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Review Article

Applications of Nd: YAG Lasers in material processing: Fundamental approach

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ABSTRACT

Lasers are devices that produce intense beams of light which are monochromatic, coherent and highly collimated. The wavelength of laser light is extremely pure when compared to other sources of light and all of the photons that make up the laser beam have a fixed phase relationship with respect to one another. Among solid state lasers, Nd: YAG laser has an important role due to its high efficiency, possibility to tune it in different wavelengths from infrared till ultraviolet and change pulse duration from milliseconds down to picoseconds. Nd: YAG lasers can operate in both pulsed and continuous mode providing power outputs between 0.04-6000 W. Solid-state lasers operate at very low wavelengths and hence cannot be operated with the naked eye. Nd: YAG is usually used in monocrystalline form, fabricated with the Czochralski growth method, but there is also ceramic Nd: YAG available in high quality and in large sizes. For both monocrystalline and ceramic Nd: YAG, absorption and scattering losses within the length of a laser crystal are normally negligible, even for relatively long crystals. One of the prime advantages of the Nd: YAG laser over the CO_2 laser is the ability to deliver laser radiation through optical fibers. This paper deals with the detailed properties and applications of Nd: YAG lasers in material processing.

Keywords: Laser, Nd: YAG laser, Principle, Design, Characteristics and Applications.

1. INTRODUCTION

Laser is a device that emits electromagnetic radiation through a process of optical amplification based on the stimulated emission of photons. Lasers are devices that produce intense beams of light which are monochromatic, coherent and highly collimated. The wavelength of laser light is extremely pure when compared to other sources of light and all of the photons that make up the laser beam have a fixed phase relationship with respect to one another. There are many types of lasers available for research, medical, industrial and commercial uses. Lasers are often described by the kind of lasing medium they use solid state, gas, excimer, dye and semiconductor lasers[1]. Lasers have been used for more than 50 years in diverse fields of application starting from simple laser micromachining processes for micro-electro-mechanical systems (MEMS), such as cutting, drilling pulse laser deposition of coatings and films; local defect annealing after ion implantation; formation the precipitation areas of impurities in Si in medicine, medical diagnosis, treatment and therapy etc. Nd: YAG (neodymium-doped yttrium aluminum garnet; Nd: $Y_3A_{l5}O_{12}$) is a crystal that is used as a lasing medium for solid-state lasers. Among solid state lasers, Nd: YAG laser has an important role due to its high efficiency, possibility to tune it in different wavelengths from infrared till ultraviolet and change pulse duration from milliseconds down to picoseconds. The dopant, triply ionized neodymium Nd(III), typically replaces a small fraction of the yttrium ions in the host crystal structure of the yttrium aluminium garnet(YAG), since the two ions are of similar size. It is the neodymium ion which proves the lasing activity in the crystal, in the same fashion as red chromium ion in ruby lasers. Generally the crystalline YAG host is doped with around 1% neodymium by atomic percent. Nd: YAG lasers can operate in both pulsed and continuous mode providing power outputs between 0.04-6000 W. Solid-state lasers operate at very low wavelengths and hence cannot be operated with the naked eye.

Operators must wear special eyewear or use special screens to prevent damage to the retina[2].

2. GENERAL LASER PROPERTIES

All lasers produce intense beams of light that are monochromatic, coherent and highly collimated. The wavelength of the laser light is extremely pure when compared to other sources of light and all of the photons that make up the laser beam have a fixed phase relationship with respect to one another. This causes the light to form a beam with a very low rate of expansion that can travel over great distances or can be focused to a very small spot with a brightness that can approximate that of the sun. Because of these properties, lasers are used in a wide variety of applications in all walks of life. All lasers include a gain medium, an excitation source and a resonator structure. Beyond these basic similarities, the lasers are very different in their size, output, beam quality, power consumption and operating life[3].

3. CHARACTERISTICS OF Nd: YAG LASERS

Nd: YAG is a four-level gain medium, offering substantial laser gain even for moderate excitation levels and pump intensities. The gain bandwidth is relatively small, but this allows for a high gain efficiency and thus low threshold pump power. Nd: YAG lasers can be diode pumped or lamp pumped. Lamp pumping is possible due to the broadband pump absorption mainly in the 800 nm region and the four-level characteristics. The most common Nd: YAG emission wavelength is 1064 nm. Starting with that wavelength, outputs at 532, 355 and 266 nm can be generated by frequency doubling, frequency tripling and frequency quadrupling, respectively. Other emission lines are at 946, 1123, 1319, 1338, 1415 and 1444 nm. When used at the 946 nm transition, Nd: YAG is a quasi-three-level gain medium, requiring significantly higher pump intensities. All other transitions are four-level transitions. Some of these, such as the one at 1123 nm, are very weak, so that efficient laser operation on these wavelengths is difficult to obtain: Even a moderate gain requires a high excitation density, which favors detrimental quenching effects, in addition, lasing at 1064 nm, the wavelength with much higher gain, has to be suppressed, for example by using suitable dichroic mirrors for building the laser resonator. However, with careful optimization, even on these weak transitions one can obtain substantial output powers[4]. Nd: YAG is usually used in monocrystalline form, fabricated with the Czochralski growth method, but there is also ceramic Nd: YAG available in high quality and in large sizes. For both monocrystalline and ceramic Nd: YAG, absorption and scattering losses within the length of a laser crystal are normally negligible, even for relatively long crystals. Fig. 1 shows common pump and laser transitions of Nd: YAG laser.

4. DESIGN OF Nd: YAG LASER

The Nd: YAG laser is an optically pumped solid state laser system that is capable of providing high power laser beam. The lasing medium is a colorless and isotropic crystal Yttrium aluminium garnet (YAG: $Y_2A_{l5}O_{12}$) having a four operational levels of energy. The yttrium aluminium garnet is doped with some amount of neodymium. When sufficiently intense light is allowed to fall on this crystal, population inversion occurs and atoms in the crystal structure absorb this incident light to perform transitions from the ground state to the absorption bands. This is often done with the help of a flash tube. The transition from the absorption bands to the upper energy laser levels is very smooth. The decays from these higher levels back to the ground state are longer in duration than the transitions to the higher levels. Due to this long lifetime, the atoms deexcite back to the ground states almost spontaneously, thus producing a laser beam. Fig. 2 shows the schematic representation of Nd: YAG laser[5]. For continuous wave (CW) operation, it is often more desirable to have a steady pump beam, and less waste heat whenever possible. For these reasons, along with falling prices, solid state CW lasers are becoming increasingly pumped with semiconductor diode lasers. The other notable reason is overall efficiency flash lamp pumps typically provide up to 3% efficiency, whereas diode lasers permit almost 50% efficiency. Fig. 3 shows the energy level diagram of Nd: YAG laser. The typical diode laser is simply tuned to output along the required 808.4 nm line. Due to the relationship between current, temperature, and wavelength outputted from a diode laser, these pumps employ a computerized controller for both consistent power delivery and stable temperature. Only with these tools can the diode laser output be both accurately tuned and stable, and the expected efficiency realized[6].

5. APPLICATIONS

One of the prime advantages of the Nd: YAG laser over the CO_2 laser is the ability to deliver laser radiation through optical fibers. Fortuitously, the 1.06 μm output wave length of the Nd:YAG laser falls within the wavelength range in which glass fibers have low attenuation, so propagation of Nd: YAG laser radiation over distances of as much as several hundred meters is possible with minimal loss[7]. Manufacturers recommend the use of Nd: YAG laser for soft tissue periodontal procedures such as debridement of diseased epithelial linings, gingivoplasty, crown lengthening, vestibuloplasty, gingivectomy and reduction of drug-induced gingival hypertrophy. Many of these procedures involve removal of soft tissue in areas adjacent to teeth which may have amalgam restorations in close proximity to the working area. Accidental laser exposure to such restorations is a distinct possibility[8].

With the development of modern medical lasers, laser therapy has gained an increasing role in the wide spectrum of treatment modalities. Also in oncology, laser techniques have become interesting alternatives in radical tumor resection and to palliative tumor treatment methods. Due to the great variability of induced tissue reactions from microsurgical precise coagulation and cutting to voluminous coagulation or tumor vaporization, the Nd: YAG laser is the most important surgical laser. The possibility of transmitting its light through flexible fibers allows wide variation of applications and tissue effects. Even if this laser is mostly known for its ability of volume coagulation, which is due to its large optical penetration depth, it shows a reaction depth which can be varied in the widest range of all medical lasers by using the appropriate parameters[9]. The longest experience exists with all applications of voluminous coagulation for hemostasis and tumor destruction. Microsurgical preparation with the Nd: YAG laser became possible for the first time with the introduction of contact surgery with sapphire tips. The great disadvantages of sapphire tips in practical use led us to introduce bare fiber contact surgery in 1983. Due to the easy handling and cheap method of bare fiber, this is at present our standard method for all contact applications, especially in endoscopic procedures. Because light in the near-infrared range has the greatest penetration depth in tissue, it is also possible to produce homogeneous coagulation during direct irradiation of the diseased area by the fiber introduced percutaneously into the tissue to be treated. This method, called interstitial laser-induced thermotherapy (LITT)[10]. At the same time, interstitial laser therapy with bare fiber was introduced in our center. The first applications were for vascular malformations and hemangiomas[11].

Today, the most used laser in dentistry operates in the pulsed regime with pulse duration ranging from a millisecond to nanoseconds. Q-switched Nd: YAG normally operates in 300 ns, while Nd: YAG free-running presents operation in the 1-ms regime. Down to ns pulse duration is normally referred to as a short-pulsed laser. In this regime of operation, the main mechanism of ablation occurs through vaporization. Larger pulses up to the microsecond range generate much heat during the ablation process and normally encounter constraints and limitations in applications of dentistry. Collaterally damaged material due to thermal effects is commonly present[12]. The laser pulse duration is an important parameter due to the fact that, in this time frame, heat diffusion plays a very important role in the interaction mechanism involving light and tissue. The excess heating may have strong side effects, since the temperature in the inner part of the tooth can reach variation values higher than 10^0C with great chance of permanent damage. Shortening the pulses minimizes heating effects and introduces new mechanisms, such as plasma-mediated ablation[13, 14].

Nd: YAG laser cutting becomes an excellent machining process because of high laser beam intensity, low mean beam power, good focusing characteristics due to very small pulse duration and narrow heat affected zone (HAZ). There has been growing interest in recent years in the use of pulsed Nd: YAG lasers for precision cutting of thin sheet metals and for applications that demand narrow kerf widths and intricate cut profiles[15]. Due to its shorter wavelength in comparison to CO_2, it is reflected to a lesser extent by metallic surfaces and this high absorptivity of the Nd: YAG laser enables cutting of even highly reflective materials with relatively less power. Materials having high thermal conductivity give poor results when cut by CO_2 laser. Due to shorter thermal interaction time Nd: YAG laser gives better results. In pulsed mode, high incident peak power output facilitates thick material cutting. Furthermore, enhanced transmission through plasma, wider choice of optical materials and flexibility in handling with the advent of fibre optic beam delivery is also some of the interesting characteristics of the Nd: YAG laser[16, 17]. Fig. 4 shows Nd: YAG laser beam cutting machine.

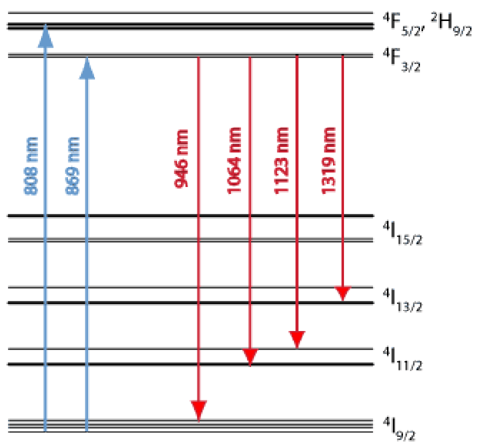

Fig. 1: Common pump and laser transitions of Nd: YAG laser

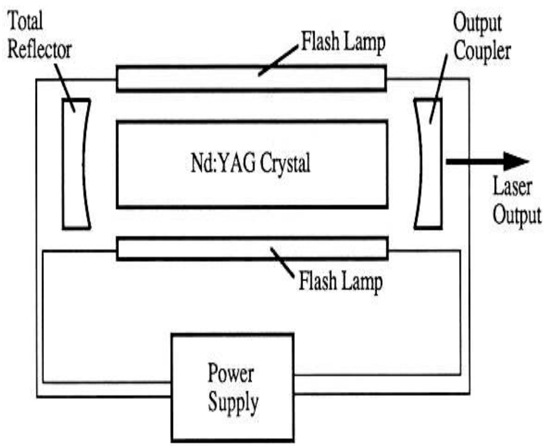

Fig. 2: Schematic representation of Nd: YAG laser

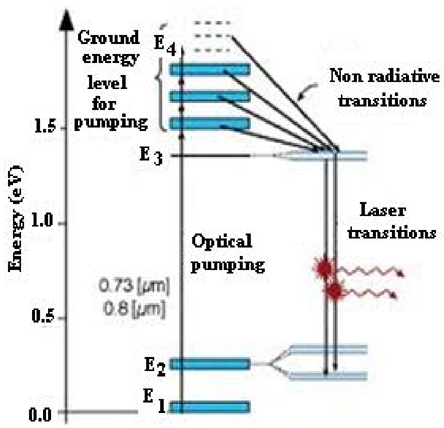

Fig. 3: Energy level diagram of Nd: YAG laser

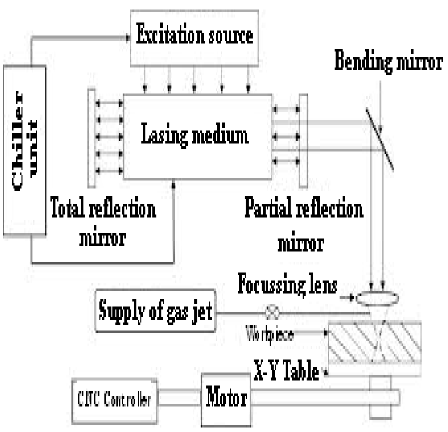

Fig. 4: Nd: YAG laser beam cutting machine

6. CONCLUSIONS

A laser is a device that emits electromagnetic radiation through a process of optical amplification based on the stimulated emission of photons. The wavelength of laser light is extremely pure when compared to other sources of light and all of the photons that make up the laser beam have a fixed phase relationship with respect to one another. Among solid state lasers, Nd: YAG laser has an important role due to its high efficiency, possibility to tune it in different wavelengths from infrared till ultraviolet and change pulse duration from milliseconds down to picoseconds. Nd: YAG is a four-level gain medium, offering substantial laser gain even for moderate excitation levels and pump intensities. The gain bandwidth is relatively small, but this allows for a high gain efficiency and thus low threshold pump power. Nd: YAG lasers can be diode pumped or lamp pumped. With the development of modern medical lasers, laser therapy has gained an increasing role in the wide spectrum of treatment modalities. Also in oncology, laser techniques have become interesting alternatives in radical tumor resection and to palliative tumor treatment methods. Due to the great variability of induced tissue reactions from microsurgical precise coagulation and cutting to voluminous coagulation or tumor vaporization, the Nd: YAG laser is the most important surgical laser. Today, the most used laser in dentistry operates in the pulsed regime with pulse duration ranging from a millisecond to nanoseconds. Q-switched Nd: YAG normally operates in 300 ns, while Nd: YAG free-running presents operation in the 1-ms regime.

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