Pulsed Lasers

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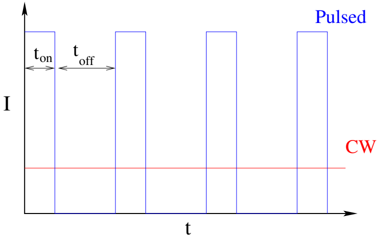
ME 677: Laser Material Processing

Pulsed lasers



Pulsed Laser Parameters

- Pulse on-time (t_{on})
- Pulse repetition rate
- Peak power (W)
- Fluence ($\mathrm{J/cm^2}$)

Laser intensity shows both temporal and spatial variation.

Laser Intensity Profile
Gaussian with Full-Width at Half-Maximum (FWHM)

$$I = I_{max} e^{-\beta(\frac{t}{t_p} - \frac{3}{2})^2} \qquad (1)$$

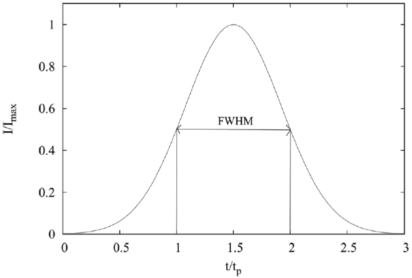
t_p is defined as the width of the pulse at half the peak intensity.

For FWHM Gaussian Pulse:

$$I(t_p) = I(2t_p) = 0.5 I_{max}$$

Substituting in Eqn. 1 gives,

$$\beta = 4 \ln 2$$



- Maximum occurs at $1.5t_p$
- The peak is chosen at $1.5t_p$ to avoid the concept of negative time

Laser Pulse Transient Profile

Laser Fluence (F)

F is the total energy of the pulse

$$F = \int_{-\infty}^{\infty} I \; dt = \int_{-\infty}^{\infty} I_{max} e^{-\beta(\frac{t}{t_p} - \frac{3}{2})^2} \; dt \tag{2}$$

Gaussian integral

$$\int_{-\infty}^{\infty} e^{-x^2} dx = \sqrt{\pi}$$

$$\int_{-\infty}^{\infty} e^{-a(x+b)^2} dx = \sqrt{\frac{\pi}{a}}$$

Eqn. 2 can be evaluated as:

$$F = \sqrt{\frac{\pi}{\beta}} \cdot I_{max} t_p \tag{3}$$

Pulsing Techniques

1. Cavity Dumping
2. Q-switching
3. Mode-locking

Cavity Dumping

- The basic idea of cavity dumping is to keep the optical losses of the laser resonator as low as possible for sometime, so that intense energy builds up in the resonator, and then to extract this energy within a short pulse using an optical switch.
- It can be combined with Q-switching or Mode-locking.

Q-Switching

- The output of some pulsed solid-state lasers such as the ruby laser usually consists of a number of random spikes, each of about a microsecond duration, with the individual spikes spaced apart by about 1 μs and with peak powers of the order of kilowatts. The entire pulse duration may be about 1 ms.
- Q-switching is a technique that is used to produce laser outputs of higher power (of the order of megawatts) and shorter duration (of the order of nanoseconds).
- It must be noted, however, that even though the output power is increased, the total energy content of the pulse is not, and may even be less.

Q-Factor (Q_f)

The Q-factor or quality factor, Q_f, is a measure of the losses or energy dissipation in any mode of the laser cavity and is defined as:

$$Q_f = \frac{\omega_0 \times \text{Energy stored in the mode}}{\text{Energy lost or dissipated in the mode per unit time}} \quad (4)$$

$$= \frac{\omega_0 \times Q}{q_l} \quad (5)$$

This gives:

$$q_l = \frac{\omega_0 \times Q}{Q_f} \quad (6)$$

$$\implies \frac{dQ}{dt} = -\frac{\omega_0 \times Q}{Q_f} \quad (7)$$

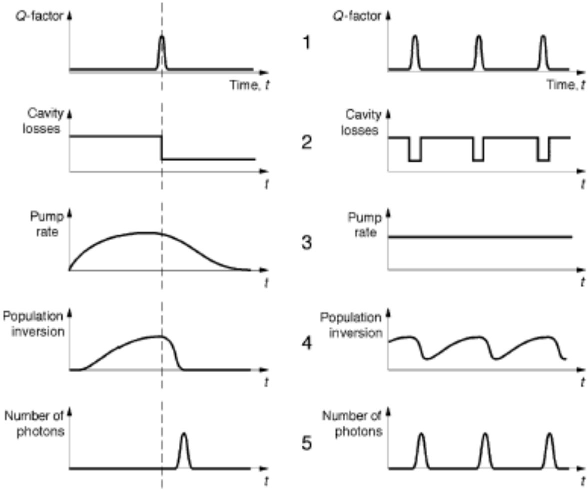
$$\implies Q(t) = Q_0 \mathrm{e}^{-\frac{\omega_0}{Q_f} t} \quad (8)$$

Q_0 is the initial energy at time, $t = 0$.

Principle of Q-Switching

- Consider a laser cavity in which a shutter is placed in front of one of the mirrors.
- When the shutter is closed, it prevents light energy from reaching the second mirror, and thereby being reflected back into the cavity.
- The Q-value of the cavity is then very low, since the losses are high
- As pumping of the laser continues, the population inversion keeps building up, far in excess of the threshold value, without any oscillation taking place.
- When a significantly high value of population inversion has been achieved, the shutter is suddenly opened to reduce the losses.
- At this point, the gain of the laser (due to the high population inversion) is much greater than the losses.
- The high energy accumulated as a result of the large difference between the instantaneous and threshold population inversions is then released as an intense beam of short duration.

Principle of Q-Switching



Single pulse

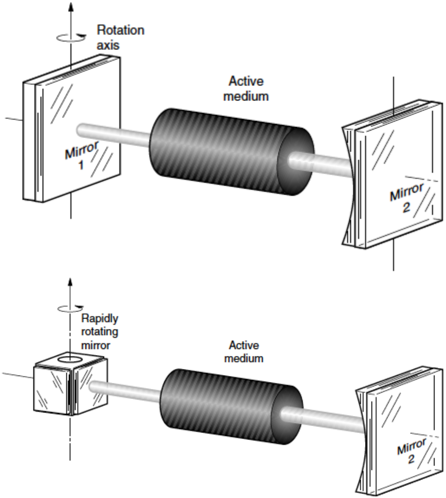
Multiple pulses

Q-Switching Techniques

1.Mechanical Shutters

- With mechanical shutters, one of the cavity mirrors, usually the total reflector, is rotated about an axis perpendicular to the resonator axis.
- Just before the two mirrors become parallel, the flash lamp is triggered to initiate pumping action.
- However, since the mirrors are then not aligned (closed shutter case), the cavity losses are too high to sustain oscillation.The population inversion is thus increased beyond the threshold value.
- The flash lamp trigger is timed in such a way that the population inversion will be a maximum just when the two mirrors are parallel.
- The energy stored in the form of high population inversion is then released as a high-power pulse when the mirrors become aligned.
- The typical pulse duration obtained when using mechanical shutters is of the order of 400 ns.
- Issues: Noise and vibrational problems

Mechanical Shutters



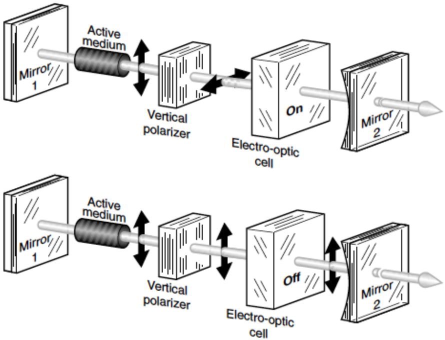
2. Electro-optic Shutters

- A polarizer is placed between the active medium and one of the mirrors. An electro-optic cell (Pockels cell) is then placed between the polarizer and the mirror closest to it.
- The electro-optic cell becomes birefringent when a dc voltage is applied to it, and the extent of induced birefringence depends on the applied voltage.
- The cell is oriented such that the induced birefringence lies in a plane normal to the resonator axis.
- Light from the active medium is first linearly polarized as it passes through the polarizer. The linearly polarized light then becomes circularly polarized by the cell.
- After reflection from mirror 2, the light is converted back to a linearly polarized light by the cell, but this time, with the plane of polarization orthogonal to the original direction. It is therefore blocked by the polarizer on the return trip. In this state, the system acts as a closed shutter, not permitting any light back into the active medium, and that results in high cavity losses and low Q-value.

Q-Switching Techniques

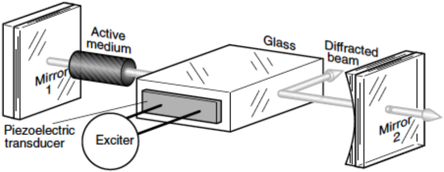
2. Electro-optic Shutters

- When the dc voltage is removed from the cell, the birefringence vanishes and light from the active medium is reflected back without change in polarization, thereby being retransmitted, resulting in an open shutter.
- Peak power outputs obtained by this method are of the order of 100MW, with pulse duration of the order of 10 ns.



3. Acousto-Optic Shutters

- An optical material such as ordinary glass is positioned between the active medium and the output mirror
- A beam of ultrasonic waves applied to the optical material induces local strains in the material, resulting in spatial variations in its refractive index (phase grating effect).
- If the ultrasonic waves are made to propagate in a direction normal to the direction of the incident laser beam, laser beam diffracts out of the cavity, inducing cavity losses (Closed shutter).
- Removal of the transducer voltage removes the phase grating effect, thereby acting as an open shutter



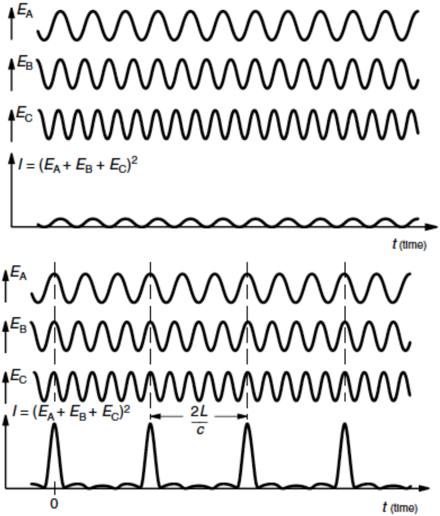
3. Passive Shutters

- Passive Q-switching does not involve the use of either electronic circuits or mechanical devices, but is based on saturable dyes or absorbers, that is, materials whose absorptivity decrease with increasing beam intensity.
- A cell containing the dye material is placed between the active medium and one of the mirrors.
- In the initial stages of pumping, most of the incident
- The population inversion thus increases with pumping, increasing the light intensity inside the cavity.
- At a certain level of intensity, the dye begins to bleach, that is, its transmittance is significantly increased.
- The increased transmittance further enhances the rate of increase of power level within the cavity, making the dye transparent.
- When the dye is almost transparent (that means the shutter is open) oscillation then begins, causing a high power pulse to be generated.
- Passive shutters are normally used for single-pulsed operation.

Mode Locking

- Mode-locking is used to generate pulses of higher peak power (of the order of gigawatts or more) than can be achieved by Q-switching and of very short duration (of the order of picoseconds or even femtoseconds).
- A laser cavity generally sustains a large number of oscillating modes. The oscillation of each of these modes is normally independent of other modes.
- Mode-locking is achieved by combining a number of distinct longitudinal modes of a laser in phase, with each mode having a slightly different frequency.

Mode Locking



Mode Locking

Standing wave condition:

$$m\lambda = 2L \tag{9}$$

m: order, L: length of cavity

$$\nu = \frac{mc}{2L} \tag{10}$$

Gap between modes:

$$\Delta\nu = \frac{c}{2L} \tag{11}$$

Time gap (t_g) = 1 round trip of the pulse

$$t_g = \frac{1}{\Delta\nu} = \frac{2L}{c} \tag{12}$$

$$\tau_p = \frac{1}{N\Delta\nu} \tag{13}$$

N: Number of modes taking part

Mode Locking

Problem:
Spectral Bandwidth of Ti:Sapphire Laser = 128 THz
Cavity length = 200 cm

$$\Delta\nu = \frac{c}{2L} \tag{14}$$

$$N = \frac{\text{Bandwidth}}{\text{Gap}} \tag{15}$$

$$t_g = \frac{1}{\Delta\nu} \tag{16}$$

$$\tau_p = \frac{1}{N\Delta\nu} \tag{17}$$