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Chapter 14

"Tunable Dye Lasers"

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Introduction:

In a dye laser the active lasing medium is an organic dye dissolved in a solvent such as alcohol. These lasers may be pumped by either flashlamps (like a solid-state laser) or by another laser. The major advantage of this laser over other types is continuous tunability over a wide range. By changing the dye employed, the range can be selected. Hundreds of dyes are known to lase.

<u>Some examples of dye laser</u> –

> - Laser-pumped dye lasers normally employ nitrogen or excimer pump lasers and hence are pulsed, but continuous dye lasers are possible using a CW argon-ion laser as a pump source.
> - A laser employing rhodamine-6G, for example, can be tuned continuously through a range of wavelengths spanning visually from a shade of green–yellow to a shade of red.

Lasing Medium:

In a dye laser the active medium is a fluorescent organic dye dissolved in a solvent (usually, an alcohol). The dye is pumped optically by a laser or by a flashlamp to produce a population inversion followed by stimulated emission to produce a laser gain.

- Lasing begins when incident energy is absorbed by the dye, exciting it from the lowest singlet state to a high-energy level within the upper singlet band, as shown in Figure 1.
- From the high-energy level the dye falls to a slightly lower state within the same singlet band, which serves as an upper lasing level.
- A laser transition can then occur between the upper lasing level and the lower singlet state, which serves as a lower lasing level.

The dyes involved are large molecules with molecular weights in the range 400 to 500 amu. Most laser dyes belong to one of several families of dyes such as rhodamines or coumarins.

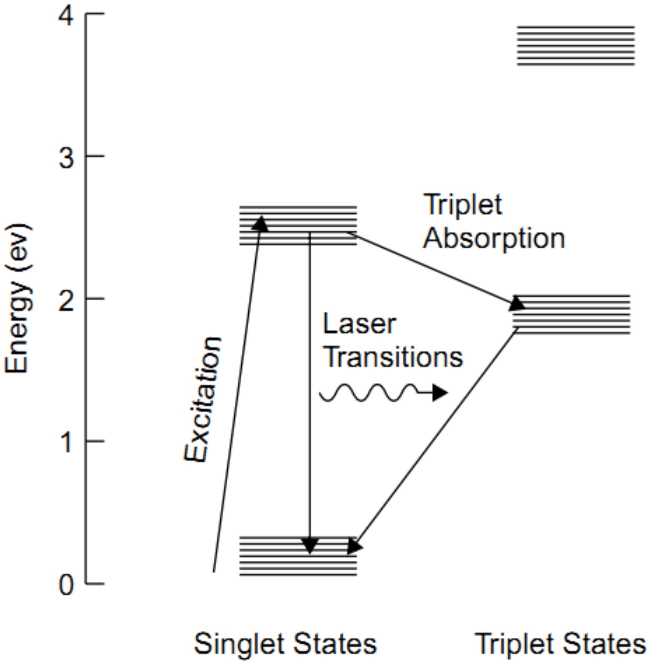

Figure 1: Laser dye energy levels.

- An alternative pathway exists to foil laser action in the triplet states of the dye, also shown on Figure 1.

Triplet states originate when excited electrons in the dye molecule spin in the same direction as that of the remaining electrons in the dye molecule (the **singlet states** result when the excited electron spins in the direction opposite to the lower-energy-state valence electrons still in the dye molecule).

- Because triplet states have lower energies than corresponding singlet states, dye molecules can easily migrate to those states and in doing so depopulate the upper lasing level.

- To make matters worse, triplet states are metastable and have much longer lifetimes than the singlet levels. When a short pump pulse such as that from a nitrogen laser (at 10 ns) is employed, triplet states do not form and do not present a problem for lasing, but when a flashlamp is used (which generally have pulse widths of over 1 ms), triplet states can form.

For this reason, flashlamps must be designed to discharge as quickly as possible. Ordinary photographic strobes, for example, often have pulse lengths of 1 ms and will not work for pumping most dye lasers. In addition to a fast pump pulse to prevent triplet formation, triplet quenching additives can be mixed with many dyes, such as cyclooctatetraene (COT). These additives work by providing a deexcitation pathway from the triplet states, allowing the dye molecule involved to reenter the lasing process.

- An enormous number of dyes are commercially available which span the entire spectrum from UV to IR.

Pumping of Dyes -

Dyes may be pumped by flashlamp or by a pump laser. Pump lasers include excimer, frequency-doubled or frequency-tripled YAG, nitrogen, or CW ion lasers. Regardless of the source, large power densities, typically around 100 kW/cm^2, are required to pump a dye to a level where lasing is possible. It should also be noted that some success has been achieved by dissolving dyes into a host of resin which is solidified into solid acrylic. Such materials have been made to lase when pumped by another laser.

Laser Structure:

- Perhaps the simplest form of a dye laser is the flashlamp-pumped laser, which closely resembles a solid-state laser with a liquid-filled cell instead of a solid crystal rod.
- Flash-lamps may be either linear, with light from the lamp focused onto the dye cell using an elliptical reflector (in the same manner as that used for the YAG laser) or using a coaxial lamp.
- The coaxial configuration used in the first lasers of this type is constructed of a space created between the dye cell at the center of the laser and a larger outer jacket, as shown in the cross section of Figure 2.

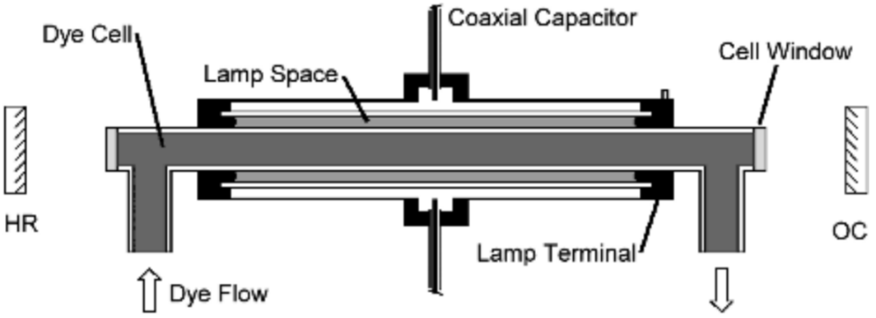

Figure 2: Flashlamp-pumped dye laser configuration.

- This space between the two quartz tubes is evacuated and filled with a low-pressure gas such as xenon.

<u>The coaxial approach offers an extremely low inductance path</u> for current if the discharge capacitor is also coaxial (i.e., the entire dye cell and lamp assembly is inserted into the center of a circular capacitor). This approach allows extremely fast discharges, with rise times of well under 1 ms, to be generated. The approach is not limited to the use of a coaxial capacitor, but that configuration certainly produces the fastest discharges.

Other configurations for a flashlamp-pumped dye laser include -

> A slab configuration in which the dye cell is formed between two slabs of glass that have a different index of refraction than the dye solution between the slabs. Total internal reflection confines light within the cavity, producing a long optical path and hence large amplification. This is similar to the confinement provided by various guiding layers in a practical semiconductor diode laser.

In a flashlamp-pumped dye laser, circulation of the dye is required to keep the temperature of dye across the cell consistent. If one region of the dye is warmer than another region, a thermal gradient develops, with the result being a difference of indexes of refraction of liquid in the dye cell which spoil the Q of the cavity, preventing laser oscillation.

Usefulness of flashlamp-pumped dye lasers -

> Flashlamp-pumped dye lasers feature large pulse energies and are a useful source for opthalmological procedures, where they may be used for retinal photocoagulation.

However, pulse rate is severely limited to the rate at which dye can flow through the dye cell to remove heat and suppress thermal gradients that may occur. In addition, electrical discharge paths in a flashlamp-pumped dye laser are critical and must be manufactured with extremely low inductance.

<u>The other type of dye laser is pumped by another laser</u> - such as an excimer or nitrogen laser as in Figure 3.

- These lasers are fairly simplistic and, compared to flashlamp-pumped types, exhibit unusually high gain, allowing the use of a short dye cell.
- In this arrangement, the pump laser beam is focused to a line on a dye cell using a cylindrical lens, as shown in Figure 4, in which the focused beam from a nitrogen or excimer pump laser strikes the side of a dye cell exciting dye molecules along the length of the cell.

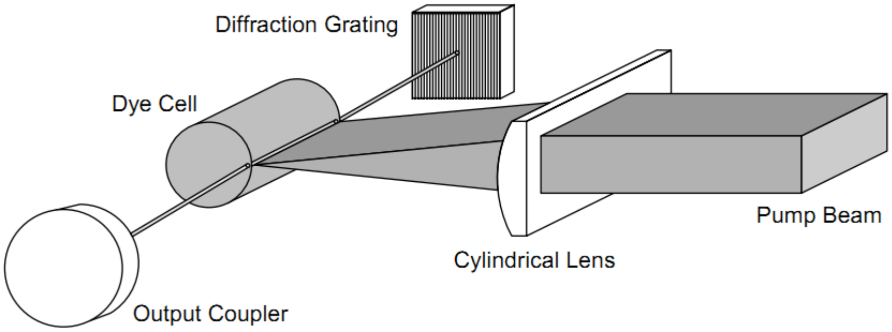

Figure 3: Flash Laser-pumped dye laser.

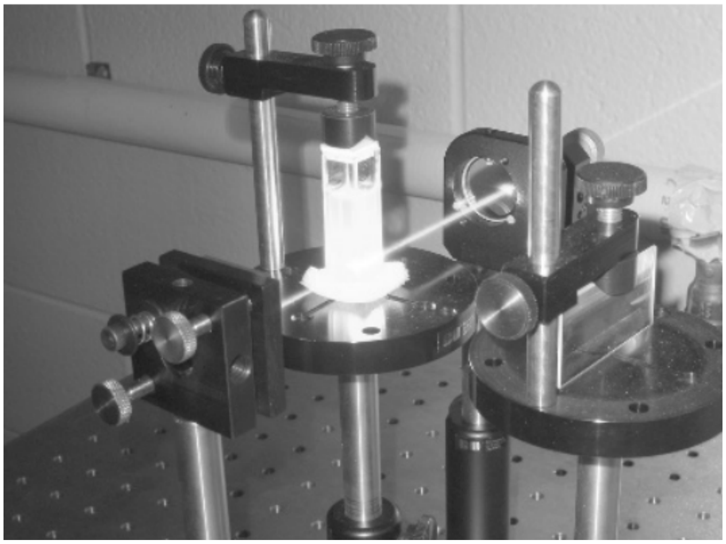

Figure 4: Excited dye cell.

In most cases <u>it is possible to operate the dye laser superradiantly by focusing the pump laser tightly onto the dye cell, but this is not desirable</u> since a dye laser operated in such a way is not tunable, losing the major advantage of this laser over other lasers, so pump light is not focused so tightly that superradiance occurs. Pump light striking the dye cell excites dye molecules in a narrow channel physically just inside the dye cell itself: Penetration of the pump light into the cell is minimal, and essentially all is absorbed within the first few millimeters of dye within the cell.

<u>Optics for a laser-pumped dye laser -</u>

- Usually consist of an output coupler and a diffraction grating. Although a simple mirror (HR) could be used in the cavity, a grating is invariably used to allow tuning of the laser across the wide gain bandwidth of the laser, the biggest advantage of a dye laser.
- In a practical dye laser a beam expander consisting of two lenses is placed between the dye cell and the diffraction grating to utilize more of the grating area.
- An etalon may also be placed in the optical path to reduce spectral width.
- Finally, a MOPA configuration may be used in which a separate amplifier is placed in front of the oscillator (complete with wave- length selector). The configuration for a complete dye laser with narrow spectral output width is shown in Figure 5.

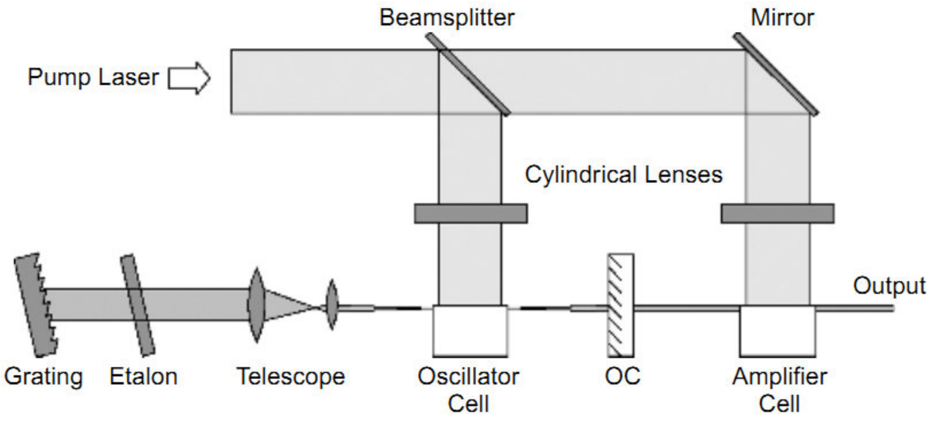

Figure 5: Optics for a dye laser.

- The pump laser is usually a nitrogen or excimer laser emitting in the UV range, but frequency-doubled YAG lasers may also be used. Because the pump laser is pulsed, the dye laser also has a pulsed output, but it is possible to build a CW dye laser pumped by a CW laser source such as an ion laser.

> <u>In this case the biggest problem becomes heat management and degradation of the dye itself</u>. Both problems are alleviated by forming the dye into a continually flowing sheet of liquid called a laminar flow.

- Flowing dye is pumped through a nozzle to create a broad, flat stream onto which pump laser light (usually from an argon-ion laser given that many laser dyes absorb strongly in the violet-to-green band where the argon-ion laser has the strongest output) is focused by a lens (or a concave mirror) onto the surface of the flowing dye.
- In a manner similar to that of the laser-pumped arrangement described previously, a column of excited dye molecules serves as the gain medium, which, is off-axis (usually at the Brewster angle) from the axis of the optical resonator.
- A typical CW dye laser arrangement is shown in Figure 6. Like most dye lasers, intracavity wavelength selectors are also often included (although they are not shown in the figure).

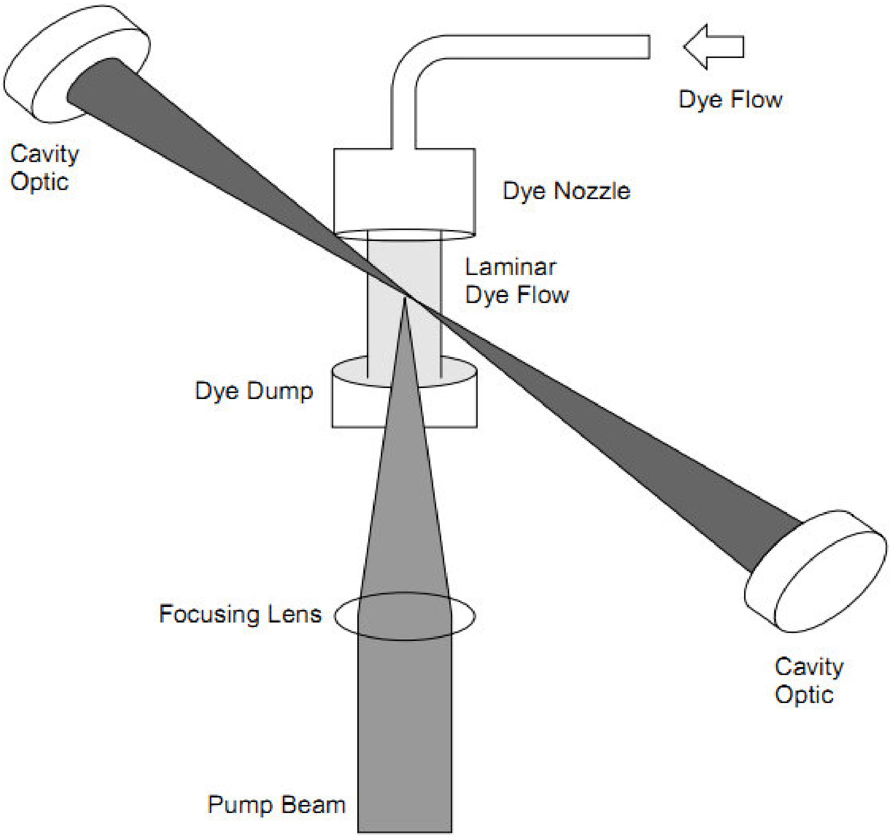

Figure 6: CW dye laser.

Aside from heat removal (required when the pump laser is a 10-WCW argon-ion laser!), dye flow helps suppress the effects of triplet absorption in the dye by ensuring a fresh supply of dye in the area irradiated by pump laser light. Fast dye flow is hence required to ensure that dye molecules are exchanged before triplet absorption becomes problematic and affects lasing action.

Optics and Cavities:

Most dye lasers are used for their tunability over wide wavelength ranges, and as such, most lasers have integral wavelength selectors in the cavity.

- Depending on the application, a simple grating may be sufficient to render a spectral output width.
- Regular diffraction gratings diffract incident light into many orders, so reflectivity of this element as a cavity optic is generally poor. As such, the laser must be operated at a high gain, sometimes close to superradiance, resulting in a broad spectral output.

To increase reflectivity, a special type of grating called an **echelle grating** may be used which is designed to have a reflecting surface as large as possible. Such gratings can reflect up to 70% of incident light into one order.

- Further enhancement of the laser may be accomplished by using a beam-expanding telescope in the cavity.
- Aside from allowing the use of a larger grating area than the normally tiny beam emitted from the dye cell, the telescope can also collimate the highly divergent beam exiting from the dye cell.
- Without collimation the angular spread of light striking the grating limits the resolution possible with the grating alone.
- In addition to a diffraction grating, an etalon is frequently included to reduce output bandwidth.

  - A tilted Fabry–Perot etalon between the telescope and the grating greatly reduces the spectral width of the output.
  - The etalon is placed in this manner to ensure that the beam passing through it is collimated, a requirement for proper operation.
  - Etalons may be fine-tuned by changing the angle within the cavity or by changing the pressure of the gas (usually, air or dry nitrogen) between the plates of the etalon. The change of pressure results in a change of refractive index and hence a shift in the resonant frequency of the device.
  - As well, etalons may be fabricated from a solid piece of quartz with reflective coatings on both sides. In this case, angle or temperature tuning may be used.
- Since the gain of a dye laser is generally large, output couplers are usually plane reflectors with reflectivities below 50%.

<u>Another popular use of a dye laser -</u>

> It is used to produce ultrashort modelocked pulses. Modelocking requires an intracavity switch such as a passive saturable absorber or an EO modulator, usually a Pockels cell.

Output Characteristics:

The output characteristics of a dye laser are highly dependent on the optics employed.

- A laser employing broadband optics would feature a naturally broad spectral width, typically spanning almost the entire range of the dye (especially in a laser-pumped dye laser, in which gain is usually large); this can be as large as 100 nm. A laser with such characteristics is not particularly useful, so wavelength selection is invariably employed.

- Use of a diffraction grating alone as a wavelength selector (with suitable beam- expanding optics allowing utilization of a large area of the grating surface) renders a spectral width of 0.01 nm, which is suitable for many applications, but to reduce linewidth an intracavity etalon is often included in the optical path.
- Use of an etalon along with a diffraction grating can render spectral widths as low as 0.0005 nm. Such linewidths are required when a dye laser is used as a tunable laser source for spectroscopy.
- Etalons may be angle- or pressure-tuned, with pressure tuning preferred for simplicity.
- As a modelocked laser, dye lasers have produced the shortest pulses produced from any laser source.
- The wide gain bandwidth of a typical dye allows the production of a series of extremely short pulses, in the femtosecond range.

Applications:

- As a source for spectroscopy, the dye laser is ideal given the wide range over which tuning may be accomplished and the narrow spectral width of the output.
- It is used in situations such as atomic absorption spectroscopy, where the beam is passed through a sample in a cell or a hot gas such as exhaust gas from a flame or the gases burning inside the cylinder of an internal combustion engine.
- Compact flashlamp-pumped dye lasers are occasionally employed in the field of opthalmology for retinal photo- coagulation. Tunability allows the output to be optimized for the peak absorption wavelength of hemoglobin, and the pulses are short enough to coagulate blood with-out generating an explosive shock wave within tissue as Q-switched laser pulses can.

Conclusions:

A dye laser uses an organic dye as the lasing medium, usually as a liquid solution. Compared to gases and most solid state lasing media, a dye can usually be used for a much wider range of wavelengths. The wide bandwidth makes them particularly suitable for tunable lasers and pulsed lasers. Moreover, the dye can be replaced by another type in order to generate different wavelengths with the same laser, although this usually requires replacing other optical components in the laser as well.

Dye lasers are very versatile. In addition to their recognized wavelength agility these lasers can offer very large pulsed energies or very high average powers. Flashlamp-pumped dye lasers have been shown to yield hundreds of Joules per pulse.

Dye lasers are used in many applications including: astronomy (as laser guide stars), atomic vapor laser isotope separation, manufacturing, medicine, spectroscopy etc.