Optimization of the active medium length in longitudinally pumped continuous-wave lasers

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Using a space-dependent rate-equation analysis and considering the gain medium within the confocal region, we developed a method to calculate the output power in longitudinally pumped cw lasers as a function of a single parameter: the active medium length. It is possible to find an optimum laser design for maximum output power for a specified laser medium and pump wavelength. Some well-known longitudinally pumped laser systems, Ti:Al_2O_3, KCl:Tl^0(1), and Cr:LiSAF, are discussed. In particular, we also analyzed the Nd:YLF laser under two pumping conditions: pumped by a diode laser at $\lambda_P = 797$ nm and pumped by an argon-ion laser at $\lambda_P = 514.5$ nm. For the diode-pumped configuration, efficiencies as high as 50% can be expected.

1. INTRODUCTION

Because of their low thermal load and high efficiencies, several solid-state lasers longitudinally pumped by other lasers are objects of current interest. In these cases the overlap of the spatial distribution of the pump and emission beams in the active medium region are of fundamental importance. In particular, in the case of bulk lasers the effective active region is limited by the confocal parameter of the pump beam. The absorption coefficient at the pump wavelength, the resonator mode, and the scattering and reabsorption losses are also important parameters for determination of an optimum laser configuration.

We present a method to calculate the optimum active medium length that in turn determines the maximum output power of a quasi-four-level laser, i.e., a laser medium with low reabsorption losses.

2. THEORY

The energy scheme considered is shown in Fig. 1. The upper and the lower laser levels belong to manifolds, denoted n_U and n_L, respectively, with population densities given by $n_2 = \beta_2 \times n_U$ and $n_1 = \beta_1 \times n_L$; $\beta_{1,2}$ is the thermal distribution factor for the populations. The rate equation for the population difference, $\Delta n = n_2 - n_1$, is

$$\frac{\mathrm{d}(\Delta n)}{\mathrm{d}t} \cong (\beta_1 + \beta_2)R_P - \frac{\Delta n - \Delta n^0}{\tau} - (\beta_1 + \beta_2)\frac{\sigma I}{h\nu}\Delta n, \tag{1}$$

where R_P is the pump rate, τ is the upper laser level lifetime, σ is the stimulated-emission cross section, I is the intracavity optical intensity, and Δn^0 is the thermal equilibrium population difference without pumping.[1,2] The pump rate is given by

$$R_P(r, z) = \frac{\eta_P}{h\nu_P} P_P \alpha_P \exp(-\alpha_P z) f_P(r, z), \tag{2}$$

where P_P is the pump power, α_P is the absorption coefficient at the pump wavelength, η_P is the excitation quantum efficiency, and $f_P(r, z)$ is the spatial distribution of the pump power. Considering Gaussian spatial distributions for the pump and emission beams, and integrating the stationary Δn over the active medium volume, a closed expression for the unsaturated double-pass logarithmic power gain (the small-signal gain for the emission beam with Gaussian profile) is obtained (see Appendix A)[2,3]:

$$\Gamma^0 = P_P[1 - \exp(-\alpha_P l)]\frac{4\eta_P(\lambda_P/\lambda)\beta}{\pi({w_E}^2 + {w_P}^2)I_S}, \tag{3}$$

where l is the active medium length, λ and λ_P are the emission and the pump wavelengths, respectively, w_E and w_P are the emission and the pump beam waists, respectively, $I_S = (h \times \nu)/(\sigma \times \tau)$ is the saturation intensity, and $\beta = \beta_1 + \beta_2$.

The equilibrium condition for the resonator is given by (see Appendix A)

$$\Gamma^0\chi(\xi) - 2l\sigma {n_1}^0\frac{\ln(1 + \xi)}{\xi} - 2ls = L - \ln(R), \tag{4}$$

where

$$\xi = \frac{4\beta P}{\pi {w_E}^2 I_S}, \tag{5}$$

P is the intracavity stationary optical power, L is the intracavity double-pass logarithmic loss, R is the output mirror reflectivity, s is the loss coefficient (scattering, linear absorption) of the active medium, and ${n_1}^0 = \beta_1 \times n_0$, where n_0 is the total active center concentration. $\chi(\xi)$ is the gain saturation factor, given by

$$\chi(\xi) = \frac{{w_E}^2 + {w_P}^2}{{w_P}^2}\int_0^1 \frac{\epsilon^{(w_E/w_P)^2}}{1 + \xi\epsilon}\mathrm{d}\epsilon. \tag{6}$$

The absorption coefficient at the pump wavelength is a function of the pump and emission power:

$$\alpha_P(I_P, I) = \frac{\sigma_P n_0}{1 + I_P/I_{SA}}, \tag{7}$$

where $I_P = P_P/(\pi {w_P}^2)$, $I_{SA} = h\nu_P/(\sigma_P\tau_{tot})$, and σ_P is the

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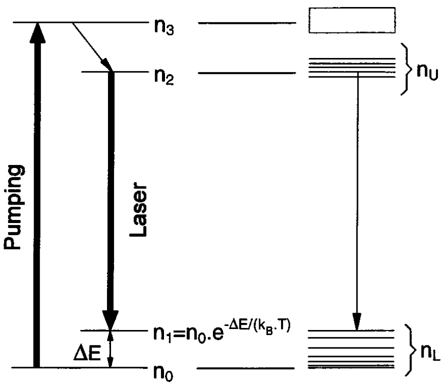

Fig. 1. Energy-level diagram considered.

absorption cross section at this wavelength. The upper laser level lifetime, τ_{tot}, decreases with the onset of the laser oscillation, and it is given by[4]

$$\tau_{\mathrm{tot}} = [\tau^{-1} + (\sigma I)/(h\nu)]^{-1}. \tag{8}$$

3. PROCEDURE AND RESULTS

The stationary intracavity power P that satisfies Eq. (4) is a function of the independent parameters of the laser design: l, w_P, and w_E (the dependence of P on the resonator's quality factor can be regarded separately). Thus the optimum configuration (maximum P) can be found in this four-dimensional space.[5] However, as the pump and emission beams must overlap along the gain medium, their confocal parameters must be comparable (if they are not much greater than the active medium length). Besides, if the laser medium does not exhibit strong reabsorption losses, we can consider its length a function of a conveniently defined effective pump length. In the present method the pump and emission beam waists are associated with the active medium length by $l = b_P = 2\pi(w_P)^2/\lambda_P$ and $w_E = w_P(\lambda/\lambda_P)^{1/2}$. This is justified by the following considerations: (1) if the active medium is longer than the confocal parameter b_P, the additional contribution to the total gain is small (compared with that for $0 < z < b_P$); (2) if the active medium is shorter than b_P, then the total gain is smaller because of the lower pump power absorbed. These approximations must be valid for the majority of the quasi-four-level laser media.

The possibility of considering the intracavity optical power as a function of only one variable, $P = P(l)$, leads to a direct, one-dimensional, graphic analysis. We used a simple algorithm to calculate the stationary intracavity power, as shown in Fig. 2. Typical spectroscopic parameters of some laser media are shown in Table 1. The laser operation parameters, also shown in the table, correspond to the parameters used in the experiments considered (see the references in the table).

The results of the calculation of the output power P_{OUT} as a function of the active medium length l for the vibronic

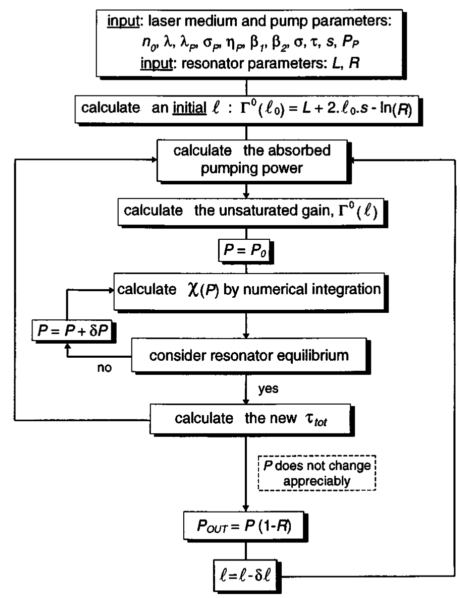

Fig. 2. Algorithm to calculate the laser output power.

Table 1. Laser System Parameters[a]

Parameter	$Ti:Al_2O_3$	$KCl:Tl^0(1)$	Cr:LiSAF	Nd:YLF	Nd:YLF
n_0 (10^{20} cm^{-3})	0.3	0.005	0.7	0.85	0.85
λ (nm)	735	1520	835	1047 (‖)	1047 (‖)
τ (μs)	3.2	1.6	67	530	530
σ (10^{-19} cm^2)	4.1 (‖)	130	0.5 (‖)	3.1 (‖)	3.1 (‖)
	2.0 (⊥)		0.2 (⊥)		
λ_P (nm)	514.5	1064	670	797	514.5
σ_P (10^{-19} cm^2)	0.6 (‖)	400	0.45 (‖)	0.24	0.035
	0.3 (⊥)		0.25 (⊥)		
s (cm^{-1})	0.07 (‖)	0.01	0.002	0.003	0.003
	0.12 (⊥)				
$P_P(w)$	~10*	4*	1	3*	3
L	0.20*	0.20*	0.05*	0.03*	0.03
R	0.80*	0.66	0.97	0.60*	0.80
l (cm)	~1*	0.2	0.3	~1*	3.3
w_P (μm)	—	~20	—	—	~70
P_{out} (w)	~1.2	1.3	~0.2*	~1.5*	0.5
References	4, 6, 7	8, 9	10–12	13, 14	15

[a]For all media, $\eta_P = 1$, $\beta_1 = 0$, and $\beta_2 = 1$, except for Nd:YLF, where $\beta_2 = 0.43$. The laser parameters and results can be found in the references, except for $Ti:Al_2O_3$, for which we refer to the specifications of two commercial models: the Spectra-Physics model Tsunami and the Coherent model Mira. The values marked with * are estimated or extrapolated.

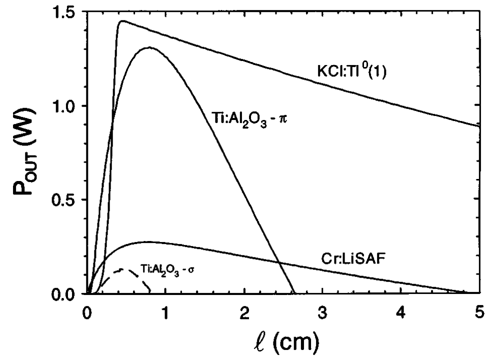

Fig. 3. Calculated output power for the vibronic lasers considered.

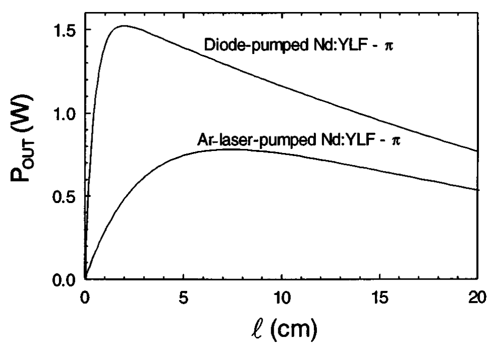

Fig. 4. Calculated output power for the Nd:YLF laser. Two configurations are considered for pumping: a diode laser at $\lambda_P = 797$ nm and an Ar laser at $\lambda_P = 514.5$ nm.

media lasers under study are shown in Fig. 3. The optimum configurations and the optimum output power agree, with good precision, with those reported in the literature (see Table 1).

The output power calculation for the two Nd:YLF systems considered (Fig. 4) clearly shows the effect of the absorption cross section in the optimum configuration, because the same pump power was considered for both systems. The Ar-laser-pumped Nd:YLF laser was experimentally studied and the expected output power verified.[15] As is easily seen, the overall efficiency is ~50% with diode pumping and ~26% for Ar-laser pumping for the best cases.

Finally, it must be remembered that after the identification of an optimal configuration (l, w_P, w_E) for the laser system one can obtain an ultimate optimization of the output power by using the following expression[16]:

$$R^{\text{opt}} = \exp(L - \sqrt{L_x \Gamma^0})\,. \tag{9}$$

4. CONCLUSION

Starting from a rate equation with spatial dependence it was possible to obtain closed expressions for the unsaturated gain and the condition for the steady-state intracavity power in longitudinally pumped laser systems. Although similar expressions are found in the literature, the present formalism leads to a much simpler and more practical expression for the steady-state condition. Besides, suitable associations among the parameters of laser design permitted the intracavity power to be described as a function of a single parameter, the active medium length. With this procedure it was possible to find the optimum configurations for the laser systems considered, with good agreement with previously reported performances. Thus we have demonstrated the validity of this method to the design of optimized quasi-four-level laser systems.

APPENDIX A. THE RESONATOR'S EQUILIBRIUM CONDITION

We start from the well-known expression for the one-dimensional model of gain saturation

$$\gamma(r, z) = \frac{\gamma^0(r, z)}{1 + \beta I(r, z)/I_S}\,, \tag{A1}$$

where $\gamma^0(r, z) = \sigma \times \Delta n(I = 0, r, z)$ can be obtained from relation (1), also using the definition [Eq. (2)] for the pump rate. The emission intensity is given by $I(r, z) = P(z) \times f_E(r)$, where $f_E(r)$ is the normalized radial dependence of the emission beam. Assuming that $\partial I(r, z)/\partial z \cong [\gamma(r, z) - s]I(r, z)$, one obtains

$$\frac{dP(z)}{dz} = 2\pi \int_0^\infty \left[\frac{\partial I(r, z)}{\partial z}\right] r\,dr = [G(z) - s]P(z)\,, \tag{A2}$$

where s is the scattering loss coefficient and $G(z)$ is the saturated logarithmic power gain, given by

$$G(z) = 2\pi \left\{ H(z) \int_0^\infty \frac{f_P(r, z) f_E(r, z) r}{1 + f_E(r, z)[2\beta P(z)/I_S]}\,dr - \sigma n_1{}^0 \int_0^\infty \frac{f_E(r, z) r}{1 + f_E(r, z)[2\beta P(z)/I_S]}\,dr \right\}, \tag{A3}$$

where $H(z) = \beta(\lambda_P/\lambda)(P_P/I_S)\eta_P \alpha_P \exp(-\alpha_P z)$.

Considering Gaussian distributions for both the pump and emission beams:

$$f_{E,P}(r, z) = \frac{2}{\pi w_{E,P}{}^2(z)} \exp[-2r^2/w_{E,P}{}^2(z)]\,, \tag{A4}$$

the power gain can be written as

$$G(z) = G^0(z)_x \chi(\xi) - \sigma n_1{}^0 \frac{\ln(1 + \xi)}{\xi}\,, \tag{A5}$$

where

$$\xi = \frac{4\beta P}{\pi w_E{}^2 I_S}\,, \qquad \chi(\xi) = \frac{w_E{}^2 + w_P{}^2}{w_P{}^2} \int_0^1 \frac{\epsilon (w_E/w_P)^2}{1 + \xi\epsilon}\,d\epsilon$$

is a normalized saturation factor [$\chi(0) = 1$] for the unsaturated four-level power gain (as a function of z), given by

$$G^0(z) = \frac{2H(z)}{\pi(w_E{}^2 + w_P{}^2)} = P_P \alpha_P \exp(-\alpha_P z) \frac{2\eta_P(\lambda_P/\lambda)\beta}{\pi(w_E{}^2 + w_P{}^2)I_S}\,. \tag{A6}$$

The second term on the right-hand side of the second of Eqs. (A5) is due to the reabsorption loss.

In the low-loss approximation the steady-state intracavity power must obey

$$2\int_0^l [G(z) - s]\mathrm{d}z = L - \ln(R)\,, \qquad \text{(A7)}$$

where L is the double-pass logarithmic loss. Considering also that $w_E(z) \cong w_E$ and $w_P(z) \cong w_P$, in the interval $0 \leq z \leq l$ we have

$$\Gamma^0 \chi(\xi) - 2l\sigma n_1{}^0 \frac{\ln(1 + \xi)}{\xi} = L - \ln(R) + 2ls\,, \qquad \text{(A8)}$$

which is the equilibrium condition [Eq. (4)]. The left-hand side of Eq. (A8) is the double-pass logarithmic power gain, Γ. The unsaturated, four-level ($n_1{}^0 = 0$) value of Γ is given by

$$\Gamma^0 = P_P[1 - \exp(-\alpha_P l)]\,\frac{4\eta_P(\lambda_P/\lambda)\beta}{\pi(w_E{}^2 + w_P{}^2)I_S}\,, \qquad \text{(A9)}$$

that is, Eq. (3).

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