PHY208 – Atoms and lasers
Lecture 7

Pulsed Laser Technology: Short but Powerful

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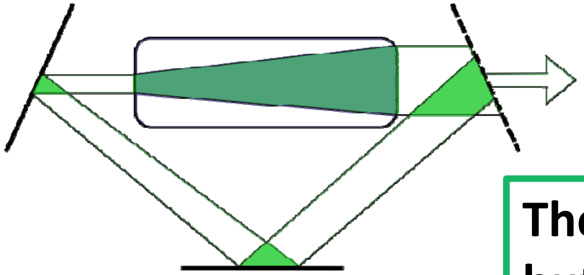
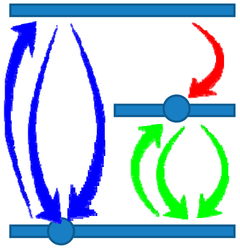
What have we seen so far? LASER

An optical cavity (« oscillator ») → condition on phase

An amplifying medium (« gain ») → condition on ampl. / intensity



Introduced a 3 level systems.



$$r_{\mathrm{abs}} = r_{\mathrm{stim}} = \frac{\sigma I}{h\nu} = W$$

$$r_{\mathrm{spont}} = \Gamma$$

These are all steady state solutions to rate equations, but we can use these ideas to understand pulsing

Need gain to compensate losses (output + parasitic)

Impossible in Lorentz model,
requires population inversion.

$$g = \sigma_{eg}\underbrace{(n_e - n_g)}_{\Delta n}$$

Basic laser properties

$$g = \frac{g_0}{1+I/I_{\mathrm{sat}}}$$

Laser threshold,
Gain saturation,
Steady state intensity,
Steady state population inversion

Why would we want to pulse a laser?

- Some lasers must be operated in a pulsed mode since CW operation cannot be sustained.
- High speed optical communications require sending HI/LO bits
- Instantaneous optical power can be greatly increased when the output pulse has a limited duration.
- Processing outcome is different when exposure causes little heating
- Short pulses can probe very fast physical processes

External vs internal modulation

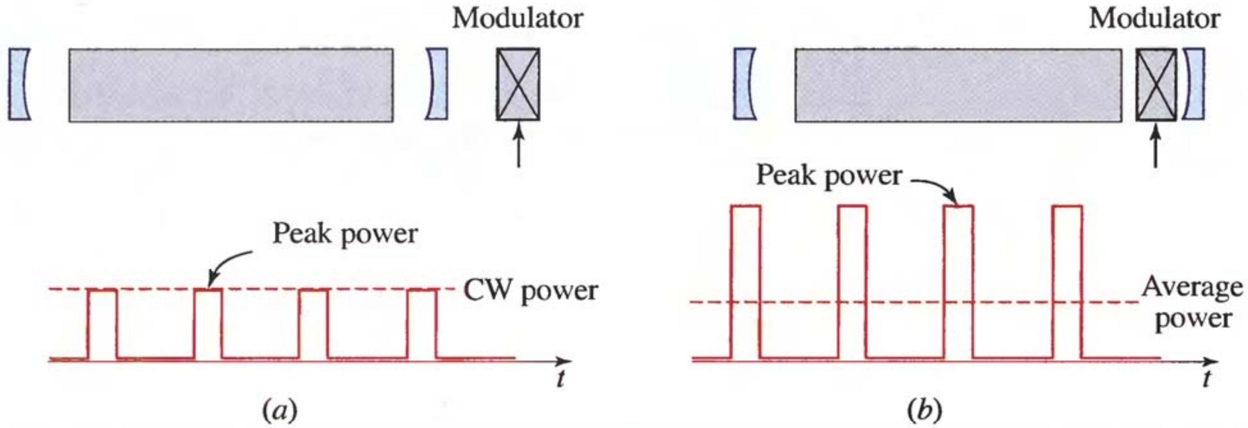


Figure 15.4-1 Comparison of pulsed laser outputs achievable with (a) an external modulator, and (b) an internal modulator.

Outline of Lecture

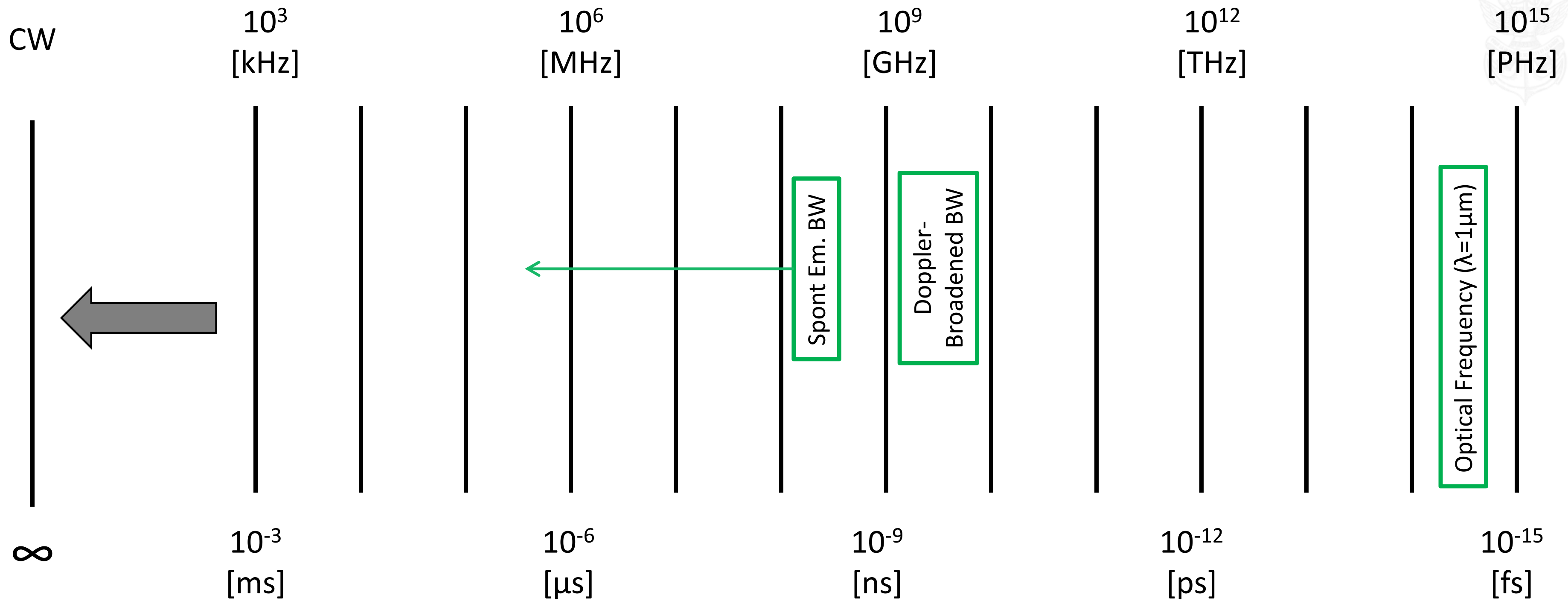
Laser Pulsing

I. Modulation for Telecommunications
  - Semiconductor lasers
  - Direct gain modulation

II. Advanced Techniques for Shorter Pulses
  - Q-switching (and cousins)
  - Mode locking

III. Even higher power
  - Chirped pulse amplification

Time scales for laser pulsing



CW

10^3 [kHz]

10^6 [MHz]

10^9 [GHz]

10^{12} [THz]

10^{15} [PHz]

Spont Em. BW

Doppler-Broadened BW

Optical Frequency (λ=1µm)

∞

10^{-3} [ms]

10^{-6} [µs]

10^{-9} [ns]

10^{-12} [ps]

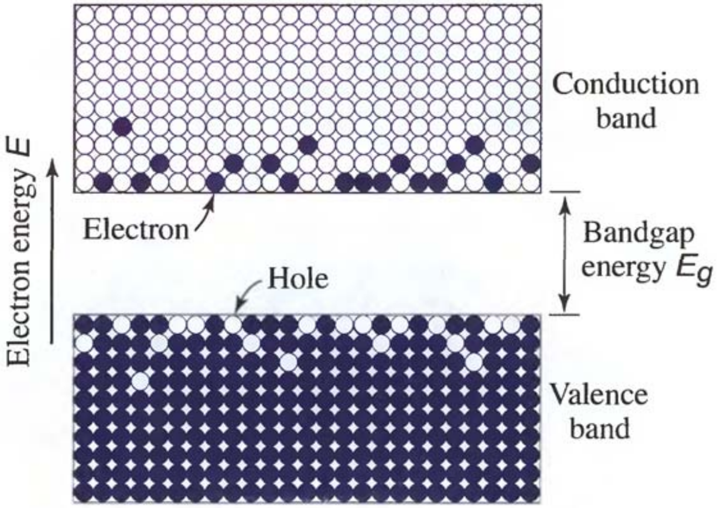
10^{-15} [fs]

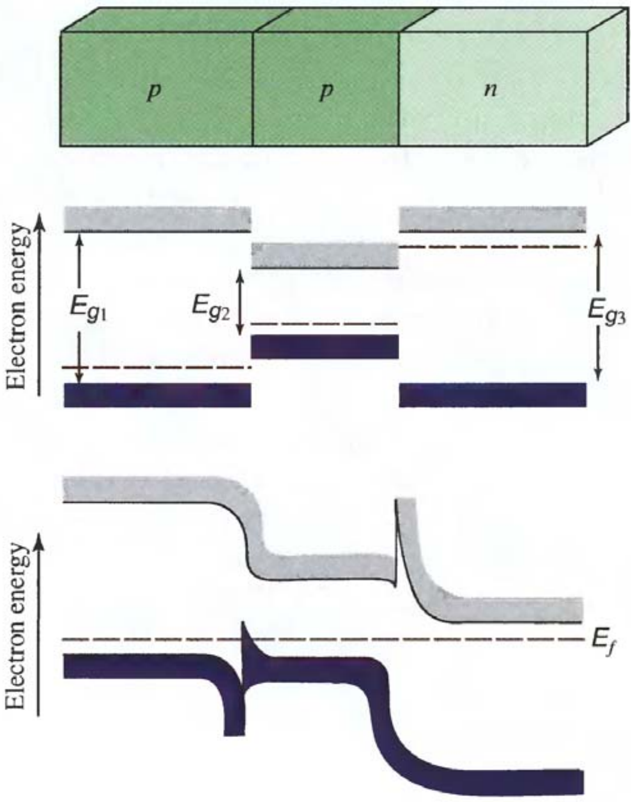
Optical frequency (λ = 1 µm)

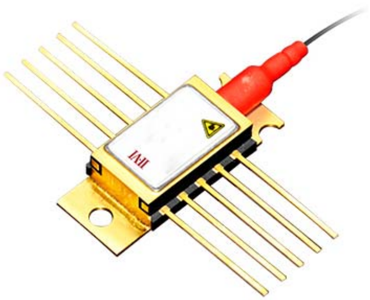
Bandwidth due to Spontaneous Emission

Bandwidth due to Doppler Broadening

I – Semiconductor Lasers



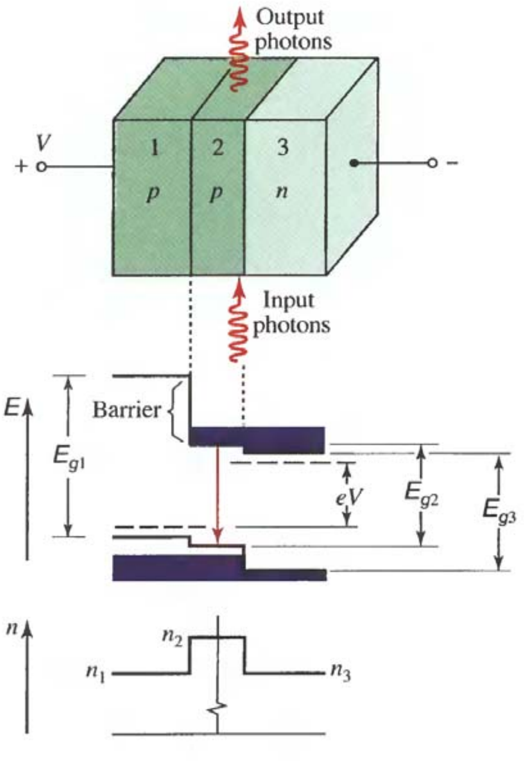




Applying a voltage will inject electrons from one side, and « holes » from the other side.

They accumulate and recombine in the middle.

Localizing gain in a semiconductor laser



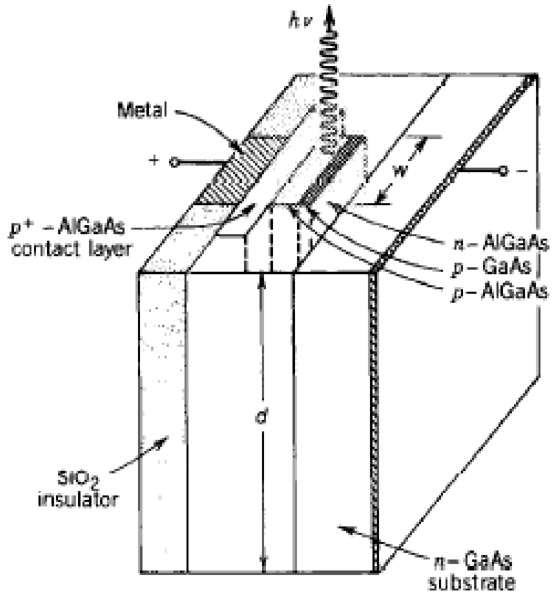


Figure 16.3-7 Schematic diagram of an AlGaAs/GaAs buried-heterostructure semiconductor injection laser. The junction width w is typically 1 to 3 μm, so that the device is strongly index guided.

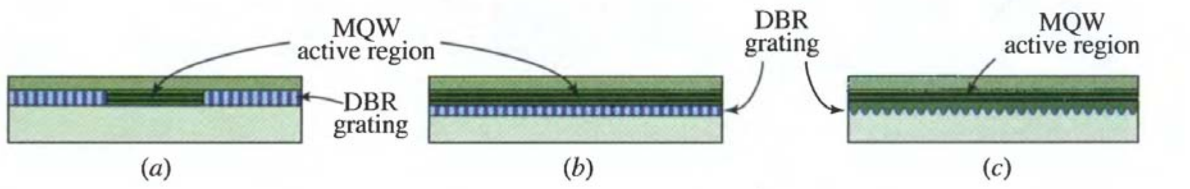
Feedback in Semiconductor Lasers

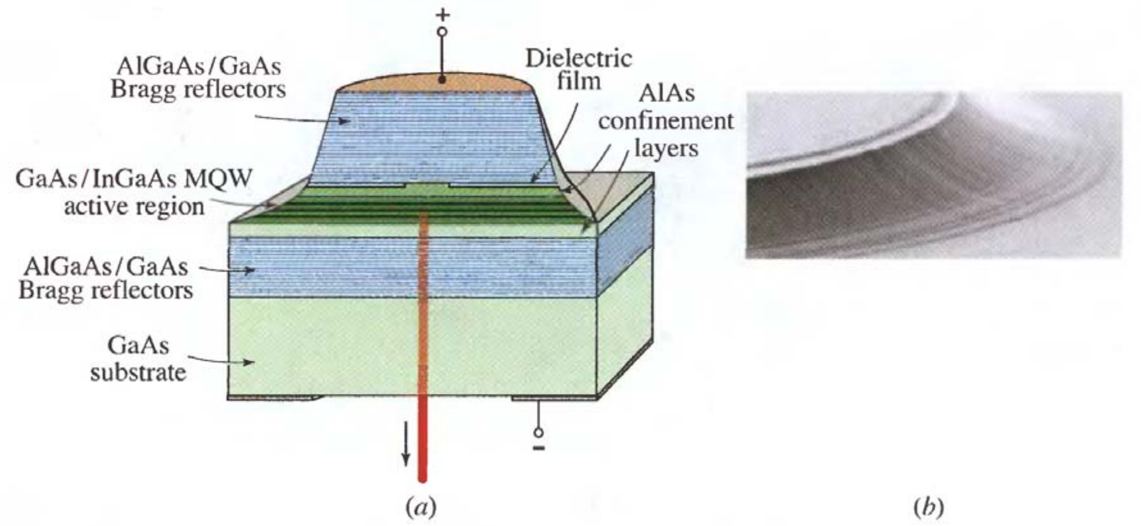
Tricky to put a metallic mirror in place for a semiconductor layer.

Reflector may be a:

- Cleaved facet
- Distributed Bragg reflector
- Distributed Feedback (everywhere)

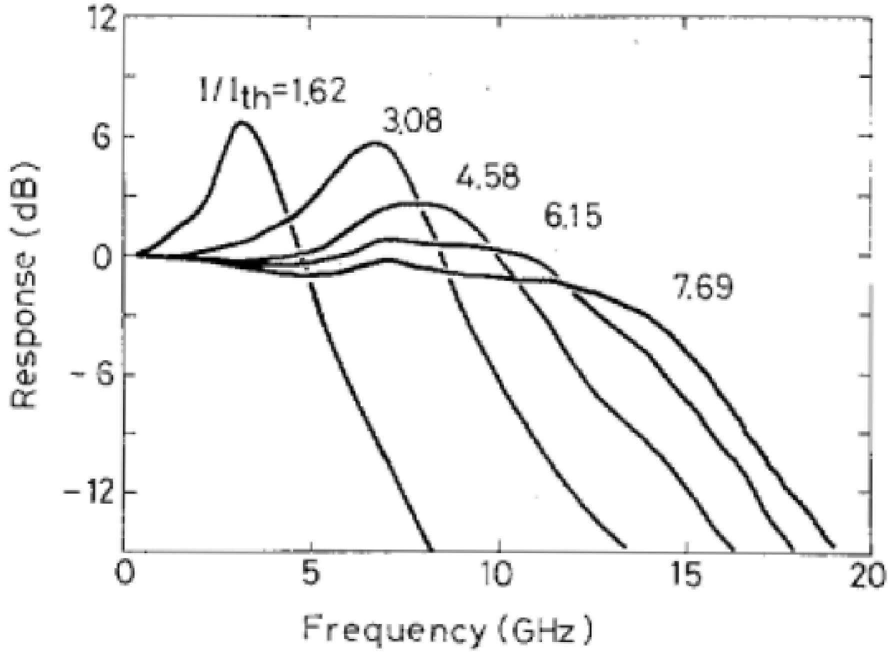
- In vertical cavity, surface emitting lasers, Bragg reflectors can be stacks (more reflective)
- Gain medium is shorter (need multiple quantum wells for greater gain)



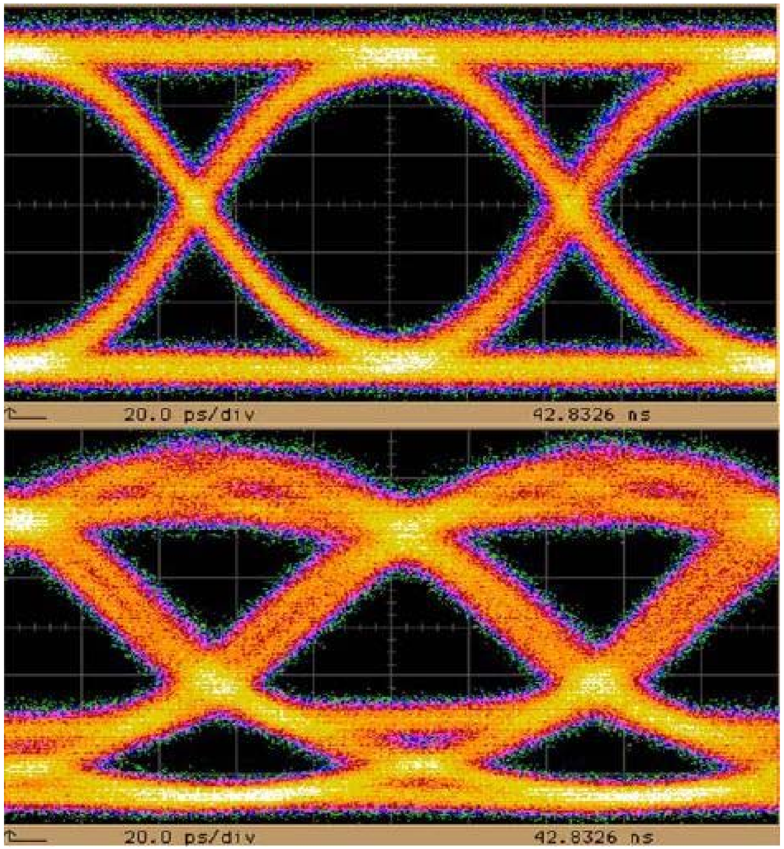


Modulation for Optical Communication

- Semiconductor lasers are biased at some current, then modulated around a small swing

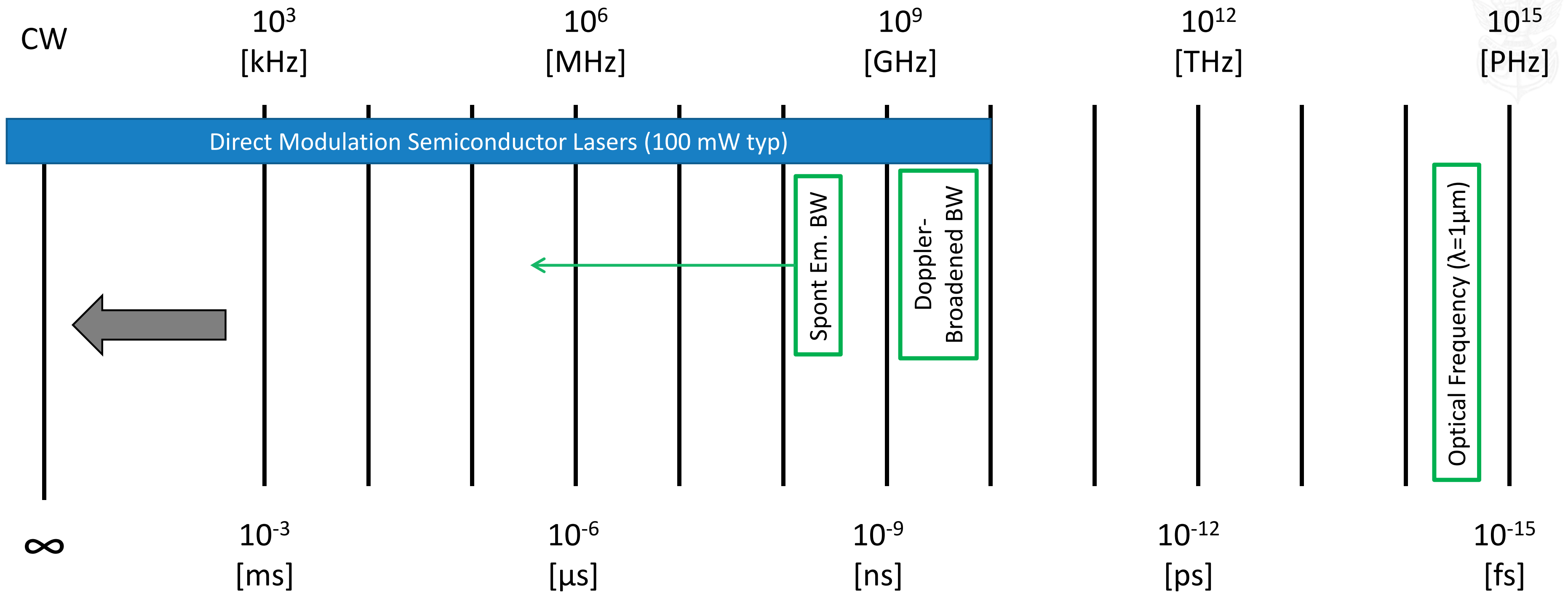


Transfer characteristic of DFB InGaAsP laser



Eye diagram showing received signal in optical telecom system

Time scales for laser pulsing



CW

10^3 [kHz]

10^6 [MHz]

10^9 [GHz]

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Direct Modulation Semiconductor Lasers (100 mW typ)

Spont Em. BW

Doppler-Broadened BW

Optical Frequency (λ=1μm)

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   - Chirped pulse amplification

III. Optical gain (from lecture 2)

Gain in a 3 level system : $g = \sigma \Delta n = \frac{g_0}{1+I/I_{sat}}$ (actually, very generic form)

Unsaturated gain $g_0 = \sigma \frac{W_p - \Gamma_{eg}}{W_p + \Gamma_{eg}} n_{tot}$ *[m^{-1}]*

Saturation intensity $I_{sat} = \frac{h\nu_L}{2\sigma_{eg}} (W_p + \Gamma_{eg})$ *[W.m^{-2}]*

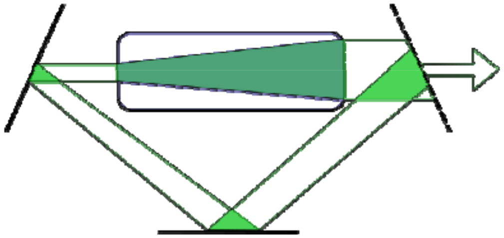
- Unsaturated gain increases with pumping rate (W_p), interaction cross section (σ), atomic density (n_{tot})
- Unsaturated gain decreases with recombination rate (Γ_{eg})

All atoms in g state $-\sigma n_{tot} \leq g_0 \leq \sigma n_{tot}$ *All atoms in e state*

- Gain decreases with laser intensity

At low laser intensity, $g = g_0$ At high laser intensity, $g \underset{I \gg I_{sat}}{\sim} g_0 \frac{I_{sat}}{I} \rightarrow 0$

III. Laser steady-state (from lecture 2)



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$$I(L) = I(0)$$

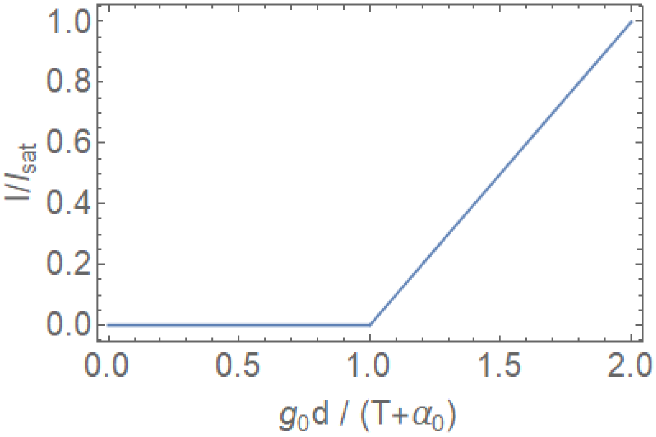
$$R\,\exp\left(-\alpha_0 L\right)\exp\left(g\,d\right) = 1$$

$$\Rightarrow \quad \frac{g_0 d}{1+I/I_{\mathrm{sat}}} = \alpha_0 L + T$$

Optical gain Optical losses

Laser intensity

$$I = I_{\mathrm{sat}}\left(\frac{g_0 d}{T+\alpha_0 L} - 1\right)$$



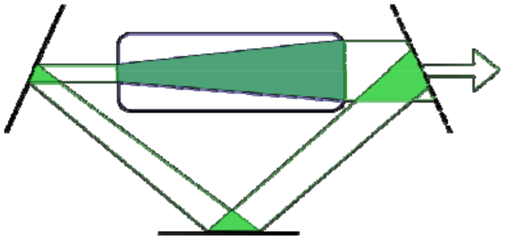
Laser intensity adjusts to unsaturated gain and losses,

so that total gain (including saturation) = total loss

Necessary condition for I>0 :

Lasing threshold $g_0 d \geq T + \alpha_0 L$

III. Laser steady-state (from lecture 2)



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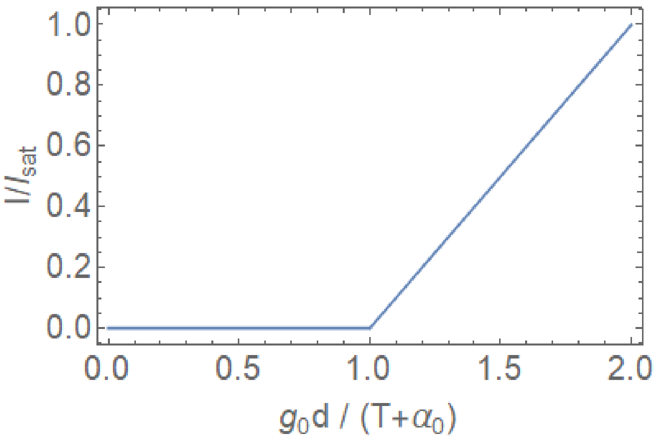
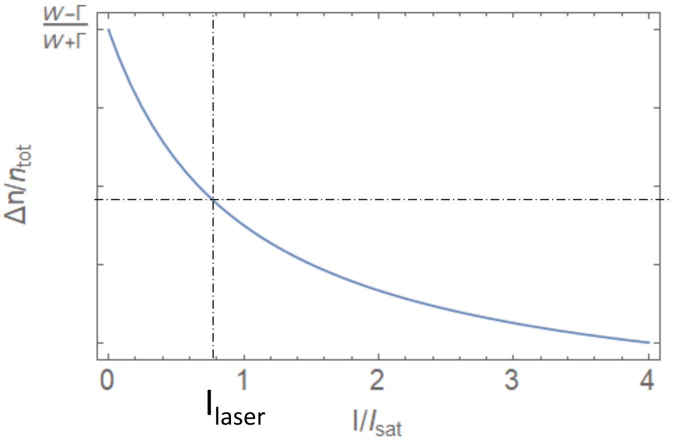


Population inversion



$$\Delta n = \frac{g_0}{\sigma}\,\frac{1}{1+I/I_{\mathbf{sat}}}$$

$$= \frac{T+\alpha_0 L}{\sigma d}$$

Such that gain = losses

No explicit dependence on I

Gain Switching

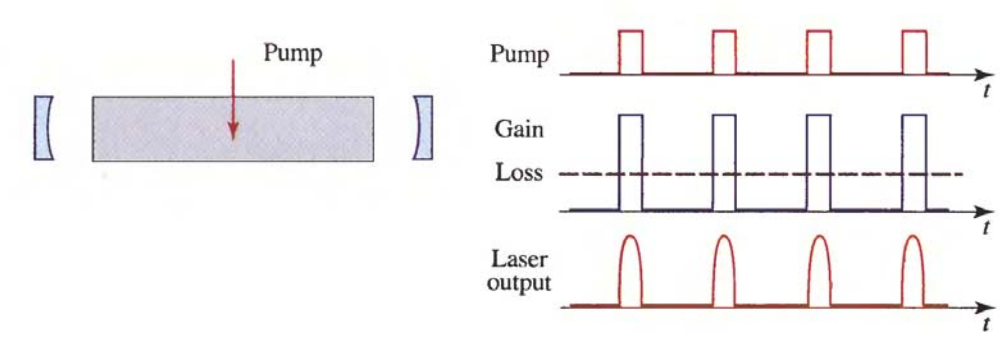


Figure 15.4-2 Gain switching.

Direct approach, involves turning « pump » on and off

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Gain Switching

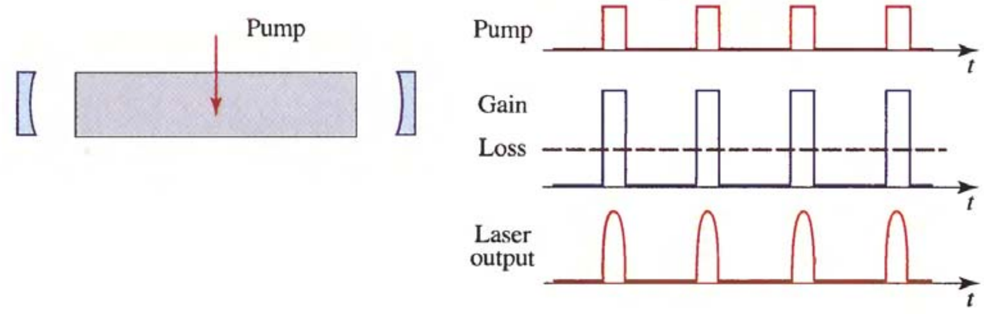


Figure 15.4-2 Gain switching.

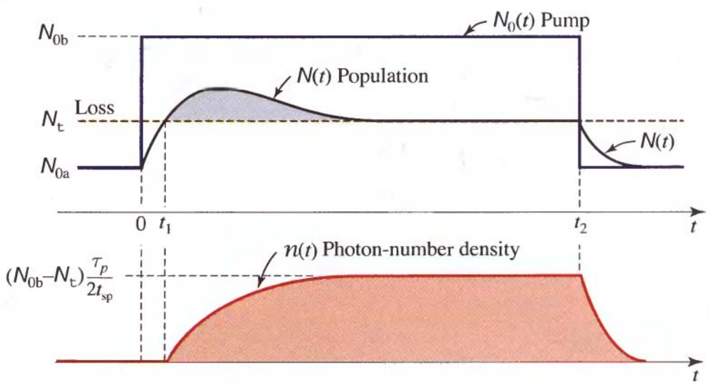


Figure 15.4-5 Variation of the population difference $N(t)$ and the photon-number density $n(t)$ with time, as a square pump results in N_0 suddenly increasing from a low value N_{0a} to a high value N_{ob}, and then decreasing back to a low value N_{0a}.

Direct approach, involves turning « pump » on and off

Inversion builds up, overcomes loss, and lasing stabilises population

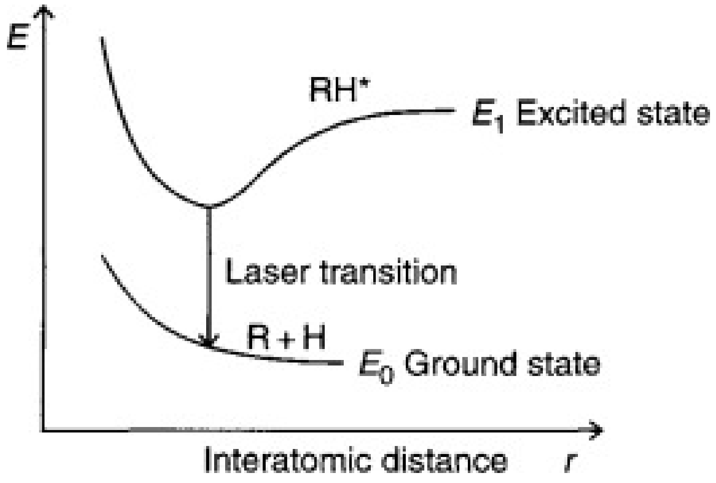
This is essentially what is being done in semiconductor laser diodes, but without fully shutting off current (small signal, to keep linearity)

Example: Excimer (exciplex) lasers

Formation of excited dimer (excimer) or excited complex (exciplex) states driven by an pulsed electrical discharge through a gas.

These states are only stable when excited, and dissociate upon relaxation.

Helpful to create population inversion.

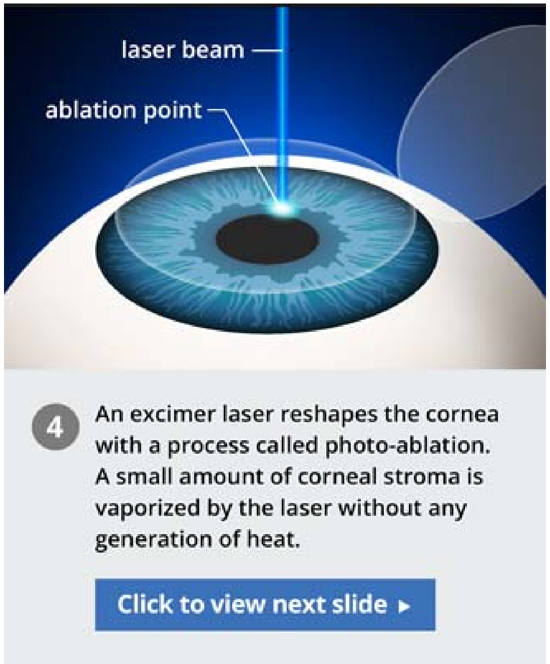


Excimer	Wavelength	Relative power
Ar_2^*	126 nm	
Kr_2^*	146 nm	
F_2^*	157 nm	
Xe_2^*	172 & 175 nm	
ArF	193 nm	60
KrCl	222 nm	25
KrF	248 nm	100
XeBr	282 nm	
XeCl	308 nm	50
XeF	351 nm	45

Equivalent to gain switching
Results in 10 nanosecond length pulses

UV emission helpful for absorption in surface layers

Example: Excimer (exciplex) lasers



4 An excimer laser reshapes the cornea with a process called photo-ablation. A small amount of corneal stroma is vaporized by the laser without any generation of heat.

Material is ablated from surface without heating surroundings

Very useful for LASIK eye surgery

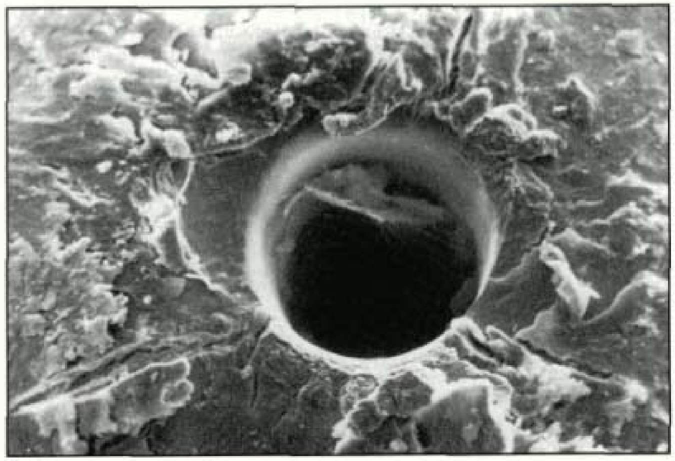


Figure 1: Scanning electron microscopy of a crater formed in lens nucleus following ablation in air with the 308 nm excimer laser (60 ×).

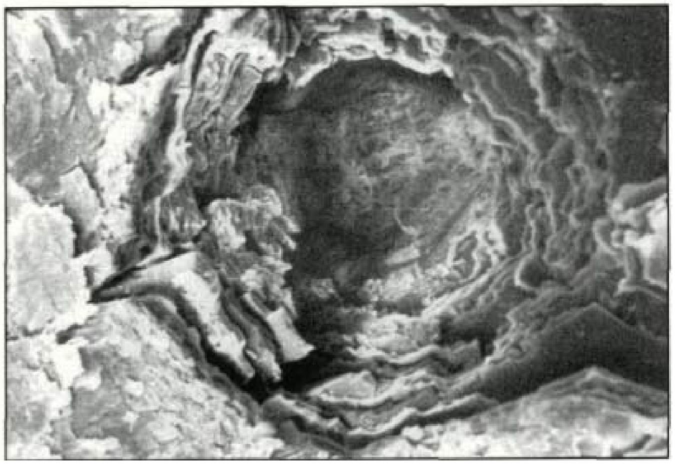


Figure 2: Scanning electron microscopy of crater formed in lens nucleus following ablation in normal saline with the 308 nm excimer laser (60 ×).

Q Switching (Loss switching)

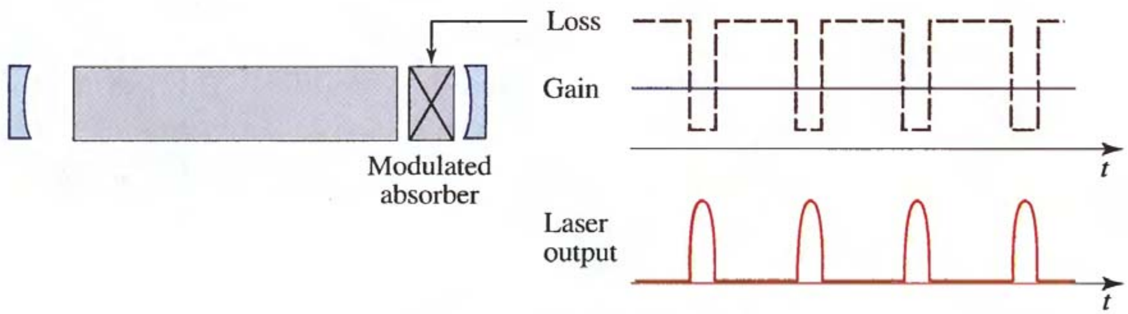


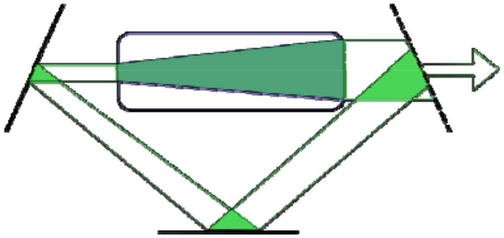
Figure 15.4-3 *Q*-switching.

For Q-switching, we are modulating the **loss** in the cavity

Q is the « quality » of the cavity.

Loss is first set to be high.

III. Laser steady-state (from lecture 2)



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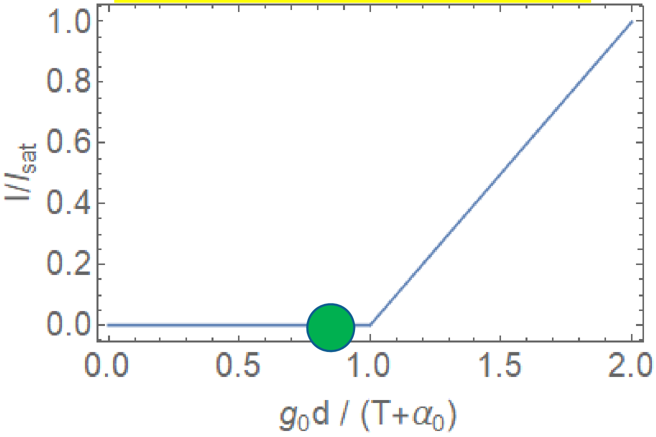
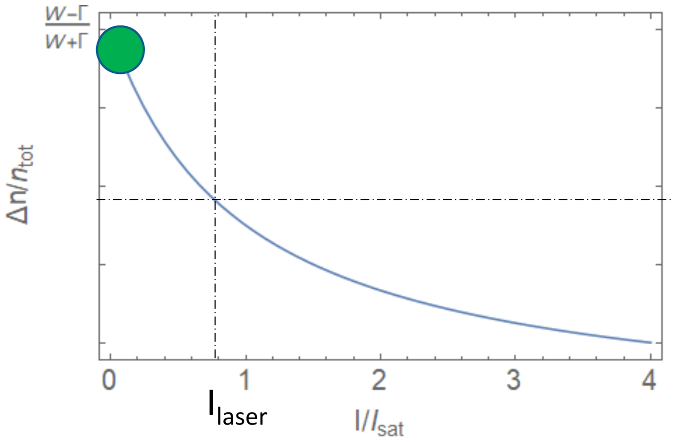
$$\Rightarrow \quad \frac{g_0 d}{1+I/I_{\mathrm{sat}}} = \alpha_0 L + T$$

Laser intensity

$$\boxed{I = I_{\mathrm{sat}}\left(\frac{g_0 d}{T+\alpha_0 L} - 1\right)}$$



Population inversion



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Such that gain = losses

No explicit dependence on I

Q Switching (Loss switching)

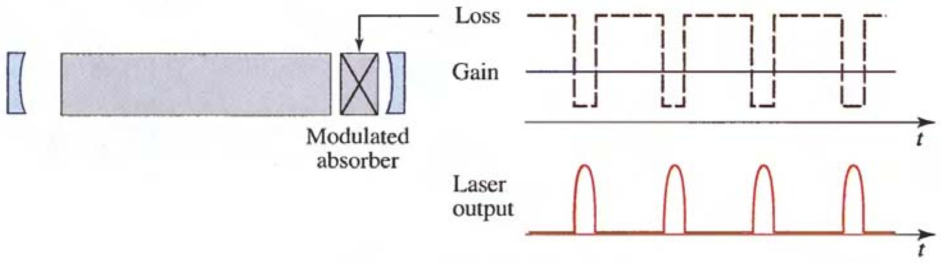


Figure 15.4-3 *Q*-switching.

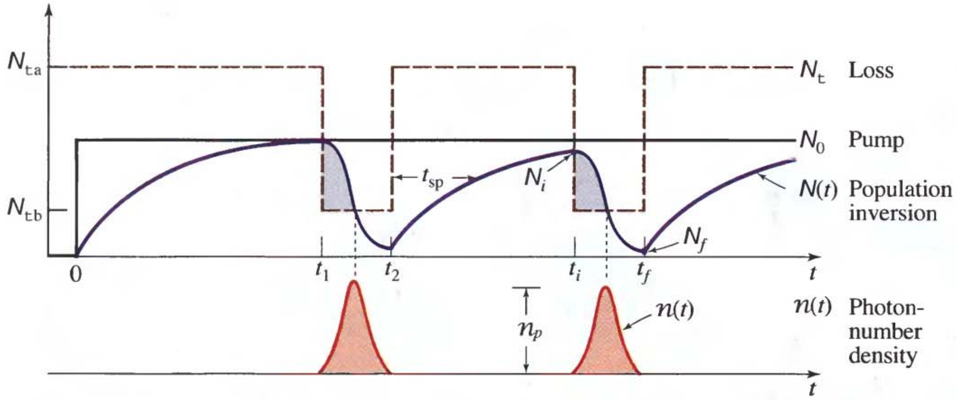


Figure 15.4-6 Operation of a Q-switched laser. Variation of the population threshold N_t (which is proportional to the resonator loss), the pump parameter N_0, the population difference $N(t)$, and the photon number $n(t)$.

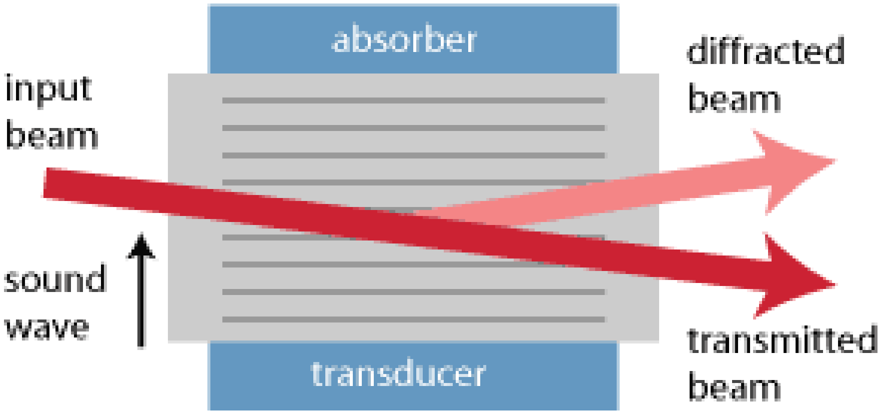
First, loss set to be high, so inversion (Δn) builds up.

Loss is then minimized, lasing begins and photon density increases

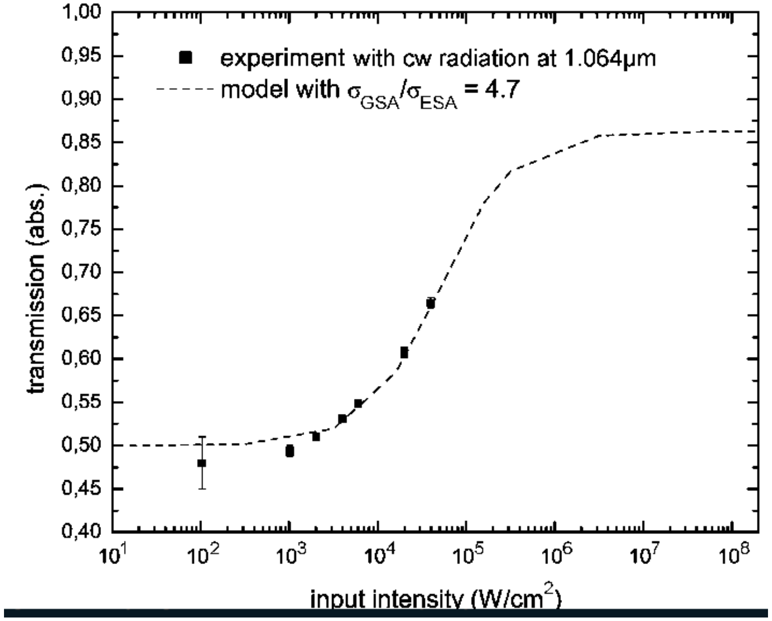
Stimulated emission depopulates excited state, lasing ends, and we start again.

Optical switches for Q-…..switching…

Active Q-switching:
acousto-optic modulator



Passive Q-switching:
Saturable absorbers



Cr 4+ YAG crystal

Cavity Dumping

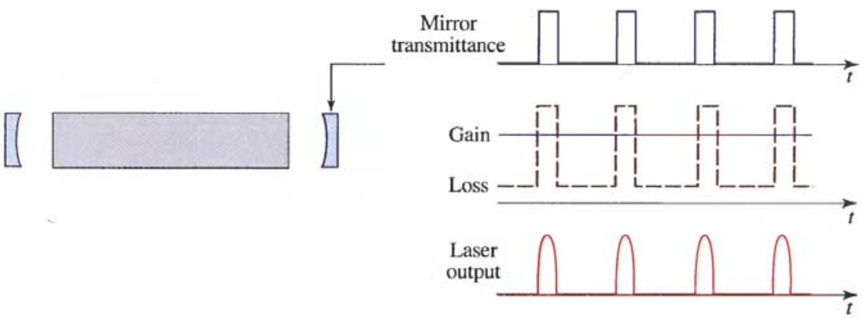
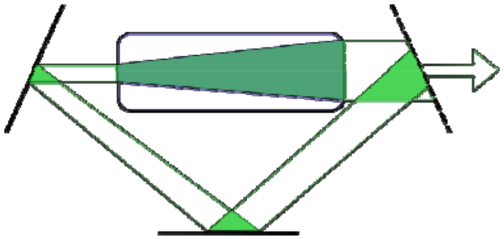


Figure 15.4-4 Cavity dumping. One of the mirrors is removed altogether to dump the stored photons as useful light.

In cavity dumping (which is still some form of Q-switching), pulse is stored as photons (as opposed to electrons

Initially, highly reflective mirror is used and no light is extracted.

III. Laser steady-state (from lecture 2)



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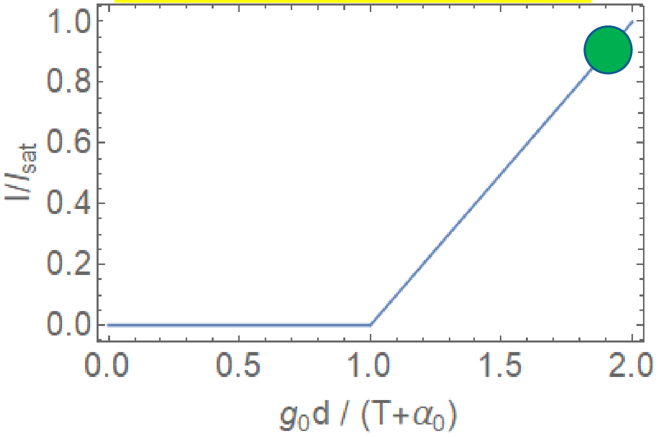
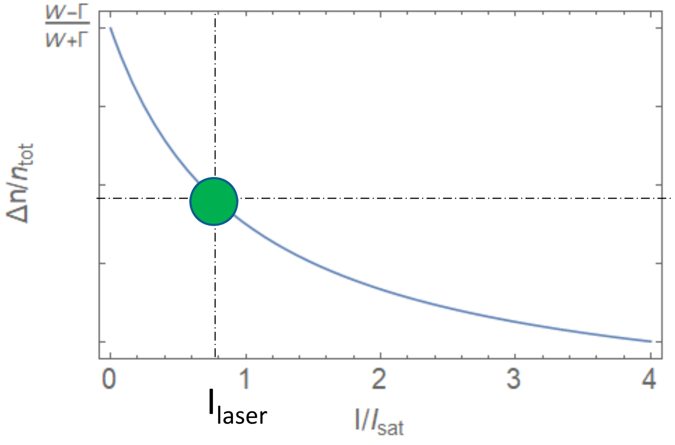
Laser intensity

$$\boxed{I = I_{\text{sat}}\left(\frac{g_0 d}{T+\alpha_0 L} - 1\right)}$$



Population inversion



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Such that gain = losses

No explicit dependence on I

Cavity Dumping

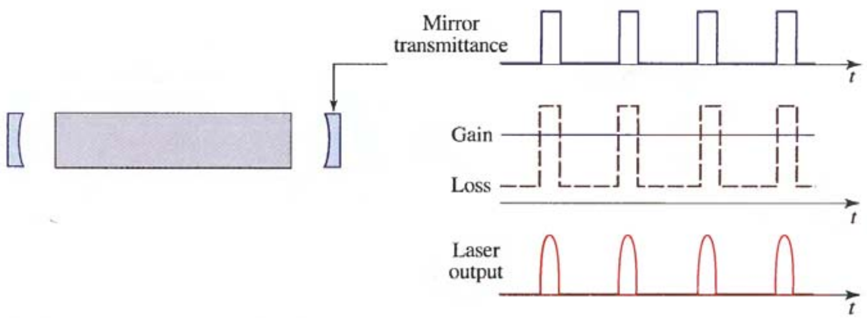


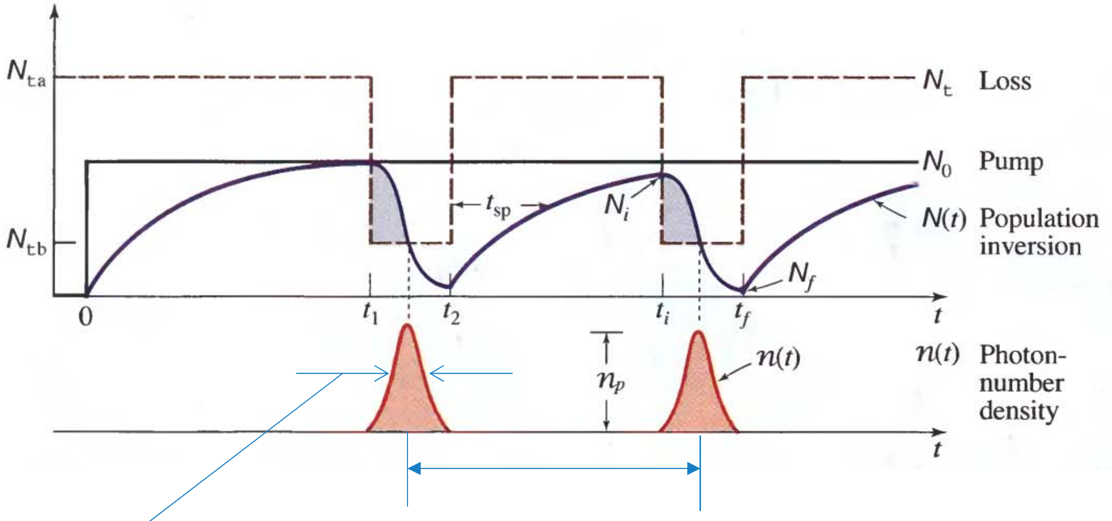
Figure 15.4-4 Cavity dumping. One of the mirrors is removed altogether to dump the stored photons as useful light.

High reflectance mirror allows photon number to build up

Removing mirror

- Allows all accumulated photons to escape
- Removes feedback mechanism and increases loss, leading to end of lasing after photons escape

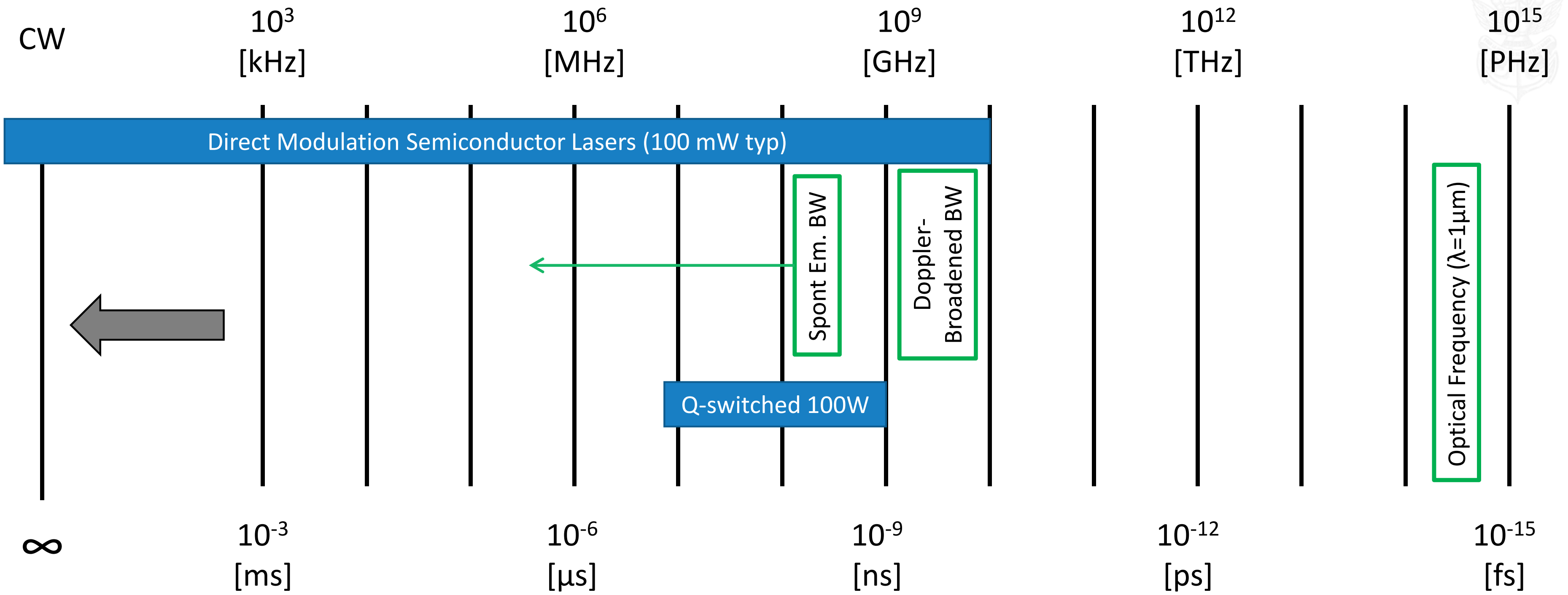
Details on pulse trains



Pulse width: will be limited by how quickly we can extract stored energy. Will determine peak power/intensity.

1/Repetition rate: Will be limited by how quickly energy can be built back up again.
At fixed power, will determine energy per pulse.

Time scales for laser pulsing



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Doppler-Broadened BW

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Q-switched 100W

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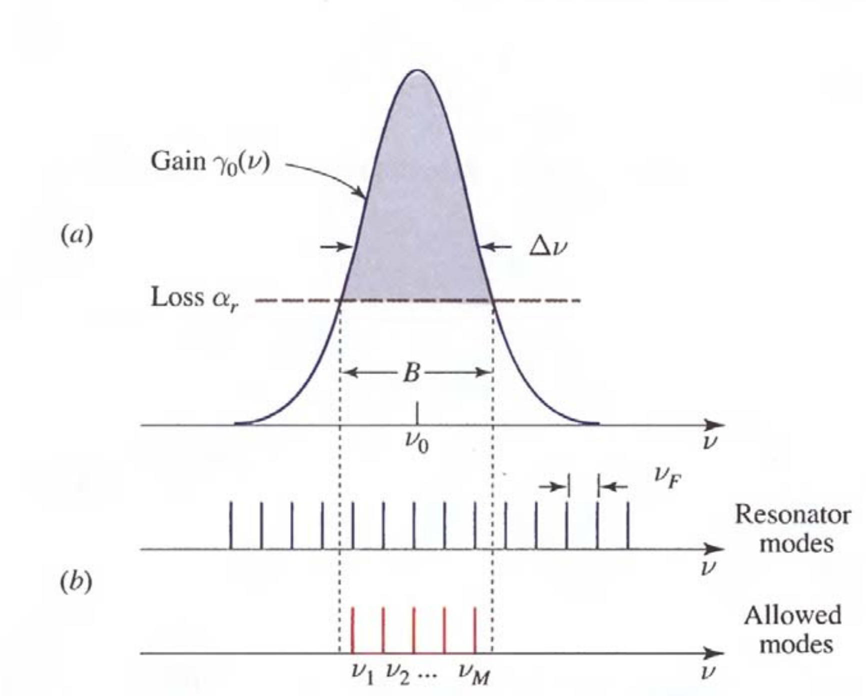
10^{-15} [fs]

Mode Locking



Need a system where multiple longitudinal modes can lase. Each longitudinal mode has a different frequency, and allowed modes are determined by the feedback of the cavity.

III. Mode competition (from Lecture 2)

We further increasing pumping, such that
two modes are well above threshold

Inhomogeneous gain :

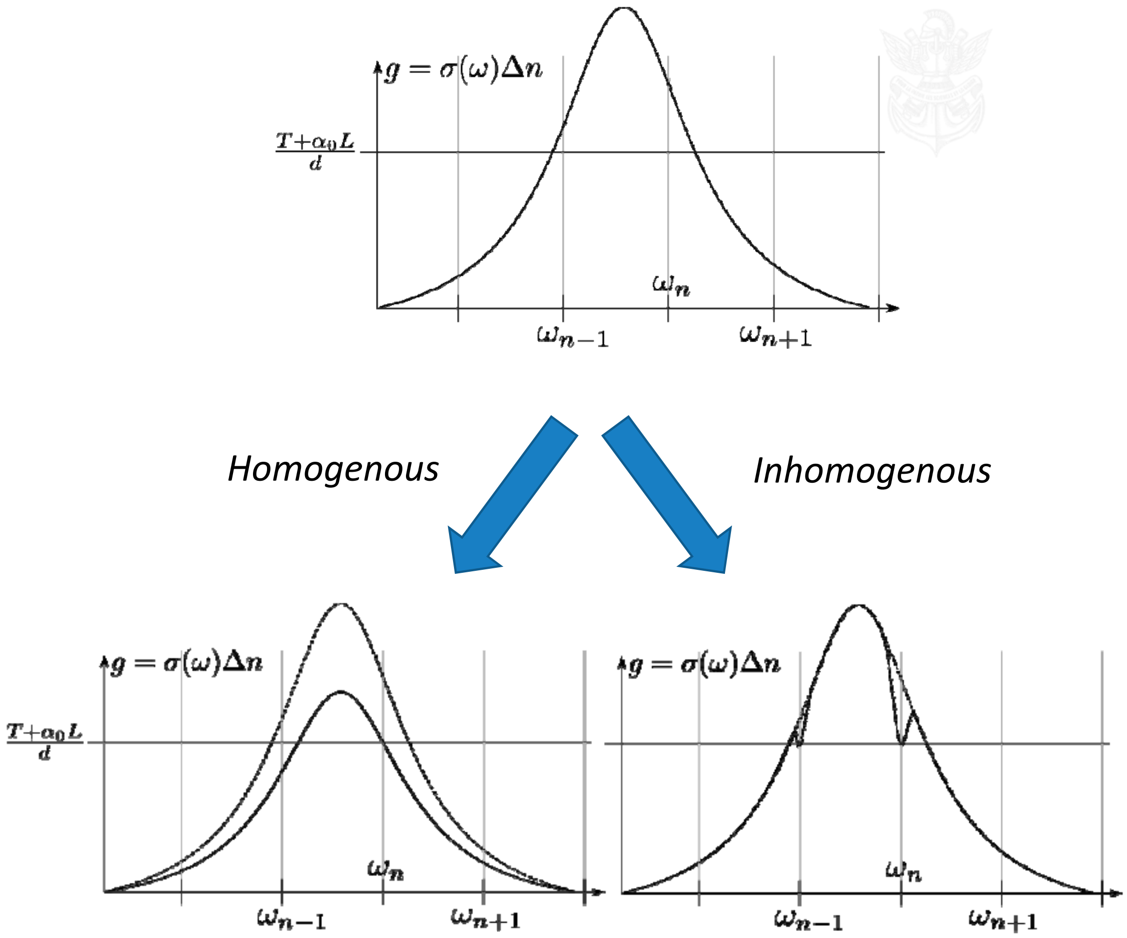
Laser intensity in 1 mode decreases gain in this mode

Modes are independent

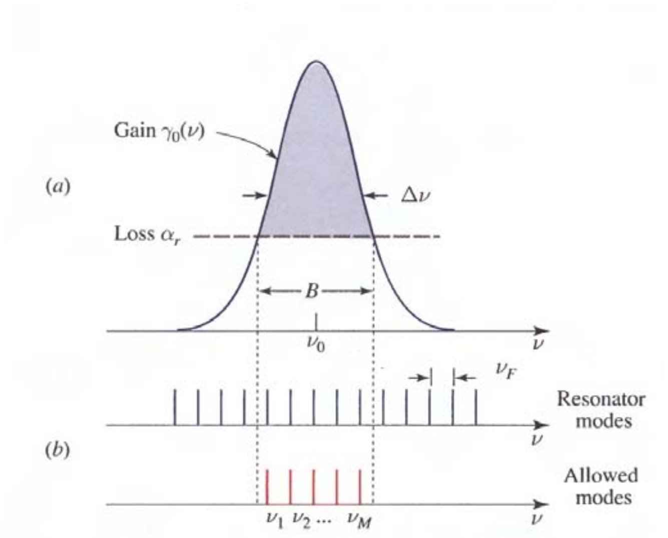
Homogeneous gain :

Laser intensity in 1 mode decreases gain in all modes

Mode competition !



Mode Locking

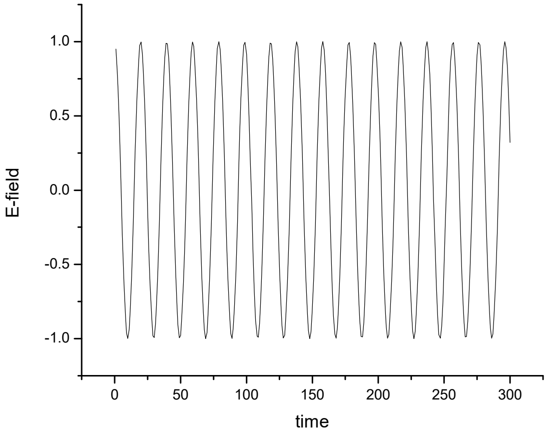


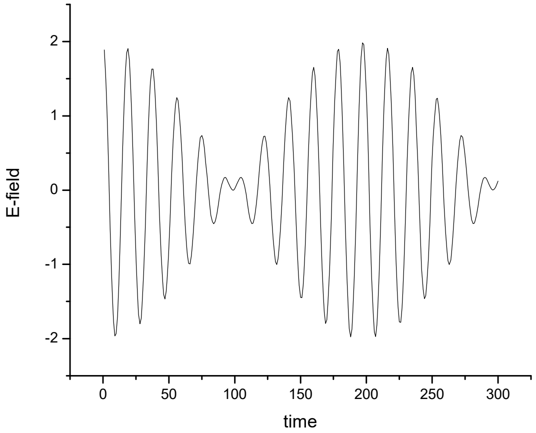
Although multiple modes may lase simultaneously, they are not coherent with each other (they have no defined phase relationship with each other).

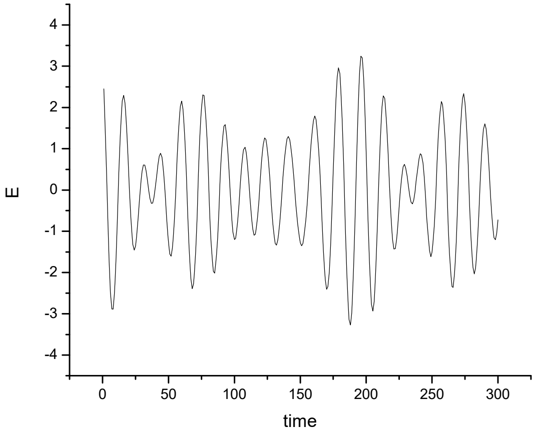
Spontaneous emission will make modes drift around in relative phase.

The challenge is “encouraging” them to have the same phase (and so to add amplitudes at one time).

Modes without any phase relationship

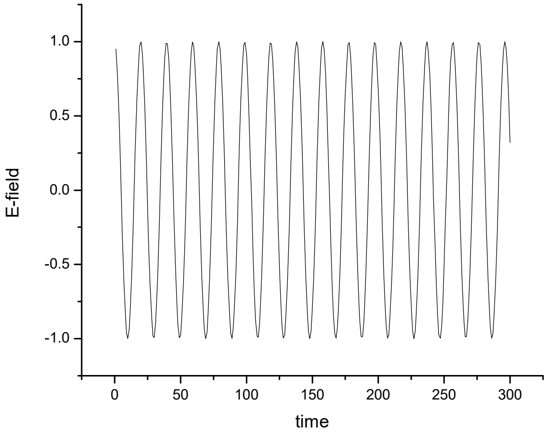


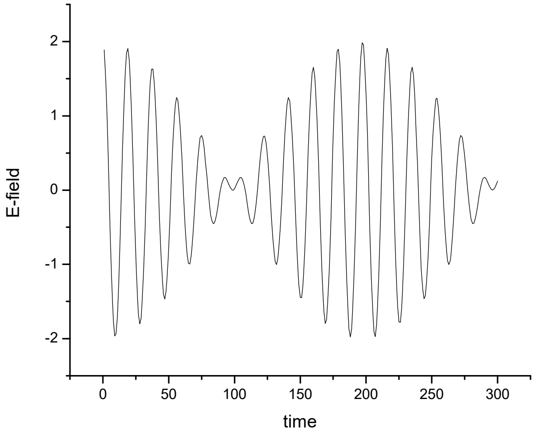


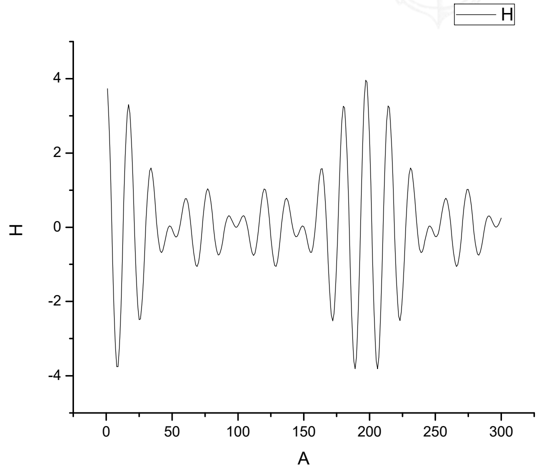


Two modes will always « beat » together.
Beating frequency will reflect changes in phase of both modes.
Three or more modes will make beating less evident
SE will make modes drift around in phase – we need to “lock” them in when then phase is right.

Modes with constant phase relationship

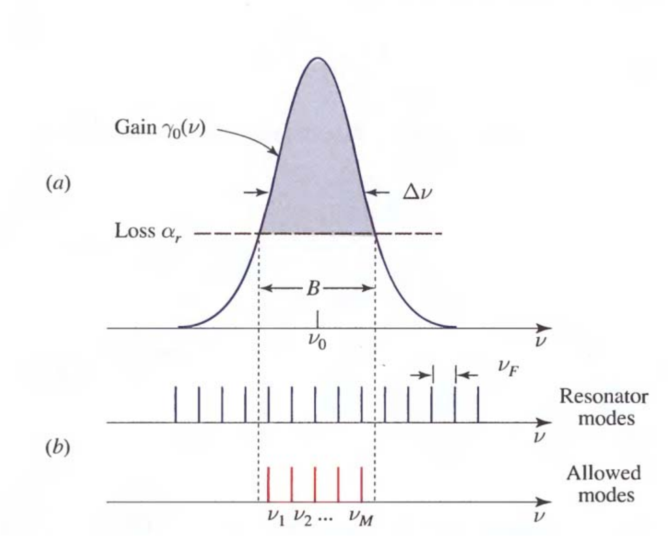






If phase relationship is fixed between modes, then they are coherent with each other
We can now add amplitudes and get +/- interference
Enough modes will give a pulse train

Mode Locking



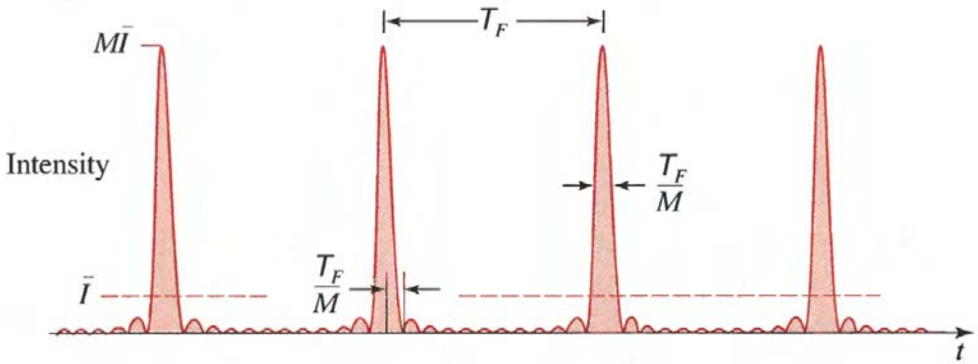


Figure 15.4-9 Intensity of the periodic pulse train resulting from the sum of M laser modes of equal magnitudes and phases. Each pulse has a duration that is M times smaller than the period T_F and a peak intensity that is M times greater than the mean intensity.

Effect is even more obvious if we consider envelope function of the intensity.

The more modes, the narrower the peak widths.

The repetition rate will be determined by the mode spacing (shorter cavity, more widely spaced modes, faster rep rate).

Mode Locking

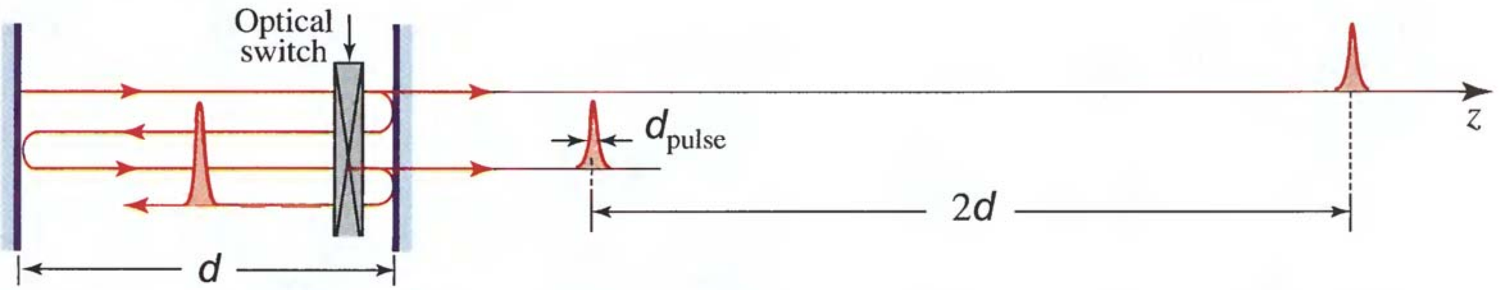


Figure 15.4-10 The mode-locked laser pulse reflects back and forth between the mirrors of the resonator. Each time it reaches the output mirror it transmits a short optical pulse. The transmitted pulses are separated by the distance $2d$ and travel with velocity c. The switch opens only when the pulse reaches it and only for the duration of the pulse. The periodic pulse train is therefore unaffected by the presence of the switch. Other wave patterns, however, suffer losses and are not permitted to oscillate.

Sounds easy… so what is this switch?

Optical Switches – Saturable Absorber

Active Mode Locking: Acousto-optic or electro-optic switch, activated periodically

Passive Mode Locking:
- Saturable absorber (colliding-pulse ring laser)
- Non-linear optical effects (Kerr lensing: $n=n_0+n_2I$)

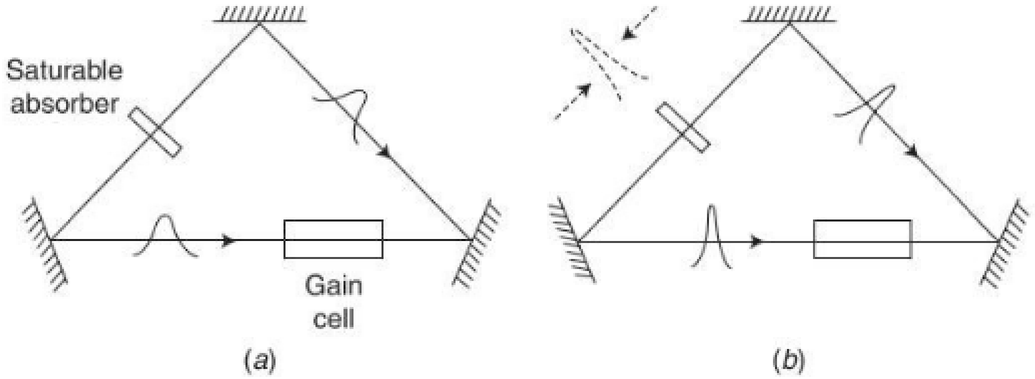
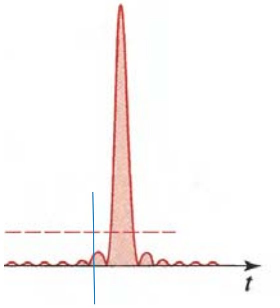


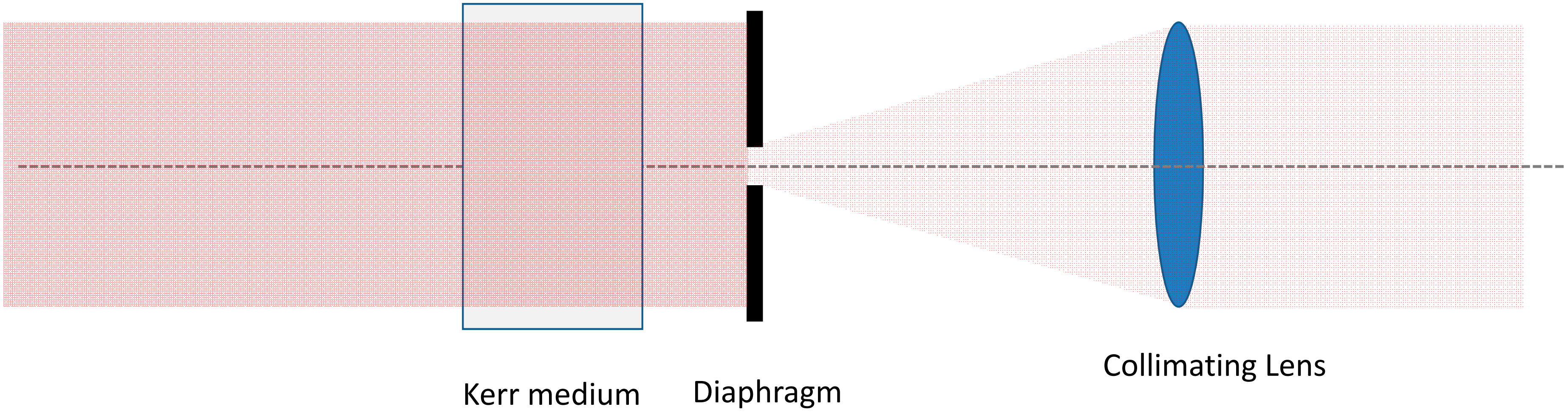
Figure 6.17 (*a*) A colliding-pulse ring laser with countercirculating pulses. (*b*) The lowest-loss condition is for the colliding pulses to synchronize and overlap inside the thin saturable absorber.

Optical Switches – Kerr lensing

Active Mode Locking: Acousto-optic or electro-optic switch, activated periodically

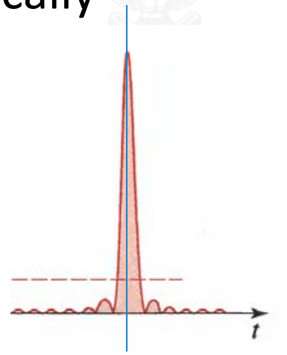
Passive Mode Locking:
- Saturable absorber
- Non-linear optical effects (Kerr lensing: $n=n_0+n_2I$)





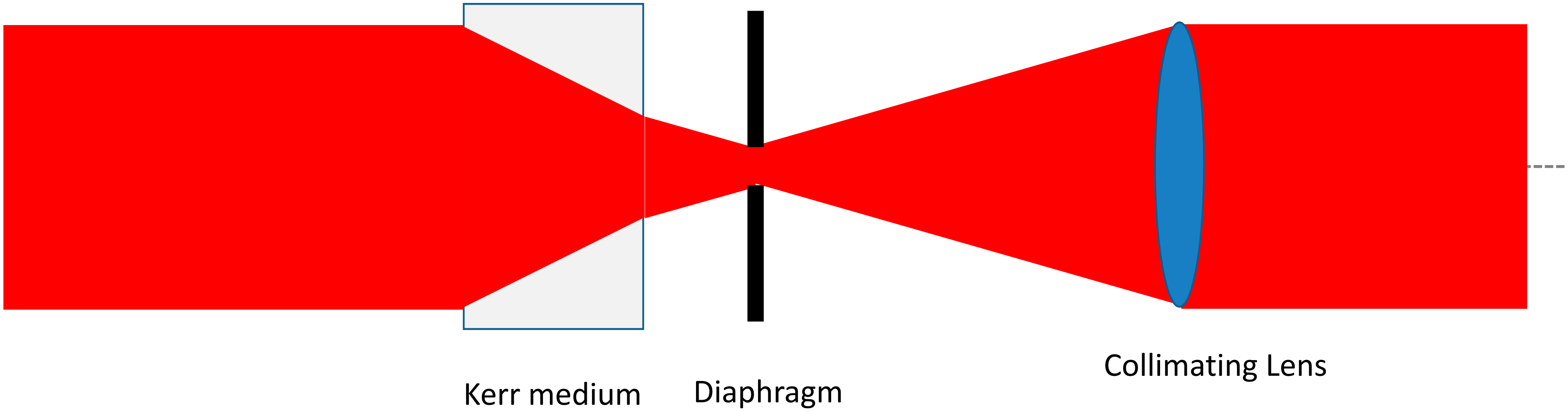
Optical Switches – Kerr lensing

Active Mode Locking: Acousto-optic or electro-optic switch, activated periodically



Passive Mode Locking:

- Saturable absorber
- Non-linear optical effects (Kerr lensing: $n=n_0+n_2I$)



Mode Locking

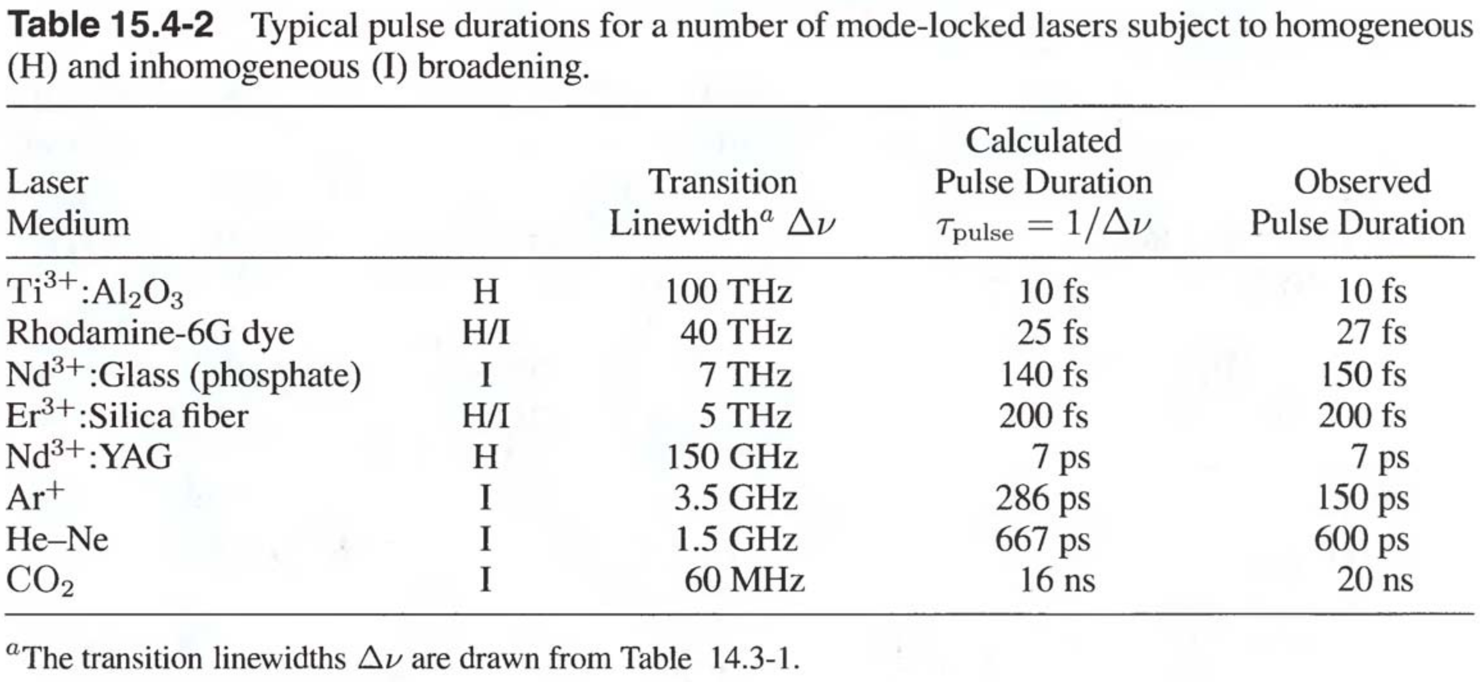


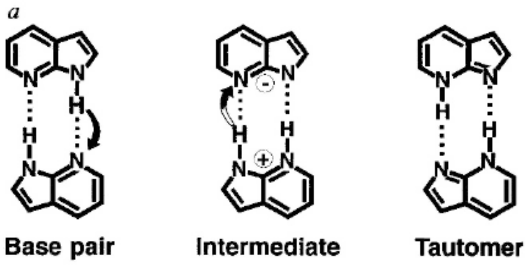
Table 15.4-2 Typical pulse durations for a number of mode-locked lasers subject to homogeneous (H) and inhomogeneous (I) broadening.

Laser Medium		Transition Linewidth[a] $\Delta\nu$	Calculated Pulse Duration $\tau_{\text{pulse}} = 1/\Delta\nu$	Observed Pulse Duration
Ti^{3+}:Al_2O_3	H	100 THz	10 fs	10 fs
Rhodamine-6G dye	H/I	40 THz	25 fs	27 fs
Nd^{3+}:Glass (phosphate)	I	7 THz	140 fs	150 fs
Er^{3+}:Silica fiber	H/I	5 THz	200 fs	200 fs
Nd^{3+}:YAG	H	150 GHz	7 ps	7 ps
Ar^+	I	3.5 GHz	286 ps	150 ps
He–Ne	I	1.5 GHz	667 ps	600 ps
CO_2	I	60 MHz	16 ns	20 ns

[a] The transition linewidths $\Delta\nu$ are drawn from Table 14.3-1.

Ultrashort pulse science

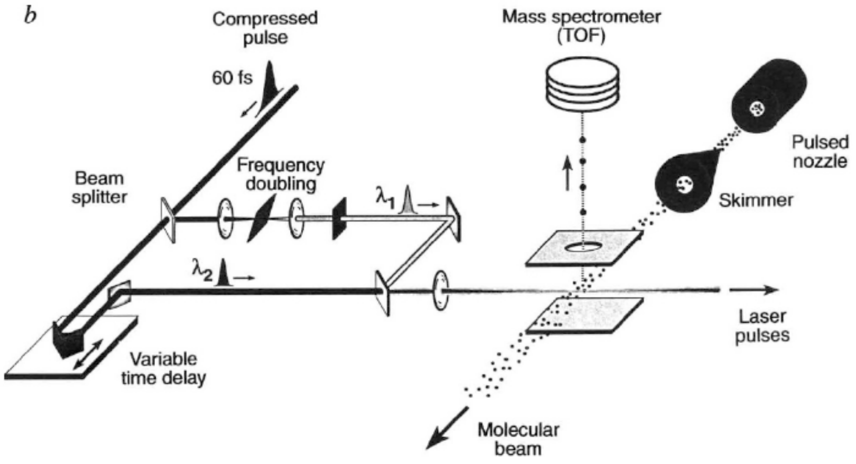
FIG. 1 *a*, The molecular structures involved in the two-step, or one-step, cooperative double proton transfer dynamics of the base pair (7-azaindole dimer); *b*, schematic diagram of part of the experimental apparatus showing the generation of the femtosecond (λ_1, pump; λ_2, probe) pulses (ref. 9, pages 120–134) and the skimmed molecular beam (ref. 9, pages 319–327), together with the detection compartment which uses time-of-flight mass spectrometry. The compressed, amplified pulses were 60 fs in duration and had an energy of ~0.5 mJ. The cross-correlation of the pump and probe pulses was measured *in situ* to be ~150 fs. The power of the pulses were controlled to study their effect on the transients.



Femtosecond molecular dynamics of tautomerization in model base pairs

A. Douhal, S. K. Kim & A. H. Zewail

NATURE · VOL 378 · 16 NOVEMBER 1995



Femtochemistry

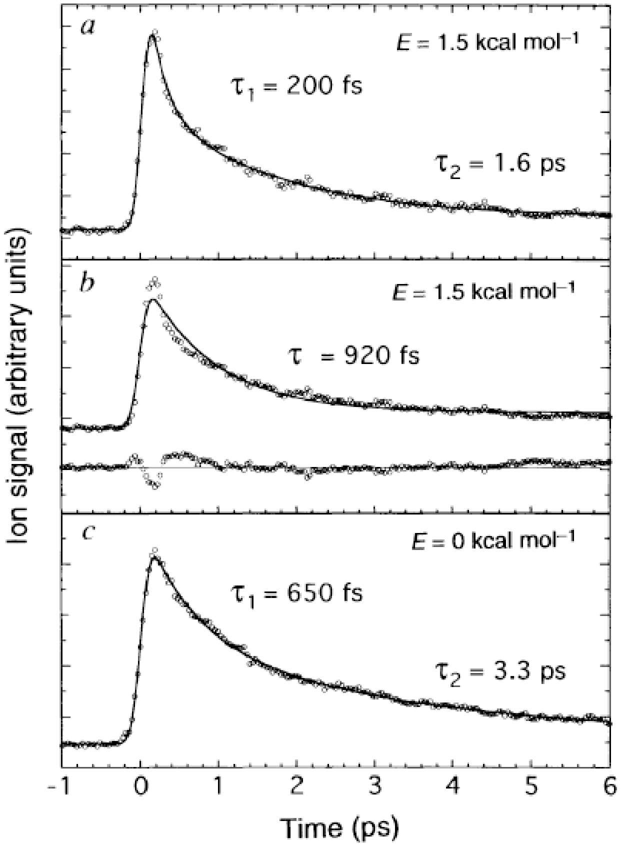
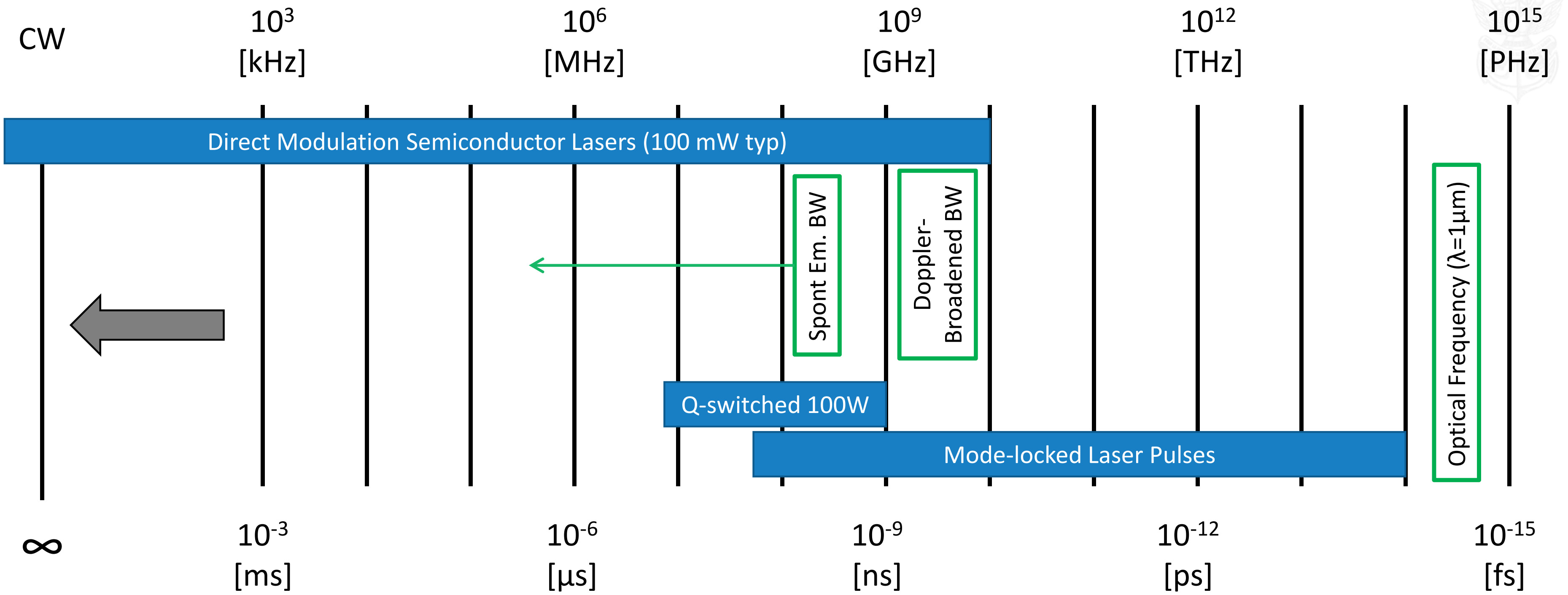


FIG. 3 Femtosecond transients of the base pair (236 AMU) as a function of the time delay. *a*, Excitation with an excess vibrational energy $E \approx 1.5$ kcal mol^{-1}; *b*, a single exponential fit of the same data; and *c*, excitation with $E \approx 0$. A bi-exponential function (and a small constant background) is used to fit both decays in *a* and *c*. The constant takes into account the nanosecond decay, a contribution of ~10%, of the total signal. Note the distribution of residuals (lower trace) in *b* when a single exponential decay is assumed. The observed transient is not power-dependent, and only one ultraviolet photon excitation is responsible for the observed dynamics.

Time scales for laser pulsing



Outline of Lecture

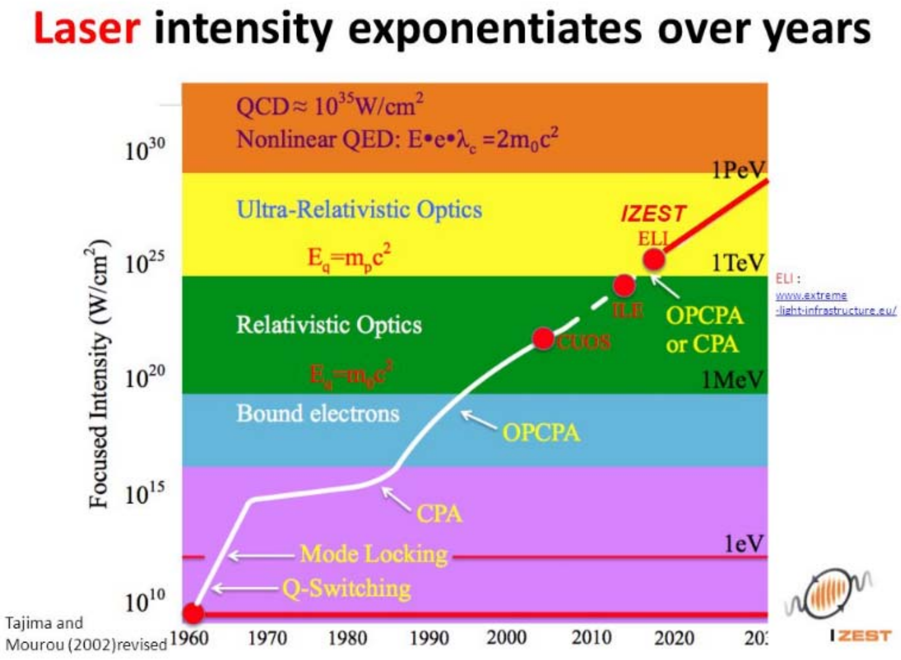
Laser Pulsing

I. Modulation for Telecommunications
   - Semiconductor lasers
   - Direct gain modulation

II. Advanced Techniques for Shorter Pulses
   - Q-switching (and cousins)
   - Mode locking

III. Even higher power
   - Chirped pulse amplification

Pulsing for High Instantaneous Power


Laser **intensity exponentiates over years**

ELI : www.extreme -light-infrastructure.eu/

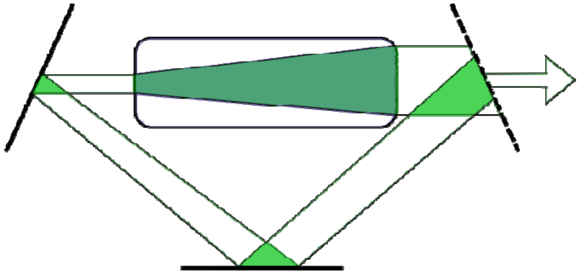
Tajima and Mourou (2002)revised

Remember, to focus perfectly, all photons must be in the same transverse mode (Lecture 3)

Optical Amplification

An optical cavity (« oscillator ») → condition on phase

An amplifying medium (« gain ») → condition on ampl. / intensity



The saturation intensity becomes the barrier to obtaining a higher instantaneous intensity beam

Need gain to compensate losses (output + parasitic)

Impossible in Lorentz model,
requires population inversion.

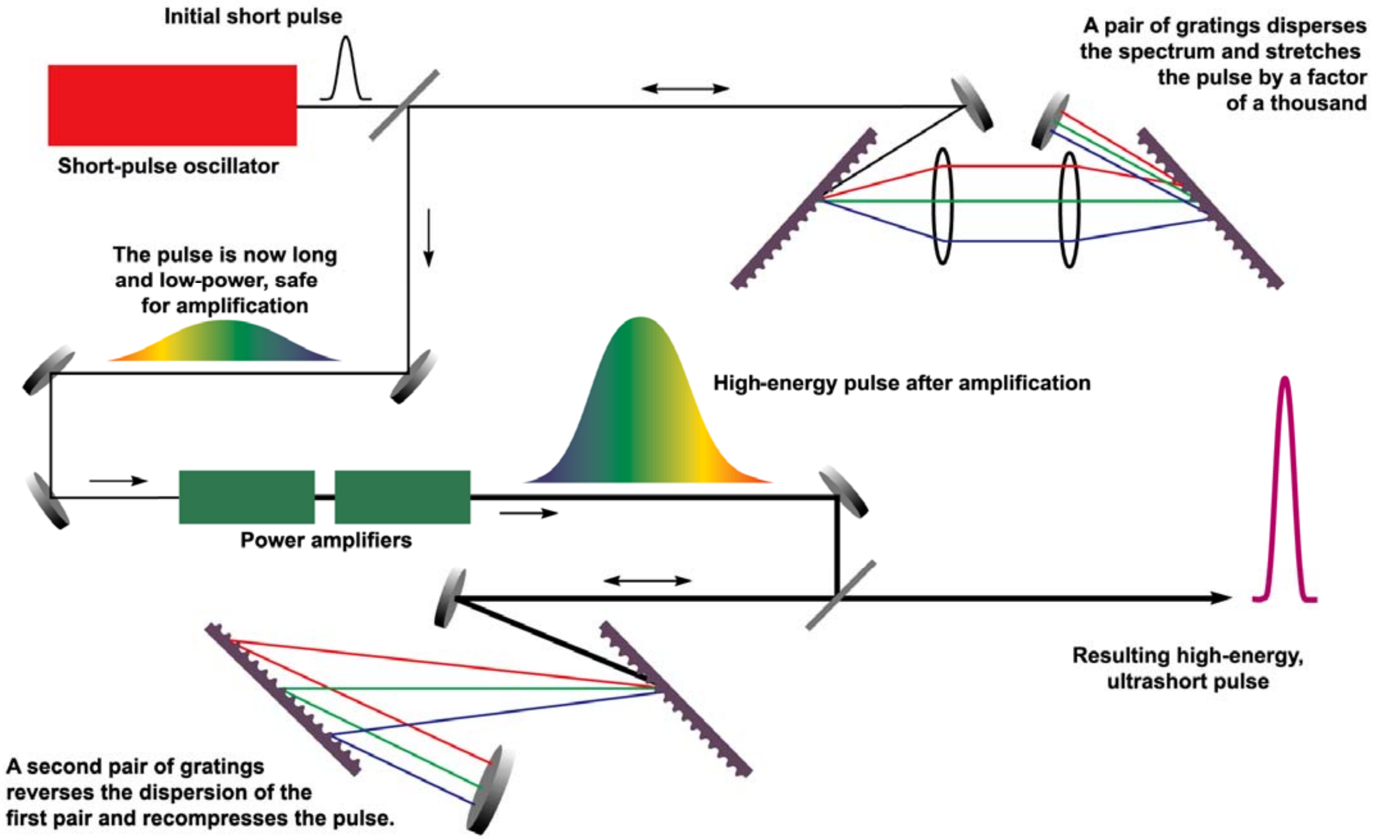
$$g = \sigma_{eg} \underbrace{(n_e - n_g)}_{\Delta n}$$

Basic laser properties

$$g = \frac{g_0}{1+I/I_{\text{sat}}}$$

Laser threshold,
Gain saturation,
Steady state intensity,
Steady state population inversion

Chirped Pulse Amplfication


Initial short pulse

A pair of gratings disperses the spectrum and stretches the pulse by a factor of a thousand

Short-pulse oscillator

The pulse is now long and low-power, safe for amplification

High-energy pulse after amplification

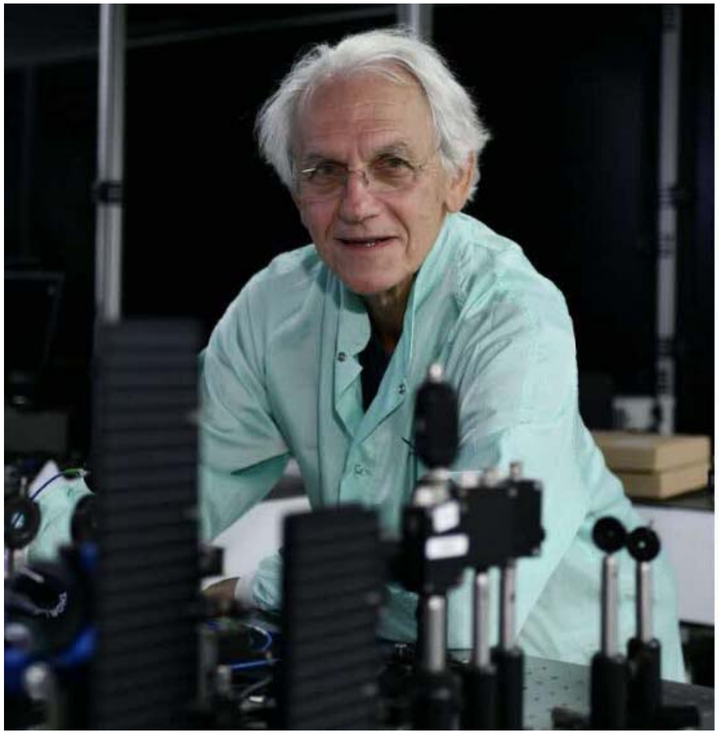
Power amplifiers

Resulting high-energy, ultrashort pulse

A second pair of gratings reverses the dispersion of the first pair and recompresses the pulse.

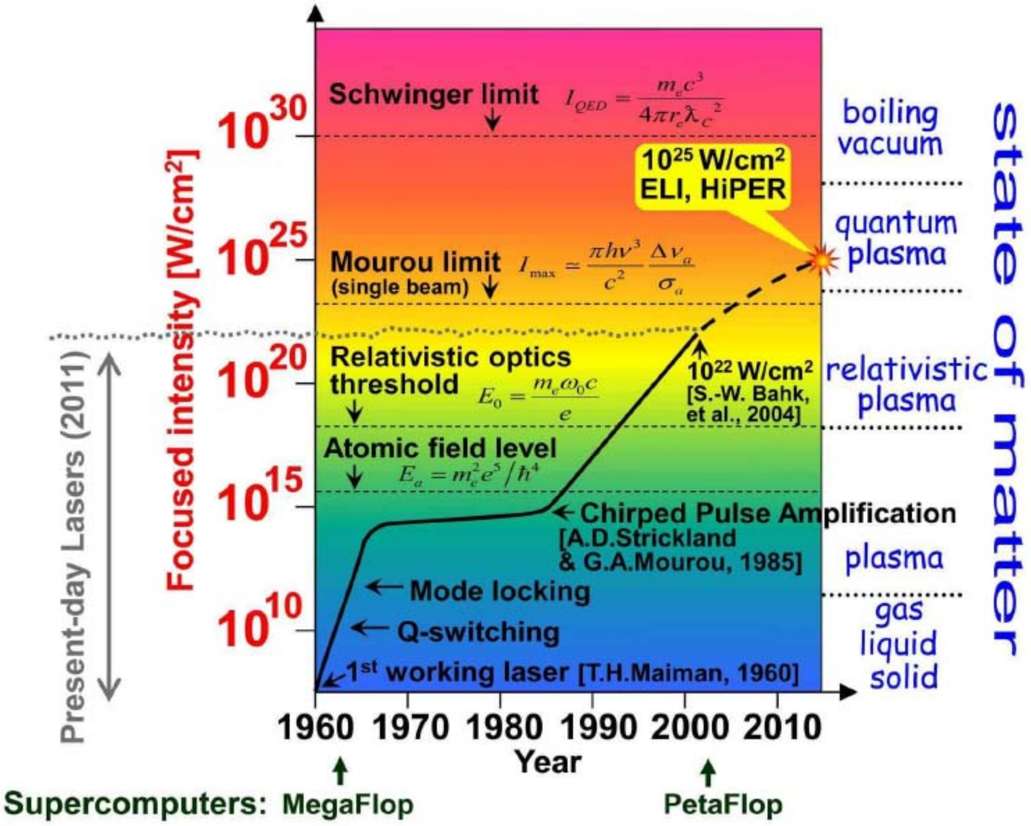
2018 Nobel Prize Winners for CPA

Prof. Donna Strickland
University of Waterloo



Prof. Gerard Mourou
Ecole Polytechnique

Pulsing for High Instantaneous Power



HiPER Workshop at SPIE Lasers and Optoelectronics Conference, April 2015

The HiPER Project

HiPER, the European High Power laser Energy Research facility, is dedicated to demonstrating laser driven fusion as a future energy source.

Fusion energy will be a sustainable, environmentally clean power source using sea water as its principal source of fuel. It will produce no greenhouse gases or long-lived radioactive waste materials and will deliver energy security for the long term.

Demonstration of the scientific proof of principle for laser fusion is expected in the next couple of years at the National Ignition Facility in the USA. The HiPER Project will drive the transition from scientific proof of principle to a demonstration power plant, capable of delivering electricity to the grid.

While the primary mission of HiPER is energy, HiPER will also support a wide range of science research.

Inertial confinement fusion (using lasers to drive fusion) saw a big push that came up short of ignition (by about a factor of 3)

See National Ignition Facility (NIF) LLNL

Since 2012, used mostly to do science (and weapons research).

See Extreme Light Infrastructure for latest project in Europe, Station of Extreme Light in China…

Take home message

Aside from technology, you already knew how to pulse a laser

- The gain/loss balance in a laser cavity is a core concept of this course (which you already knew)
- Playing with one or the other is how we get a short pulse
- Mode-locking is establishing coherence between modes (as we did for a single mode using stimulated emission and feedback)
- Chirped Pulse Amplification is just a way around I_{sat} (which you already knew about)
- So it all fits together

References

Saleh & Teich, Fundamentals of Photonics

- Chapter 14, Laser Amplifiers
- Chapter 15, Lasers
- Chapter 17, Semiconductor Photon Sources

Milonni & Eberly, Lasers