HOW WIDE CAN BE A DISC LASER?

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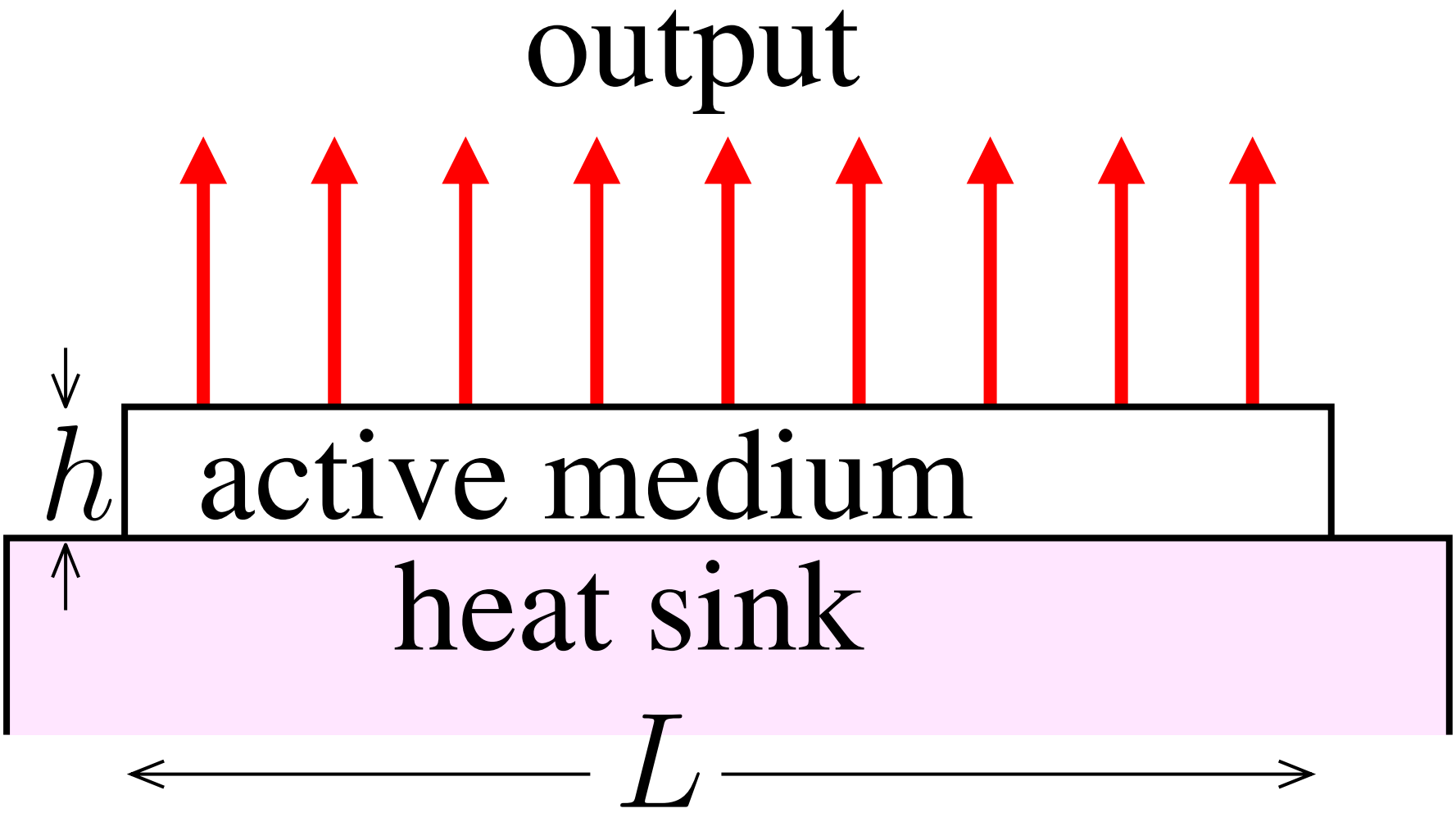


The scaling of size L increases the Amplified Spontaneous Emission (ASE); the gain G should be reduced. The round-trip gain $g = 2Gh$ should remain larger that the surface scattering losses β ; the thickness h should be increased. At some critical size $L_{\max}$, the overheating does not allow to pump the medium well above the threshold.

The general limit of the power scaling comes not only from the overheating and ASE but also from the surface scattering losses (which are usually believed to be negligible small).

Simple model of laser

Coefficient of surface losses of signal $\beta \ll 1$.

Round-trip gain $g \ll 1 \longrightarrow$ constant intensity .

Let θ be output coupling parameter; $g = \theta + \beta$.

It determines the gain $G = g/(2h)$ and the

output efficiency $\eta_{\text{output}} = \dfrac{\theta I_{\text{s}} L^2}{g I_{\text{s}} L^2} = 1 - \dfrac{\beta}{g}$

Threshold pump power $P_{\text{th}} = (\hbar\omega_{\text{p}}/\tau) L^2 g/(2\sigma)$

B.Henderson, R.H.Bartram, *Crystal-field engineering of solid-state materials.* Cambridge University Press, 2000.

Assume that there is no parazitic oscillations.

Amplified Spontaneous Emission (ASE):

Assume that ASE travels a distance L with gain,

so, the effective lifetime $\tau = \tau_{\mathrm{o}} \exp(-GL)$.

where gain $G = g/(2h)$.

Then, the threshold pump power

$$P_{\mathrm{th}} = QgL^2 \exp\left(\frac{Lg}{2h}\right) \quad ; \qquad Q = \frac{\hbar\omega_{\mathrm{p}}}{2\tau_{\mathrm{o}}\sigma}$$

Maximal pump power: $$P_{\mathrm{p,max}} = \frac{RL^2}{h}$$

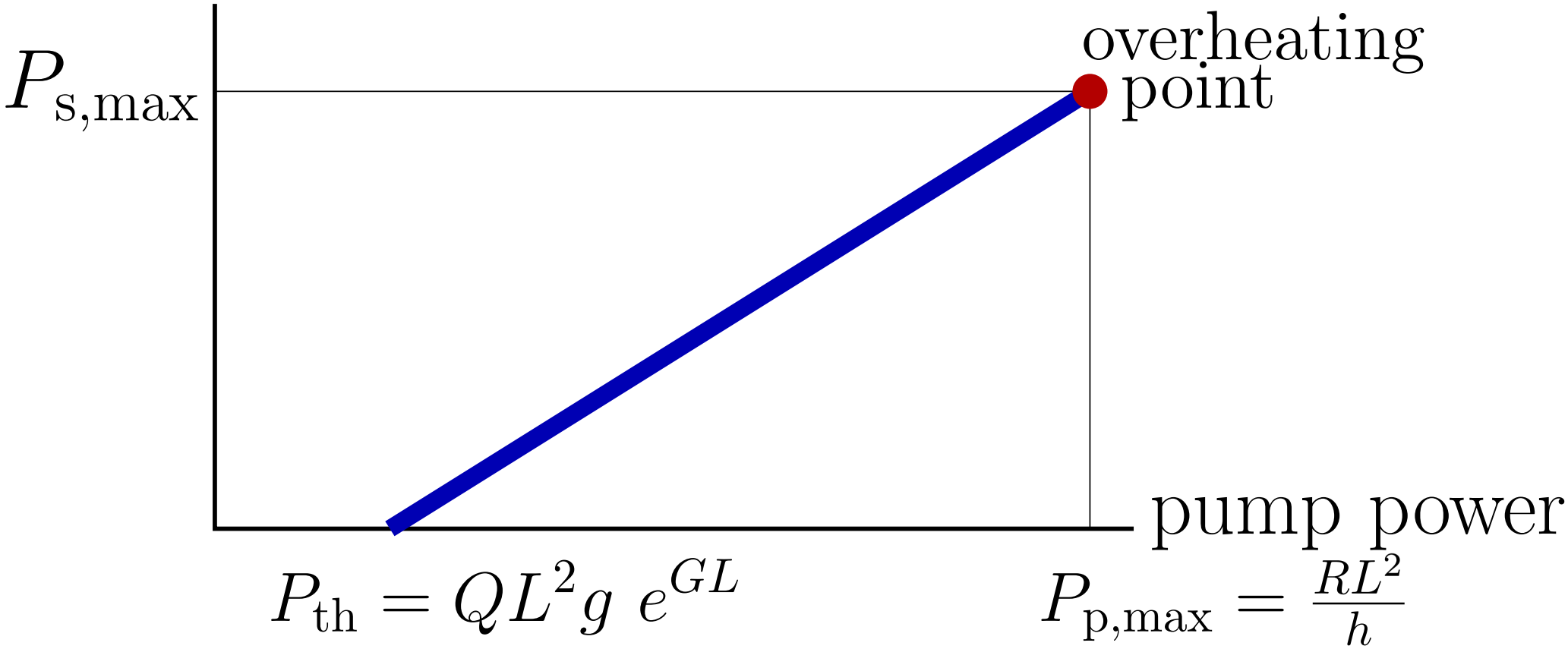
where $$R = \min \begin{cases} 3R_{\mathrm{T}}/\eta_{\mathrm{h}} \\ 2k\Delta T_{\mathrm{max}}/\eta_{\mathrm{h}} \end{cases},$$

maximal increase of temperature ΔT allowed;

thermal shock parameter $R_{\mathrm{T}} = \dfrac{k\sigma_{\mathrm{t}}(1-\nu)}{\alpha E}$

W.F.Krupke, M.D.Shinn, J.E.Marion, J.A.Caird, S.E.Stokowski. Spectroscopic, optical, and thermomechanical properties of Nd- and Cr-doped gadolinium scandium gallium garnet. — JOSA **B 3** (1), 102-114 (1986).

Output signal power $P_\mathrm{s} = \eta_\mathrm{o}\left(1 - \frac{\beta}{g}\right)\left(P_\mathrm{p} - P_\mathrm{th}\right)$



What values of g, h, L are optimal?

Maximize $P_{\mathrm{s}} = \eta_{\mathrm{o}} \left(1 - \frac{\beta}{g}\right) \left(P_{\mathrm{p}} - QL^2 g \exp\left(\frac{gL}{2h}\right)\right)$

at given P_{p} as function of L, g ; $h = \frac{RL^2}{P_{\mathrm{p}}}$

$$\frac{\partial P_{\mathrm{s}}}{\partial L} = 0 \longrightarrow \frac{gP_{\mathrm{p}}}{2RL} = 2 \quad \text{Then} \quad L = \frac{gP_{\mathrm{p}}}{4R}$$

$$P_{\mathrm{s}} = \eta_{\mathrm{o}} P_{\mathrm{p}} \left(1 - \frac{\beta}{g}\right) \left(1 - \frac{e^2}{4} \frac{QP_{\mathrm{p}} g^3}{R^2}\right) \quad .$$

$$P_{\mathrm{s}} \approx P_{\mathrm{p}} \eta_{\mathrm{o}} \left(1 - \frac{\beta}{g} - \frac{e^2}{4} \frac{QP_{\mathrm{p}}}{R^2} g^3\right)$$

maximum at $g = \left(\frac{4\beta}{3e^2} \frac{R^2}{QP_{\mathrm{p}}}\right)^{1/4}$

Maximize P_s at given efficiency $\eta = \dfrac{P_\mathrm{s}}{P_\mathrm{p}}$

$$P_\mathrm{p} = \frac{27}{64e^2}\left(1 - \frac{\eta}{\eta_\mathrm{o}}\right)^4 \frac{R^2}{Q\beta^3}$$

$$P_\mathrm{s}(\eta) = \frac{27}{64e^2}\left(1 - \frac{\eta}{\eta_\mathrm{o}}\right)^4 \eta\,\frac{R^2}{Q\beta^3}$$

Maximal power achievable at given β, R, Q:

$$L_{\max} = \frac{9}{8e^2}\,\frac{R}{Q}\,\frac{1}{\beta^2}$$

$$P_{\mathrm{p,max}} = \frac{27}{8e^2}\,\frac{R^2}{Q}\,\frac{1}{\beta^3}$$

$$h_{\max} = \frac{3}{8e^2}\,\frac{R}{Q}\,\frac{1}{\beta}$$

$$P_{\mathrm{s,max}} = \frac{27}{64e^2}\,\frac{R^2}{Q}\,\frac{\eta_{\mathrm{o}}}{\beta^3}$$

$$g_{\max} = \frac{4}{3}\,\beta$$

$$\frac{P_{\mathrm{s,max}}}{P_{\mathrm{p,max}}} = \frac{\eta_{\mathrm{o}}}{8}$$

Maximal output power implies low efficiency $\sim 10\%$

Key parameter $P_{\mathrm{D}} = \dfrac{R^2 \eta_{\mathrm{o}}}{Q \beta^3}$

determines the maximal power of the disk laser.

For the efficient operation ($\eta > 50\%$), the laser should be optimized for power of order of few percents of the maximal power achievable in this configuration.

Example of parameters optimized for given P_{p}

$R = 5\,\mathrm{W/mm}$, $Q = 50\,\mathrm{W/mm^2}$, $\eta_{\mathrm{o}} = 0.91$, $\beta = 0.01$

P_{p}, kW	L, mm	h, mm	g	G, mm^{-1}	P_{s}, kW	η, %
1	1.541	0.012	0.031	1.298	0.598	60
2	2.592	0.017	0.026	0.772	1.082	54
4	4.359	0.024	0.022	0.459	1.894	47
6	5.908	0.029	0.020	0.339	2.574	43
8	7.330	0.034	0.018	0.273	3.157	39
10	8.666	0.038	0.017	0.231	3.664	37
228	10.	0.508	0.013	0.026	26.0	11

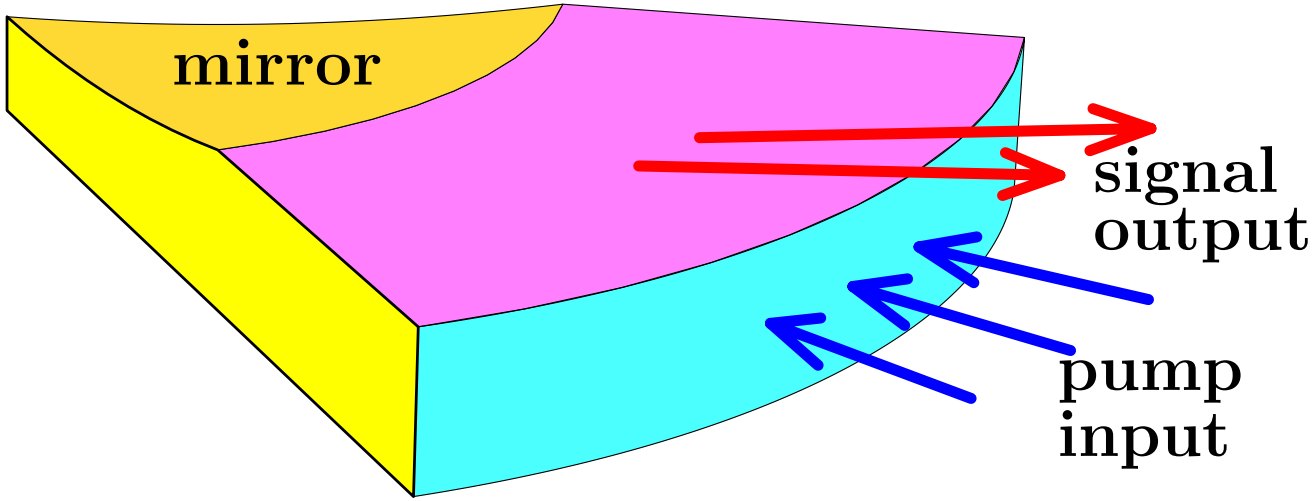
Example of scaling up $P_{\mathrm{s,max}}$ reducing β :

$R = 5\,\mathrm{W/mm}$, $Q = 50\,\mathrm{W/mm^2}$, $\eta_{\mathrm{o}} = 0.91$

β	L, mm	h, mm	g	G, mm^{-1}	$P_{\mathrm{p,max}}$, kW	$P_{\mathrm{s,max}}$, kW
0.002	3806	2.538	0.003	0.001	28547.286	3247.254
0.004	952	1.269	0.005	0.004	3568.411	405.907
0.010	152	0.508	0.013	0.026	228.378	25.978
0.020	38	0.254	0.027	0.105	28.547	3.247
0.040	10	0.127	0.053	0.420	3.568	0.406
0.070	3	0.073	0.093	1.287	0.666	0.076
0.100	2	0.051	0.133	2.627	0.228	0.026

Overheating of laser with short wide unstable cavity

The surface loss β limits also the size and power of the laser with short wide unstable cavity [7].



For the example with Yb, at $\beta = 0.05$, the robust operation is possible only in the pulsed regime.

For the efficient cw operation, β should be reduced to 0.01 ; then the magnification coefficient can be reduced from 1.2 to 1.05 , and the size of the laser can be increased from $2\,\mathrm{mm}$ to $8\,\mathrm{mm}$.

CONCLUSIONS

Maximal power of a disc laser is determined by raito $\omega_{\mathrm{s}}/\omega_{\mathrm{p}}$, saturation parameter Q , overheating parameter R , and the surface loss β . Power $P_{\mathrm{D}} = \dfrac{R^2 \eta_{\mathrm{o}}}{Q \beta^3}$ is **key parameter** in the choice of material for a high power disc laser.

The maximal power $P_{\mathrm{s,max}} = \frac{27}{64e^2} P_{\mathrm{D}} \approx 0.06 P_{\mathrm{D}}$ corresponds to the size $L = \frac{9}{8e} R/Q \approx 0.4 R/Q$ and efficiency $\sim 10\%$.

The efficient operation is possible at power smaller than $10^{-3} P_{\mathrm{D}}$.

The scaling up the size and power of a disc laser requires moderate scaling down the surface loss β .

LIMITS OF THE MODEL and EXTENSIONS

Our estimates apply also to an amplifier, then g becomes gain per single element. Similar estimate takes place for the pulsed lasers.

Additional limitations may be caused by the problems of

efficient absorption of pump in the optically-thin medium,

dissipation of the Amplified Spontaneous Emission, and

deformation of the active mirror due to the thermal loading.

The widely scalable architecture of powerful laser may include the active adjustment of phase of each of cheap and efficient partial lasers to some master oscillator which plays the role of clock operating at optical frequency. Minimal power of the reference signal required to adjust the phase of a partial laser should be estimated.

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THIS POSTER: `http://www.ils.uec.ac.jp/~dima/howwide.pdf`

UPCOMMING PRESENTATIONS

D.Kouznetsov. Single-mode solid-state laser with short wide unstable resonator.

Arizona Center for Mathematical Sciences (Cesar Chavez Building, room 200), University of Arizona, Tucson, AZ; Monday Oct. 24, 2005. Slideshow:

`http://www.ils.uec.ac.jp/~dima/jerry.pdf`

D. Kouznetsov. Filling of classical and quantum billiards.

Optical Sciences Center (Menuel Building, room 654), University of Arizona, Tucson, AZ; 2005, October 26, 13h. Slideshow:

`http://www.ils.uec.ac.jp/~dima/billiards.pdf`