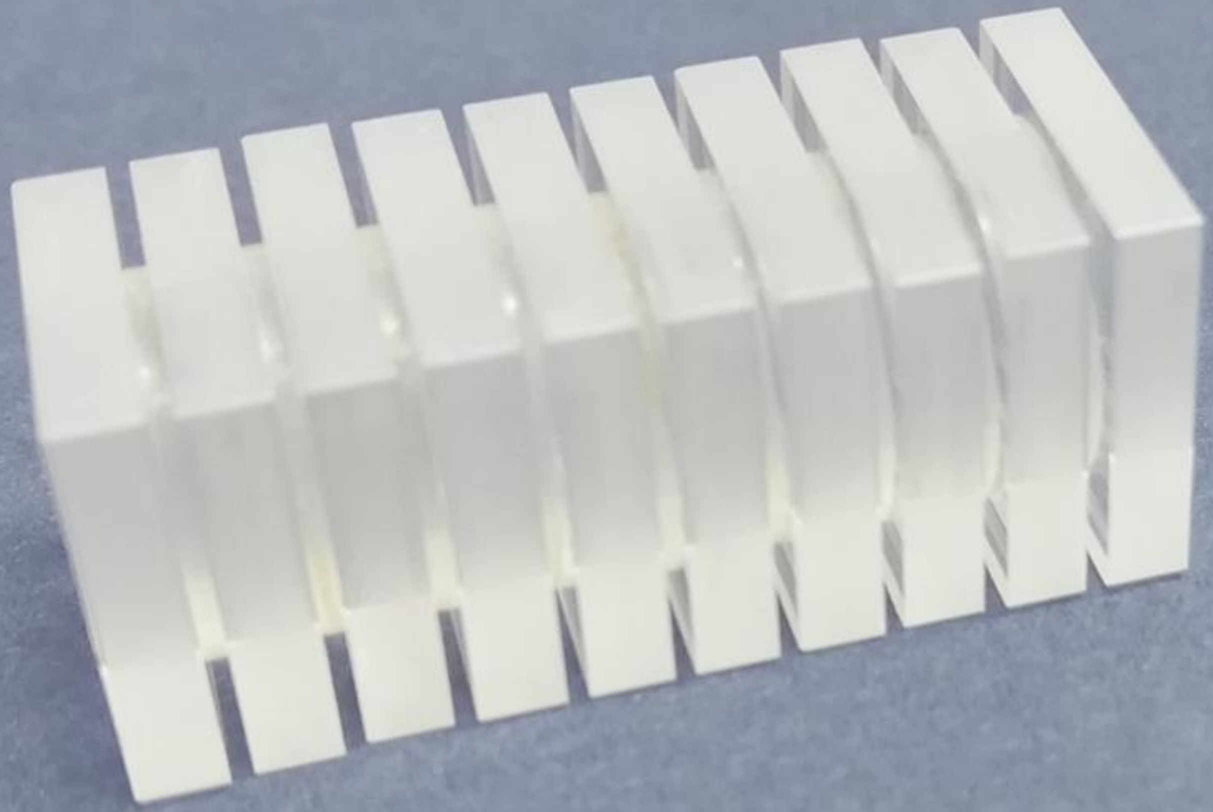
High energy laser amplifier by direct-bonded DFC chip



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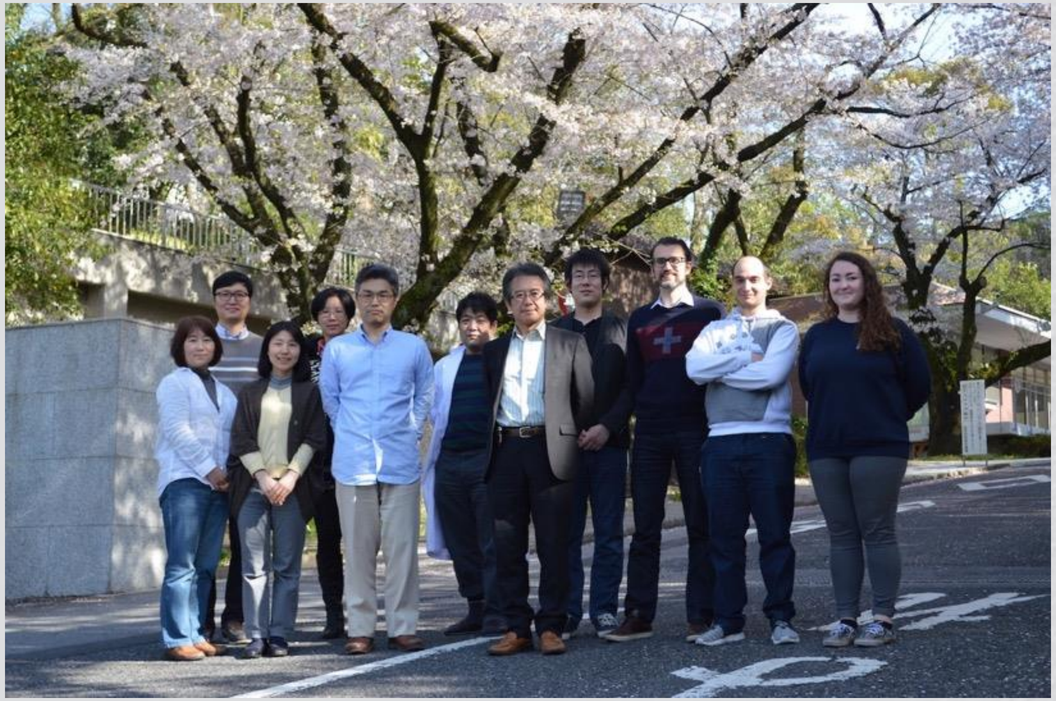
2020/07/08

Acknowledgements

Taira group, Okazaki



https://www.jst.go.jp/impact/sano/
https://www.jst.go.jp/impact/index.html
https://www.jst.go.jp/mirai/jp

- This work was funded by ImPACT project, Program of Council for Science, Technology and Innovation (Cabinet Office, Government of Japan).

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<u>Taira lab group members</u>
H. Ishizuki
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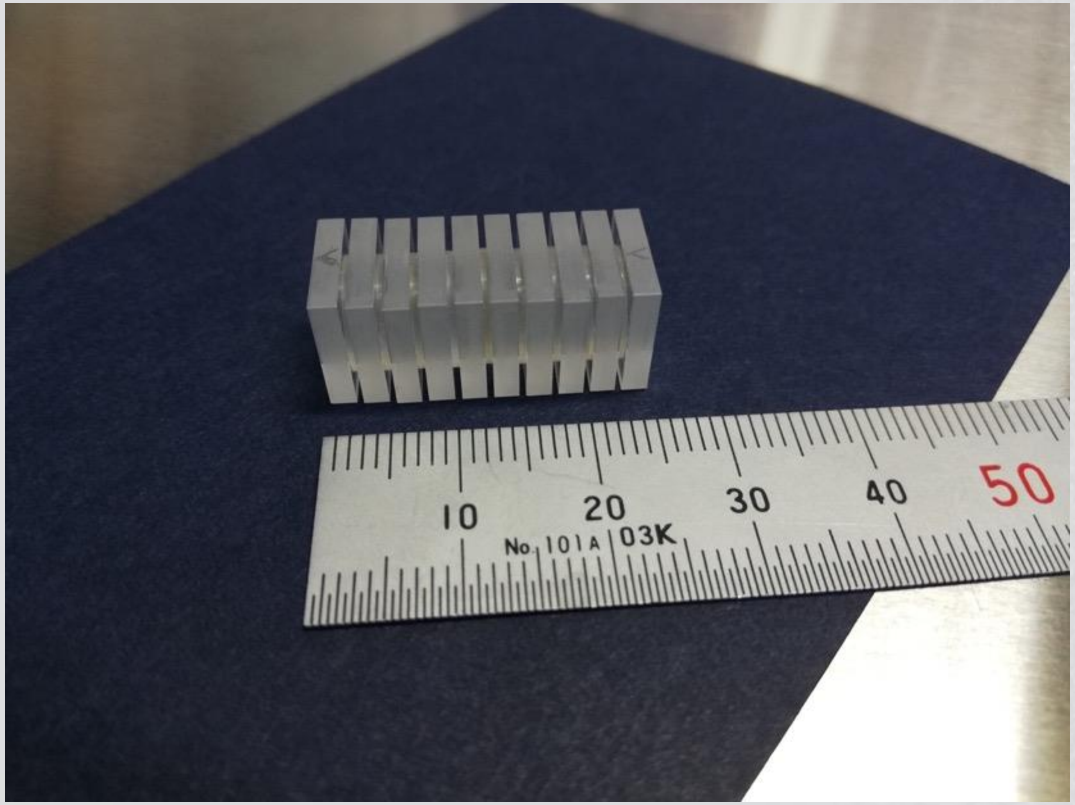
V. Yahia
T. Kawasaki
H. Lim

T. Kondo, for building bonding machine for Taira group

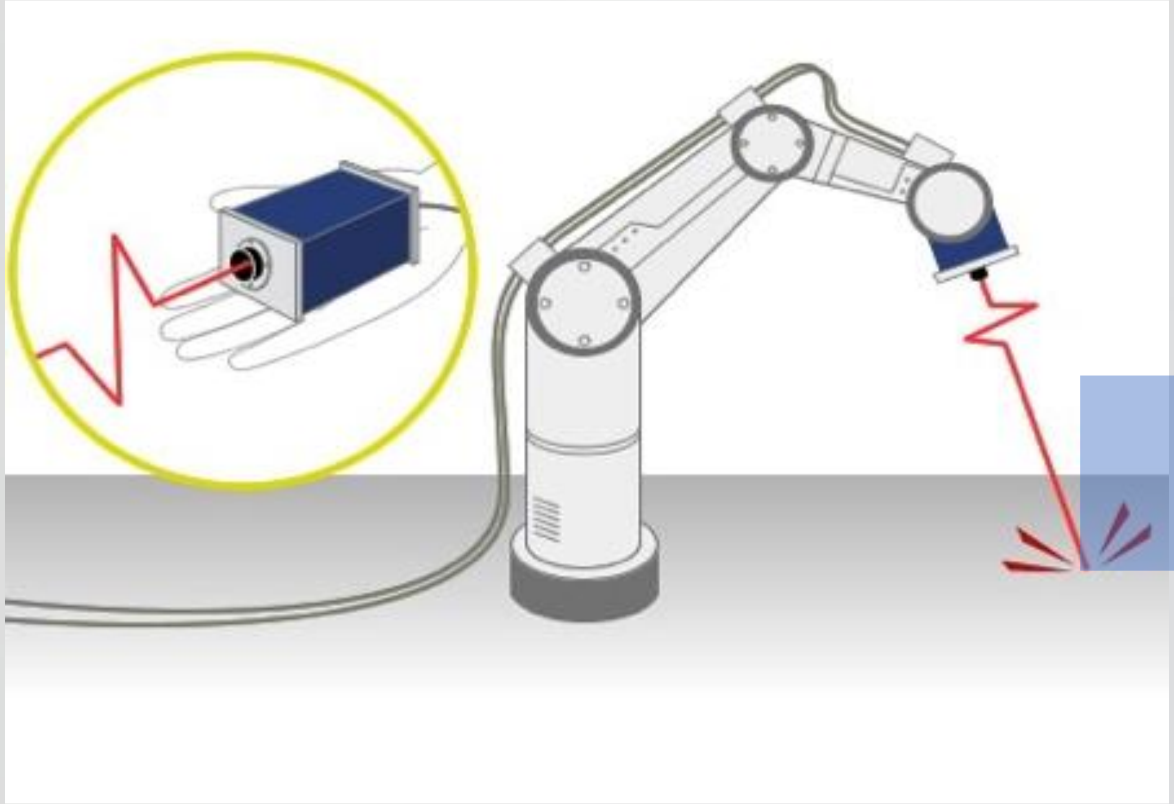
Outline

- Motivation
- DFC concept
- Surface activated bonding
- CW and pulse laser operation
- 300 mJ amplifier system
- Discussions
- Conclusions

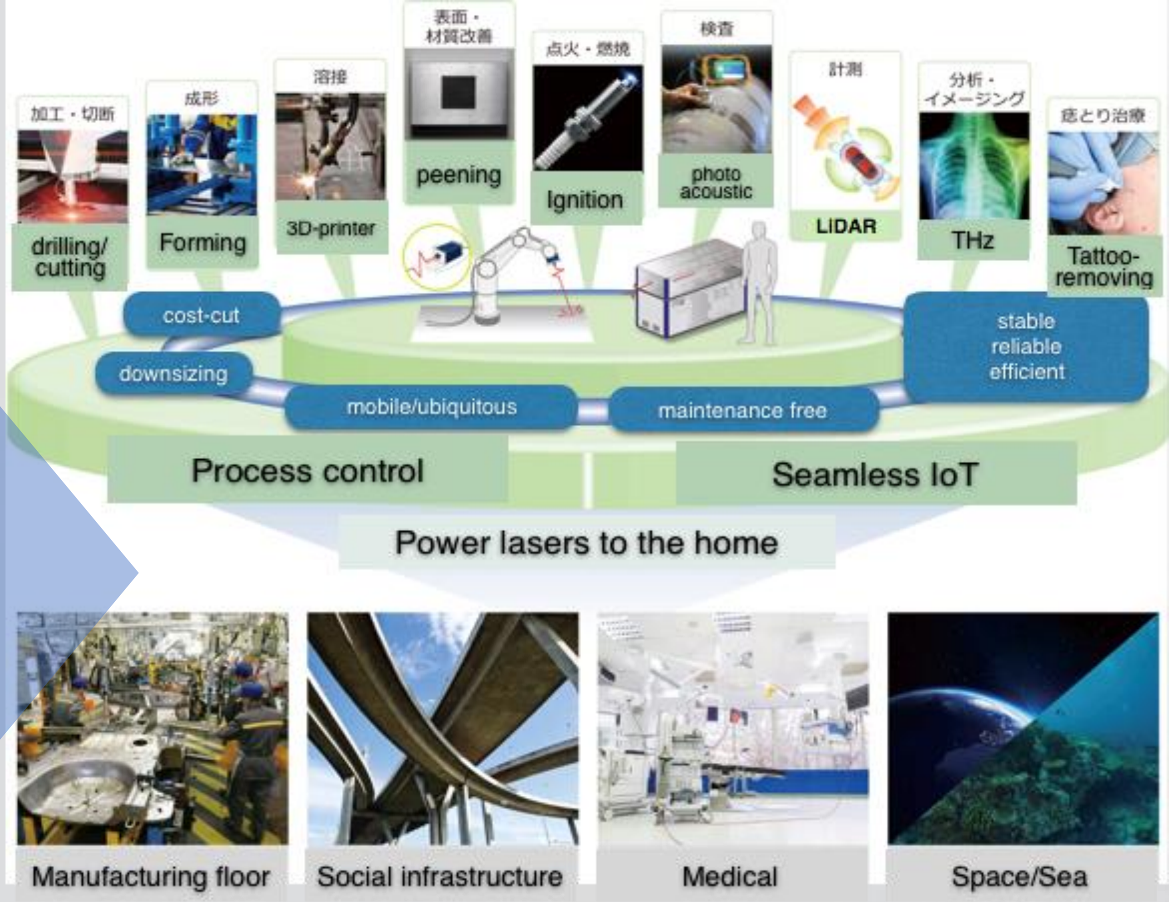


19-crystal composite chip comprised of sapphire and ceramic Nd^{3+}:YAG crystals

Motivation for compact systems

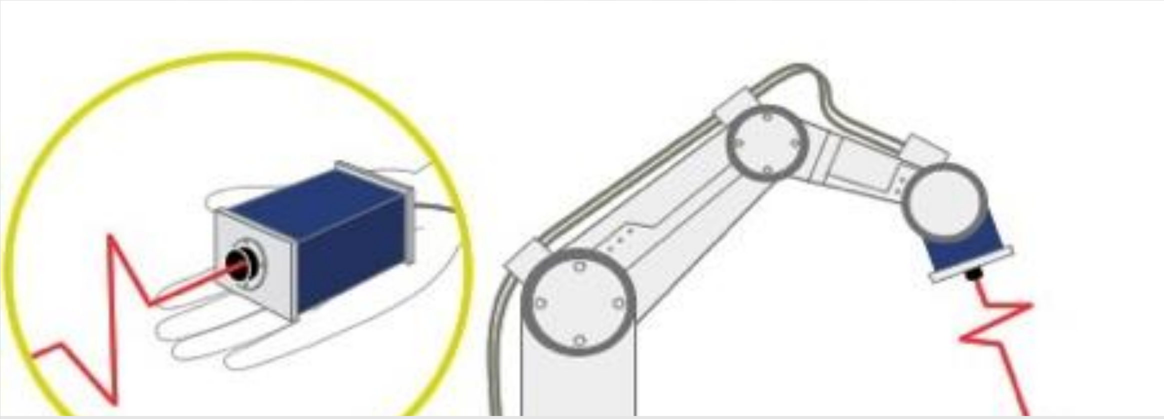


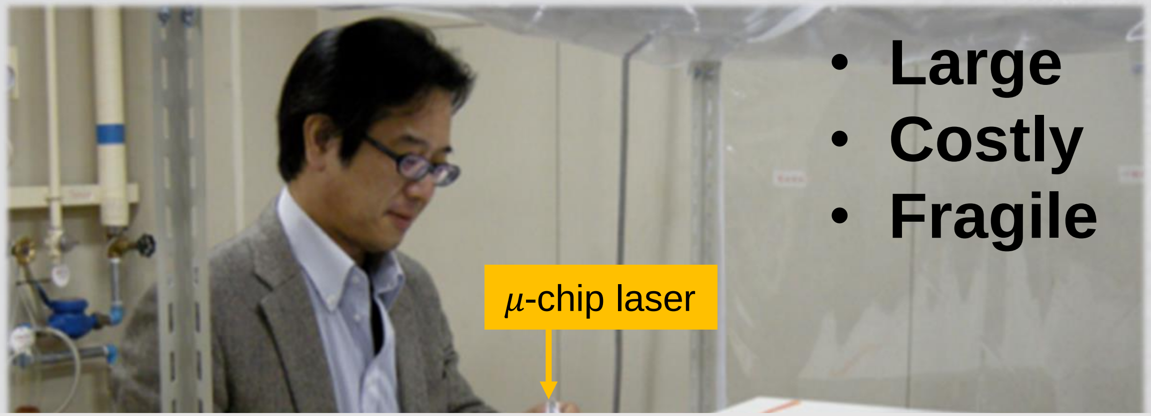
Tiny-integrated system



Ubiquitous power laser

Motivation for compact systems





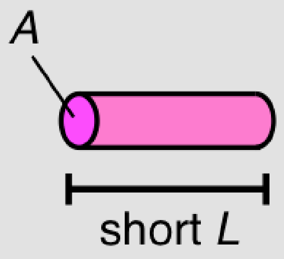
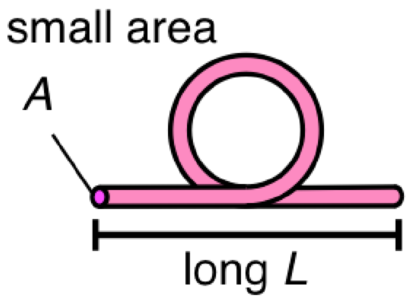
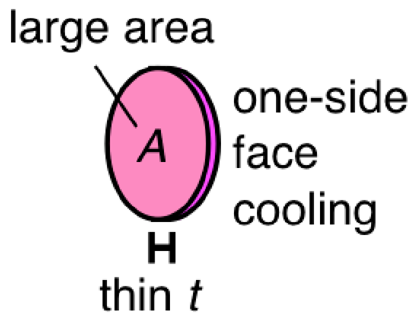
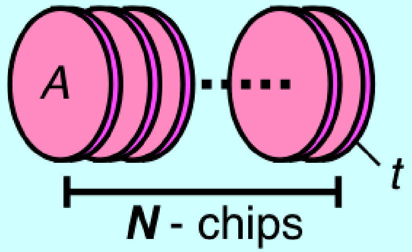
- Large
- Costly
- Fragile

OUR AIM

- ➢ Compact amplifier system
- ➢ Pulse energy = 2J
- ➢ Repetition rate = 100 Hz

Current limitation: heat generation

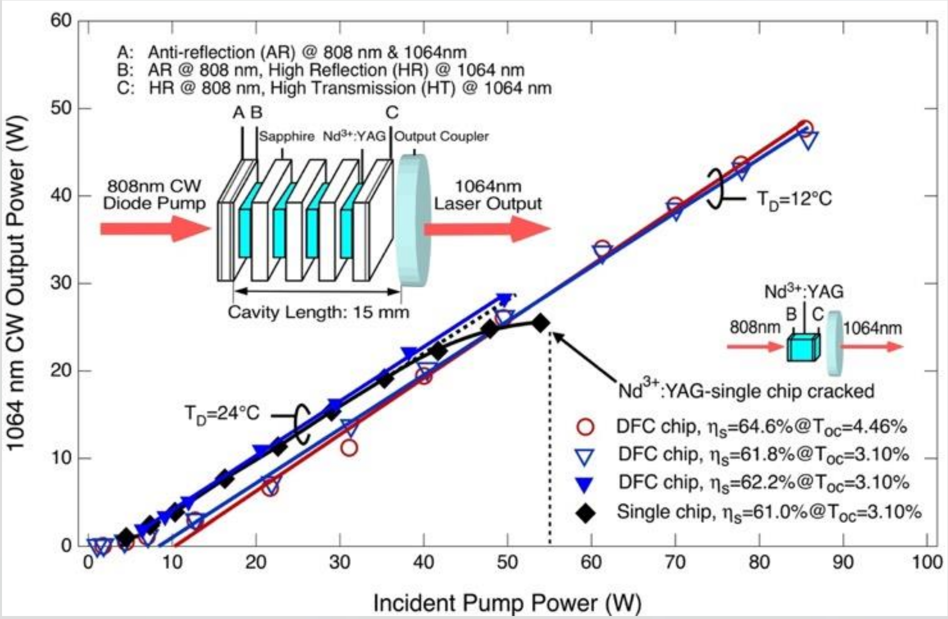
Power scalability for various laser configurations

Parameter \ Shape	Rod	Fiber	Thin disk	**DFC**
Shape				double-side face cooling 
Maximum extractable power	$P_{ex} = \frac{8\pi R_T L}{\chi}$	$P_{ex} = \frac{8\pi R_T L}{\chi}$	$P_{ex} = \frac{12 R_T}{\chi}\left(\frac{A}{t}\right)$	$P_{ex} = \frac{24 N R_T}{\chi}\left(\frac{A}{t}\right)$
Power scalability	poor	high	medium	**high**
Gain	medium	high	poor	**high**
Damage threshold	medium	poor	high	**high**

DFC: distributed face cooling, R_T: thermal shock parameter, *A*: area of a gain medium, *L*: gain medium length, *t*: gain medium thickness, χ: heating parameter, *N*: number of chips or disks

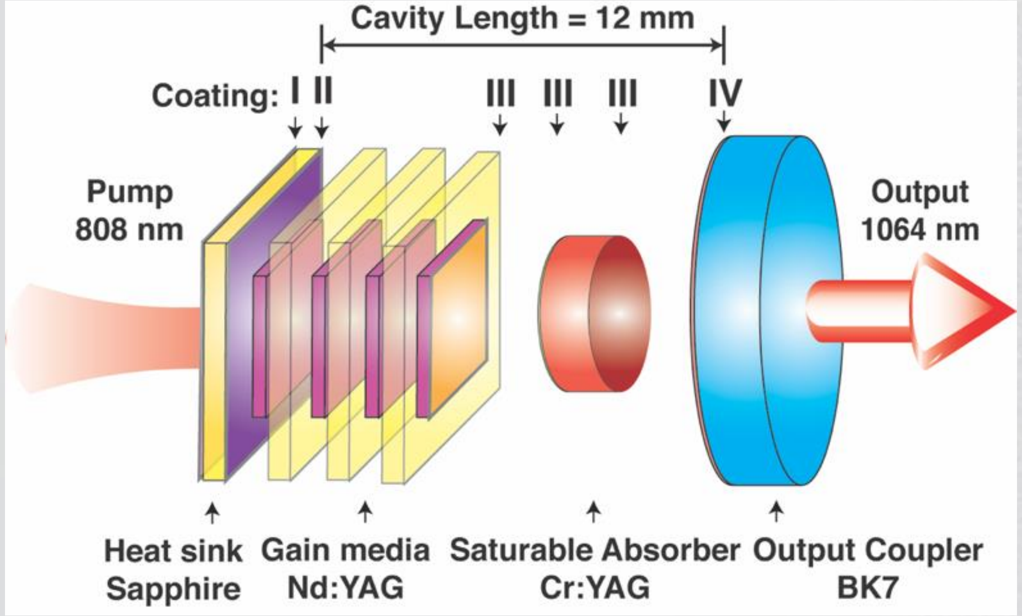
Research work based on DFC chip

CW operation



2x power increase compared to same gain length rod laser

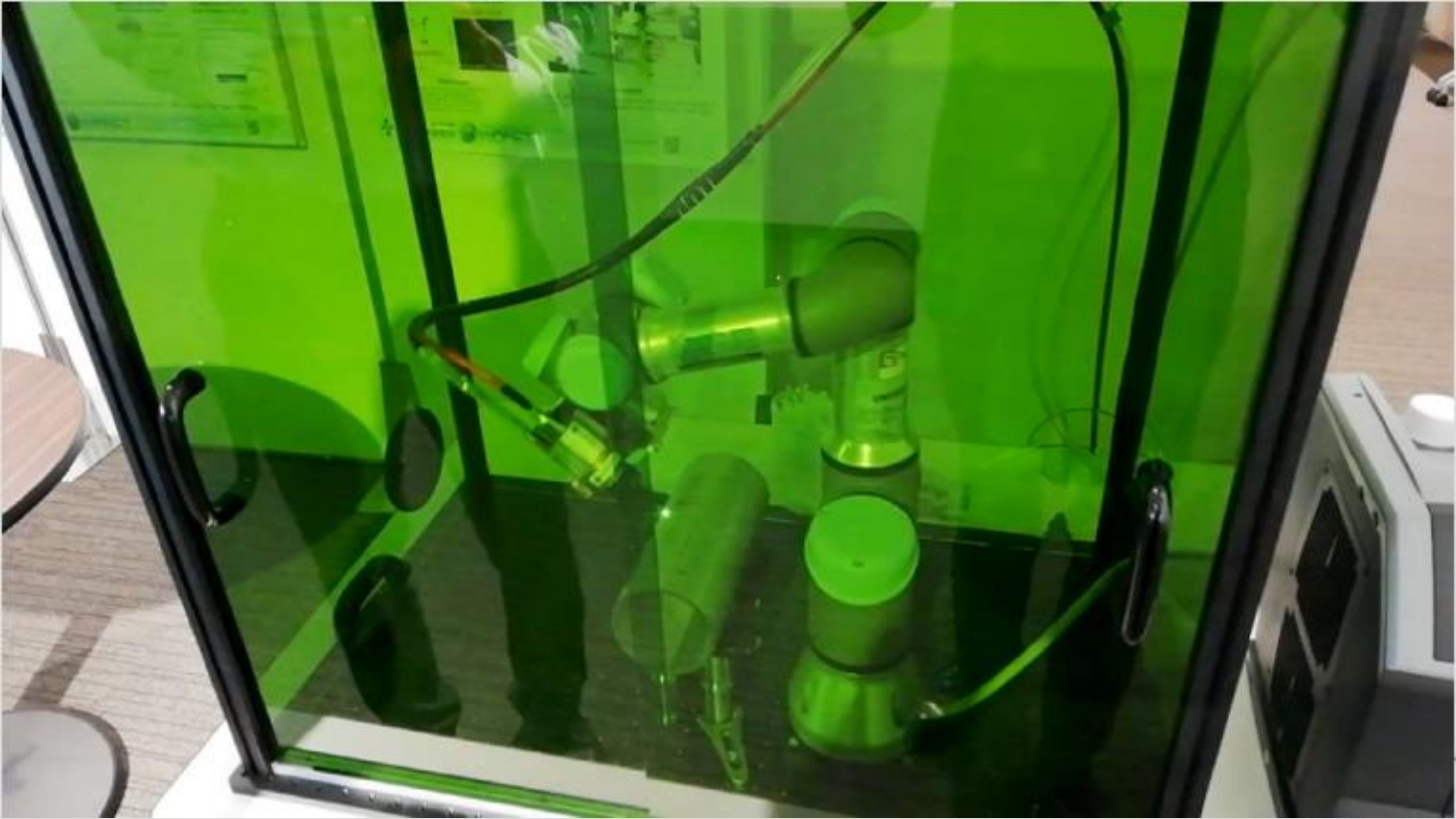
Pulsed operation



Energy 21.5 mJ
Pulse duration <670 ps
Peak power > 32 MW
Rep. rate 10 Hz

Lihe Zheng, Arvydas Kausas, and Takunori Taira, "Drastic thermal effects reduction through distributed face cooling in a high power giant-pulse tiny laser," Opt. Mater. Express 7, 3214-3221 (2017)

Lihe Zheng, Arvydas Kausas, and Takunori Taira, ">30 MW peak power from distributed face cooling tiny integrated laser," Opt. Express 27, 30217-30224 (2019)



DFC concept

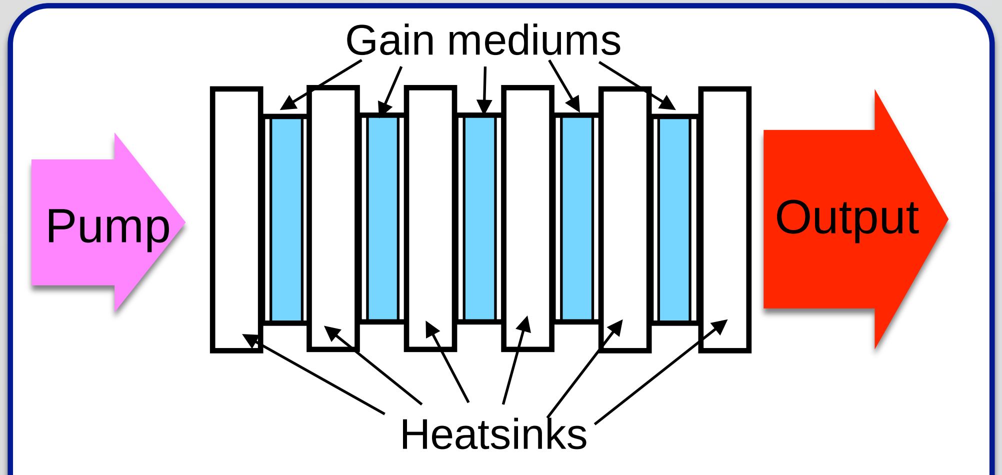
Maximum extractable power

For rod $$P_{ex} = \frac{8\pi R_T L}{\chi}$$

For disk $$P_{ex} = \frac{12 R_T}{\chi}\left(\frac{A}{t}\right)$$

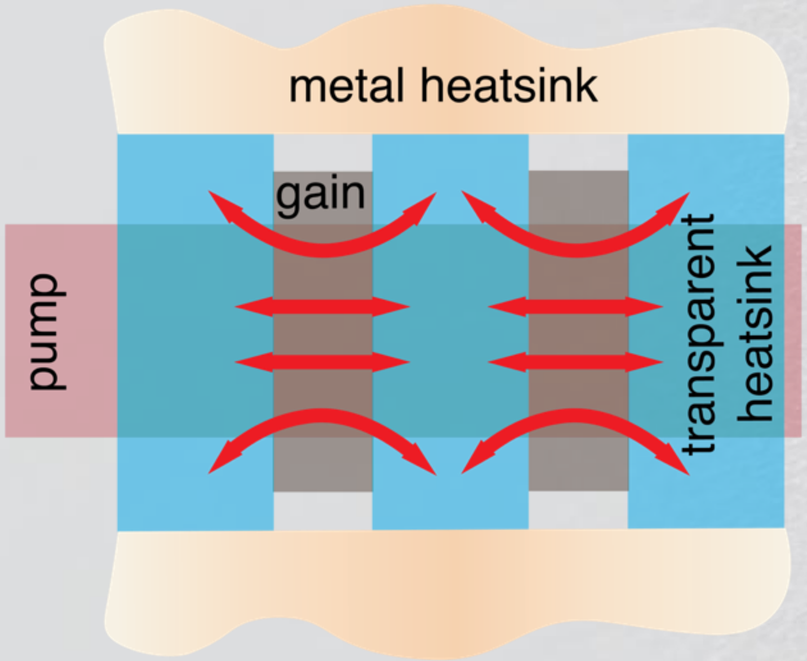
For DFC $$P_{ex} = \frac{24 N R_T}{\chi}\left(\frac{A}{t}\right)$$

R_T – thermal shock parameter
A – area of gain medium
L – length of gain medium
t – gain thickness
χ – heating parameter
N – number of gain chips



http://www.jst.go.jp/impact/program/03.html

Heat management



Transparent heatsink

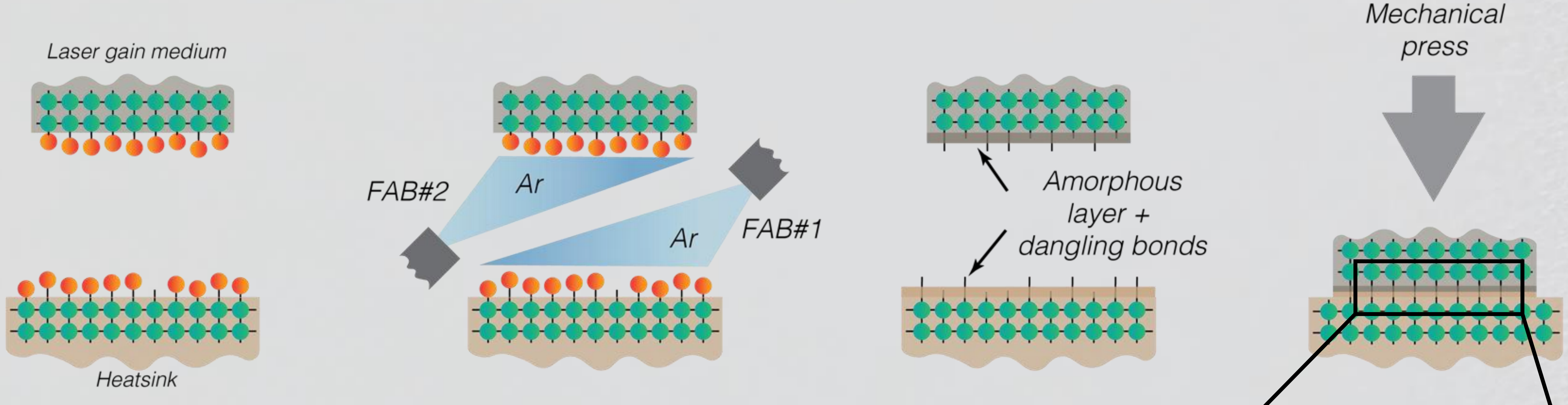
- YAG
- Sapphire
- Diamond

Gain medium

- Nd:YAG
- Yb:YAG
- Cr:YAG
- …etc.

Surface Activated Bonding (SAB)

b) T. Suga et. al, Acta Metall.Mater. 40, S133-S137 (1992).
c) L. Zheng et. al, *Optical Materials Express*, *7*(9), 3214 (2017).

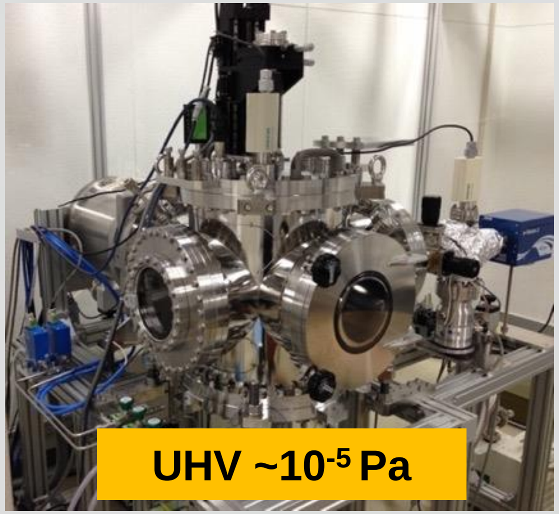


a) Initial state

b) FAB
(Fast Atom Beam)

c) Amorphous layer
creation

d) Bonding



DFC-structure Tiny Integrated Laser

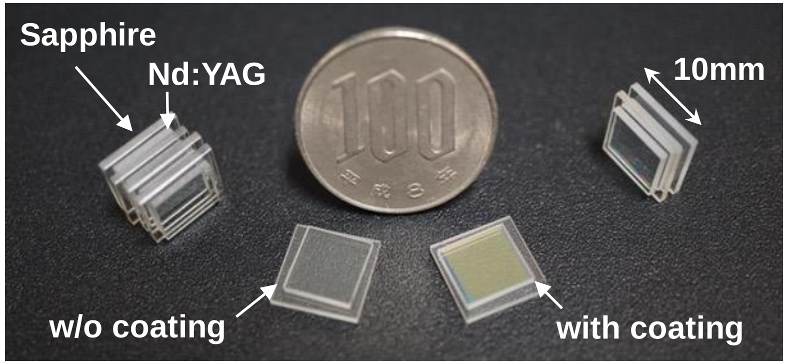
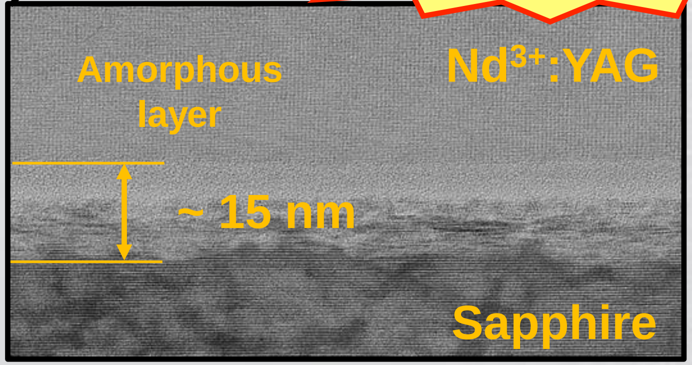
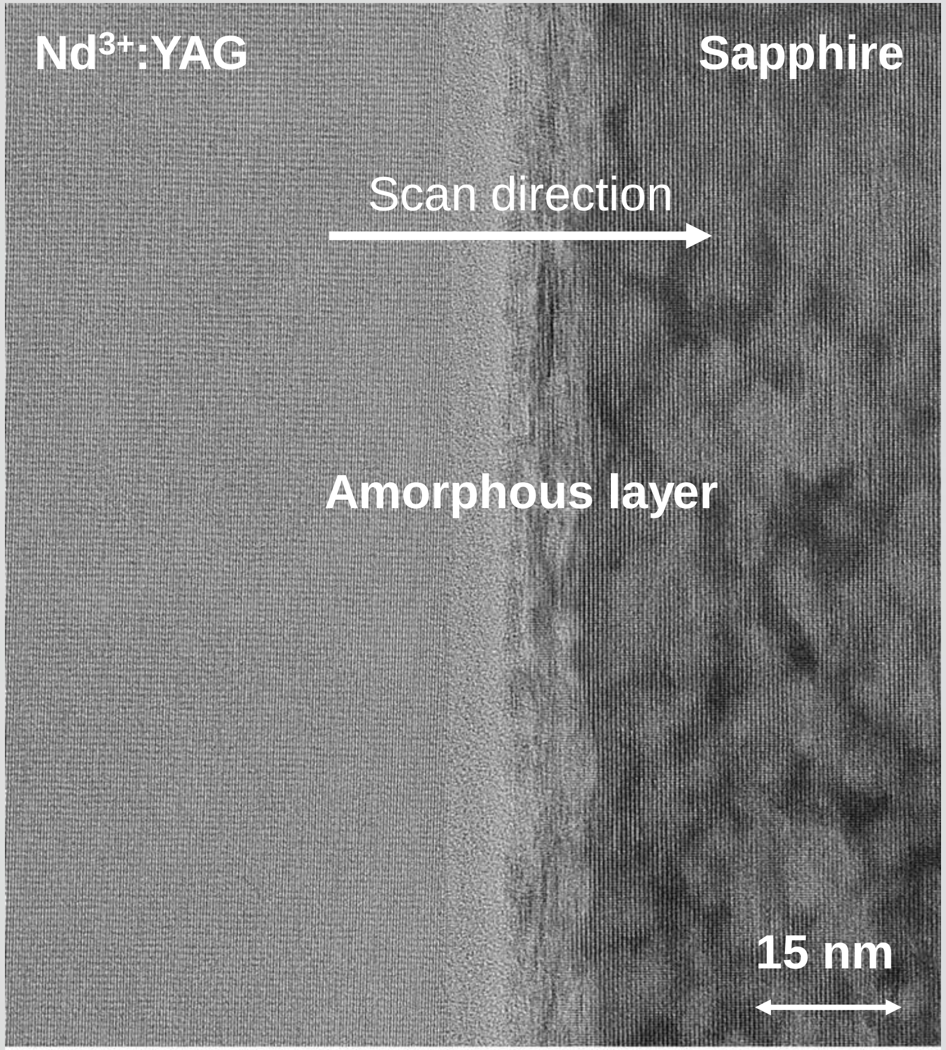


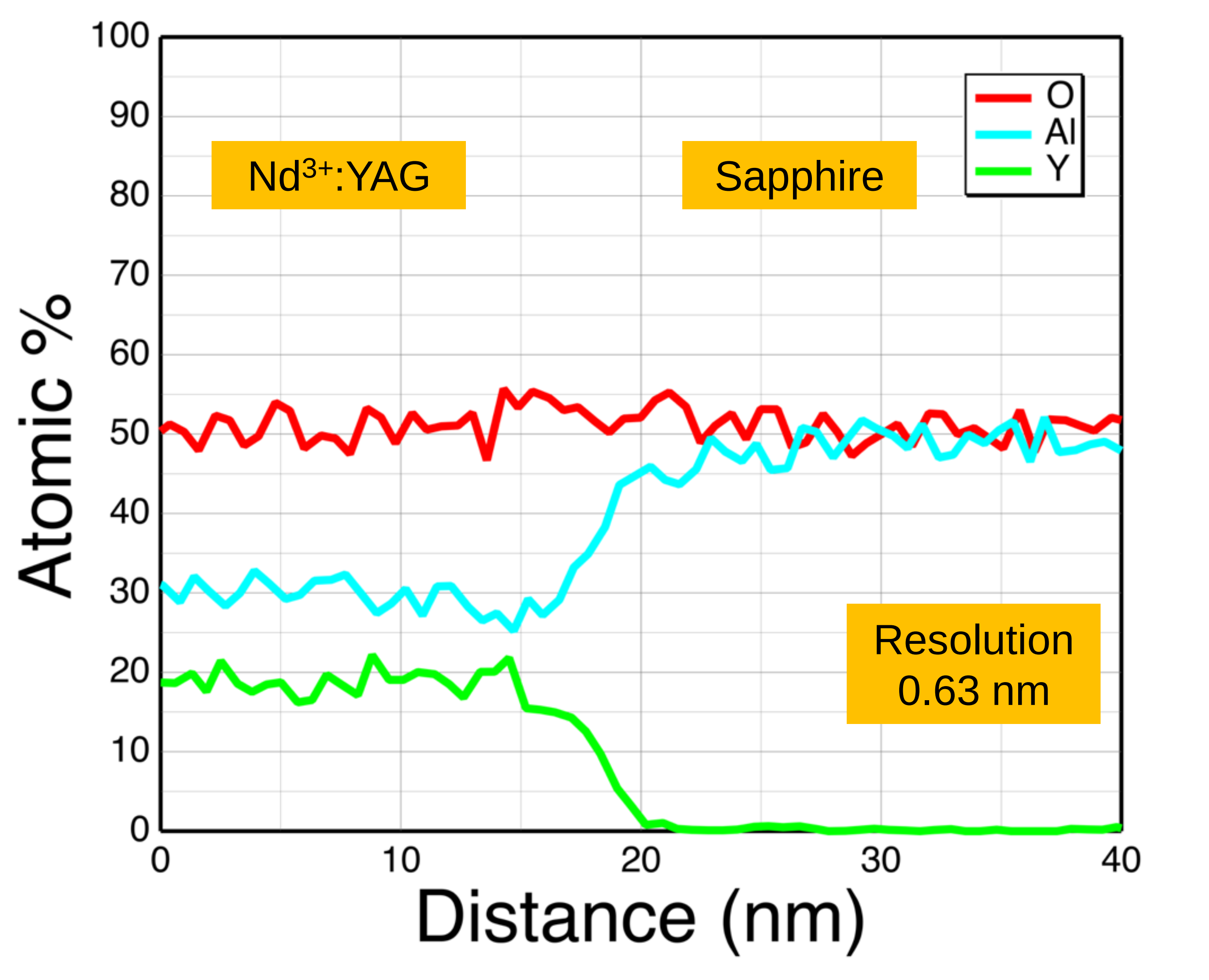
Photo : Aug. 15th, 2016

Patented

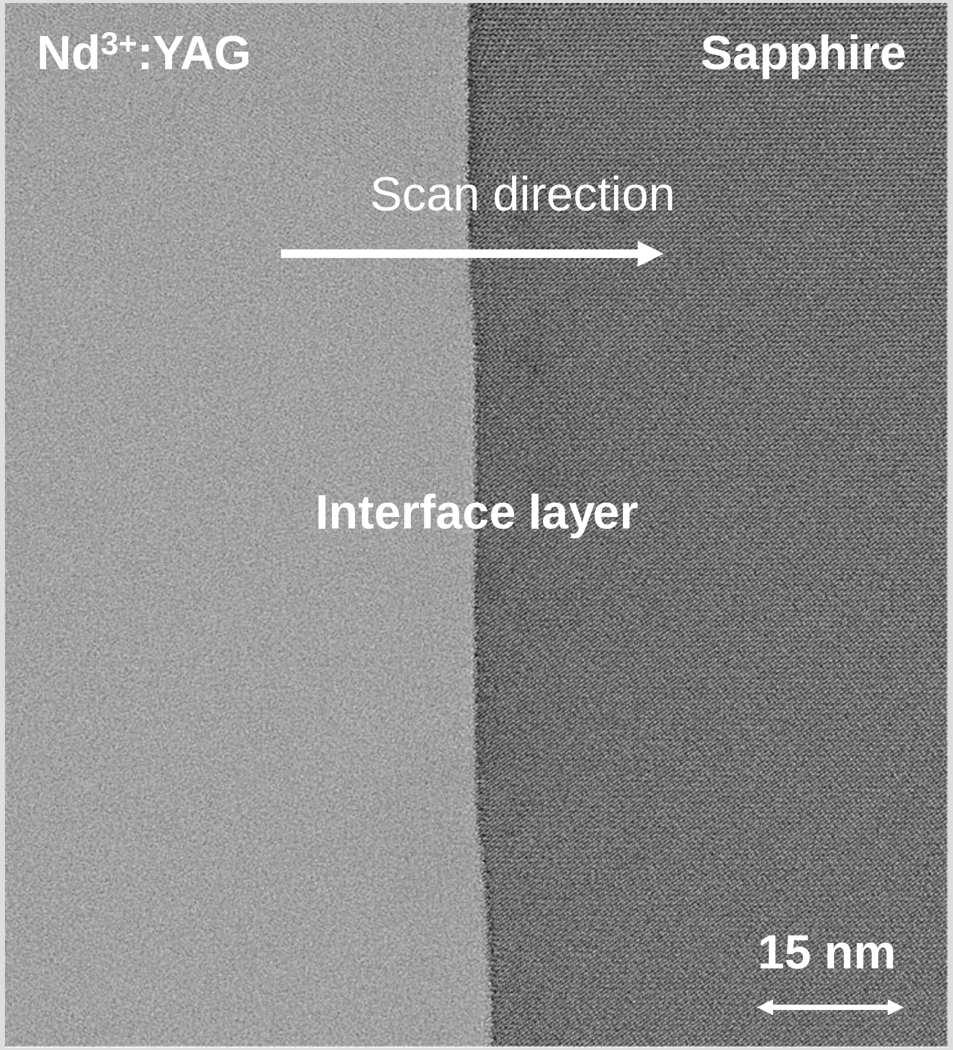


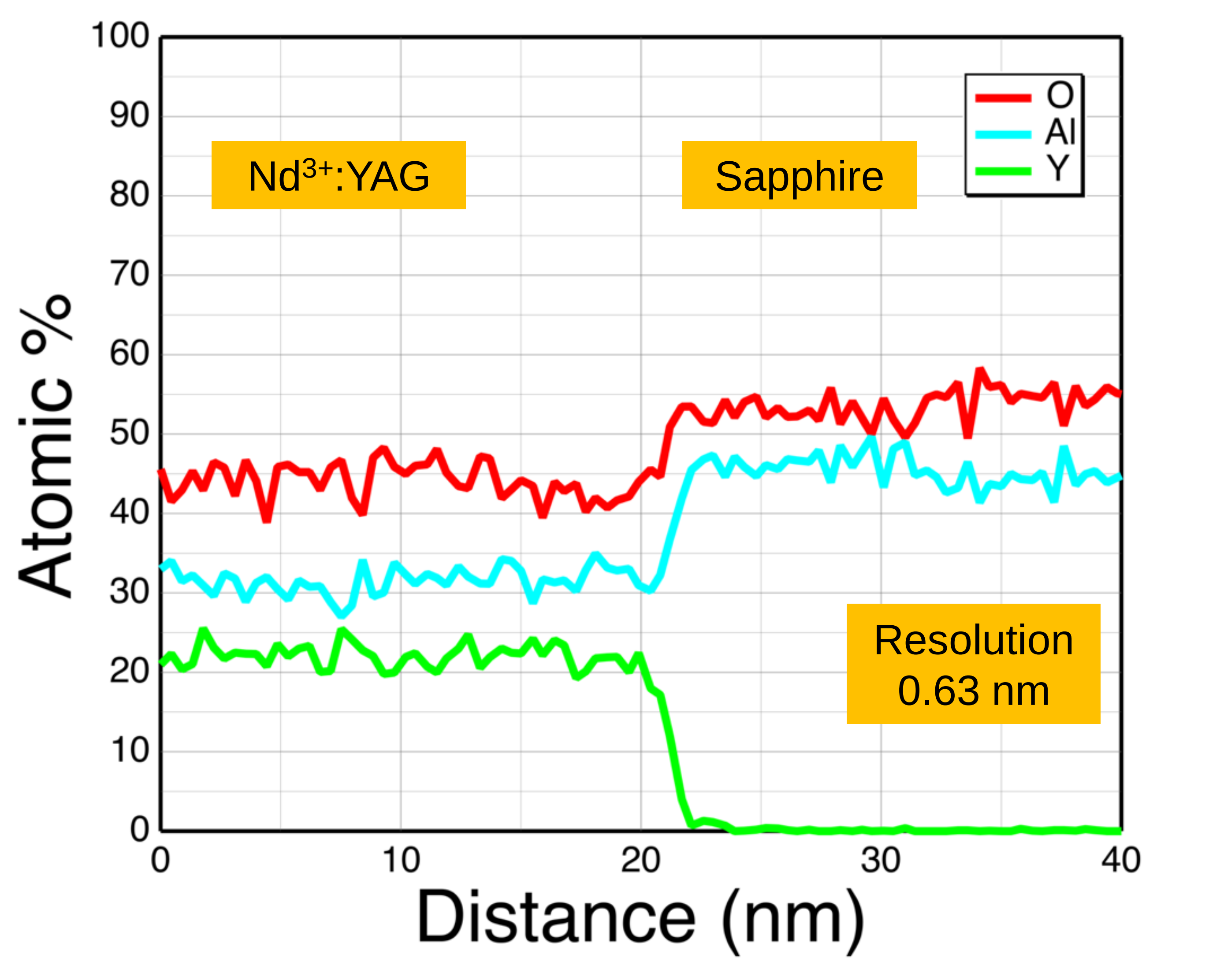
TEM and EDX measurements. Reference crystal



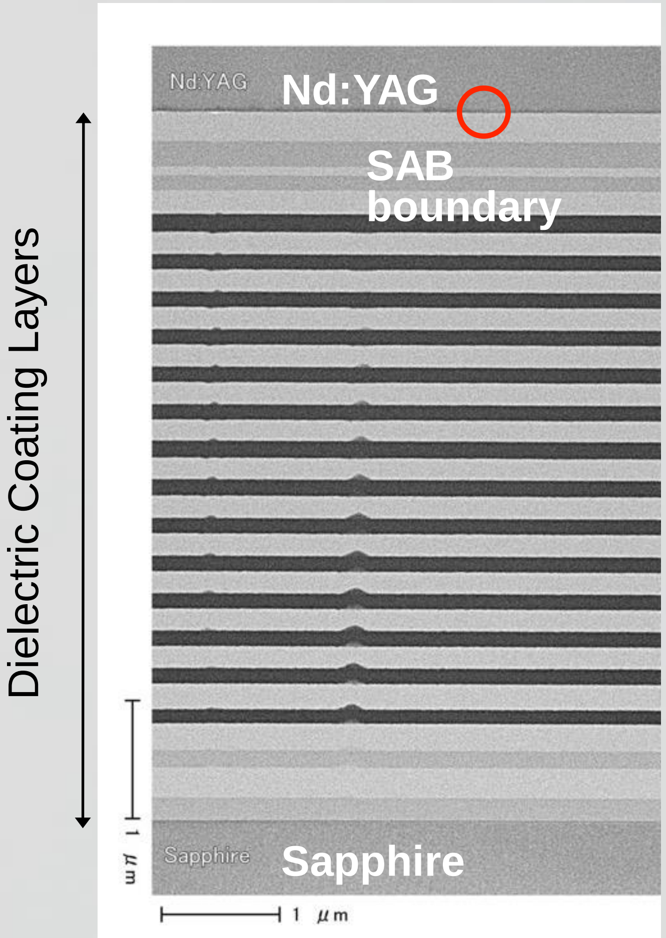


TEM and EDX measurements. Annealed crystal

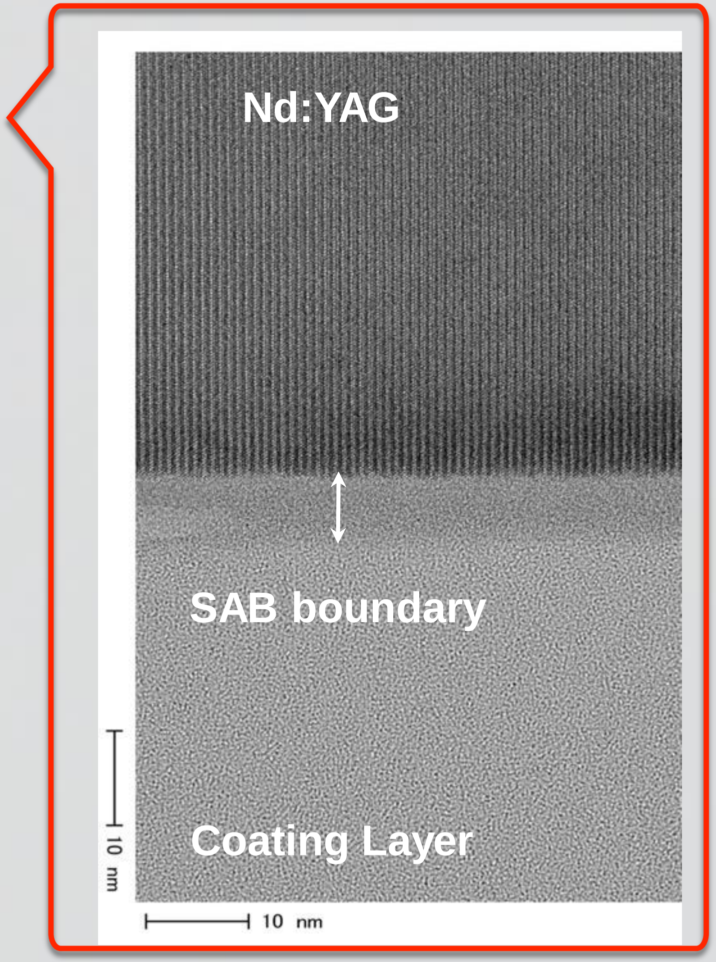




Coated material bonding

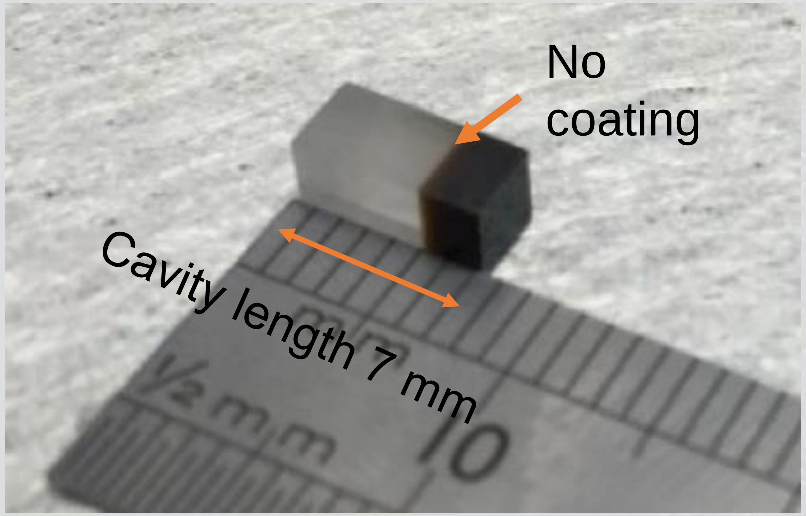


(a) Magnification : x 25,000

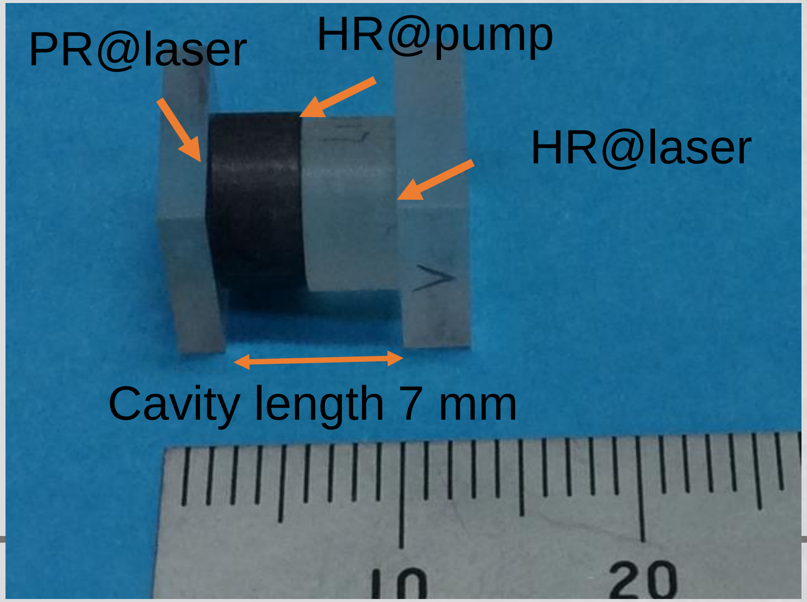


(b) Magnification : x 20,000,000

Ceramic crystal bond (diffusion bond)

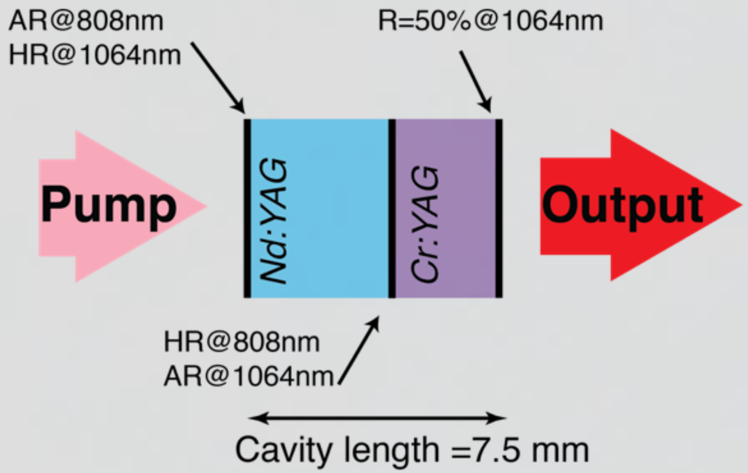


Crystal bond (SAB, with interface coating)

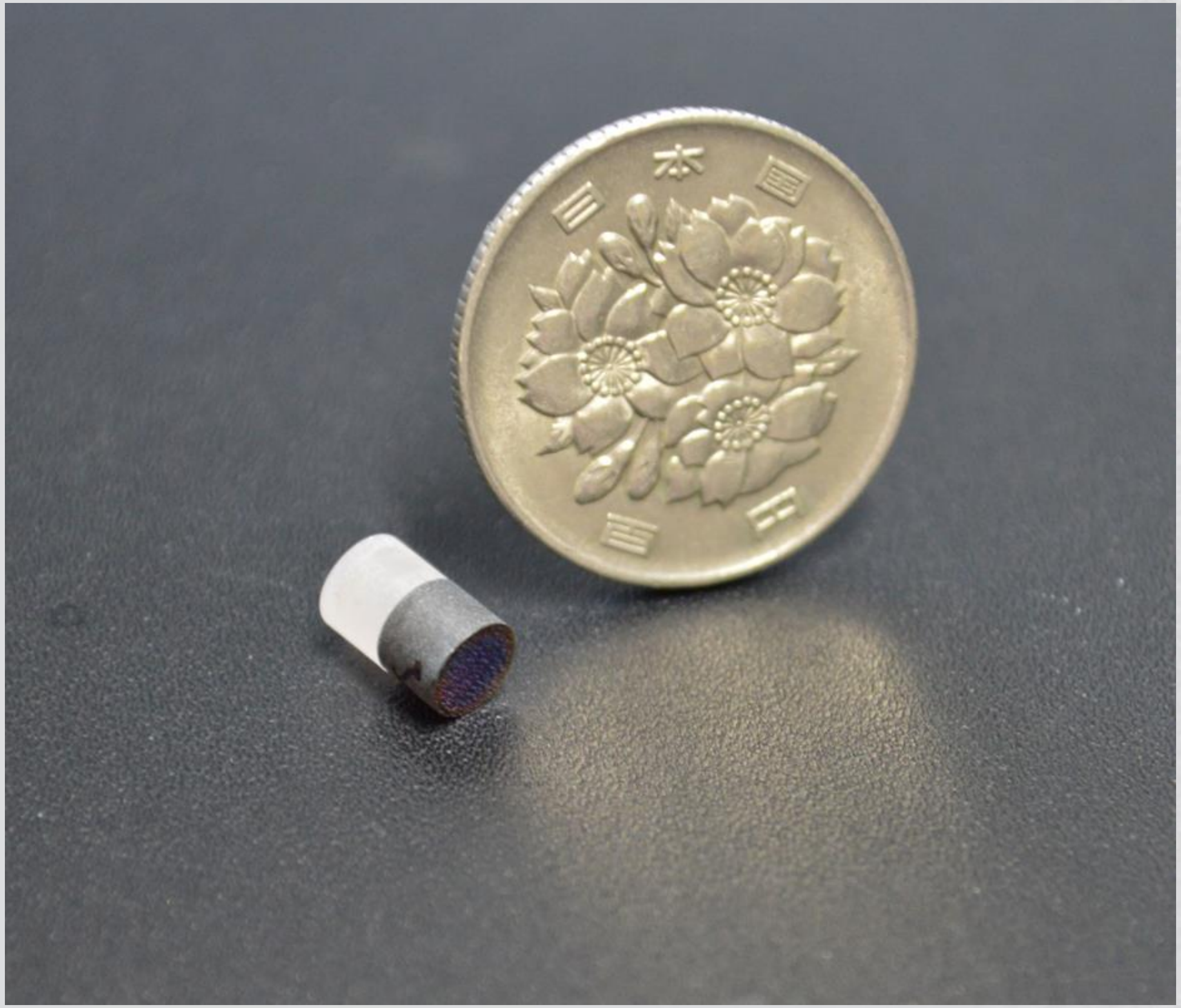


TEM analysis of SAB boundary: Coated samples

No end-cap composite chip

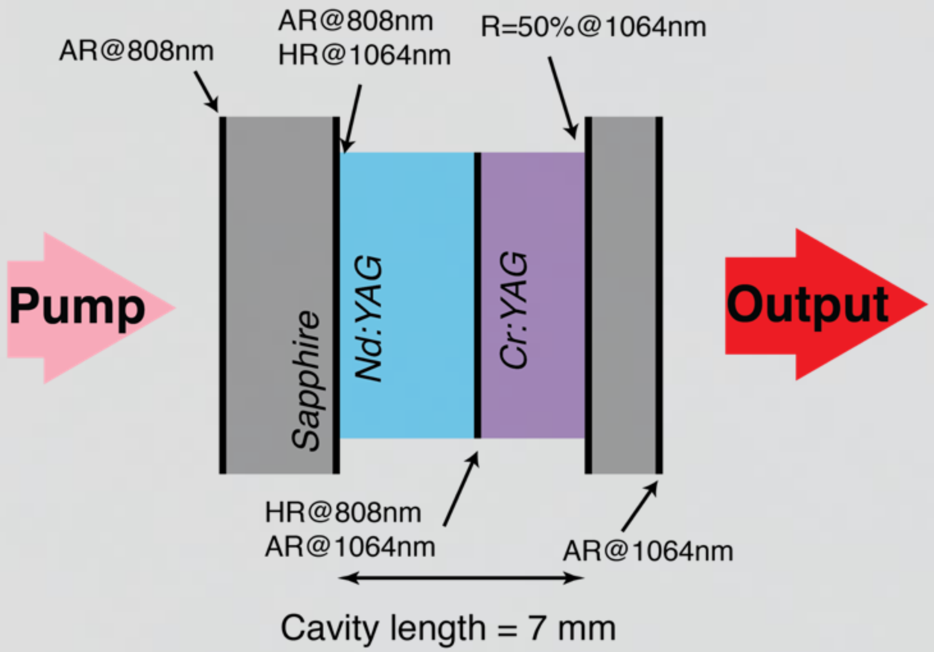


Nd:YAG, <111>, 1.1-at.% *ø5x4 mm*
Cr:YAG, [110], T_0 *=30%* *ø5x3.5 mm*

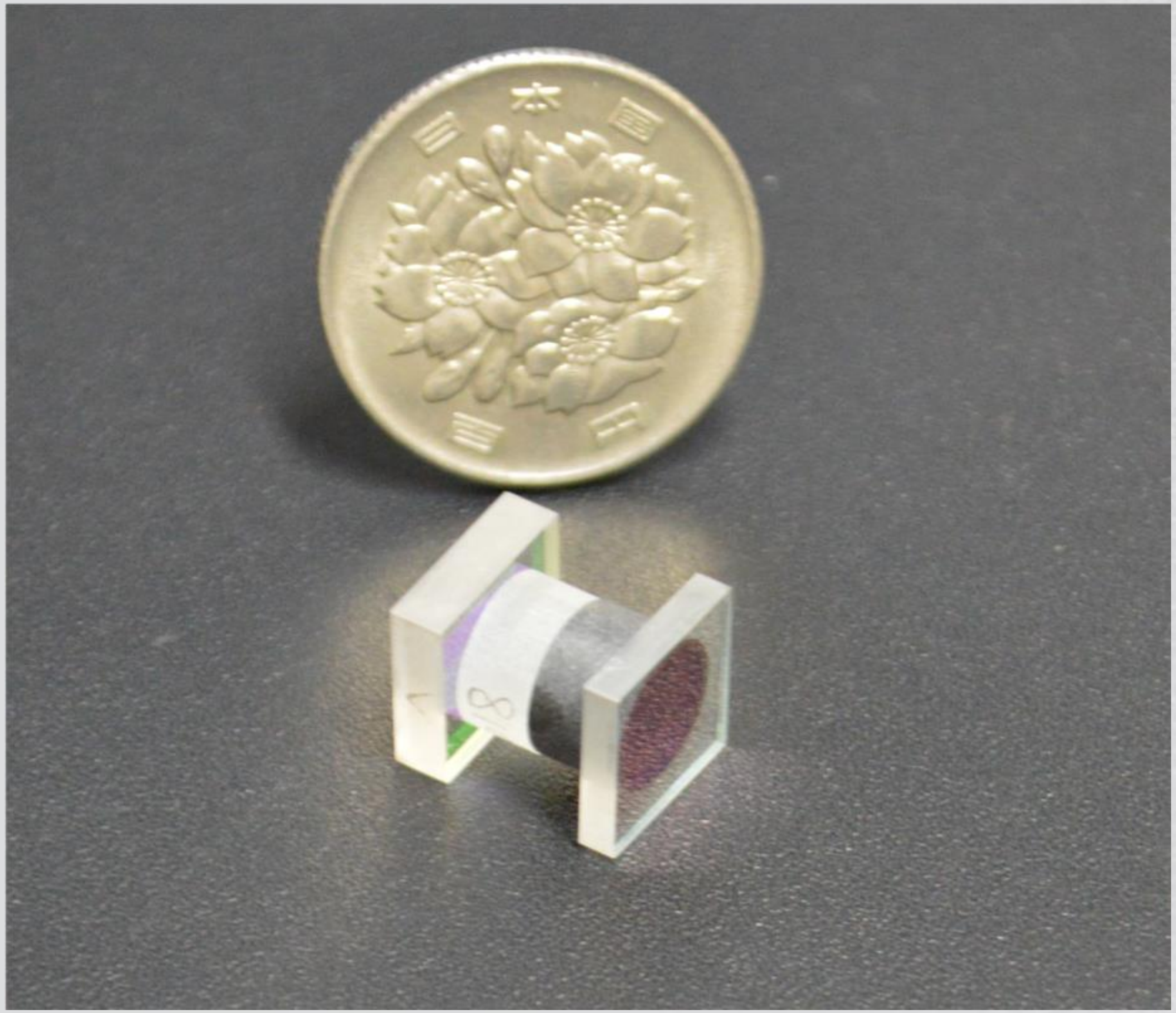


Pump Beam size:	0.77 mm
Pump peak power:	150 W
Pump pulse duration:	80 μs
Repetition rate:	100-1000 Hz

With end-cap composite chip



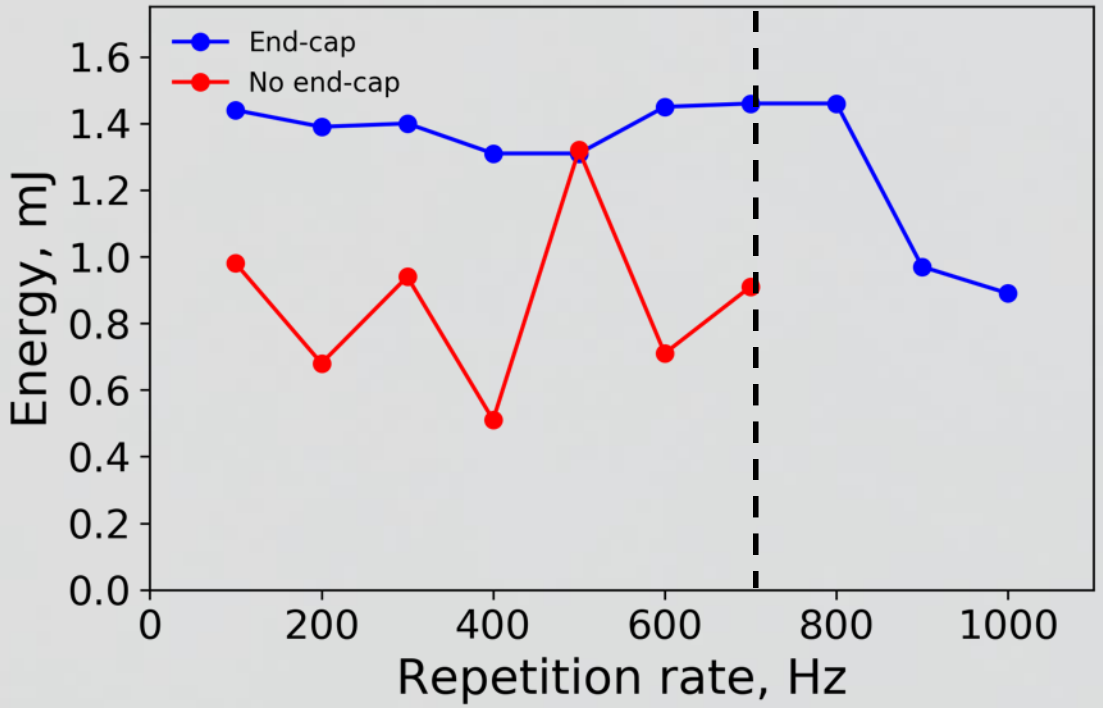
Sapphire, c-cut	*10x10x2-3 mm³*
Nd:YAG, <111>, 1.1-at.%	*ø8x4 mm*
Cr:YAG, [110], T_0 =30%	*ø8x3 mm*



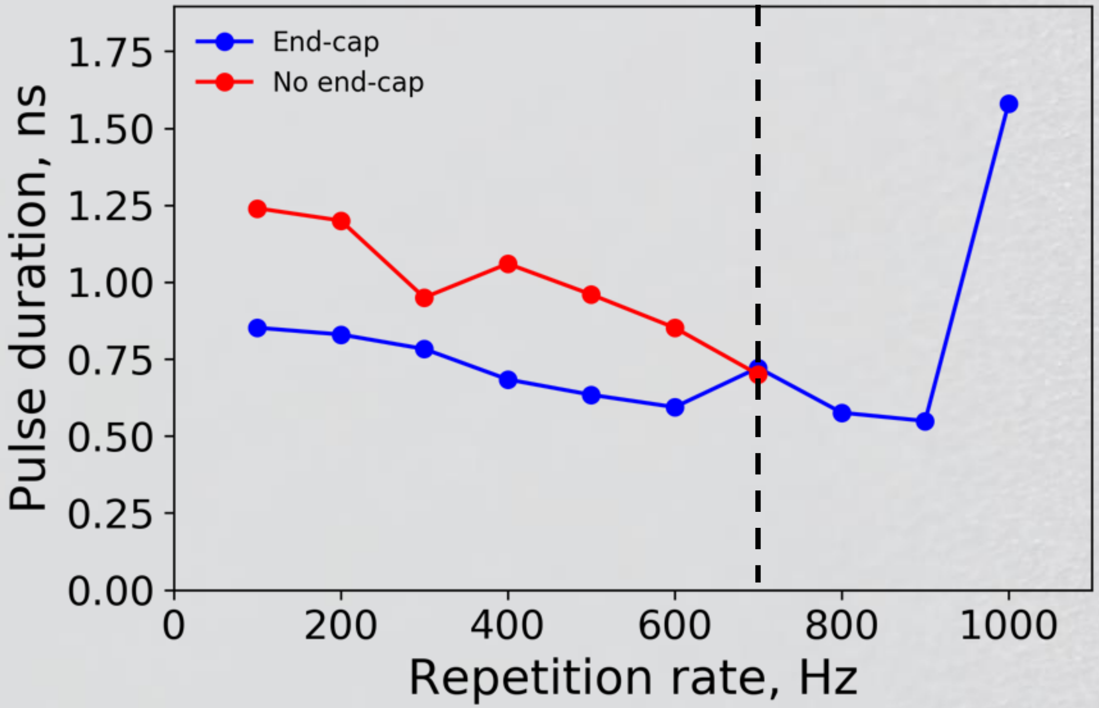
Pump Beam size:	0.77 mm
Pump peak power:	150 W
Pump pulse duration:	80 μs
Repetition rate:	100-1000 Hz

Output parameters. Pulse energy and duration

Pulse energy



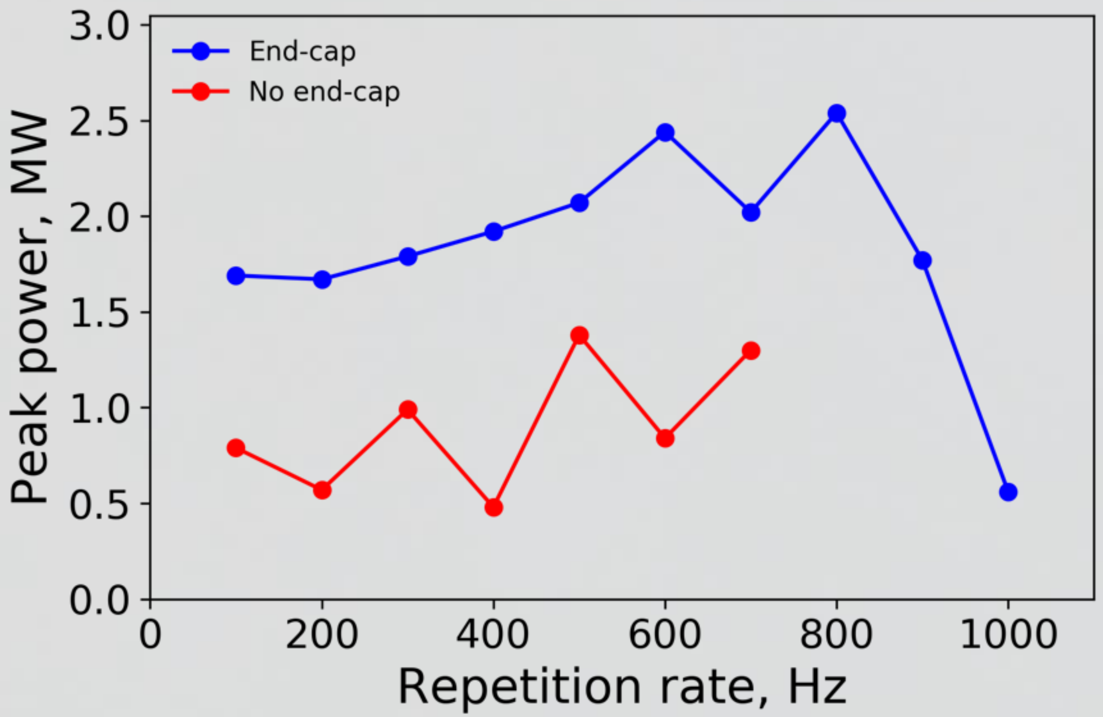
Pulse duration



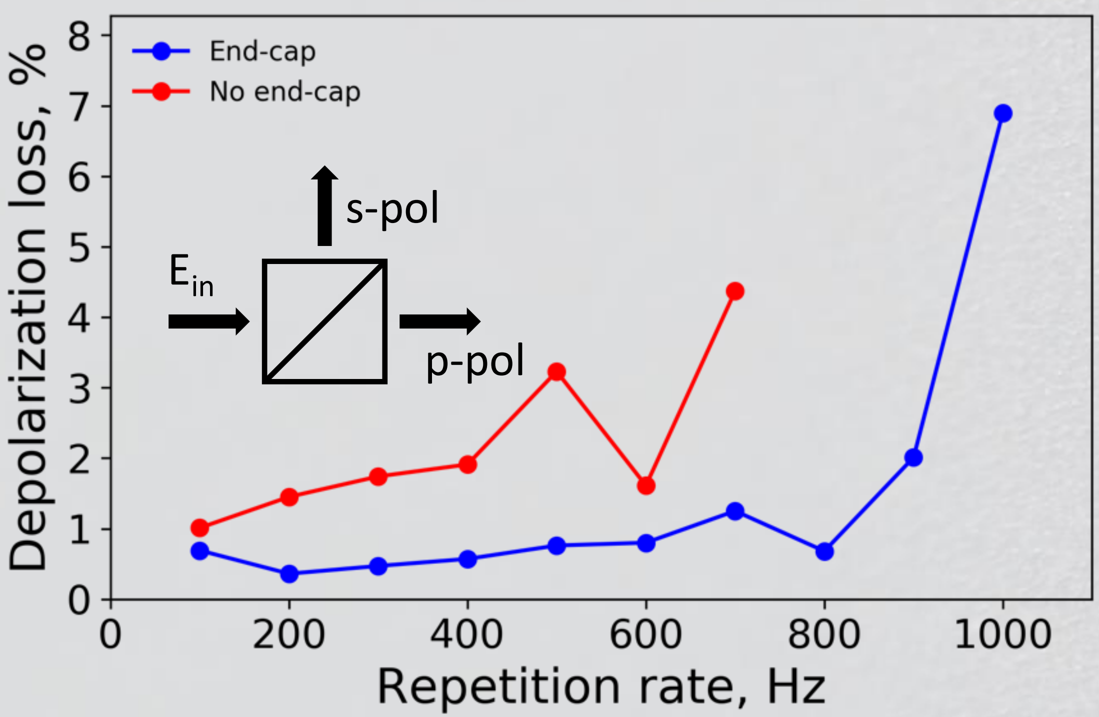
- No data after this 700 Hz for no end-cap case
- Heat generation increased

Output parameters. Pulse peak power and depolarization loss

Peak power



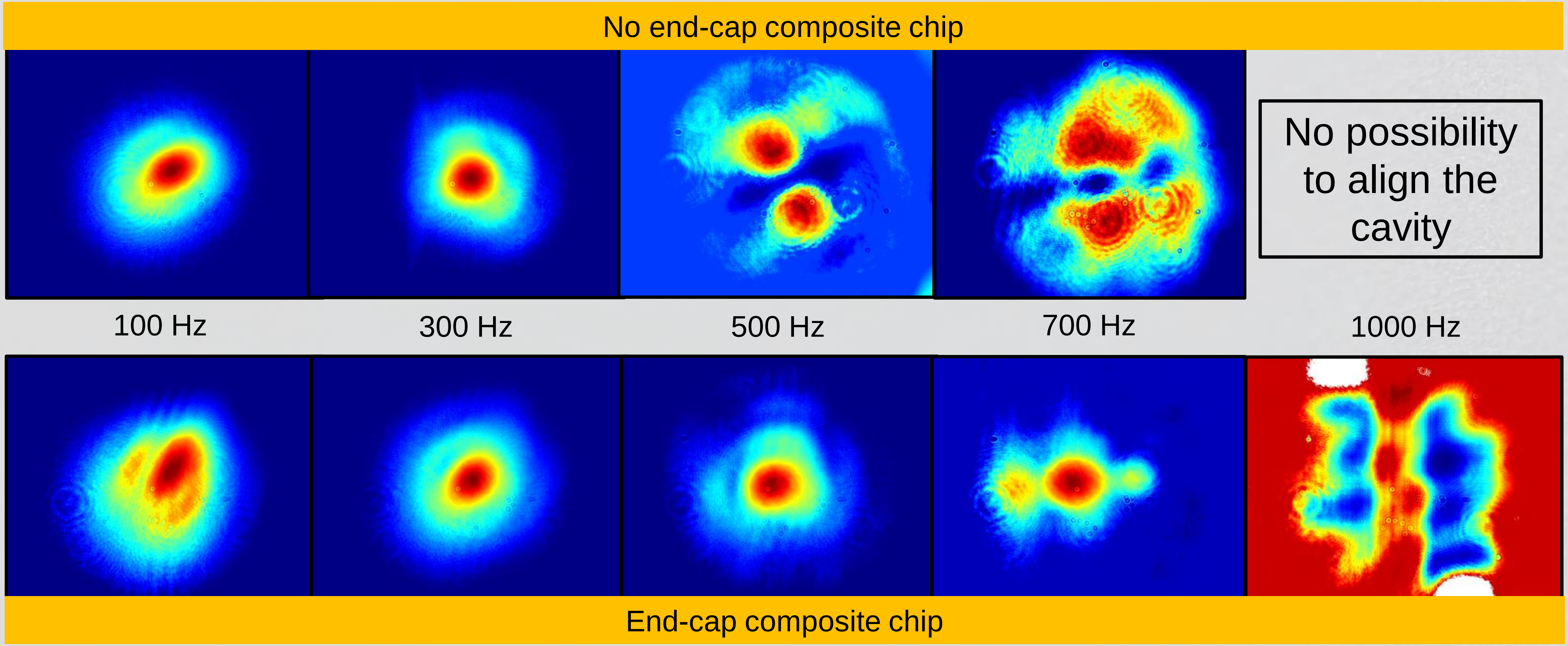
Depolarization loss



- No data after this 700 Hz for no end-cap case
- Heat generation increased

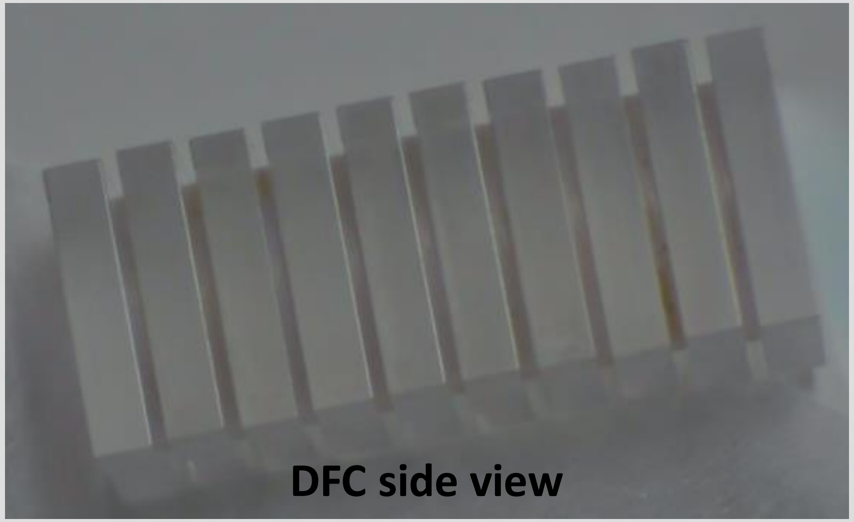
$$D_{loss} = \frac{s - pol}{(s - pol) + (p - pol)}$$

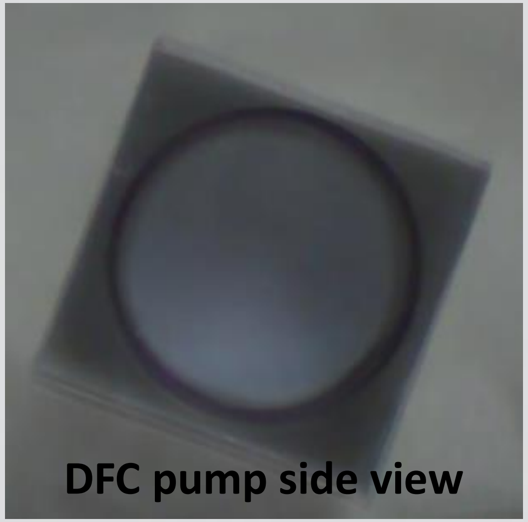
Beam profile at different repetition rates values

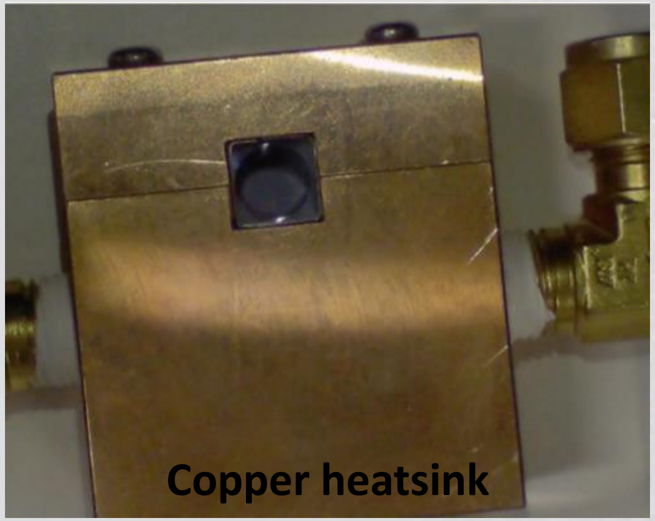


Amplifier setup (High Energy Accelerator Research Organization, KEK)

With prof. M. Yoshida group

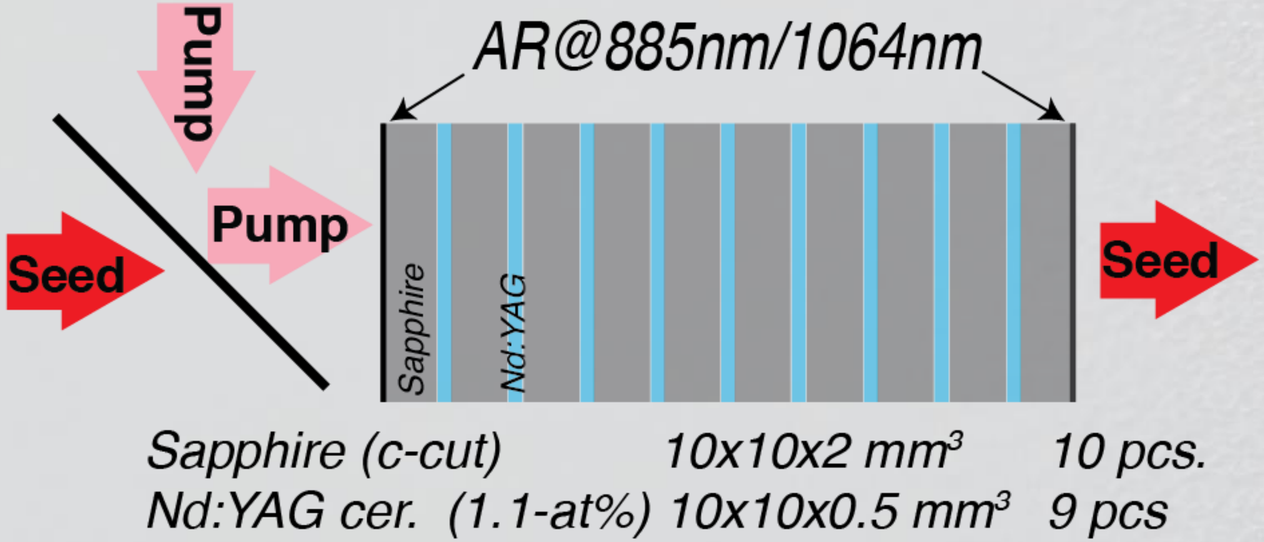




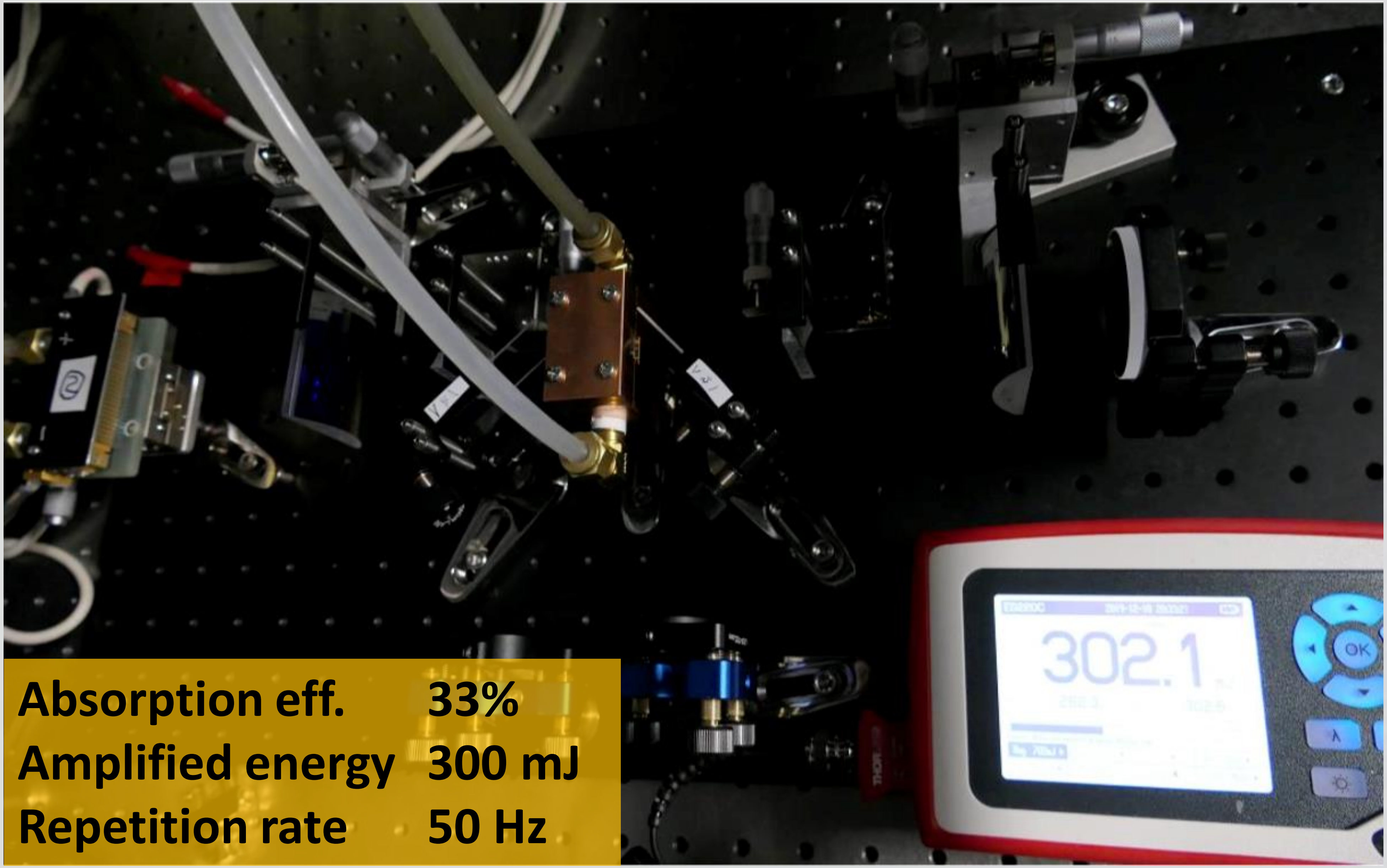


Pump parameters:

Pump power	8.85 kW
Pulse duration	250 μs
Pump energy	2.2 J
Rep. rate	10-50 Hz



Experimental results



Absorption eff.	33%
Amplified energy	300 mJ
Repetition rate	50 Hz

Finite element analysis calculation

Pump beam profile:

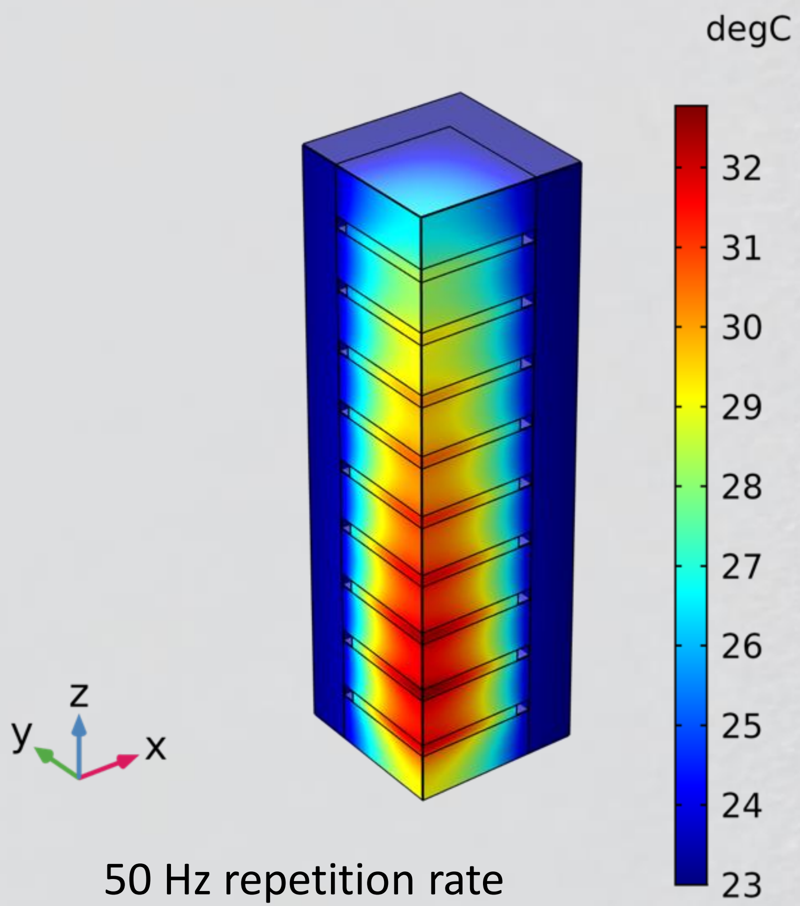
- Top-Hat profile
- Beam waist is constant along the crystal, $2w$ =10 mm

Absorption coefficient in Nd^{3+}:YAG crystal:

- Absorption coefficient is constant and does not depend on a temperature, α=1.5 cm^{-1}
- No pump saturation occur* ($I_{pump} \ll I_{saturation,pump}$)

Fractional heat load:

- η_h equal to 0.317

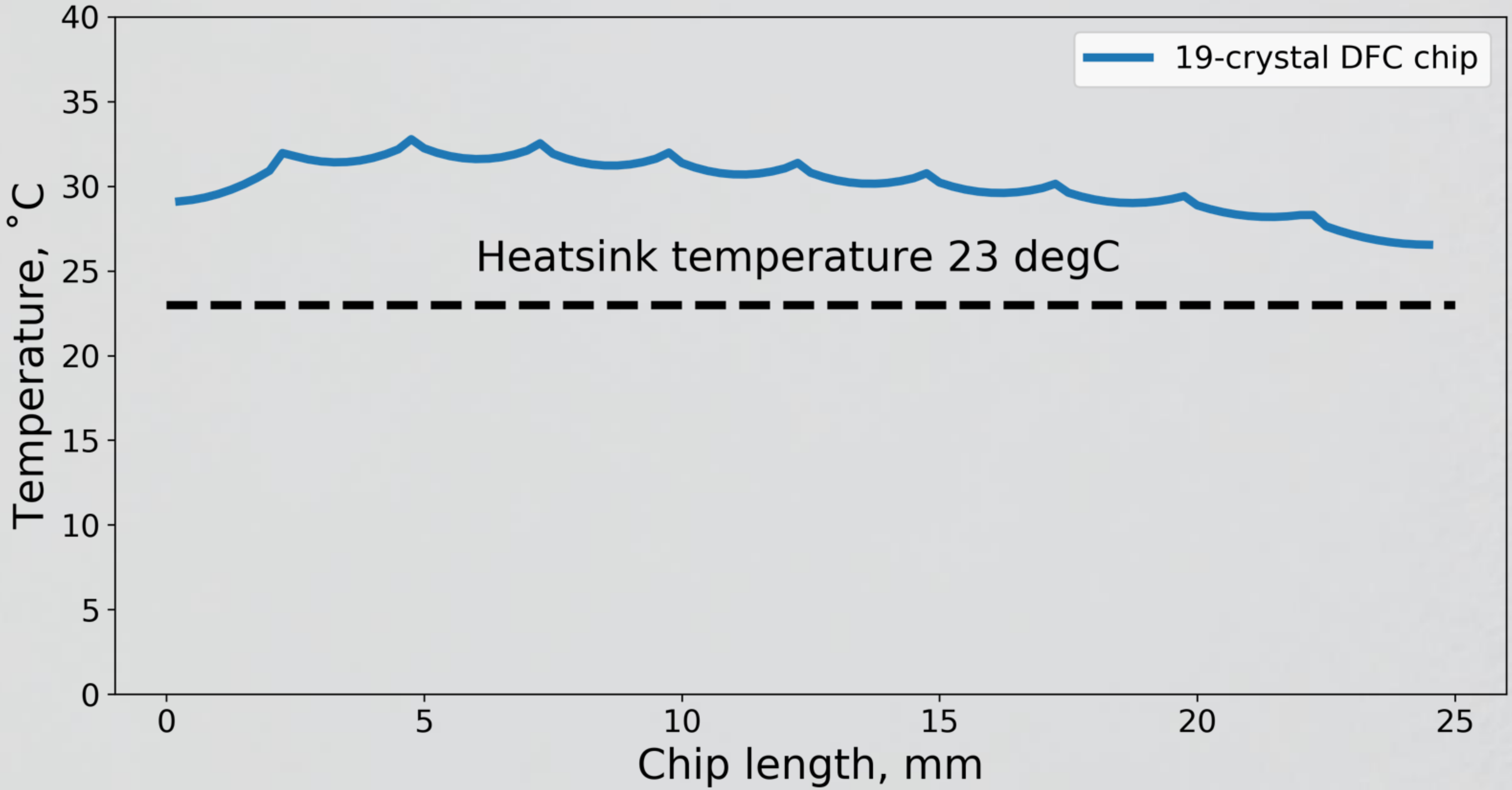


50 Hz repetition rate

$$Q(x,y,z) = \frac{P_{in} \cdot \eta_h \cdot \alpha(z)}{\pi w^2} \cdot e^{-\int_0^l \alpha(z) \cdot dz}$$

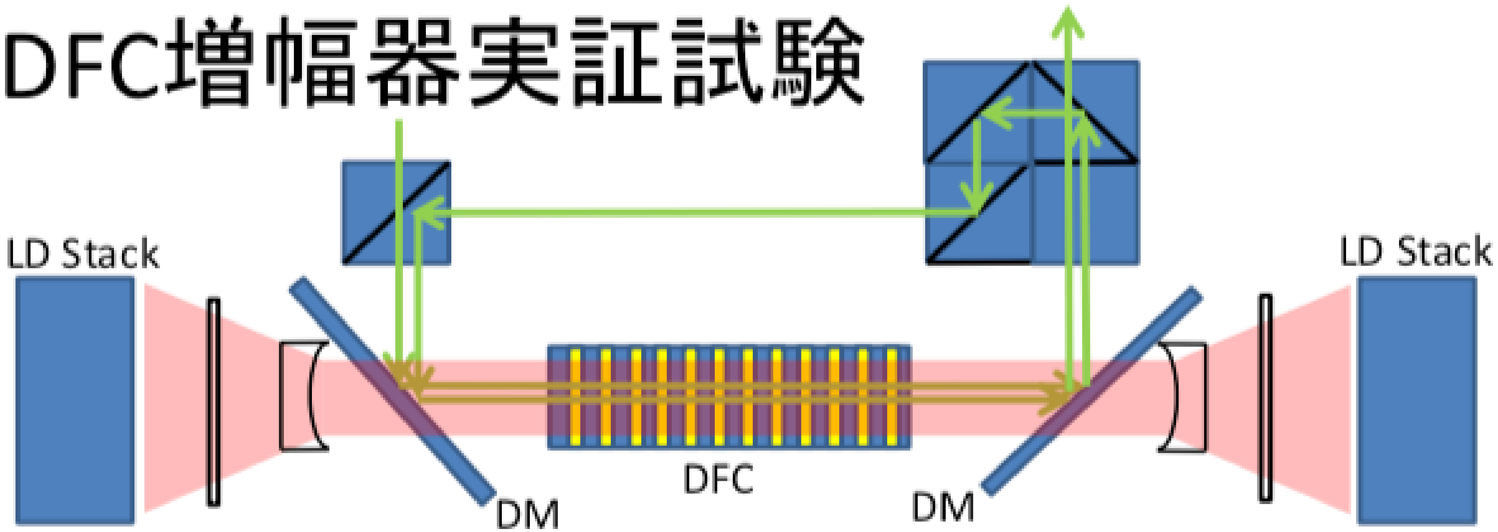
* Y. Sato et al. in *IEEE JQE*, vol. 40, pp. 270-280 (2004)

Simulated temperature distribution



Future work

DFC増幅器実証試験

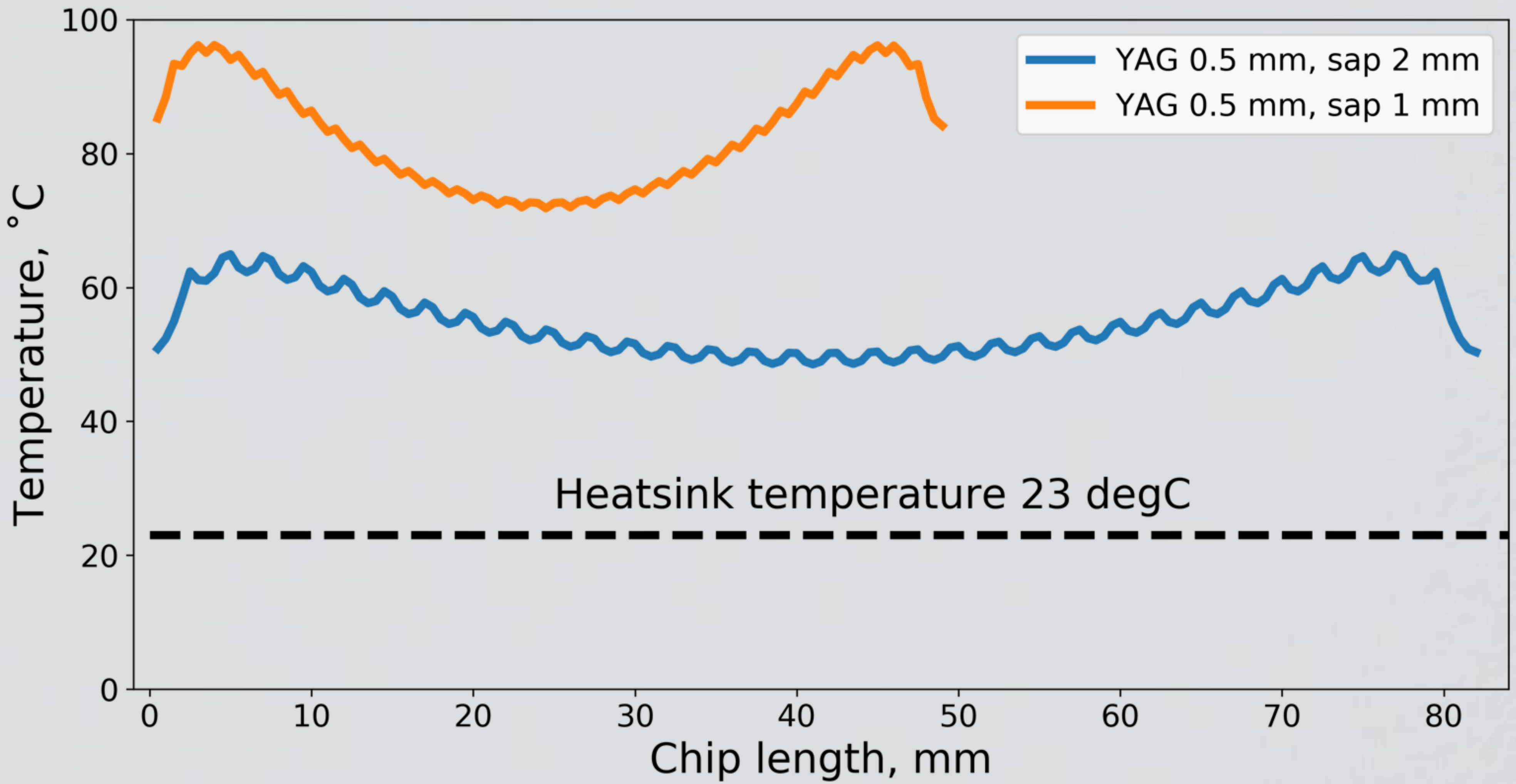


２ループにする事で戻り光を無くす & 90度回転
(結晶の複屈折による偏光回転の戻り等)

- 増幅率
  - 8 kW x 4 (両方向On-Axis励起) x 250μs = 8 J / cm^2
  - G= 5 for L(Nd:YAG) = 1.3cm($1/e^2$) (2-passで50倍)
- Pump(885nm)　　　　Output

  4 stack(32kW, 8J)　　　→ 2 J→ 1 J @ SHG

Future work. Simulated temperature distribution



Conclusion

- **DFC** concept is originally developed by SAB for **H**andheld **I**ntense **T**iny **I**ntegrated **L**aser (**HITILA**)
  - micro-laser energy scaling
  - sub-nanosecond (sub-ns) pulse duration

- We produced composite crystals for CW and Q-switch operation by SAB. The interface between crystal was coated and helped to increase pump absorption efficiency.

- By use 19-crystal DFC chip, amplification up to 300 mJ at 50 Hz repetition rate was achieved.

- We are working towards optimization of amplifier setup and DFC chip in order to achieve 2 J amplifier laser at 100 Hz repetition rate