Modeling of end-pumped quasi-three-level lasers by using a M^2 factor and cw operation of tunable Yb:YAG miniature lasers

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Abstract

A simple model has been presented for diode-laser pumped quasi-three-level lasers by including the effect of pump-beam quality as a M^2 factor. The design model was examined by using a diode pumped Yb:YAG laser. 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. In a coupled-cavity configuration, with a quartz birefringent tuning filter, 8.2 THz 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.

Keywords

Laser resonators, Optical resonators, Laser materials, Rare earth solid-state lasers

Introduction

Diode laser pumped ytterbium ion doped solid-state lasers have been extensivily studied because of its low thermal loading and its broad absorption band for InGaAs 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 works attest to enormous potential for high power and high efficiency of Yb:YAG lasers [7][8].

This paper focuses on diode-laser pumping of a quasi-three level laser and a simple design guideline using the M^2 factor is 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 an intracavity birefringent filters. The laser tuned over 8.2 Thz (29 nm) with multi-mode oscillation using intracavity birefringent filters. Single-mode-oscillation output power of 500-mW has been observed using a 1-mm thick calcite biregringent filter in the coupled-laser-cavity.

Modeling

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 diode-laser is 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][11]; here we analyze this problem using a beam quality description [9].

An arbitrary diode laser beam used for an end-pumped laser is considered. Using 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 [10].

For optimum mode matching of the pump and laser beam, the confocal length of pump beam must be longer than the absorption length of a gain medium L as shown in Fig. 1. Of course, for a four-level-laser, the pump beam radius at end of the gain medium should be smaller than a spot size of a laser cavity mode, i.e. $w_p(L/2) \le w_{\ell 0}$. In other hand, for the quasi-three-level laser, the waist size of pump beam should be larger than a spot size of a laser cavity mode, $w_{p0} \ge w_{\ell 0}$ [2][12]. As a result, the

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Clifford R. Pollock and Walter R. Bosenberg (ed.)

minimum focused beam radius is given by

$$w_{p0} > \sqrt{\frac{M^2 \lambda_p L}{2 n \pi}}\ , \qquad (1)$$

where w_{p0} is the beam waist, λ_p is the pumping wavelength and n is the propagation medium refractive index. This equation indicates the minimum focus size to keep a good overlap between the pumped volume and TEM_{00} cavity mode.

In other hand, for highly efficient operation, a pumping intensity is required that saturates the lower laser level absorption. To achieve the condition the pump intensity should be 5 times greater than the laser threshold pump intensity [12]. 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,

$$I_p \approx \frac{\eta_a P_i}{\pi w_{p0}^2} > 5 I_{\ell,th}\ , \qquad (2)$$

where η_a is the absorption efficiency and P_i is the input pump power, and $I_{\ell,th}$ is the local threshold intensity which is given by [6]

$$I_{\ell,th} = f_1 N_0 L h \nu_p / (f_1 + f_2) \tau\ , \qquad (3)$$

where N_0 is the total Yb^{3+} ion number, τ is the lifetime of the upper manifold, f_1 and f_2 are the fractional population of the lower and upper laser levels, respectively. As a results, the appropriate focusing spot size is given by Eqns (1) and (2)

$$\sqrt{\frac{\eta_a P_i}{5 \pi I_{\ell,th}}} > w_{p0} > \sqrt{\frac{M^2 \lambda_p L}{2 n \pi}}\ . \qquad (4)$$

This equation indicates the requirement for the pumping beam and laser material characteristics to obtain a good overlap. From the RHS of Eq. (4) with the M^2 factor of the pump beam and the material length, we have minimum focus size. In other hand, a large focused beam realizes a good mode matching, however, it is difficult to keep a highly pumping intensity to saturate the reabsorption loss. From LHS of Eq.(4) with the local threshold and the absorbed pump power, we have an upper limit of the focus size.

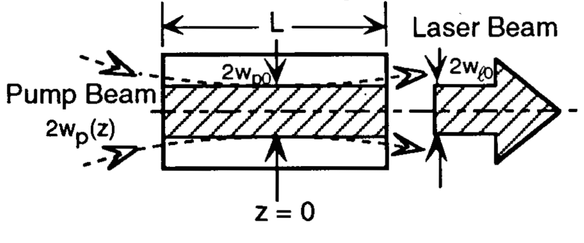

Fig. 1 The model of an end-pumped quasi-three-level solid-state laser.

Experiments

Figure 2 shows the schematic of the diode-pumped wide tunable Yb:YAG laser geometry. The laser cavity consists of a Yb:YAG crystal, birefringent filters and a 30-mm radius of curvature output coupler. The Yb:YAG crystal with 25 at.-% Yb^{3+} doping (Scientific materials Co.), with dimensions of 4 x 4 mm^2 and thickness of 200 and 400-μm was 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 (>99.9 %) at the lasing wavelength. An opposite side of the Yb:YAG has high reflectivity (~90 %) at the pump wavelength and few percent reflectivity at the lasing wavelength for the coupled-cavity. An external mirror was coated for a reflectivity of 95 % at lasing wavelength. The position of this external mirror was separated by 25 mm from the crystal. For a wide tuning experiment and single-axial mode operation, 1 mm thickness quartz and calcite plate were inserted in the laser cavity, respectively. The Yb:YAG crystal was longitudinally pumped by the beam from the fiber bundled diode-laser (Opt Power Co., OPC-C005-FC), which was collimated by use of a 12.5 mm focal-length lens. Then a 2.6 and 3.0 mm focal-length lens was used to focus the pump beam to a diameter of 68 and 78 μm in the laser crystal. The temperature of the laser holder was held at at 20 °C by using a thermo-electric cooler. In our case, the free spectral ranges (FSR) of the Yb:YAG microchip and a total cavity length are ~200 GHz and ~6 GHz, respectively.

The Yb:YAG output power as a function of absorbed pump power is shown in Figure 3. Because the pump wavelength of diode laser, 933 nm, is far from maximum absorption wavelength, 940 nm, the absorption coefficient is limitted to $\alpha = 11\ \mathrm{cm}^{-1}$. Therefore we evaluated the laser performance to use effective absorbed power. For 400 μm thickness

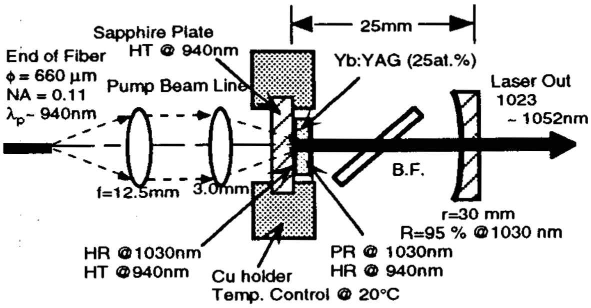

Fig. 2 Schematic of the coupled cavity Yb:YAG laser. For tuning and mode selection, 1mm thickness birefringent filters were used.

Yb:YAG crystal, the threshold was measured to be ~480 mW and the slope efficiency was η_S = ~63 % relative to the absorbed power with 68 μm spot size. The maximum output power reached 1.33 W with M^2 of 1.15 for multi axial mode oscillation at 3.3 W of absorbed pump power. On the other hand, for 200 μm thickness Yb:YAG crystal, the slope efficiency was increased to 70 % because this case satisfies the conditions of equation (4) because the pump laser has M^2 ~ 120.

Then, to evaluate the tunability of the Yb:YAG laser, we used internal birefringent filter in previous cavity. The Yb:YAG laser has wide gain width, 1026~1035 nm. In addition, it is possible to oscillate at variable wavelengths beyond the laser gain because it has simple energy levels. Figure 4 shows tuning of Yb:YAG laser using a 1-mm thickness quartz filter which effective free spectral range was ~ 17 THz. In this configuration, tuning from 1023 to 1052 nm (29 nm, 8.2 THz) was achieved with two or three longitudinal modes. The observed free spectral range of 0.63 nm (~180 GHz) was in agreement with Yb:YAG cavity mode space. Then the quartz birefringent filter was changed to a 1-mm thickness calcite birefringent filter because the effective free spectral range was reduced to ~ 0.94 THz. Although the tuning range was limited to ~ 7 nm around 1030 nm region, single-frequency oscillation was achieved with 500-mW output power.

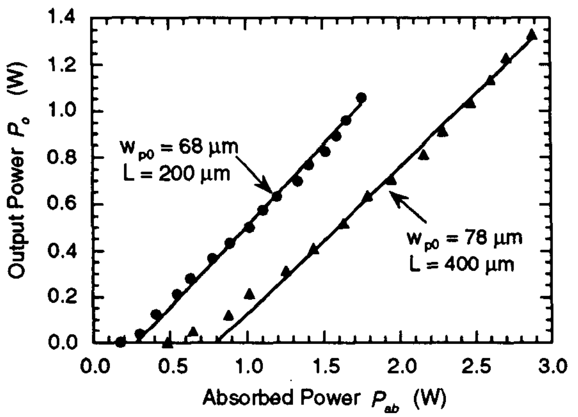

Fig. 3 Input-output power characteristics for a 400 μm Yb:YAG chip placed with a 50 mm radius of curvature mirror and for a 200 μm chip with a 30 mm radius of curvature mirror configuration.

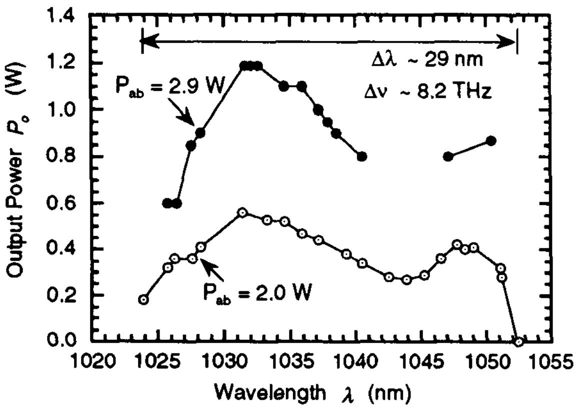

Fig. 4 Output power as a function of wavelength for the 400 μm Yb:YAG chip using 1-mm thick quartz birefringent filter.

Summary

A design approach for optimizing end pumping of quasi-three-level lasers has been present. 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. Next, replacing the calcite birefringent filter by the quartz filter, tunable single-frequency operation has been realized. These performances are expected to be improved by 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.

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