Nd:YAG Laser Manual
(for Undergraduate Physics Students)

(neodymium-doped yttrium aluminum garnet; Nd: $Y_3Al_5O_{12}$)

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1. THE ND:YAG LASER

1.1. History

The invention of laser (Light Amplification by Stimulated Emission of Radiation) has greatly advanced a vast array of technology across different fields because of its many applications ranging from simple elevator light sensors, optical fiber communications, and sensitive medical procedures. The fundamental physics research in lasers can be traced back to when Albert Einstein predicted, in his paper on the quantum theory of radiation, the possibility of stimulated emission of radiation in 1917 [1] . He postulated that photons prefer to travel together in the same state and can spontaneously emit a photon randomly. He then realized that a cascading effect of stimulated emission can also happen when a stray photon with the right amount of energy stimulates an atom to emit a photon, which then stimulates another and so on.

In 1955, this concept was used by Charles Townes of Columbia University and his colleagues to develop the maser (Microwave Amplified Stimulated Emission of Radiation) for generating or amplifying microwaves [2]. After 3 years, he and Arthur Schawlow showed how to extend this concept to visible and infrared frequencies, which essentially describes a laser. This sparked the race in finding the right lasing medium and developing the first laser among the physicists at the time. Theodore Maiman's successful production of the first operating laser in 1960 by shining a high-power flash lamp on a ruby rod with silver-coated surfaces inspired more researchers to discover more materials capable of lasing action [3].

In December 1964, Geusic, Marcos, and Van Uitert at Bell Laboratories developed the first neodymium-doped yttrium aluminum garnet (Nd:YAG) laser, which has become one of the most common lasing mediums owing to its versatility [4]. This active lasing medium is a cubic garnet crystal ($Nd:Y_3Al_5O_{12}$) grown using the Czochralski method. The Nd:YAG laser is classified as a four-level solid-state system because of the trivalent Nd^{3+} ions doped (at a level of about 1%) into the YAG crystal, and the four energy levels used in its operation [5].

1.2. General use

Medical physicists were quick to realize its potential use in medical procedures. In 1975, Dr. Peter Kifhaber pioneered the use of Nd:YAG laser as a substitute for argon laser for its greater penetrating power and capability of laser photocoagulation to control massive gastrointestinal bleeding in humans [6]. More researchers began to study the Nd:YAG as a lasing medium because of its high energy output despite low power consumption and good thermal, mechanical, and optical properties that are ideal for diverse applications.

1.3. Current applications

The Nd:YAG laser remains relevant in modern technology as it has revolutionized medical procedures such as endoscopy, post-cataract surgery, laser peripheral iridotomy, several cosmetic procedures, and general and dental surgery. It is extensively used in manufacturing and automotive industries and super alloy drilling. It is also utilized in the military mainly as laser designator and laser rangefinders [7].

2. LASER STRUCTURE AND WORKING PRINCIPLE

2.1. Energy level diagram

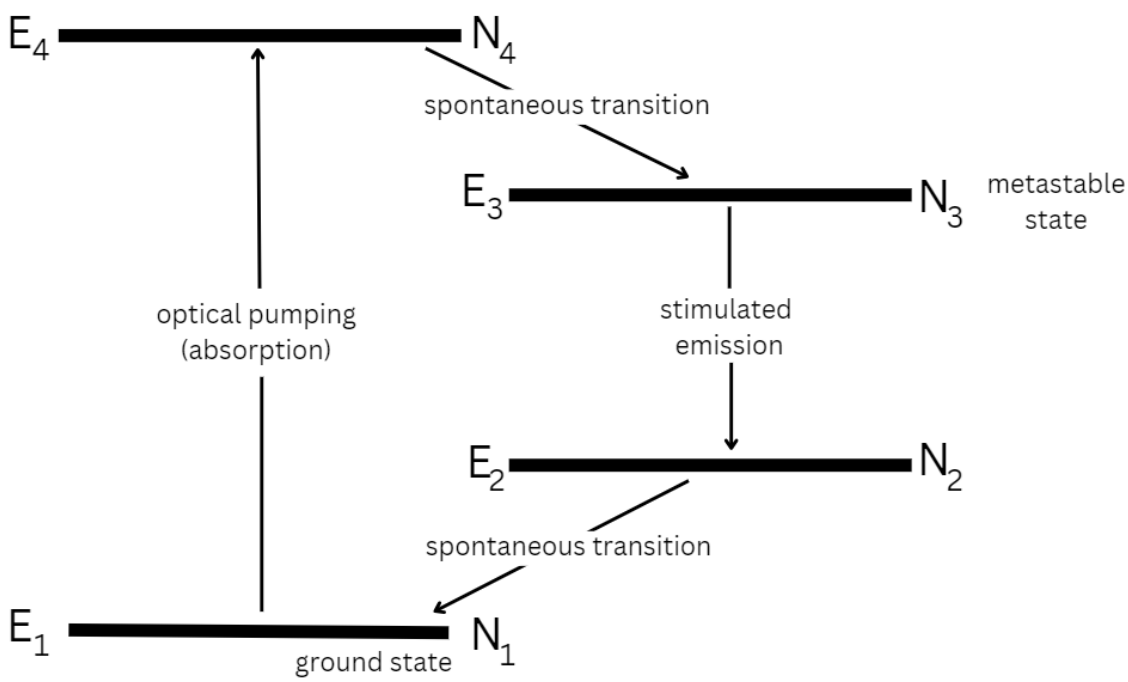

Figure 1. Typical diagram of a four level laser system

The Nd:YAG lasing medium is a four-level system which acts as the active medium in which optical gain can occur. The operation of the laser can be described using the typical four-level laser system diagram shown in Figure 1. To analyze it, we assume that the energy levels of the system are as $E_1<E_2<E_3<E_4$ with populations $N_1>N_2>N_3>N_4$ at equilibrium [8]. Now, when the flash tube or diode supplies photons into the active medium, the electrons in the lower energy state E_1 are pumped into the higher state E_4. But since the lifetime of state E_4 is short, they quickly move to the next lower state E_3 through non-radiative decay. Comparatively, the lifetime of electrons in E_3 is long enough that the population N_3 can become greater than N_2, thus achieving population inversion. Incoming photons create optical gain by stimulating the laser transition from E_3 to E_2 which produces new photons that can stimulate other excited electrons and create more photons. The light produced becomes the output of the laser. Finally, the lifetime of state E_2 is also short, so that the electrons in this state quickly fall (by non-radiative decay) to the ground state E_1 which can be pumped once more.

The photons generated by the active medium are trapped within an optical resonator or cavity containing the active medium which ensures the availability of photons to simulate the laser transition and repeated gain. The light bounces off the mirrors of the cavity many times until it passes through the partially reflecting mirror or escapes the system if the cavity were unstable. The laser transitions that are narrated here can be further described by employing an 808nm pumping of an Nd:YAG component.

2.2. Pump mechanism

An overview of the Nd:YAG material's excitation spectra under 808 nm pumping is shown in Figure 2 [9]. The pump process starts from the ground state $^4I_{9/2}$ and populates at $^4F_{5/2}$. The energy level displays more sublevels as a result of the alleged Stark splitting. This is evident as the ground state contains five sublevels allowing for four pump transitions to the excited sublevels of the $^4F_{5/2}$ state. From this point, the $^4F_{3/2}$ laser levels are filled by fast radiationless transfer. Various final states can result from the transition, depending on the wavelength. Fast radiationless transfers also occur as it returns to the ground state $^4I_{9/2}$.

Typically, krypton flash lamps are used to pump the electrons of the neodymium ion to the desired excited state, but diode-pumps are becoming more common for low-pulse energy or continuous wave (CW) applications. However, the overall efficiency of Nd:YAG lasers is about 1-2%, so high-power lasers using discharge lamps for pumping must provide a relatively large amount of power. Much of this energy is wasted because Nd:YAG can only accept light within a number of narrow absorption bands whereas discharge lamps produce light with a broad spectral distribution.

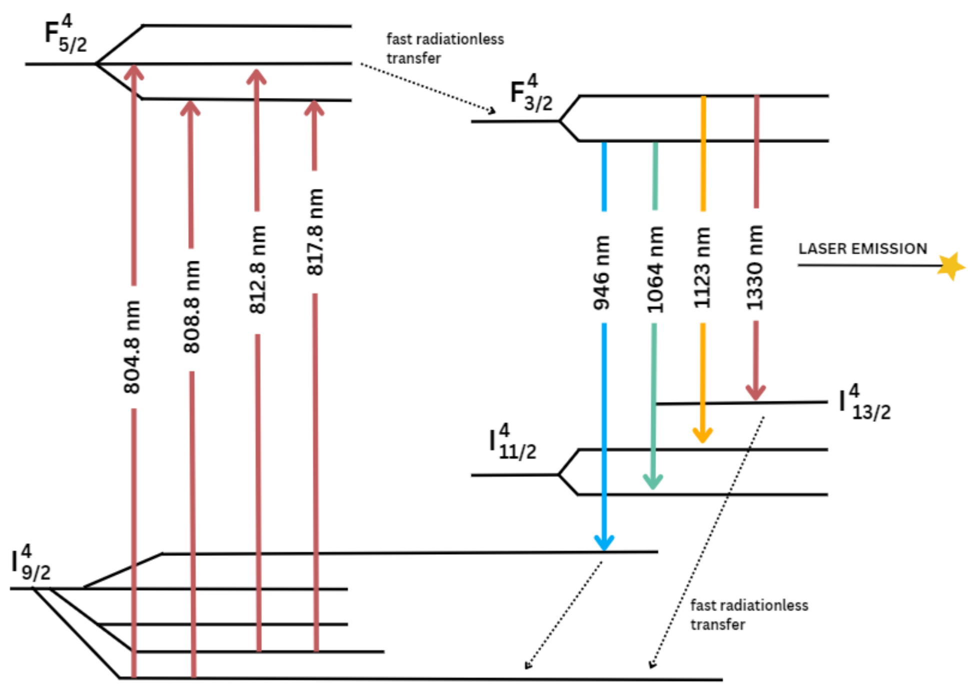

Figure 2. Energy level system of an Nd:YAG laser under 808nm pumping [9]

2.3. Four-level system

To further explain the operation of the Nd:YAG laser, we follow the analysis by Siegman [10]. We write down the rate equations using the simple four-level model (Figure 1); in doing so, we have considered the upper level E_4 to be the combination of all the possible upper energy levels, which is desirable because for the Nd:YAG lasing medium, these higher states quickly relax to the sharp and metastable state $^4F_{3/2}$ (which is E_3 in our discussion). This also shows why broadband pump lamps are often chosen for the laser, because the broad upper level makes pumping efficient.

2.3.1. Rate equations

We begin by assuming that $\hbar\omega \gg kT$, so that upward transitions due to thermal effects can be neglected, which is often the case for optical frequencies. We also assume that all states have the same degeneracy ($g = 2$). Where the pump transition probability between E_1 and E_4 is $W_{14}=W_{41}=W_p$ and the transition rate from state i to j is γ_{ij}, the rate equation in the optical approximation for state E_4 is then…

$$\frac{\mathrm{d}N_4}{\mathrm{d}t} = W_p(N_1 - N_4) - (\gamma_{43} + \gamma_{42} + \gamma_{41})N_4 = W_p(N_1 - N_4) - \frac{N_4}{\tau_4}$$

We assume that the probability that electrons from the ground state are pumped to E_3 is negligible. Now, the rate equations for states E_3 and E_2 are…

$$\frac{\mathrm{d}N_3}{\mathrm{d}t} = \gamma_{43}N_4 - (\gamma_{32} + \gamma_{31})N_3 = \frac{N_4}{\tau_{43}} - \frac{N_3}{\tau_3}$$

$$\frac{\mathrm{d}N_2}{\mathrm{d}t} = \gamma_{42}N_4 + \gamma_{32}N_3 - \gamma_{21}N_2 = \frac{N_4}{\tau_{42}} + \frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_{21}}$$

Solving for the steady-state populations gives…

$$N_4 = \frac{W_p\tau_4}{1 + W_p\tau_4}N_1 \approx W_p\tau_4 N_1 \text{ if } W_p\tau_4 \ll 1$$

$$N_3 = \frac{\tau_3}{\tau_{43}}N_4$$

and so…

$$N_2 = \left(\frac{\tau_{21}}{\tau_{32}} + \frac{\tau_{43}\tau_{21}}{\tau_{42}\tau_3}\right)N_3 = \beta N_3$$

where $\beta = \tau_{21}/\tau_{32} + \tau_{42}\tau_{21}/\tau_{21}\tau_3$

2.3.2. Population inversion

First, notice that if $\tau_3 \gg \tau_{43}$, that is, the transition rate from state E_4 to E_3 is very fast, then the upper laser level gets filled quickly and $N_3 \gg N_4$ and that the condition for the desired population inversion to occur becomes $\beta = N_2/N_3 \ll 1$. Next, If we also assume that the upper levels E_4 decays primarily into E_3, so that $\tau_{42} = \infty$, then we see that the population-inversion condition reduces to

$$\beta = \frac{N_2}{N_3} \approx \frac{\tau_{21}}{\tau_{32}} \ll 1$$

This inequality also implies that the excited electrons should decay from E_2 into lower energy levels much faster than atoms decay into E_2 from upper energy levels. In other words, the population inversion between E_3 and E_2 becomes certain if the upper laser level E_3 is long lived (τ_3 and τ_{32} both large) and the lower laser level is short lived (τ_{21} small).

3. LASER RESONATOR

3.1. Main geometry of reflectors

The optical resonator of the Nd:YAG laser is formed with two differently slivered mirrors placed on opposite sides of the crystal. One is fully optically coated, which makes it 100% fully reflecting, and one is partially coated making it reflect only most of the light while allowing a small portion of light pass through it which essentially produces a laser beam. Typically, an Nd:YAG laser uses a separate mirror on each end along with other components for various optical processes. Figure 3 below shows a typical Nd:YAG resonator.

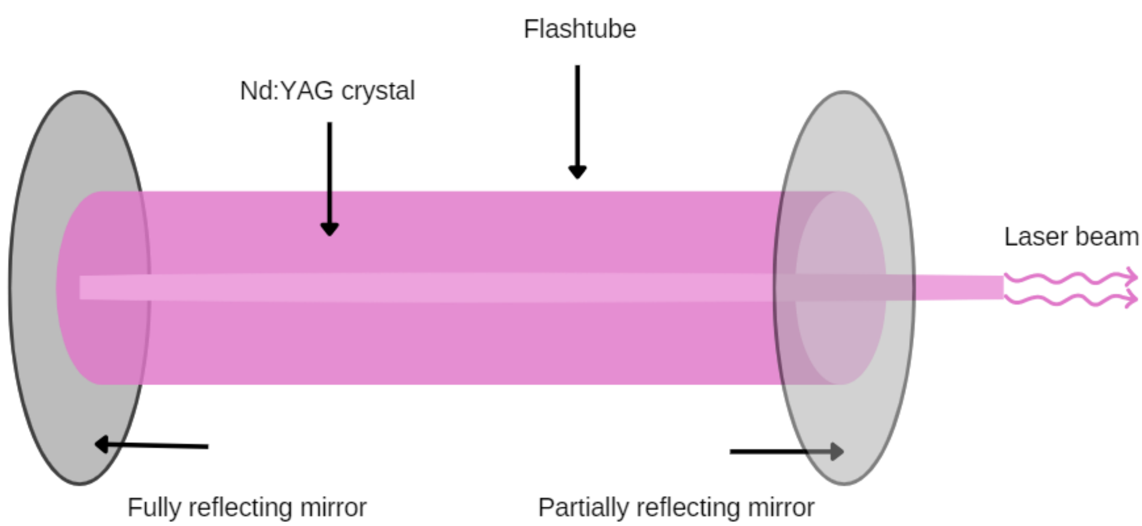

Figure 3. Typical structure of Nd:YAG resonator [8]

3.2. Stability of optical resonators

When considering a new laser system, laser beam drift and stability performance are frequently taken into account. Manufacturers specify these qualities for a laser operating under equilibrium conditions following its prolonged use in operation

[11]. However, these qualities may vary before the optical system reaches a state of equilibrium.

The ND:YAG laser can either be stable or unstable. We can say that its resonator is optically stable if the light still stays inside the resonator due to the properties of the mirrors utilized (i.e. the light rays do not exit the resonator as it goes beyond the edges of the configured mirrors).

A typical ND:Yag laser consists of a plane-parallel resonator, also known as the Fabry-Perot [12]. In this type of resonator, the light beam is only reflected and not modified by the mirrors. As such, the latter must be adjusted to be exactly parallel with each other [13]. The stability of such resonator cavity can be analyzed with the inequality:

$$0 \leq g_1 g_2 \leq 1$$

where $g_1 = 1 - \frac{L}{R1}$ and $g_2 = 1 - \frac{L}{R2}$, L is the cavity length, and R_1 and R_2 is the radius of curvature for the left and right mirrors respectively. Since the radius of curvature of both plane laser mirrors is at infinity, then…

$$R_1 = R_2 = \infty$$

As such, $g_1 g_2 = 1$. Thus, an Nd:YAG laser with a plane-parallel resonator has a stable resonator configuration.

4. LASER OUTPUT

4.1. Round-trip efficiency

The optimization procedure of a laser system heavily depends on its gain coefficient and resonator losses as the pump power required to reach the laser threshold is determined by the excitation efficiency. Higher losses results in lower excitation efficiency, resulting in a higher laser threshold that has to be attained by the pump.

The product of the excitation efficiency and the extraction efficiency can be used to define the overall efficiency of a solid-state laser. While the extraction efficiency explains the laser system's resonator, the excitation efficiency describes the pumping configuration of a solid-state laser. The excitation efficiency is simply the product of four individual efficiencies of the system. It is expressed as

$$\eta_{\text{excit}} = \eta_1\eta_2\eta_3\eta_4$$

where η_1 is the ratio of the fluorescence power at threshold to the total absorbed pump power; η_2 is the ratio of lamp radiation power within absorption bands of the laser material to electrical input power; η_3 is the efficiency obtained in transferring the useful radiation power to laser rod; and η_4 is the fraction of useful pump radiation power which is actually absorbed by the laser rod [14].

The extraction efficiency η_{extr} specifies which part of the excited power can be converted into laser radiation and coupled out of the resonator. It depends on parameters such as the resonator losses (e.g. scattering and diffraction), transmission of the output coupling mirror and the ratio of the radiation mode and laser rod volumes. It is can expressed as

$$\eta_{\text{extr}} = \eta_5 = \frac{2(1 - R_1)}{R_1^{1/2}(L - \ln\ R_1)}$$

where η_5 is the output coupling efficiency. One generally uses the equation below to calculate the output power:

$$P_{\text{out}} = \eta_{\text{tot}}\,(P_{\text{in}} - P_{th})$$

where P_{out} and P_{in} are the output and input power, respectively. P_{th} is the threshold pump power and is the slope output given by...

$$\eta_{tot} = I_s A k \eta_5$$

Here, I_s is the saturation power density, A is the cross-sectional area of the rod, and k is the slope gain.

The slope efficiency and laser threshold can be determined when the laser has been set to its maximum output power. The measured values tell us whether the system is efficient and operates within acceptable limits. An optical power meter is used to measure the output power at various pump powers. Here, it is important to make sure that the appropriate laser diode temperature is adjusted for each injection current value. By lowering the pump power until the laser simply stops oscillating, the laser threshold can be discovered. At this stage, the resonator should be re-adjusted and the temperature should be fine-tuned.

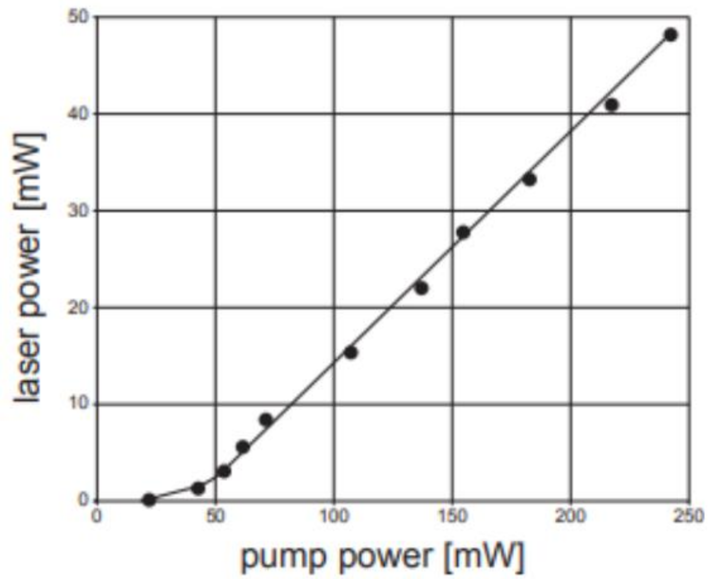

Figure 4. The laser output power plotted against the pump power [15].

4.2. Bandwidth

The Nd:YAG crystal has an absorption bandwidth of around 730-760 nm and 790-820 nm when pumped by either a flash tube or laser diode. The laser can emit an output beam with wavelengths of 946 nm, 1120 nm, 1320 nm, or 1140 nm, but laser light is usually generated in the near-infrared region at 1064 nm [8].

4.3. On longitudinal mode

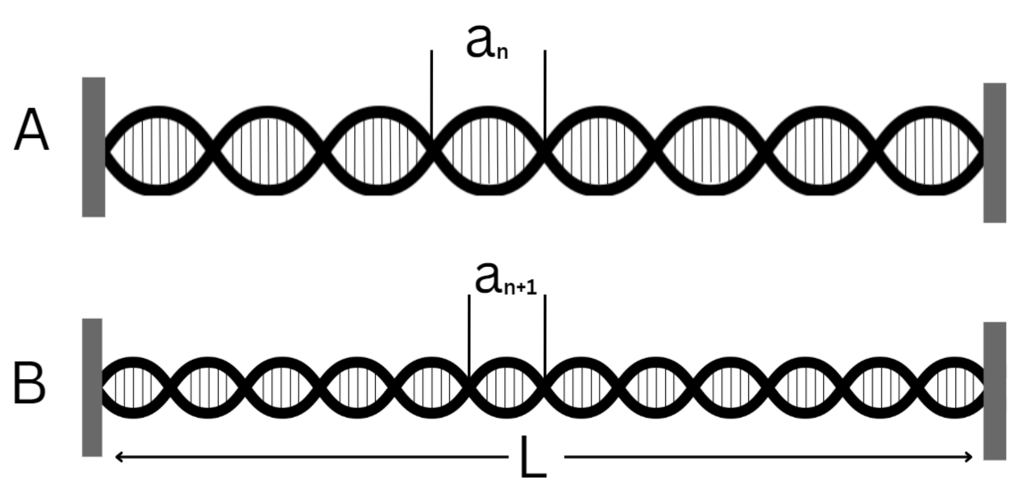

Figure 5. Standing waves in a resonator with plane parallel mirrors of length L with n=8 (A) and n=12 (B).

In a typical resonator, the light wave is reflected back and forth between the mirrors. For a given mirror separation L, only waves that satisfy the boundary condition of zero field strength at both mirrors can exist. To restate this condition, the allowed oscillating modes (or simply just modes) must fit an integer number n of half wavelengths $\lambda/2$ inside the resonator. Where $a_n = \lambda/2$ and n indexes the number of half-wavelengths (see Figure 4), the equation $na_n = L$ gives the allowed modes [16]. Since the next mode fulfills $(n+1)a_{n+1} = L$, the mode spacing $\delta\lambda$ will be given by

$$|\delta\lambda| = |\lambda_{a(n+1)} - \lambda_{a(n)}| = \frac{2 \cdot L}{n \cdot (n+1)} \Rightarrow |\delta\lambda| = \frac{c}{2 \cdot L}$$

4.4. On transverse modes

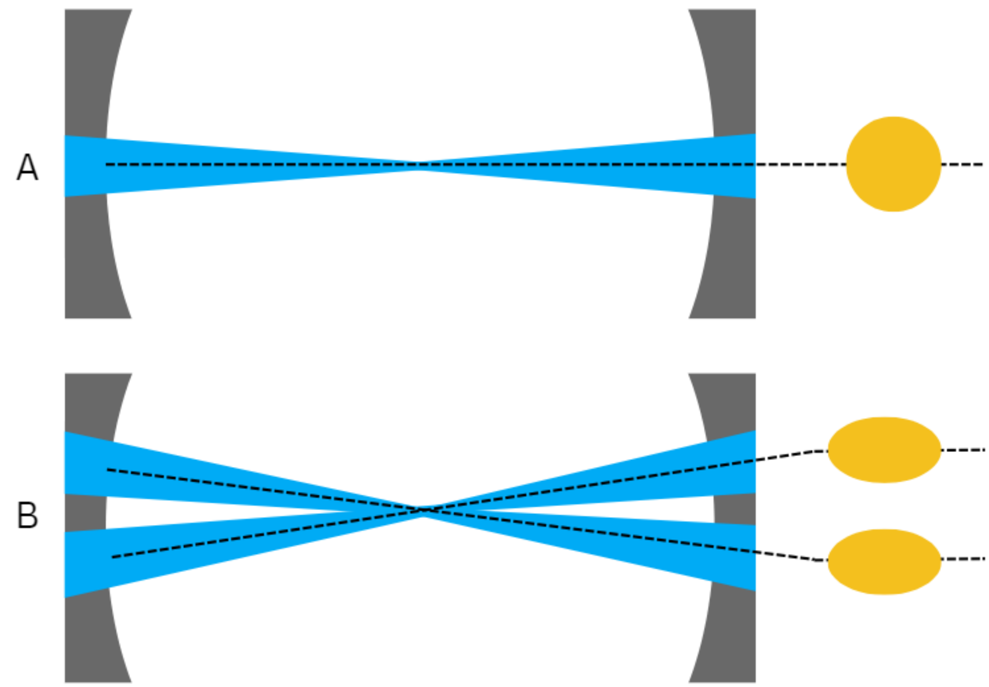

Figure 6. Spherical resonator with oscillation of transverse mode TEM_{00q} (A) and TEM_{01q} (B)

Transversal modes develop in spherical resonators as longitudinal modes do in plane-parallel resonators. The beam of the former type of mode follows a geometrical shape Here, a steady-state laser would result in an equal radius of curvatures to the mirrors and its wavefronts. As observed in diagram (A) in Figure 6, a symmetrical radiation field is formed which results in a round Gaussian shaped intensity distribution to its output.

In some cases, the radiation field is set at an angle with respect to the optical axis of the resonator. This produces an output of intensity distributions that are spatially separated, and asymmetrical to the radiation axis, resulting in a transversal oscillation along the optical axis. Thus, in order to observe these modes, modifications in the input and output mirror are necessary for the cavity alignment to be adjusted.

Transversal modes are universally designated as TEM_{mnq}. Its m and n indices correspond to the number of intensity spots minus in the x-axis and y-axis, respectively, while the q index is the number of nodal points on the standing wave in the resonator. As such, a mode of TEM_{00q} will produce a round spot, as shown in Figure X. A mode TEM_{01q} results in a spherical resonator with oscillation similar to diagram (B) in Figure 6. This is further verified by a study in March 2012 that experimentally obtained the transversal modes for different alignments of an Nd:YAG resonator [17]. Figure 7 below shows their results.

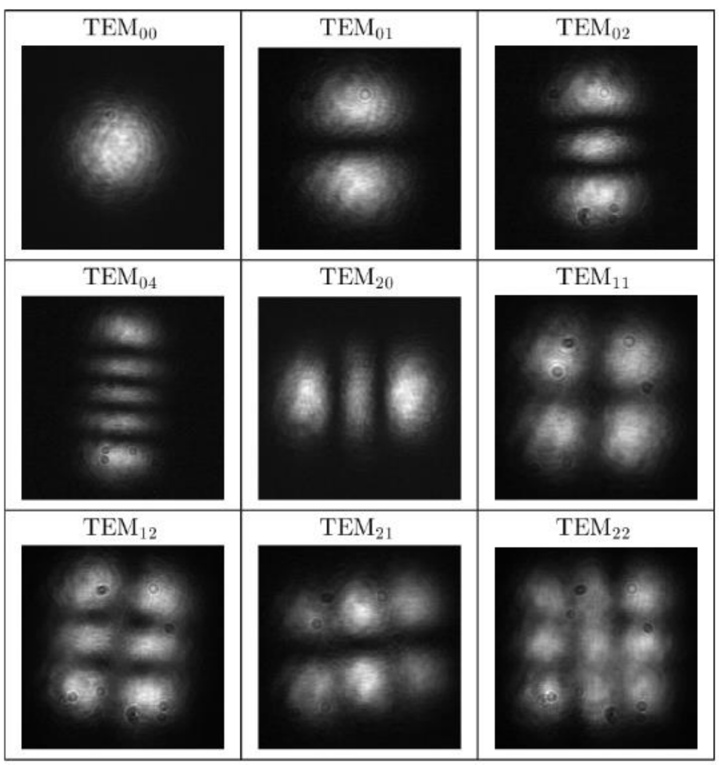

Figure 7. Transverse modes obtained for different alignments of an Nd:YAG resonator [17].

4.5. On mode-locking

While multiple laser transitions are possible from the higher lasing level 4F3/2, the usual transition to the state 4I11/2 associated with the wavelength =1.064 m is homogeneously broadened at room temperature due to lattice phonon interactions. The corresponding width at T=300 K is $\Delta v = 4.2$ cm^{-1} $= 126$ GHz which makes the Nd:YAG laser a good candidate for mode-locked operation, which occurs when a laser with a large number of longitudinal modes has these modes oscillate with some definite relation between their phases. The process which causes the modes to adopt a phase relation is called mode locking [18].

Active mode-locking can be achieved by inserting a modulator into the optical cavity which results in a time-varying loss at frequency ω_m. If $\omega_m \neq \Delta\omega = 2\pi\Delta v$ where Δv is the difference in frequency between longitudinal modes, this loss will amplitude modulate the electric field of each cavity mode.

However, if now $\omega_m = \Delta\omega$, the equation for cavity modes become coupled. Assuming that the modulator is placed very close to a cavity mirror, the laser becomes mode locked, that is, the phases φ_l obey the relation

$$\varphi_l - \varphi_{l-1} = \varphi$$

Then, the modulation period will be equal to the cavity round-trip time and the stable steady-state condition will correspond to light pulses passing through the modulator. Each pass of the pulse through the modulator shortens the pulse-duration, but this does not tend to zero because of the finite bandwidth of the gain medium. With this method, 125-picosecond pulses can easily be achieved with the Nd:YAG laser.

On the other hand, passive mode-locking with the Nd:YAG laser can be done by making use of a suitable fast saturable absorber. One such configuration can be made by inserting a multiple-quantum well between two mirrors of the cavity such that the resulting Fabry-Perot etalon operates at anti-resonance (points where a minimum of transmission or a maximum of reflection occurs). This anti-resonance-Fabry-Perot-saturable absorber (A-FPSA) is widely used to generate both picosecond and femtosecond laser pulses with the Nd:YAG laser. Using other passive mode-locking setups, Nd:YAG lasers can generate pulses as short as 5 picoseconds.

4.6. On multi-mode

As the aperture size inside the optical cavity is changed from large to small, the transverse mode transitions from multi-mode to single-mode. A laser is in multimode when more than one longitudinal mode lases. Otherwise, it is in single-mode when it only lases at a single frequency.

Most of the scientific lasers employ graded-reflectivity mirrors for minimal beam divergence [5]. Since a tightly focused spot is not necessary for many commercial applications, the more traditional multimode stable resonator is frequently utilized. In stable resonators operating in multimode, a relatively high power output is ejected as the lasing diameter is larger than if confined to the single TEM_{00} mode.

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