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Short communication

High-power TEM_{00} composite solid-state laser with a short, telescopic resonator

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A short, telescopic laser resonator design is proposed for high-power, single-transverse mode emission from a lens shape composite solid-state laser. Such a laser combines the simplicity of the edge-pumped thin disk laser with the great advantage of axial heat flow in a very thin, below 50 μm, active media thickness. The efficiency, output power and conditions of the single transverse mode oscillation are analyzed. For a device of a few millimeters wide, the slope efficiency of 49% and the threshold of a few watts are predicted. The possibility of output power of kW level is analyzed.

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1. Introduction

Appropriate choice of the pump geometry is the key issue in the optimization of diode-pumped ytterbium-doped lasers. A number of representative designs have already been presented in related literature: high-power thin disks with multiple mirrors pumps [1], high-energy cascaded plates [2] with lens-duct coupled large pumps, end-pumped rods [3] and slabs [4], edge-pumped composite microchips, at various pump powers. Several applications, like two-photon microscopy, precise cutting in micromachining, require high-beam-quality, high-power laser sources. The most appropriate geometry for TEM_{00}, high power, high efficient laser operation is thin disk geometry. The main advantage of disk lasers is given by large ratio of cooling surface to pumped volume which is the basic advantage to extract high output power from small volume. If the one face of the disk is cooled the heat flux and the laser beam are collinear to each other. As a consequence, thermal lensing effects are dramatically reduced. Due to small thickness of the crystal, this configuration leads to low absorption efficiency since the effective absorption length, the unabsorbed power is reimaged onto the crystal several times making a complicated setup. Alternative solution is given by edge-pumped [5,6] composite microchip configuration giving good absorption efficiency while preserves setup's simplicity. For scaling up the output power one requires more effective crystal cooling and a key issue is decreasing the thickness of the crystal [7]. Composite microchips with thickness lower than 200μm are not suitable for edge-pumping because it requires complicated optics to focus high power diode lasers bellow this dimension. We want to overcome this impediment by proposing a new design for the geometry of the Yb based microchip laser. It keeps the edge of the crystal large enough for simple diode pumping optics while the doped active region has a thickness bellow 100μm. The laser gain media has a composite structure that consists of cylindrical core doped gain media (single crystal or ceramic material) surrounded by highly transparent ceramic undoped YAG. A very thin plane-concave lens having all surfaces polished at high quality level is fabricated from the composite material. The diameter of the doped core is around several millimeters. Such a large gain area makes quite difficult TEM_{00} mode laser oscillation by using resonators of reasonable length. Unstable resonators are not a good choice due to intrinsically low gain through the thin dimension of the gain medium.

In this paper we analyze the output power and efficiency of the composite microchip lens shape concept together with a short telescopic resonator which allows TEM_{00} operation for large beam diameter.

2. Lens built of composite active media

The structure proposed to be used is a composite structure that consists of cylindrical core doped gain media (single crystal or ceramic material) surrounded by highly transparent ceramic undoped YAG. A very thin plane-concave lens having all surfaces polished at high quality level is fabricated from the composite material[8].

The flat surface of the microchip has high reflectivity dielectric coating and is attached to a heat sink by using gold-tin technology in order to have an efficient heat transfer, Fig. 1. The design makes use of several collimated high power naked diode lasers surrounding, in a circular arrangement, the laser gain media. By using a cylindrical lens the pump radiation is focused on the microchip's edge and propagates by total internal reflection (TIR) inside the gain media. Because of the lens shape design the pump beam changes its direction many times inside the core giving good absorption efficiency. Depending on the doping level and on the core's diameter, good absorption uniformity may be obtained.

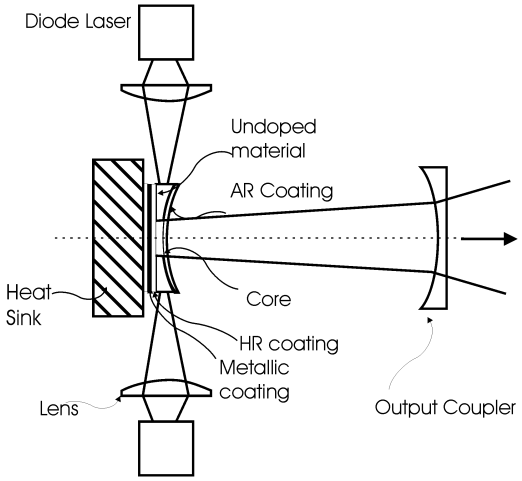

Fig. 1. Edge pumped lens-shape gain media laser, side view.

Fig. 2 shows ray tracing simulation obtained by using the RAYICA software. The pump beam parameters used in these simulations are those of high power stack diode laser, 10 mm wide, 1.75 mm pitch, 34° fast axis divergence and 6° slow axis divergence. The important advantage of this configuration is given by the very thin-disk laser crystal working as an active mirror which allows high power laser operation while keeping the temperature at low level. This arrangement is very attractive especially for quasi-three level lasers like Yb:YAG or Yb:KGW which are sensitive to the operation temperature.

Fig. 2. Yb:YAG/YAG microchip laser: side view of the ray propagation inside of the microchip (ray hits first the spherical surface).

3. Numerical calculations

In order to determine the design and operation parameters of lens shape microchip laser that is expected to work at higher temperature, a numerical model is used. In particular, it allows the determination of the scaling properties of this laser concept. For the calculation various properties of Yb:YAG are needed, which are discussed in details in Ref. 9. As the temperature distribution inside the crystal has a strong effect on the output power, a detailed knowledge of the heat conductivity is important. We use the data provided by Ref 10. The numerical model consists of three main steps: (1) the calculation of the distribution of the absorbed pump radiation through the composite lens shape crystal by using commercial RAYICA ray tracing software; (2) the calculation of the temperature-dependant output power; (3) based on temperature distribution inside the core, the thermal lens is approximated and telescopic resonator is calculated. The generation of the heat is assumed to result from the Stokes defect of 8.6% between the energy of the pump and the laser photon. The heat load is calculated according to the distribution of the absorbed pump radiation. In the calculations a heat resistance between the crystal and the cooling medium is included, which is determined from finite–element calculations taking into account the cooling medium.

4. Basic relations

In the pump configuration mentioned above, neglecting losses and not taking into account mechanical fracture limits, output power and optical efficiencies as shown in Fig. 3 and 4 are calculated for varying pump power.

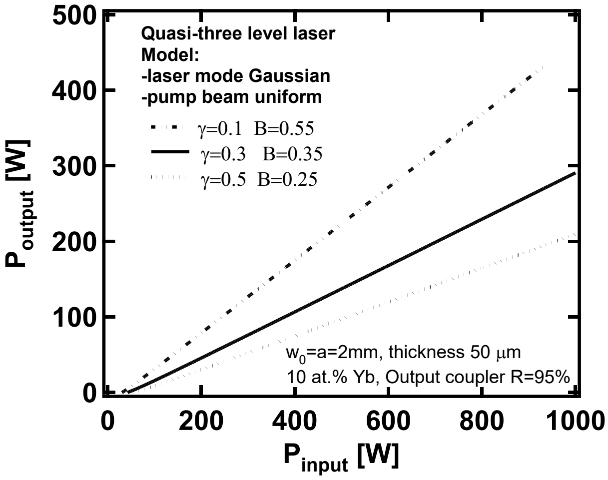

Fig. 3. *Output power versus input power for quasi-three level laser.*

For a quasi-three level laser with the mode distribution and pump rate spatially dependent (See Fig. 3), the parameters **γ** , **B** , **w_0** and **a** are:

$$\gamma = \gamma_i + \frac{\gamma_1 + \gamma_2}{2}; \; B = \frac{\sigma_a^{eff} N_t l}{\gamma}; \quad w_0 = a$$

where

γ – total loss per pass of the cavity **γ_i**- internal loss per pass, **γ_1, γ_2**- the logarithmic losses of the two cavity mirror; **σ_a^{eff}**- the effective cross section for absorbtion; **N_t**- the total population; **l**- the length of active media; **w_0**- the mode spot size; **a**- the rod radius.

Optical efficiency is defined here as the ratio between laser output power and pump radiation power entering the pump optics. With 1000 W pump power the output power is 480 W with 92% absorption efficiency and 49% slope efficiency and a maximum temperature of the crystal at the front side of 160 °C.

With higher pump power, the absorption efficiency is reduced due to higher temperature (quasi-three level laser) and ground state depletion. The optical efficiency can be raised by reducing the heat resistance between crystal and cooling fluid. A heat resistance reduction of 2 K m^3/W increases optical efficiency by 2%. The optical efficiency increases with the increasing of the doping level. In case of thin disk operation where absorption depends on the thickness of the crystal there is an optimal thickness which maximizes the absorption and minimizes reabsorption losses.

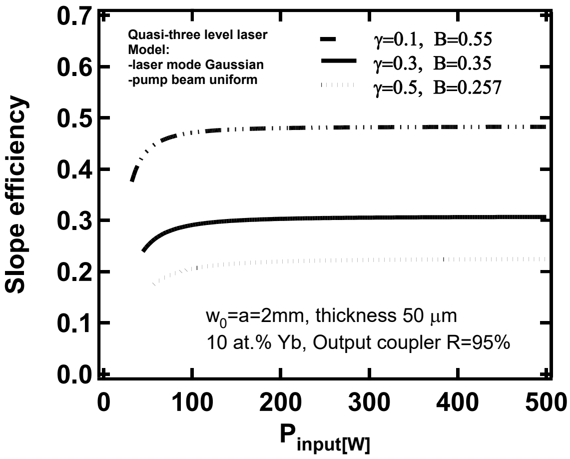

Fig. 4. Slope efficiency versus input power power for quasi-three level laser.

The microchip lens shape active media do not show such optimal thickness because the absorption efficiency depends on the diameter of the doped core not by its thickness. Therefore, lower the thickness lower the temperature of the front side of the crystal and lower the re-absorption losses. However there is an optimal doping level in order to keep a uniform absorption over the core area. Numerical simulations with ray tracing software have shown that around 3 at.% doping level is optimal for obtaining 0.90 uniformity as defined in Ref. 11 for 4 mm core diameter and seven diode laser pumping symmetrically distributed around lens chip.

We obtained, by using finite element analysis method (ANSYS FEM commercial software), the temperature of the front surface decreases 2 times when the thickness is reduced from 200 μm to 50 μm, even if the pump power absorption density is increased **four times**.

The dependence of the absorption efficiency on geometrical and material factors was numerically analyzed and we found that over 95% absorption efficiency is obtained for 5 at. % Yb:YAG, 4 mm diameter core, 15 mm undoped region diameter, 50 μm thickness at center and 400 μm thickness at the edge of the composite material. The finite element simulations have shown that the temperature gradient approximates those obtained in edge pump simulations [7]. Therefore we assumed that the thermal lens has a similar value, diopter power 0.15 m^{-1}, and we use this value in TEM_{00} resonator simulations.

5. Telescopic resonator

The characteristic one-dimensional thermal gradient of a thin-disk laser can be exploited if we make the transverse dimension of the laser aperture the principal mean of scaling the average output power. Because high radiance and high beam quality are required, the choice of resonator type become critical. The thermal lens of thin disk is quite small but still needs to be compensated in order to get high quality laser beam. Because of the large aperture of the laser gain media the mode-matching requires a very long resonator in order to discriminate the laser modes. Unstable resonators are not a good choice due to intrinsically low gain through the thin dimension of the gain medium. Since a high gain to loss ratio is required for efficient laser extraction, the resonator transverse mode must have low loss. The resonator Fresnel number $N_f=a^2/(L\lambda)$ (where **a** is the aperture radius and **L** the cavity length), determines the highest order Gaussian mode that can oscillate without significant diffractive loss ($N_{max}=\pi N_f$ for a confocal resonator). A cavity with low Fresnel number is desired however it is not practical to use the length of the resonator for mode selection. An intracavity telescope was proposed by Steffen et al.[12] and later analyzed and experimented upon by Hanna [13]. A dynamically stable resonator with an effective length M^2L_0 can be realized (where L_0 is the length at the small beam end of the resonator and M is the telescope magnification), Fig. 5. The effect of the thin telescope is to expand the spot size of the beam by a factor M and to reduce the beam curvature by a factor M, so there is a beam discontinuity in its plane. Assuming a plane–plane resonator with a thin lens very closed to gain element and the distance $L_2=f_2$, Fig. 5, one can find the equivalent matrix for this optical system. The thermal lens effect and lens shape gain media effect are included in f_{th}. From resonator equations results the relationship between normalized beam waist, W, and the defocusing parameter δ on active media and output coupler:

$$\frac{1}{f_T}=\frac{\delta}{f_2^2}$$

$$W_1=\left[\frac{M^2G_2}{G_1(1-G_1G_2)}\right]^{1/4}$$

$$W_2=\left[\frac{M^2G_1}{G_2(1-G_1G_2)}\right]^{1/4}$$

where G_1 and G_2 are generalized resonator parameters which depend on equivalent resonator length, focal length f_{th}, M, and positions.

In Fig. 6, we have represented the beam spot size on output mirror and active laser media versus δ showing that the defocusing parameter presents an optimum value and by adjusting the telescope for this value a dynamic stability range is obtained.

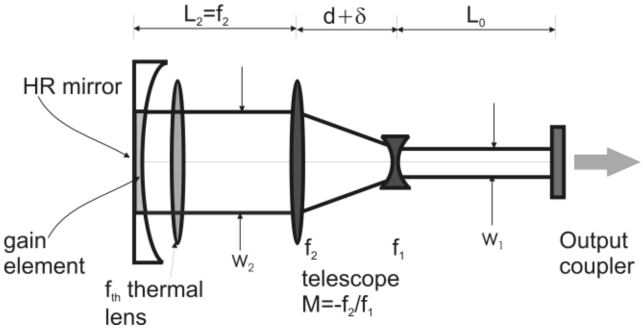

Fig. 5. The telescopic resonator. The parameter δ *is adjusted to compensate for thermal lensing lens shape active media as well as to bring the resonator into stability range.*

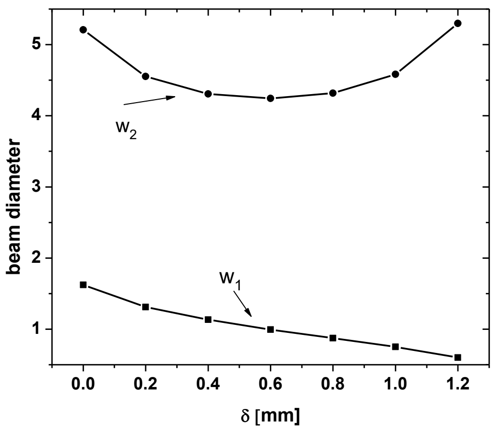

Fig. 6. Beam diameter, w_2*, on the active media keeps constant value when the thermal lens varies.*

6. Conclusions

A promising alternative for edge pumped composite microchip laser is presented. The proposed design combine the simplicity of edge-pumping with the effectiveness of cooling for very thin active laser material. The analysis of the thermal gradients by using finite element method proved the axial heat flow therefore the output power can be truly scaled up without adverse effects on thermal lens. The calculations of the distribution of the absorbed pump power inside doped core was done by ray tracing method and demonstrates good absorption uniformity. In order to compensate the optical lens induced by active media shape as well as to compensate the small thermal lens a telescopic resonator was designed and analysed. It proves that for short resonators, TEM_{00} operation is possible even for large aperture thin gain media.

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