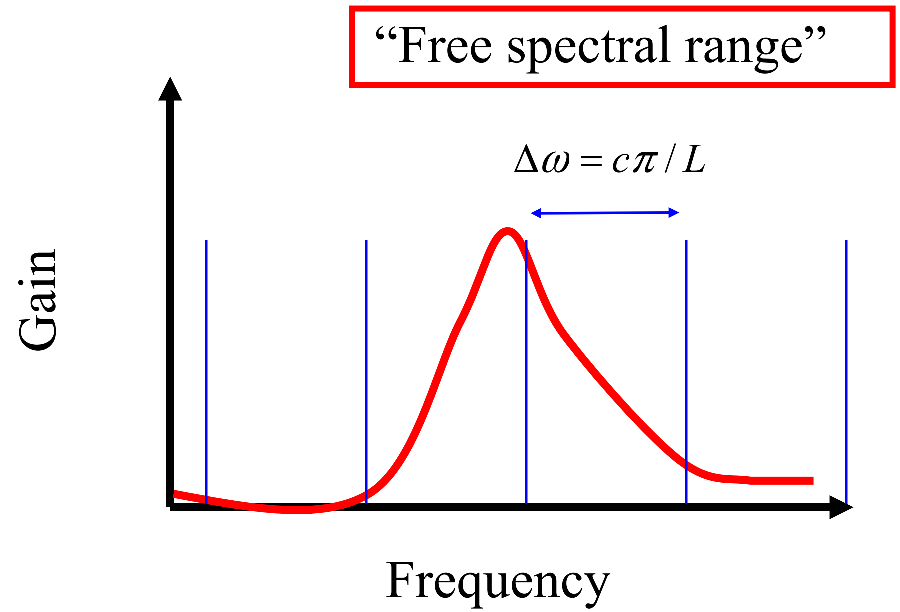
"Single vs. multi-mode lasing"

SINGLE MODE

Obviously, single mode lasers are better for communications.

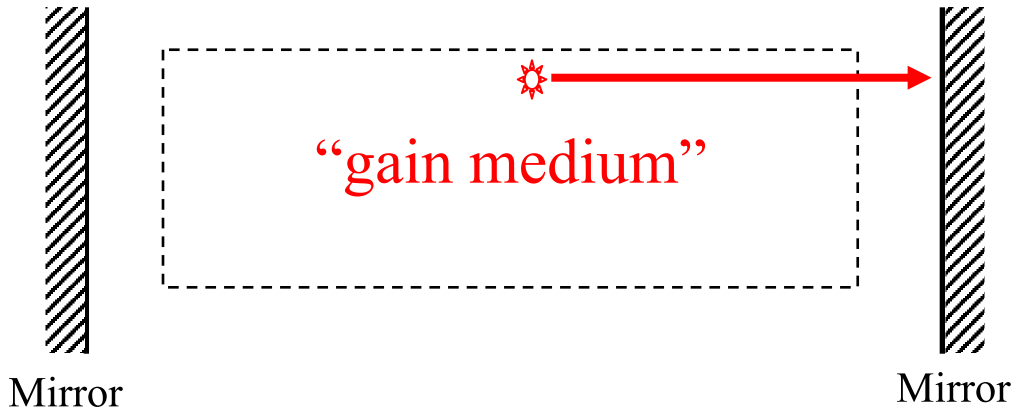


$$\omega_n = ck_n = nc\pi / L$$

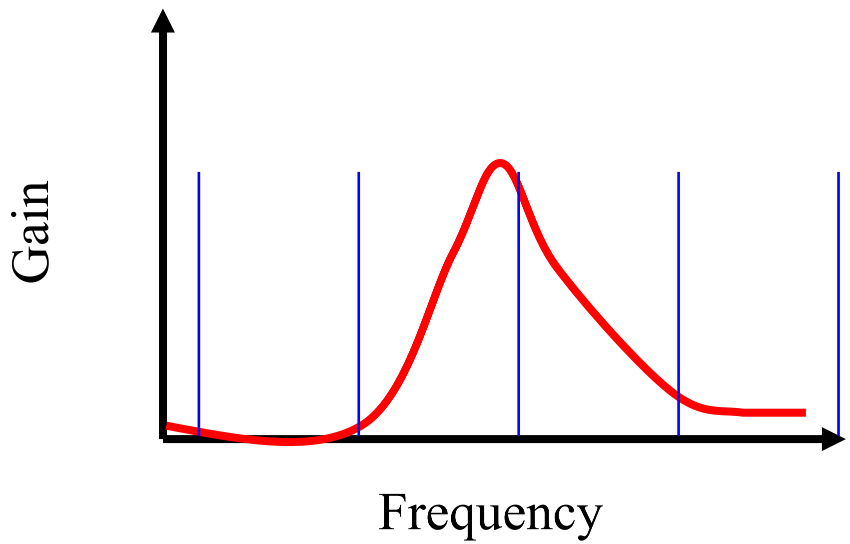


Single mode laser:

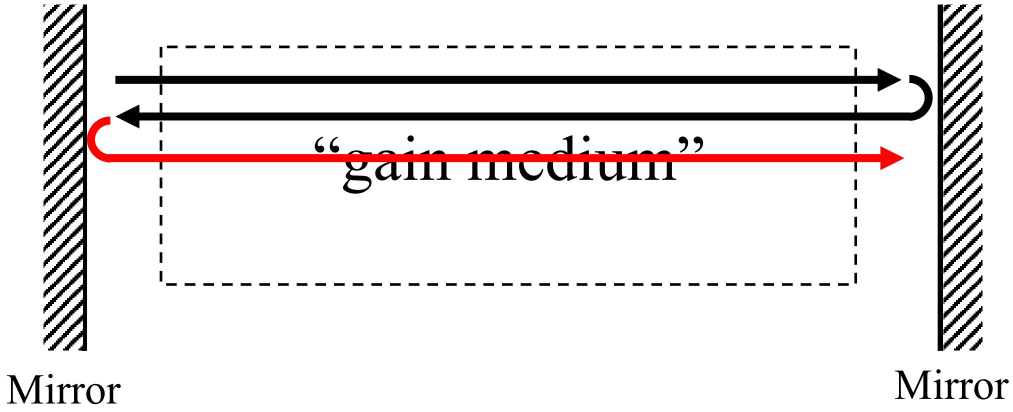
Spontaneous emission can start it up:

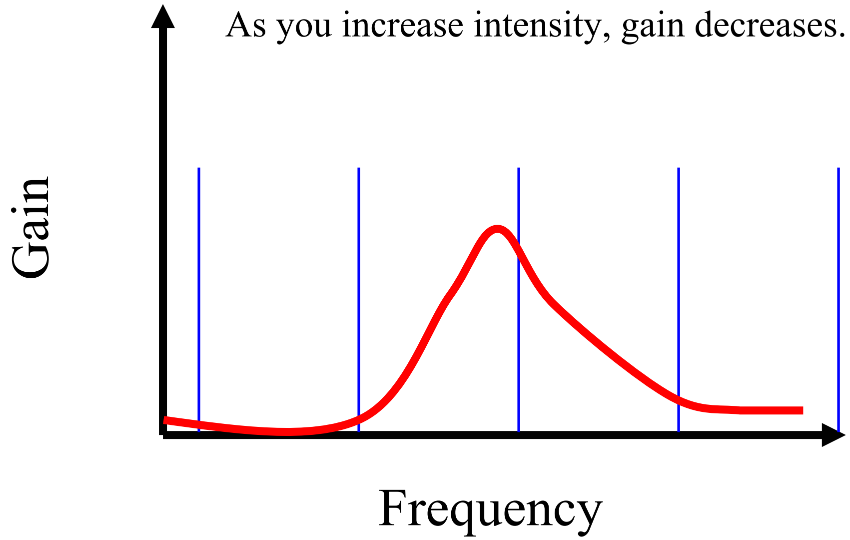


As you increase intensity, gain decreases.

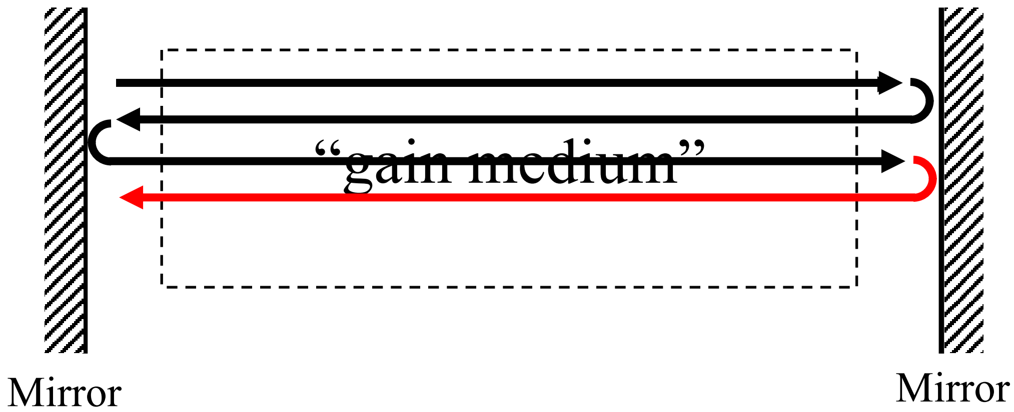


Single mode laser:





Single mode laser:



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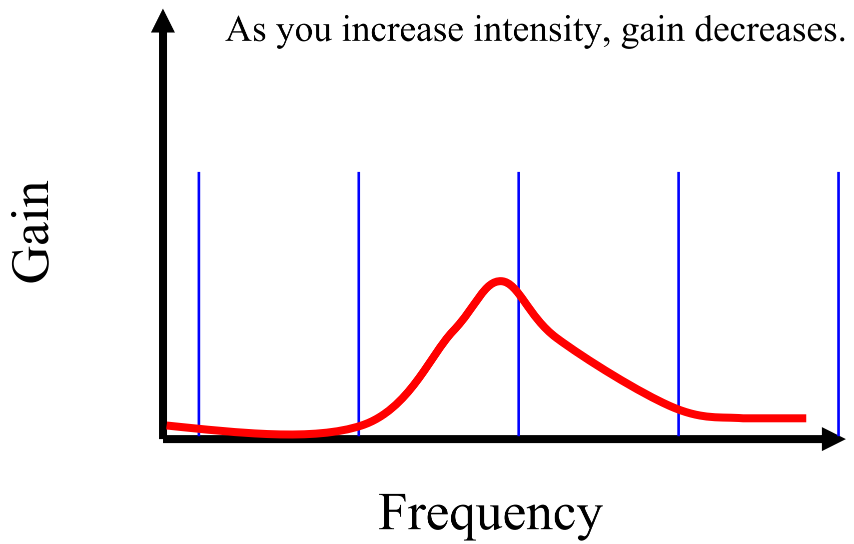
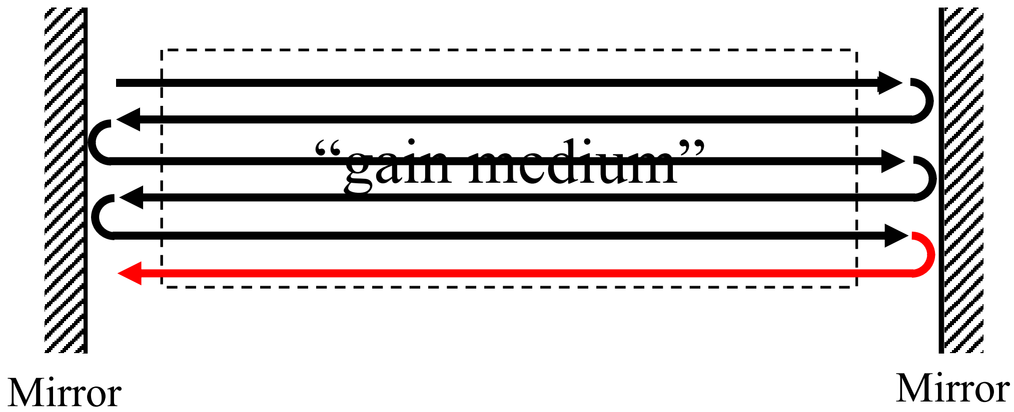
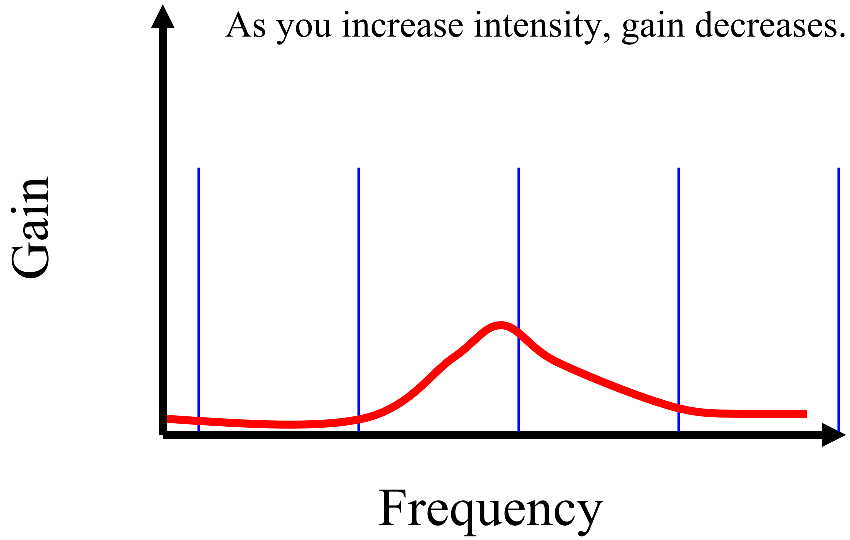
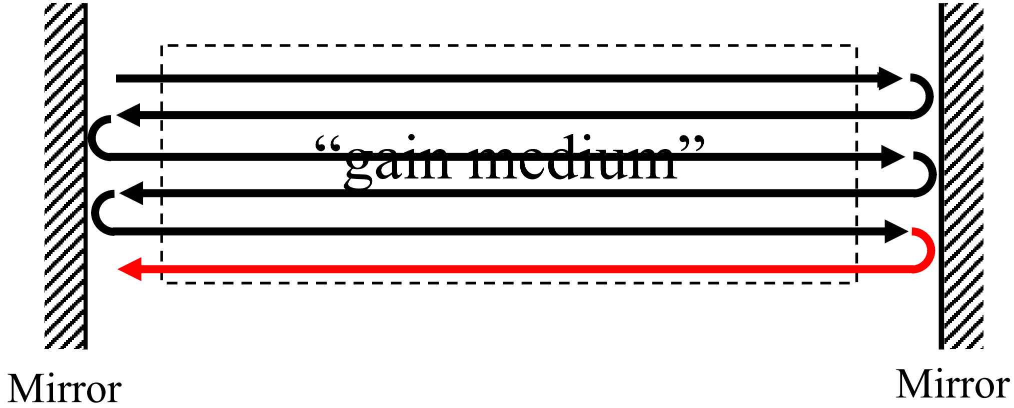


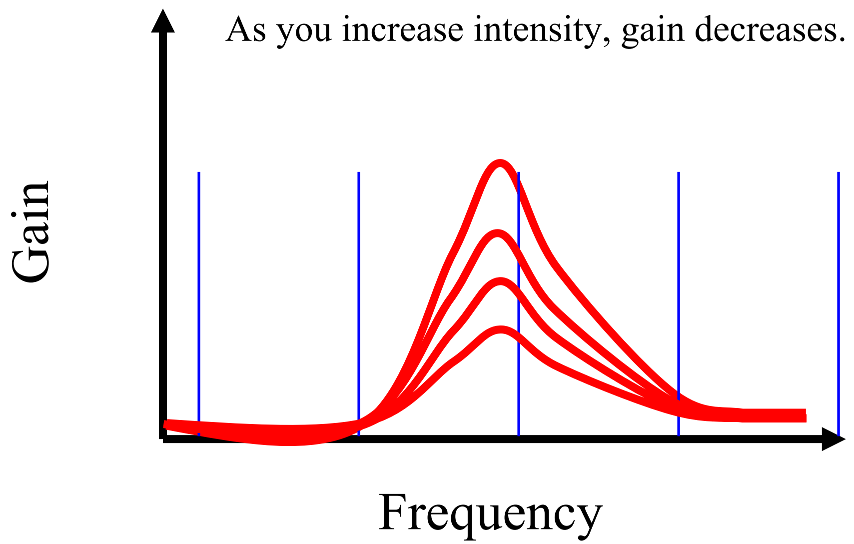
Single mode laser:



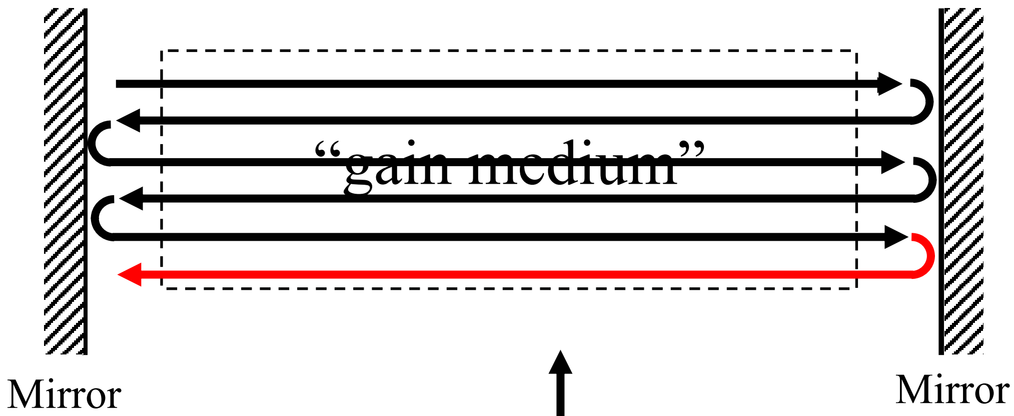


Single mode laser:

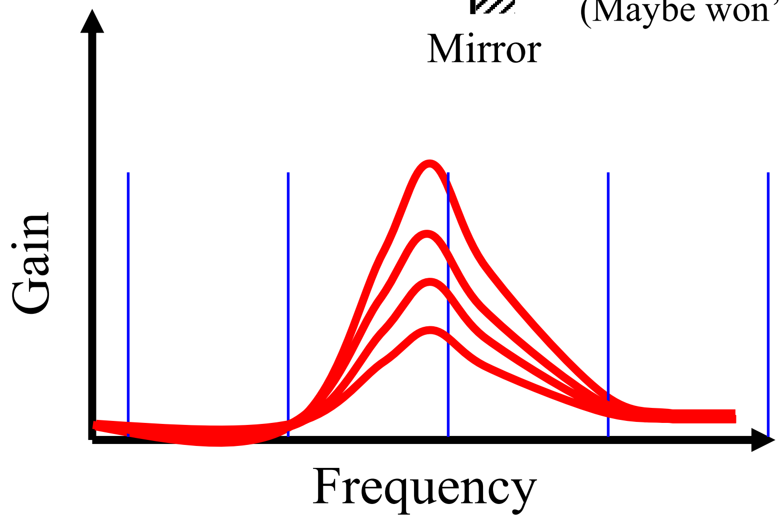




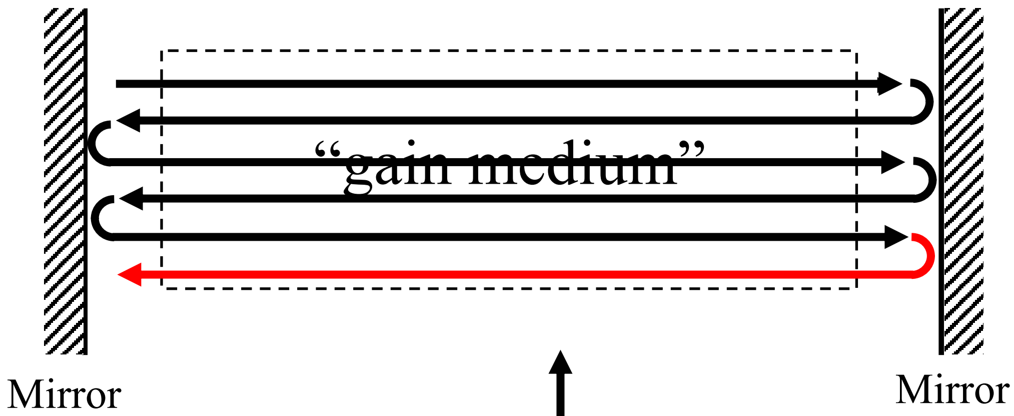
Single mode laser:

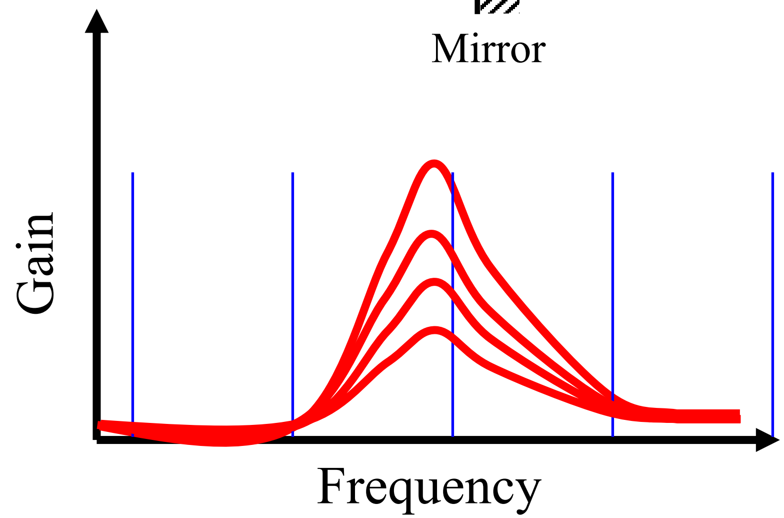


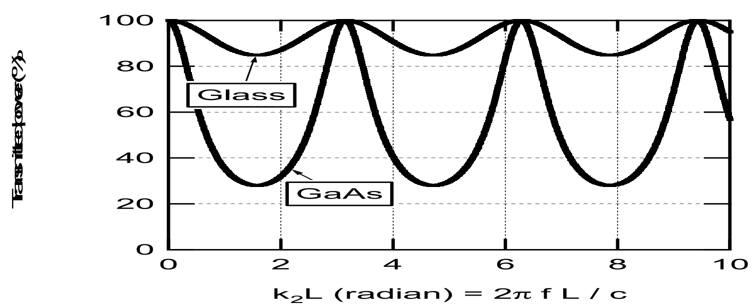
How do you get light out?
2 options:
1) Tiny extraction of light per roundtrip:
High intensity inside, but not much out.
(Maybe runs in saturation mode.)
2) A lot of extraction per roundtrip:
Large extraction, but losses are high.
(Maybe won't run in saturation mode.)



Imperfect mirrors: (HW#1)

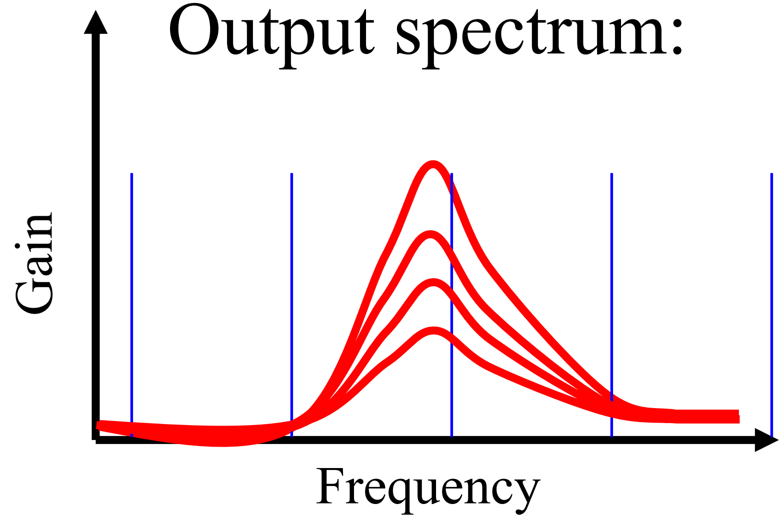




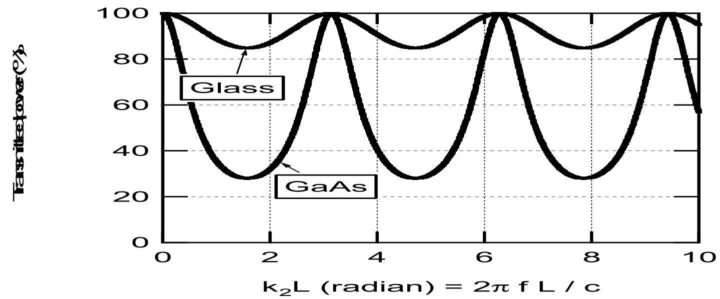


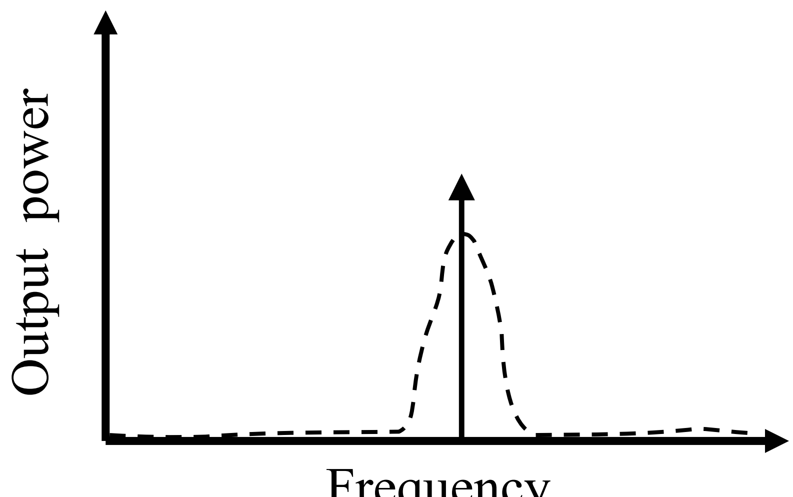
GaAs laser
cleaved facet
n=3.5

Output spectrum:



GaAs laser cleaved facet n=3.5





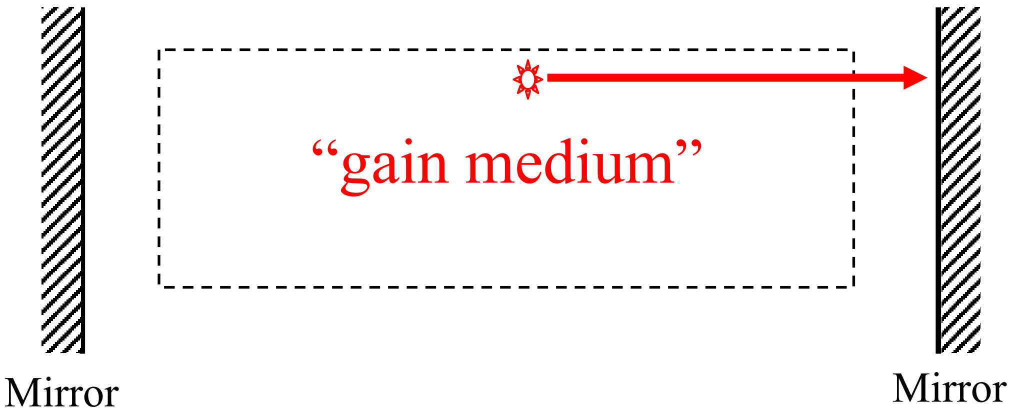
Arrow for perfect mirrors.

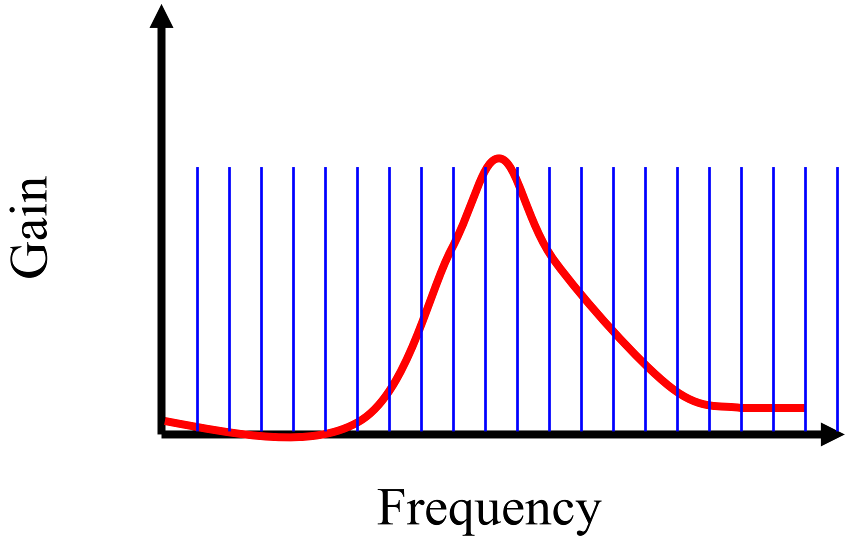
Dashed line for imperfect mirrors.

We will discuss Q of cavity later.

Multi- mode laser:

This is a little trickier.





Multi- mode laser:

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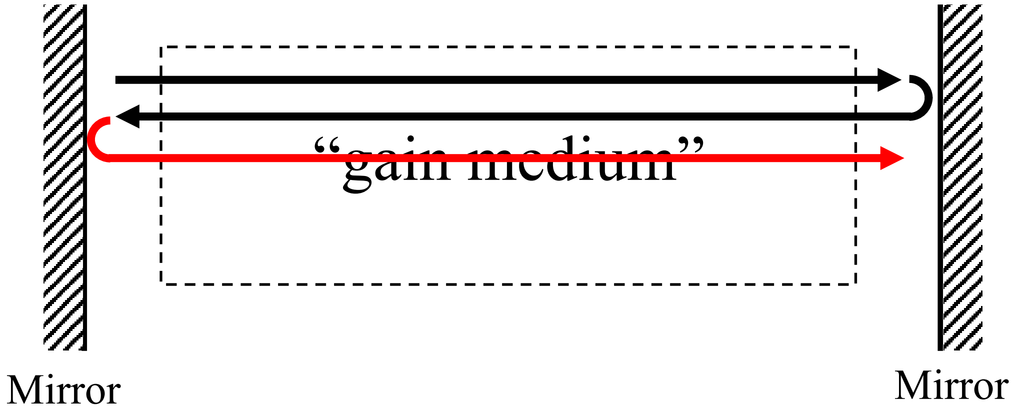

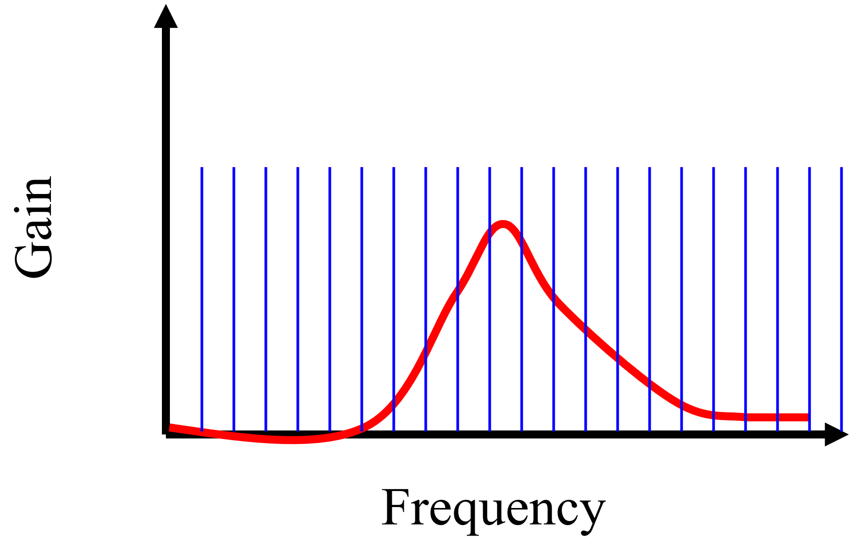

Multi- mode laser:

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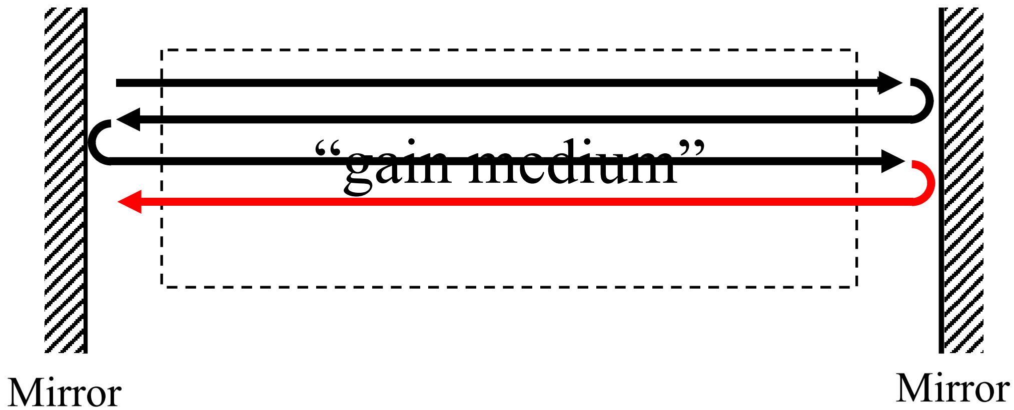

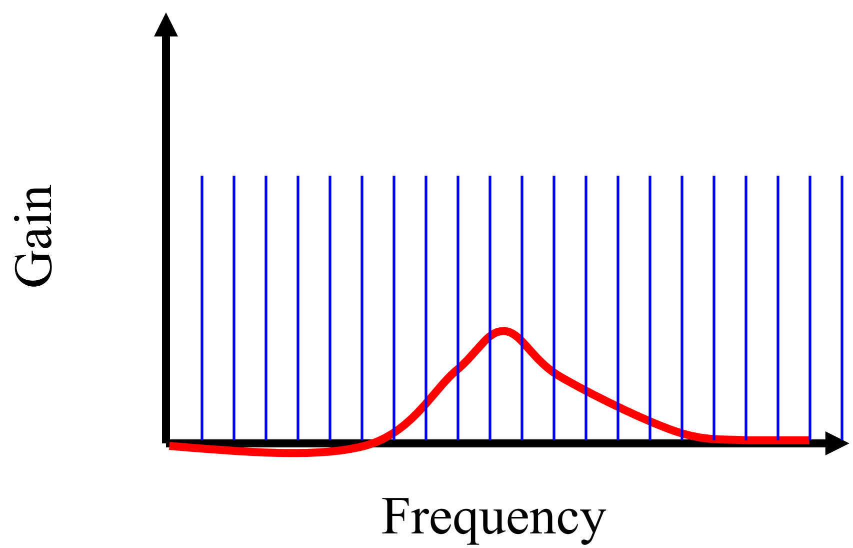

Multi- mode laser:

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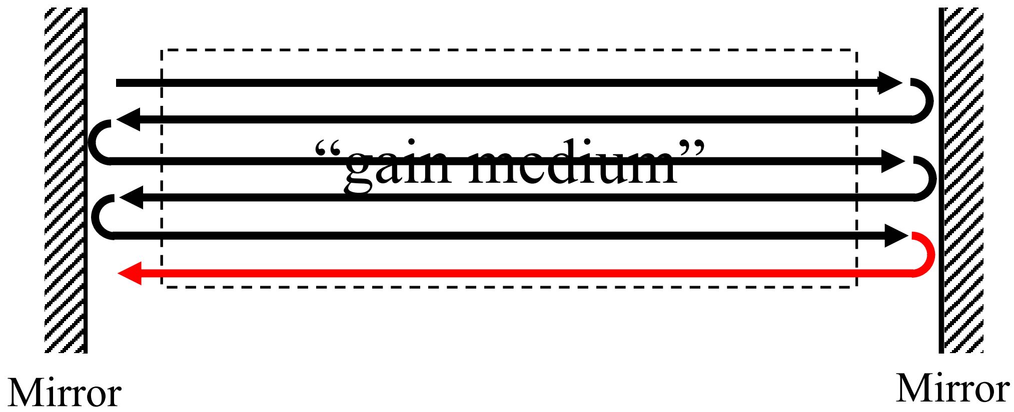

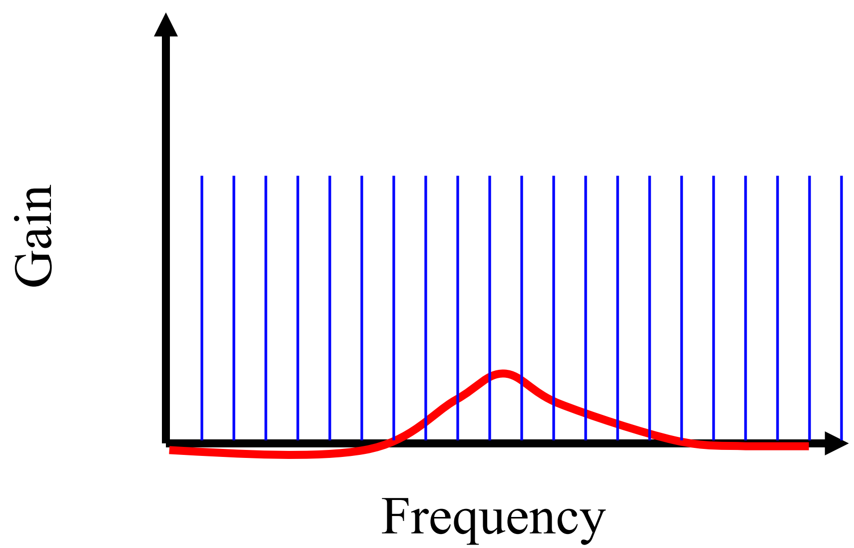

Multi- mode laser:

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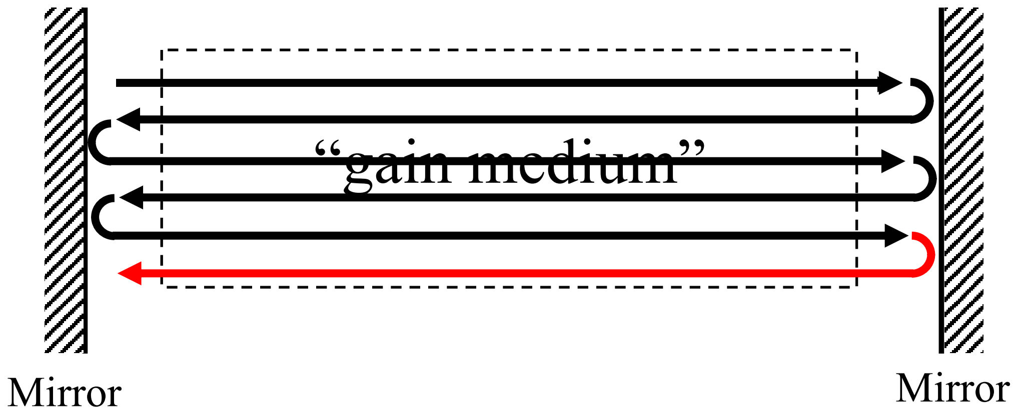
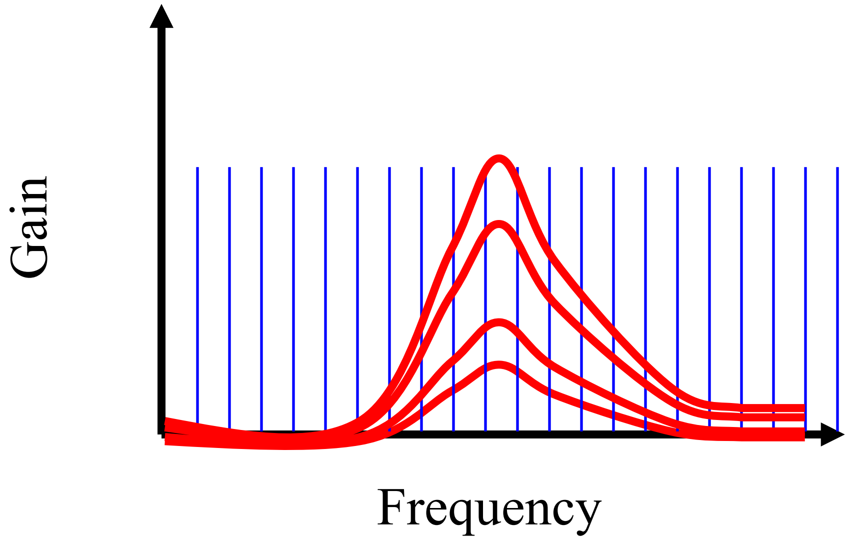
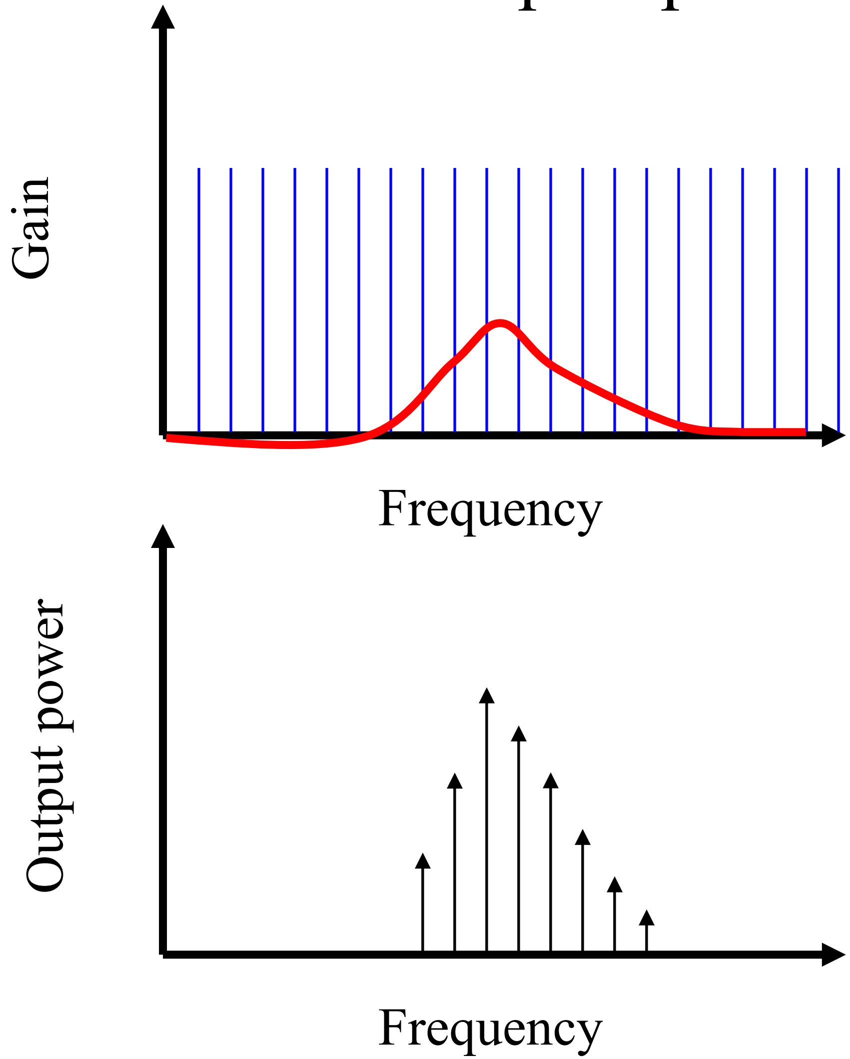




Multi-mode output spectrum:



Arrow for perfect mirrors.

Is this good for DWDM (dense wavelength division multiplexing?) NO!

Note: This analysis is wrong, because we have not considered losses.

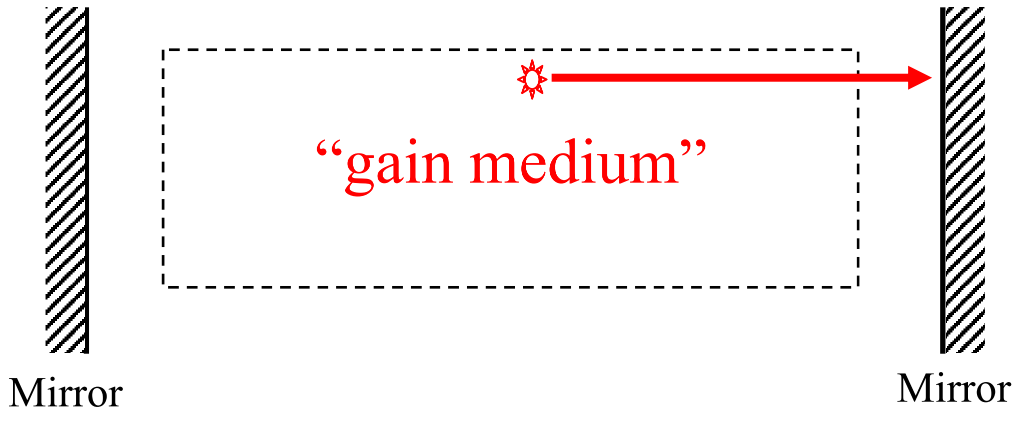
In the above case, all modes with any gain will continue to grow in intensity forever!

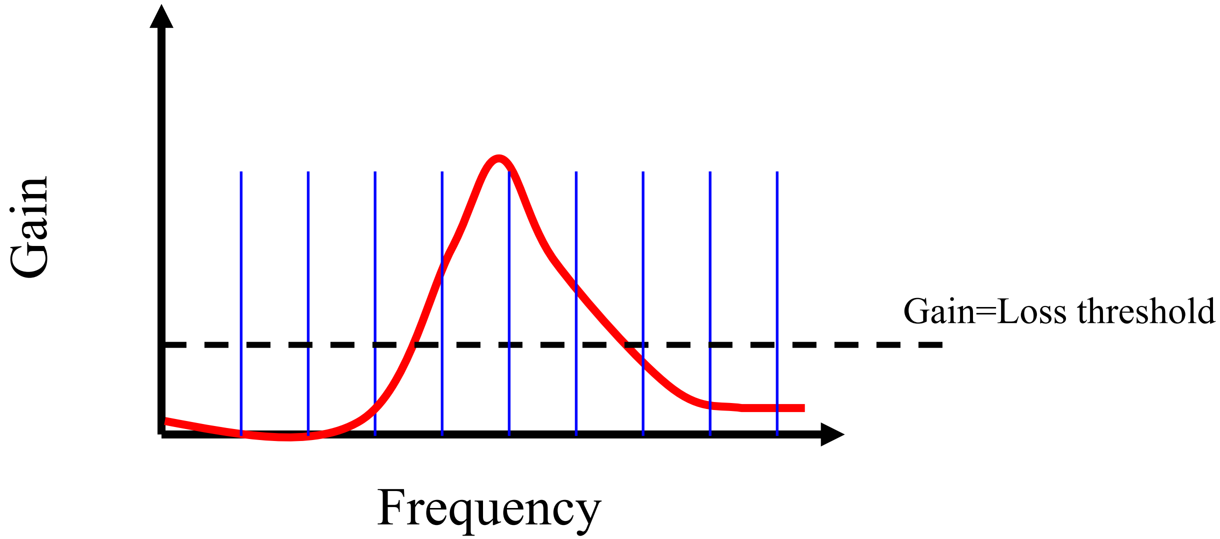
What about losses?

Recall condition for laser:

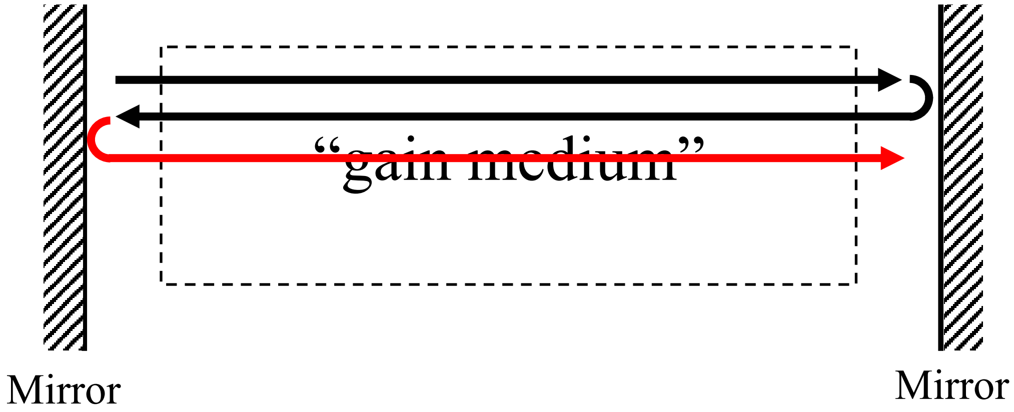
GAIN > LOSS

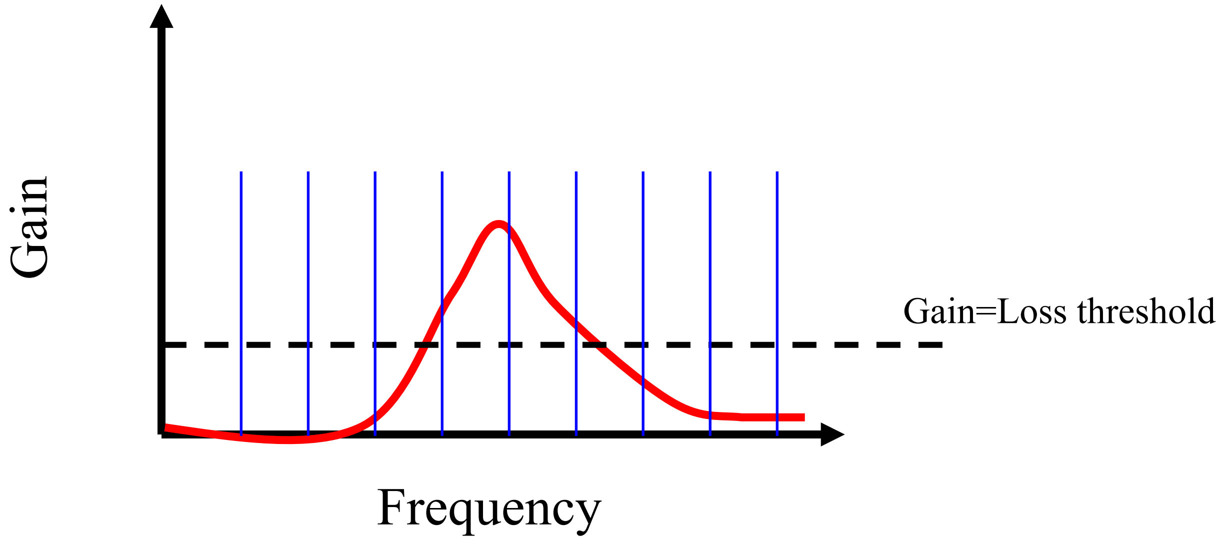
"Multi- mode" laser:



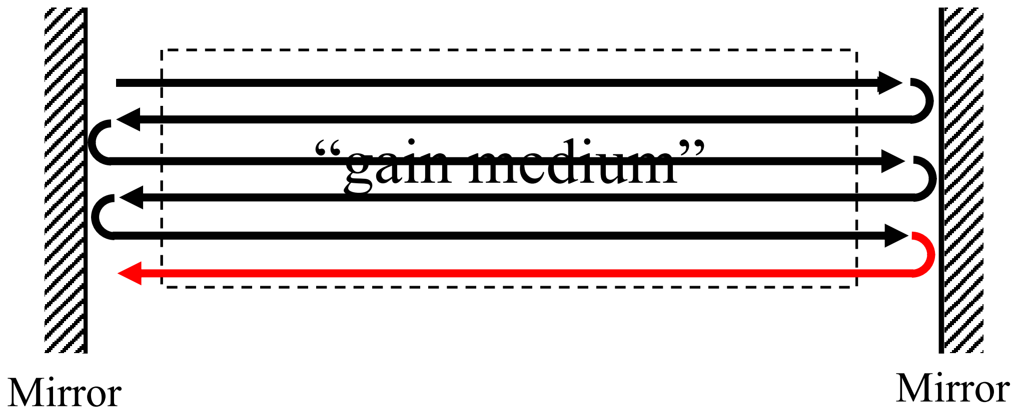


“Multi- mode” laser:

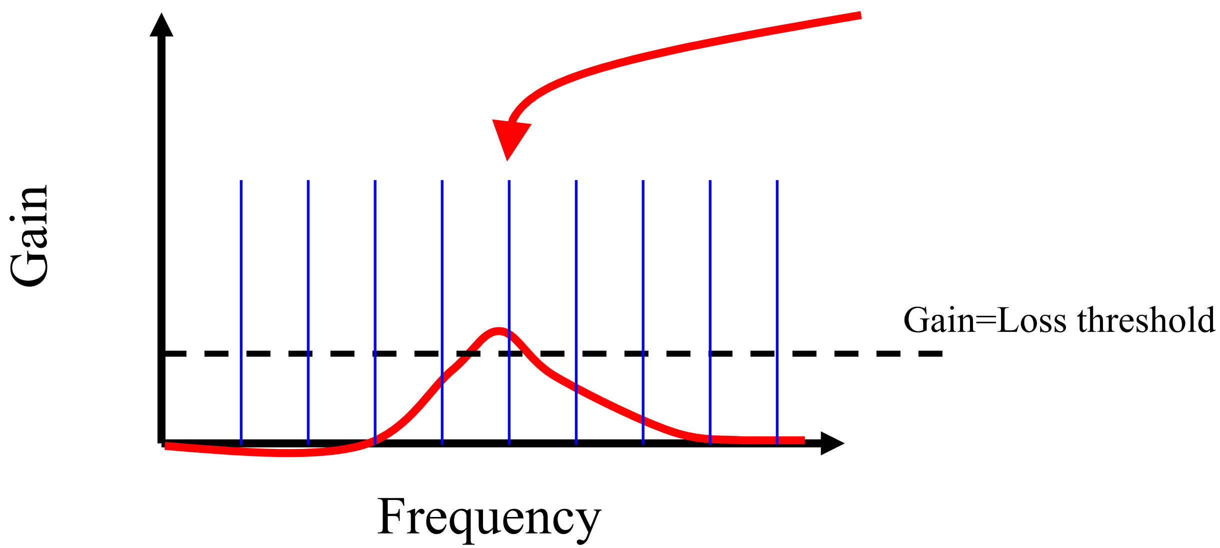




“Multi- mode” laser: Not really

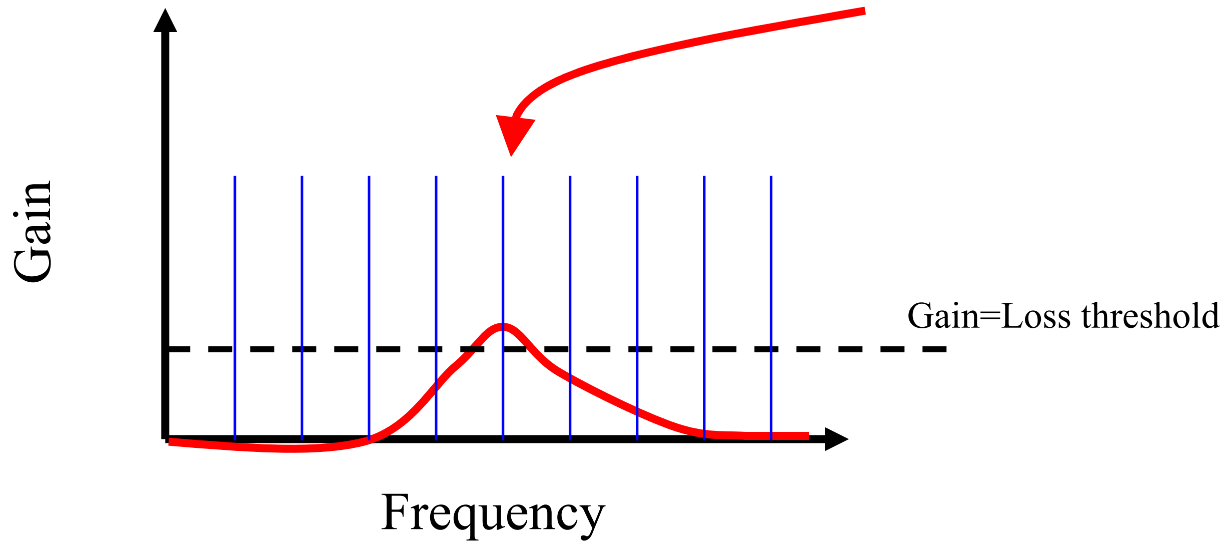


Only this mode has enough gain for laser oscillation.

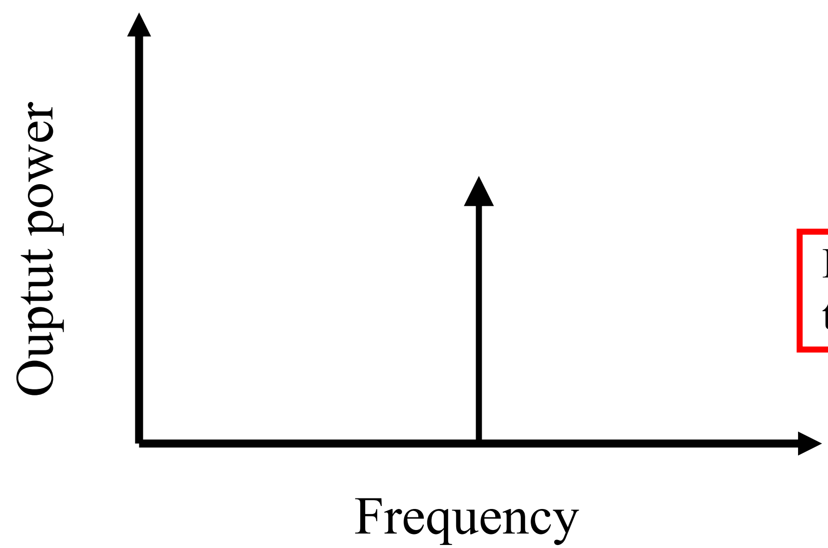


Output spectrum:

Only this mode has enough gain for laser oscillation.



Actually, the intensity will increase until the “gain” equals the loss. This will happen for generally only one mode.



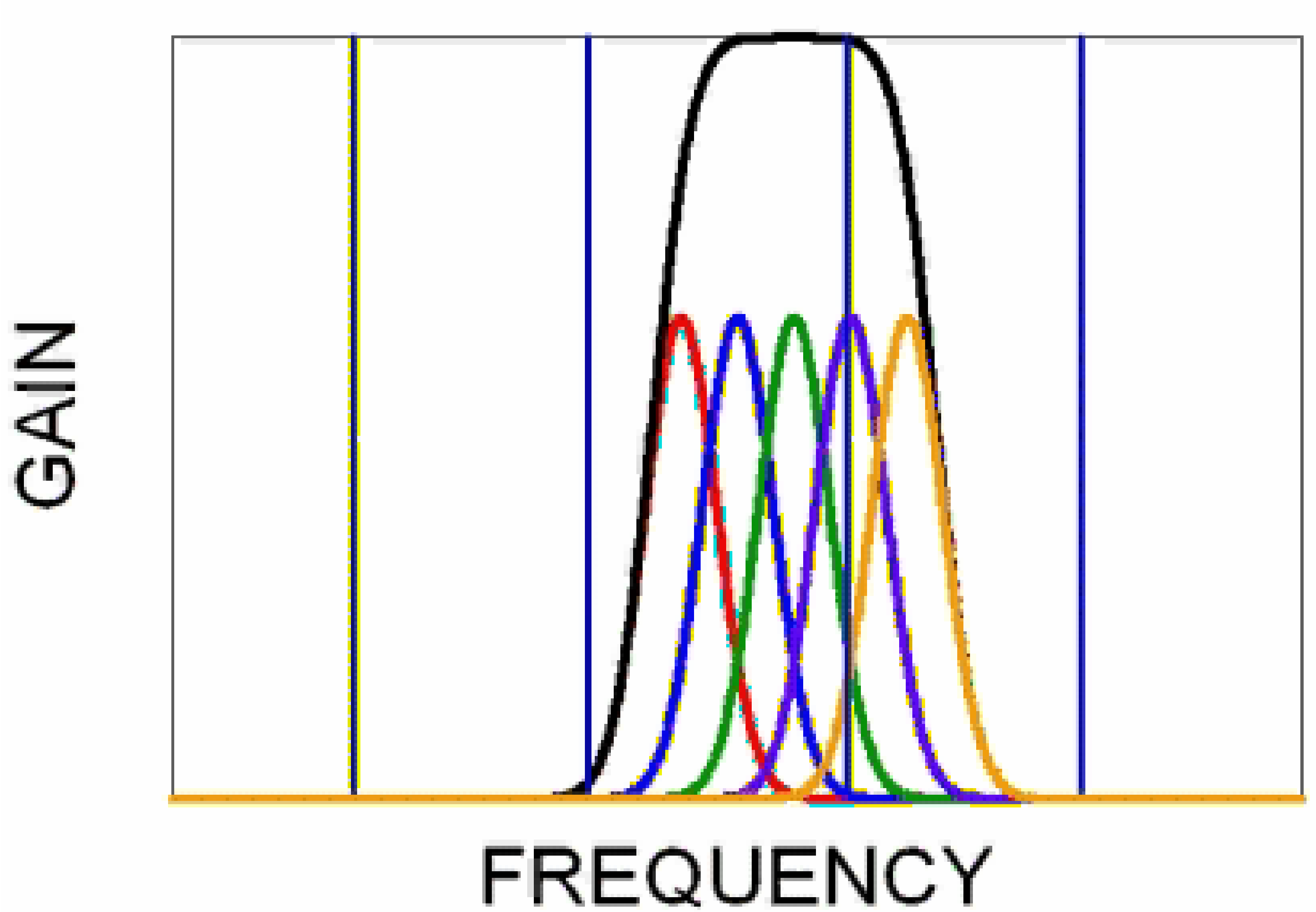
Homogenously broadened systems tend to oscillate single mode.

Inhomogeneous broadening:

If the system consists of a collection of atoms with different transition frequencies, only those atoms with transition frequencies equal to an allowed cavity frequency will participate in the lasing.

Spectral Hole Burning:

Five species of atom shown. (For example, five atoms in gas with different velocities.)
Black is total response. Blue lines are cavity modes.



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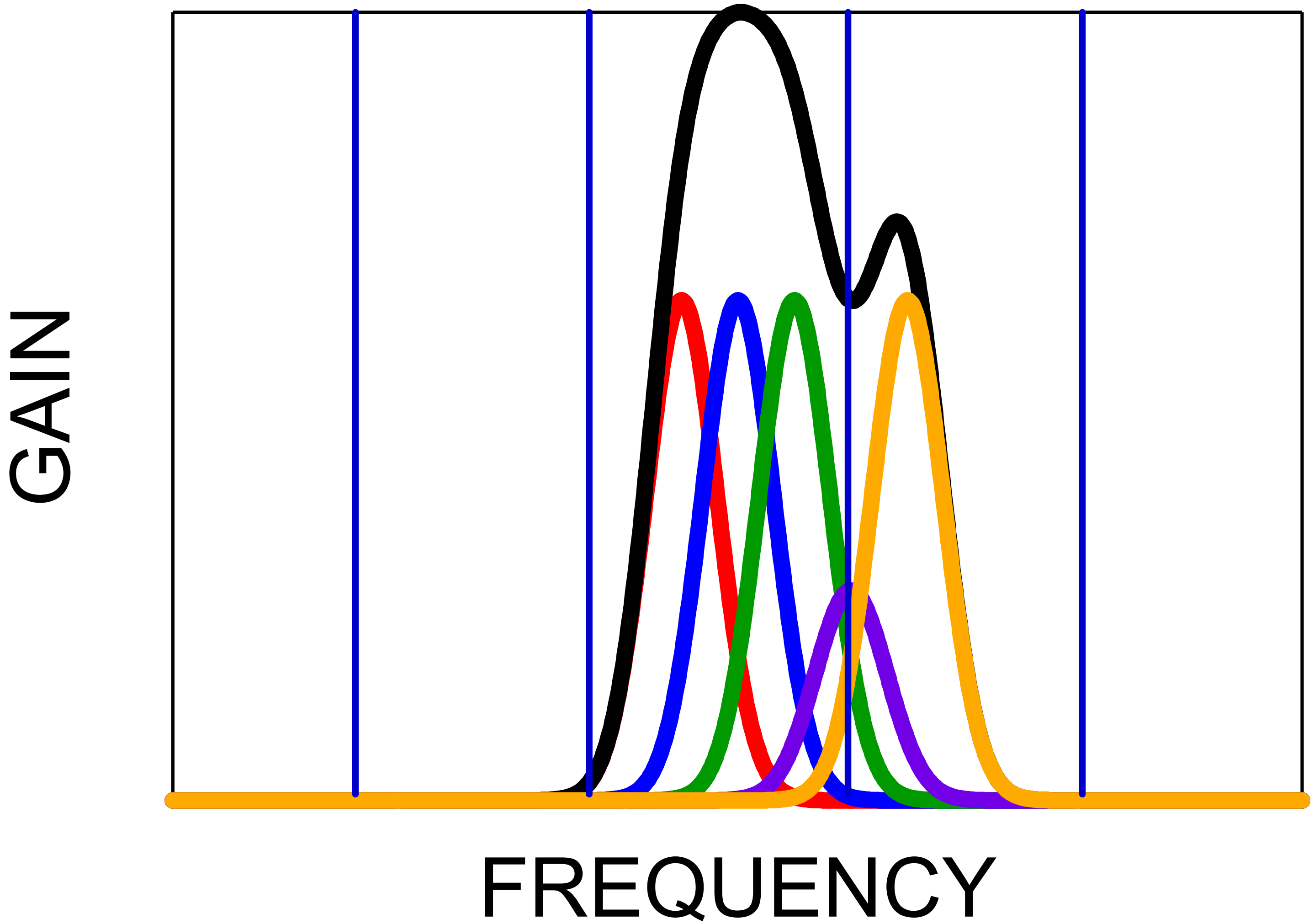
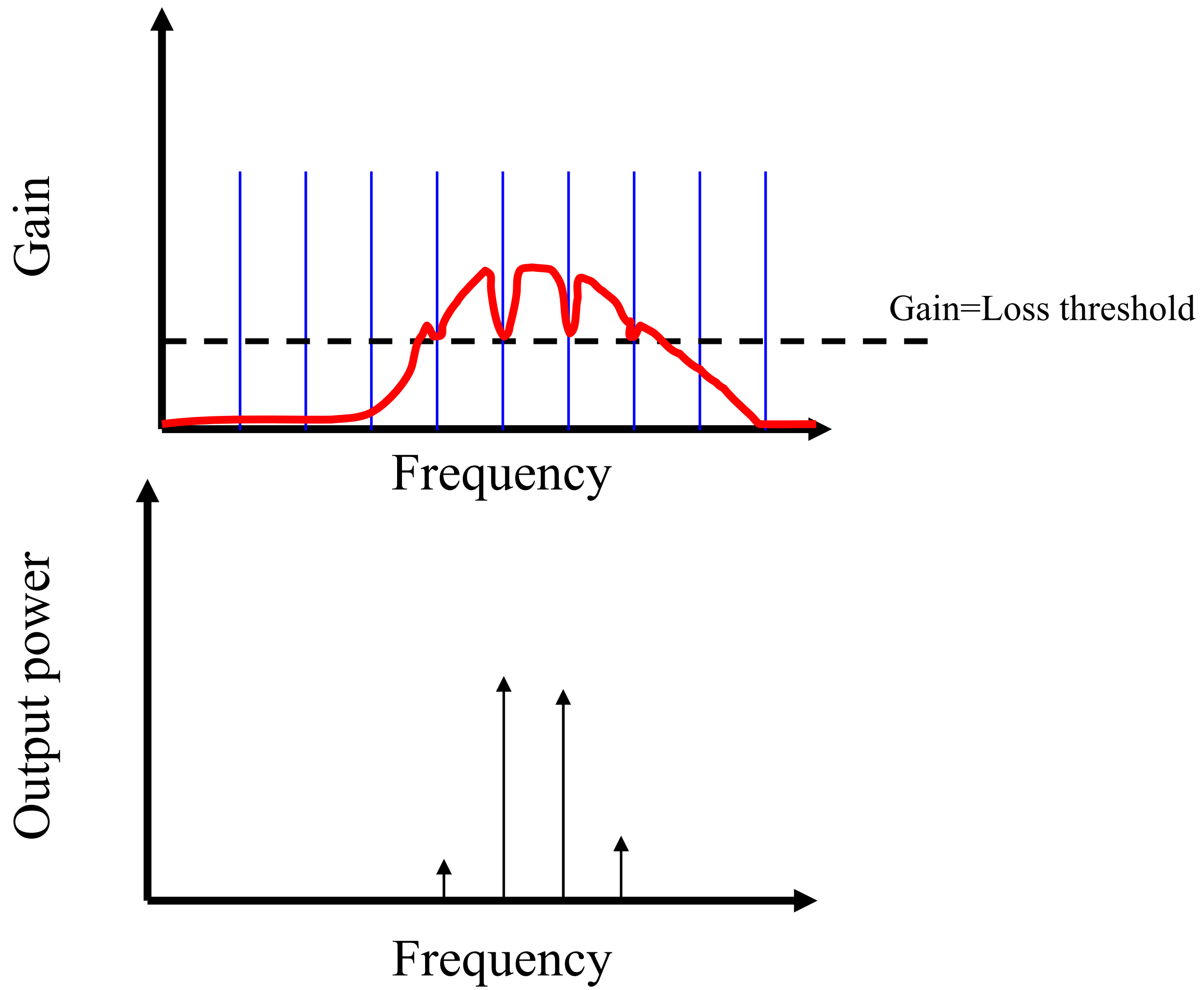


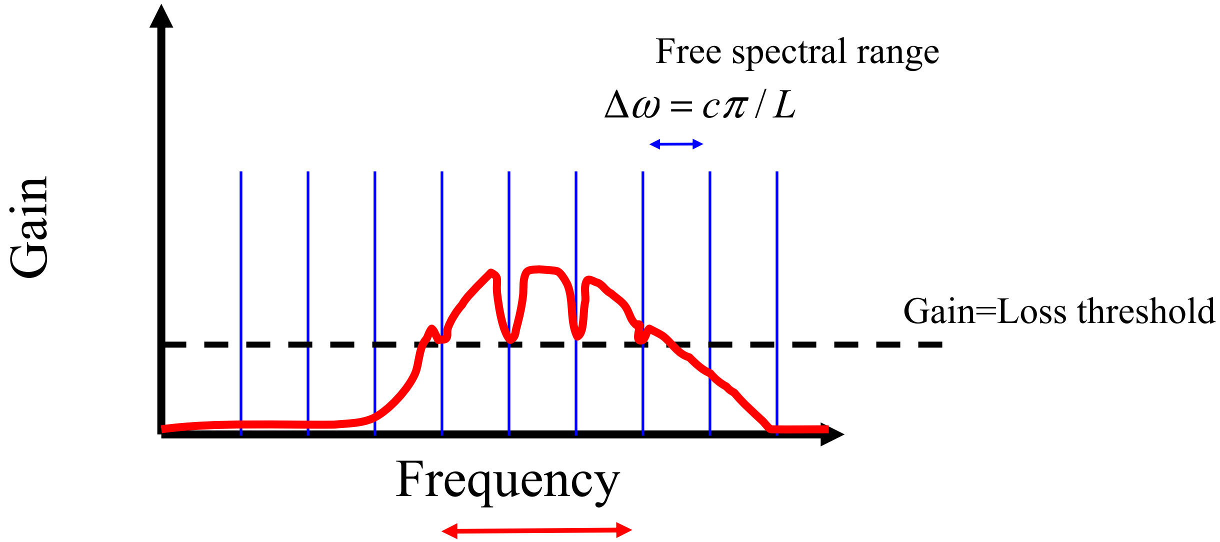
This will be a single mode laser. What if broadening > free spectral range?

Multi- mode laser:

Inhomogeneously broadened:



Multi- mode laser:



Examples:

HeNe: Doppler (inhomogeneous) broadened to 1.5 GHz
Free spectral range for 0.1 meters = 0.15 GHz
So *ten modes oscillate*.
Low pressure CO_2 laser doppler broadened to 100 MHz
If length of cavity is 0.1 meters, FSR = 0.15 GHz
So *one mode oscillates* i.e. *single mode*.
Nd-YAG homogeneous broadened to 140 GHz
Since it's homogeneous, it will tend to single mode, even though it's got 100s of allowed modes in its (unsaturated) gain curve.

To sum up:

- If only one mode is within the gain curve, laser will be single mode.
- If many modes are within the gain curve, then it depends on homogenous vs. inhomogenous broadening:
  Homogeneous: tends to single mode; gain curve is saturated equally at all frequencies
  Inhomogeneous: will oscillate multi-mode; gain curve will be saturated at mode frequencies.

(Draw on board.)

(Note: HW2 problem 4 was thus an oversimplification.)

(See Siegman, section 12.1 for discussion.)

Steady-state intensity:

- Assume that we are not letting light out yet.
- There is only absorption in the cavity.
- What is intensity in the cavity?
- Gain is saturated at loss (otherwise intensity would increase with time)
- Loss is a property of the cavity
- Gain is function of intensity
- Find intensity that gives the gain=loss, and that is the internal intensity of cavity.
- I_s (function of lifetime and frequency) important scale of intensity to expect.