Nd:YAG Lasers

The first demonstration of laser action by T. H. Maiman was achieved in 1960 using ruby (Cr^{3+}:Al_2O_3). In 1960, L. F. Johnson and K. Nassau demonstrated the first solid-state neodymium laser, in which the neodymium ion was a dopant in calcium tungstate ($CaWO_4$). Elias Snitzer demonstrated the first neodymium-glass laser at American Optical that same year. However, it took another three more years before today's best choice of neodymium host for most commercial applications - yttrium aluminium garnet (YAG) - was demonstrated as a laser material by J. E. Geutic, H. M. Marcos, and L. G. Van Uitert. Solid-state lasers are now important candidates in laser applications, e.g. material processing, laser precision measurement, laser spectroscopy, laser medicine, and laser chemistry.

Compared to other lasers, the solid-state lasers have the following advantages:

(1) Various operation modes: The solid-state lasers can operate in CW, pulsed, Q-switched, and mode-locked modes to obtain high average power, high pulse repetition rate, high pulse energy, and high peak power. The average power of 4 kW has commercially been achieved with modular construction YAG lasers. The peak power of 10^{13} - 10^{14} W has also been obtained.
(2) Wavelength diversity: More than 100 solid-state materials can produce laser beams. Most of these beams range in the visible and near infrared regions of the electro-magnetic spectrum. The UV wavelengths have also been achieved by harmonic generators due to the advent of new non-linear materials and high beam quality obtained from diode-pumped lasers. Significant progress has been made in the development of tunable solid-state lasers.
(3) Convenient optical delivery system: Laser beams produced by some solid-state lasers can be delivered with optical fibre, which makes lasers more flexible and applicable in dangerous or difficult-to-access processing environments.
(4) More compact and lower maintenance compared to high power CO_2 lasers and excimer lasers.

1. Principle of operation

Figure 8 shows the energy-level diagram of a Nd:YAG laser. Lasing is dependent on the rapid transitions from the lower lasing level to the ground state by radiationless transition. When the rod temperature is low, these transitions will occur at a high rate. Hence, lasing efficiency depends mainly on cooling efficiency. Higher output powers can be achieved by having lower operating temperature. This explains why cooling systems are generally operated at temperatures just above the threshold of this effect.

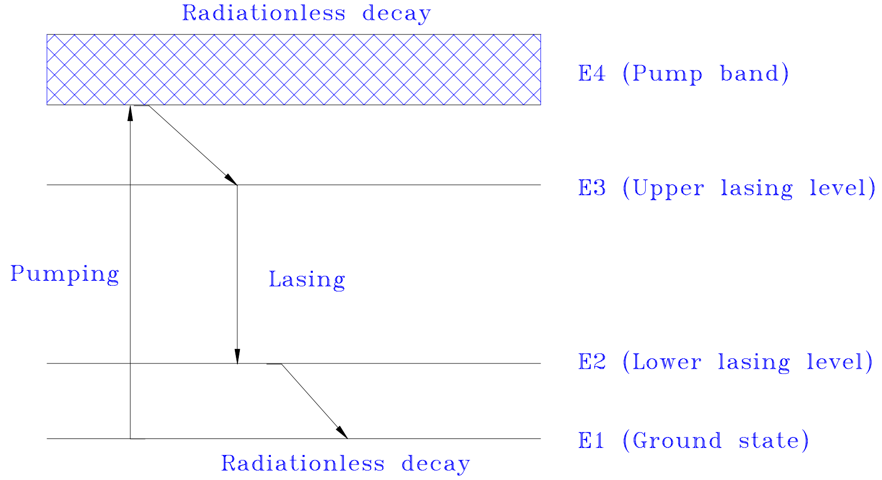


Fig. 1 Energy level system of Nd:YAG laser

In the laser pumping cavity, Nd:YAG crystals are excited by absorbing light from a krypton flash lamp. The crystal absorbs light energy in two 730 - 760 nm and 790 - 820 nm pumping bands which are provided by the krypton lamp. This causes the molecules in the crystal to excite to the E4 pump band shown. The molecules radiate heat in the E4 to E3 transition and the E2 to E1 transition. Subsequently, this heat has to be removed by cooling the crystal rod.

2 Basic Construction of Solid-state Lasers

A typical solid-state laser usually consists of a gain medium, a pumping cavity, an optical resonator, a cooling system and a power supply, as shown in Figure 2. The gain medium is placed in a gold-plated elliptical cross-section pumping cavity. Inside the cavity is an elliptical space with the rod (gain medium) at one focus of the ellipse and a flashlamp at the other focus. Ideally, all the light emitted by the lamp is coupled into the rod by the cavity. The optical resonator consists of two mirrors mounted separately from the lasing medium. The cooling system is necessary since most of the light energy from the lamp is lost as heat.

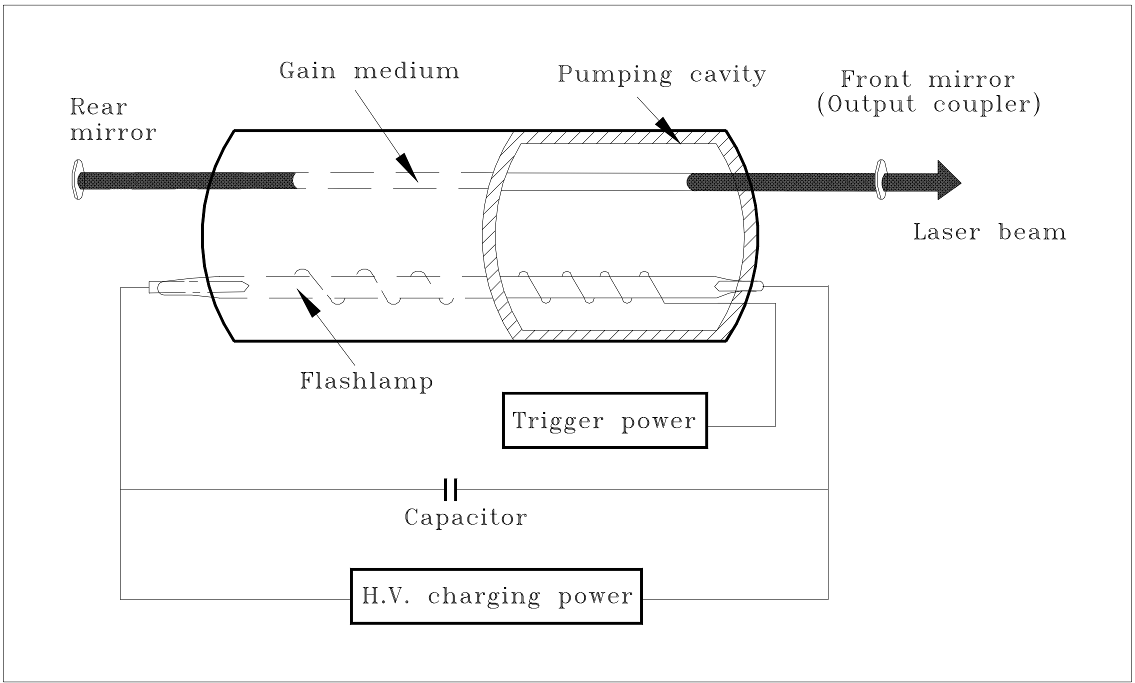
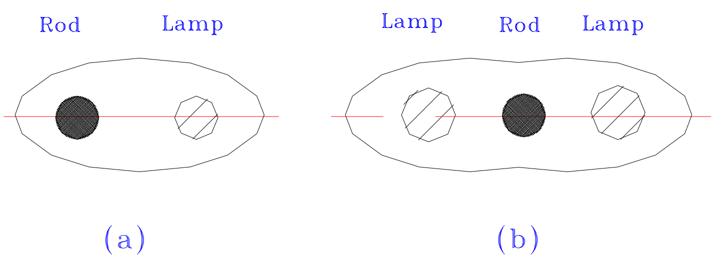


Figure 2 Basic construction of a solid-state laser

One of the most important elements in solid state lasers is pumping cavity. It, besides providing good coupling between the pumping source and the absorbing active material, is also responsible for the pump density distribution in the laser element which influences the uniformity, divergence, and optical distortion of the output beam. Depending on the shape of the active material and the type of pumping source used, pumping geometries can be broadly divided into systems in which the active material is side-pumped, end-pumped, or face-pumped. Fig. 3 shows some of the typical pumping cavities.



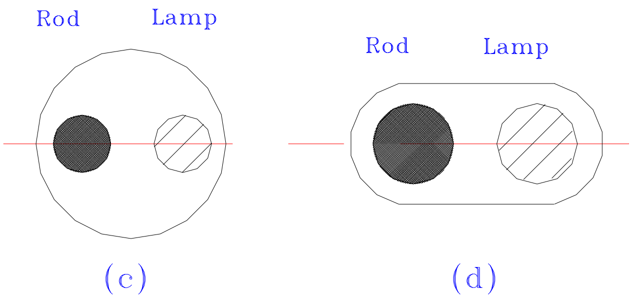


Fig. 3 Typical pumping cavities
(a) Single ellipse (b) Double ellipse (c) Circular cylinder (d) Close-wrap

Among the pumping cavities, the elliptical cavities have been most extensively discussed in the development of solid state lasers. In this configuration, a linear lamp and a laser rod, possibly with different radii, are placed at the foci of an elliptical cylinder, as shown in Fig. 3 (a).

The laser material is shaped into a cylindrical rod whose ends are round and polished to be plane parallel. When the rod is placed between two mirrors facing each other, and is strongly irradiated by an intense light source around it, laser is emitted. To minimise cooling problems, YAG rods with smaller diameter are usually used. The rod ends are usually anti-reflection coated for the Nd:YAG wavelength of 1064 nm. The rod ends are held in place and sealed by O-rings recessed in the ends of the rod holders to protect them from the pump lamp light.

3 Energy Transfer Processes in Solid-state Lasers

There are four processes involved during the energy transfer from electrical input to laser output, as shown in Figure 4, i.e. conversion of electrical input delivered to the pump source to useful pump radiation, transfer of the useful pump radiation emitted by the pump source to the gain medium, absorption of pump radiation by the gain medium and transfer of energy to the upper laser level, and conversion of the upper state energy to laser output. The transfer of flashlamp pump radiation to the laser medium is accomplished by means of a pump cavity. The transfer efficiency is a combination of the capture efficiency and the transmission efficiency. The capture efficiency is based on the geometrical shape of the pump cavity, diameter and separation of the pump source and laser rod. Therefore, the research on the geometry of the pump cavity is very important in attempting to improve the electro-optic (E-O) conversion efficiency for solid-state lasers.

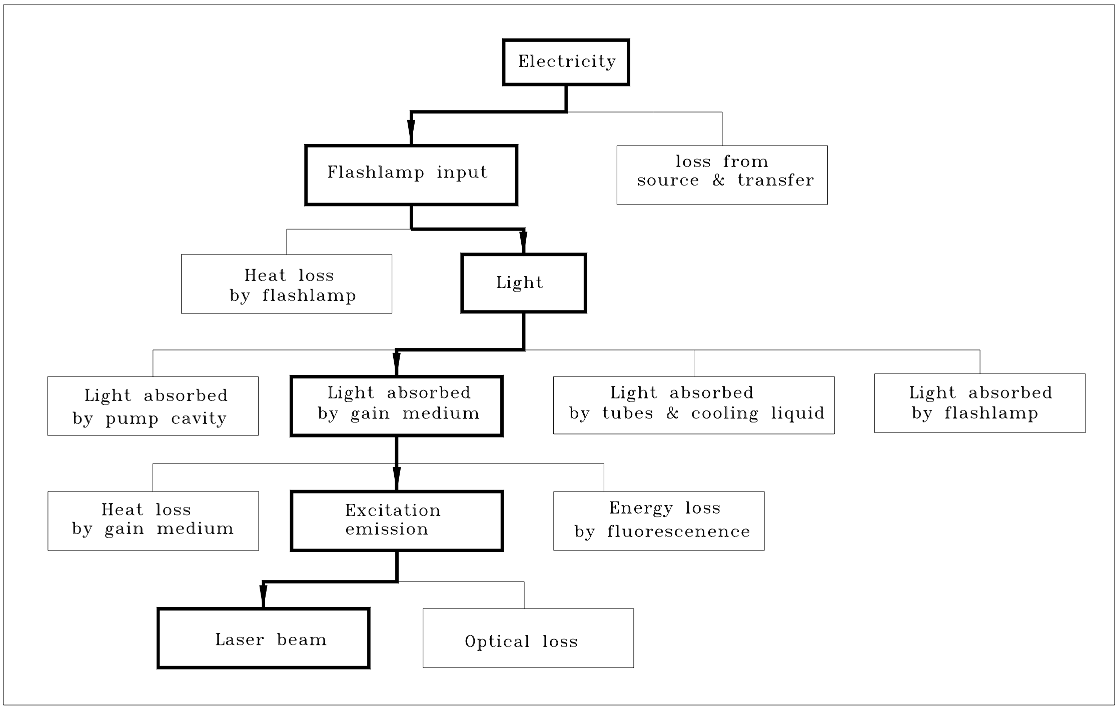


Figure 4 Schematic diagram of energy transfer in solid-state lasers

4 Thermal Phenomena in Laser Rods

In various applications of pulsed and CW Nd:YAG lasers, a lot of attention is being paid to the quality of the beam profile. This is particularly true in applications which require a constant spot size during laser processing. If a laser rod is pumped homogeneously on its surface, a parabolic temperature profile, and therefore a refractive index gradient from the centre to the surface of the rod, is built up. The Nd:YAG rod works like a focusing lens, whose focal length varies at different pumping powers.

The general steady-state temperature distribution in a solid is given by the three-dimensional Poisson equation. For the axisymmetric case of a rod with a constant heat conductivity this equation reads in cylindrical co-ordinates as follows:

$$\frac{d^2}{dr^2}T(r,z)+\frac{1}{r}\frac{d}{dr}T(r,z)+\frac{d^2}{dz^2}T(r,z)+\frac{q(r,z)}{K(T)}=0 \qquad (1)$$

where $q(r, z)$ is the heat source density and $K(T)$ is the heat conductivity in the rod. For crystals with a moderate temperature rise, such as Nd:YAG, $K(T)$ is normally assumed to be constant. For crystals with lower heat conductivities and hence, higher heat loads, $K(T)$ is given in the first approximation by

$$K(T)=K_0\frac{T_0}{T_0+\Delta T} \qquad (2)$$

where T_0 indicates the reference temperature of the cooling water, ΔT the difference to T_0, and K_0 the heat conductivity of the solid at T_0.

With the boundary condition $T(r_0)$ for $r = r_0$, where $T(r_0)$ is the temperature at the surface of the rod and r_0 is the radius of the rod, it follows that

$$T(r) = T(r_0) + \left(\frac{Q}{4K}\right)\left(r_0^2 - r^2\right) \tag{3}$$

where Q is a rate per unit volume in which heat is uniformly generated, which can simply be given by

$$Q = \frac{P_a}{\pi r_0^2 L} \tag{4}$$

where the power P_a is the total heat dissipated in the rod and L is the length of the rod.

Figure 5 shows the radial temperature profile in a Nd:YAG rod calculated from Equation (3). Here P_a is 300 W, r_0 is 2 mm, L is 100 mm, K is 0.13 W.cm^{-1}.K^{-1} [2.20], and $T(r_0)$ is 60°C. It is clear that the temperature profile is parabolic, with the highest temperature of 84.5°C attained at the centre of the rod.

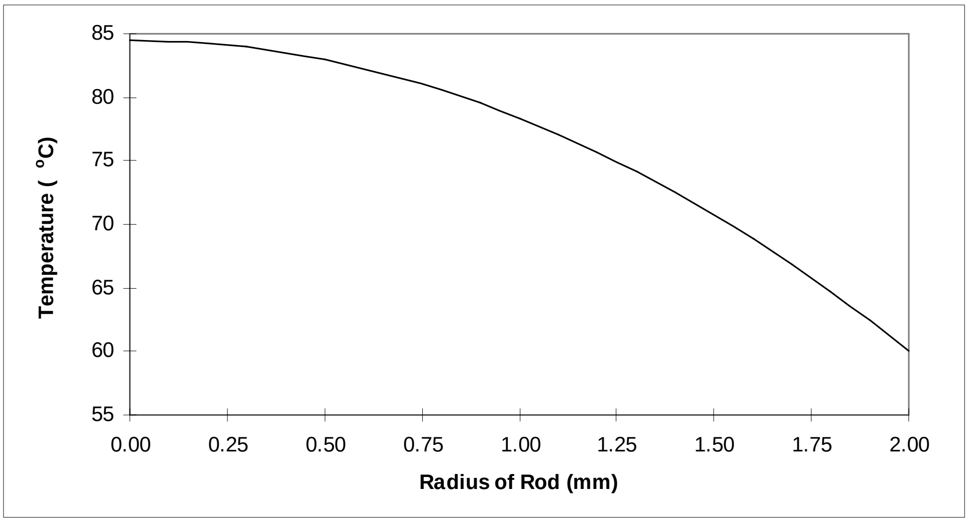


Figure 5 Radial temperature distribution
within a Nd:YAG rod as a function of radius

The parabolic temperature and phase error profiles by uniform heating was first studied by Koechner in uniformly pumped Nd:YAG rods. Then many researchers carried out further researches on the thermal effects. It is found that the temperature gradients generate mechanical stresses, strains, and displacements in the rod. Furthermore, the inhomogeneous distributions of temperature, strain, and displacement cause a change of the refractive index at each point of the rod. Since the refractive index in a laser rod shows a quadratic variation with radius, an optical beam propagating along the rod axis would suffer a quadratic spatial phase variation. This perturbation is equivalent to the effect of a spherical lens, called “thermal lensing effect” or “thermal lens”. Since the change of refractive index due to thermal strain is dependent on the polarisation of light, the focal lengths of the thermal lens for the radial (f_r) and tangential orientations (f_ϕ) are given, respectively by

$$f_r = \frac{KA}{P_a}\left(\frac{1}{2}\frac{dn}{dT} + \alpha C_r n_0^3 + \frac{\alpha r_0\left(n_0 - 1\right)}{L}\right)^{-1} \tag{5}$$

and

$$f_\phi = \frac{KA}{P_a}\left(\frac{1}{2}\frac{dn}{dT} + \alpha C_\phi n_0^3 + \frac{\alpha r_0\left(n_0 - 1\right)}{L}\right)^{-1} \tag{6}$$

where A is the cross-sectional area of the rod, α is the thermal coefficient of expansion, n is the refractive index, C_r and C_ϕ are the photoelastic coefficients for the radial and the tangential components of the polarised light, n_0 is the refractive index at the centre of the rod, and $P_a = \eta P_{in}$ (here η is an efficiency factor which relates the electrical input power to the flashlamp, P_{in}, to the power dissipated as heat in the rod).

Figure 6 shows the focal length of the thermal lens as a function of input power. Here K = 0.13 Wcm^{-1}K^{-1}, $\frac{dn}{dT}$ = 7.3×10^{-6} K^{-1}, α = 7.9×10^{-6} K^{-1}, C_r = 0.017, C_ϕ = -0.0025, n_0=1.82, r_0 = 2 mm, L = 100 mm, and η = 2.7%.

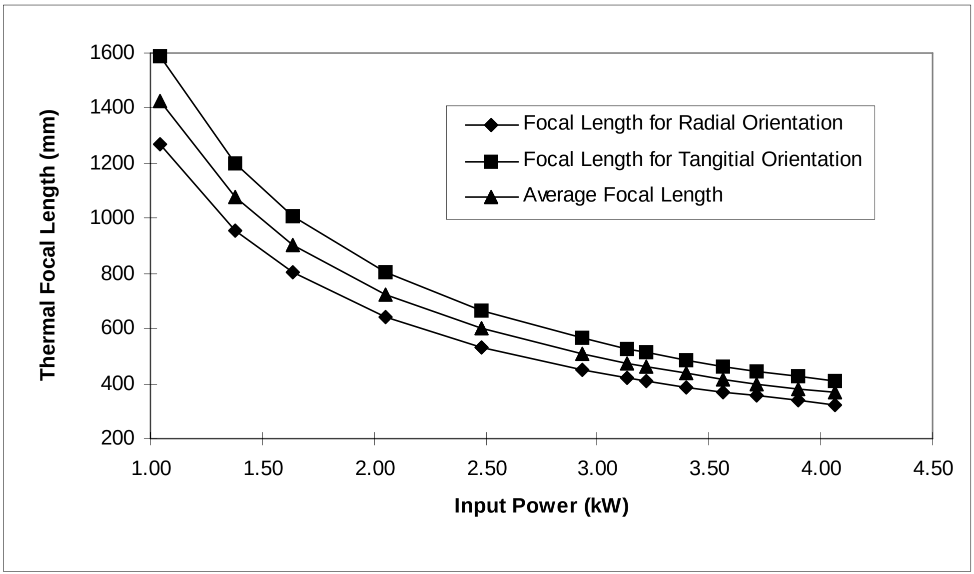


Figure 6 Theoretical thermal focal length vs. input power

In fact, the theoretical calculation of thermal focal length is very complex as many parameters are obtained from rather complex expressions and thus are often obtained empirically through experiments. Therefore the question on how to precisely measure the focal length of the thermal lens has been an important topic in laser engineering.