光電子學導論

(4) Laser Systems

郭艷光 Yen-Kuang Kuo

國立彰化師大物理系暨光電科技研究所

電子郵件: ykuo@cc.ncue.edu.tw

網頁: http://ykuo.ncue.edu.tw

Category of Laser Systems

1) **Gas Lasers (氣態雷射)**
   He-Ne Laser, Ar^+ Laser, CO_2 Laser, N_2 Laser, …
2) **Liquid Lasers (液態雷射)**
   Organic Dye Lasers, …
3) **Solid-State Lasers (固態雷射)**
   Ruby Laser, Nd:YAG Laser, Nd:Glass Laser, …
4) **Semiconductor Lasers (半導體雷射)**
   AlGaAs, InGaAsP, AlGaInP, InGaN, InGaAsN, …
5) **Other Lasers (其他雷射)**
   Chemical Laser, Free-Electron Laser, …

Typical Gas Laser Configuration

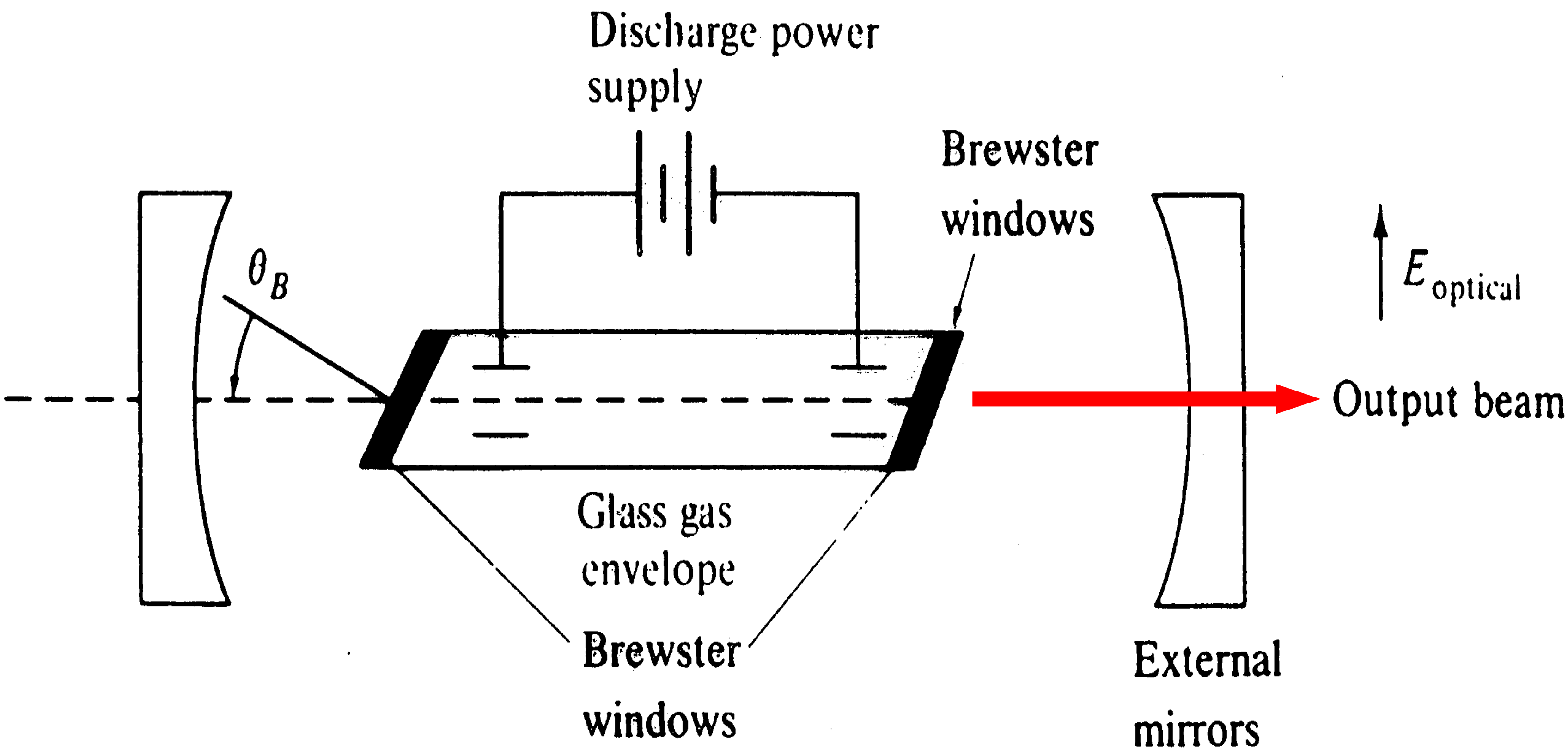


Figure 7-16 Typical gas laser.

He-Ne Laser

- The first CW laser, as well as the first gas laser, was one in which a transition between the 2S and the 2P levels in atomic Ne resulted in the emission of 1.15 μm radiation.
- Transitions in Ne were used subsequently to obtain laser oscillation at λ_0 = 0.6328 μm and at λ_0 = 3.39 μm.
- The operation of this laser can be explained as follows: a dc (or rf) discharge is established in the gas mixture containing, typically, 1.0 mm Hg of He and 0.1 mm Hg of Ne. The energetic electrons in the discharge excite helium atoms into a variety of excited states. In the normal cascade of these excited atoms down to the ground state, many collect in metastable levels 2^3S and 2^1S. Since the metastable levels nearly coincide in energy with the 2S and 3S levels of Ne, they can excite Ne atoms into these two excited states.

Energy Levels of He-Ne Laser

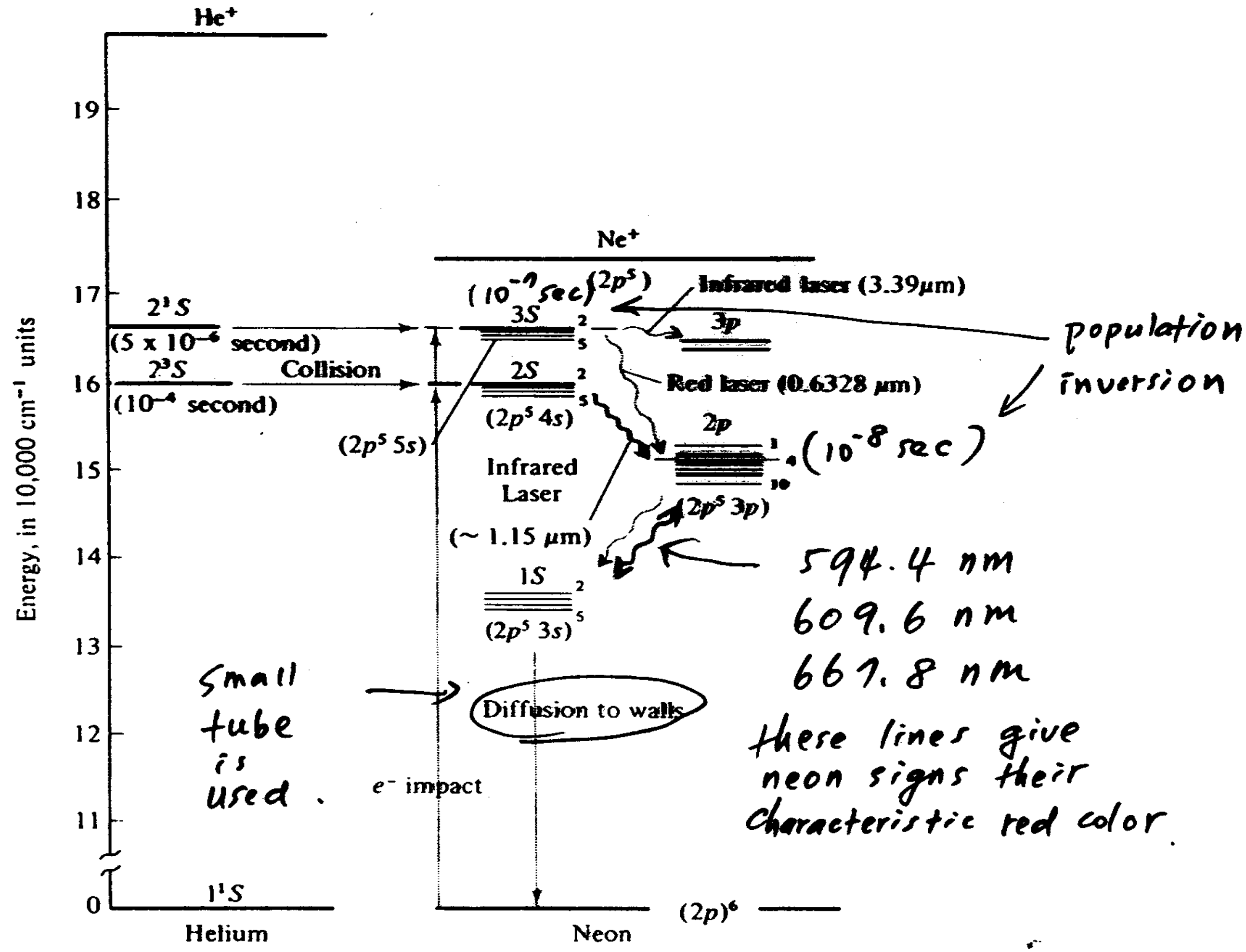


Figure 7-15 He–Ne energy levels. The dominant excitation paths for the red and infrared laser–maser transitions are shown. (After Reference [11].)

Absorption and Fluorescence of Rhodamine 6G

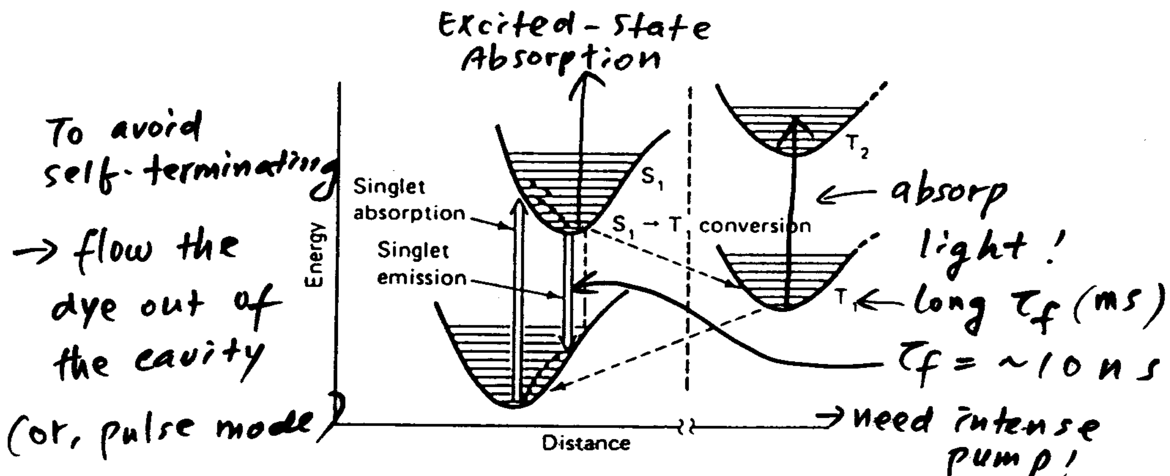


Figure 10.8 Energy-level diagram typical of a dye. (Data from Bass et al.[9])

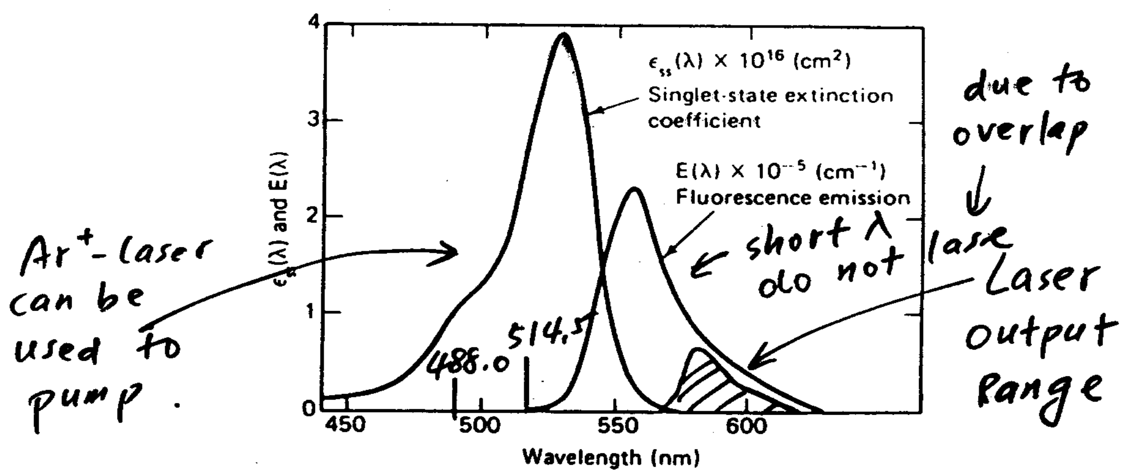


Figure 10.9 Singlet-state absorption and fluorescence spectra of rhodamine 6G obtained from measurements with a 10^{-4} M ethanol solution of the dye. (Data from Snavely.[8])

Configuration of Continuous-Wave (CW) Dye Laser

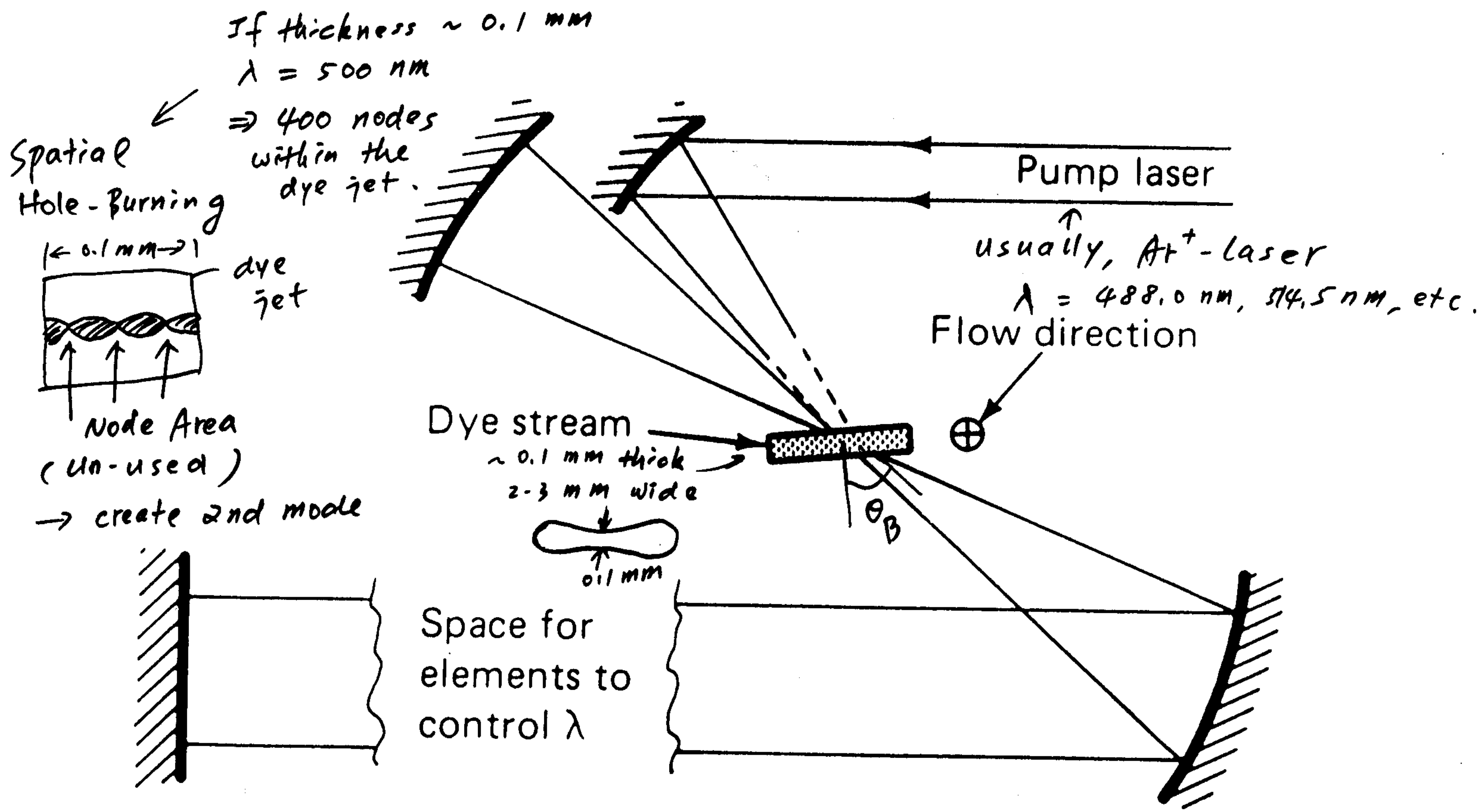


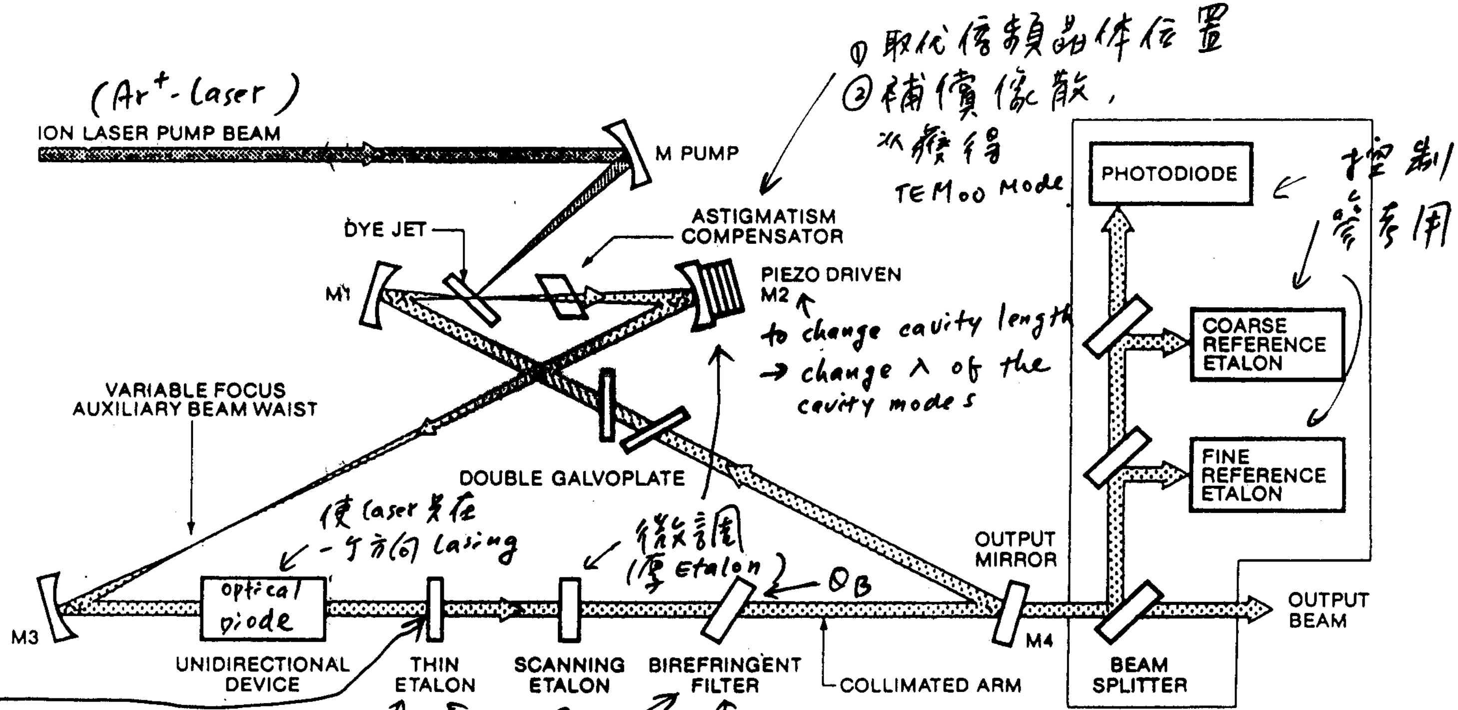
Figure 10.10 Typical configuration for a CW dye laser.

(Standing-wave configuration)

Wavelength Selection

- Some tunable lasers such as the dye, alexandrite, Cr:LiCAF, and Ti:sapphire lasers have very broad gain curves, in the operation of these lasers it is necessary to use a **wavelength selection** technique to restrict laser action to a specific wavelength and tune the laser output.
- Several different methods are available for providing the wavelength selection and tuning. These include (a) use of a **prism** inside the laser, (b) utilization of an adjustable optical **grating** within the laser, (c) use of intracavity **etalons**, or (d) use of one or more thin **birefringent plates** within the laser that are tilted at Brewster's angle.
- **Birefringent plates**: For a uniaxial crystal, the phase difference between the ordinary and extraordinary rays emerging from the crystal is proportional to the thickness of the plate and the difference between the two refractive indices ($n_o - n_e$), and inversely proportional to the wavelength. When the laser light has a wavelength corresponding to an integer number of full-wave retardations, the laser operates as if the filter were not present. At any other wavelength, the laser mode polarization is modified by the filter and suffers losses at the Brewster's surfaces.

Continuously Tunable Ring-Laser Cavity



θ ≅ 2-5°

FIGURE 13.23 ≤ 1 mm 粗調 有人使用 Thin Etalon

Example of a ring-laser cavity design with intracavity etalons, filters, and unidirectional devices, as used to provide single-frequency, continuously tunable, high-efficiency operation in a commercially available cw dye laser.

① if θ = 0°, 無法作高頻調 (二个方向厚度的变大)

② if θ = θB ⇒ 無干涉 effect ⇒ 不 work!

(Travelling-Wave Configuration) → $P_{TEM_{00}}$ can be more than 10 times higher!

standing wave configuration : $P_{TEM_{00}} \cong 100$ mW (max)

Optical Diode In Traveling-Wave Oscillator

- An optical diode, which consists of an optical activity plate and a Faraday rotator, is usually used in a traveling-wave oscillator to provide a unidirectional laser output.
- Optical activity plate: Certain optical media are found to cause a rotation of the plane of polarization of linearly polarized light passing through them.
- Faraday rotator: The Faraday effect is a property of transparent substances that causes a rotation of the plane of polarization with distance when the material is placed in a magnetic field, for light propagated along the magnetic field.
- When the clockwise and counterclockwise laser beams pass through the optical activity plate, the polarization direction of both the laser beams are rotated by an angle θ and $-\theta$ respectively. On the other hand, when the two laser beams pass through the Faraday rotator, the polarization direction of both the laser beams are rotated by an equal angle ϕ (rotated to the same direction). If the magnetic field is properly adjusted so that $\theta = \phi$, it is possible that the attenuation loss is experienced only in the counterclockwise direction, leaving the laser beam in the clockwise direction unattenuated. As a result, the laser will oscillate in a unidirectional direction. (Best design: $\theta = \phi = 45°$)

Ruby Laser – the first laser in this planet

- The $Cr{:}Al_2O_3$ (ruby) laser was the first working laser that was introduced by Theodore H. Maiman in 1960.
- Although neodymium doped YAG (Nd:YAG) laser has replaced ruby laser as general-purpose pulsed solid-state laser, ruby laser is still playing an important role in various applications.
- Ruby laser is capable of generating high-energy, visible red pulses (at 694.3 nm) which are powerful tools for removal of tattoos and disfiguring pigmented lesions from the skin.
- Ruby laser can also generate high-energy pulses from a compact package which makes the ruby laser a valuable tool for holographic nondestructive testing, double-pulse holography, and plasma diagnostics.
- The host of ruby laser is Al_2O_3 (sapphire), which is a unique host material since it is hard, durable, and chemically stable. The sapphire is transparent from 0.15 μm to 6.5 μm. When doped with chromium ions (Cr^{3+}), which substitute the Al^{3+}, the crystal becomes pink or red depending upon the doping concentration.

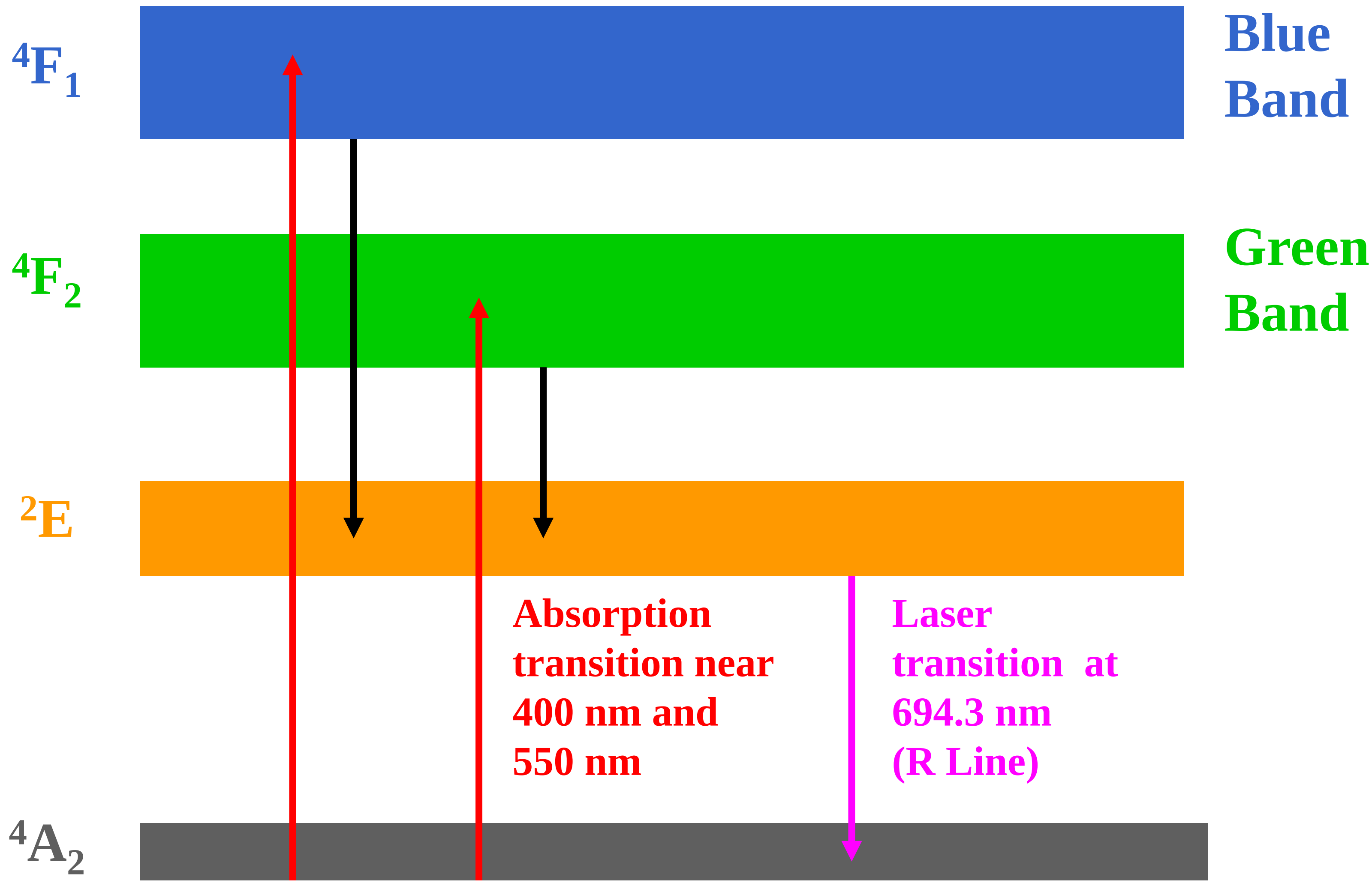
Characteristics of Ruby Laser

Chemical formula	$Cr:Al_2O_3$ (Cr-doped sapphire)
Color	Red or Pink
Type of crystal	Hexagonal, uniaxial
Main absorption peaks	400 nm and 550 nm
Laser wavelength at 25 ℃	694.3 nm (R_1 line)
Peak emission cross-section	2.5×10^{-20} cm^2
Fluorescence lifetime at 25 ℃	3.0 ms (4.3 ms at 77 K)
Density	3.98 g/cm^3
Refractive index at 694 nm	$n_o = 1.763$, $n_e = 1.755$
dn/dT	12.6×10^{-6}/℃
Melting point	2027 ℃
Thermal conductivity at 25 ℃	42 W/m℃

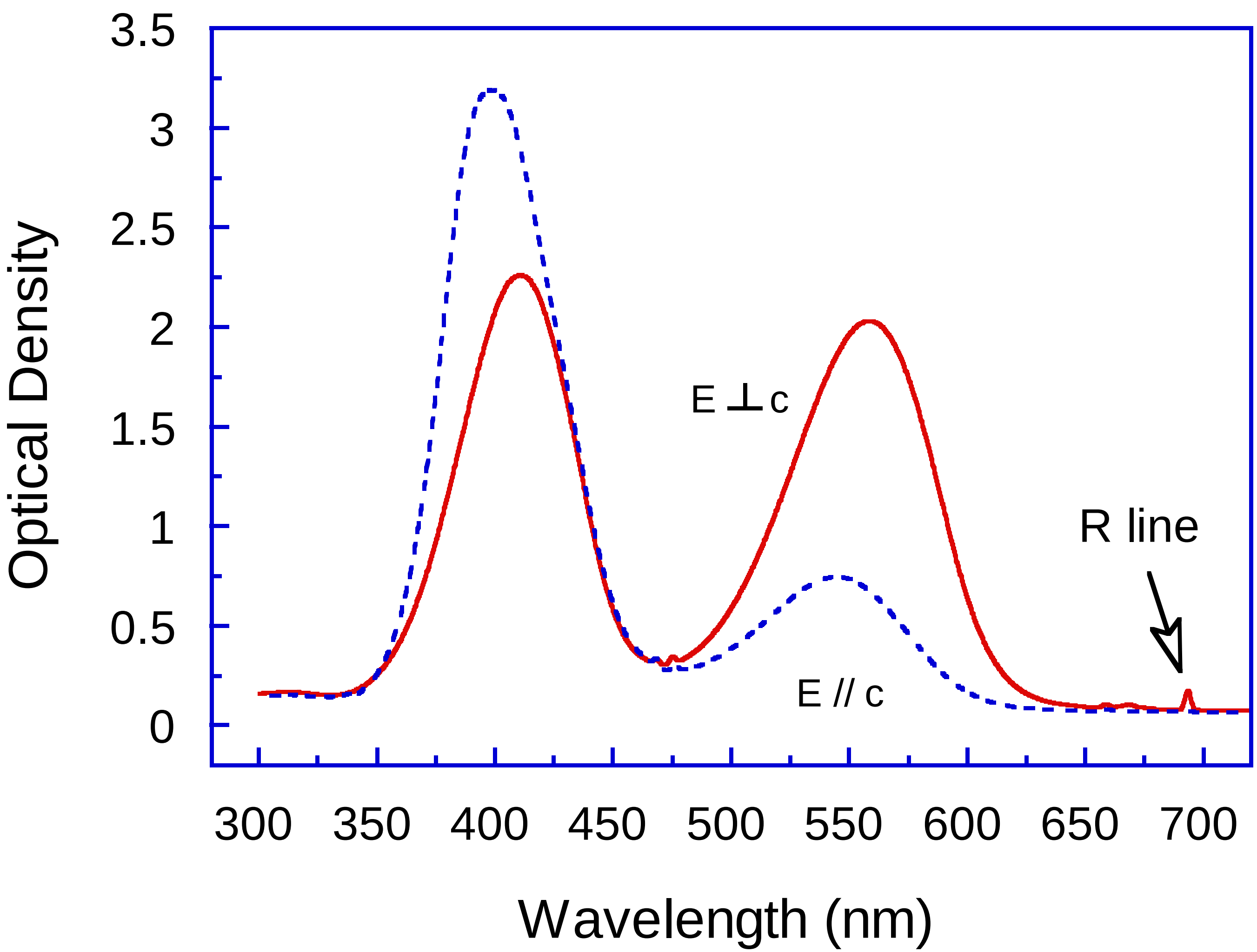
More About Ruby Laser

- the ruby laser crystal has two wide absorption bands peaking at 400 nm (blue band) and 550 nm (green band), which are assigned to the ${}^4A_2 \rightarrow {}^4F_1$ and ${}^4A_2 \rightarrow {}^4F_2$ transitions, respectively. It implies that flashlamp can be used as an efficient pump source for this laser.
- Since ruby laser is a three-level laser, ruby crystal has absorption near the laser wavelength at 694.3 nm, i.e. the so-called R line. This phenomenon indicates that the unpumped region of the ruby crystal is a potential loss source for the laser system and, therefore, attention is required to minimize this effect.
- The fluorescence lifetime of the ruby upper laser level (${}^2E$) is 4.3 ms at 77 K and 3.0 ms at room temperature. This long fluorescence lifetime benefits the ruby laser with high energy-storage capacity which is important for flashlamp pumping and Q-switched operation.

Energy Level Diagram of Cr^{3+} In Ruby



Absorption Spectra of Ruby



Characteristics of Nd:YAG Laser

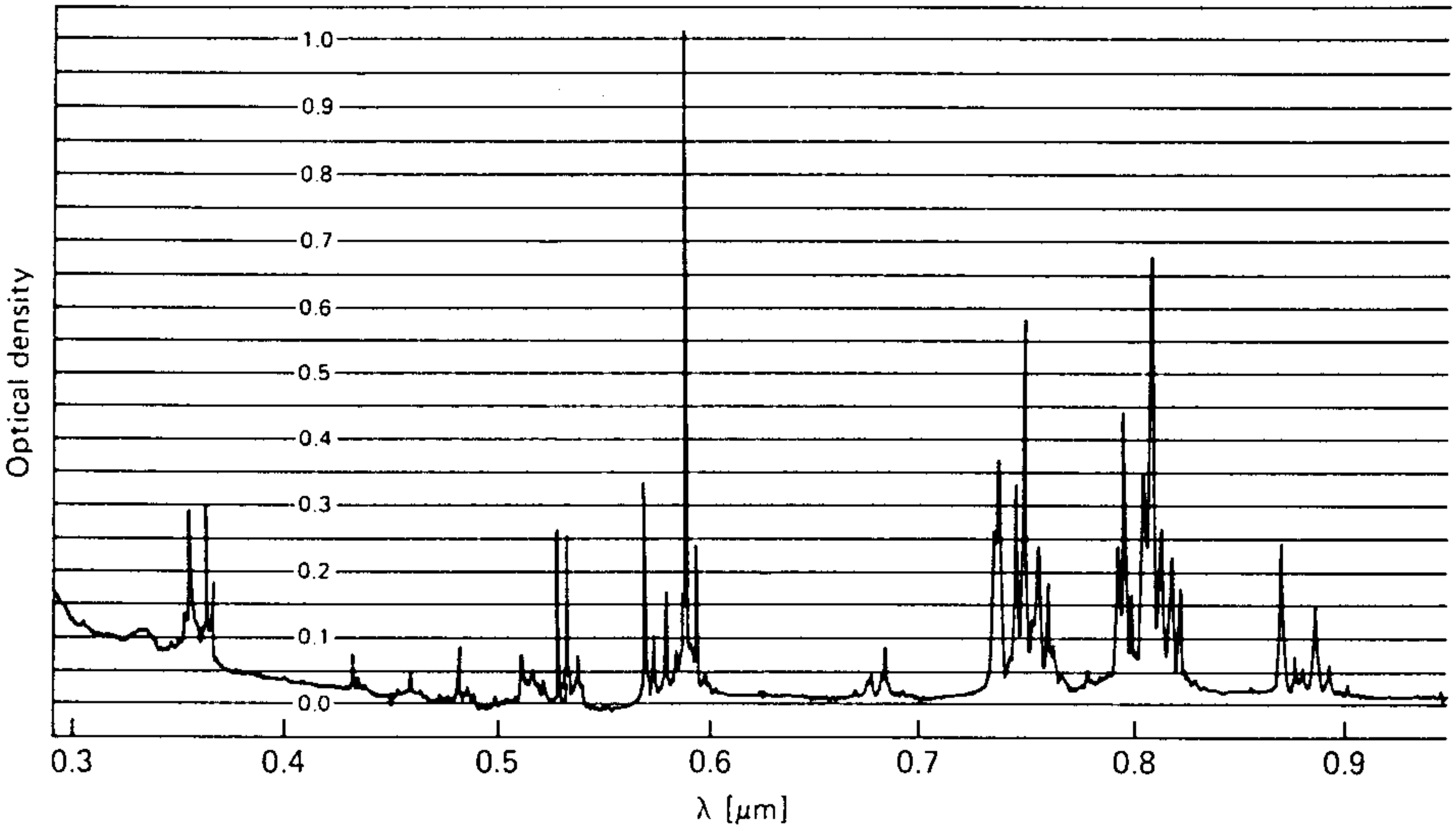
Chemical formula	$Nd:Y_3Al_5O_{12}$ (Nd-doped yttrium aluminum garnet)
Color	Light purple-blue
Type of crystal	Cubic, isotropic
Atomic % Nd	1.0
Laser wavelength at 25 ℃	1.064 μm (1064 nm)
Peak emission cross-section	2.8×10^{-19} cm^2
Fluorescence lifetime at 25 ℃	230 μs
Density	4.56 g/cm^3
Refractive index at 1064 nm	1.82
Melting point	1970 °C

- Nd:YAG has absorption near 810 nm
  ⇒ AlGaAs semiconductor laser can be used as a pump source
- Wavelength of Nd:Glass laser ≅ 1054 nm (depending on the host used)

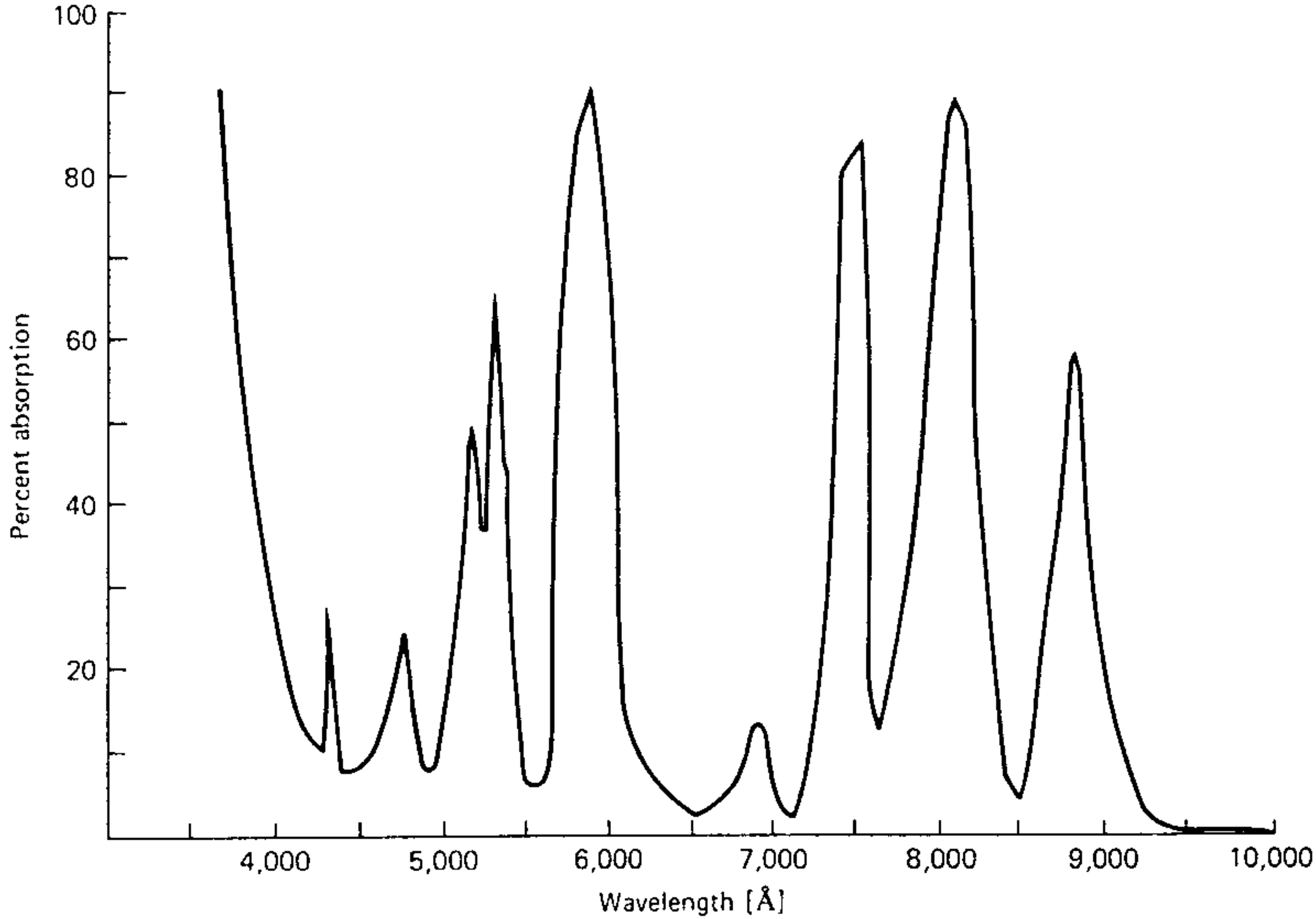
Characteristics of Nd:Glass Lasers

Glass Type / Spectroscopic Properties	$Q-246$ Silicate (Kigre)	$Q-88$ Phosphate (Kigre)	$LHG-5$ Phosphate (Hoya)	$LHG-8$ Phosphate (Hoya)	$LG-670$ Silicate (Schott)	$LG-760$ Phosphate (Schott)
Peak Wavelength [nm]	1062	1054	1054	1054	1061	1054
Cross Section [$\times 10^{20}$ cm]	2.9	4.0	4.1	4.2	2.7	4.3
Fluorescent Lifetime [μs]	340	330	290	315	330	330
Linewidth FWHM [nm]	27.7	21.9	18.6	20.1	27.8	19.5
Density [gm/cc]	2.55	2.71	2.68	2.83	2.54	2.60
Index of Refraction [Nd]	1.568	1.545	1.539	1.528	1.561	1.503
Nonlinear Index n_2 [10^{-13} esu]	1.4	1.1	1.28	1.13	1.41	1.04
dn/dt (20°–40°C [10^{-6}/°C]	2.9	−0.5	8.6	−5.3	2.9	−6.8
Thermal Coefficient of Optical Path (20°–40°C)[10^{-6}/°C]	+8.0	+2.7	+4.6	+0.6	8.0	–
Transformation Point [°C]	518	367	455	485	468	–
Thermal Expansion coeff. (20°–40° [10^{-7}/°C]	90	104	86	127	92.6	138
Thermal Conductivity [w/m]	1.30	0.84	1.19	–	1.35	0.67
Specific Heat [J/g · K]	0.93	0.81	0.71	0.75	0.92	0.57
Knoop Hardness	600	418	497	321	497	–
Young's Modulus [kg/mm^2]	8570	7123	6910	5109	6249	–
Poisson's Ratio	0.24	0.24	0.237	0.258	0.24	0.27

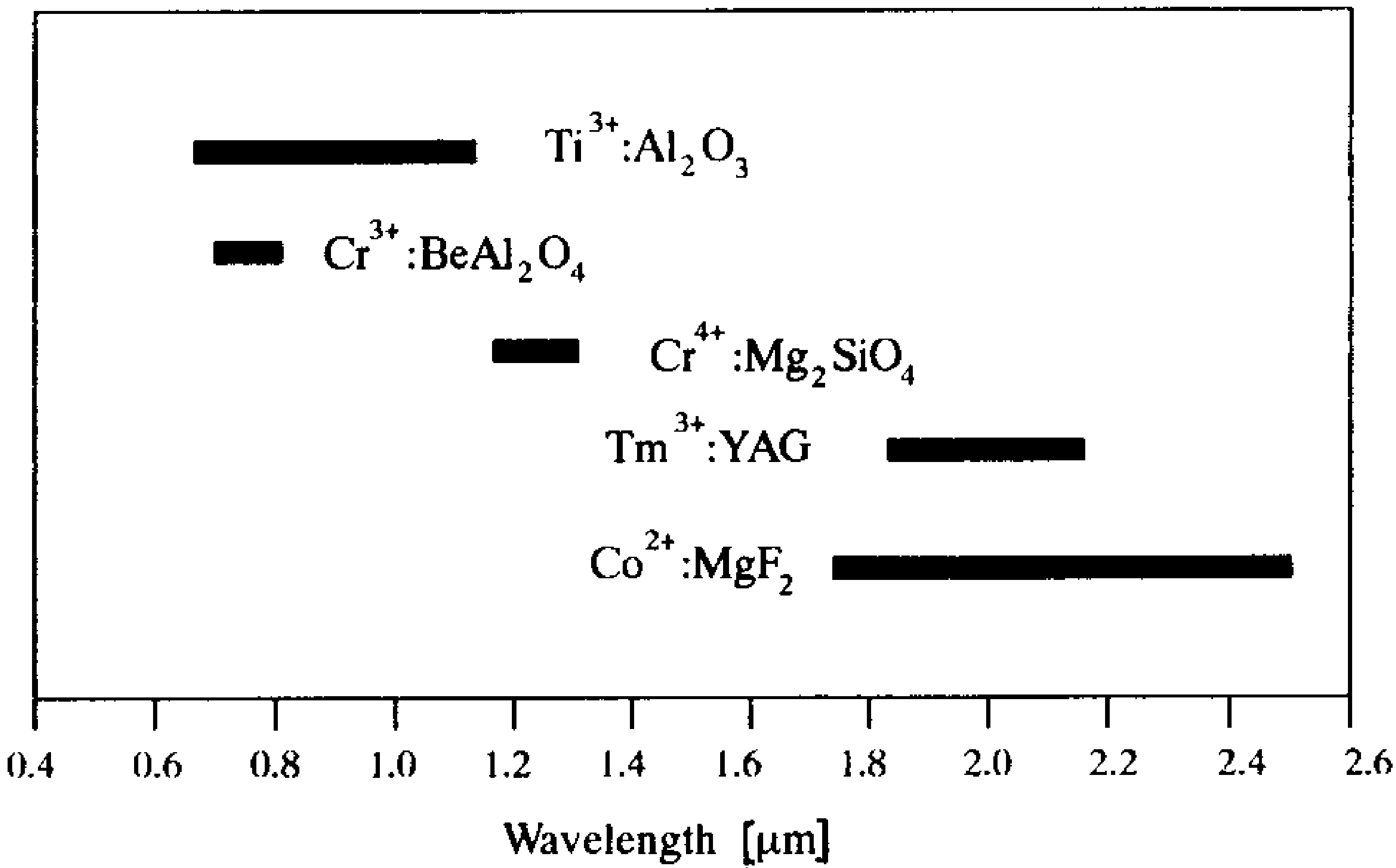
Absorption Spectrum of Nd:YAG



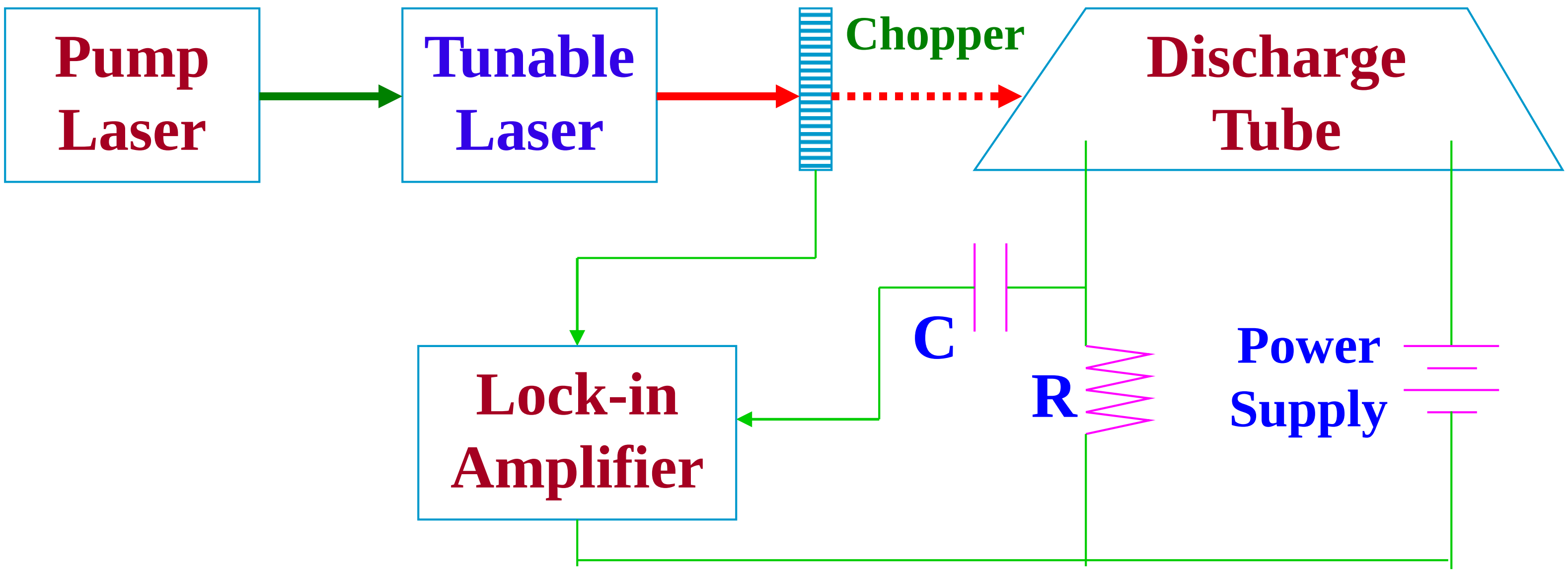
Absorption Spectrum of Nd:Glass



Spectral Range of Some Tunable Lasers



An Application of Tunable Lasers: Optogalvanic (光激放電) Spectroscopy



- The laser wavelength is continuously tuned until the laser light is absorbed by the molecules (or atoms) in the discharge tube, which results in a different ionization rate and hence the voltage across the discharge tube is varied.
- This small voltage variation is amplified and detected by the lock-in amplifier. This technique is very useful in spectroscopy (i.e., determination of energy levels).
- Since the voltage variation is proportional to the laser power, a high-power single-mode (ring-cavity) laser (e.g., dye laser, Ti:sapphire laser, etc.) is required.

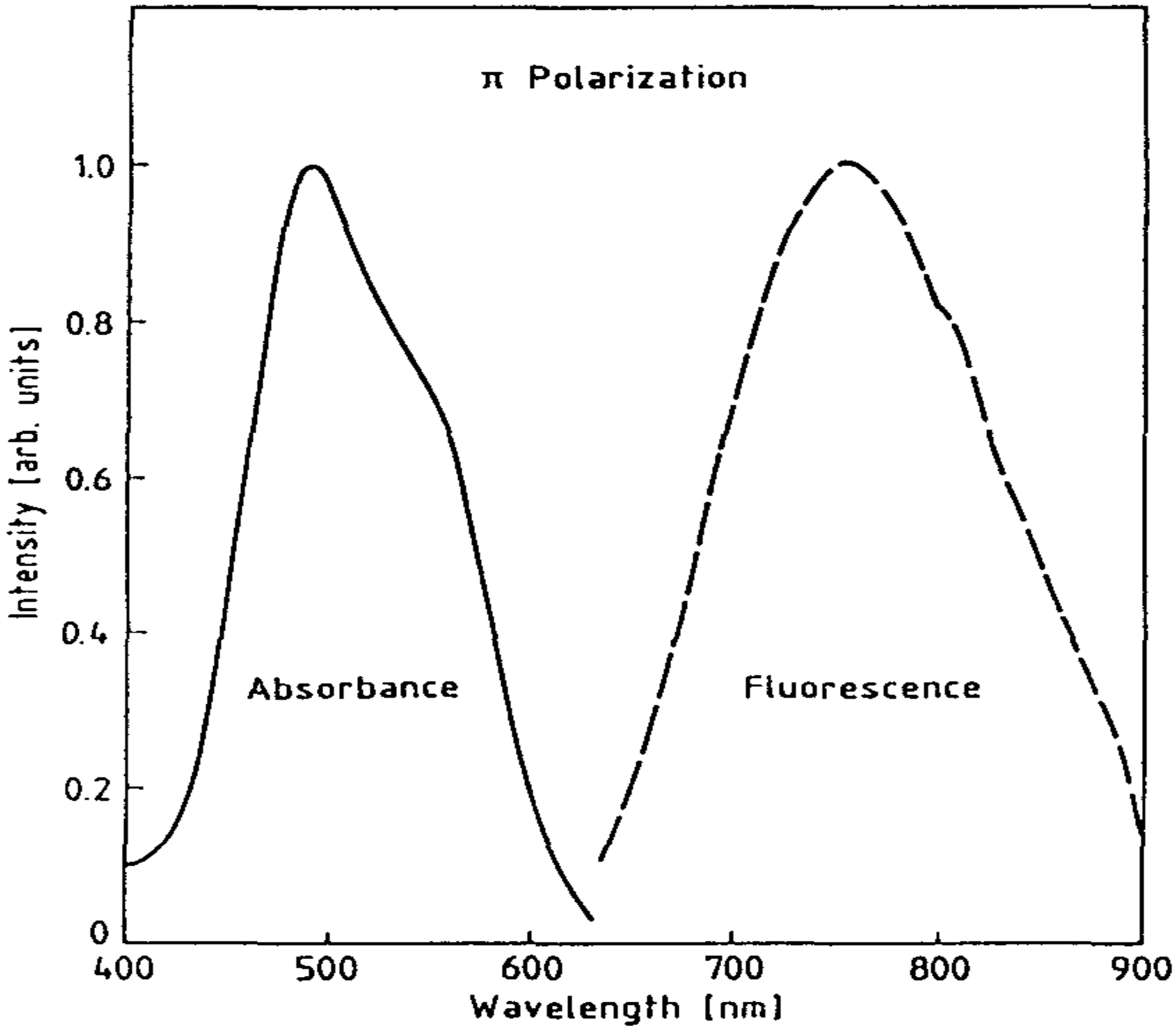
Ti:sapphire Laser – tunable between 670 and 1070 nm

- Since laser action was first reported by P. F. Moulton in 1982, the Ti:sapphire (Ti:Al_2O_3) laser, which has a broad tuning range of about 400 nm, has been the most widely used tunable solid-state laser.
- Crystal of Ti:sapphire exhibits a broad absorption band, located in the blue-green region of the visible spectrum with a peak around 490 nm. The Ti:sapphire laser is tunable from 670 nm to 1070 nm, with a peak of the gain curve around 800 nm.
- Commercial Ti:sapphire lasers are usually pumped by argon lasers to obtain continuous wave (cw) output, and by frequency-doubled Nd:YAG, Nd:YLF, or Nd:YVO_4 lasers for pulsed operation.
- Tuning ranges from about 700 nm to 1050 nm require several (usually three) sets of cavity mirrors. For pulsed solid-state lasers as pump source, output energies range from a few mJ at repetition rates of around 1 kHz, to 100 mJ per pulse at 20 pps.
- A very important application of Ti:sapphire lasers is the generation and amplification of femtosecond (10^{-15} sec) mode-locked pulses. A pulse width of a few tens of femtoseconds may be obtained easily from the Ti:sapphire lasers.

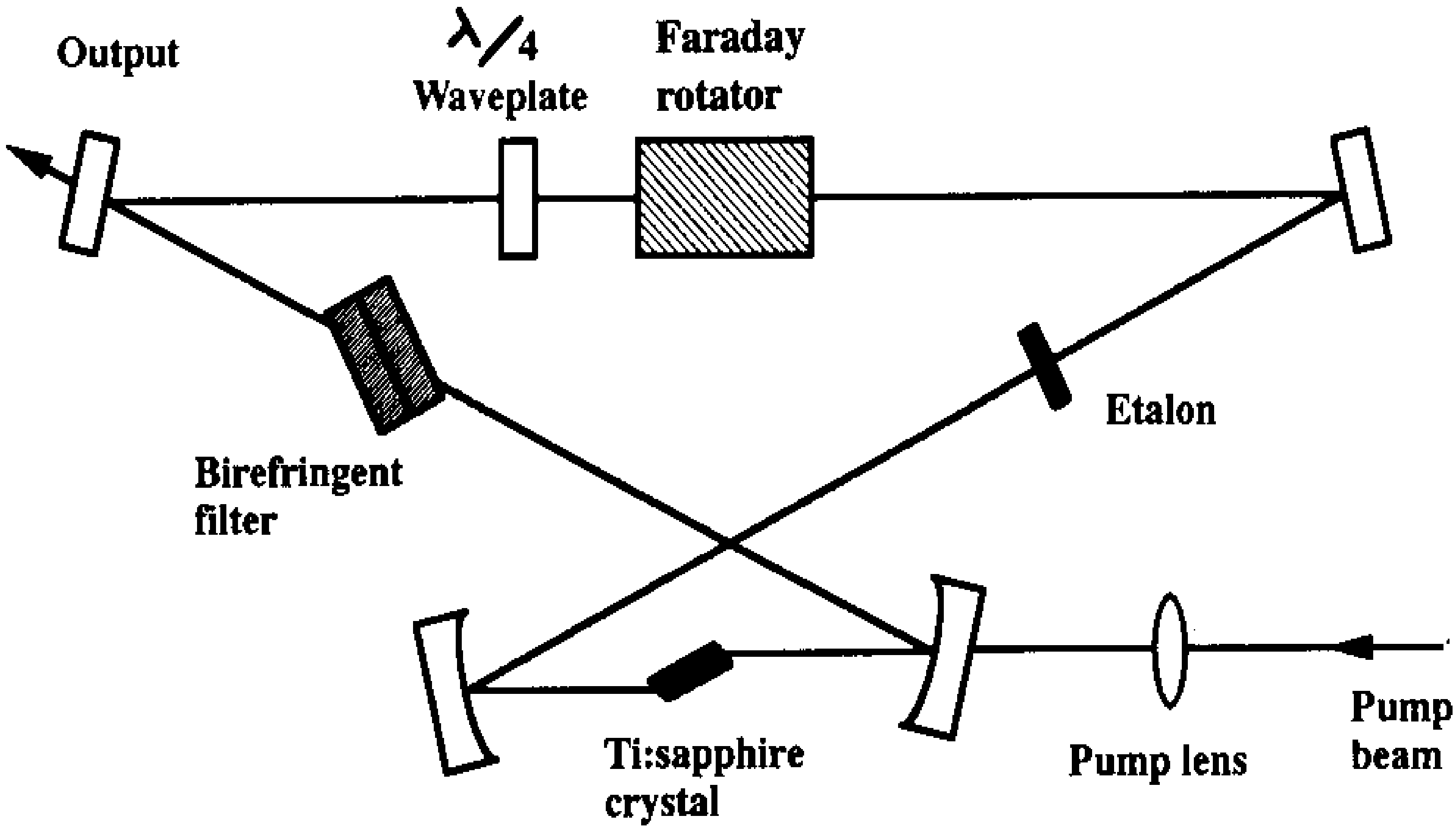
Characteristics of Ti:Sapphire Laser

Index of refraction	$n = 1.76$
Fluorescent lifetime	$\tau = 3.2\,\mu\text{s}$
Fluorescent linewidth (FWHM)	$\Delta\lambda \sim 180\,\text{nm}$
Peak emission wavelength	$\lambda_{\text{p}} \sim 790\,\text{nm}$
Peak stimulated emission cross section	
parallel to c axis	$\sigma_{\text{p}\parallel} \sim 4.1 \times 10^{-19}\,\text{cm}^2$
perpendicular to c axis	$\sigma_{\text{p}\perp} \sim 2.0 \times 10^{-19}\,\text{cm}^2$
Stimulated emission cross section	
at $0.795\,\mu\text{m}$ ($\parallel$ c axis)	$\sigma_{\parallel} = 2.8 \times 10^{-19}\,\text{cm}^2$
Quantum efficiency of converting a $0.53\,\mu\text{m}$ pump photon into an inverted site	$\eta_Q \approx 1$
Saturation fluence at $0.795\,\mu\text{m}$	$E_{\text{sat}} = 0.9\,\text{J/cm}^2$

Absorption and Fluorescence Spectra of Ti:Sapphire



Ring Configuration for a CW Ti:Sapphire Laser Cavity



Alexandrite Laser – tunable between 700 and 808 nm

- Alexandrite, discovered in 1980 by J. C. Walling *et al.*, is the common name of chromium-doped chrysoberyl ($Cr^{3+}:BeAl_2O_4$). Similar to sapphire (Al_2O_3), chrysoberyl ($BeAl_2O_4$) possesses hardness and high thermal conductivity that make it a good laser host.
- Alexandrite laser is attractive because it can be continuously tuned at least from 700 to 818 nm, can be Q-switched, and has a low threshold and high slope efficiency. The long fluorescence lifetime of 260 μs at room temperature and the broad visible absorption bands in alexandrite are of advantage for both flashlamp pumping and Q-switched operation. Laser-diode pumping for the alexandrite had been demonstrated by Scheps *et al.* in 1990. Therefore, a compact (Q-switched) alexandrite laser system is feasible.
- Alexandrite is biaxial with emitted light polarized parallel to the b axis. The broad absorption bands near 420 nm and 580 nm are assigned to the ${}^4A_2 \rightarrow {}^4T_1$ and ${}^4A_2 \rightarrow {}^4T_2$ absorption transitions, respectively.

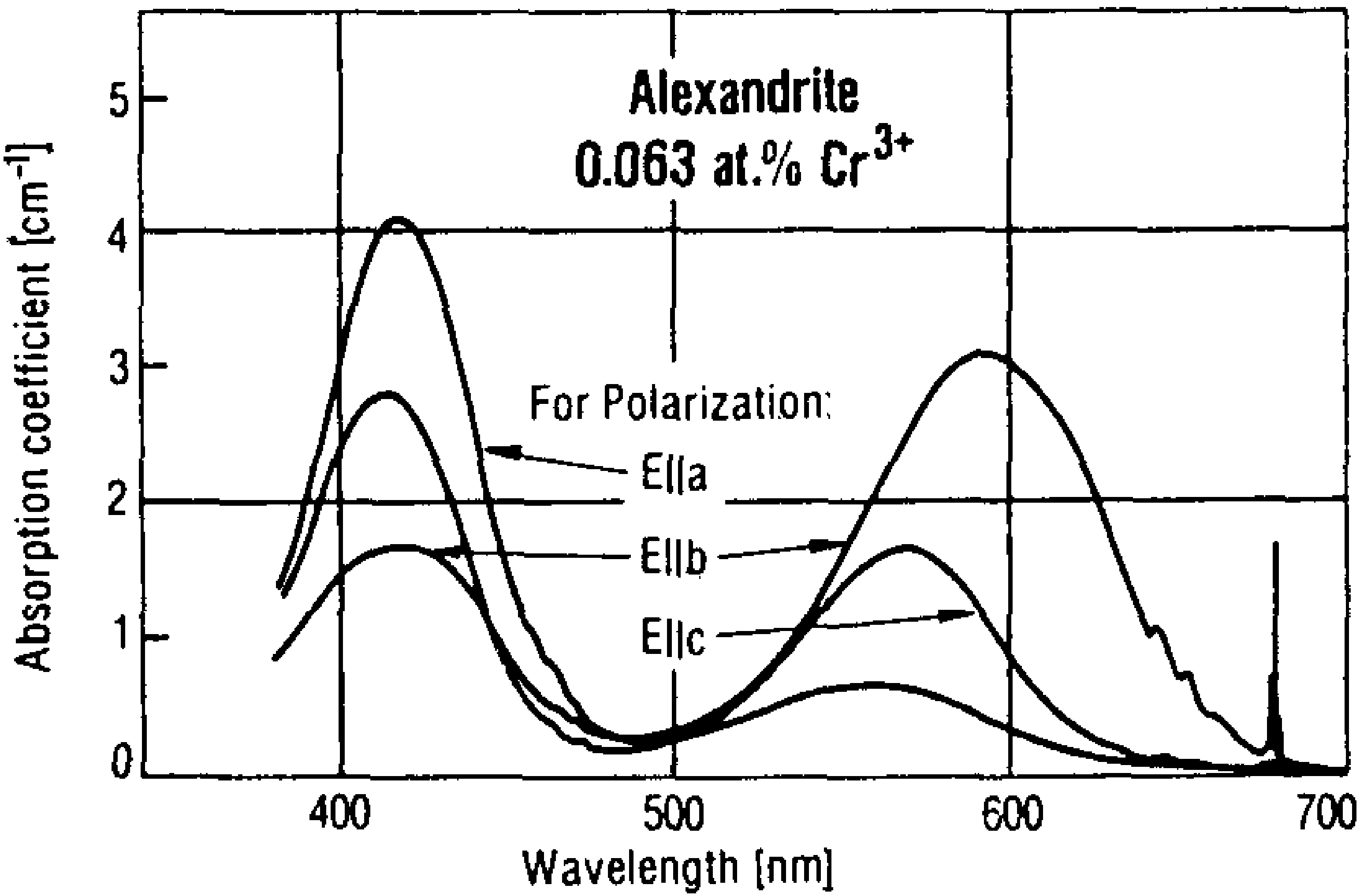
More About Alexandrite Laser

- Alexandrite can act either as a three-level laser system like ruby or as a four-level vibronic laser system. As a three-level system, laser action occurs on the R_1 line ($^2E \rightarrow {}^4A_2$) at 680.4 nm with an efficiency close to that of the ruby laser. The stimulated emission cross-section for this transition at room temperature is 2.9×10^{-19} cm^2, which is about ten times higher than that of the ruby laser at 694.3 nm.
- The main interest of alexandrite lies on its tunability. When operated as a 4-level vibronic system laser transition starts from $^4T_2$ and ends at the $^4A_2$ multiplets with ^2E serves as the energy storage level. There is coupling between ^2E and $^4T_2$ since they are close to each other ($\Delta E \approx 800$ cm^{-1}). It is interesting to note that alexandrite has better laser performance at elevated temperature. The effective emission cross-section increases from 7×10^{-21} cm^2 at 300 K to 2×10^{-20} cm^2 at 475 K. This is mainly due to the increase of the upper laser level population according to the Boltzman distribution. However, the fluorescence lifetime decreases when the temperature increases. A trade-off must be made for the Q-switched operation because long fluorescence lifetime is desired for energy storage.

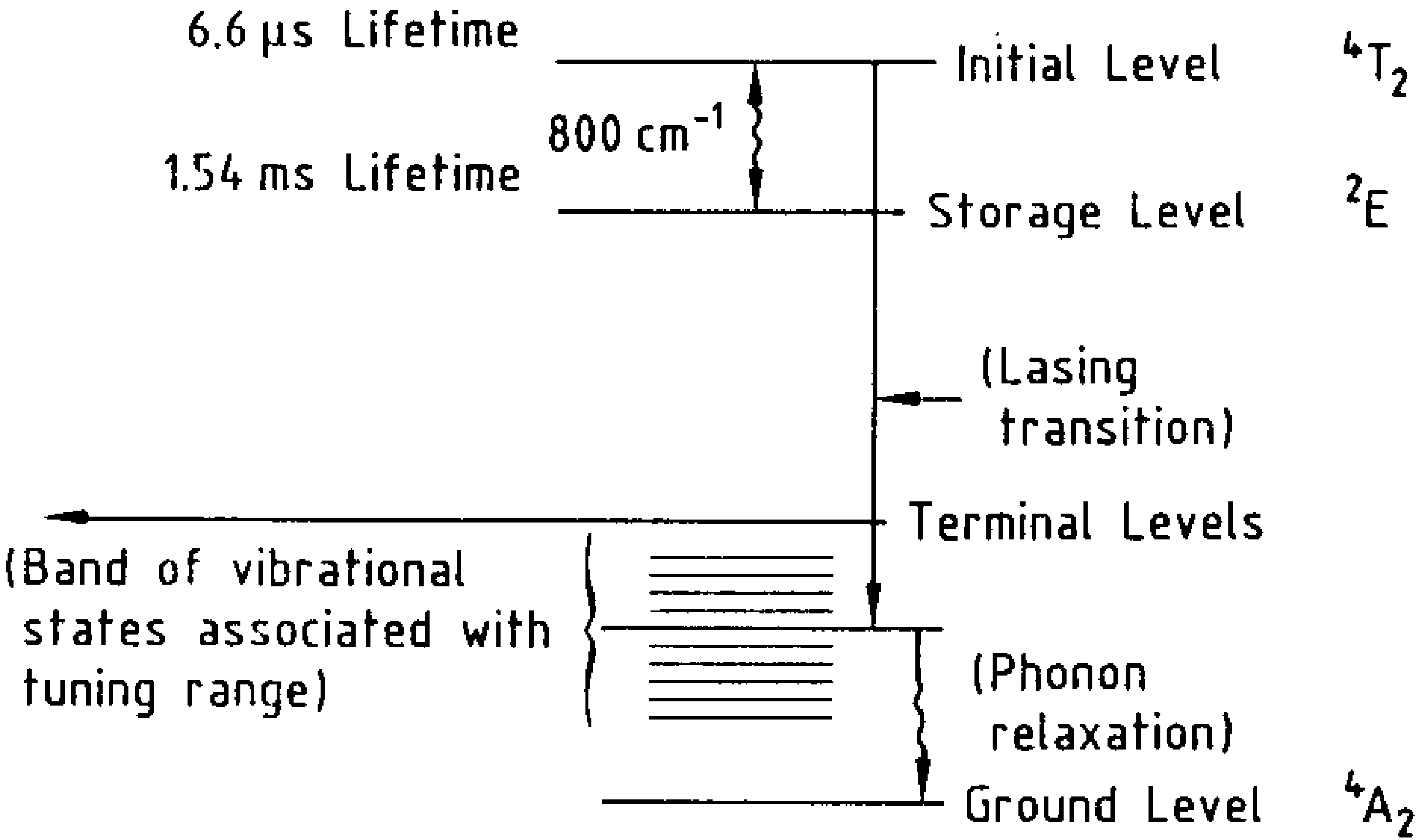
Characteristics of Alexandrite Laser

Chemical formula	$Cr:BeAl_2O_4$ (Cr-doped chrysoberyl)
Color	Brown
Type of crystal	Orthorhombic, biaxial
Main absorption peaks	420 nm and 580 nm
Laser wavelength at 25 ℃	700 nm to 818 nm (peaked near 750 nm)
Peak emission cross-section	0.7×10^{-20} cm^2
Fluorescence lifetime at 25 ℃	260 μs
Density	3.70 g/cm^3
Refractive index at 750 nm	1.7367 (//a), 1.7421 (//b), 1.7346 (//c)
dn/dT	9.4×10^{-6}/℃ (//a), 8.3×10^{-6}/℃ (//b)
Melting point	1870 ℃
Thermal conductivity at 25 ℃	23 W/m℃

Absorption Spectra of Alexandrite



Energy Level Diagram of Cr^{3+} in Alexandrite



Cr:LiCAF Laser – tunable between 725 and 840 nm

- In 1988, Steven A. Payne *et al.* discovered Cr^{3+}:$LiCaAlF_6$ (Cr:LiCAF). As a transition-metal vibronic laser Cr:LiCAF exhibits a broad emission spectrum, long lifetime of the upper laser level, low nonlinear refractive index, low thermal lensing, and low excited state absorption that make it a unique source for tunable or short pulse lasers.
- The fact that Cr:LiCAF has a relatively low melting temperature of 804 ℃, coupled with the natural abundance of the constituent elements, creates a good possibility of large-scale, inexpensive growth of laser-quality crystals.
- In Cr:LiCAF only one possible site for Al^{3+} which may be substituted by Cr^{3+}. Moreover, the Li^{+}, Ca^{2+} and Al^{3+} are very different from each other in terms of charge and size; therefore, disorder is not a significant problem for this material.

More About Cr:LiCAF Laser

- The two broad absorption bands near 425 nm and 625 nm, assigned to the $^4A_2 \rightarrow {}^4T_{1a}$ and $^4A_2 \rightarrow {}^4T_2$ absorption transitions respectively, permit efficient flashlamp pumping.
- The fluorescence spectra of the Cr:LiCAF, peaking near 765 nm, are assigned to the $^4T_2 \rightarrow {}^4A_2$ transitions. The fluorescence lifetime of the Cr:LiCAF is about 170 μs at room temperature. The long metastable lifetime makes both flashlamp pumping and Q-switched operation of the Cr:LiCAF laser superior to that of the Ti:Al_2O_3 laser (fluorescence lifetime is 3.2 μs at 25 °C) which is tunable over the same spectral range.
- The **tuning range** of the Cr:LiCAF laser had been shown to be at least from 725 nm to 840 nm with a **peak near 780 nm**. The tunability below 725 nm is limited by the internal absorption due to the $^4A_2 \rightarrow {}^4T_2$ transitions. At long wavelengths the tunability is limited by small stimulated emission cross-sections and excited-state absorption.

Characteristics of Cr:LiCAF Laser

Chemical formula	$Cr:LiCaAlF_6$ (Cr-doped LiCAF)
Color	Green
Type of crystal	Rhombohedral, uniaxial
Main absorption peaks	425 nm and 625 nm
Laser wavelength at 25 ℃	725 nm to 840 nm (peaked near 780 nm)
Peak emission cross-section	1.2×10^{-20} cm^2
Fluorescence lifetime at 25 ℃	170 μs
Density	2.99 g/cm^3
Refractive index at 694 nm	$n_o = 1.390$, $n_e = 1.388$
dn/dT	-4.6×10^{-6}/℃ (//c), -4.2×10^{-6}/℃ (⊥c)
Melting point	804 ℃
Thermal conductivity at 25 ℃	5.14 W/m℃ (//c), 4.58 W/m℃ (⊥c)

Cr:LiSAF Laser – tunable between 780 and 920 nm

- In 1989, Steven A. Payne *et al.* discovered Cr^{3+}:$LiSrAlF_6$ (Cr:LiSAF), which has a tuning range from 780 nm to 920 nm (peaked near 830 nm) and an excited lifetime of 67 μs. This material is very similar to Cr^{3+}:$LiCaAlF_6$ (Cr:LiCAF) which has a tuning range from 725 nm to 840 nm and a lifetime of 170 μs. Since the peak emission cross-section of LiSAF (4.8×10^{-20} cm^2) is four times larger than that of LiCAF, it generally performs better, and most of the recent laser work has concentrated on LiSAF.
- Peak emission of LiSAF is at a slightly longer wavelength as compared to Ti:sapphire, but there is a good overlap between the spectra. The major differences between the two crystals are the emission cross-section, fluorescent lifetime and the thermal and mechanical properties. Although the gain of Cr:LiSAF is approximately one order of magnitude lower than that of Ti:sapphire, it has a long enough lifetime of 67 μs to permit efficient flashlamp pumping.
- Cr:LiSAF is a rather soft and mechanically weak crystal with properties more related to glass than the far superior Ti:sapphire crystal.

Characteristics of Cr:LiSAF Laser

Table 2.13. Comparison of relevant laser parameters for Cr:LiSAF and Ti:Sapphire

	Cr:LiSAF	Ti:Sapphire
Peak wavelength [nm]	850	790
Linewidth [nm]	180	230
Emission cross section [10^{-19} cm^2]	0.5	4.1
Fluorescence lifetime [μs]	67	3.2
Refractive Index	1.41	1.76
Scattering loss [cm^{-1}]	0.002	0

Table 2.14. Comparison of thermal and physical properties of LiSAF and glass

	Cr:LiSAF	Glass
Thermal shock resistance [W/m$^{1/2}$]	$\sim$ 0.4	$\sim$ 0.4
Fracture strength [kg/mm^2	3.9	5
Thermal expansion coefficient ($\times 10^{-6}$/°C	22	11.4
Young's modulus [Gpa]	100	50
Microhardness [kg/mm^2]	197	$\sim$ 500
Fracture toughness [MPam$^{1/2}$]	0.4	0.45
Thermal conductivity [Wm^{-1}K^{-1}]	3.09	0.62

Absorption and Fluorescence Spectra of Cr:LiSAF