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# A compact 1.06/1.32/2.94 μm pulsed laser for dentistry

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**Abstract**

A three-wavelength pulsed laser for dental application is developed. The laser houses the Nd:YAG resonator (1.06/1.32 μm) for soft-tissue treatment and Er:YAG resonator (2.94 μm) for caries removal and fits and fissure treatment. Two heads share the cooling unit and two identical high-voltage power supply modules in order to achieve compactness. The Nd:YAG laser has 10 W at 1.06 μm and 7 W at 1.32 μm with a pulse duration of 100 μs. An Er:YAG laser of 2.94 μm has 3.5 W, 20 Hz and a pulse duration of 250 μs. The beams are delivered through fibers and the laser size is 75 × 55 × 32.5 cm. © 2002 Elsevier Science Ltd. All rights reserved.

*Keywords:* Medical laser; Dentistry; YAG

## 1. Introduction

For efficient, precise and atraumatic application of laser in surgery, the absorption properties of biological tissue at the laser wavelength are one of the most important factors. The absorption properties determine tissue damage or ablation rate. For surgery on tooth such as caries removal and fits and fissure treatment, extremely high absorption is needed and Erbium lasers of 3 μm band can comply with these requirements. Water absorption at 2.94 μm of Er:YAG laser is the highest in the entire spectrum from the visible to far-infrared region that includes all the commercially available dental lasers such as 1.06 μm Nd:YAG, 1.34 μm Nd:YAP, and 10.6 μm $CO_2$ lasers (Fig. 1).

The efficiency comparable with that of Er:YAG laser at lower threshold has been achieved in a laser on the base of scandium garnets doped with chromium and erbium (Cr, Er:YSGG, for example) [1]. However, Er:YSGG is inferior to Er:YAG in terms of maximum power and cost. The penetration depth of radiation of Erbium lasers on water is found to be in the order of μm [2]. This extremely high absorption is ideal for treating tooth, which is one of the hardest materials among biological tissues. Experiments on the channel passage in tooth dentine and enamel by using Erbium-based lasers were discussed in several papers [3–5]. The water content of enamel is about 2.5% and that of dentine 13%. These materials weakly absorb the radiation in the visible and near-IR spectral regions [6]. Due to this fact, the ablation threshold is high and the tissue surrounding the tooth can be damaged while using the visible and near-IR wavelengths. When Erbium lasers at about 3 μm are used the situation is more advantageous since the absorption coefficients and ablation thresholds are about 350 $cm^{-1}$ and 500 $J/cm^3$ for dentine and 180 $cm^{-1}$ and 3000 $J/cm^3$ for enamel, respectively. It was pointed out that the crater depths made by a free-running 3 μm Er-laser of 100–700 μs do not depend on the pulse duration and depend only on the energy density on the tooth surface and the number of pulses [3].

Another important parameter for the design of dental laser is the temperature rise in tooth during laser radiation. It was measured by a thermocouple placed into the tooth canal [3]. Without cooling the tooth surface during laser treatment, temperature rise may be as high as 2–40°C although the actual rise in vivo may be less due to heat transfer from the tooth to the surrounding tissue. It was shown that the laser drilling of the tooth without water cooling on the target zone produces the charring and cracks. But water spray

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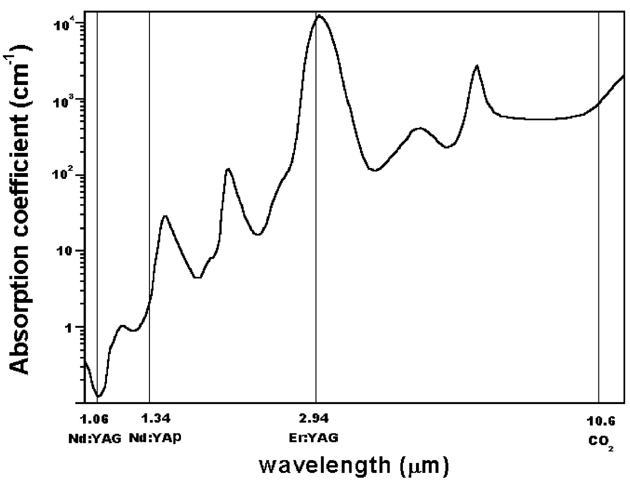



Fig. 1. Absorption spectrum of water (from G.M. Hale, M.R. Querry[2]).

cooling makes smooth holes practically without thermal damage and any other distortions of the surrounding channel in the tooth [7].

For other purposes, it is necessary to use laser wavelengths of deeper penetration and to induce thermal damage. One of such applications is soft-tissue treatment. Examples are precise and bloodless cutting gingiva, removal of bulk tissue using a cone-type contact fiber. For this purpose, Nd:YAG (1.06 μm), Nd:YAP (1.34 μm), $CO_2$ (10.6 μm) and diodes (0.85–1 μm) lasers have been used in dentistry. In order to avoid excessive heating and heat transfer, a duration of laser pulse, though varies depending on the type of laser, which is usually less than a few hundred microsecond is used. It is unlikely for a dentist to have a few or more expensive lasers in one doctor's office in terms of cost and space. A complete dental laser unit, therefore, should have wavelengths for treating both tooth and soft tissue. In this study, a compact three-wavelength dental laser system, which consists of 1.06/1.32/2.94 μm has been developed.

## 2. Design concept

We selected a pulsed Nd:YAG laser for soft tissue and an Er:YAG laser for hard tissue. A resonator using Nd:YAG crystal can emit wavelengths 1.05–1.44 μm [8]. Most of the medical Nd:YAG lasers have a wavelength of 1.06 μm. One of the limitations of using 1.06 μm for thermal treatment is its too low absorption and much deeper penetration in the tissue. Other available wavelengths from Nd:YAG are 1.32 and 1.44 μm. As shown in Table 1, 1.32 μm has the best efficiency for thermal treatment among 1.06, 1.32 and 1.44 μm since 1.32 μm has higher absorption characteristics than 1.06 μm and high efficiency of converting electrical energy into laser output than 1.44 μm. Therefore, we decided to have an additional wavelength of 1.32 μm from the same Nd:YAG crystal. The lasers specifications to be developed are summarized in Table 2 and all the requirements are to be met by a single compact dental laser system.

Fig. 2 shows a schematic of dual laser heads. Selection of 1.32 and 1.06 μm is made by a mirror whose movement is controlled by a solenoid switch. Wavelength selection and all laser control are performed by a single button operation on the control panel. Two laser heads share a common cooling unit in order to reduce the size. The schematic of cooling unit is shown in Fig. 3. In principle, Nd:YAG and Er:YAG laser resonators should have different high

Table 1
Comparison of surgical efficiency among 1.06, 1.32, 1.44 μm of Nd:YAG wavelengths

| Wavelength (μm) | Extinction coefficient for water ($k$) | Lasing efficiency with respect to 1.06 μm ($P$) (%) | Treatment efficiency $k \times P$ (ratio) |
|---|---|---|---|
| 1.06 | $1 \times 10^{-5}$ | 100 | 1 |
| 1.3188 | $1.35 \times 10^{-5}$ | 34 | 4.59 |
| 1.44 | $3.32 \times 10^{-4}$ | 0.2 | 0.66 |

Table 2
Specification for a single laser unit

| Laser head | Nd:YAG | | Er:YAG |
|---|---|---|---|
| Wavelength (μm) | 1.06 | 1.32 | 2.94 |
| Pulse duration | 100 μs | | 250 μs |
| Repetition rates (Hz) | 1–100 | 1–30 | 5–20 |
| Max. average Power (W) | 10 | 7 | 3.5 |
| Size (cm) | 32.5 × 55 × 75 | | |
| Handpiece | Bare, conical, silica fiber | | Non-contact water spray, sapphire fiber |

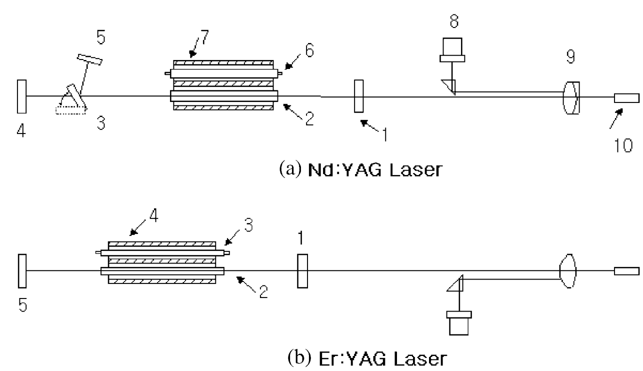



Fig. 2. Schematic of three-wavelength dual-head laser. (a) 1—output coupler, reflectivity of 45% at 1.06 μm and 75% at 1.32 μm; 2—Nd: YAG active rod, 6.3 mm in diameter and 80 mm in length; 3—wavelength splitting mirror with reflection 99.9% at 1.32 μm and transmission more then 90% for 1.06 μm; 4, 5—HR mirrors for 1.06 μm and 1.32 μm correspondingly; 6—flashlamp; 7—pump chamber, silver coated; 8—aiming beam; 9—coupling lens; 10—SMA connector; (b) 1—output coupler, reflectivity is 75% at 2.94 μm; 2—Er:YAG active rod, 5 mm in diameter and 100 mm in length; 3—flashlamp; 4—pump chamber, silver coated; 5—HR mirror.

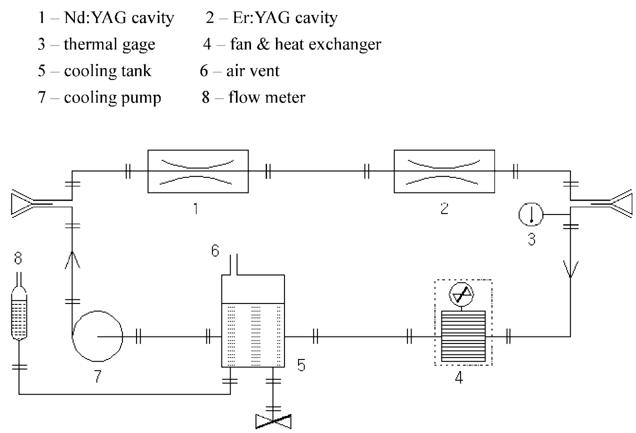



Fig. 3. Schematics of cooling unit.

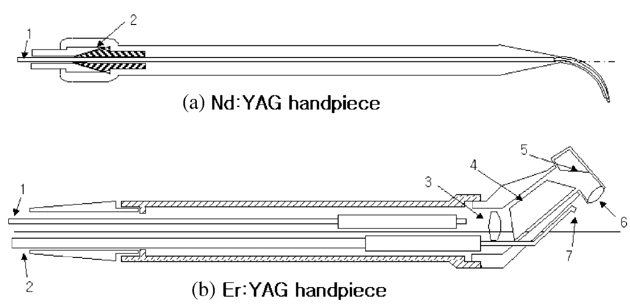



Fig. 4. Handpieces for contact-mode Nd:YAG laser and non-contact-mode Er:YAG laser with water and air spray for cooling the target region. (a) 1—fiber; 2—fiber holder; (b) 1—sapphire fiber; 2—air/water duct; 3—lens; 4—prism; 5—mirror; 6—lens; 7—air/water spray.

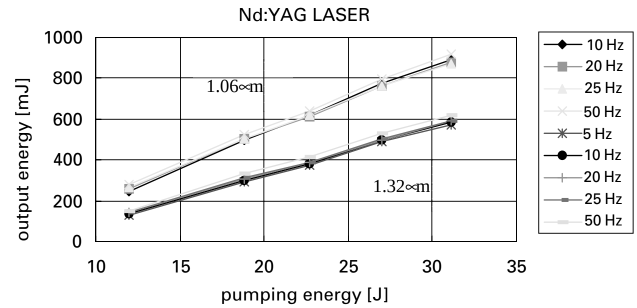



Fig. 5. Output energy with respect to pumping energy at 1.06 and 1.32 μm.

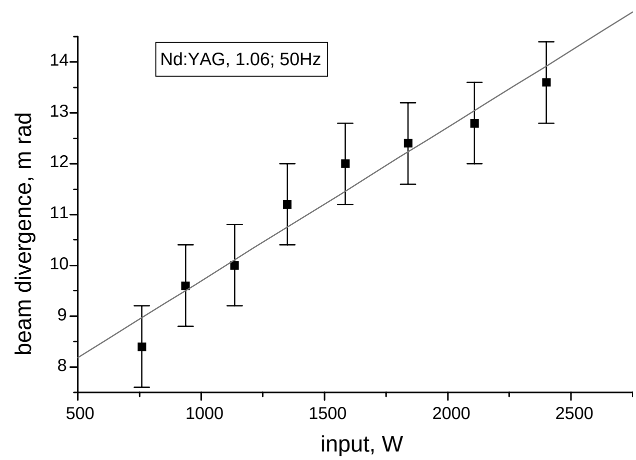



Fig. 6. Beam divergence of 1.06 μm with respect to input power.

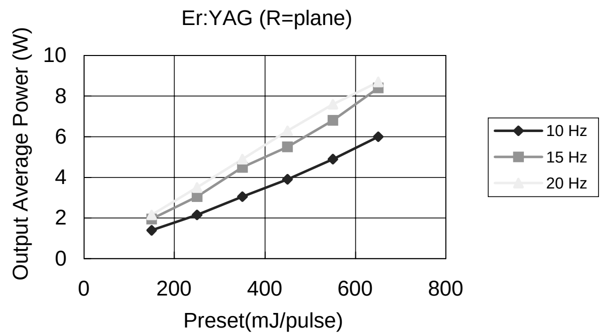
voltages for charging capacitors due to the difference in the optical characteristics between Nd:YAG and Er:YAG rods. The efficiency of Er:YAG rod is lower than that of Nd:YAG rod and higher power supply voltage is required. On the other hand, Nd:YAG has the design specification with a higher repetition rate in clinical use. In order to use the same high-voltage power supply for both Nd:YAG and Er:YAG resonators, the following design scheme is employed. Two smaller but identical power supply modules are developed. For the Nd:YAG resonator, two power supply modules charge the capacitors for igniting the flashlamp alternatively in order to increase the repetition rates. For the Er:YAG resonator, which requires higher voltage and low repetition rates, the two power supply modules work in series and simultaneously.

Laser emission is delivered by optical fibers to the operational zone. To deliver the emissions of the Nd:YAG laser, a common fused silica fiber is coupled from a SMA connector of the laser to an handpiece (Fig. 4a). A fiber whose size is between 200 and 400 μm is used and the fiber contacts the surface of soft tissue during treatment. Short pulse duration ensures that there is no need for cooling on the tissue surface. For Er:YAG laser beam delivery, the situation is different. Common silica or quarts fibers cannot deliver 3 μm light. Fluoride-based crystalline fibers can deliver this near infrared band, but the crystal fiber made from sapphire is used since the fluoride-based fibers can handle smaller power density than the sapphire fiber. Fiber toxicity and water solubility are other limitations of using the fluoride fibers. The diameter of sapphire fiber is in the range 300–400 μm. Light of 2.94 μm is delivered through a non-contact mode handpiece and the mixture of water and air is sprayed to a target area for cooling (Fig. 4b).

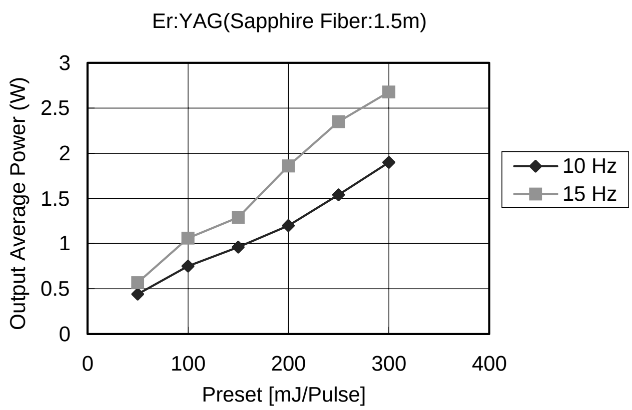
All laser operations are computer controlled. The cooling system shown in Fig. 3 is fully self-contained with an internal water circuit and external air cooling. An internal power meter monitors laser output. An additional energy meter installed inside the laser gives energy readouts at the distal end of the fiber. Two internal diode lasers are used as aiming beams. The beams of the aiming diodes are also utilized for the alignment of the laser resonators.

## 3. Results

Pumping energy versus output energy for 1.06 and 1.32 μm is illustrated in Fig. 5, where the pulse duration is 100 μs. The obtained pumping efficiencies are 2.28–2.68% for 1.06 μm and 1.16–1.93% for 1.32 μm, respectively. The efficiencies depend on the repetition rates. Our experiment




(a) at the resonator




(b) at the output fiber

Fig. 7. Output energies at the laser resonator and at the sapphire fiber (1.5 m) at 2.94 μm.

with the optical fiber shows that the total coupling coefficient is equal to 0.78. This included the Fresnel losses at the lens and fiber surfaces. Fig. 6 shows the beam divergence at 1.06 μm. As the electrical input energy from the power supply increases the beam divergence also increases. Proper coupling between the laser and the fiber is easily obtained within this range of beam divergence. The pumping efficiency of 2.94 μm also decreases as the repetition rates increase as shown in Fig. 7a. For the given preset energy per pulse (mJ/pulse), the output energies at the laser and at the end of 1.5 m-long sapphire fiber are shown in Fig. 7b. As the final arrangement of the laser system, the power meter monitors the output power at the handpiece and the actual pumping powers are adjusted during the calibration process so that the preset values on the control panel and the output energies at the handpieces become equal.

## 4. Discussion

Two types of soft-tissue surgery, i.e., precise cutting using a fiber of contact-mode and thermal coagulation or vaporization, can be successfully met by applying two wavelengths of 1.06 and 1.32 μm, respectively. These wavelengths are generated from one Nd:YAG rod that is one of the most widely used laser media for medical lasers.

However, the operation of Er:YAG laser is more complex. The Er:YAG crystal is a medium with a high thermal loading factor. Actually, the value of heat deposition may reach 35–50% of the pumping energy in comparison with about 5% of the Nd:YAG crystal. With forced cooling of the Er:YAG rod using the liquid, the thermal lensing effect generated in the rod causes a substantial decrease of lasing efficiency even at relatively low pumping level. From our investigation of output characteristics, about 30% decrease in the efficiency is observed as the pulse repetition rates increase from 10 to 20 Hz (Fig. 7a). While analyzing the output energy at different repetition rates, it is speculated that the decrease of lasing volume is responsible for the decrease of laser efficiency. Strong aberrations of thermal lensing in the active medium were observed while lasing parameters were studied in terms of the distribution of output energy over the cross-section of the beam. During the operation of 2.94 μm light with the pulse repetition rate more than 1 Hz, substantial change occurs in the beam divergence from the start of pumping to the time of reaching a steady-state thermal distribution in the rod. In the steady-state mode, the divergence is in the range 15–20 mrad, though a small divergence of 2–3 mrad is observed at the initial several pulses during a few seconds. The presence of small divergence may cause the damage on the sapphire fiber even at an energy per pulse of 200 mJ. When a very narrow divergence during the on-set of laser pulses was eliminated, no fiber damage was observed. To make the beam divergence more constant during the onset of laser, different methods may be implemented; (1) using a mechanical switch which blocks lasing during the initial period, (2) design of a pumping chamber with diffuse reflection, (3) slow increase of the pumping energy from the start to a preset value of pumping energy. The first method excludes initial laser pulses and the delayed laser output will be inconvenient for an operator. The second method, in most cases, sacrifices the pumping efficiency. For the third method, it may be difficult to control the exact pulse per energy and will be inconvenient for physicians. We adopted a simple, but efficient scheme which is the addition of a warming-up mode in laser operation. When the laser is turned on or when laser emission is not made for a certain time interval, the laser automatically goes to the warming-up mode. In the warming-up mode, the pulses of very low energy are generated for about 10 min, which warm up the laser rod. An additional advantage is longer lifetimes of the infrared optical components in the Er:YAG laser and the sapphire fiber since residual water is vaporized during the warming-up mode. Water in the infrared optics is one of the main reasons for degrading the performance because water is a highly absorbing substance in the infrared wavelengths.

From the same Nd:YAG crystal, both 1.06 and 1.32 μm are generated. Both Nd:YAG and Er:YAG resonators share the cooling unit and high-power supply modules. We demonstrate that it is feasible to develop a compact, infrared, pulsed three-wavelength dental laser system. The full size of a laser prototype is only $75 \times 55 \times 32.5$ cm, which has been achieved by the deliberate designs of optical resonators, cooling system and high-voltage power supply modules.

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