接合界面強靭化PowerChipの開発

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「ジャイアント・マイクロフォトニクスによる高出力極限固体レーザ」プロジェクトセミナー

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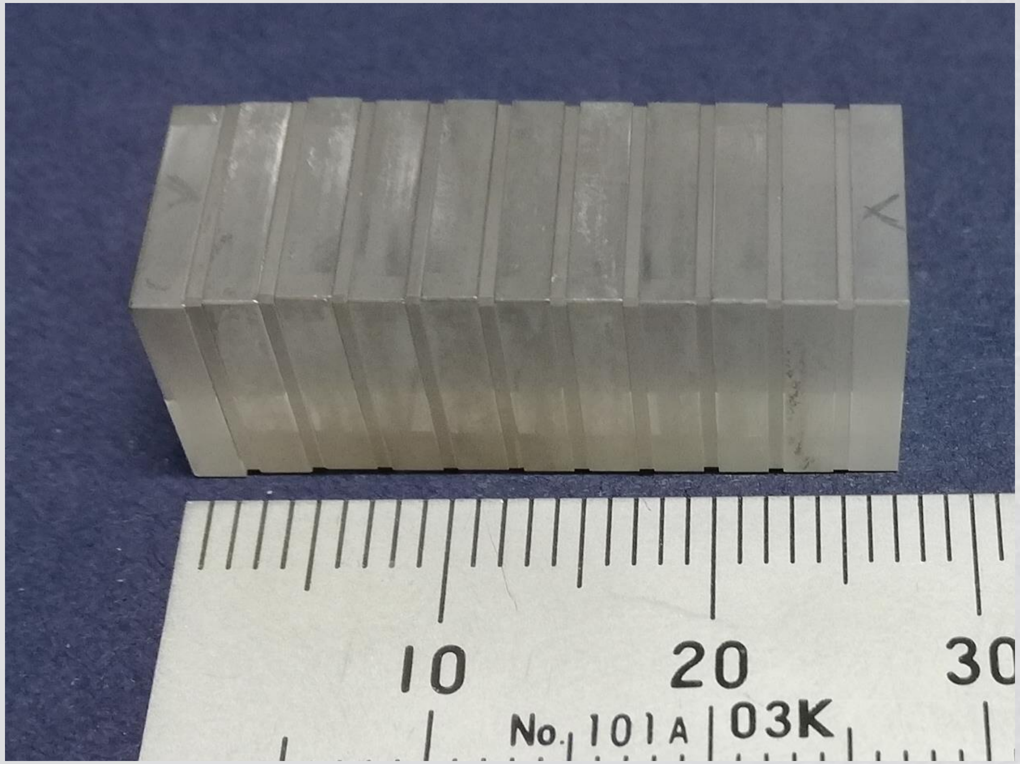
Outline

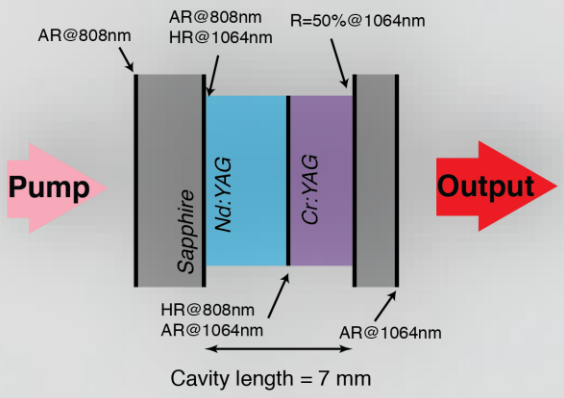
- Motivation
- New concept and methods
  - Distributed Face Cooling (DFC)
  - Surface Activated Bonding (SAB)
- Tensile strength measurement
- FEA modeling
- Bonding for KEK



21-crystal DFC chip made of bonded Nd^{3+}:YAG/Sapphire crystals

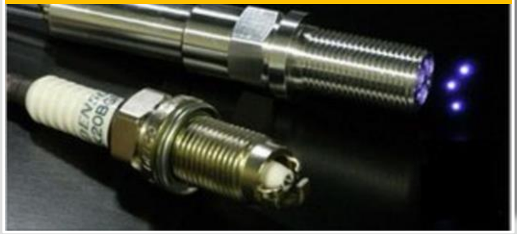
Our motivation

Composite microlaser

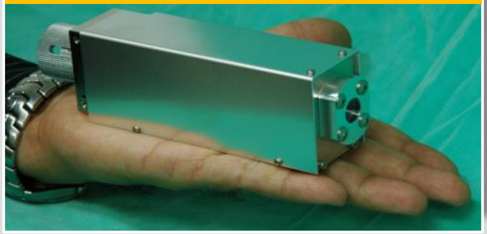


Energy: up to 25 mJ
Rep. rate: up to 100 Hz
Duration: sub-ns
Peak power: >MW

Laser ignition



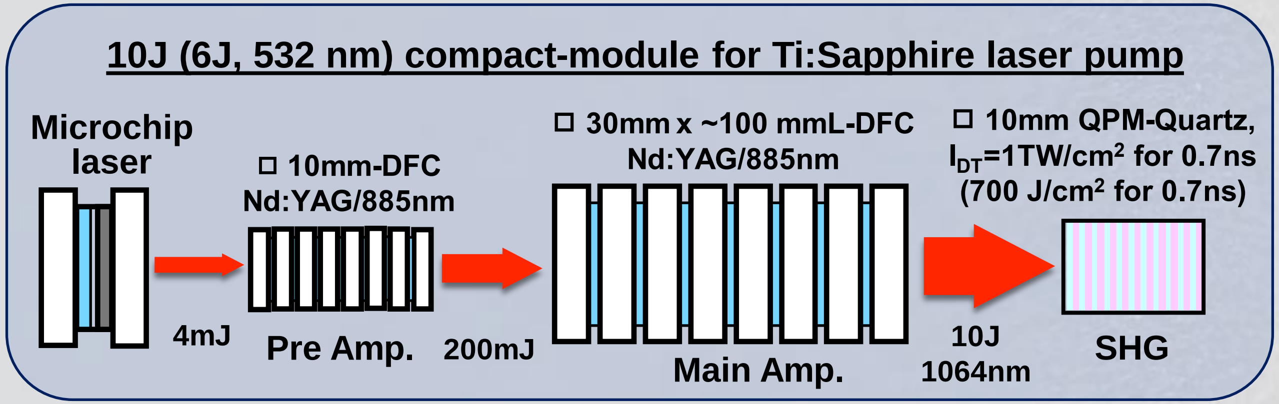
Frequency conversion



Material processing

Laser peening

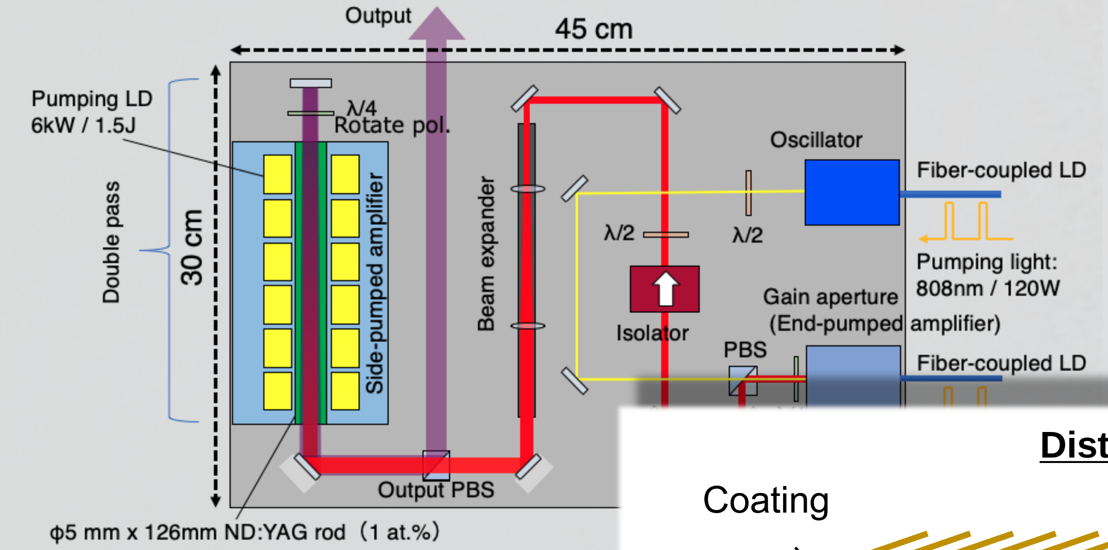
JST-Mirai project for laser-driven particle acceleration



- 10 J, 100 Hz operation at 1064 nm
  Common crystals and methods
- Room temperature operation
  Reduce need for expensive cooling system
- Compact design to fit a breadboard
  Reduce overall size of the system
- QPM-quartz crystal for frequency conversion
  High LIDT value

Power scalability

A3 paper size amplifier system



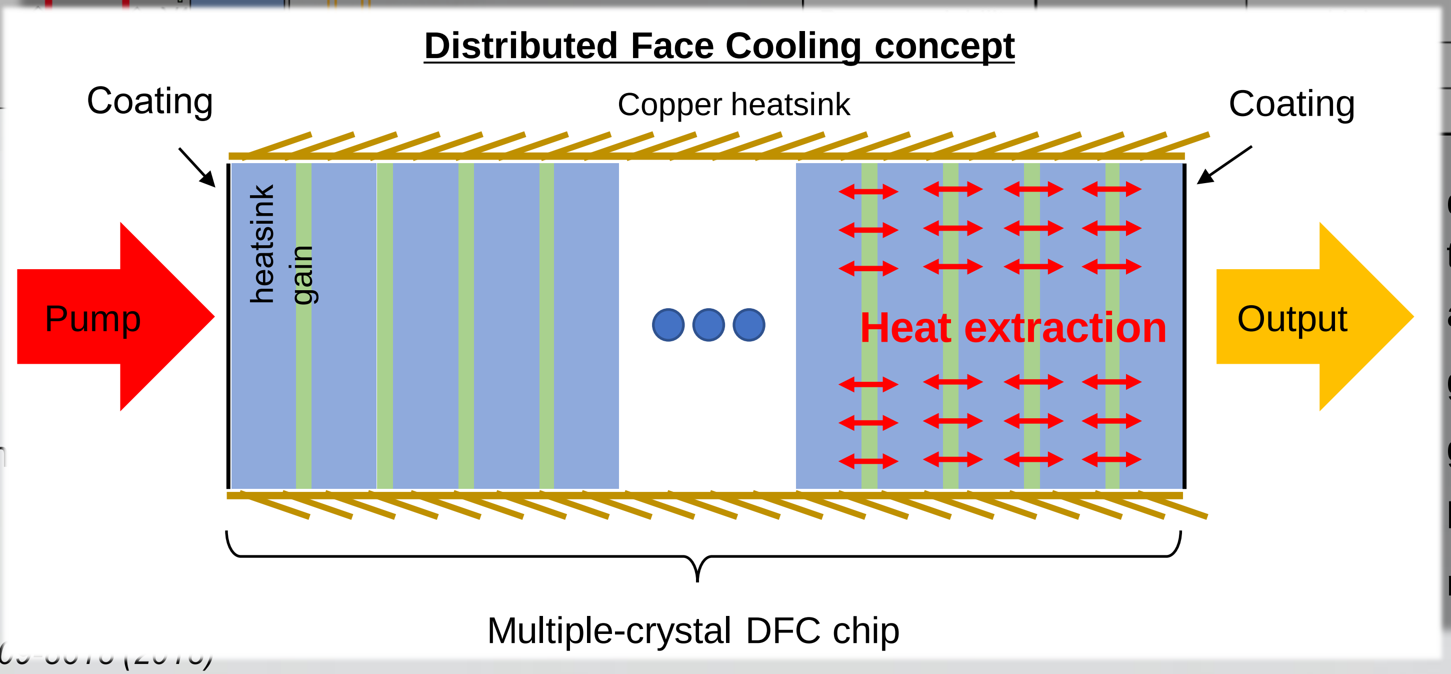
Pulse energy:	235mJ
Duration:	600ps
Rep. rate:	10 Hz
M^2:	1.4
Brightness:	18PW/sr cm
Size:	A3 paper

V. Yahia and T. Taira, Opt. Express ***26****, 860…*

Power scalability for various laser configurations

Shape / Parameter	Rod	Fiber	Thin disk	DFC
	A, short L	small area, A, long L	large area, A, one-side face cooling, thin t	double-side face cooling, A, t, N - chips
Maximum extractable power	$P_{ex}=\frac{8\pi R_T L}{\chi}$	$P_{ex}=\frac{8\pi R_T L}{\chi}$	$P_{ex}=\frac{12 R_T}{\chi}\left(\frac{A}{t}\right)$	$P_{ex}=\frac{24 N R_T}{\chi}\left(\frac{A}{t}\right)$
			medium	**high**
			low …or	**high**
			high	**high**

distributed face cooling
thermal shock parameter
area of a gain medium
gain medium length
gain medium thickness
heating parameter
number of chips or disks



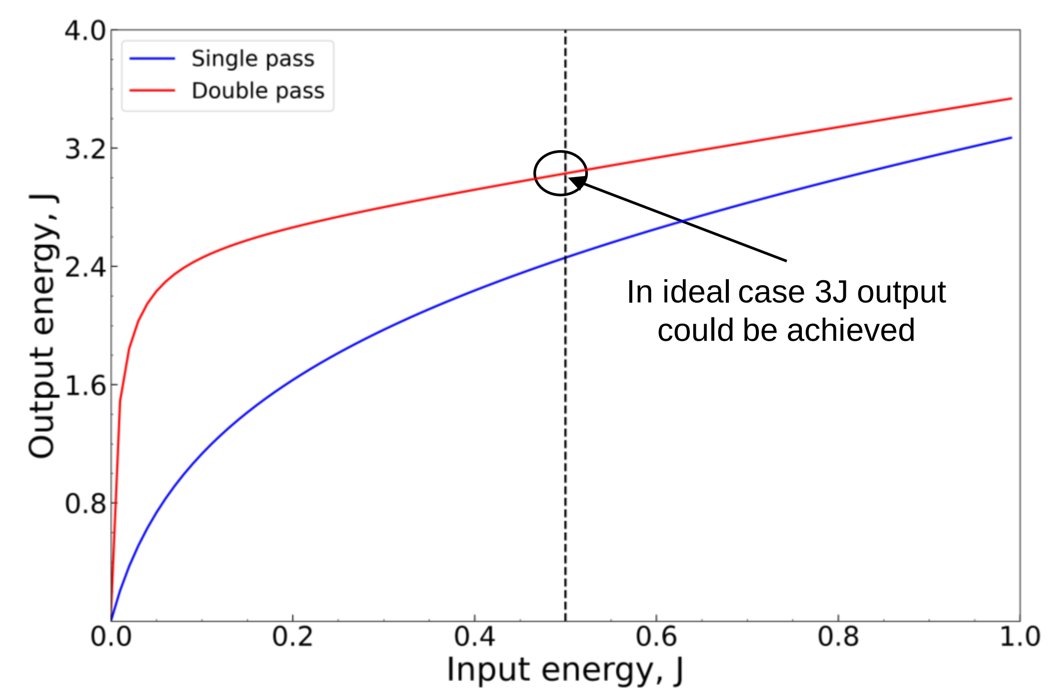
Gain evaluation for 2J, 100Hz system

Single-pass gain

$$G_1 = \frac{1}{\frac{F_{in}}{F_s}} ln\left\{1 + \left[exp\left(\frac{F_{in}}{F_s}\right) - 1\right] exp(g_0 l)\right\}$$

Double-pass gain

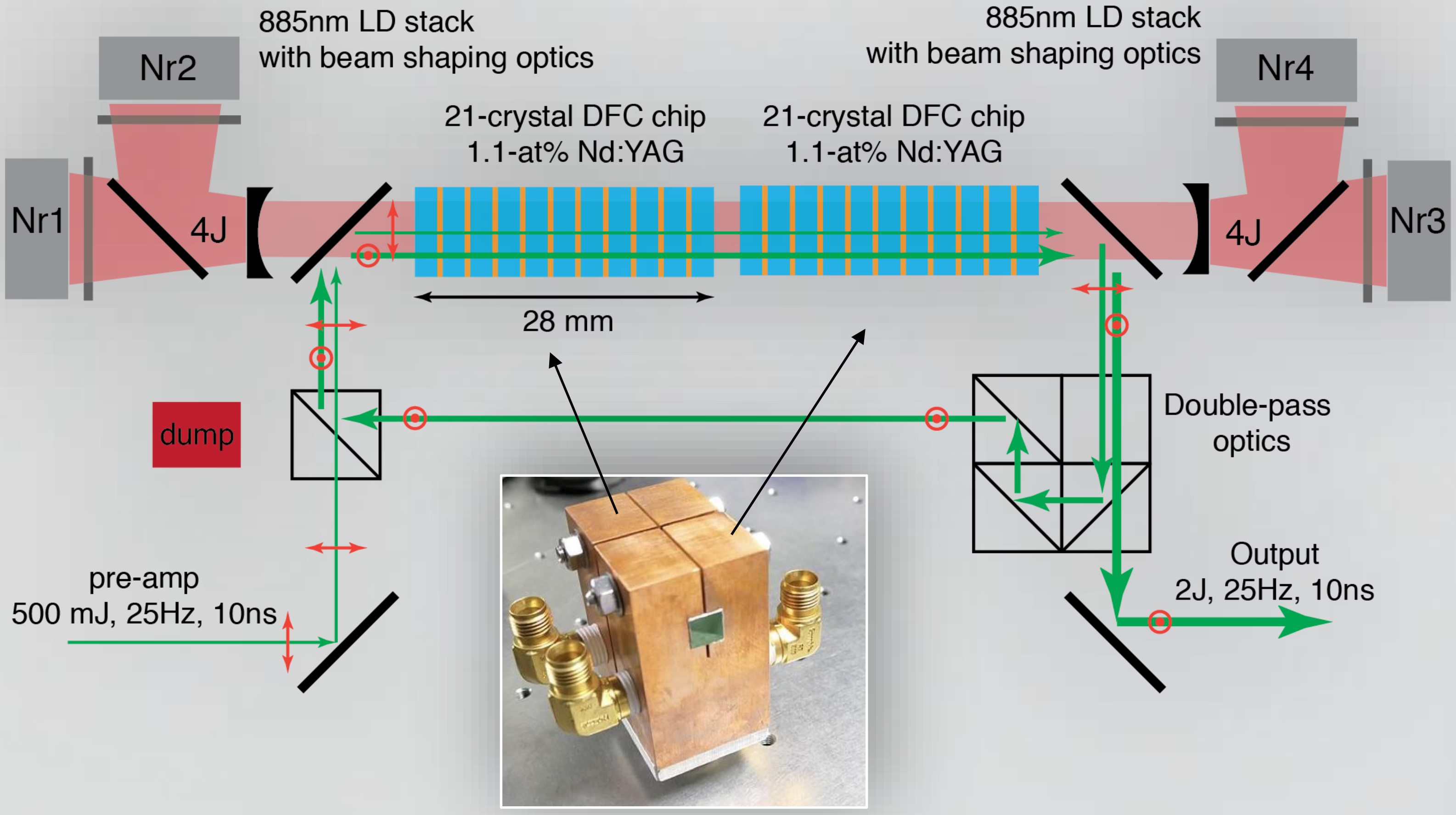
$$G_2 = \frac{1}{\frac{F_{in}}{F_s}} ln\left\{1 + \frac{\left[exp\left(\frac{F_{in}}{F_s}\right) - 1\right] exp\left(\frac{F_{in}}{F_s}\right) exp^2(g_0 l)}{1 + \left[exp\left(\frac{F_{in}}{F_s}\right) - 1\right] exp(g_0 l)}\right\}$$



Parameters used in estimations

Absorption coeff, α	1.5 cm^{-1}
Emission cross-section, σ_{em}	2.8 x 10^{-19} cm^2
Fluorescence lifetime, τ_p	250 μs
Crystal length	10 mm
Pump wavelength, λ_p	885 nm
Pump peak power	4 x 8 kW
Pump size	1 cm^2
Pump pulse duration	250 μs
Saturation fluence, F_{sat}	2.55 J/cm^2
Small-signal gain, $g_0 l$	3.14
Absorption eff, η_{abs}	0.78
Radiation quantum eff, η_q	0.78
Storage eff, η_{st}	0.632
Storage energy, E_{st}	**2.55 J**

Experimental setup



DFC chip **2x (total gain length 10 mm)**
1.1-at% doped Nd^{3+}:YAG
10x10x0.5 mm^3

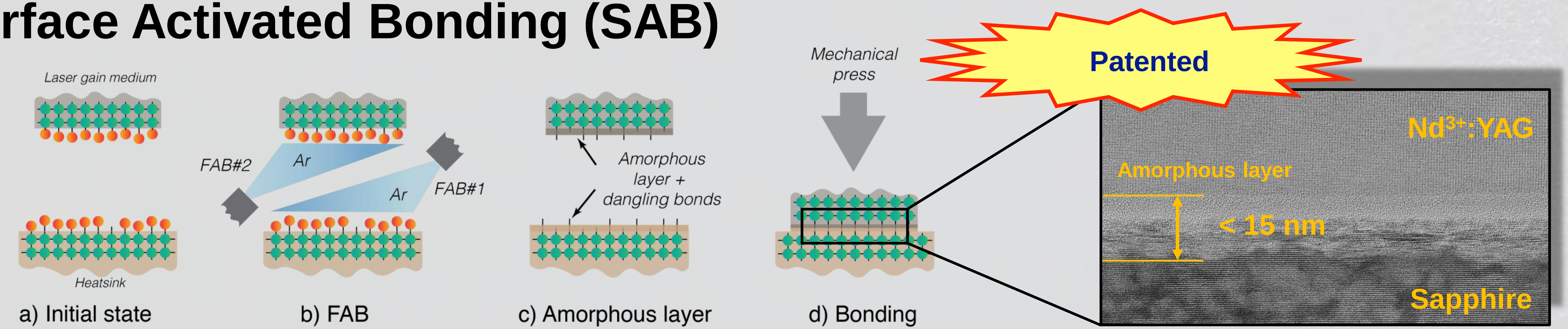
c-cut Sapphire
10x10x2 mm^3

Pump **4x LD modules**

Wavelength	885 nm
Rep. rate	1 Hz to 50 Hz
Pump pulse	250 μs
Pump power	8 kW per LD
Pump energy	2 J per LD

- Pre-amplifier is unstable if repetition rate changes due to thermal lens
- Residual pump power could damage the LD diodes

Surface Activated Bonding (SAB)



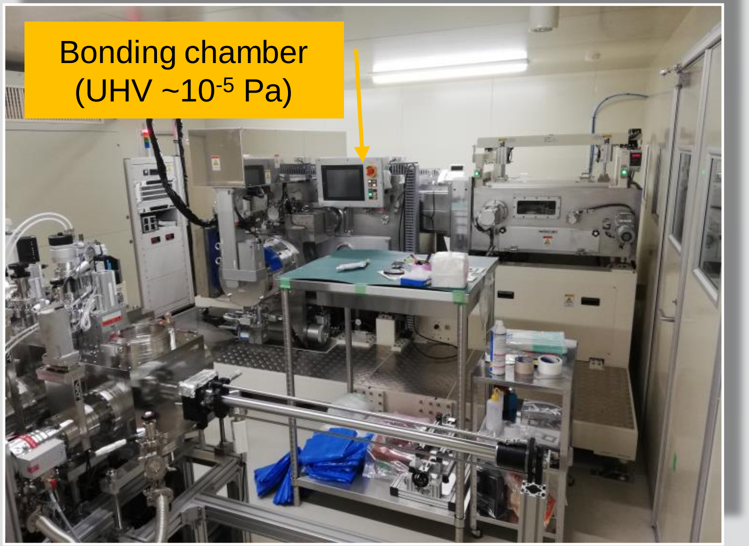
a) Initial state

b) FAB
(Fast Atom Beam)

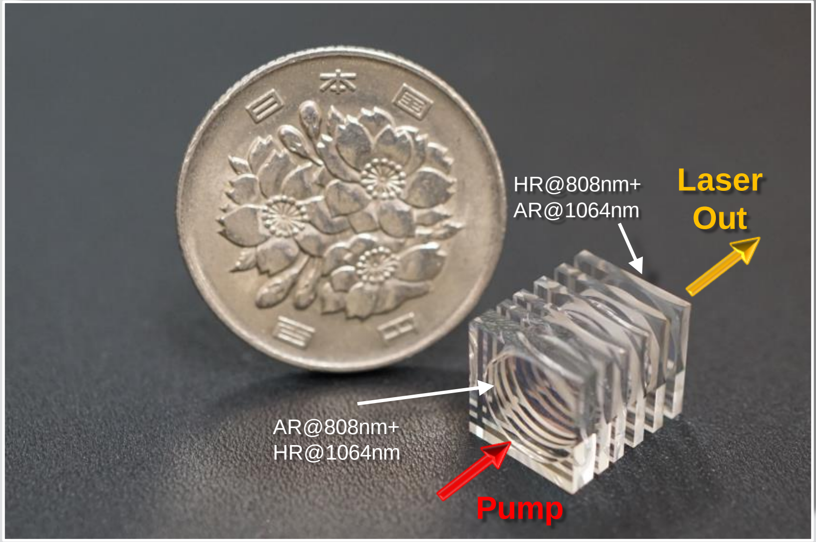
c) Amorphous layer
creation

d) Bonding

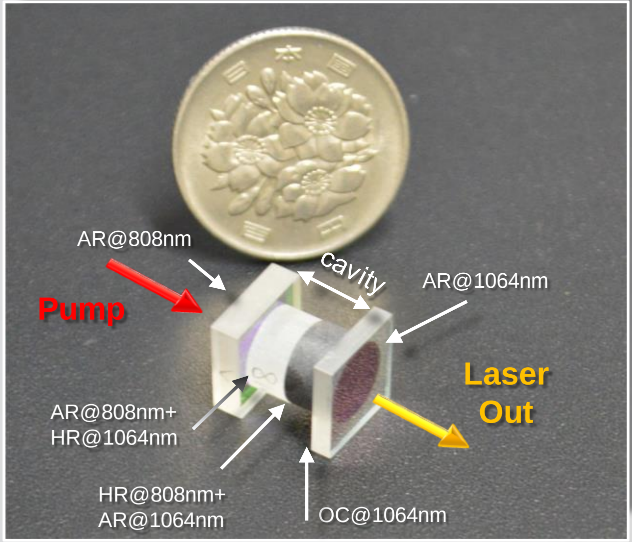
b) T. Suga et. al, Acta Metall.Mater. 40, S133-S137 (1992).
c) L. Zheng et. al, Optical Materials Express, 7(9), 3214 (2017).



Bonding system

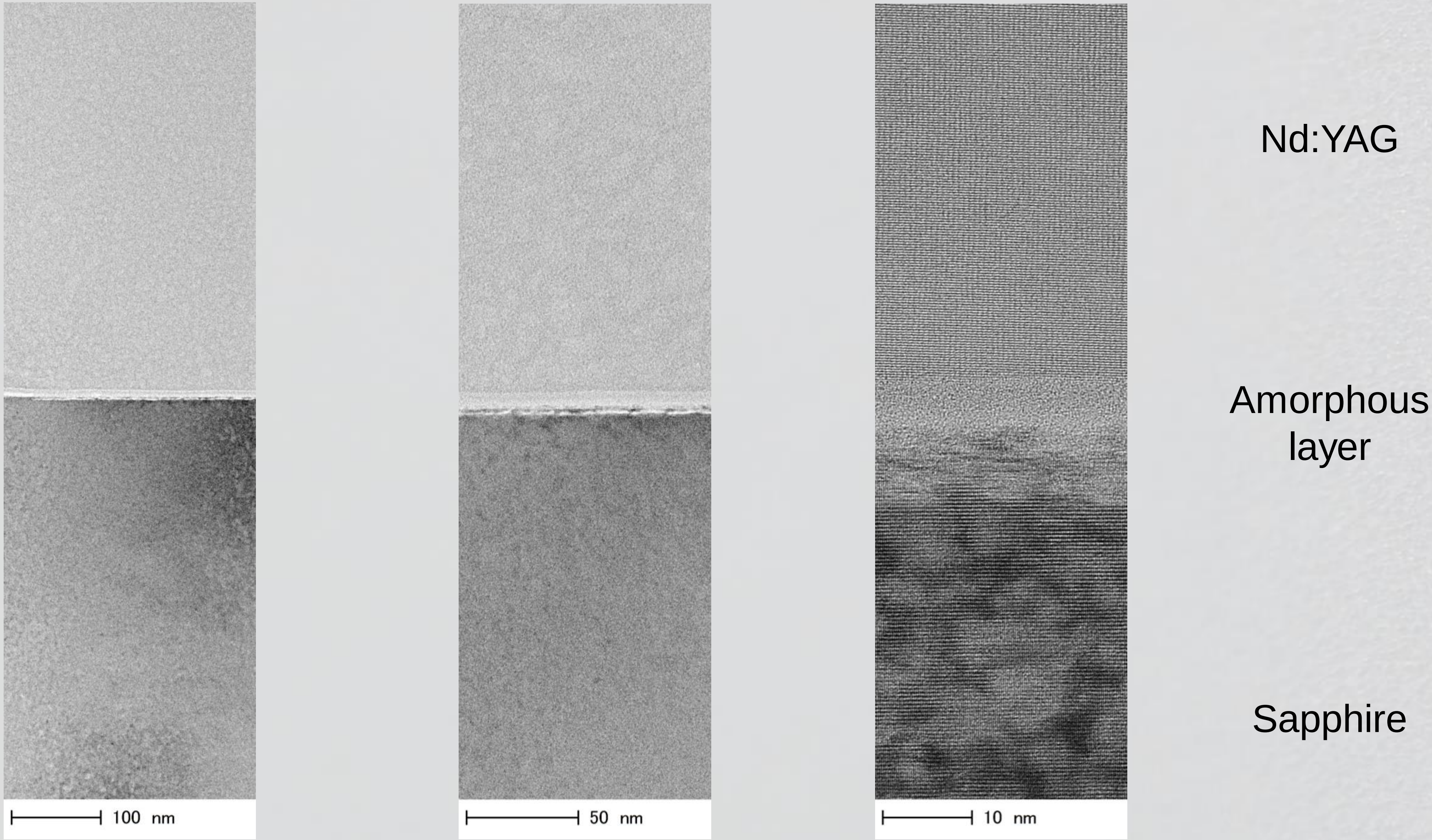


11-crystal DFC chip, Nd^{3+}:YAG/Sapphire

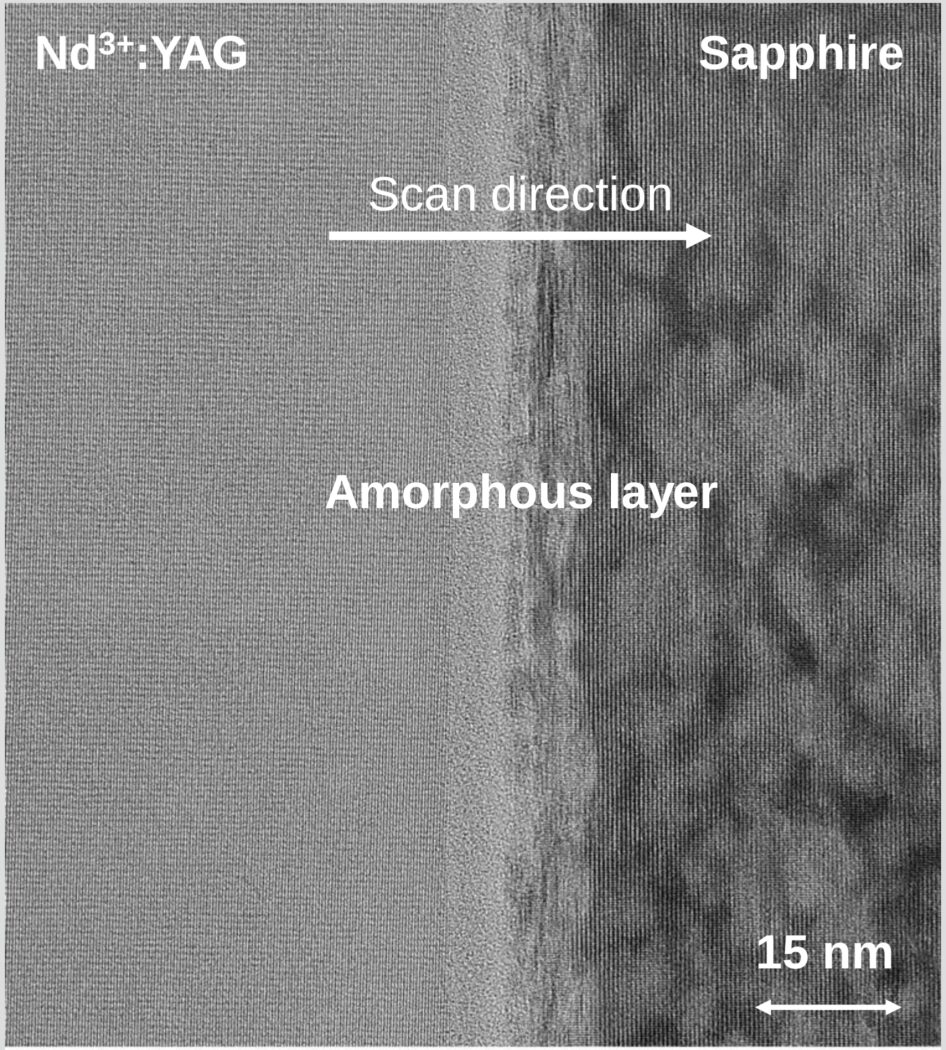


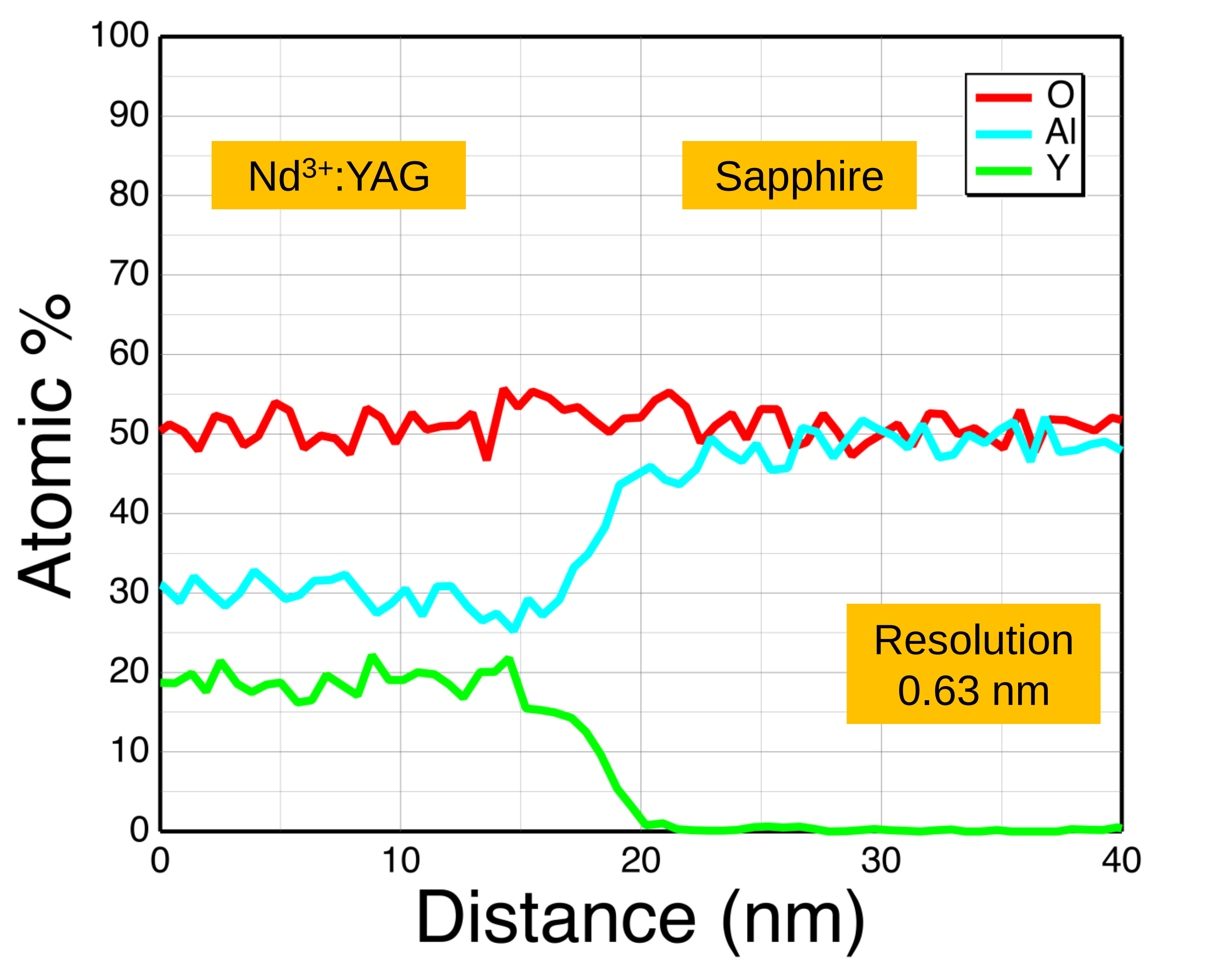
Composite chip,
Sapphire/Nd^{3+}:YAG/Cr^{4+}:YAG/Sapphire

Fast Atom Bombardment activation source



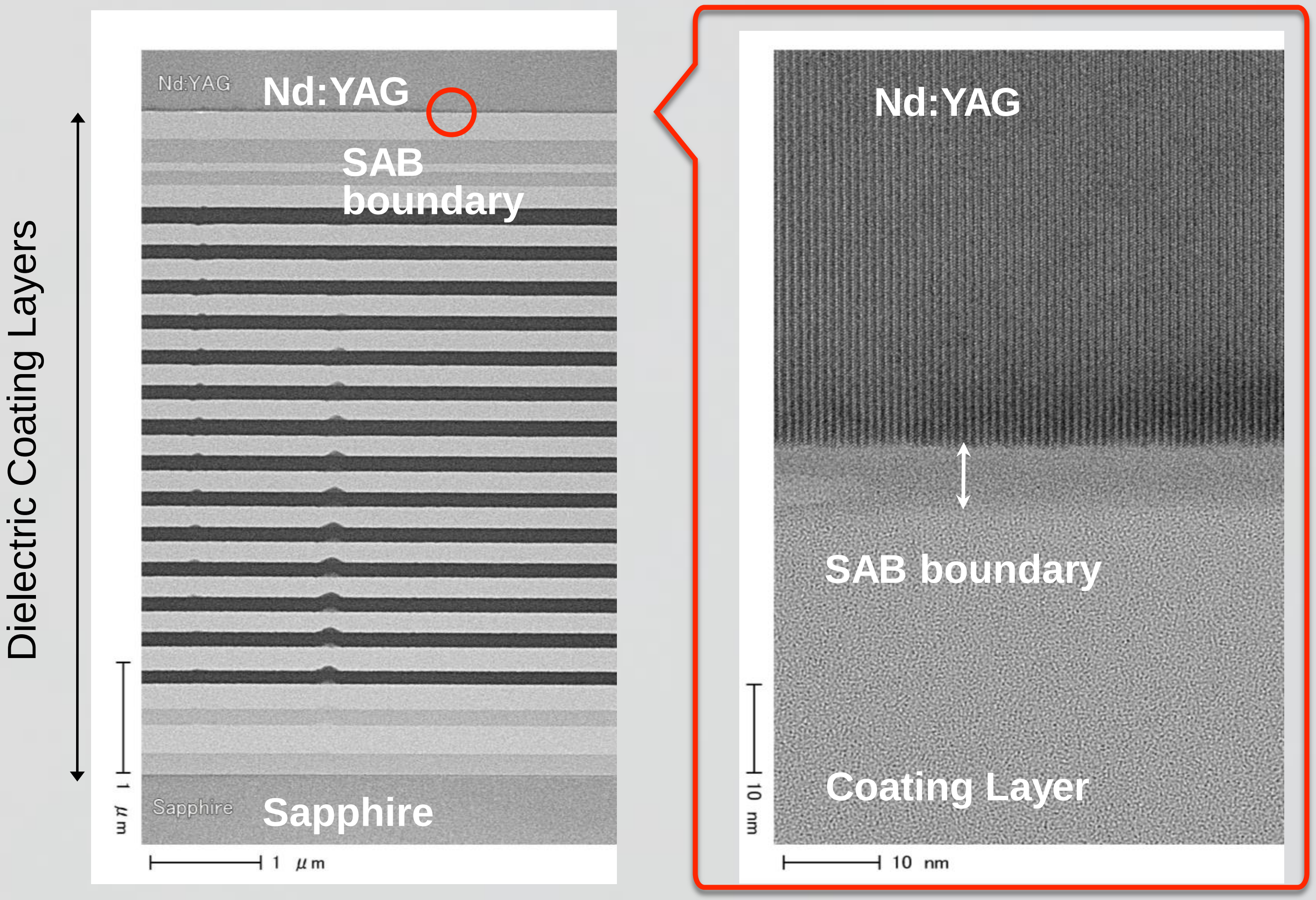
TEM and EDX measurements. Reference crystal





Arvydas Kausas, Zheng Lihe, Takunori Taira, Japanese applied physics conference, 14p-A201-2 (Spring, 2020)

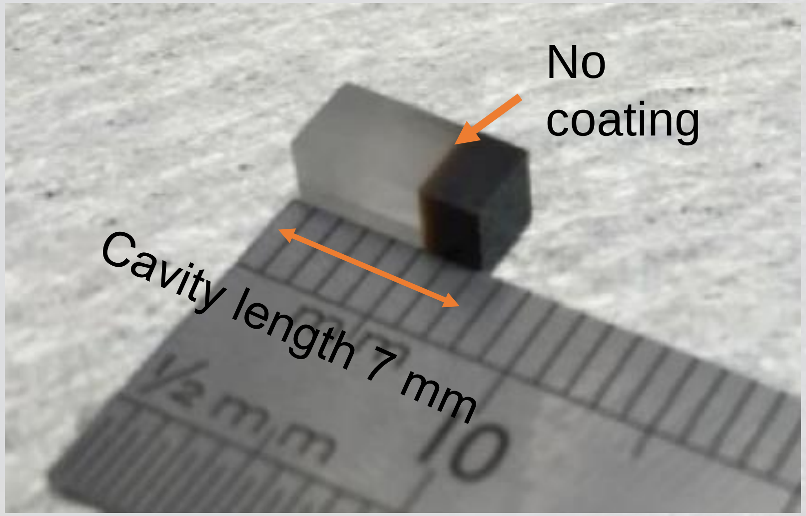
Coated material bonding



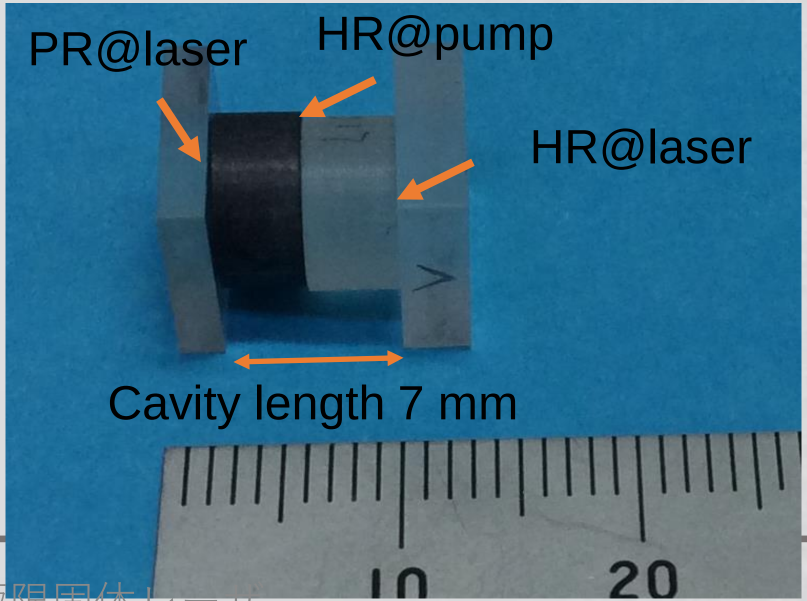
(a) Magnification : x 25,000 (b) Magnification : x 20,000,000

TEM analysis of SAB boundary: Coated samples

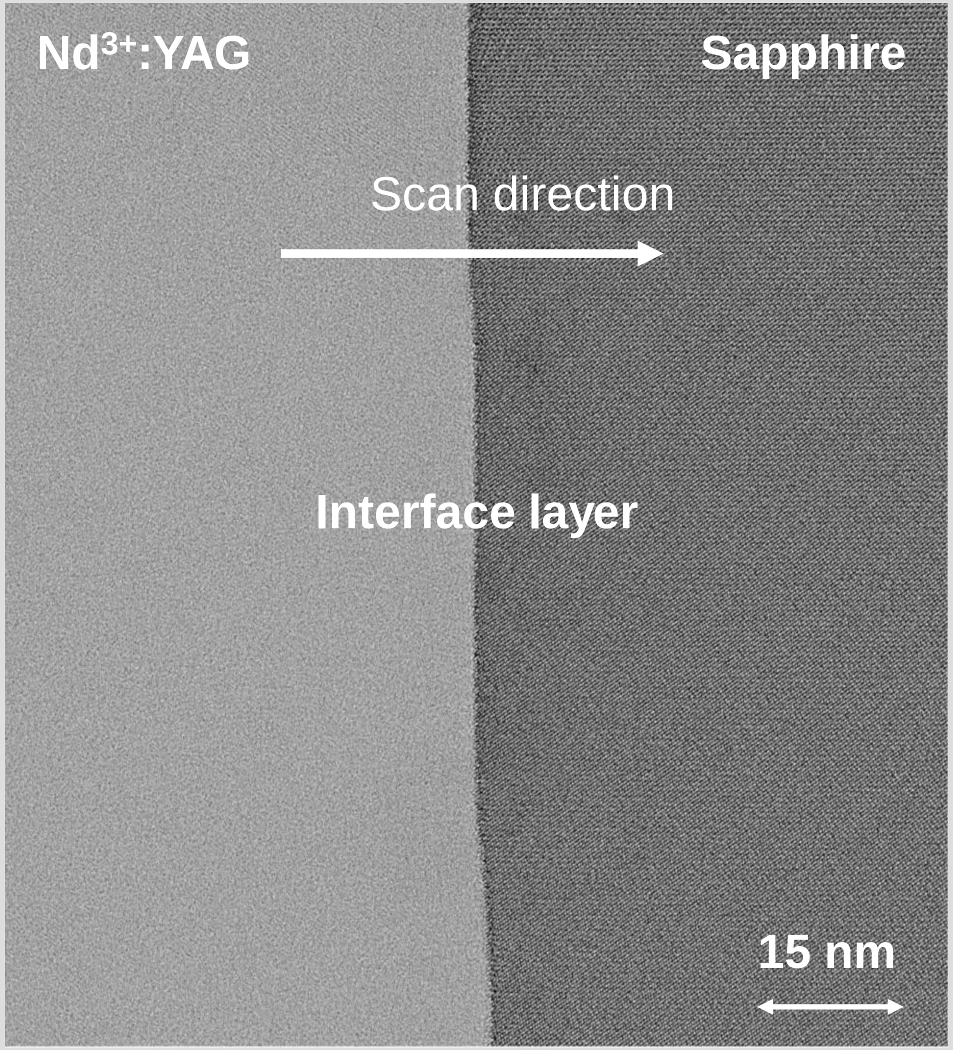
Ceramic crystal bond (diffusion bond)

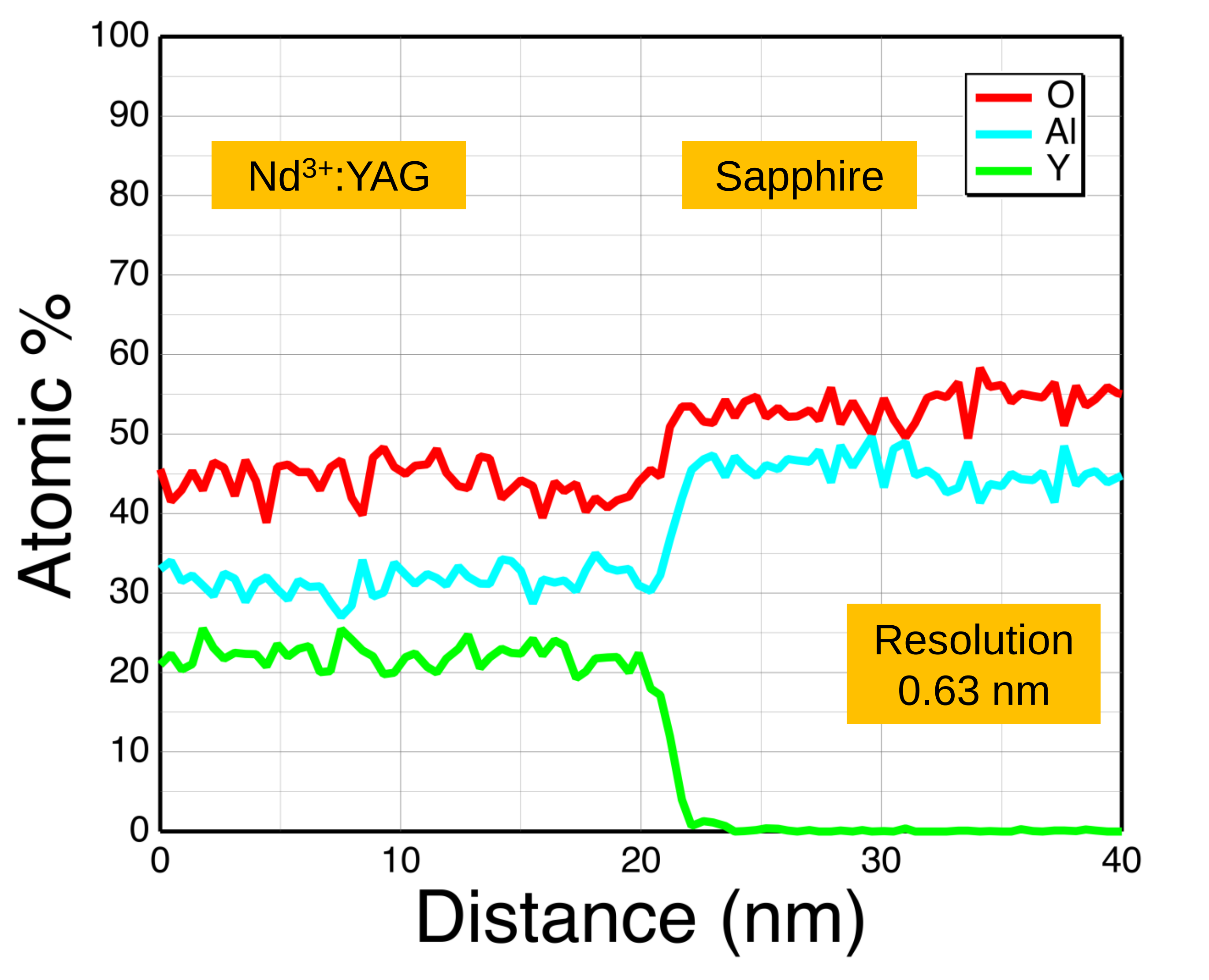


Crystal bond (SAB, with interface coating)



TEM and EDX measurements. Annealed crystal (1100˚C)



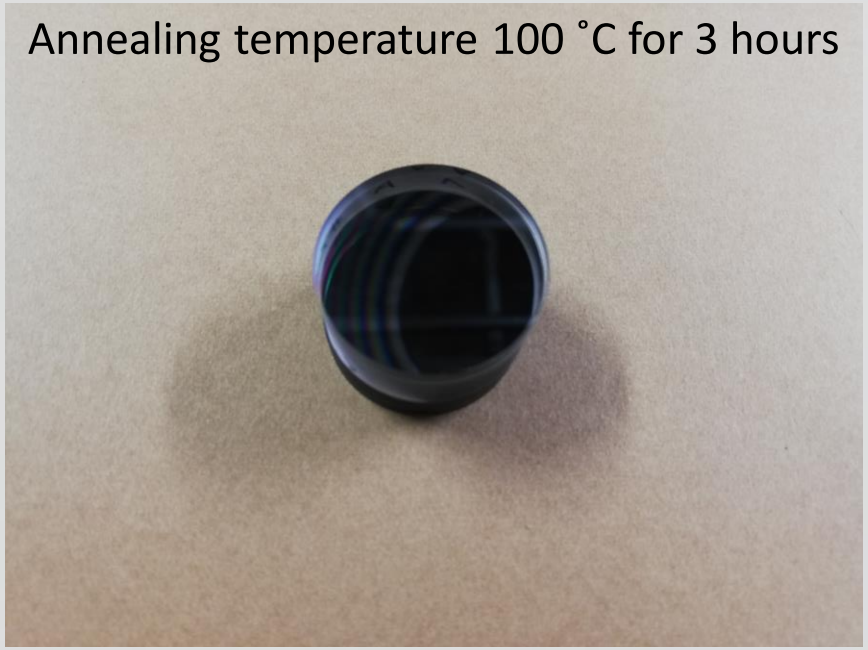


Arvydas Kausas, Zheng Lihe, Takunori Taira, Japanese applied physics conference, 14p-A201-2 (Spring, 2020)

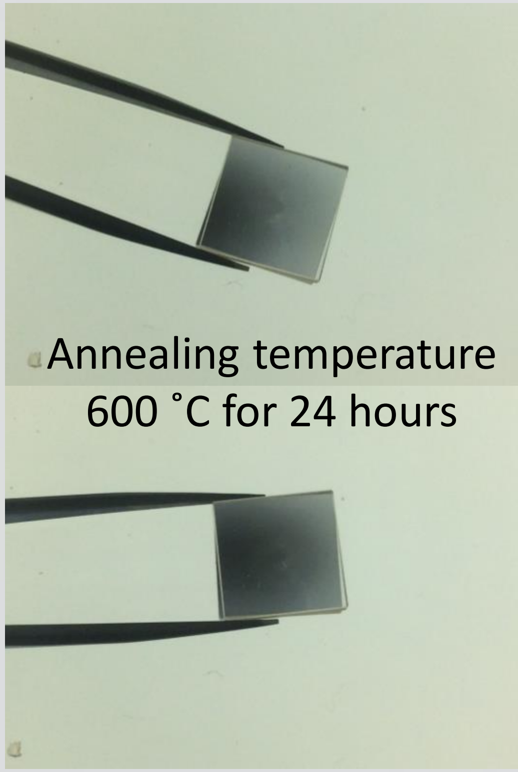
Linear thermal expansion

$$\Delta L = \alpha L \Delta T$$

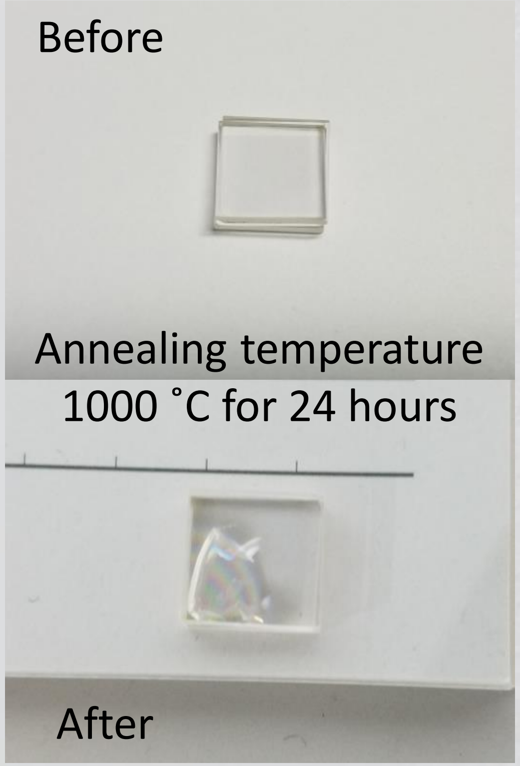
YAG crystal:	6.13×10^{-6} 1/K
Sapphire (IIc):	5.3×10^{-6} 1/K
Sapphire (⊥c):	4.5×10^{-6} 1/K



Example of ø1” bonded crystals



Example of
YAG/Sapphire bonding



Example of
Yb:YAG/Sapphire
bonding

Tensile strength measurement

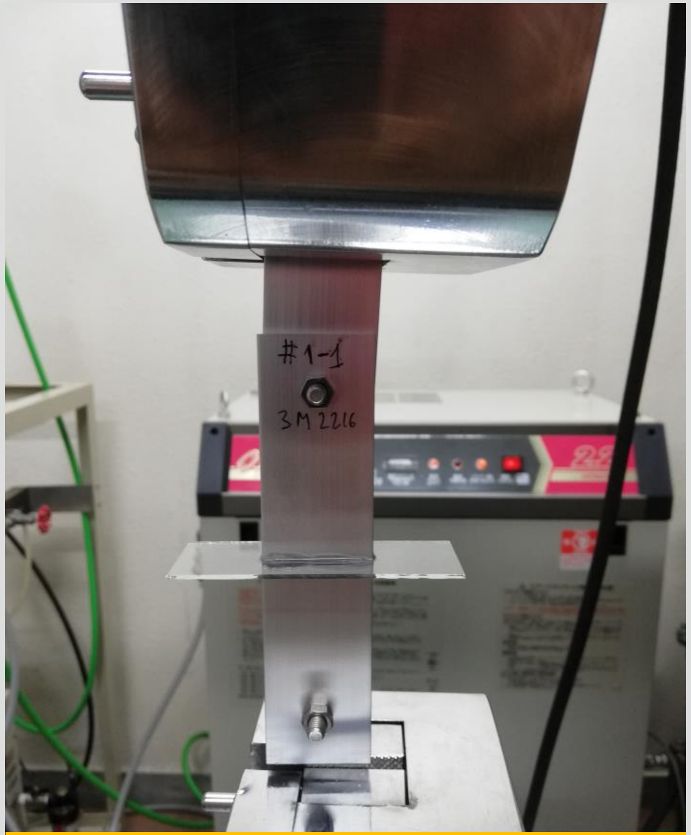
- Device preparation
- First measurements with the various adhesive
- New holder setup
- Crystal preparation
- Crystal annealing
- Tensile strength measurement
- Additional water drop test

Initial setup

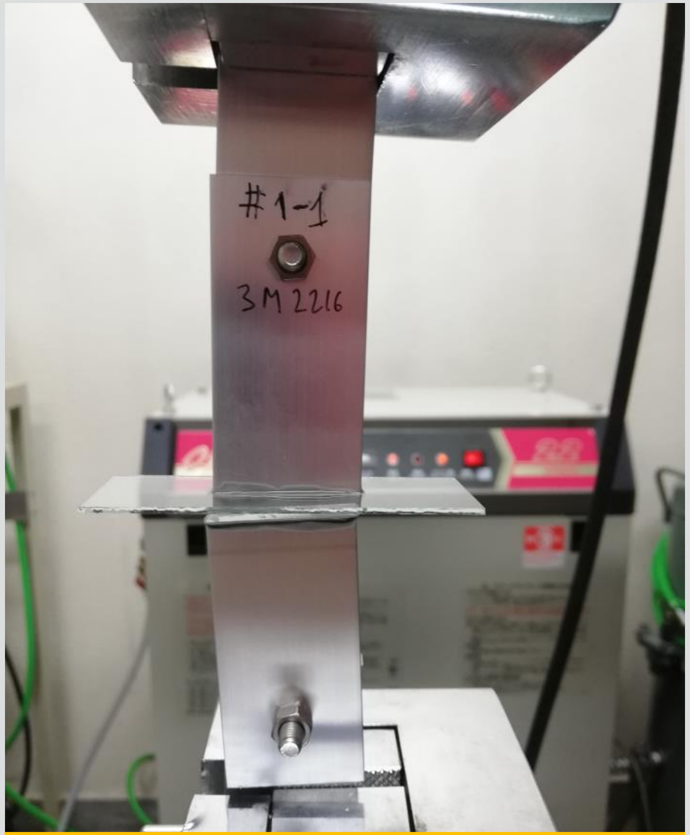
Test adhesive for bonding test

- Aluminum plate samples glued to a glass sample were prepared to test the strength of adhesive, which could potentially be used for real bonding tensile strength measurement.

- Tensile strength of each adhesive was evaluated



Sample before the test

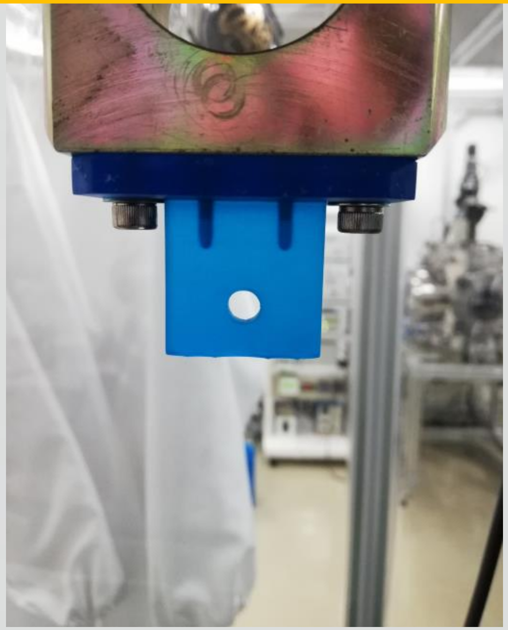


Sample after the test

Adhesive	Sample Nr 1, MPa	Sample Nr 2, MPa
アラルダイト (2019/07/19)	5.37	-
3M 2216 (2019/07/25)	6.97	6.84
Permabond ET500 + primer 2K (2019/10/03)	1.15	-

New tool by Kondo san, 2019/11/20

Top holder



Bottom holder

Sample

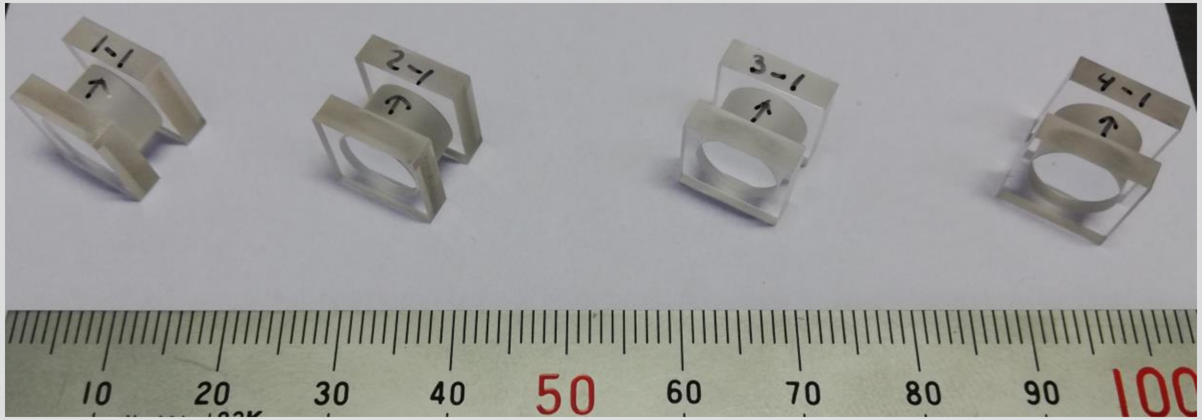
Crystal preparation. Bonding 2020/02/10 – 02/12

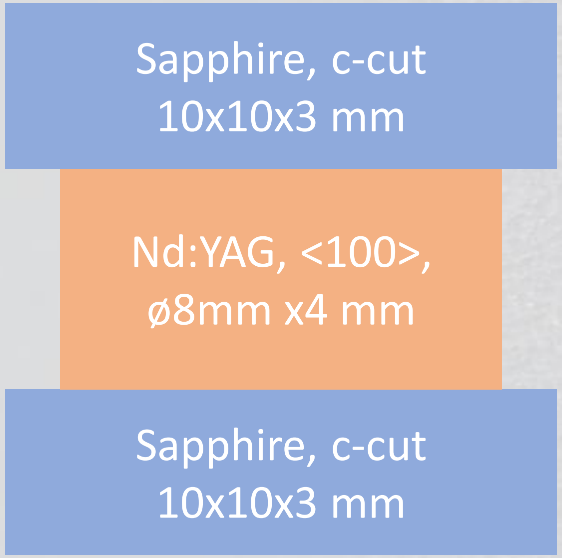
FAB machine, Gen 2, room 104

Sample N	FAB time	Load_1, N	Time_1, min	Load_2, N	Time_2, min
Nr. 1	8 min	202	20	301	23
Nr. 2	8 min	202	900	316	360

Ion source machine, LAN, room 302

Sample N	Activation scan	Load, N	Time, min
Nr. 3	5 scan	500	5
Nr. 4	5 scan	500	5





- Load_X – bonding force applied for 1st or 2nd bonding procedure
- Time_X – time spent under applied force for 1st or 2nd bonding procedure

Crystal preparation. Temperature annealing 2020/02/13

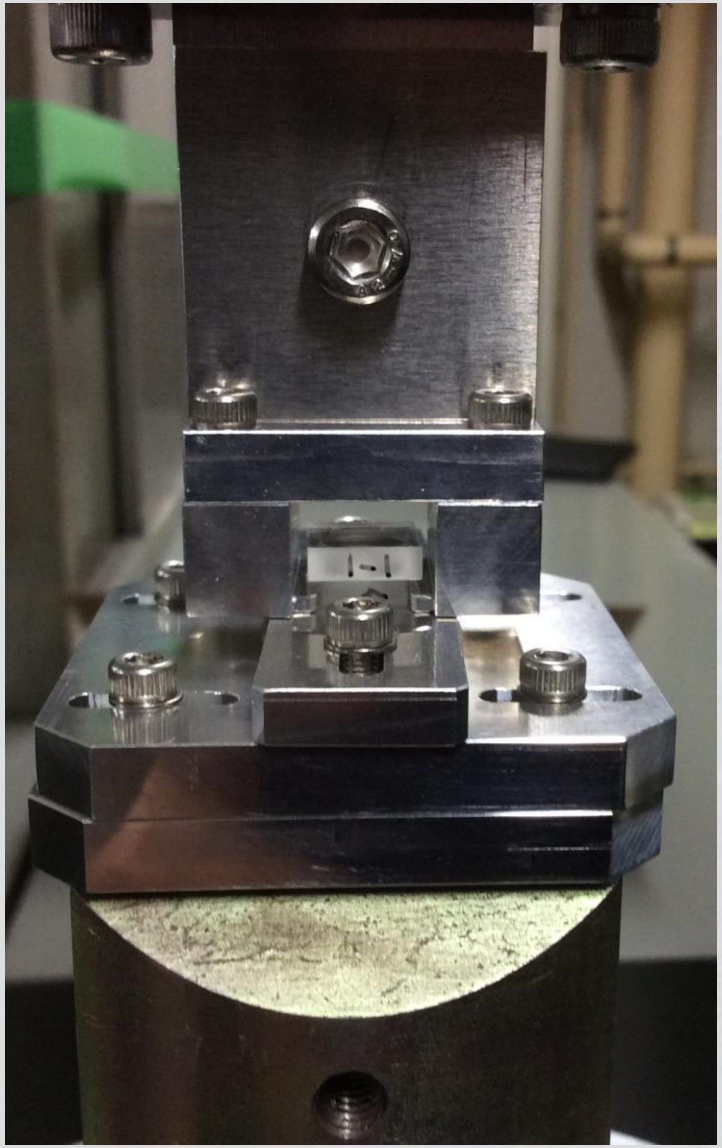
Samples Nr 2 and Nr 4 are placed inside muffle furnace

1	From Room T to 500 ˚C	10 h
2	500 ˚C constant	24 h
3	From 500 ˚C to RT	8 h

Tensile strength results

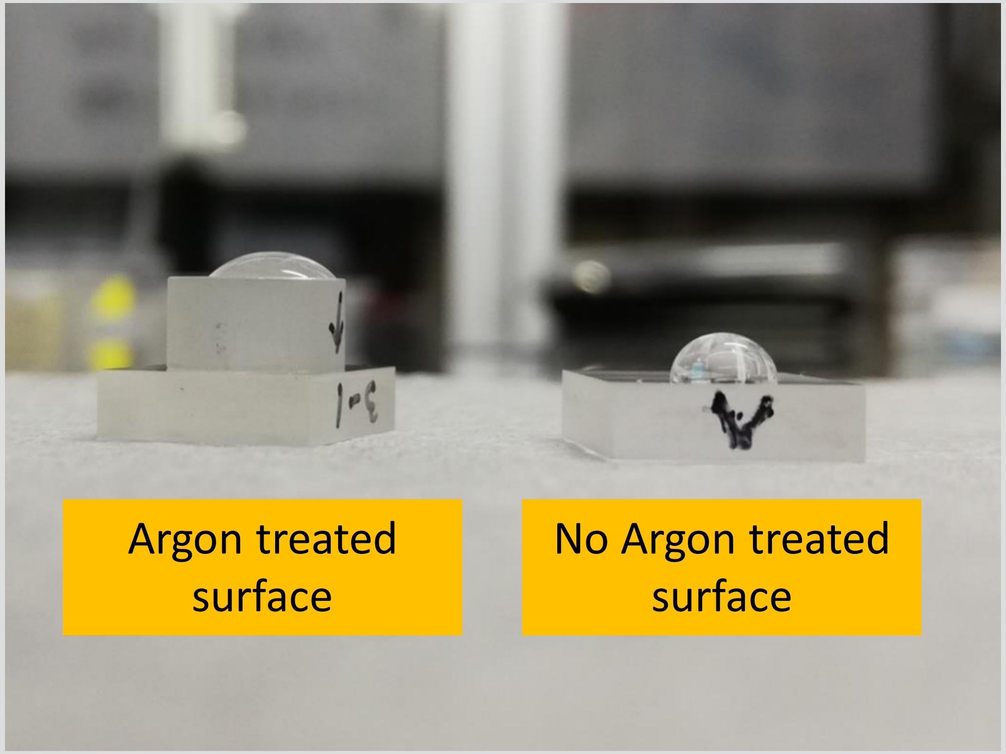
Sample Nr	Condition	Tensile strength, MPa
1	FAB, ref	1.170
2	FAB, 500˚C	1.365
3	Ion, ref	1.951
4	Ion, 500˚C	5.852

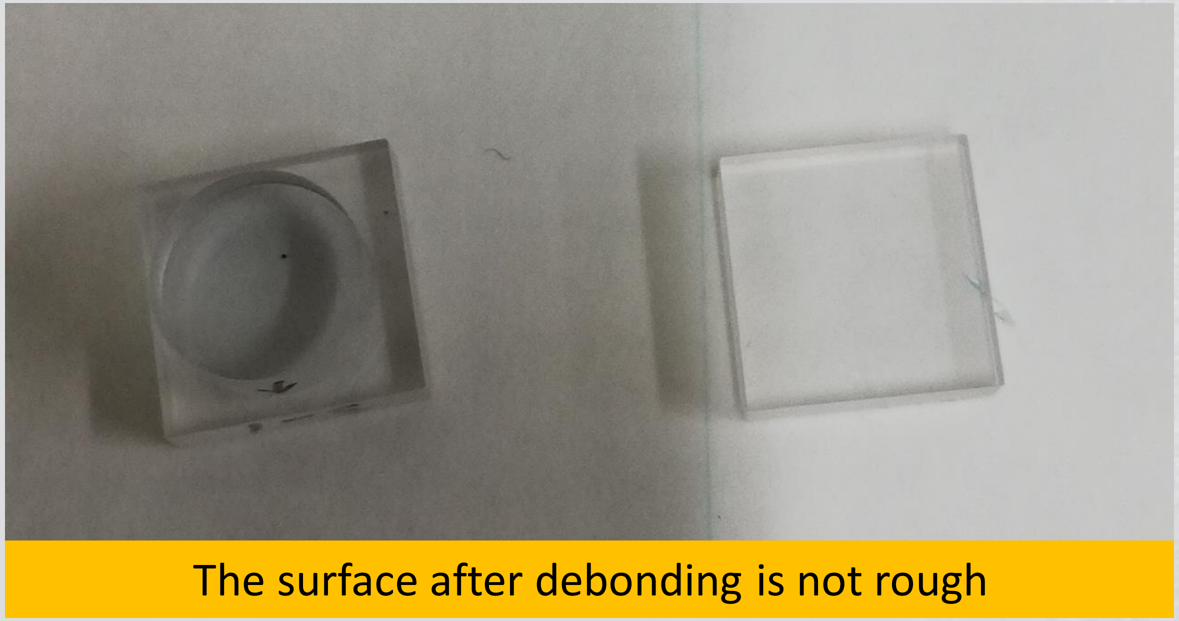
Electrical discharge is visible for sample Nr 1 and Nr 3 (not annealed samples)



Water drop test

Test could show the surface preparation by applying one drop to a surface of a crystal, if surface is rough the drop will have high angle because of the surface tension forces





Future work

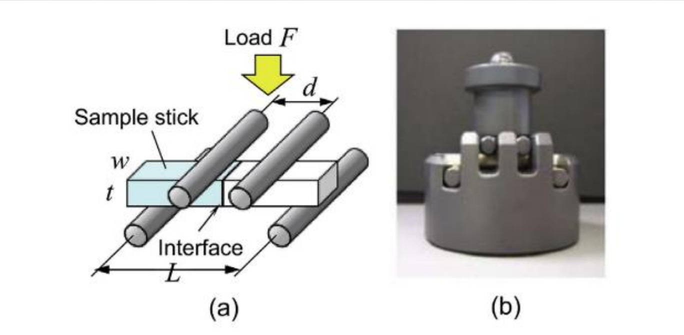


Fig. 4. (a) Experimental setup of four-point bending strength test and (b) photograph of a jig used in the test.

Fujioka, K et al. “Room-temperature bonding with post-heat treatment for composite Yb:YAG ceramic lasers. *Optical Materials*, *91*, pp. 344–348 (2019)

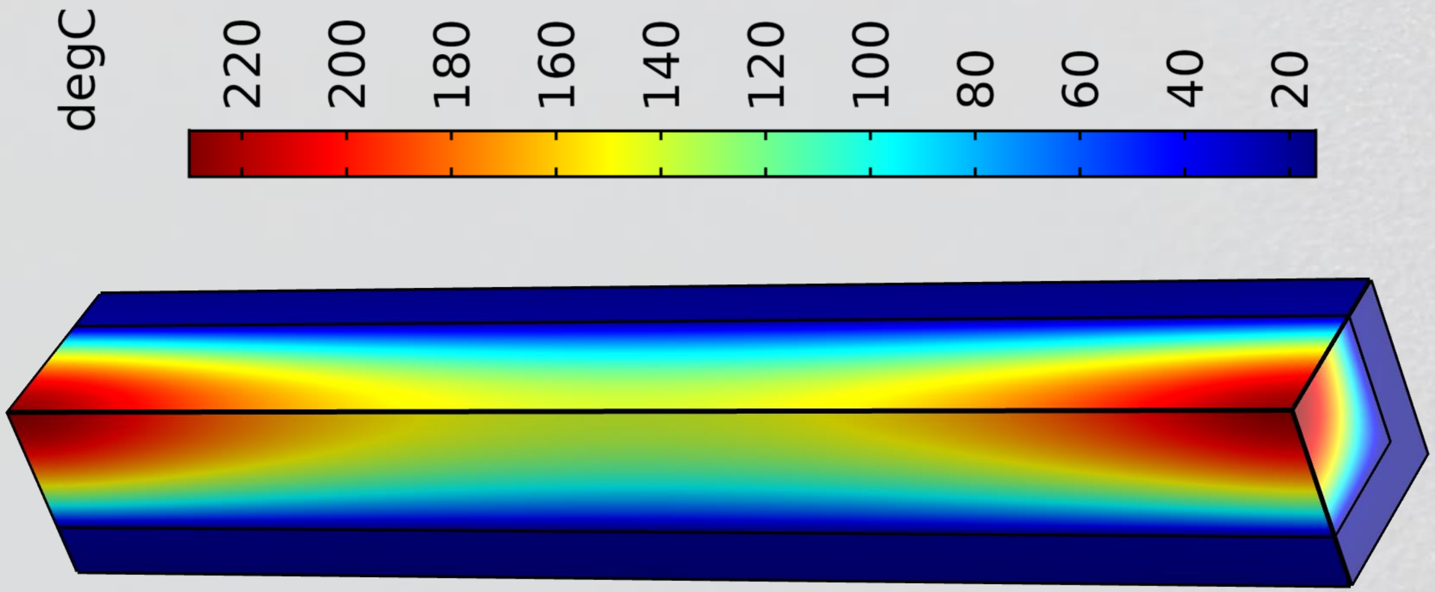
Autograph AGX-V (Shimazu)

Conclusions

- 4 samples were prepared for tensile stress measurement.
- Bonding strength varied from 1.2 MPa to 5.8 MPa, depending on the sample preparation condition.
- Highest bonding strength was achieved in the sample which was made by ion source and later annealed at 500˚C.
- Reference samples produced electrical discharge during crystal separation.

Comsol Multiphysics simulations

- FEA model
- Evaluation of beam propagation
- Power distribution in DFC chip
- Temperature distribution
- Phase shift evaluation
- Thermal lens model



Finite element analysis calculation

Pump beam profile:
- Square Top-Hat profile
- Beam waist is constant along the crystal, $2w$ =10 or 15 mm

Absorption coefficient in Nd^{3+}:YAG crystal:
- Absorption coefficient is constant and does not depend on a temperature
- No pump saturation occur* ($I_{pump} \ll I_{saturation,pump}$)

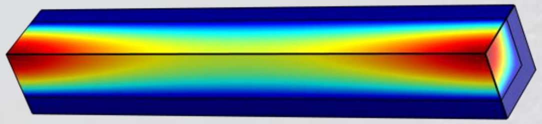
Fractional heat load:
- η_h equal to 0.318 (for 885 nm pump)

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

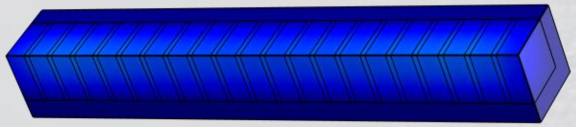
* Y. Sato et al. in IEEE JQE, vol. 40, pp. 270-280 (2004)

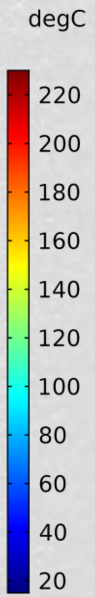
Quarter size FEA simulation

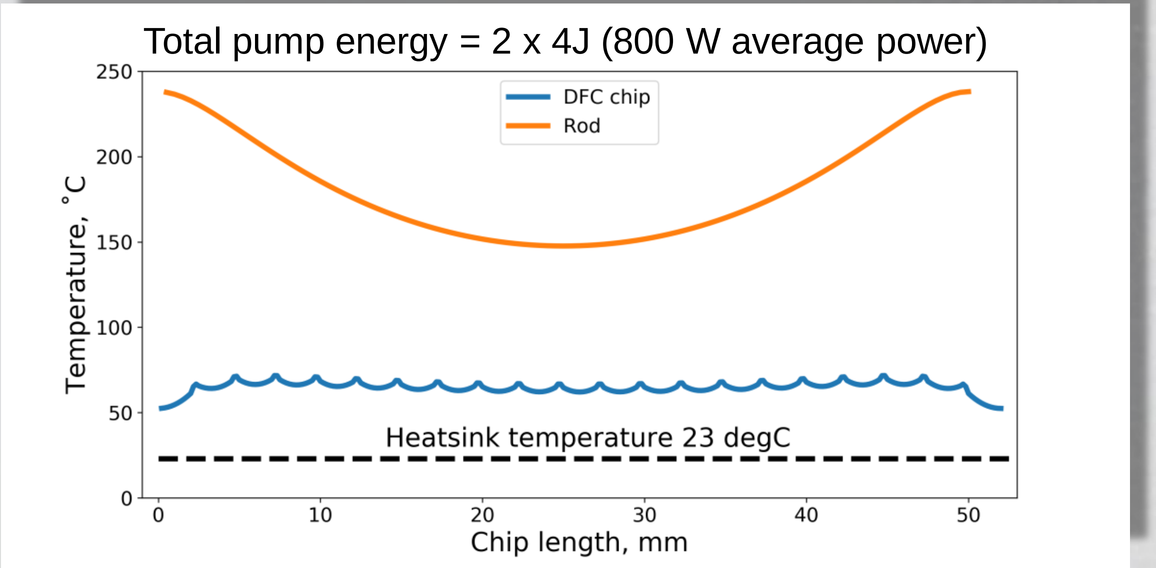
Nd^{3+}:YAG rod
1.0-at%
□10 mm aperture
50 mm length
Absorption eff ~ 92%



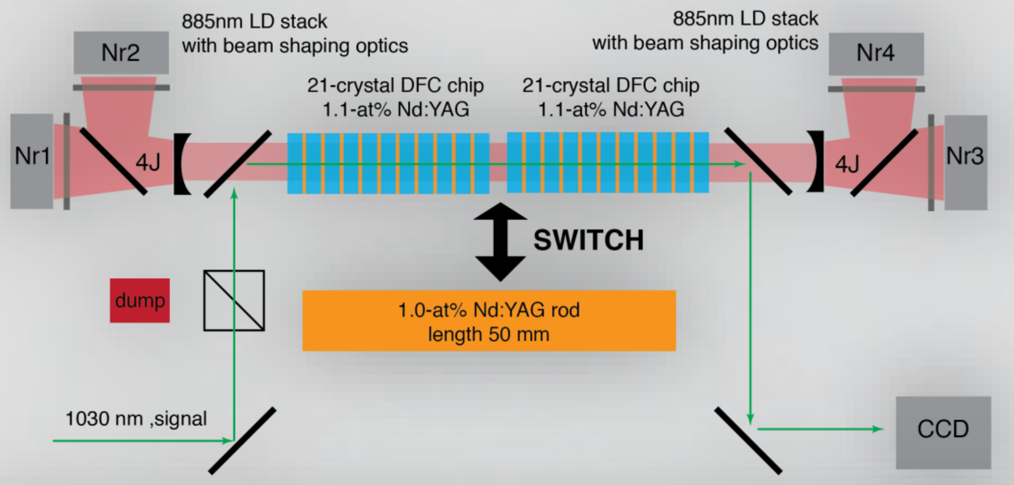
DFC chip
1.1-at%
□10 mm aperture
53 mm length
Absorption eff ~ 77.7%

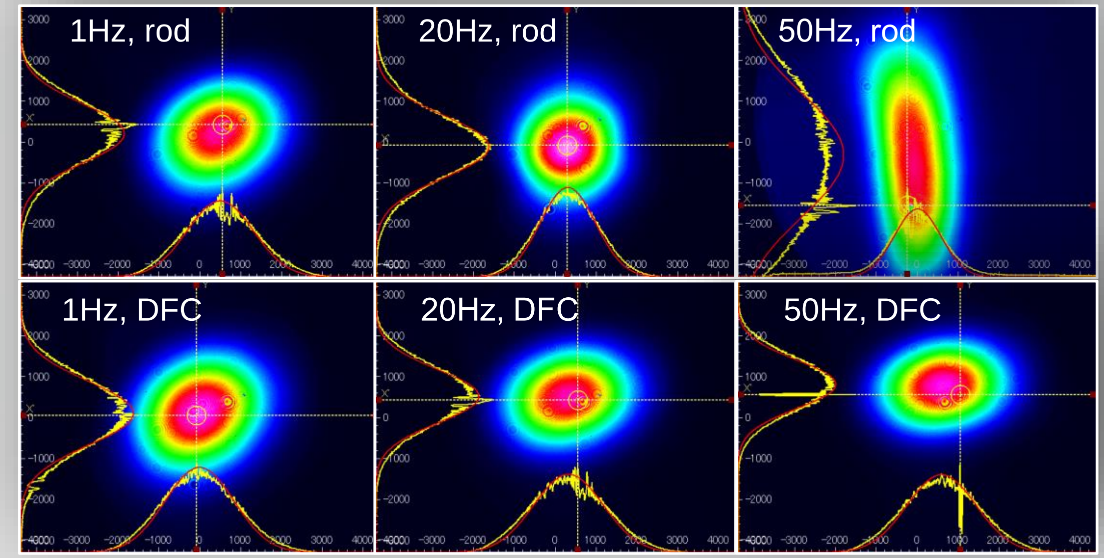




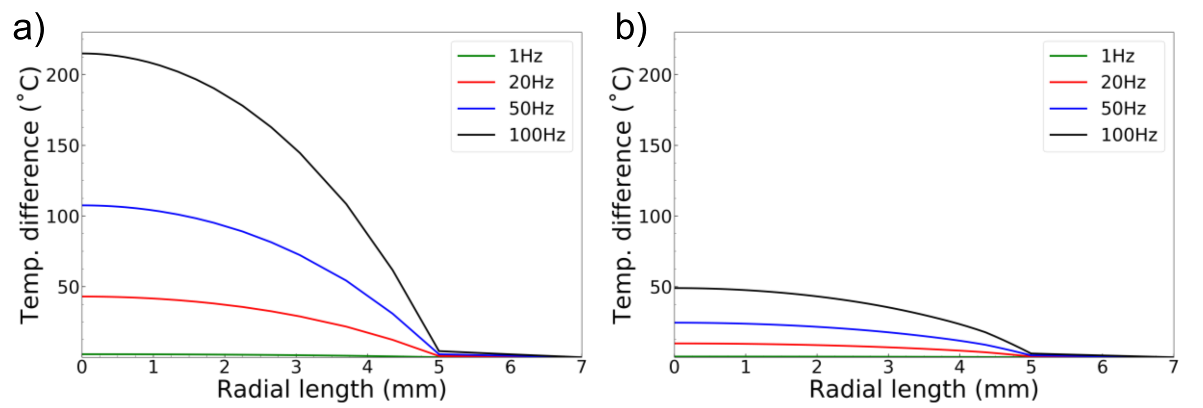


Thermal effects

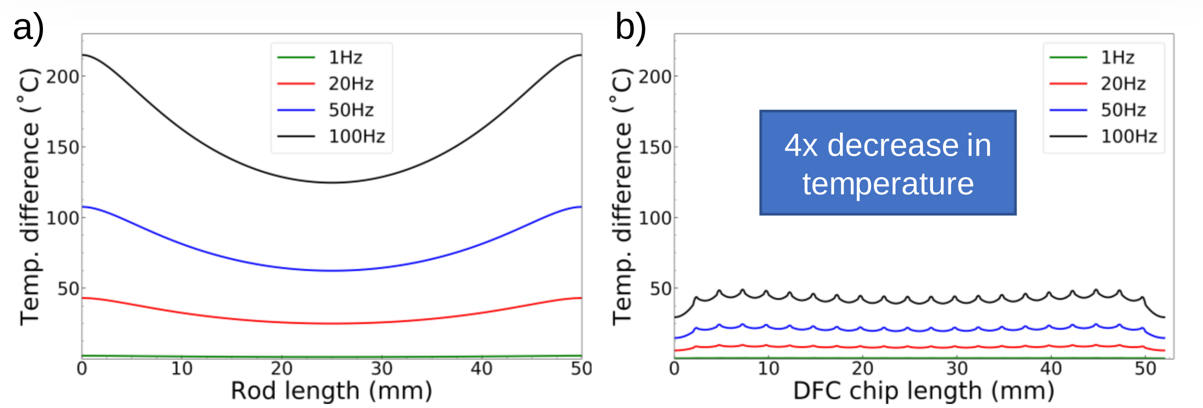




FEA simulation for Rod and DFC chip

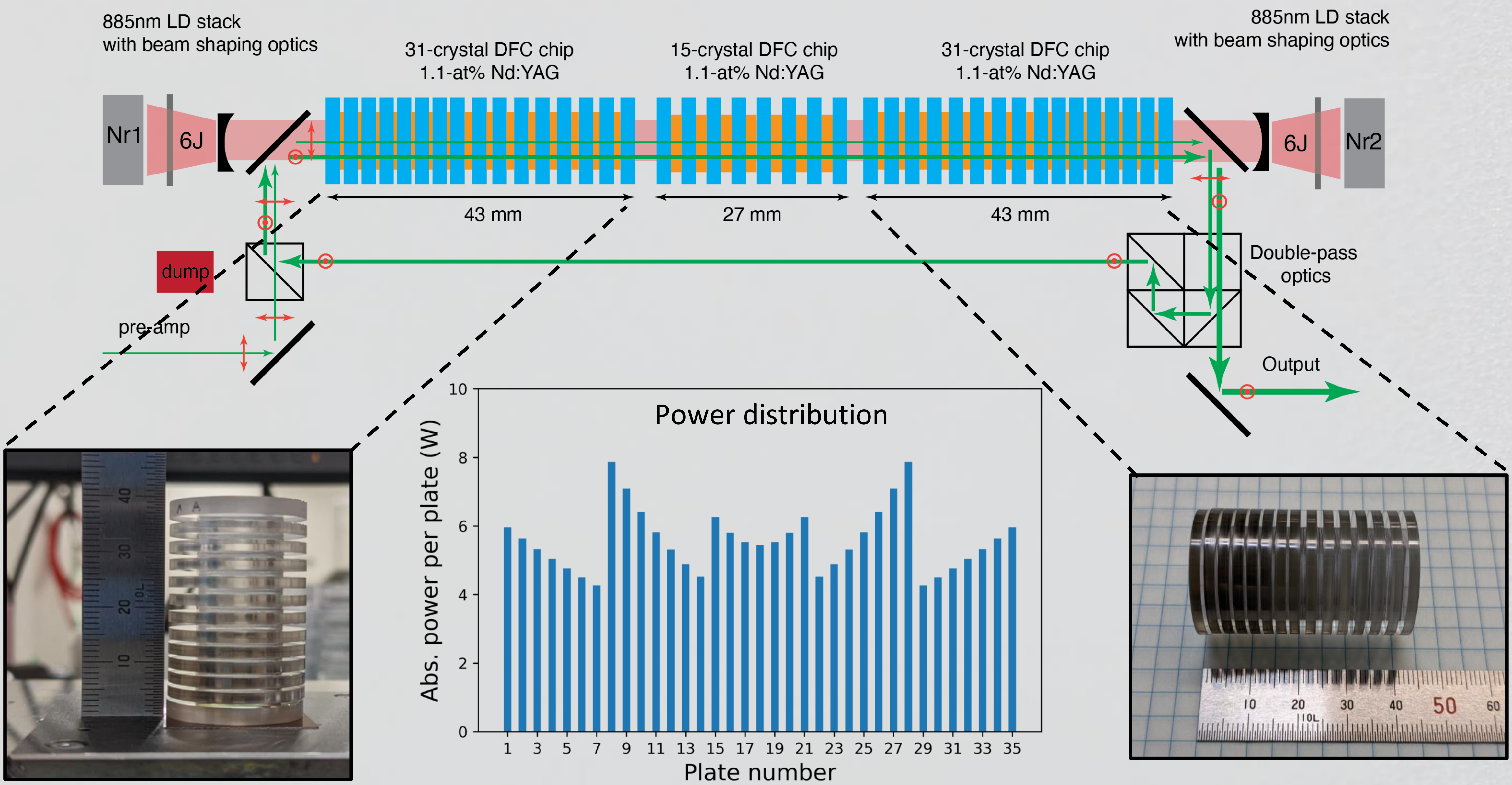


Comparison between Rod (a) and DFC chip (b).
Radial temperature distribution

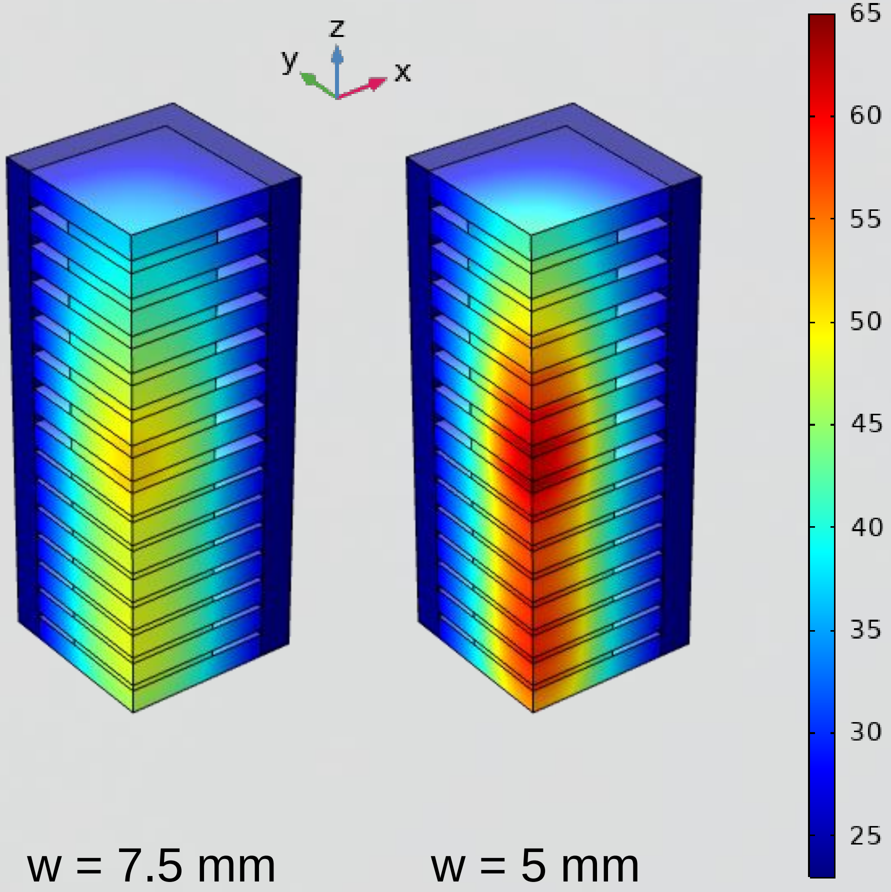


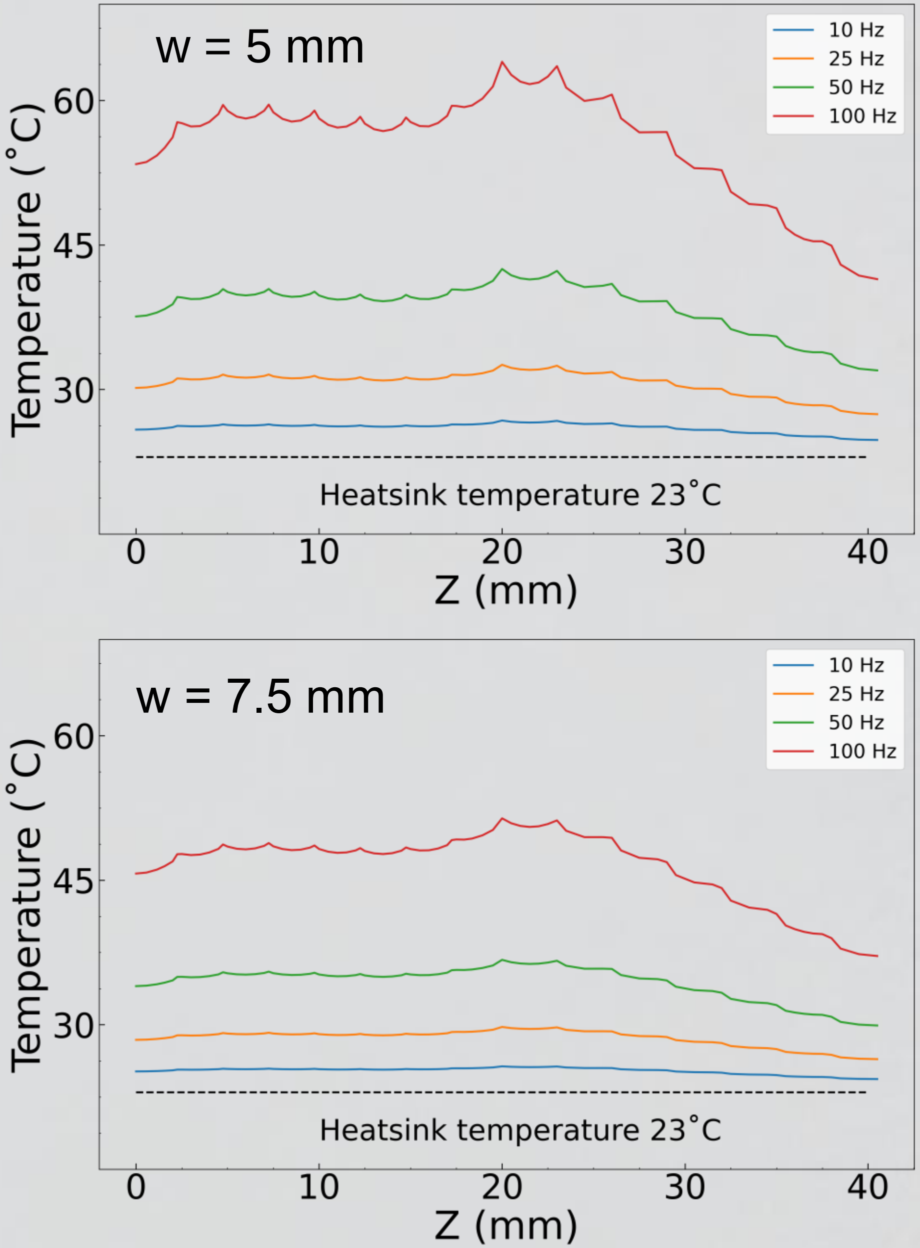
Comparison between Rod (a) and DFC chip (b).
Longitudinal temperature distribution

Power distribution inside chip



Temperature distribution



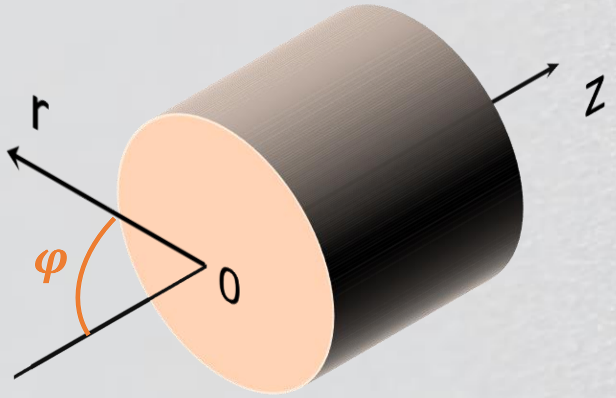


Optical Path Difference (phase shift) in end-pumped rod crystal

The **relative path difference** (or **phase shift**) traveled between two rays that pass through different mediums from the same object point.

OPD of an ideal lens (parabolic)

$$OPD(r) - OPD(0) = -\frac{r^2}{2f}$$



Thermally induced OPD

$$dOPD(r,z) = \left[\frac{\partial n}{\partial T} + (n-1)(1+\upsilon)\alpha_T + 2C_r n^3 \alpha_T\right]\Delta T(r,z)dz$$

- $\frac{\partial n}{\partial T}$: Refractive index change with temperature
- $(n-1)(1+\upsilon)\alpha_T$: End-faces bulging
- $2C_r n^3 \alpha_T$: Stress induced birefringence

r - radial direction
α_T - thermal expansion coeff
$\frac{\partial n}{\partial T}$ - refr. Index change with temperature
n – material refractive index
υ – Poisson's ratio
C_r - photo-elastic coeff

Temperature change

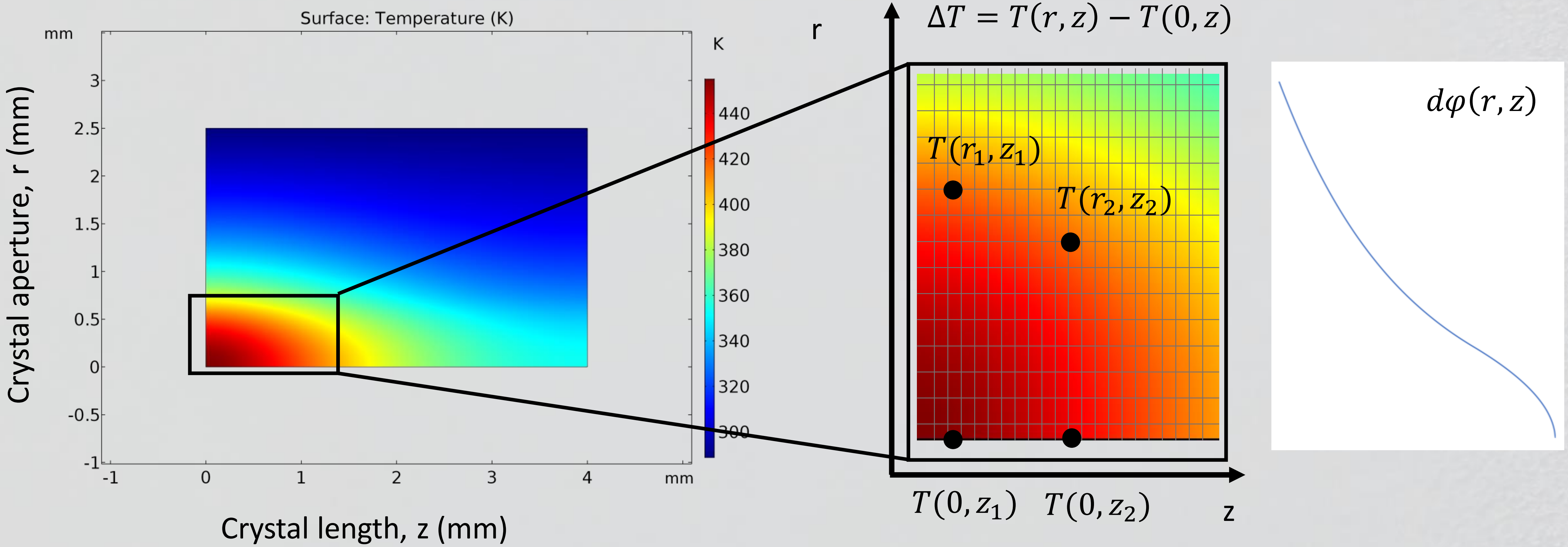
$$\Delta T(r,z) = [T(r,z) - T(0,z)]$$

S. Fan et al, *Opt. Comm.,* 266, p620 (2006)

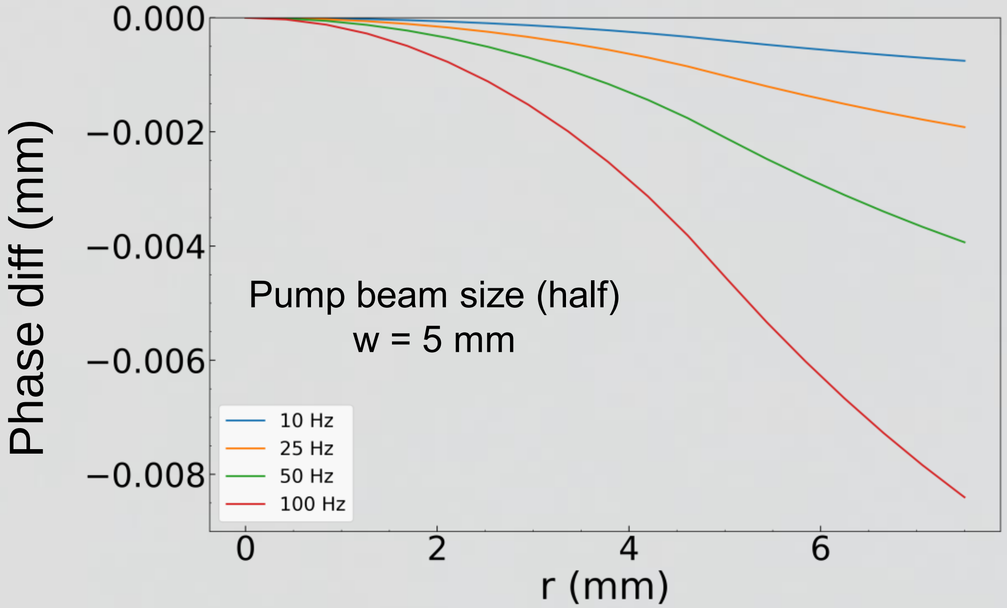
Optical Path Difference (phase shift) in end-pumped rod crystal

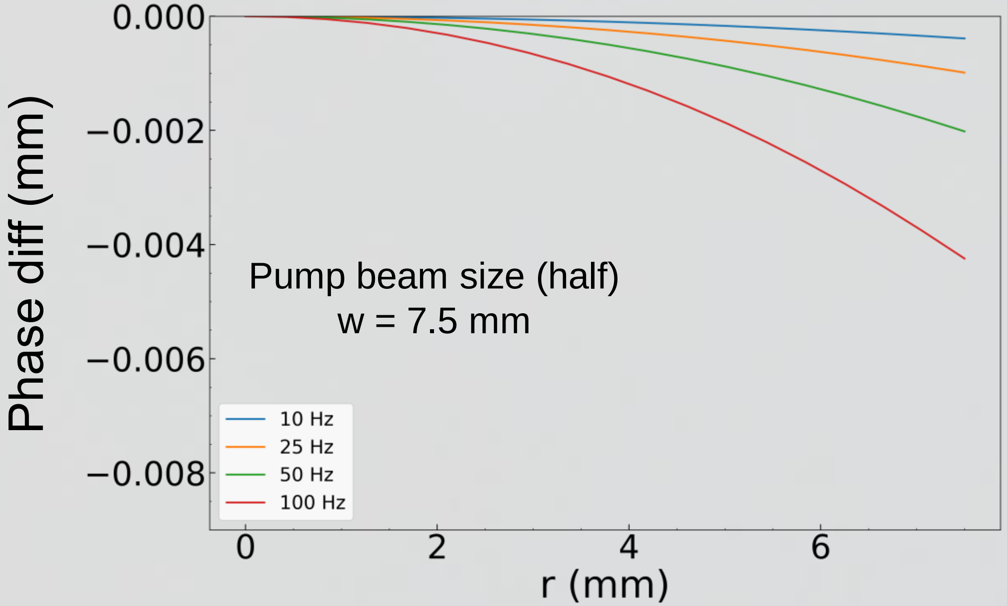
1. Calculate 2D surface temperature
2. Calculate temperature difference by ***at2(0, y, z, T)- at2(0, 0, z, T)*** function

Temperature difference: Temp at radial position of a rod – temperature at the rod center

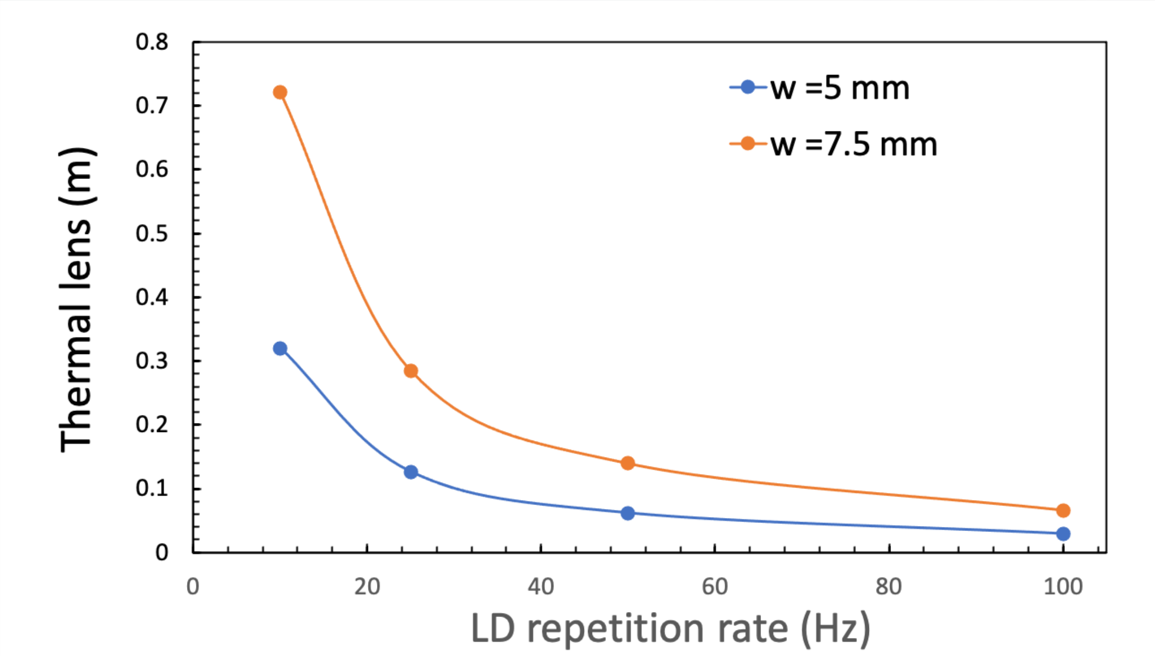


Phase difference evaluation for the DFC chip



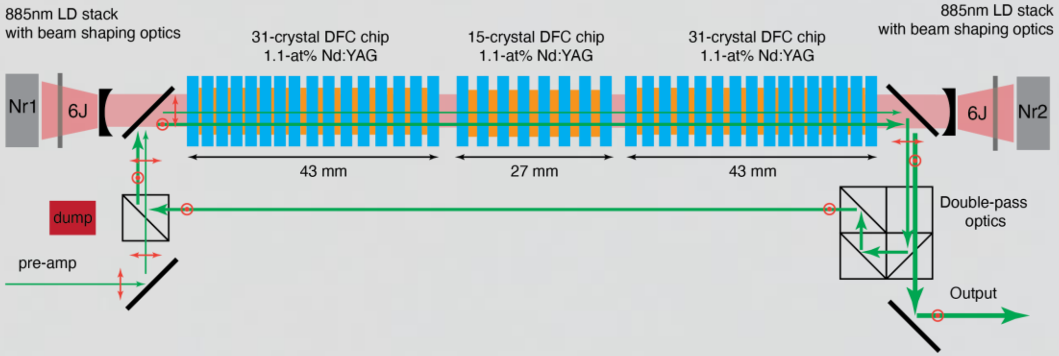


Thermal lens evaluation in large aperture DFC

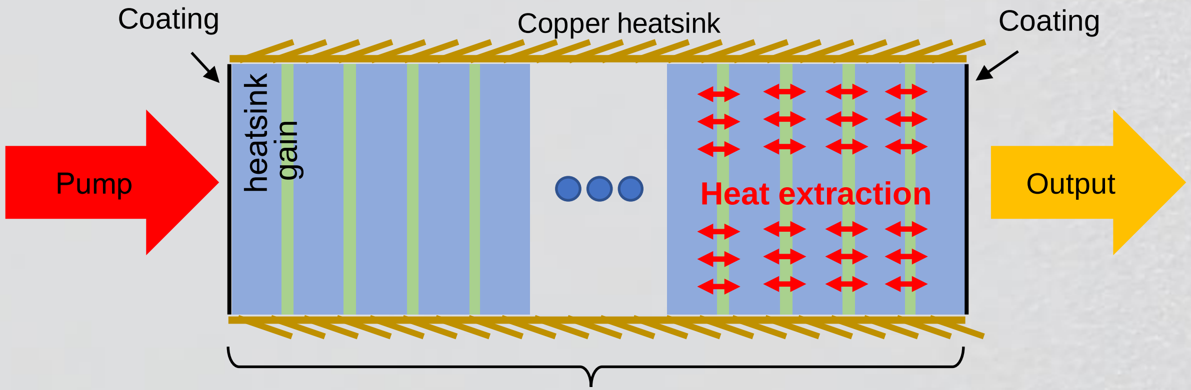


Future work

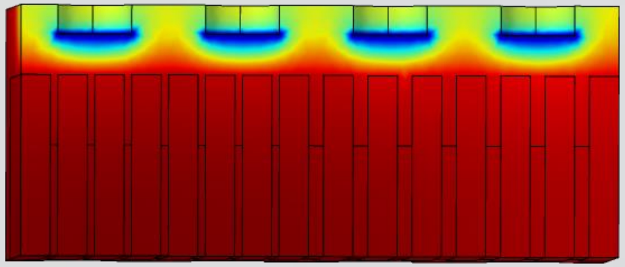
1. Full simulation for amplifier case



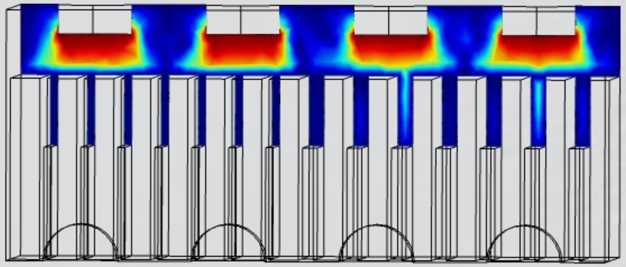
2. New model for thermal lens and stress induced birefringence



3. Water flow simulation

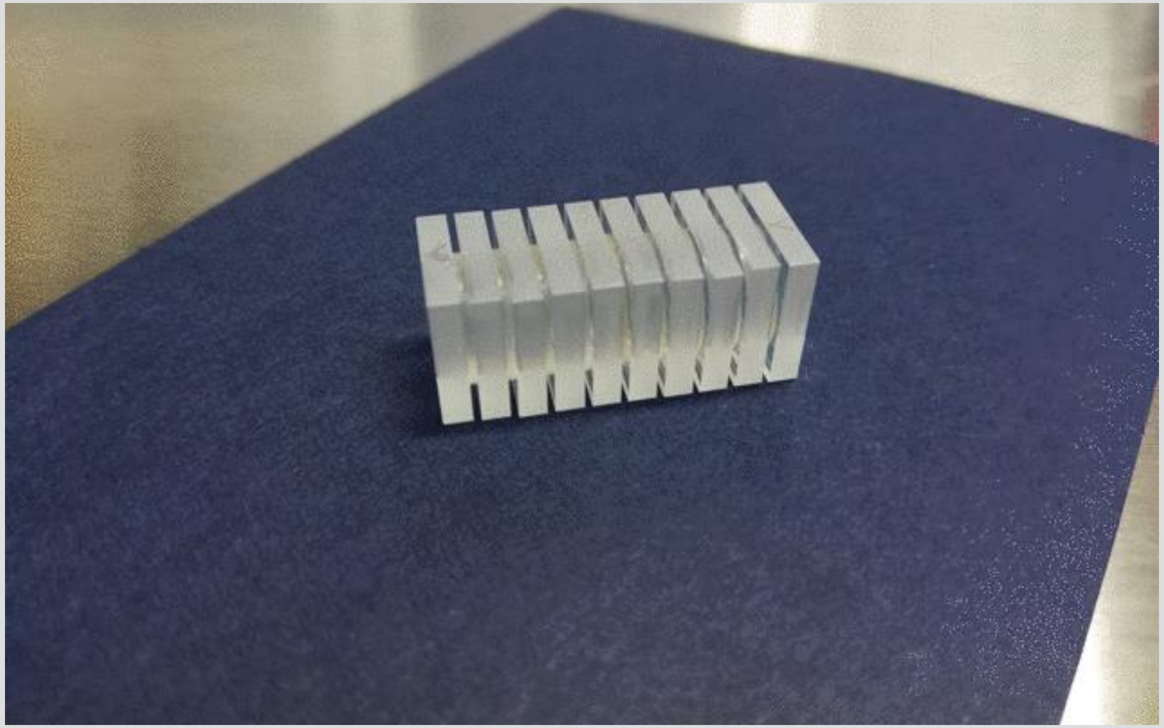


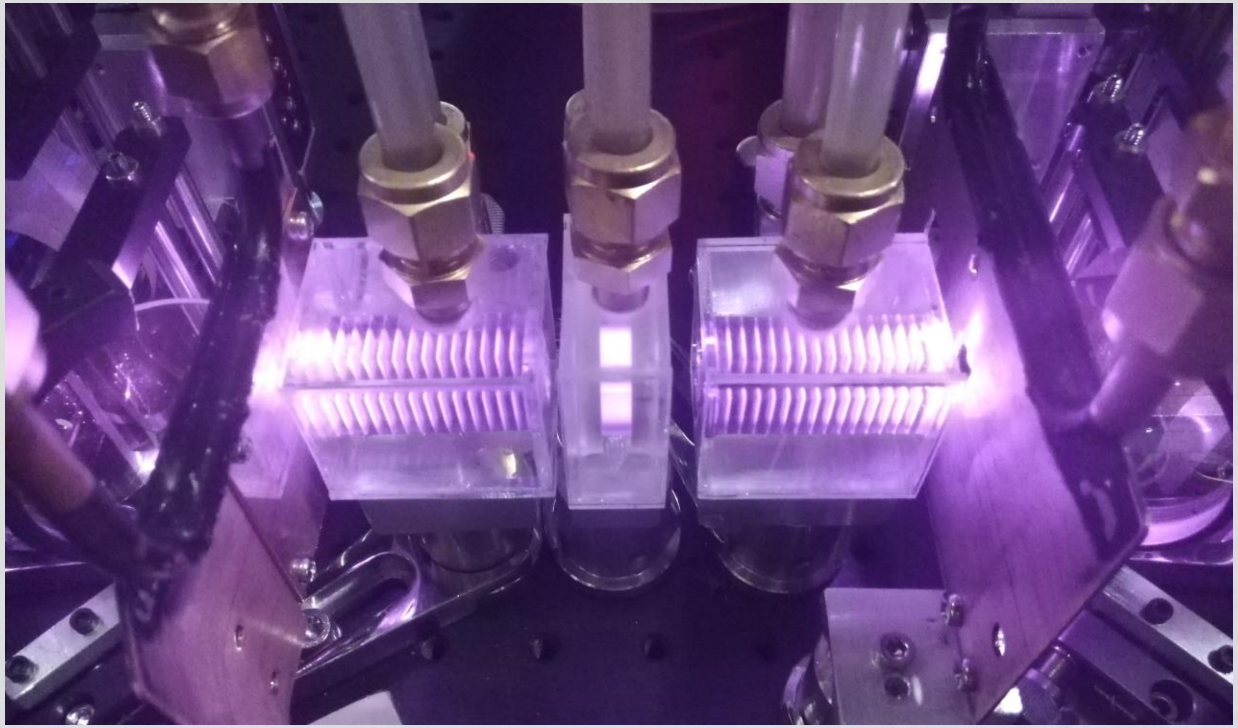
Temperature distribution



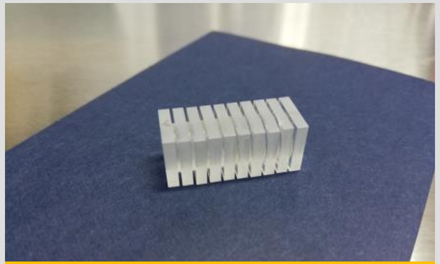
Water flow distribution

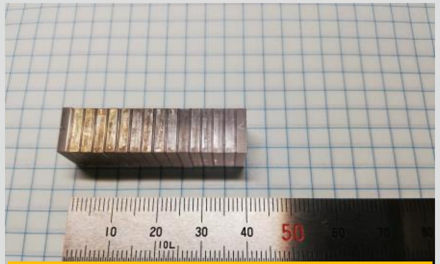
Bonding for KEK

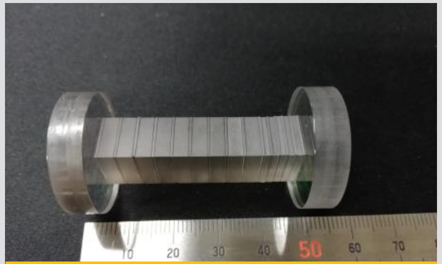


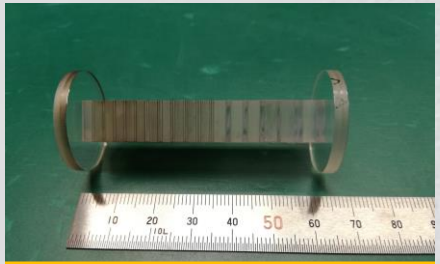


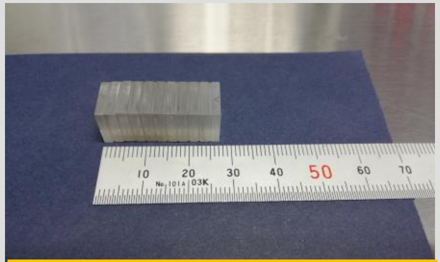
DFC chips for KEK experiment

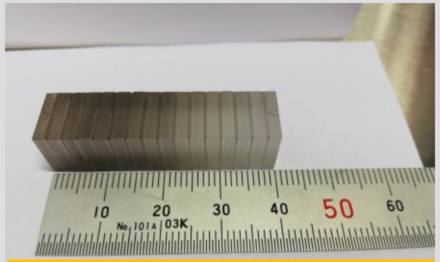

DFC #1, 19-crystal

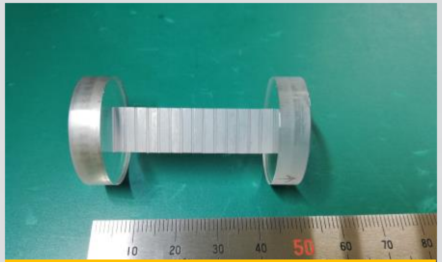

DFC #4, 31-crystal

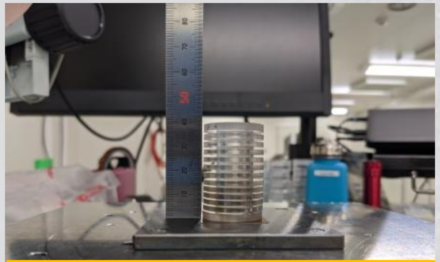

DFC #7 , 31-crystal

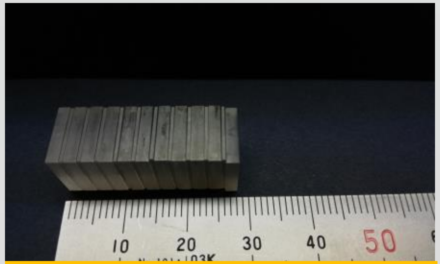

DFC #10 , 45-crystal

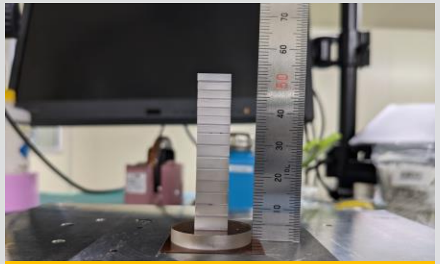

DFC #2, 21-crystal

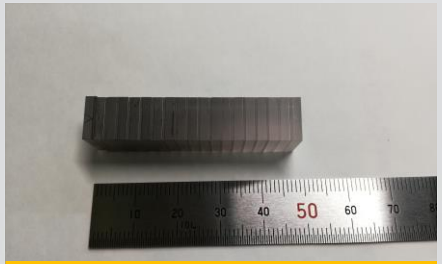

DFC #5 , 31-crystal


DFC #8 , 31-crystal


DFC #11 , 32-crystal


DFC #3, 21-crystal


DFC #6, 31-crystal


DFC #9 , 37-crystal


DFC #12 , 36-crystal