Optics Communications 319 (2014) 100–105

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Thin-disk athermal laser system

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ARTICLE INFO

Article history:
Received 6 November 2013
Accepted 3 January 2014
Available online 18 January 2014

Keywords:
Radiation-balanced laser
Athermal laser
Laser cooling of solids

ABSTRACT

We present a theoretical scheme for Yb^{3+}-doped high power radiation-balanced (athermal) thin-disk laser system. This high power laser system consists of several thin disks operating athermally. Athermal amplification is achieved by the balance between heat generated during the amplification process and laser cooling with anti-Stokes fluorescence in the system of active Yb^{3+} ions doped in a KGW host. For athermal operation the pump power has to be distributed properly in the system of several thin disks.

1. Introduction

Traditional solids state lasers are exothermic. The quantum defect between energies of the pump and laser photons is a source of heat generation in the gain medium, which results in increased temperature, stress and strain [1]. This causes poor beam quality and limits the average output power. In the form of an optical fiber [2] or the thin disk [3], the ratio of the surface to the pumped volume increases considerably compared to the rod laser. These two new shapes for a gain medium permit scaling dramatically the output laser power with a relatively good beam quality. It is important to emphasize that although all undesirable effects caused by internal heat generation in the laser medium have been considerably mitigated in the fiber and thin disk lasers at very high powers they have not been eliminated at all [4,5], and heat transport remains a problem. Indeed, the quantum defect has not been compensated for in these new approaches to shaping the laser gain medium. The fiber and thin disk shapes of the gain medium simply improve the heat dissipation in the system. The idea to cool solids optically with anti-Stokes fluorescence was proposed by Pringsheim [6]. Dr. Bowman proposed cooling with anti-Stokes fluorescence to provide radiation-balanced operation of a solid state rod laser. It has been shown that the heat generated during the amplification process can be completely compensated for by the anti-Stokes cooling effect [7]. In 2002 the first operation of the radiation-balanced (athermal) solid state rod laser was experimentally demonstrated [8]. In the case of radiation-balanced operation the pump wavelength, λ_P, of a laser has to be chosen in the interval between the mean fluorescence wavelength, λ_F, and the wavelength of the laser emission, λ_L, that is $\lambda_F<\lambda_P<\lambda_L$, and the pump power has to be properly arranged at each point along the length of the laser rod. Since 1999, a number of different schemes of athermal lasers and amplifiers have been proposed [9–15].

Our new scheme considered in this paper is based on a series of radiation-balanced Yb^{3+}:KGW thin disks placed in one resonator (Fig. 1). Each of these disks has to be pumped with a predetermined pump power, which provides its athermal operation. All these disks are free from physical heat sinks. Contrary to the traditional scheme for radiation-balanced lasers based on a gain medium in the shape of a rod, our scheme provides considerable improvement in the control of pump power distribution, which is a key element for athermal operation of the laser. A theoretical description of operation of our scheme is presented in Section 2. The results of the simulations are discussed in detail in Section 3.

2. Theoretical analysis

Thin disk lasers have developed rapidly since their invention in 1994 by the group of Giesen at the University of Stuttgart, Germany [3,5]. The main difference from traditional solid state rod lasers is the geometry of the gain medium. The thin disk laser crystal has a thickness considerably smaller than the laser beam diameter. This disk is mounted on a heat sink. The cooled end has a dielectric coating which reflects both the laser radiation and the pump radiation. The main heat flux propagates along the axis of the disk. The laser beam axis is parallel to the heat flux. Thermal lensing is significantly suppressed compared to the rod laser, but not eliminated. High-power thin disk lasers with good beam quality have been realized during this time. However, heat generated in the laser medium is one of the key limiting factors

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0030-4018/$ - see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.optcom.2014.01.003

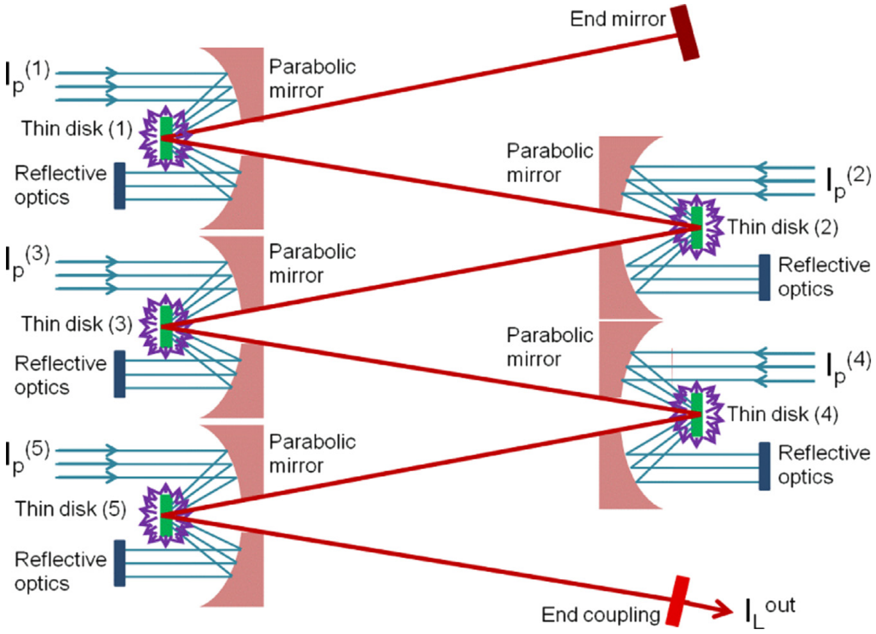

Fig. 1. Structure under investigation. $I_p^{(1)}$, $I_p^{(2)}$, $I_{p,}^{(3)}$ $I_p^{(4)}$, and $I_p^{(5)}$ are the pump intensities, I_L^{out} is the intensity of the output laser signal. The violet arrows around the disks illustrate anti-Stokes fluorescence.

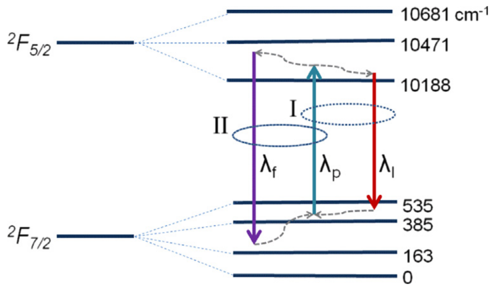

Fig. 2. Energy level diagram of the Yb^{3+}:KGW system. Cooling cycle I competes with cooling cycle II in the athermal laser system.

in scaling of the output beam to high powers with a high beam quality [16–18].

We will consider Yb^{3+}-doped potassium gadolinium tungstate crystal (Yb^{3+}:KGd(WO$_4$)$_2$) widely known as Yb^{3+}:KGW [19] as a gain medium in the shape of thin disk, and the operation of a laser at room temperature. The energy-level diagram of Yb^{3+}:KGW is illustrated in Fig. 2. The upper and lower electronic levels are split into sublevels with a total manifold width in the order of kT. The thermalization of the excited electron takes place on a picoseconds scale. The Stark-level Boltzmann occupation fractions connected with the absorption and stimulated emission processes are given by the relations (1-a,b) and (2-a,b), respectively.

$$f_0^p = \exp\left[\frac{-\varepsilon_0^p}{kT}\right] \Big/ \sum_j^{\text{level}-0} \exp\left[\frac{-\varepsilon_0^j}{kT}\right], \qquad (1-a)$$

$$f_1^p = \exp\left[\frac{\varepsilon_1-\varepsilon_1^p}{kT}\right] \Big/ \sum_j^{\text{level}-1} \exp\left[\frac{\varepsilon_1-\varepsilon_1^j}{kT}\right], \qquad (1-b)$$

and

$$f_0^l = \exp\left[\frac{-\varepsilon_0^l}{kT}\right] \Big/ \sum_j^{\text{level}-0} \exp\left[\frac{-\varepsilon_0^j}{kT}\right], \qquad (2-a)$$

$$f_1^l = \exp\left[\frac{\varepsilon_1-\varepsilon_1^l}{kT}\right] \Big/ \sum_j^{\text{level}-1} \exp\left[\frac{\varepsilon_1-\varepsilon_1^j}{kT}\right], \qquad (2-b)$$

where *level*-0 is the ^{2}F$_{7/2}$ level, *level*-1 is the ^{2}F$_{5/2}$ level. ε_1 is the energy of the lowest sublevel in the ^{2}F$_{5/2}$ level. T is the temperature of the system and $k=1.38\times10^{-23}$ J/K is the Boltzmann constant. At the pump $h\nu_p=\varepsilon_1{}^p-\varepsilon_0{}^p$. In the case of stimulated emission $h\nu_l=\varepsilon_1{}^l-\varepsilon_0{}^l$. The rate equations for the system of excited Yb^{3+} ions have the form:

$$\frac{\partial N_1}{\partial t} = W_p - W_l - \frac{N_1}{\tau}, \qquad (3-a)$$

$$N_T = N_0 + N_1, \qquad (3-b)$$

where W_p is a pumping rate, W_l is a stimulated emission rate.

$$W_p = \frac{\sum_{i=1}^{N}(I_{p,i}^{+}+I_{p,i}^{-})}{h\nu_p}\sigma_p(f_0^p N_0 - f_1^p N_1), \qquad (4-a)$$

$$W_l = \frac{(I_l^{+}+I_l^{-})}{h\nu_l}\sigma_l(f_1^l N_1 - f_0^l N_0), \qquad (4-b)$$

where σ_p and σ_l are the absorption and emission cross sections at the pump, ν_p, and the laser, ν_l, frequencies, respectively. $h=6.626\times10^{-34}$ J s is Planck's constant, τ is the fluorescence lifetime. N_0 is the population density of the ^{2}F$_{7/2}$ level. N_1 is the population density of the ^{2}F$_{5/2}$ level. N_T is the total population density. $I_p{}^{\pm}$ and $I_l{}^{\pm}$ are pump and laser intensities in the gain medium, respectively. The superscripts + and − represent the forward and backward directions of the pump and laser signal propagation along the disk axis. N is the number of times the pump beam passes in the thin disk pumping scheme. The evolution of the intensity of the laser signal in the gain medium can be described with the system of equations for $I_l{}^{+}$ and $I_l{}^{-}$

$$\frac{\partial I_l^{\pm}}{\partial z} = \pm\sigma_l[(f_0^l+f_1^l)N_1 - f_0^1 N_T]I_l^{\pm}. \qquad (5)$$

z coincides with the axis of the thin disk. The boundary conditions have the form

$$I_l^{+}(0) = R_L^l I_l^{-}(0), \qquad (6-a)$$

$$I_l^{-}(d) = R_R^l I_l^{+}(d), \qquad (6-b)$$

where d is the thickness of the disk. R_L^l and R_L^l are the reflectivity on the left and the right sides of the thin disk at the frequency of