LIMITS OF POWER SCALING OF LASERS

D. Kouznetsov, J.-F. Bisson, J. Dong,
A. Shirakawa, K. Ueda

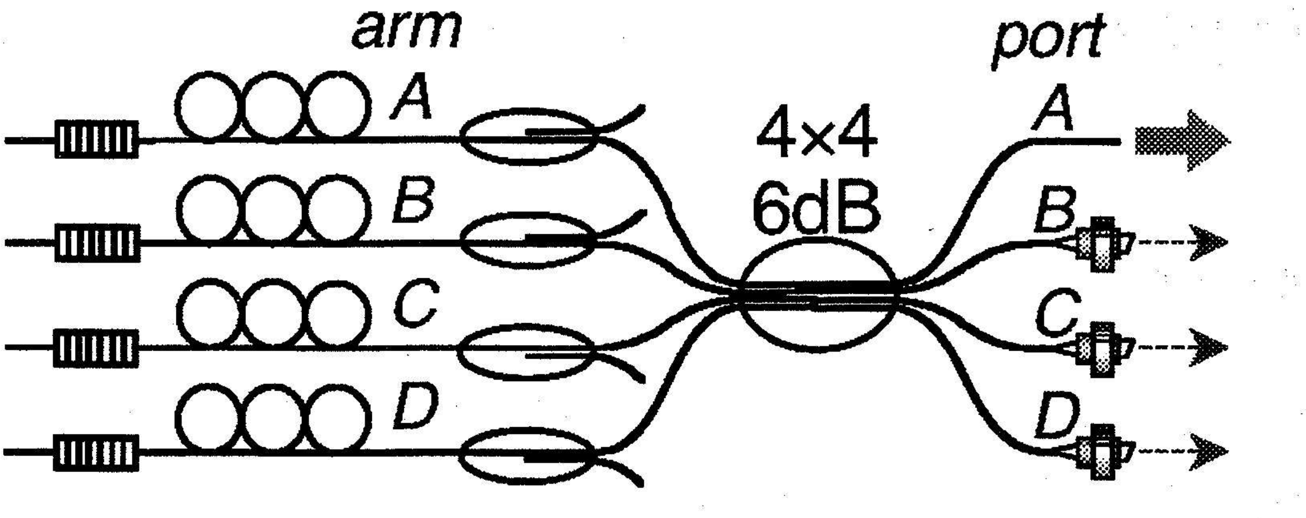
Inst. for Laser Science,
Univ. of Electro-Communications,
1-5-1 Chofu-Gaoka, Chofu, Tokyo, 182-8585, Japan.

email:dima@ils.uec.ac.jp;
http://www.ils.uec.ac.jp/∼dima

All scaling laws have limits.

We discuss the output power limitations of two possible architectures for powerful lasers: the coherent combining of fiber lasers and the size scaling of the disk lasers.

Coherent combining of fiber lasers



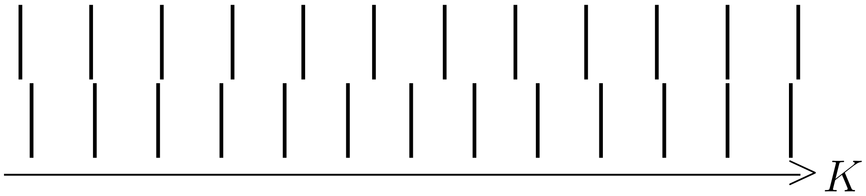
Example by

A.Shirakawa, A.T.Sekiguchi, K.Matsuo, K.Ueda. Coherent addition of fiber lasers by use of a fiber coupler. – OSA Tops 83 (2003) 82.

Scaling up to much larger numbers of arrays looks attractive, but:

How many lasers can be combined in such a way?

Simple model of combining



Occasional coincidence of spectral lines of two lasers.

Let L be the optical round-trip length.
Let K be wavenumber and δK be the bandwidth.
One laser can oscillate at $\delta K\, L$ modes.

An additional nth laser should oscillate at frequencies close to those of the system of $n-1$ lasers.

Assume, modes with losses larger than $1-\eta$ are suppressed. η appears as combining efficiency.
At each round-trip, the coupler rotates the wave

in a laser by the angle $\phi = (L_1 - L_2)K + 2\pi m$

For the efficient operation, $\cos(\phi) > \eta$

An added laser reduces the number of modes by factor

$$\frac{1}{2\pi}\int_{-\pi}^{\pi} \vartheta(\cos\phi - \eta)\ \mathrm{d}\phi \approx \frac{\sqrt{2(1-\eta)}}{\pi}$$

this is the probability that a mode of the system
is close enough to any mode of new added laser.

Let M_n be the number of spectral lines of n lasers;

$$M_1 = \delta K\, L \quad , \qquad M_n = \left(\frac{\sqrt{2(1-\eta)}}{\pi}\right)^{n-1} M_1$$

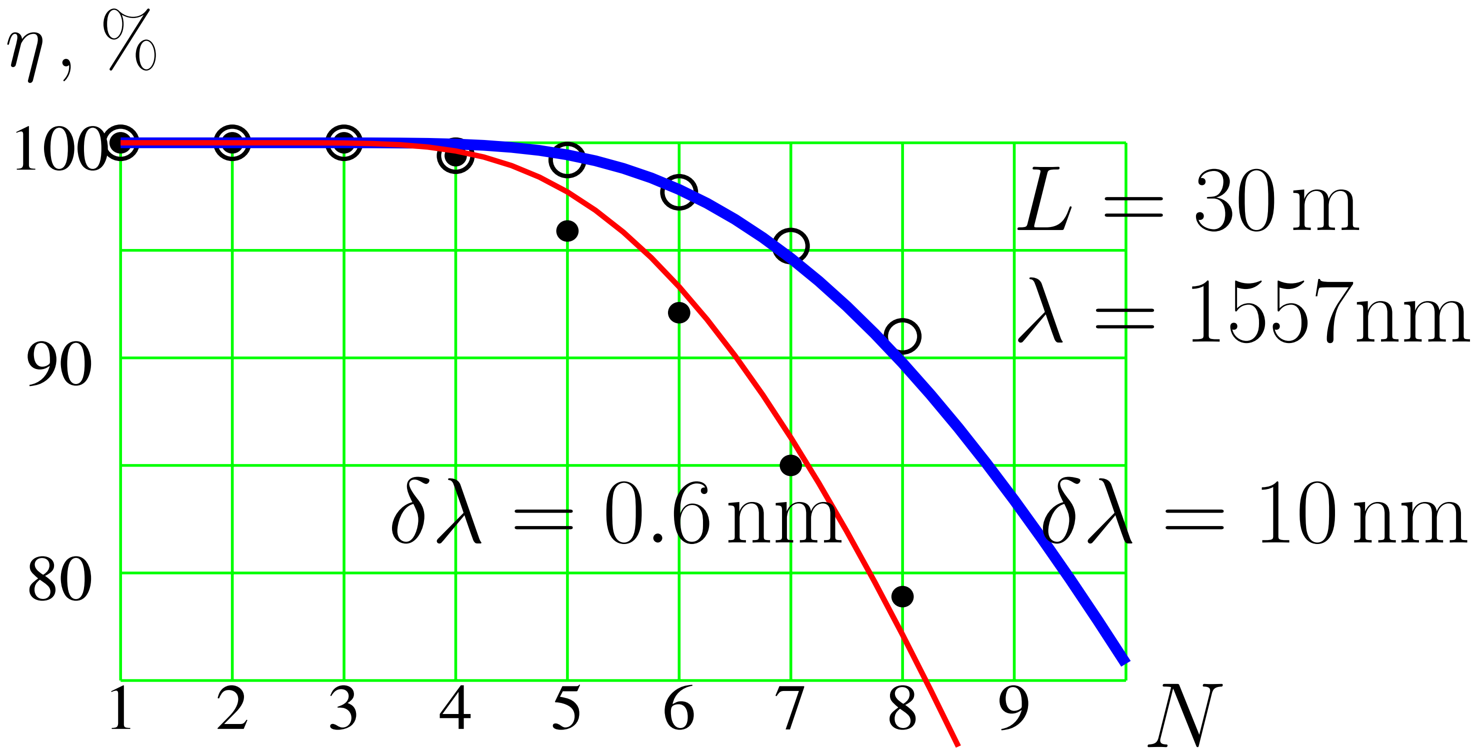
At some $n = N$, the coherent addition is over:,
$M_N \approx 1$, and no more laser can be coupled without to loss the efficiency. N is the maximal number of lasers that can be combined.

$$\left(\frac{\sqrt{2(1-\eta)}}{\pi}\right)^{N-1} \delta K\, L = 1$$

$$N = 1 + \frac{\ln(\delta K\, L)}{\ln\left(\pi/\sqrt{2(1-\eta)}\right)}$$

At given N, the efficiency of combining

$$\eta = 1 - \frac{\pi^2}{2} \exp\left(-2\, \frac{\ln(\delta K\, L)}{N-1}\right)$$



dots: simulations by Shirakawa (2003)

Coherent addition of lasers is limited.

We suggest the simple estimate of efficiency η as function of number N of lasers combined.

Practically, about 8 lasers can be combined.

The increase of number N at given efficiency η requires an exponential grow of $\delta K\,L$ product.

Our estimate agrees with simulations:
see A. Shirakawa et al.,(2003) and

A. E. Siegman (2004):
Resonant modes of linearly coupled
multiple fiber laser structures.
http://www.stanford.edu/~siegman/Coupled_fiber_modes.pdf

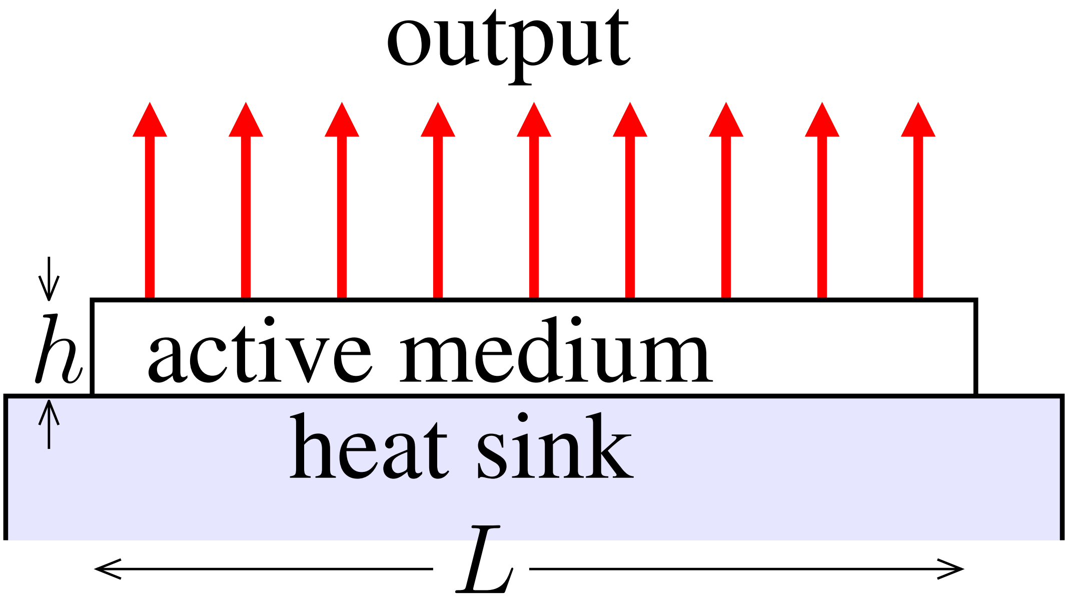
Full text will be published:

D.Kouznetsov, J.-F.Bisson, A.Shirakawa, K.Ueda.
Limits of coherent addition of lasers: simple estimate.
– Optical Review, 2005, No.6, in press. **Preprint:**
http://www.ils.uec.ac.jp/∼dima/coupledOptRev.pdf

Power scaling of a disc laser

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 $L_{\rm max}$, 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).



D. Kouznetsov, J.-F. Bisson, J. Dong, K. Ueda.
Surface losses limit the power scaling of disc laser.
JOSA B, under consideration. Preprint:
http://www.ils.uec.ac.jp/~dima/disc.pdf (207k) or
http://www.ils.uec.ac.jp/~dima/disc.ps.gz (87k)

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

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

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

Assume that ASE travels a distance L with gain, so, the effective lifetime $\tau = \tau_{\mathrm{o}} \exp(-GL)$.

Then $P_{\mathrm{th}} = Q g L^2 \exp\left(\dfrac{Lg}{2h}\right)$; $Q = \dfrac{\hbar\omega_{\mathrm{p}}}{2\tau_{\mathrm{o}}\sigma}$

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

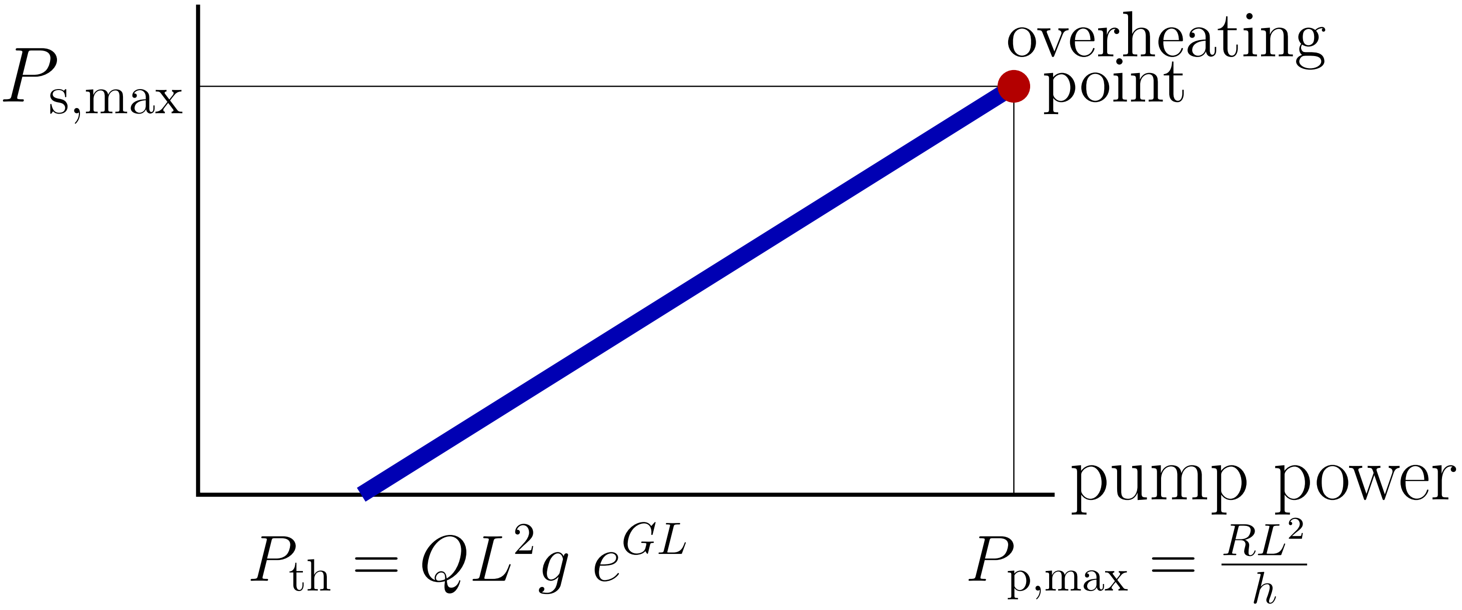
where $R = \min \left\{ \begin{array}{c} 3R_{\mathrm{T}}/\eta_{\mathrm{h}} \\ 2k\Delta T_{\mathrm{max}}/\eta_{\mathrm{h}} \end{array} \right.$,

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

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).

What values of g, h, L are optimal?

Output signal power $P_{\rm s} = \eta_{\rm o}(1-\beta/g)(P_{\rm p} - P_{\rm th})$



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

as function of L, g; $\quad h = PL^2/P_{\rm p}$

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

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

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

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

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

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

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

Maximal power achievable at given β, R, Q:

$$L_{\max} = \frac{9}{8e^2}\;\frac{R}{Q}\;\frac{1}{\beta^2} \qquad P_{\mathrm{p,max}} = \frac{27}{8e^2}\frac{R^2}{Q}\frac{1}{\beta^3}$$

$$h_{\max} = \frac{3}{8e^2}\;\frac{R}{Q}\;\frac{1}{\beta} \qquad P_{\mathrm{s,max}} = \frac{27}{64e^2}\frac{R^2}{Q}\frac{\eta_{\mathrm{o}}}{\beta^3}$$

$$g_{\max} = \frac{4}{3}\beta \qquad \frac{P_{\mathrm{s,max}}}{P_{\mathrm{p,max}}} = \frac{\eta_{\mathrm{o}}}{8} \quad .$$

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 one percent of the maximal power achievable in this configuration.

Optimized output for given pump power

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

P_p, kW	L, mm	h,mm	g	G, mm^{-1}	P_s,kW
1	1.541	0.012	0.031	1.298	0.598
2	2.592	0.017	0.026	0.772	1.082
4	4.359	0.024	0.022	0.459	1.894
6	5.908	0.029	0.020	0.339	2.574
8	7.330	0.034	0.018	0.273	3.157
10	8.666	0.038	0.017	0.231	3.664
228	10.	0.508	0.013	0.026	26.0

Optimization for maximal power

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

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	0.002	3568.411	405.907
0.010	152	0.508	0.013	0.013	228.378	25.978
0.020	38	0.254	0.027	0.052	28.547	3.247
0.040	10	0.127	0.053	0.210	3.568	0.406
0.070	3	0.073	0.093	0.644	0.666	0.076
0.100	2	0.051	0.133	1.314	0.228	0.026

CONCLUSIONS

1. Scaling of power with passive coherent combining of lasers is limited. Maximal number N of lasers combined can be estimated as logarithm of the number M of longitudinal modes of partial lasers: $N \approx \ln(M)$.

2. Power scaling of the disk lasers is also limited. The maximal power is determined by the saturation parameter Q, overheating parameter R and the surface scattering losses β.
Power $P_{\mathrm{D}} = \frac{R^2}{Q\beta^3}$ is key parameter in the choice of the material for the high power disk laser.

3. Ruture work. 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.

1. K.Naito et al., “Conceptual design of a laser diode pumped solid state laser system for laser fusion reactor driver”, Jpn.J.Appl.Phys. **31** (2A), 259-273 (1992)

2. A.Giesen et al., “Scalable concept for diode-pumped high-power solid-state lasers”, Appl. Phys. **B 58** (5), 365-372 (1994)

3. C.Li, D.Y.Shen, J.Song, N.S.Kim K.Ueda, “Theoretical and experimental investigations of diode-pumped Tm : YAG laser in active mirror configuration”, Optical Review **6**(5), 439-442 (1999)

4. N.P.Barnes, B.M.Walsh, “ASE – Application to Nd:YAG lasers”, IEEE J. Quantum Electron. **35** (1), 101-109 (1999); **35**(7), 1100 (1999)

5. C.Stewen, K.Contag, M.Larionov, A.Giesen, H.Hügel, “A 1-kW CW thin disc laser”, IEEE J. of Selected Topics in Q.E., **6** (4), 650-657 (2000)

6. J.Lu, J.Lu, T.Murai, K.Takaichi, T.Uematsu, K.Ueda, H.Yagi, T.Yanagitani, A.A.Kaminskii, “Nd^{3+} : Y_2O_3 Ceramic Laser”, Jpn.J.Appl.Phys., **40** part 2, L1277-L1279, (2001)

7. K.Contag, S.Erhard, M.Karszewki et al., “Power scalbility and beam quality of the thin disc laser”, Conference on Lasers and Electro-optics (CLEO 2000), Technical digest, TOPS, v.39, p.198-199 (2000)

8. D.Kouznetsov, J.-F.Bisson, K.Takaichi, K.Ueda, “High-power single mode solid state laser with short unstable cavity”, JOSA **B 22**, No.8, p.1605-1619 (2005)

9. T.Y.Fan, “Heat generation in Nd:YAG and Yb:YAG”. IEEE J. of QE, **29** (6), 1457-1459 (1993)

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

11. T.Kasamatsu, H.Sekita, Y.Kuwano, “Temperature dependence and optimization of 970 nm diode-pumped Yb:YAG and Yb:Lu:YAG lasers”, Appl. Opt. **38** (24), 5149-5153 (1999)

12. N.Uehara, A.Ueda, K.Ueda, H.Sekiguchi, T.Mitake, K.Nakamura, N.Kitajima, I.Kataoka, “Ultralow-loss mirror of the parts-in-10^6 level at 1064 nm”, Opt. Lett. **20** (6), 530-532 (1995)

13. B.Henderson, R.H.Bartram, *Crystal-field engineering of solid-state materials*, (Cambridge Univ. Press, 2000)