Single-mode, scalable, solid-state laser with short wide unstable cavity

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Unstable cavity laser design is proposed in order to obtain high power, single longitudinal, single transverse mode emission from a solid-state laser. Such laser combines the single-mode master oscillator and the amplifier in a single piece. Design formulas in order to achieve the efficient operation are suggested.

The single-mode operation requires special design of the cavity. Ring cavity [1] and/or spectral and spatial filters and/or $\lambda/4$ dichroic coating of surface of the mirror [2] are usually used to fight the spatial hole burning [3]. Here we consider the single longitudinal mode operation in short (hundreds of microns) cavity. In order to achieve high efficiency, the optical path of pump in the medium should be large (few millimeters); the width of the cavity should be larger than its length. In order to keep spatial coherence in powerful device, the unstable resonator [4] should be used. We consider such a device with of-axial configuration [5]. For short wide cavity, this leads to the geometry shown in Fig.1,2.

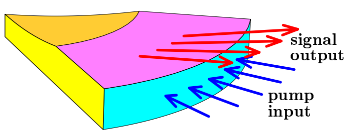

Fig.1. Short wide off-set resonator.

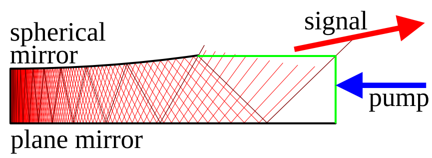

Fig.2. Rays of signal in the resonator.

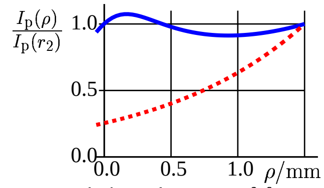

Fig.3. Rarial distribuiton of focused (solid curve) and unfocused (dashed) pump.

The depletion of pump intensity can be partially compensated by the focusing of pump into the seed region of the cavity. This is analogy of the fiber-optical amplifier with constant pump intensity [6]. However, without waveguide, the compensation is not perfect. The right hand figure shows the radial distribution of the pump intensity for the case of saturated absorption $A = 0.9$/mm and radius of the device $r_2 = 1.5$mm (solid curve); for comparison, the dashed curve shows the depletion of pump in the case without focusing of the pump. The NA of the pump is adjusted in such a way that the intensity at the seed region is equal to that at the input window. Then the relative variation of the intensity does not exceed 7%; so we assume constant intensities.
The ouptput power of such a laser can be estimated as follows. Let M be magnification coefficient of the resonator, and h be the length. The size w of region of seed corresponds to the equivalent Fresnel number $N_{\rm eq} = 1/2$. This gives $w = \sqrt{(2\lambda_{\rm s} h/n)/(M - 1/M)}$, where n is index of refraction and $\lambda_{\rm s}$ is signal wavelength. We need to illuminate with pump a spot of size w at the optical axis. In order to keep the pump intensity approximately constant, the spot size L at the input window should be $L = w \exp(Ar_2)$; this gives the relation between pump power $P_{\rm p}$ and pump intensity $I_{\rm p} = P_{\rm p}/2Lh$. More detailed approach could take into account also the distribution of pump intensity (and phase) along the input window. The signal intensity can be found from the relation $\exp(2Gh) = M^2/R^2$ where R is reflection coefficient of the mirror. Then, output power of the device $P_{\rm s} = (r_2 - r_1)Lh$, where $r_2 - r_1$ is the size of the output window; in the paraxial case, $r_1 = r_2/M$.
Consider the Nd:YAG ceramic with concentration $N = 1.380 \times 10^{26}\,{\rm m}^{-3}$, let pump wavelength be 808.4nm,with non-saturated absorption $A_0 = 1.0$/mm and maximal achievable gain $G_0 = 3.4$/mm. Then, the pump saturation intensity of $I_{\rm po} = 1.3 \times 10^8\,{\rm W/m^2}$ and the signal saturation intensity $I_{\rm so} = 0.27 \times 10^8\,{\rm W/m^2}$ can be estimated. Assume that the principal mode is tuned in resonance with the center of spectral line of gain. Then, for values $h = 0.5$mm, $R = 0.95$, $M = 1.2$ (the corrresponding radius of curvature of mirror $r_0 = 4hM/(M-1)^2 = 6$cm), the saturated gain $G = 0.78$/mm, and the generation begins at pump power of $P_{\rm pt} = 3$W. At pump power of $P_{\rm p} = 20$W, the output power reaches 25% of the input power. The efficiency can be improved by using the twisted modes [2] and/or improving the reflectivity of mirrors. Similar results can be obtained for the Yb-doped ceramics. The increase of transversal size r_2 of the device allows scaling of power [7], keeping the single-mode characteristics.

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