14: Pulsed lasers: gain-switching and Q- switching

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- Gain switching
- Relaxation oscillations
- Q-switching basics
- Q-switching methods
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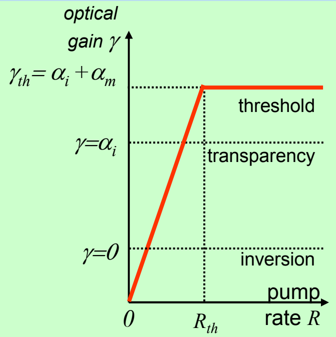
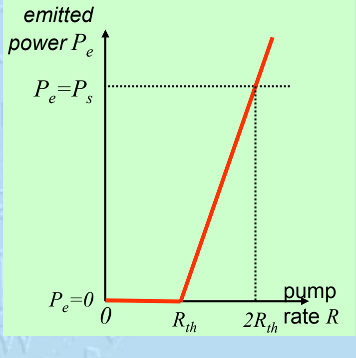
Methods for laser switching

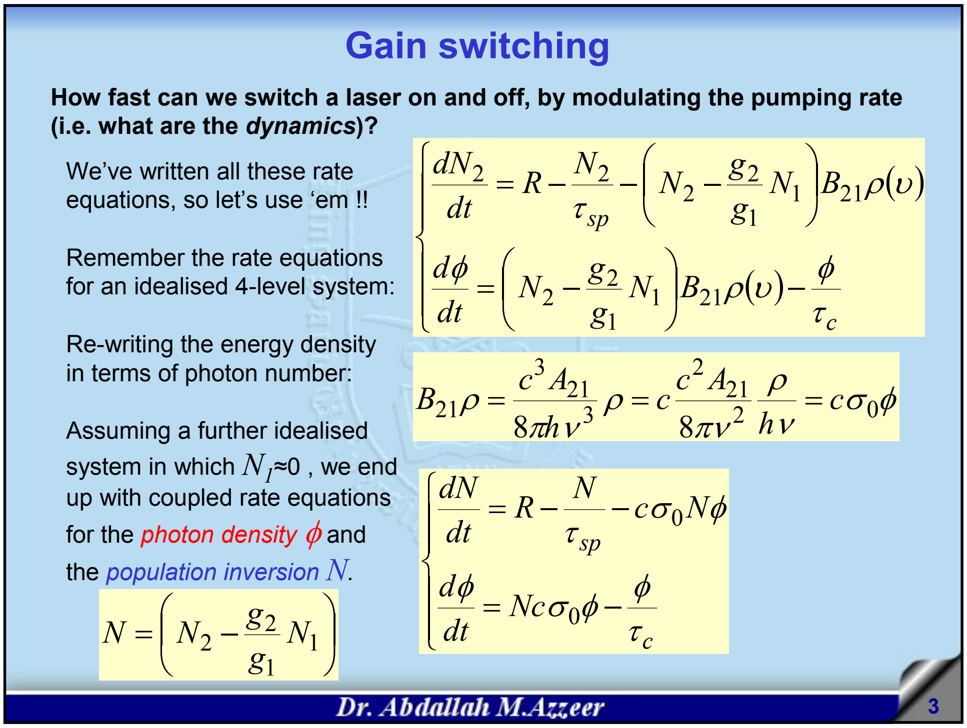
So far, we have looked at the *steady-state* (CW) output from a laser:





But how can we turn a laser on and off ?

1. Change the pump rate R to modify the gain (“gain switching”)
2. Change the cavity loss $\alpha_i+\alpha_m$ to modify the lasing threshold (“Q-switching”)
3. Employ beating between multiple modes of the laser cavity (“mode-locking”)



Gain switching

How fast can we switch a laser on and off, by modulating the pumping rate (i.e. what are the *dynamics*)?

We've written all these rate equations, so let's use 'em !!

Remember the rate equations for an idealised 4-level system:

$$\begin{cases} \dfrac{dN_2}{dt} = R - \dfrac{N_2}{\tau_{sp}} - \left(N_2 - \dfrac{g_2}{g_1} N_1\right) B_{21}\rho(\upsilon) \\ \dfrac{d\phi}{dt} = \left(N_2 - \dfrac{g_2}{g_1} N_1\right) B_{21}\rho(\upsilon) - \dfrac{\phi}{\tau_c} \end{cases}$$

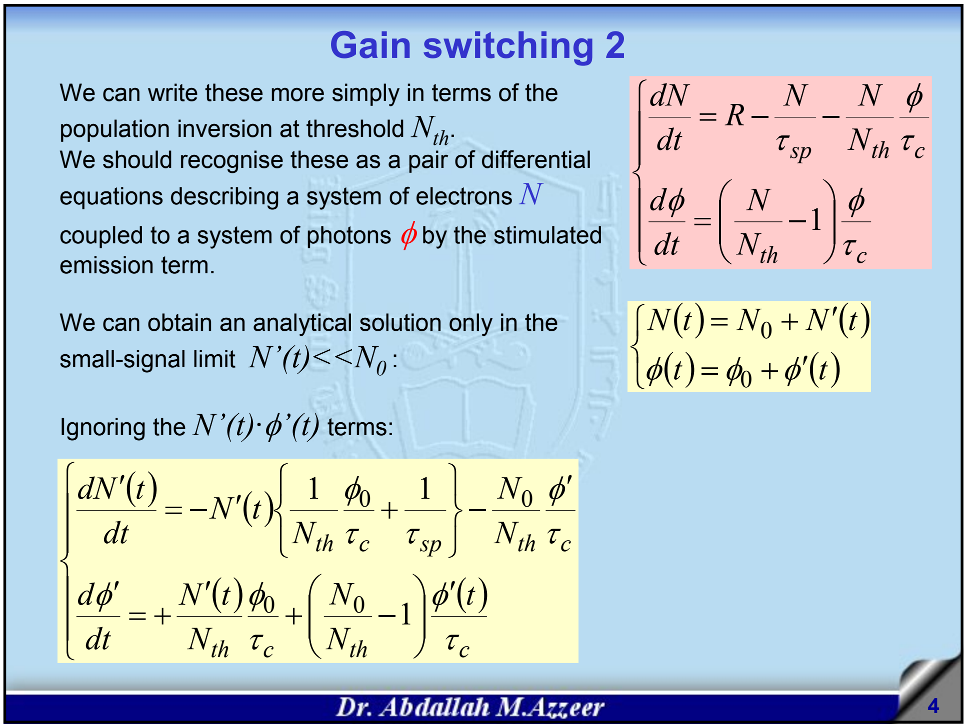
Re-writing the energy density in terms of photon number:

$$B_{21}\rho = \frac{c^3 A_{21}}{8\pi h\nu^3}\rho = c\frac{c^2 A_{21}}{8\pi\nu^2}\frac{\rho}{h\nu} = c\sigma_0\phi$$

Assuming a further idealised system in which $N_1 \approx 0$, we end up with coupled rate equations for the *photon density* ϕ and the *population inversion* N.

$$N = \left(N_2 - \frac{g_2}{g_1} N_1\right)$$

$$\begin{cases} \dfrac{dN}{dt} = R - \dfrac{N}{\tau_{sp}} - c\sigma_0 N\phi \\ \dfrac{d\phi}{dt} = Nc\sigma_0\phi - \dfrac{\phi}{\tau_c} \end{cases}$$



Gain switching 2

We can write these more simply in terms of the population inversion at threshold N_{th}.
We should recognise these as a pair of differential equations describing a system of electrons N coupled to a system of photons ϕ by the stimulated emission term.

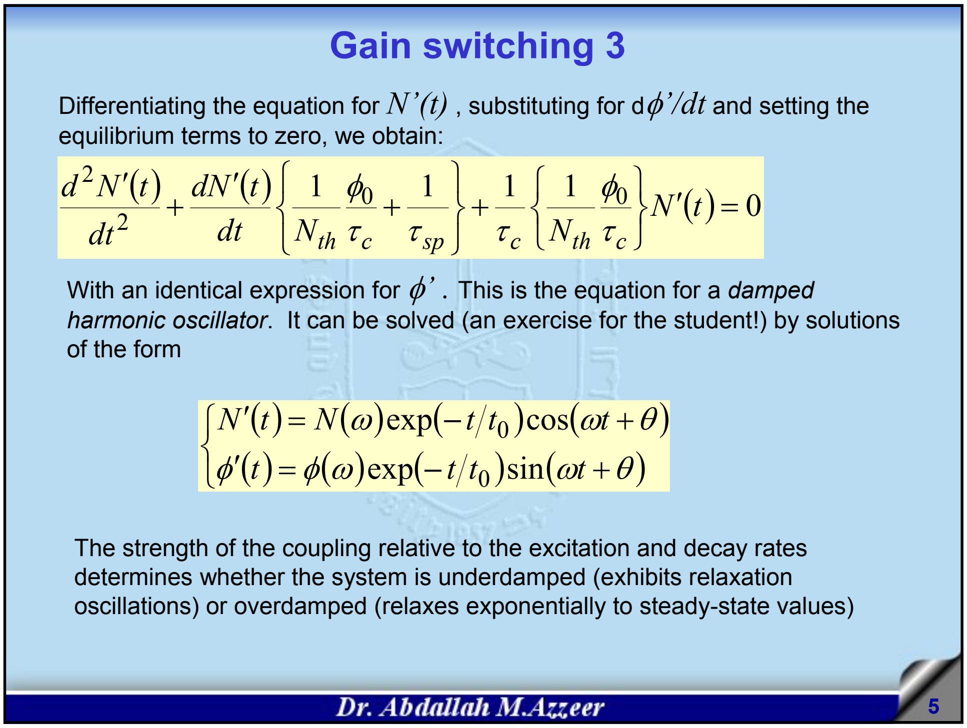
$$\begin{cases} \dfrac{dN}{dt} = R - \dfrac{N}{\tau_{sp}} - \dfrac{N}{N_{th}}\dfrac{\phi}{\tau_c} \\ \dfrac{d\phi}{dt} = \left(\dfrac{N}{N_{th}} - 1\right)\dfrac{\phi}{\tau_c} \end{cases}$$

We can obtain an analytical solution only in the small-signal limit $N'(t) << N_0$:

$$\begin{cases} N(t) = N_0 + N'(t) \\ \phi(t) = \phi_0 + \phi'(t) \end{cases}$$

Ignoring the $N'(t)\cdot\phi'(t)$ terms:

$$\begin{cases} \dfrac{dN'(t)}{dt} = -N'(t)\left\{\dfrac{1}{N_{th}}\dfrac{\phi_0}{\tau_c} + \dfrac{1}{\tau_{sp}}\right\} - \dfrac{N_0}{N_{th}}\dfrac{\phi'}{\tau_c} \\ \dfrac{d\phi'}{dt} = +\dfrac{N'(t)}{N_{th}}\dfrac{\phi_0}{\tau_c} + \left(\dfrac{N_0}{N_{th}} - 1\right)\dfrac{\phi'(t)}{\tau_c} \end{cases}$$



Gain switching 3

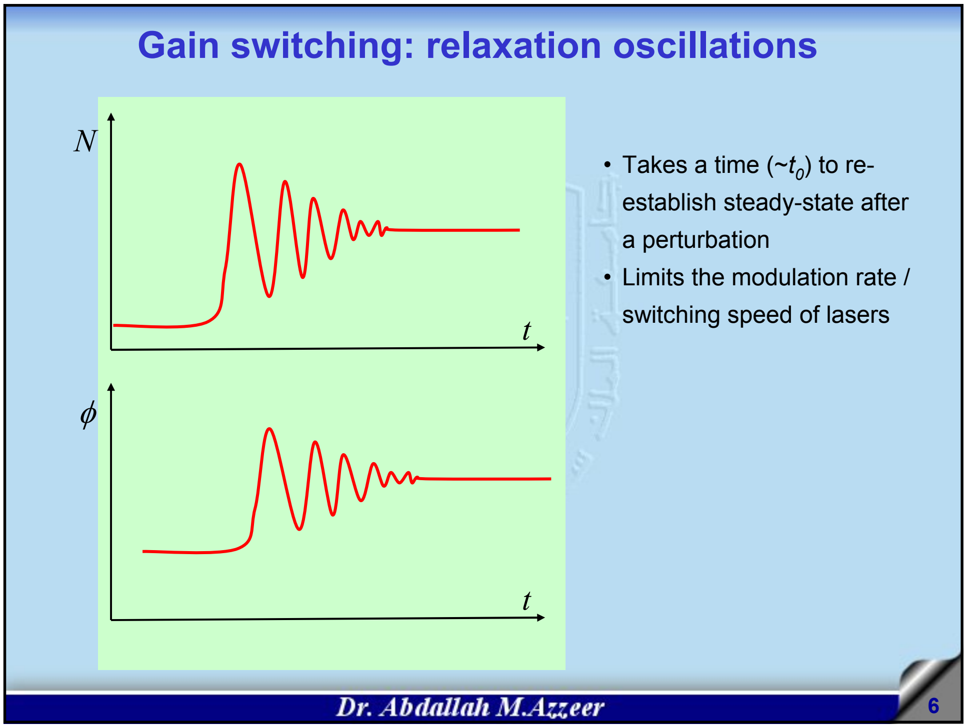
Differentiating the equation for $N'(t)$, substituting for $d\phi'/dt$ and setting the equilibrium terms to zero, we obtain:

$$\frac{d^2N'(t)}{dt^2}+\frac{dN'(t)}{dt}\left\{\frac{1}{N_{th}}\frac{\phi_0}{\tau_c}+\frac{1}{\tau_{sp}}\right\}+\frac{1}{\tau_c}\left\{\frac{1}{N_{th}}\frac{\phi_0}{\tau_c}\right\}N'(t)=0$$

With an identical expression for ϕ' . This is the equation for a *damped harmonic oscillator*. It can be solved (an exercise for the student!) by solutions of the form

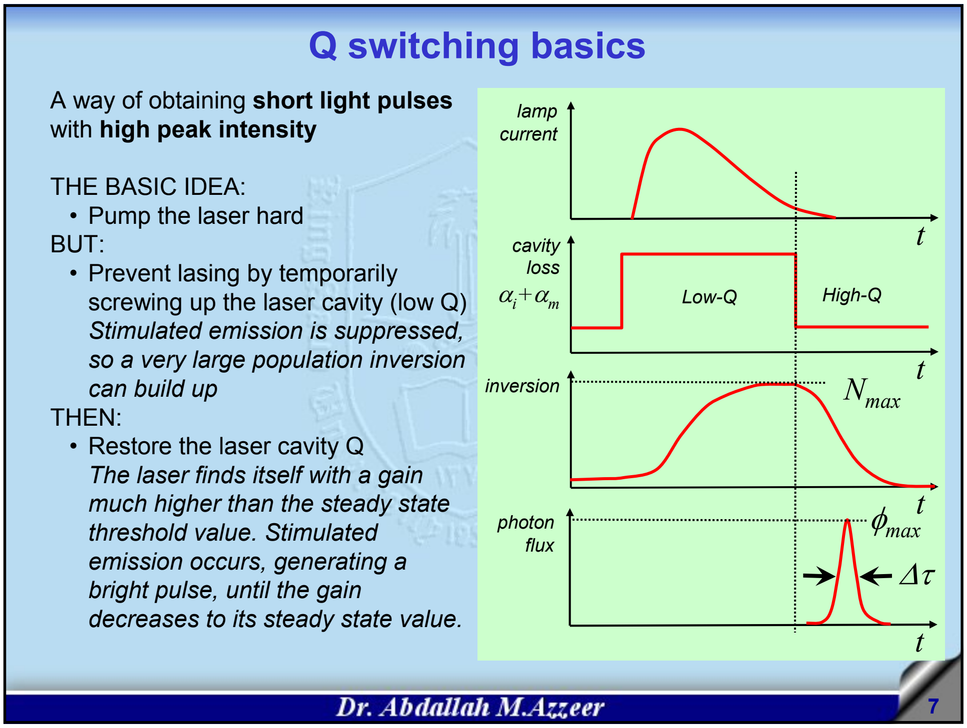
$$\begin{cases} N'(t)=N(\omega)\exp(-t/t_0)\cos(\omega t+\theta) \\ \phi'(t)=\phi(\omega)\exp(-t/t_0)\sin(\omega t+\theta) \end{cases}$$

The strength of the coupling relative to the excitation and decay rates determines whether the system is underdamped (exhibits relaxation oscillations) or overdamped (relaxes exponentially to steady-state values)



Gain switching: relaxation oscillations

- Takes a time (~t_0) to re-establish steady-state after a perturbation
- Limits the modulation rate / switching speed of lasers



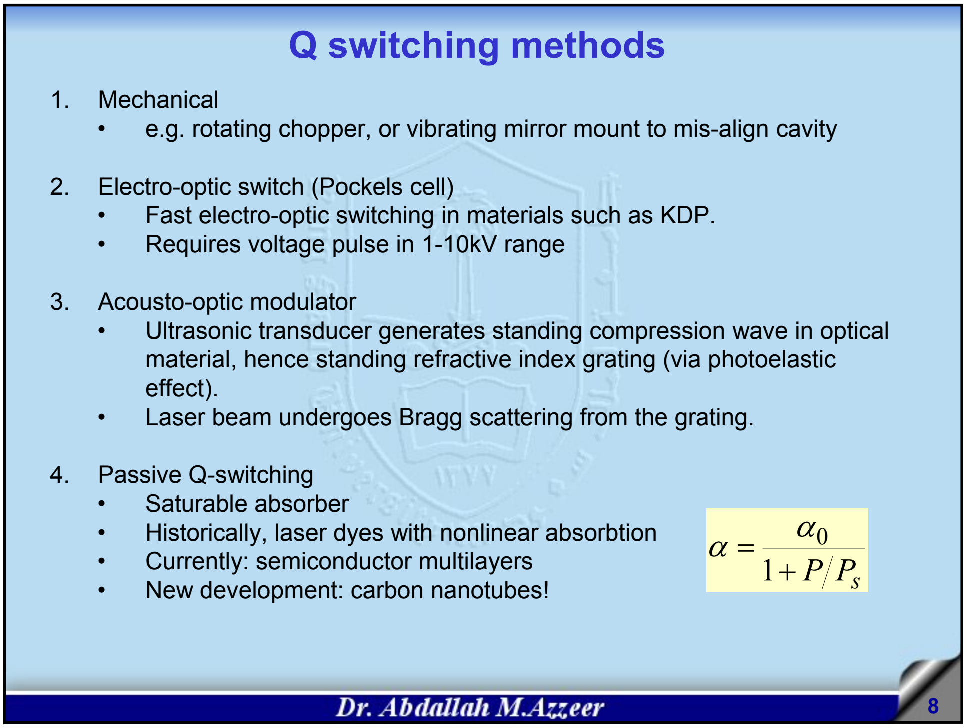
Q switching basics

A way of obtaining **short light pulses** with **high peak intensity**

THE BASIC IDEA:
- Pump the laser hard

BUT:
- Prevent lasing by temporarily screwing up the laser cavity (low Q)
  Stimulated emission is suppressed, so a very large population inversion can build up

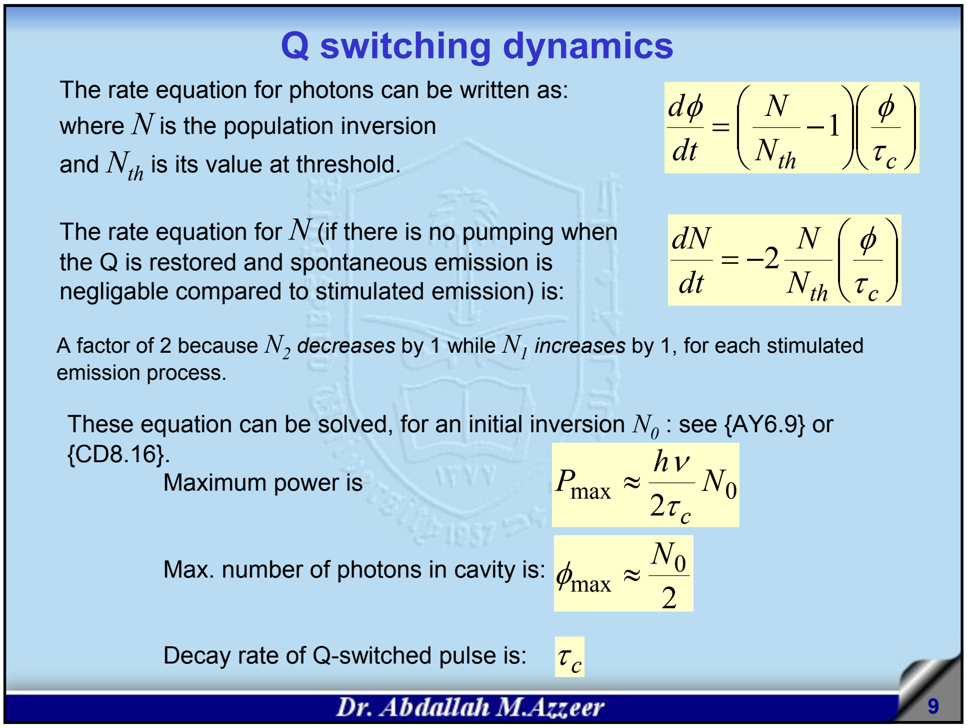
THEN:
- Restore the laser cavity Q
  The laser finds itself with a gain much higher than the steady state threshold value. Stimulated emission occurs, generating a bright pulse, until the gain decreases to its steady state value.



Q switching methods

1. Mechanical
   - e.g. rotating chopper, or vibrating mirror mount to mis-align cavity
2. Electro-optic switch (Pockels cell)
   - Fast electro-optic switching in materials such as KDP.
   - Requires voltage pulse in 1-10kV range
3. Acousto-optic modulator
   - Ultrasonic transducer generates standing compression wave in optical material, hence standing refractive index grating (via photoelastic effect).
   - Laser beam undergoes Bragg scattering from the grating.
4. Passive Q-switching
   - Saturable absorber
   - Historically, laser dyes with nonlinear absorbtion
   - Currently: semiconductor multilayers
   - New development: carbon nanotubes!

$$\alpha = \frac{\alpha_0}{1+P/P_s}$$



Q switching dynamics

The rate equation for photons can be written as:
where N is the population inversion
and N_{th} is its value at threshold.

$$\frac{d\phi}{dt}=\left(\frac{N}{N_{th}}-1\right)\left(\frac{\phi}{\tau_c}\right)$$

The rate equation for N (if there is no pumping when the Q is restored and spontaneous emission is negligable compared to stimulated emission) is:

$$\frac{dN}{dt}=-2\frac{N}{N_{th}}\left(\frac{\phi}{\tau_c}\right)$$

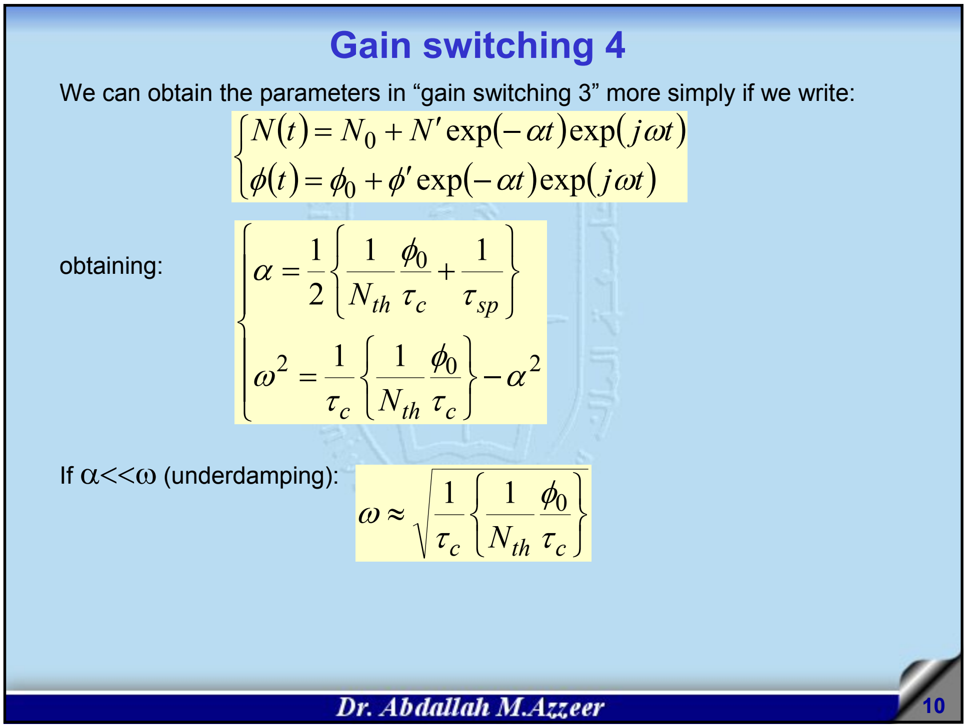
A factor of 2 because N_2 *decreases* by 1 while N_1 *increases* by 1, for each stimulated emission process.

These equation can be solved, for an initial inversion N_0 : see {AY6.9} or {CD8.16}.

Maximum power is $P_{\max}\approx\frac{h\nu}{2\tau_c}N_0$

Max. number of photons in cavity is: $\phi_{\max}\approx\frac{N_0}{2}$

Decay rate of Q-switched pulse is: τ_c



Gain switching 4

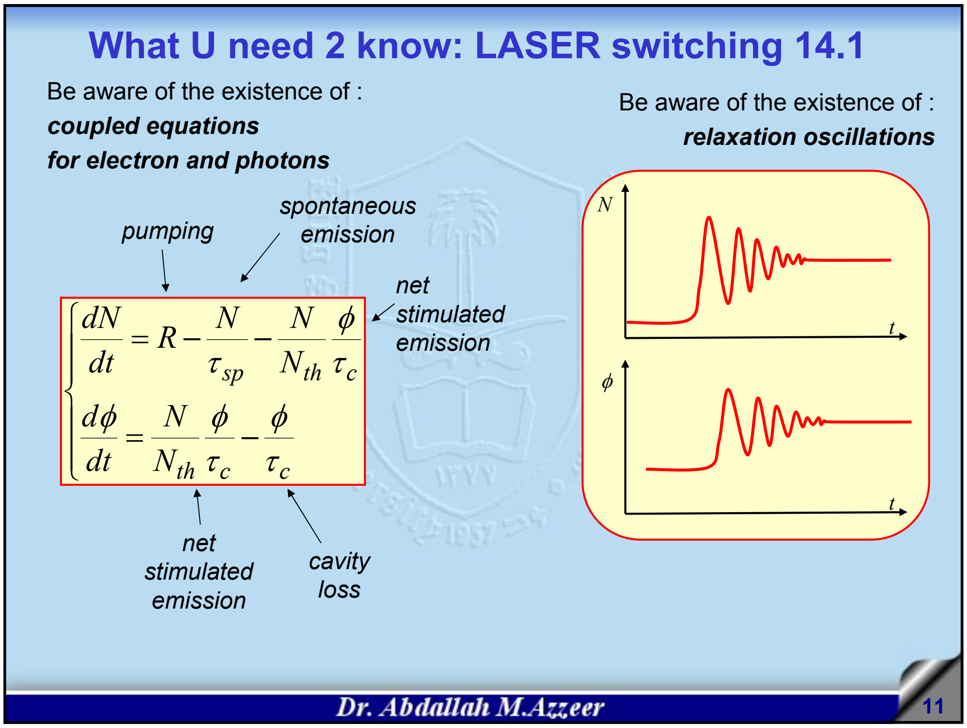
We can obtain the parameters in “gain switching 3” more simply if we write:

$$\begin{cases} N(t)=N_0+N'\exp(-\alpha t)\exp(j\omega t) \\ \phi(t)=\phi_0+\phi'\exp(-\alpha t)\exp(j\omega t) \end{cases}$$

obtaining:

$$\begin{cases} \alpha=\frac{1}{2}\left\{\frac{1}{N_{th}}\frac{\phi_0}{\tau_c}+\frac{1}{\tau_{sp}}\right\} \\ \omega^2=\frac{1}{\tau_c}\left\{\frac{1}{N_{th}}\frac{\phi_0}{\tau_c}\right\}-\alpha^2 \end{cases}$$

If α<<ω (underdamping): $\omega\approx\sqrt{\frac{1}{\tau_c}\left\{\frac{1}{N_{th}}\frac{\phi_0}{\tau_c}\right\}}$



What U need 2 know: LASER switching 14.1

Be aware of the existence of :

coupled equations

for electron and photons

pumping

spontaneous emission

net stimulated emission

$$\begin{cases} \dfrac{dN}{dt} = R - \dfrac{N}{\tau_{sp}} - \dfrac{N}{N_{th}}\dfrac{\phi}{\tau_c} \\ \dfrac{d\phi}{dt} = \dfrac{N}{N_{th}}\dfrac{\phi}{\tau_c} - \dfrac{\phi}{\tau_c} \end{cases}$$

net stimulated emission

cavity loss

Be aware of the existence of :

relaxation oscillations

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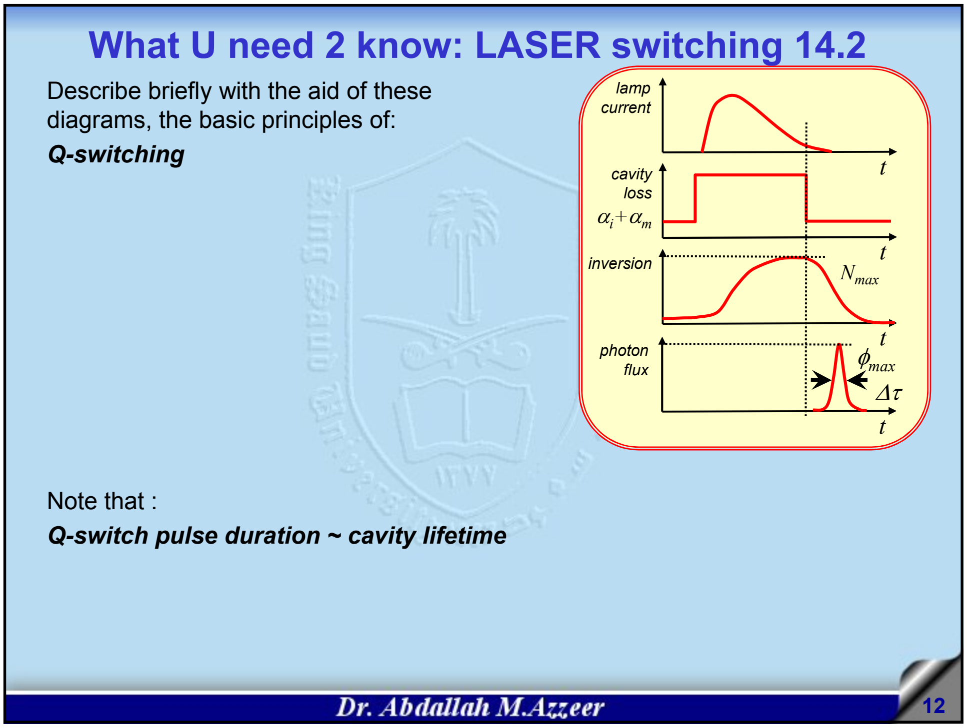

What U need 2 know: LASER switching 14.2

Describe briefly with the aid of these diagrams, the basic principles of:

Q-switching

Note that :

Q-switch pulse duration ~ cavity lifetime

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