Diode-Pumped Tunable Yb:YAG Miniature Lasers at Room Temperature: Modeling and Experiment

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***Abstract*— We present a simple design rule for diode-laser-pumped quasi-three-level lasers by using the M^2 factor. The validity of this model was demonstrated by diode-pumped Yb:YAG laser experiments. The maximum output power of 1.33 W and optical slope efficiency of 63% were obtained in a 400-μm Yb:YAG-chip miniature laser. Using a 200-μm Yb:YAG chip, a 70% optical slope efficiency was reached. In a coupled-cavity configuration, with a quartz birefringent tuning filter, 8.2 THz (29 nm) of tuning was obtained at room temperature. By changing to a calcite birefringent filter, single-axial-mode oscillation with an output power of 500 mW was observed.**

***Index Terms*— Birefringent filter, coupled-cavity, diode-pumped solid-state laser, M^2 factor, microchip crystal, quasi-three-level laser, single-mode oscillation, tunable laser, Yb:YAG.**

I. Introduction

THERE has been considerable interest in the trivalent ytterbium-ion-doped solid-state laser because of its low thermal loading and its broad absorption band for In–Ga–As diode-laser pumping. The Yb^{3+} ion's simple electronic structure prevents excited-state absorption, up-conversion, or concentration quenching. Moreover, YAG has excellent thermomechanical properties as a laser host. Recent literature attests to enormous potential for high power and high efficiency of Yb:YAG lasers [10], [11]. The Yb:YAG laser has a relatively wide fluorescence bandwidth that is good for both a tunable laser [6], [8] and a mode-locked laser [9]. Several techniques [6], [9], [13] have been used to demonstrate wide tuning and single-mode operation. Due to its simplicity and low-loss configuration, the coupled-cavity technique is one approach to obtain single-mode laser operation at room temperature. However, a poor frequency tunability of a Yb:YAG laser using a coupled-cavity pumped by a Ti:sapphire laser has been observed [14].

This paper focuses on diode-laser pumping of a quasi-three-level laser using the M^2 factor and a simple design guideline derived for the Yb:YAG laser. Room-temperature tunable-single-axial-mode oscillation was demonstrated using a coupled-cavity miniature laser with a 400-μm Yb:YAG microchip. We obtained 1.33-W output power at 1.03 μm with a 2.9-W absorbed pump power using intracavity birefringent filters. The coupled-cavity laser tuned over 8.2 THz (29 nm) with multimode oscillation. Single-mode-oscillation output power of 500-mW has been observed using a 1-mm-thick calcite birefringent filter.

Manuscript received December 2, 1996; revised January 3, 1997. This work was supported by the Grant-in-Aid for Encouragement of Young Scientists (Project 08 750 054), The Ministry of Education, Science, Sports, and Culture, Japan.

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Publisher Item Identifier S 1077-260X(97)03763-5.

II. Design Methods

The main disadvantage of Yb:YAG as compared with Nd:YAG is its reabsorption loss due to the significant population in the lower laser level at room temperature. This leads to a number of deleterious effects, including increased laser threshold and reduced slope efficiency. However, by increasing the pump intensity to overcome the lower laser absorption, highly efficient laser operation can be achieved [1], [5]. The salient issue which must be addressed in the design of a practical Yb:YAG laser is how to realize the higher brightness pumping because the output beam from a diode laser is in a higher order transverse mode. The requirements of the light beam for efficient coupling to a laser-cavity mode can be described in various ways [3], [4], [17]; here, we analyze this problem using a beam-quality description [12].

An arbitrary diode-laser beam used for an end-pumped laser is considered. Using an M^2 factor, the propagation of a higher order transverse-mode beam from a high-power diode laser can be described as a Gaussian beam [15], [16]. The spot size as a function of the distance z from the beam waist expands as a hyperbola, which has the form

$$w_p(z) = w_{p0}\sqrt{1+\left(\frac{M^2\lambda_p z}{n\pi w_{p0}^2}\right)^2} \tag{1}$$

where w_{p0} is the beam waist, λ_p is the pumping wavelength of free space, and n is the propagation medium refractive index. The conforcal parameter $\ell_{\rm cp}$, defined as the distance between the points at each side of the beam waist for which $w(z) = \sqrt{2}w_{p0}$, is given by

$$\ell_{\rm cp} = \frac{2n\pi w_{p0}^2}{M^2\lambda_p}. \tag{2}$$

For optimum mode matching of the pump and laser beam, the confocal length of the pump beam must be longer than the absorption length of gain medium L, as shown in Fig. 1. Of course, for a four-level laser, the pump-beam radius at the end of the gain medium should be smaller than the spot size of a laser-cavity mode, i.e., $w_p(L/2) \le w_{\ell 0}$. On the other hand, for the quasi-three-level laser, the waist size of the pump

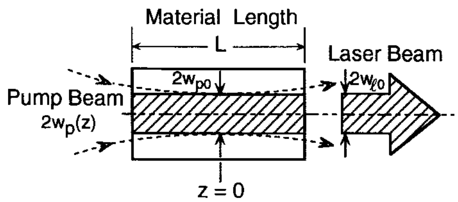


Fig. 1. The model of an end-pumped quasi-three-level solid-state laser. For a four-level laser, the radius of the focused pump beam at the end of the active medium $w_p(L/2)$ has to be smaller than the laser spot size $w_{\ell 0}$.

beam should be larger than a spot size of a laser-cavity mode $w_{p0} \geq w_{\ell 0}$ [2], [18]. As a result, the minimum focused beam radius is given by

$$w_{p0} \geq \sqrt{\frac{M^2 \lambda_p L}{2n\pi}}. \tag{3}$$

The effective pump intensity is given by

$$I_p \approx \frac{\eta_a P_i}{\pi w_{p0}^2} \tag{4}$$

where η_a is the absorption efficiency and P_i is the input pump power. Laser oscillation occurs when the effective pump intensity exceeds an absorbed threshold intensity $I_{\rm th}$, which is given by

$$I_{\rm th} = \frac{h\nu_p}{2(f_1+f_2)\sigma\tau}(L_i + T + 2f_1 N_0 \sigma L) \tag{5}$$

where $h\nu_p$ is the pump photon energy, L_i is the intrinsic cavity loss, T is the transmittance of the output coupler, N_0 is the total Yb^{3+} ion number, σ is the spectroscopic cross section for the laser transition, τ is the lifetime of the upper manifold, and f_1 and f_2 are the fractional population of the lower- and upper-laser levels, respectively. For highly efficient operation, a pumping intensity is required, which saturates the lower laser-level absorption. To achieve the condition, the pump intensity should be five times greater than the laser-threshold pump intensity [18]. In general, the threshold pump intensity due to lower laser-level absorption is few times larger than that due to cavity loss. Consequently, we state the requirement as

$$I_p \geq 5 I_{\ell,\rm th} \tag{6}$$

where $I_{\ell,\rm th}$ is the local threshold intensity, which is given by substracting the cavity losses $(L_i + T)$ from (5) [7]. Finally, the appropriate focusing spot size is given by (3), (4), and (6):

$$\sqrt{\frac{\eta_a P_i}{5\pi I_{\ell,\rm th}}} \geq w_{p0} \geq \sqrt{\frac{M^2 \lambda_p L}{2n\pi}}. \tag{7}$$

This equation indicates the requirement for the pumping-beam and laser-material characteristics to obtain a good overlap between the pumped volume and TEM_{00} cavity mode in the active medium. As the pumping- and cavity-mode spot sizes decrease under a good mode overlap each other, it is evident that the reabsorption loss becomes saturated so that the slope efficiency is increased. From the right-hand side (RHS) of (7) with the M^2 factor of the pump beam and the material length, we have the minimum focus size. On the other hand, although a large focused beam realizes good mode matching,

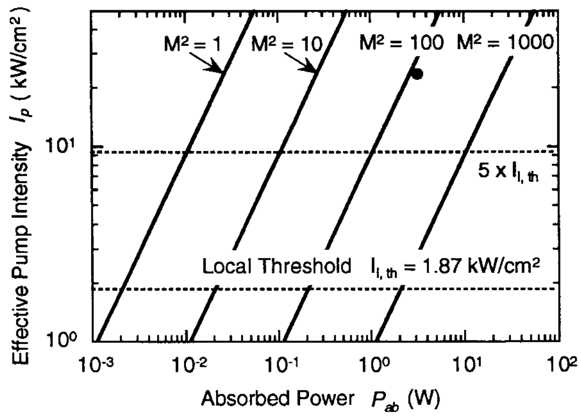


Fig. 2. Effective pump (4) intensity as a function of absorbed power. The Yb:YAG absorption coefficient at 940-nm pump wavelength was taken as 23 cm^{-1}. The OPC-C005-FC diode pump system used in our experiments are indicated by the black point.

it is difficult to keep a highly pumping intensity to saturate the reabsorption loss. From the left-hand side (LHS) of (7), along with the local threshold and the absorbed pump power, we have an upper limit of the focus size. Consequently, the multifold pass-pumping configuration [7], the resonantly pumping one [9], and the relatively high doped-Yb:YAG active media are effective solutions to obtain the desired absorption efficiency.

Fig. 2 shows the effective pump intensity I_p obtained by substituting the pump radius given by (2) into (4). In this calculation, we assumed that the Yb:YAG crystal length is equal to the inverse active-medium absorption coefficient at the pump wavelength. To increase the effective pump intensity, we chose a 25 at.-% Yb^{3+}-doping YAG crystal with its absorption coefficient of 23 cm^{-1} at 940 nm. Added to this, the effective pump intensity depends on the M^2 factor and the maximum output power of pump source. For a high slope-efficiency operation in a quasi-three-level laser, a pump intensity of at least five times the local threshold intensity ($I_{\ell,\rm th} \sim 1.9$ kW/cm^2) must be obtained. This figure shows that M^2 times higher absorption power is required for effective pumping by using high-order transverse mode lasers compare with fundamental mode lasers. The fiber bundled diode laser (Opt Power Co., OPC-C005-FC) for which M^2 is ~120 at a 5-W pump power is shown in Fig. 2. This diode laser available to us has an enough effective pump intensity.

III. Experiment

Fig. 3 shows the schematic of the diode-pumped tunable Yb:YAG miniature laser. The laser cavity consists of a Yb:YAG chip, a birefringent filter, and a 95% reflectivity output coupler placed 25 mm apart from the laser crystal. The mirror radius was 30 mm. The Yb:YAG crystals (Scientific Materials Co.), with dimensions of 4 × 4 mm^2 and a thickness of 200 and 400 μm were used. Yb:YAG crystals were assembled on sapphire substrates by the optical bond to facilitate handling and heat removal. The interface between the sapphire and the Yb:YAG crystal has high transmission (>95%) at the pumping wavelength and high reflectivity

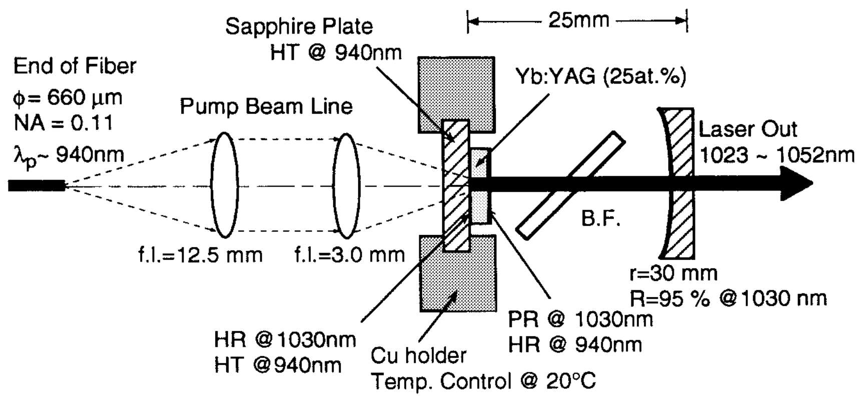


Fig. 3. Schematic of the coupled-cavity Yb:YAG laser. For tuning and mode selection, 1–mm-thick birefringent filters were used.

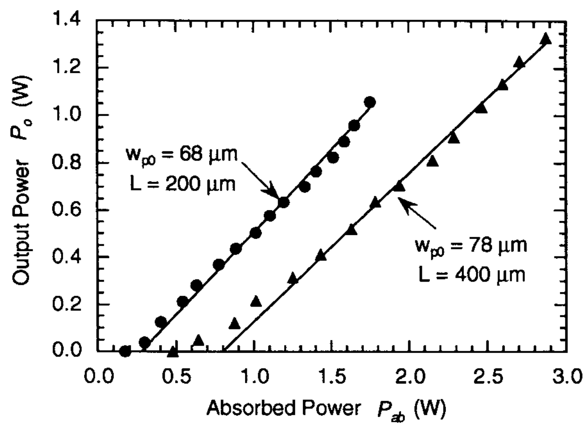


Fig. 4. Input–output power characteristics for a 400-μm Yb:YAG chip placed with a 50-mm radius of a curvature mirror and for a 200-μm Yb:YAG chip with a 30-mm radius of curvature mirror configuration. The reflectivity of output mirrors was 95%. The Yb:YAG crystal was held at a holder temperature of 20 °C.

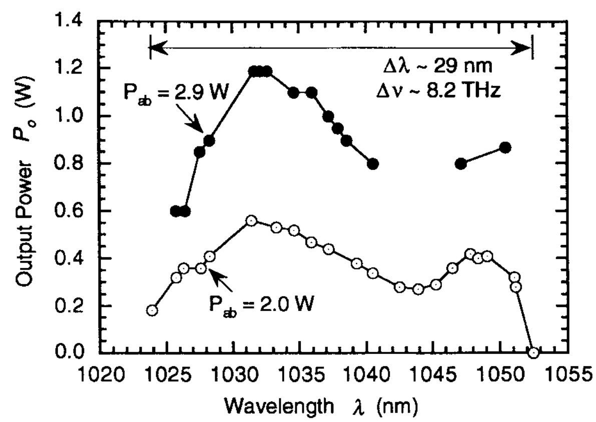
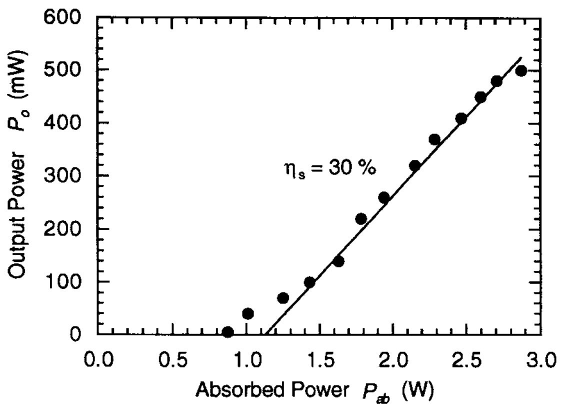


Fig. 5. Output power as a function of wavelength for the 400-μm Yb:YAG chip using 1-mm-thick quartz birefringent filter.

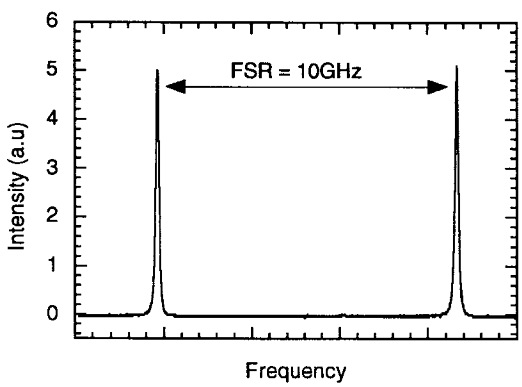
(>99.9%) at the laser wavelength. The dielectric coating condition for the Yb:YAG crystal was decided by taking the refractive index of the bond into account. The opposite side has high reflectivity (~90%) at the pump wavelength and a small percentage of reflectivity at the laser wavelength for the coupled cavity. The temperature of the laser holder was controlled by using a thermo-electric cooler set at 20 °C. In this case, the free spectral ranges (FSR's) of the Yb:YAG microchip and cavity are ~200 and ~6 GHz, respectively. For a wide tuning experiment, a 1–mm-thick quartz plate was inserted in the laser cavity. The OPC-C005-FC fiber bundled diode-laser beam, collimated by a 12.5-mm focal length lens, was used to longitudinally pump the Yb:YAG crystals. Using lenses of a 2.6- and 3.0-mm focal length, the pump beam was focused at 68- and 78-μm radius in the active media.

The Yb:YAG output power as a function of absorbed pump power is shown in Fig. 4. Because the 933-nm pump wavelength of the diode laser is far from maximum absorption wavelength in crystal (which occurs at 940 nm) the absorption coefficient is limited to $\alpha = 11$ cm^{-1}. Therefore, laser performances were evaluated by using the absorbed power in crystals. For the 400-μm-thick Yb:YAG chip, the threshold was measured to be ~480 mW and the slope efficiency was η_s =63% relative to the absorbed power with a 78-μm spot size. The output mirror had a radius of curvature of 50 mm and a cavity length of 7 mm. The maximum output power of 1.33 W was at 2.9 W of absorbed pump power with M^2 of 1.15 for multiaxial-mode oscillation. According to (7), for the 400-μm Yb:YAG crystal, the proper focused-pump-beam radius is from 88.8 to 92.2 μm. By changing the focused spot size to 99 μm with a set of 10.0 and 3.0 mm focal-length lenses, and the output coupler to a 100-mm radius of curvature mirror (95% refractivity), the maximum slope efficiency was increased to ~70%. However, because the laser-threshold power was increased to 800 mW, the maximum output power was limited to 1.20 W. On the other hand, for the 200-μm-thick Yb:YAG crystal with a 68-μm radius of focused pump beam, the slope efficiency was increased to 70%. We note that this case satisfies the conditions of (7). In this experiment, a set of 12.5- and 2.6-mm focal-length lenses were used for the pump-beam line and the laser resonator of 4-mm cavity length was equipped with a output mirror of 30-mm curvature mirror radius.

The Yb:YAG laser has a wide gain width of 1026–1035 nm. In addition, because it has a simple energy-level scheme, it is possible to oscillate at wavelengths that extend beyond the laser gain peak. To evaluate the tunability of the Yb:YAG laser in the previous 400-μm Yb:YAG chip configurations, we



(a)



(b)

Fig. 6. (a) Single-axial-mode output power as a function of absorbed power in the 400-μm Yb:YAG chip using 1-mm-thick calcite birefringent filter. (b) Optical spectrum of single-axial-mode operation at 1.03 μm measured by using a scanning Fabry–Perot interferometer with a 10-GHz FSR.

introduced a birefringent filter. Fig. 5 shows tuning curves of the Yb:YAG laser using a 1-mm-thick quartz birefringent filter whose effective FSR was ~17 THz. At room temperature, tuning from 1023 to 1052 nm (29 nm, 8.2 THz) with two or three longitudinal modes was obtained. The mode spacing at 0.63 nm (~180 GHz) is in agreement with the Yb:YAG crystal-mode space. Although the output power at 1032 and 1050 nm was up to 1.19 and 0.87 W, with the absorbed power of 2.9 W, we recognized a tuning gap from 1041 to 1047 nm. The Yb:YAG laser gain at ~1030 nm is higher compared with that corresponding to 1041–1045 nm region, but at the same time, the reabsorption losses at ~1030 nm are significant. However, became the reabsorption losses are saturated by the high value of the pumping, it was impossible to keep the laser oscillation at the 1040-nm region.

The quartz birefringent filter was replaced by a 1-mm-thick calcite birefringent filter for single-axial-mode experiments. The effective FSR was reduced to ~0.94 THz. Although the tuning range was limited to ~7 nm around a 1030-nm region, single-frequency oscillation with 500-mW maximum output power was achieved, as shown in Fig. 6(a). The optical spectra were monitored with a scanning confocal interferometer with 60-MHz resolution and a 10-GHz FSR for 1.064 μm. Fig. 6(b) shows the longitudinal modes of the Yb:YAG laser with 500-mW output power at 1030 nm. The maximum output power of 1 W was obtained with the two axial modes operating in the same laser cavity, so that the 500-mW single-mode power limit is due to the spatial hole-burning effect.

IV. Conclusion

A design approach for optimizing end pumping of three- and four-level lasers has been presented. Using this design method we have developed a simple and practical Yb:YAG miniature laser. A maximum slope efficiency of ~70% was obtained in fundamental transverse-mode operation. By inserting a birefringent filter into the cavity, the Yb:YAG laser was tuned over 29 nm (8.2 THz) at room temperature. By replacing the calcite birefringent filter by the quartz filter, tunable single-frequency operation has been realized. These performances are expected to be improved by a cooling of the Yb:YAG active medium.

The possible applications of this kind of laser includes laser remote-sensing systems, light source for injection-locking pump source for nonlinear frequency conversion, and Pr^{3+} fiber amplifier system.

Acknowledgment

The authors wish to thank N. Pavel of Fukui University for an enlightening discussion and also appreciate the skilled technical assistance by T. Motegi of Oyokoden Laboratory Company.

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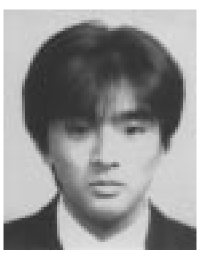

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