Development of Kumgang (金剛;diamond) laser: 4 x 0.1J@10kHz/10ns coherent beam combination laser using stimulated Brillouin scattering phase conjugate mirrors (SBS-PCM)

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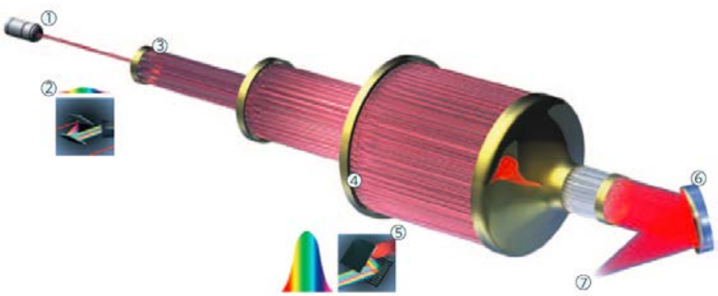
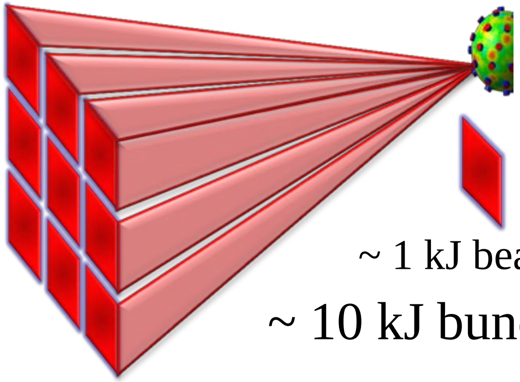
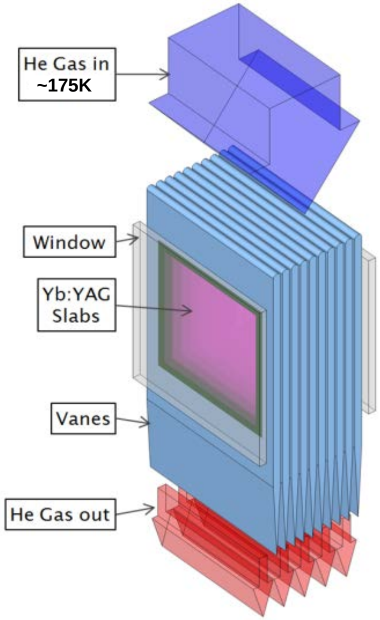
Beam Combination for Dream Lasers



>10J >10kHz ~100-200fs by 1000s fibers combination
G.Mourou et al., Nature Photonics, VOL 7, 258, APRIL 2013



P.Mason et al., HiPER, LCS2012



Schematic of 1 kJ head design

Powerful Dream Lasers
for
CW or High rep. rate ≥ 10kHz
with small energy

Beam combination of
Many Fiber Lasers
(more than 1,000)

Energetic Dream Lasers
for
Low rep. rate ≤ 10kHz
with high energy

Beam combination of
Several Bulk Lasers
(less than 1,000)

Most challenging issues in LFE

DT Laser ignition → DT Burn → Fusion Energy → Dream Energy

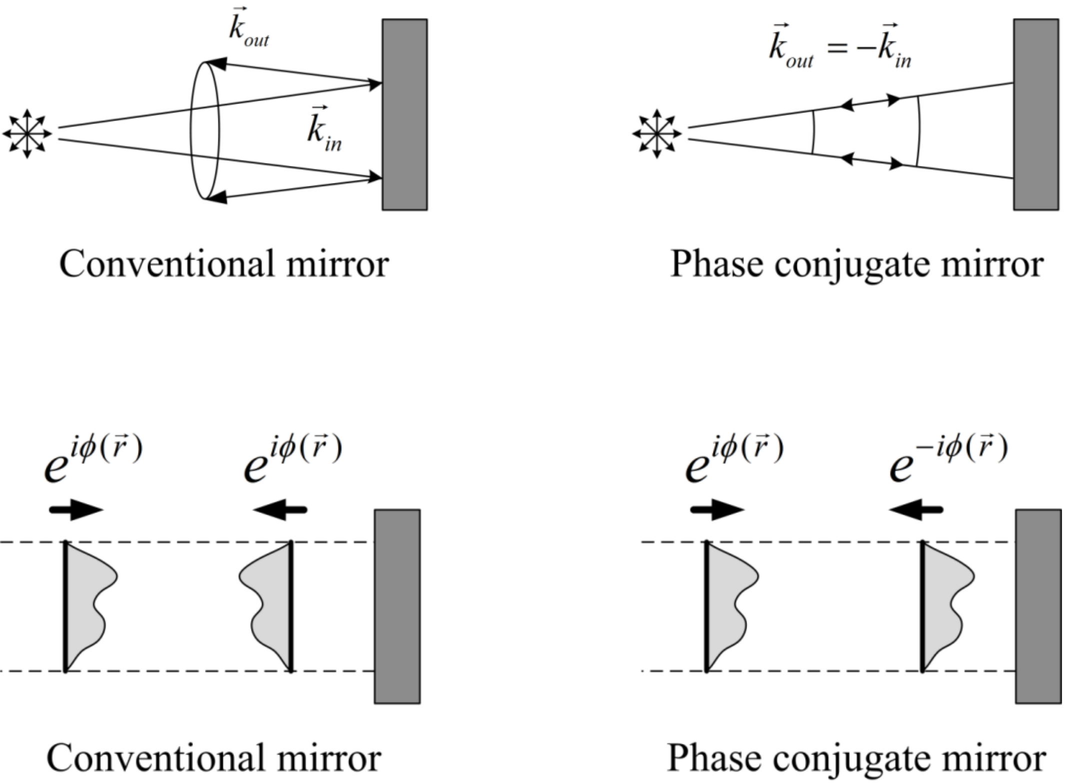
- High Rep. Rate Laser (25kJ@10Hz module)
- Target injection (< 20μm@400m/s@5meters)
- Protection of windows from explosion debris

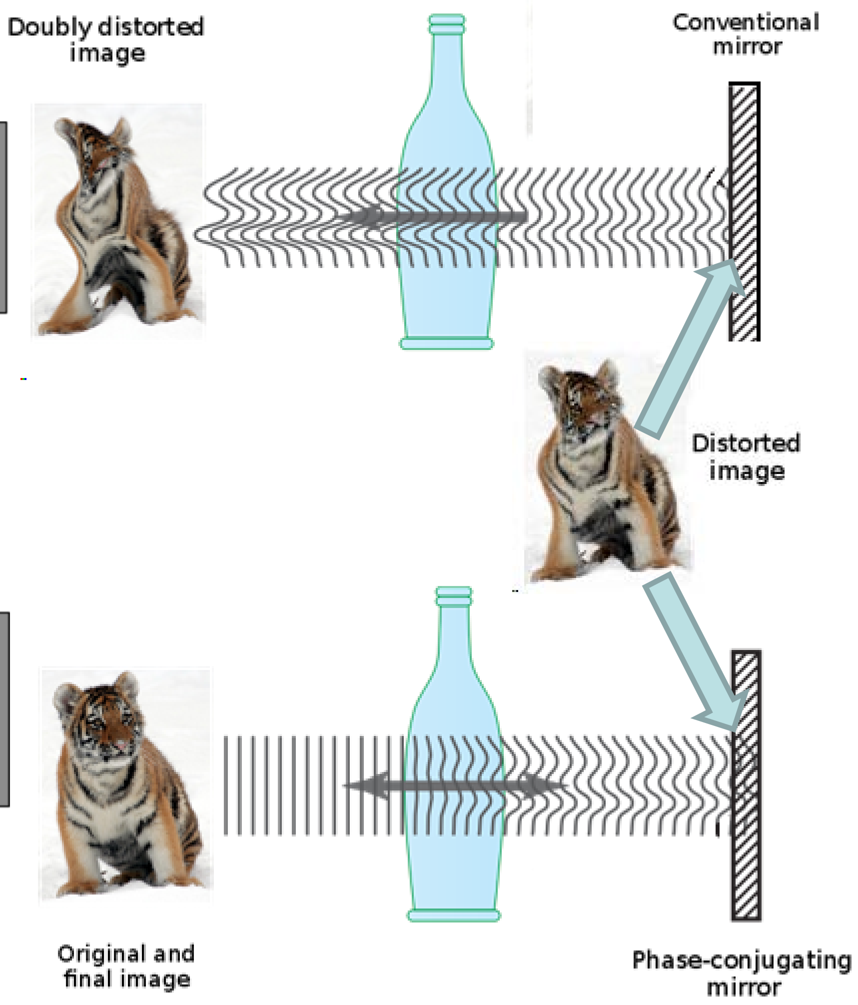
→ Resolved by Coherent Beam Combination SBS-PCM

Motivation

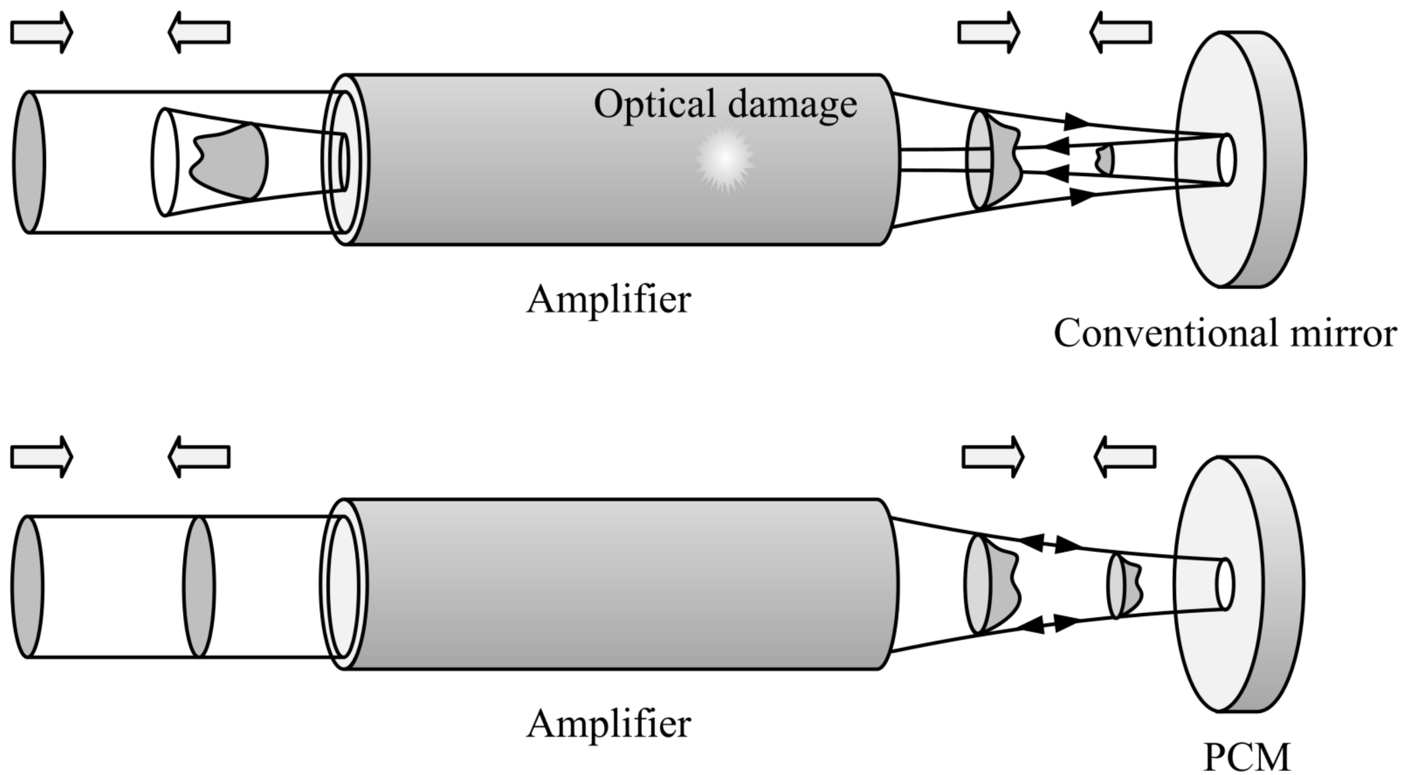
- **High Repetition-Rate/Energy/Power Dream Lasers are strongly required for**
  - **Laser peening**
  - **2-D laser machining by holography**
  - **Laser n/p accelerator**
  - **Laser fusion driver**
  - **Tremendous applications…**
- **Solutions to increase the output energy/power :**
  - LD pumping
  - High thermal conductivity laser media (Ceramic laser materials)
  - **Cryogenically cooled ceramic lasers (Yb:YAG, ….)**
- **Cooling problem(thermal) and parasitic oscillation**
  - **limit the size of the laser media > limit attainable output energy/power**
  - **Beam combination of available lasers ;**
    - **extends the attainable energy/power → Energetic Dream Laser**
- **Demonstration of CBC by using phase controlled SBS-PCM in high power regime is very important step for the Dream Laser Technology**

Phase conjugate mirror





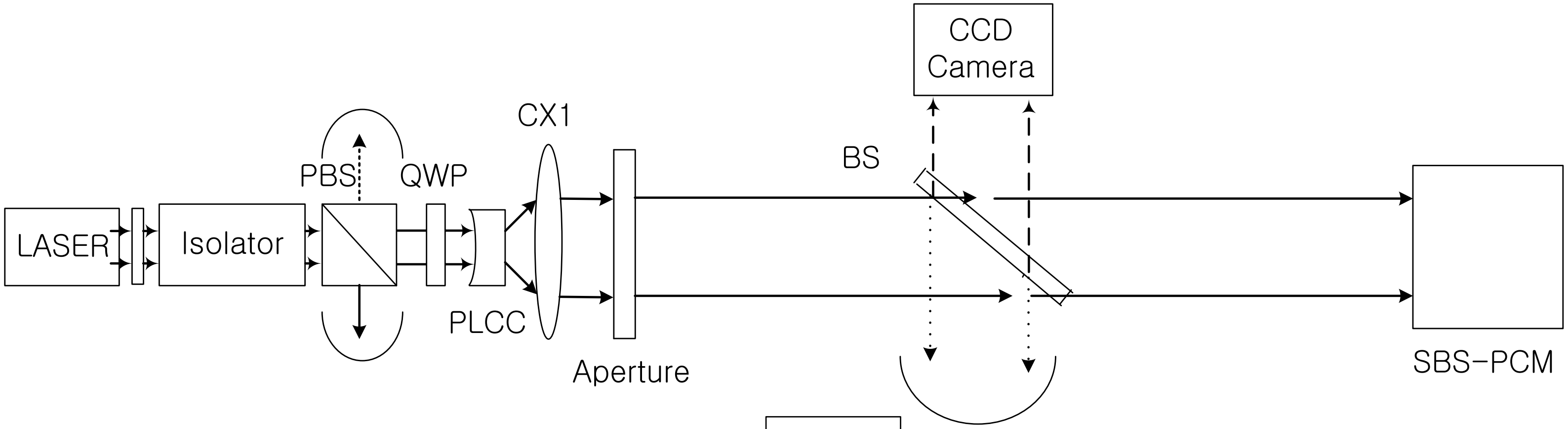
Practical Application of SBS-PCM



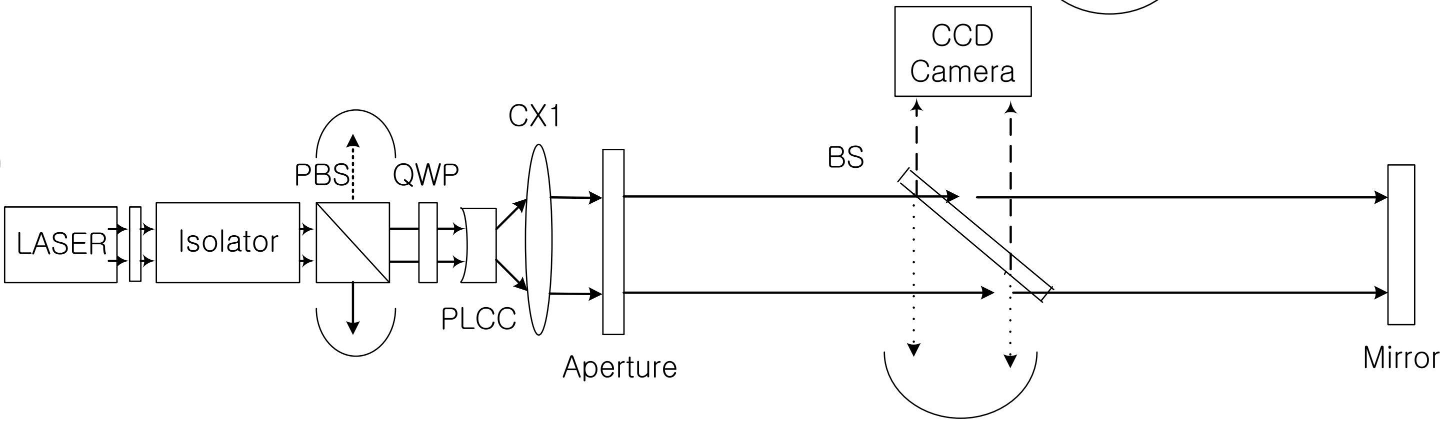
Master oscillator power amplification (MOPA) with phase conjugate mirror (PCM)

Image reconstruction by SBS-PCM

(a)



(b)

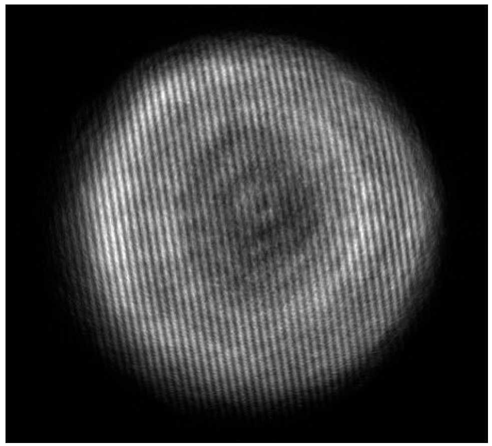


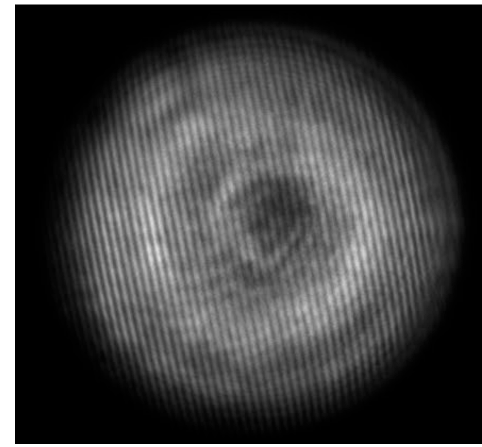
PBS : Polarizing beam splitter; BS : Beam splitter; QWP : Quarter wave plate;
CX1, 2, PLCC : Lenses

Image reconstruction by SBS-PCM

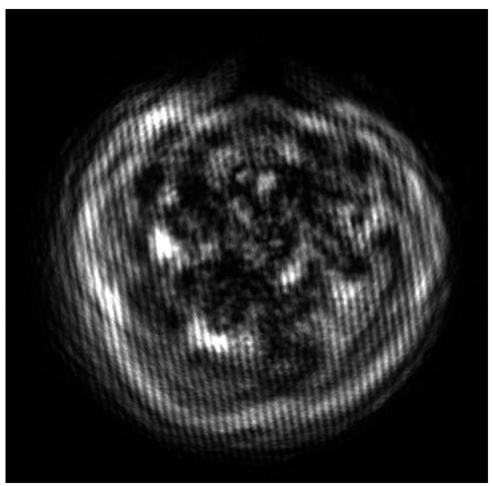
Conventional mirror **SBS-PCM**

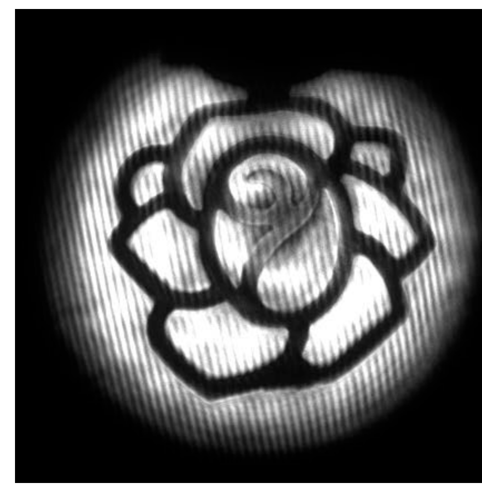
Without aperture



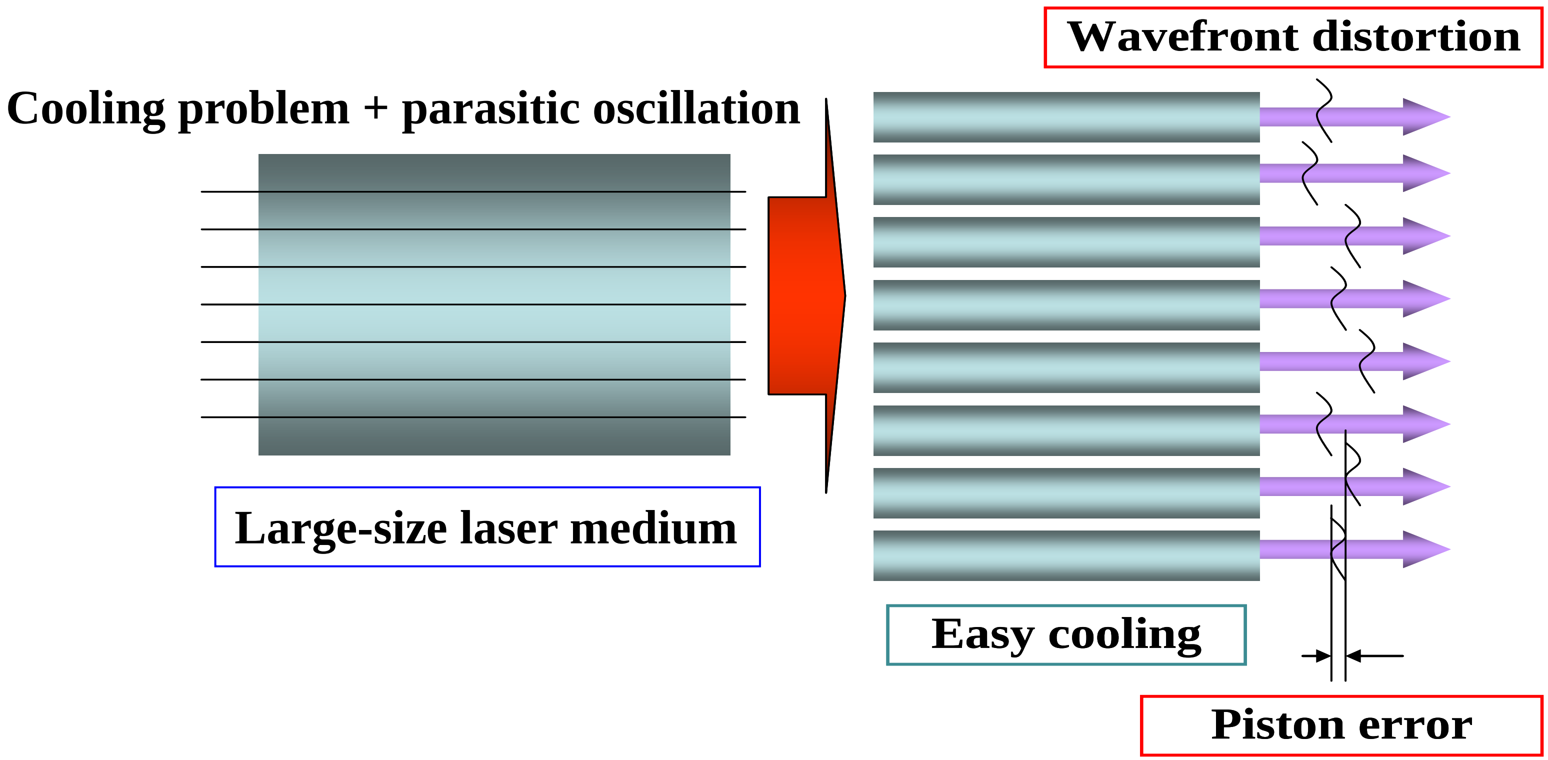


Rose shaped aperture





Beam combination and its problems



Ways of clean-up of wave-front distortion

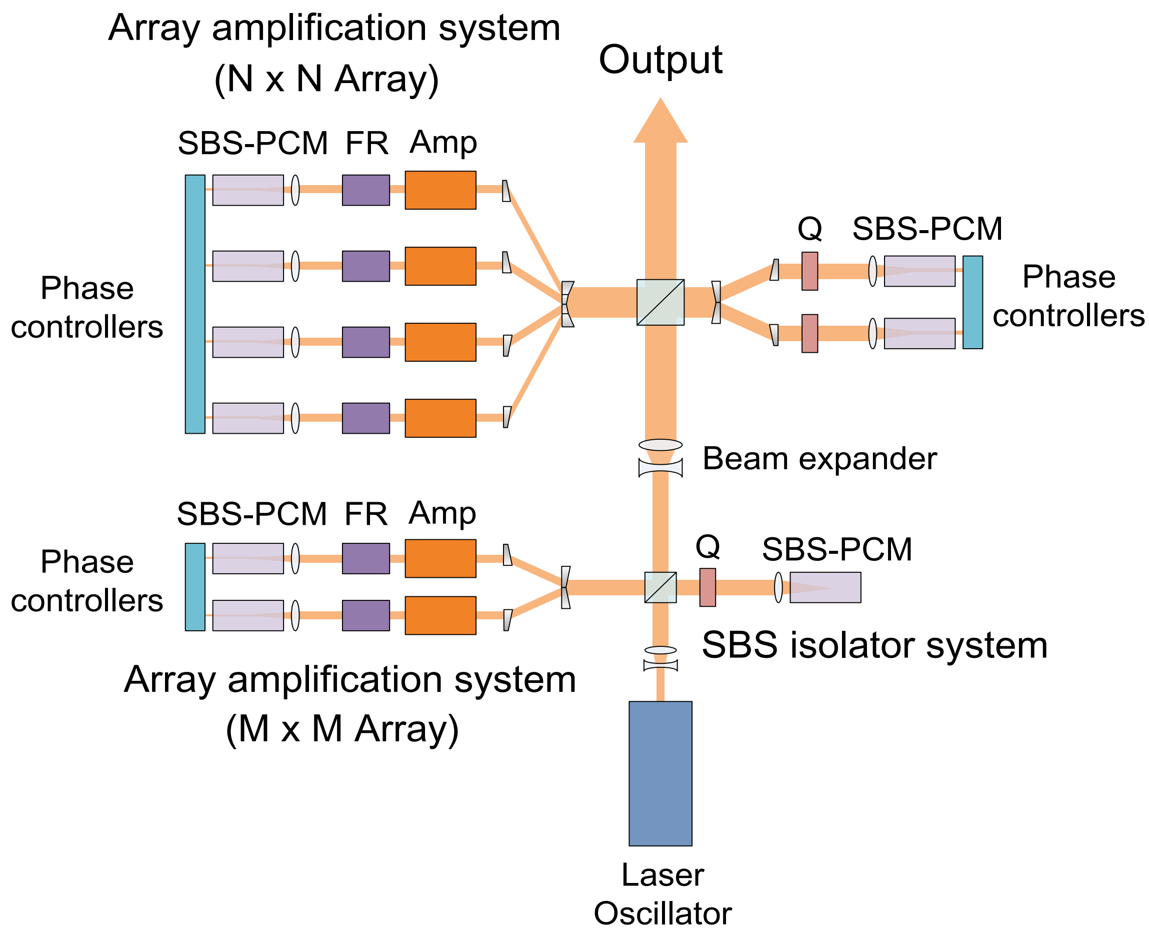
	Spatial filtering	Adaptive Optics	Phase Conjugate	
			SBS	4Wave Mixing
Loss of Energy	Depends on the beam quality	small	small	small
system	Simple	Complicated	Most simple	Complicated
Input energy	No limit	No limit	No limit	Small
Piston error correction	OK	OK	Was No Now OK*	OK

*** Random Piston Error of SBS-PCM**

- inherent problem of SBS,
- but it was resolved by H. J. Kong in 2003 by **the self-phase-control technique**

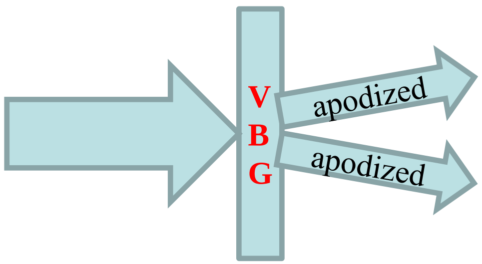
Beam combination laser system using SBS-PCMs

Wave-front dividing method

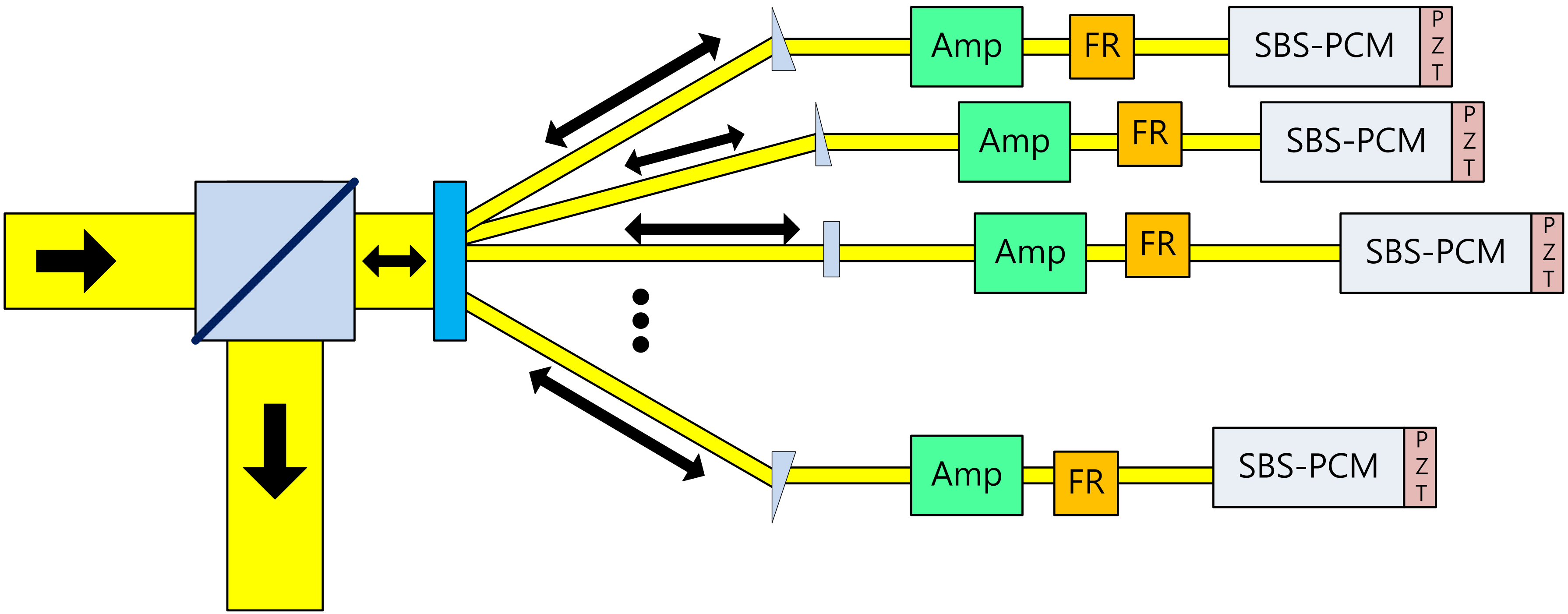


H. J. Kong, J. Y. Lee, Y. S. Shin, J. O. Byun, H. S. Park, and H. Kim, Opt. Rev. 4, 277 - 283, 1997.

WD M X M Amp array

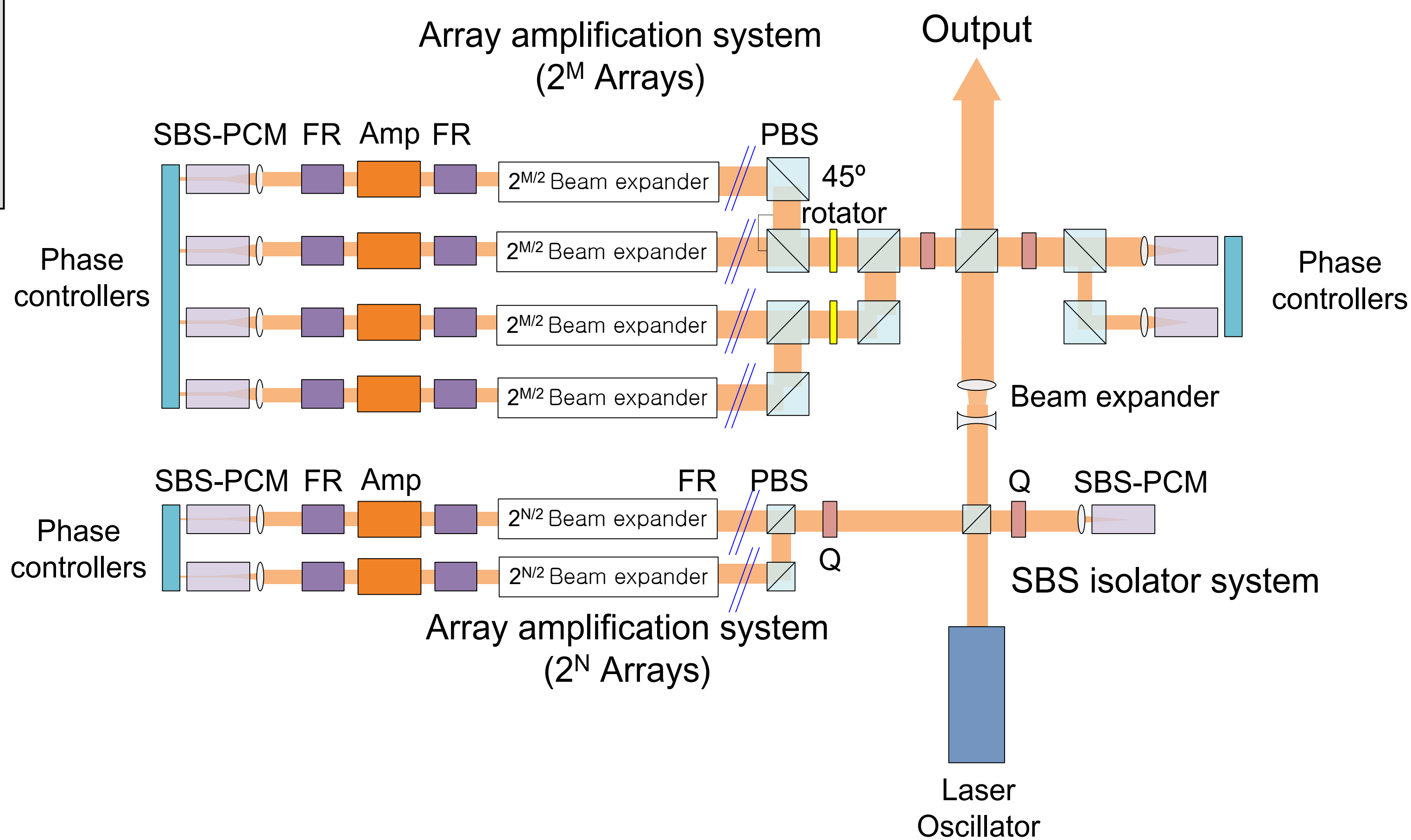


WD M X M Amp array



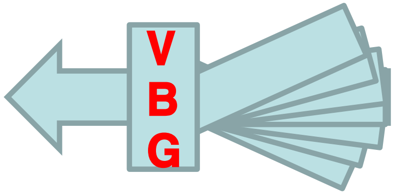
Beam combination laser system using SBS-PCMs

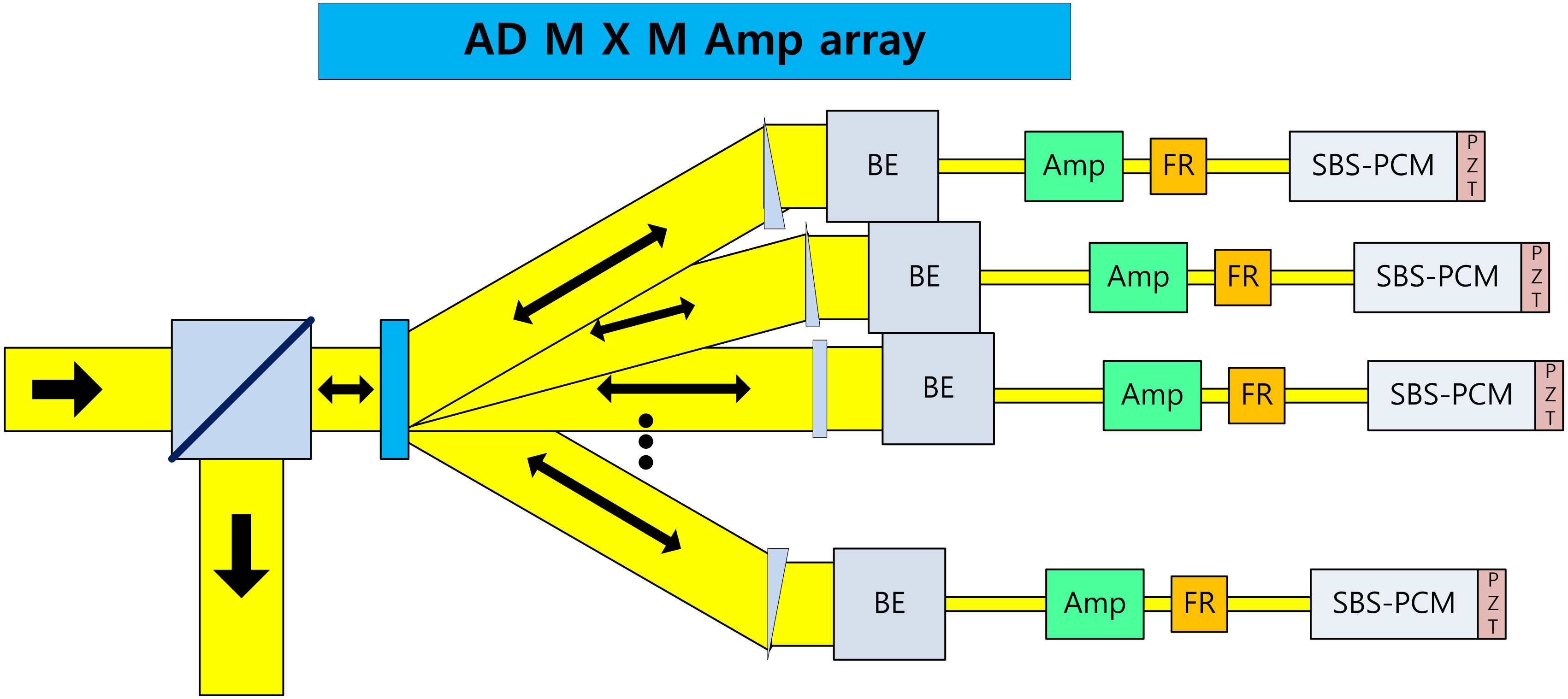
Amplitude dividing method



H. J. Kong, S. K. Lee, J. W. Yoon, and D. H. Beak, Opt. Rev. 13, 119, 2006.

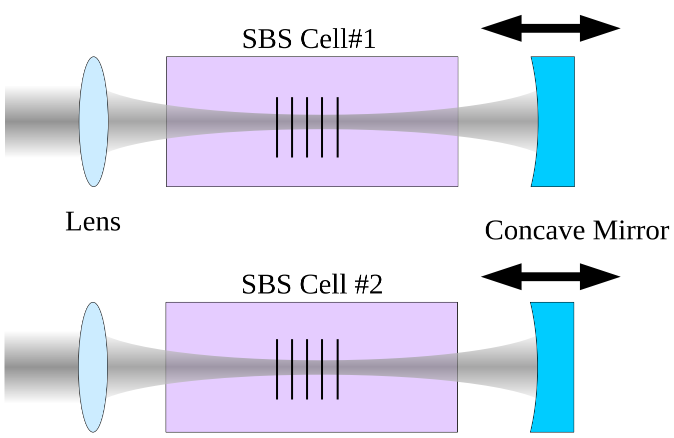
AD M X M Amp array



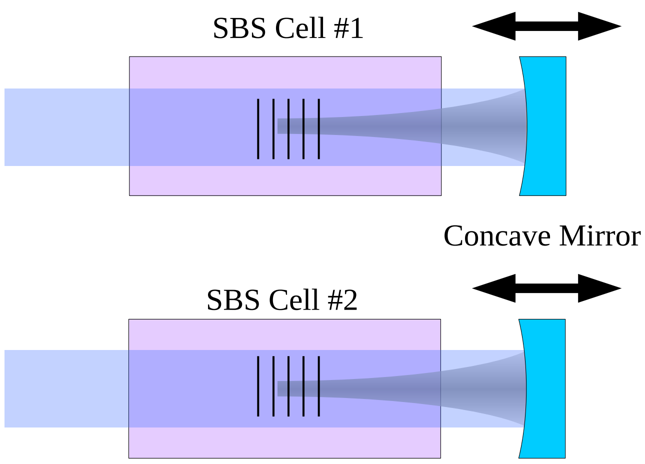


"Self-phase control" method

- Feed back mirror > Counter propagating beams > Standing wave > Density modulation
- Standing density modulation locks the ignition position of the moving Bragg grating.
- The Bragg grating locks the phase of the SBS wave.
- Phase controlling of SBS wave is possible by positioning the feed back mirror.

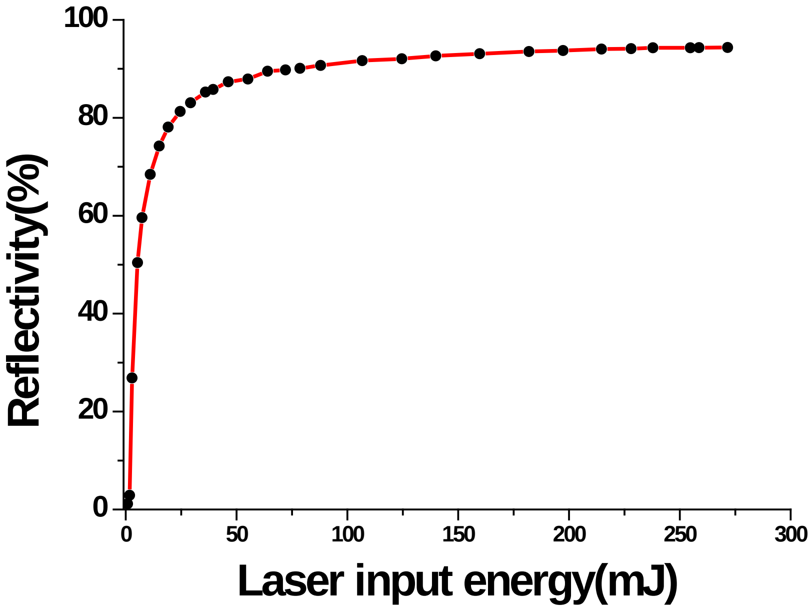


(a)Concentric type

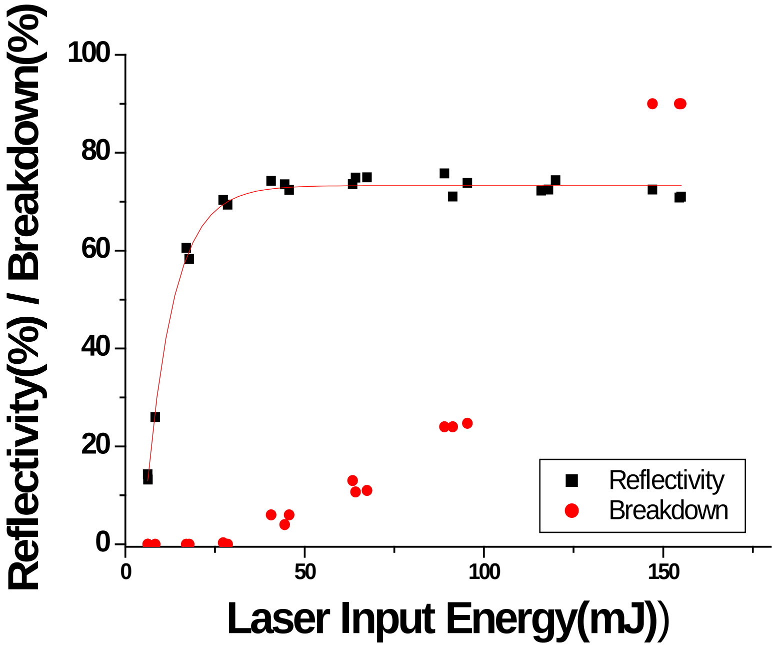


(b) Confocal type

Reflectivity and breakdown probability depending on the laser mode of SBS-PCM with FC-75



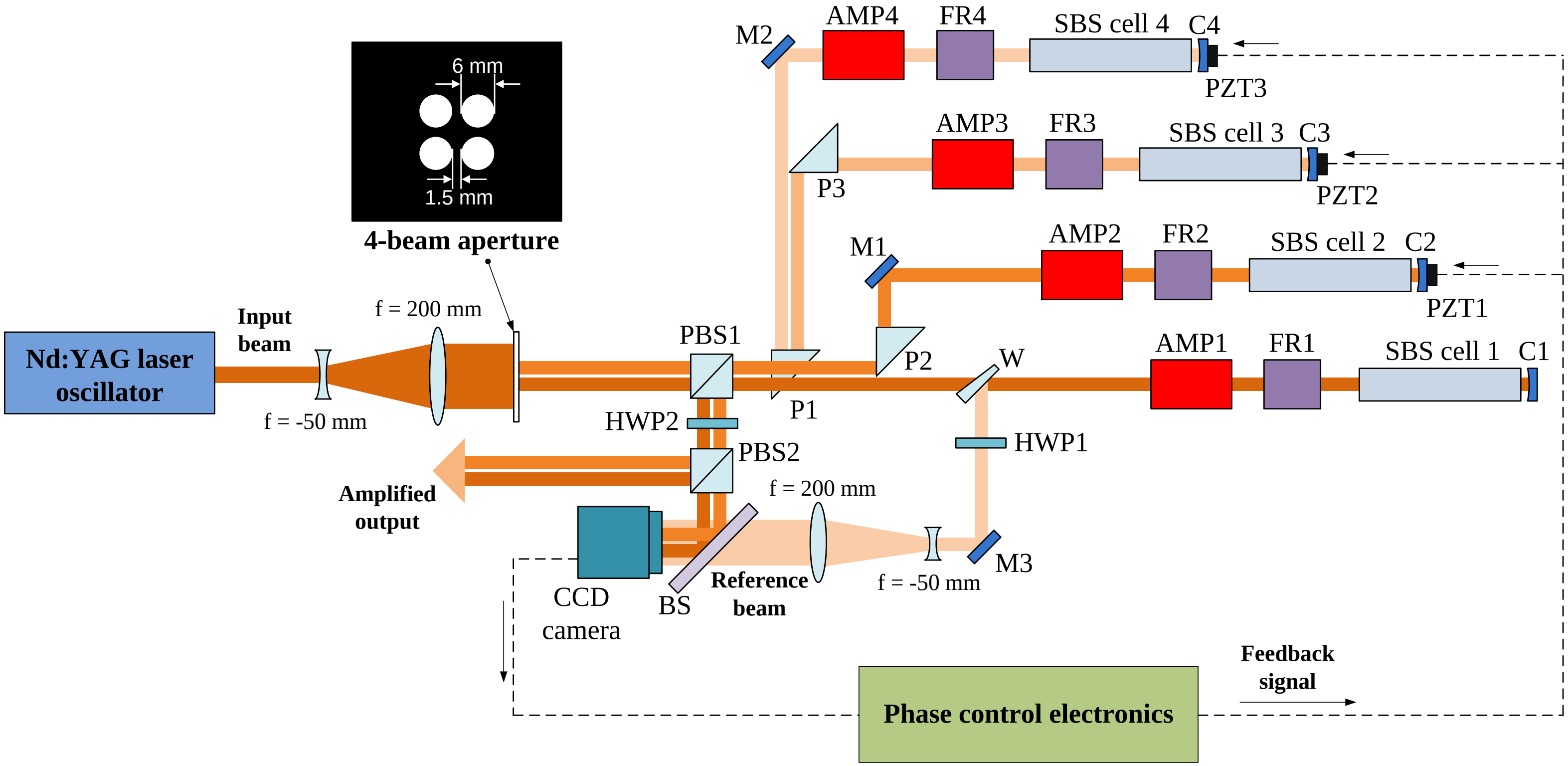
Single mode pumping
(Δν~120MHz, Γ=350MHz)
(No break down)



Multi mode pumping
(Δν~30GHz, Γ=350MHz)
(Break down occurs)

Seong Ku Lee, et. al, JKPS 46, pp.443~447, 2005.

Experimental setup for the wave-front dividing 4-beam combination

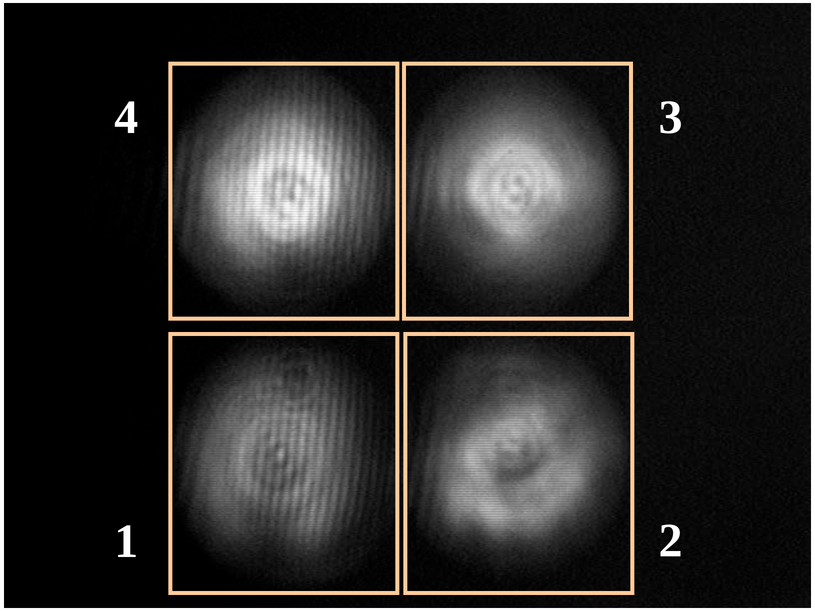


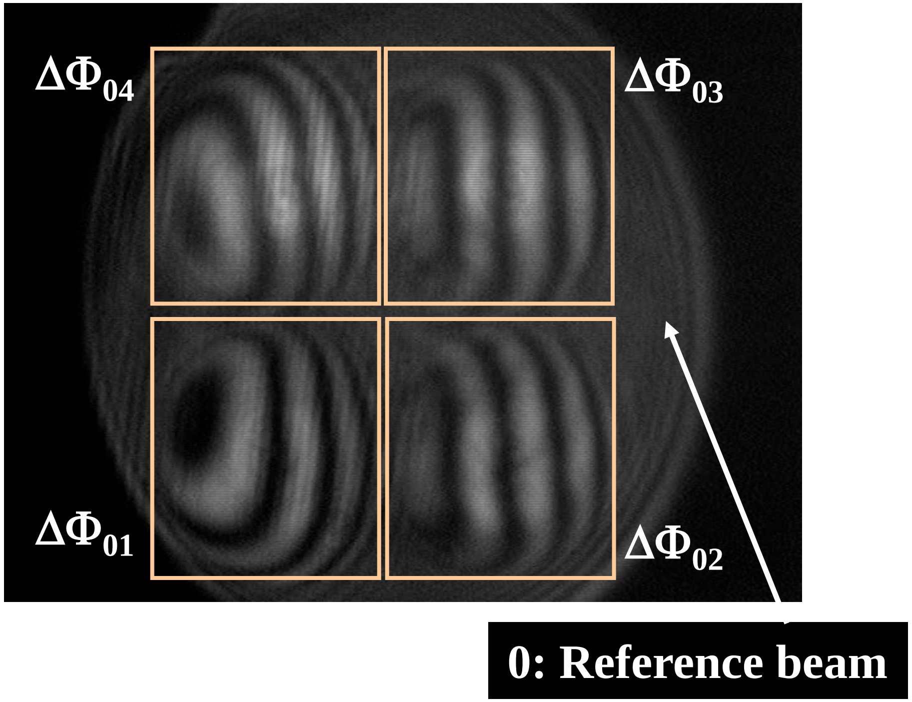
PB1&PBS2, polarizing beam splitters; HWP1&HWP2, half wave plate; P1, P2&P3, 45 degree prisms; BS, beam splitter; W, wedged window; FR1, FR2, FR3&FR4, Faraday rotators; C1, C2, C3&C4, concave mirrors; PZT1, PZT2&PZT3, piezoelectric translators.

J. S. Shin, S. Park, H. J. Kong, and J. W. Yoon, Applied Physics Letters. 96.131116, 2010.

4-beam output profile & Interference patterns

4-beam combined output profile	Interference patterns at CCD camera





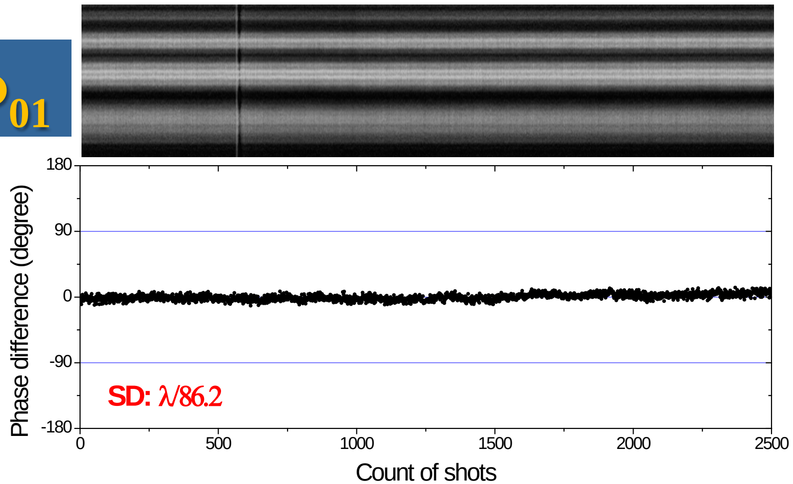
J. S. Shin, S. Park, H. J. Kong, and J. W. Yoon, Applied Physics Letters. 96.131116, 2010.

Beam Energy – AMP off case

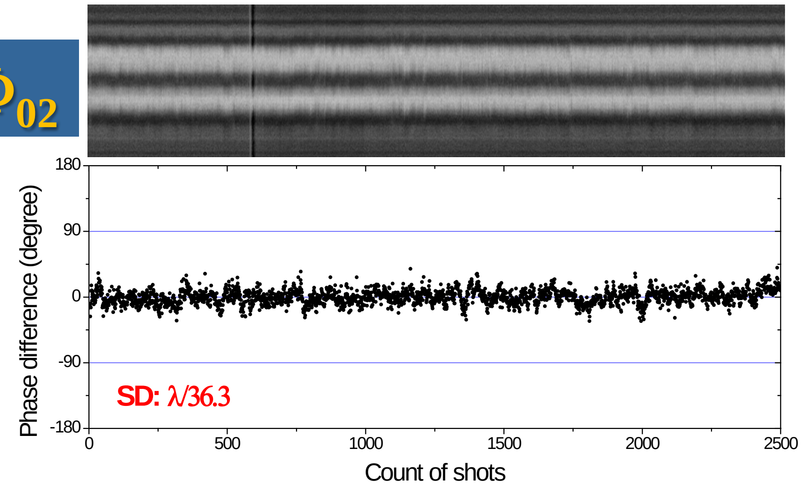
- **Input energy :** 32.2 ± 0.3 mJ
- **Output energy**
  - AMP off : 9.9 ± 0.5 mJ (reflected by SBS-PCMs)

Phase fluctuation without amplifier operation

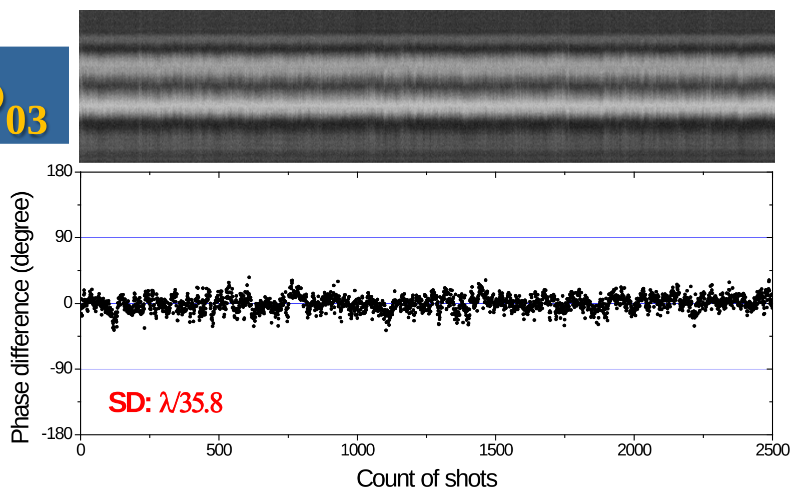
$\Delta\Phi_{01}$



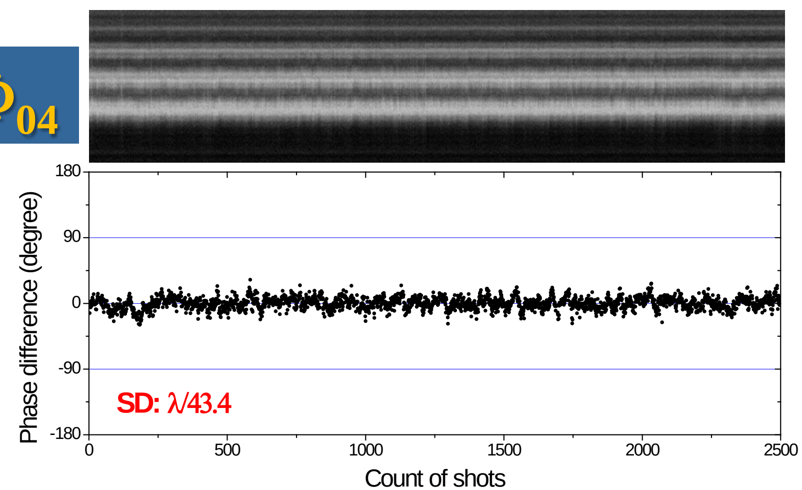
$\Delta\Phi_{02}$



$\Delta\Phi_{03}$



$\Delta\Phi_{04}$



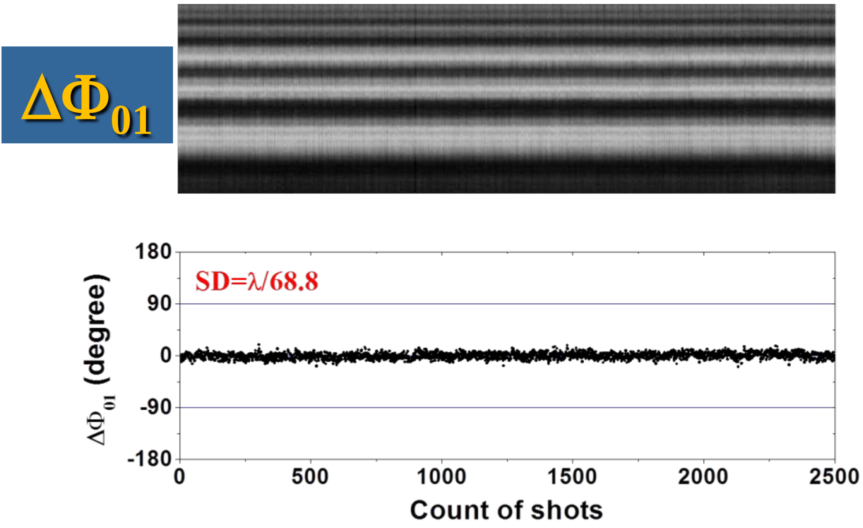
J. S. Shin, S. Park, H. J. Kong, and J. W. Yoon, Applied Physics Letters. 96.131116, 2010.

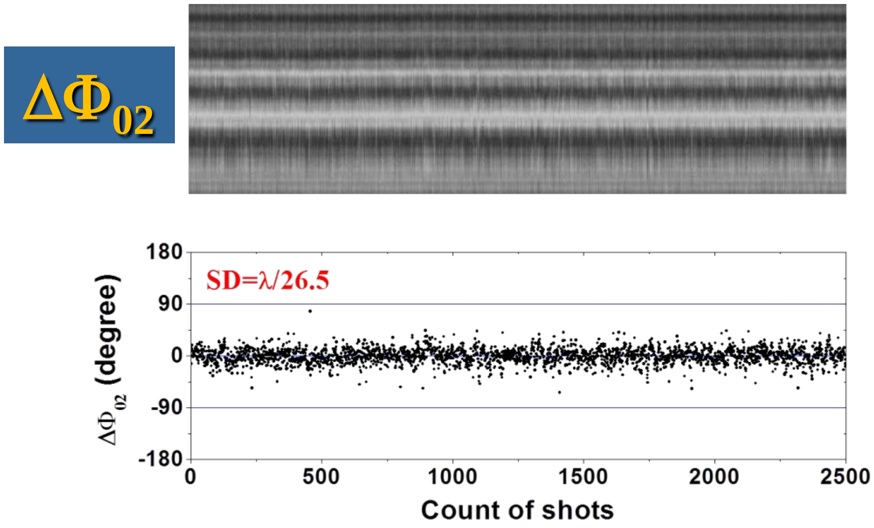
Beam Energy – AMP on case

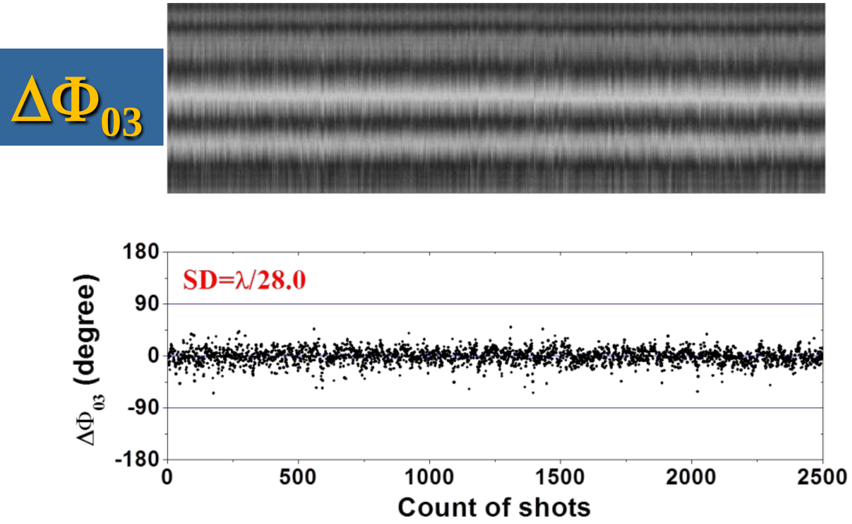
- **Input energy :** 32.2 ± 0.3 mJ

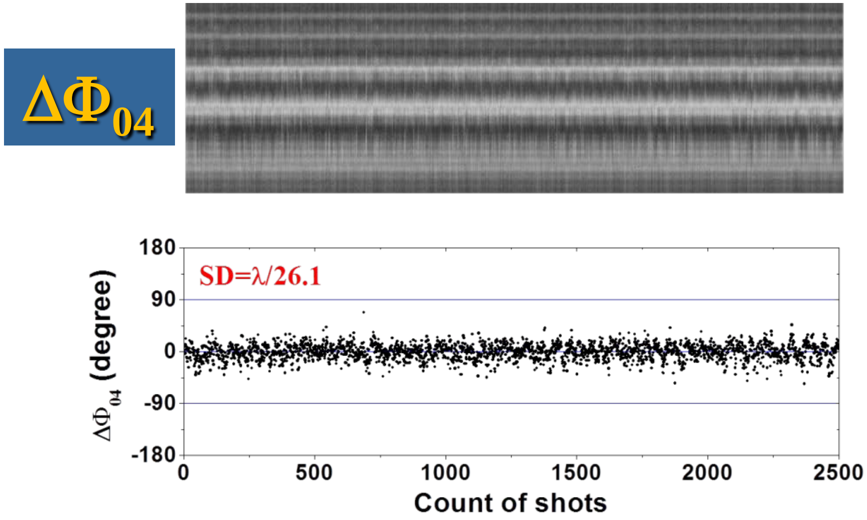
- **Output energy**
  - AMP off : 169 ± 6 mJ (gain : 5.3)

Phase fluctuation with amplifier operation





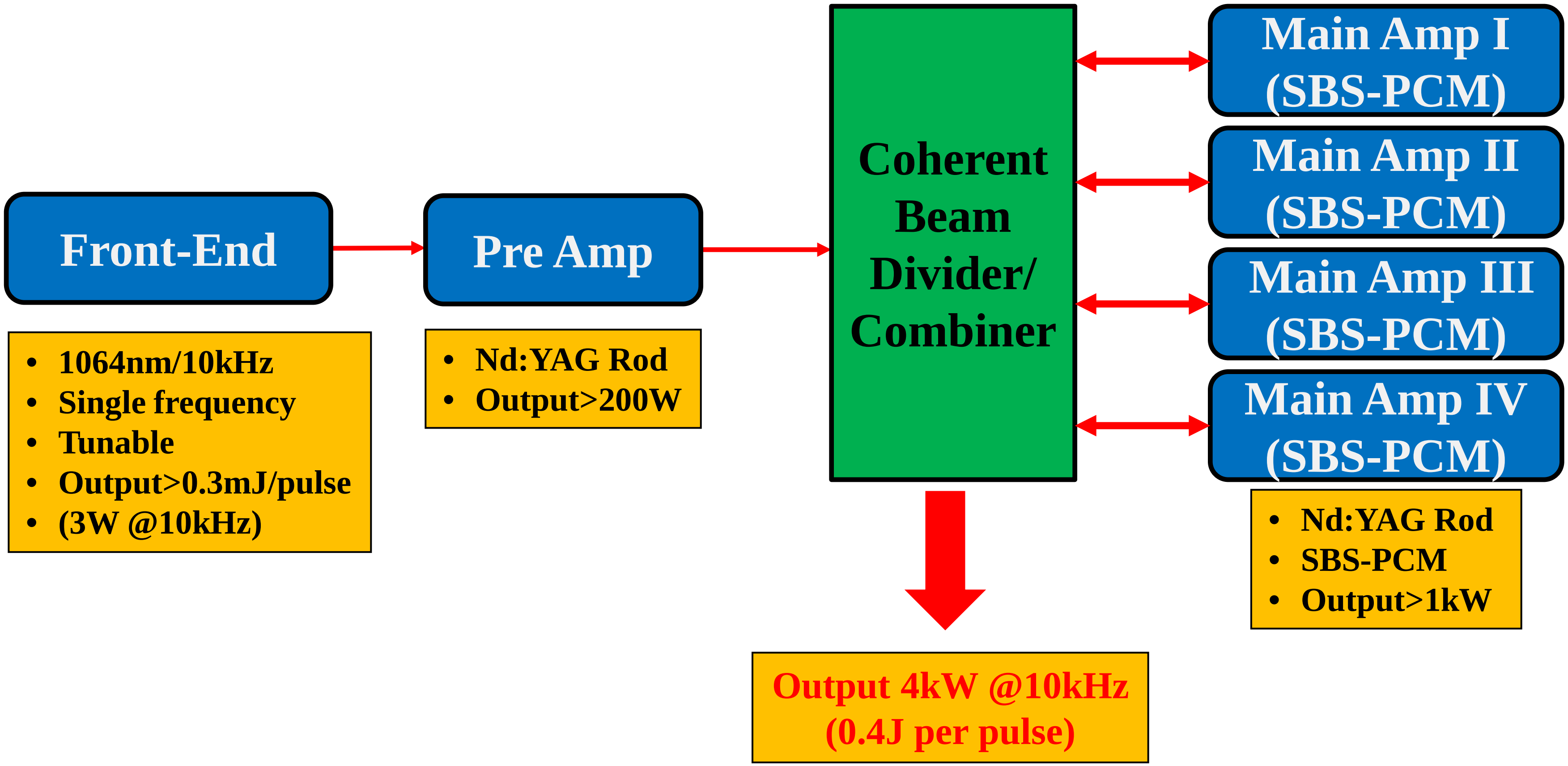


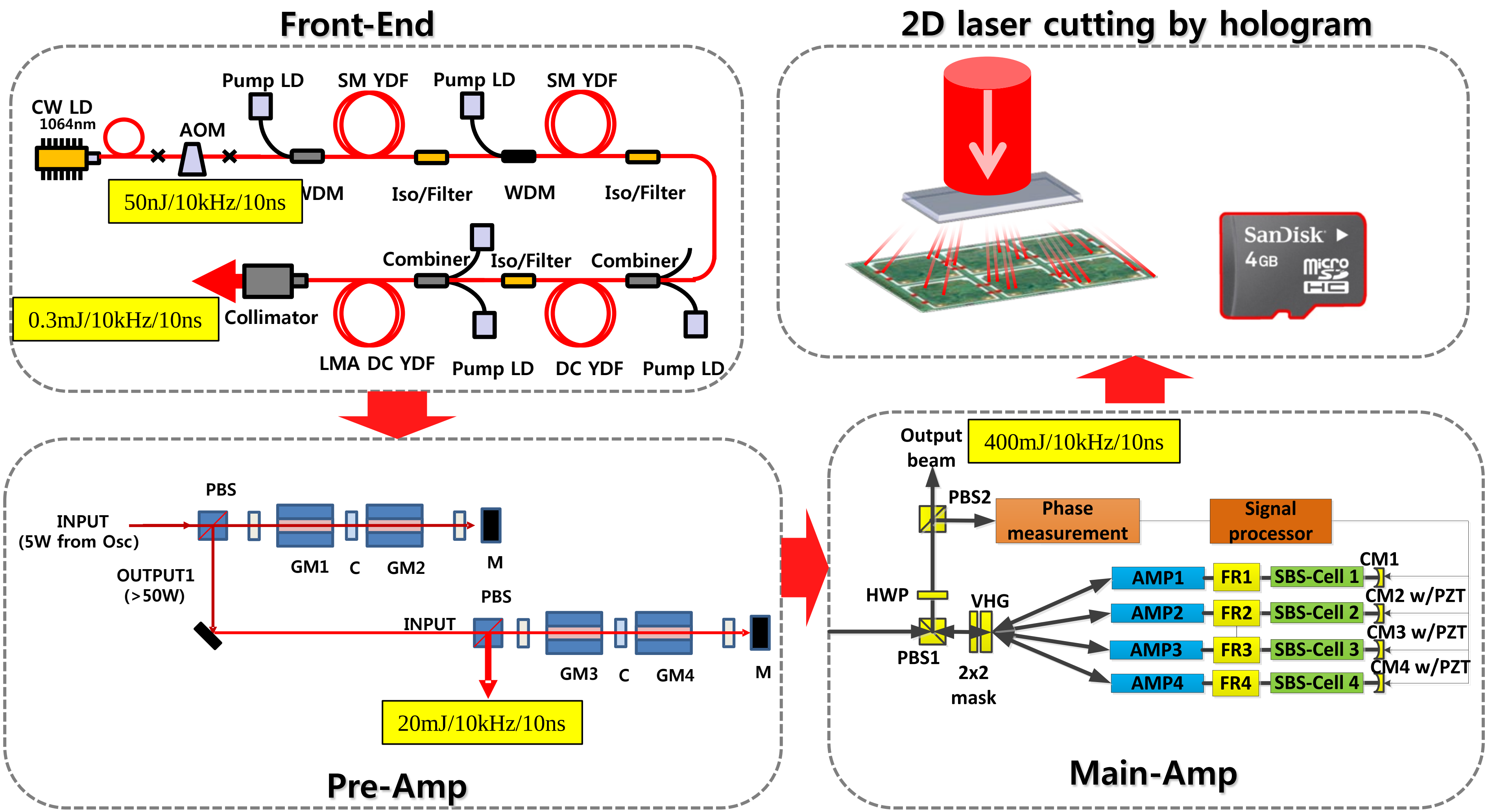


J. S. Shin, S. Park, H. J. Kong, and J. W. Yoon, Applied Physics Letters. 96.131116, 2010.

0.1J@10ns@10kHz laser modules and beam combination for 4 kW using SBS-PCMs

Laser System Configuration




Front-End
Pump LD
SM YDF
Pump LD
SM YDF
CW LD
1064nm
AOM
WDM
Iso/Filter
WDM
Iso/Filter
50nJ/10kHz/10ns
Combiner
Iso/Filter
Combiner
0.3mJ/10kHz/10ns
Collimator
LMA DC YDF
Pump LD
DC YDF
Pump LD
2D laser cutting by hologram
SanDisk
4GB
micro SD HC
Pre-Amp
PBS
INPUT
(5W from Osc)
GM1
C
GM2
M
OUTPUT1
(>50W)
PBS
INPUT
GM3
C
GM4
M
20mJ/10kHz/10ns
Main-Amp
Output
beam
400mJ/10kHz/10ns
PBS2
Phase
measurement
Signal
processor
HWP
VHG
PBS1
2x2
mask
AMP1
FR1
SBS-Cell 1
CM1
AMP2
FR2
SBS-Cell 2
CM2 w/PZT
AMP3
FR3
SBS-Cell 3
CM3 w/PZT
AMP4
FR4
SBS-Cell 4
CM4 w/PZT

Front-End system

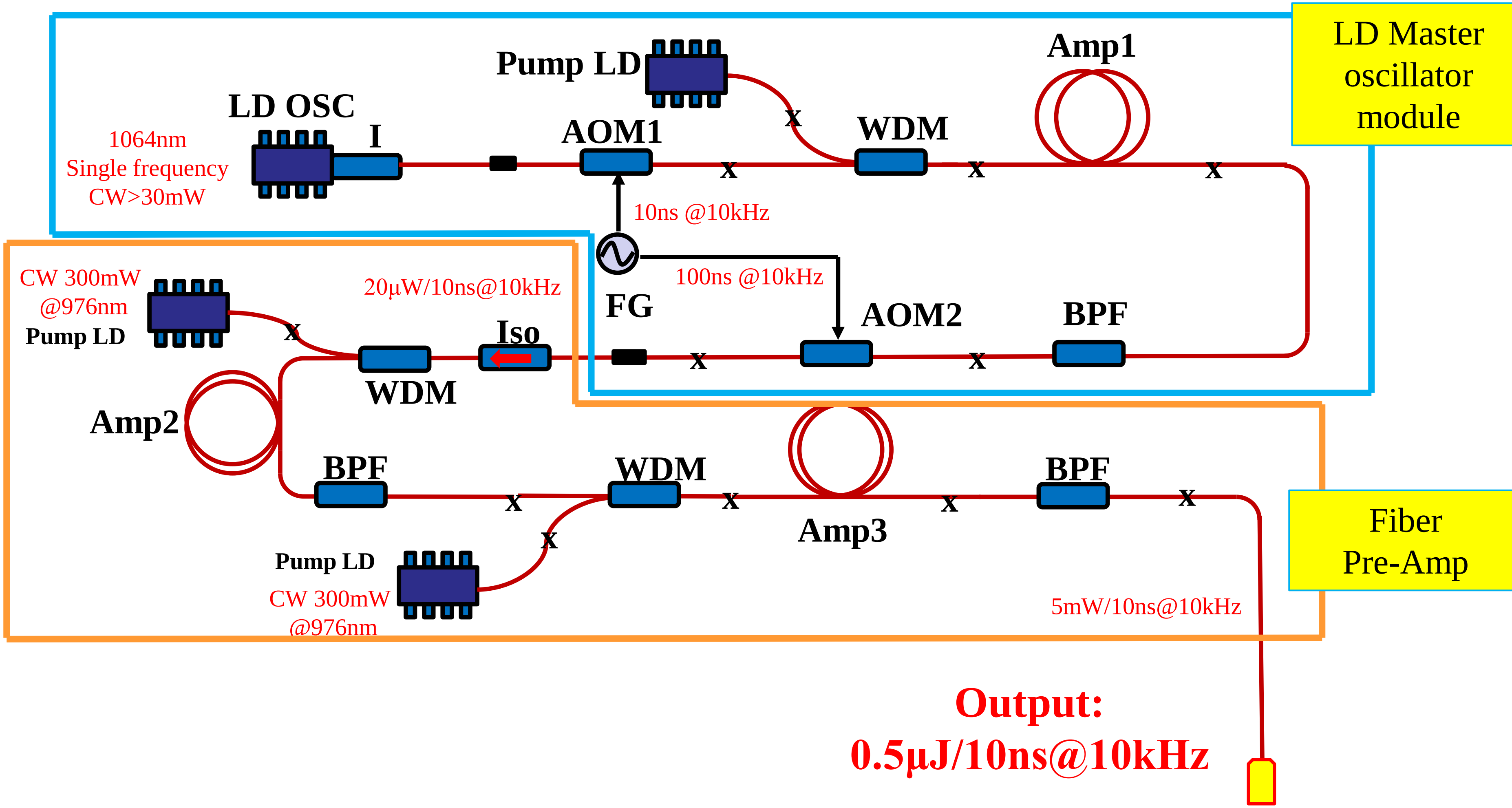
Hybrid Pulsed Seed Laser

CW single frequency diode laser
- Tunable wavelength 1064nm+/-1nm
- Single frequency line-width <1MHz
- Output power >30mW
- PM fiber coupled

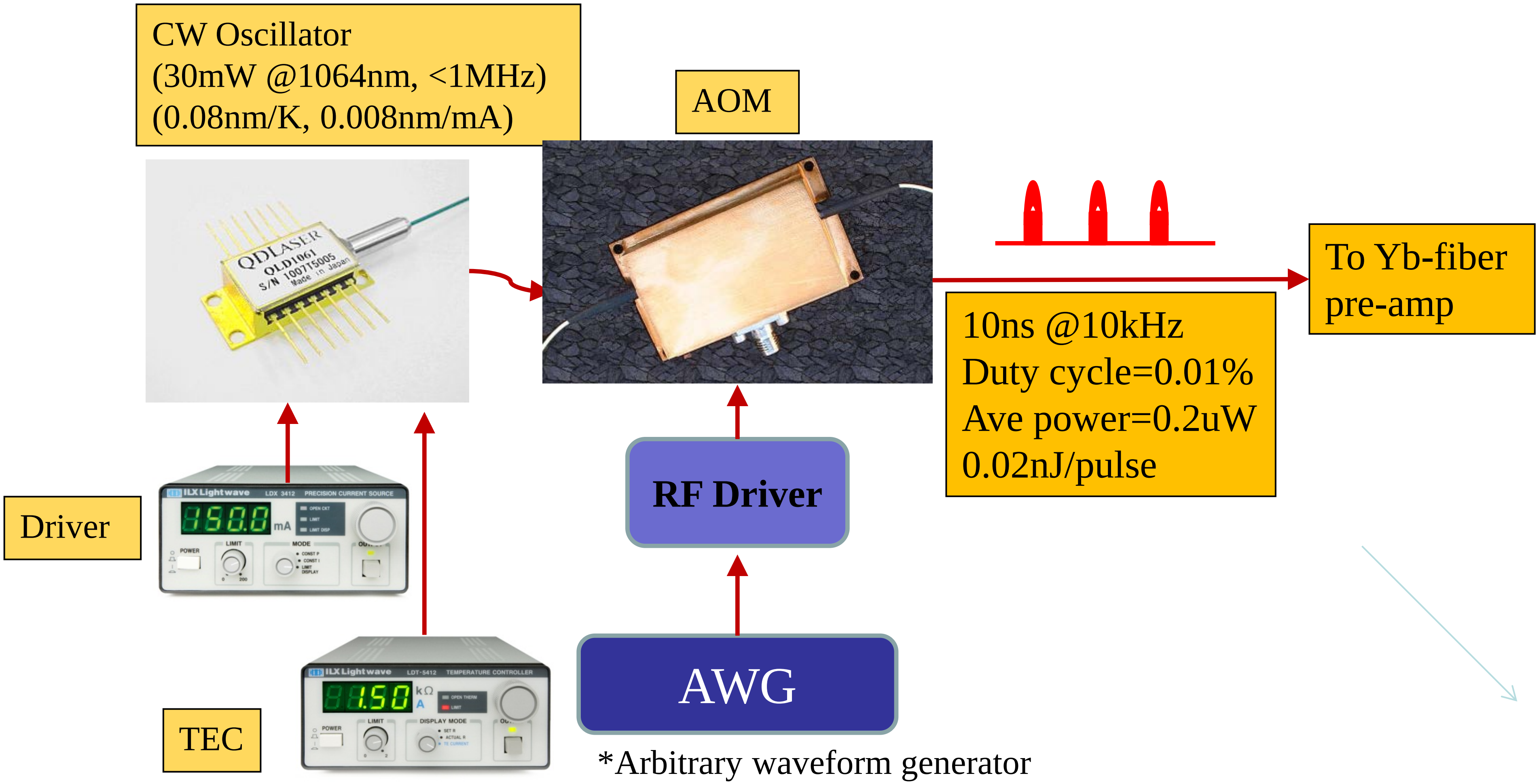
Pulse Slicer
- Fiber coupled fast AO modulator
- Pulse shape near Gaussian
- Pulse width ~10ns & Rep rate 10kHz
- Pulse energy ~0.15nJ per pulse

Fiber amplifier
- Yb-doped PM fiber amplification pumped with 980nm LD
- Output pulse energy ~50nJ per pulse
- Pulse width ~10ns (near Gaussian)
- Wavelength 1064nm with single frequency line-width <100MHz

Hybrid Pulsed Seed Laser setup

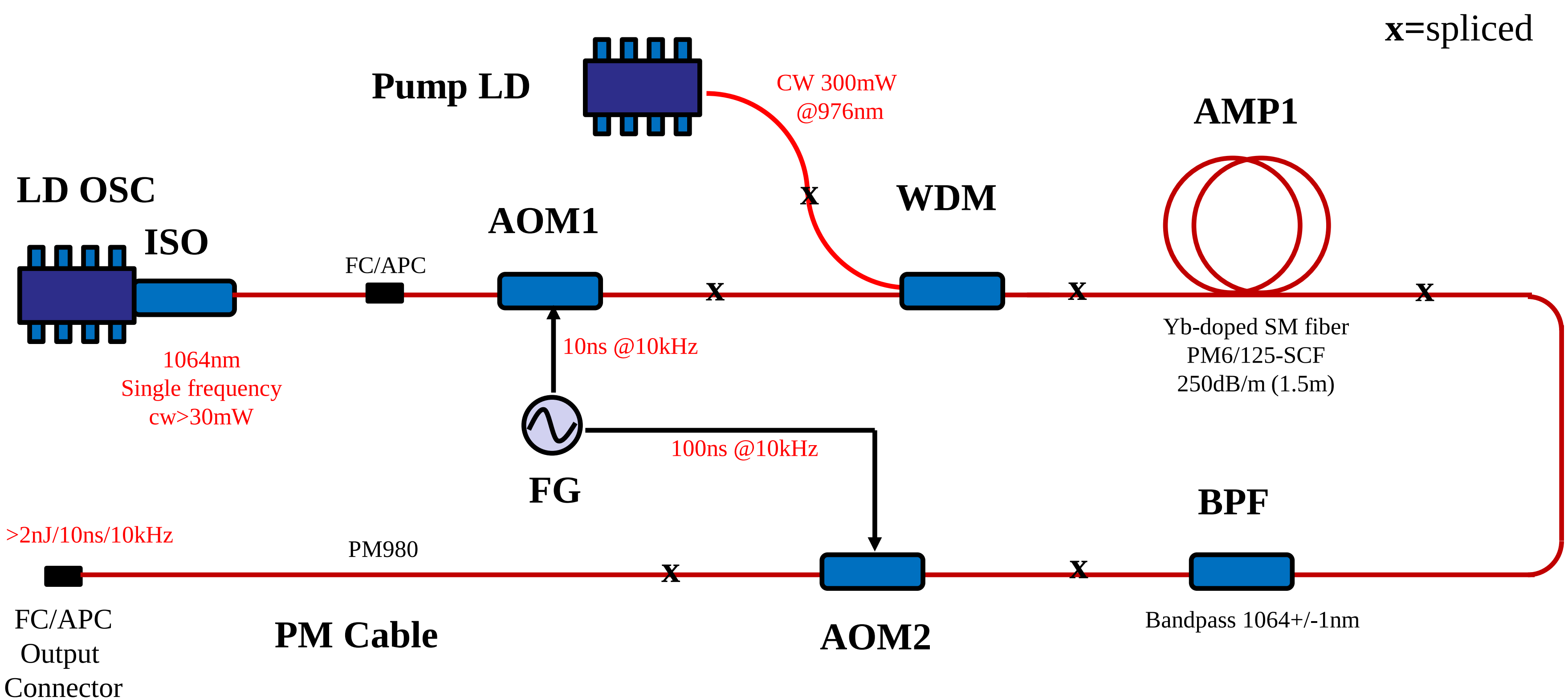


CW Diode Oscillator



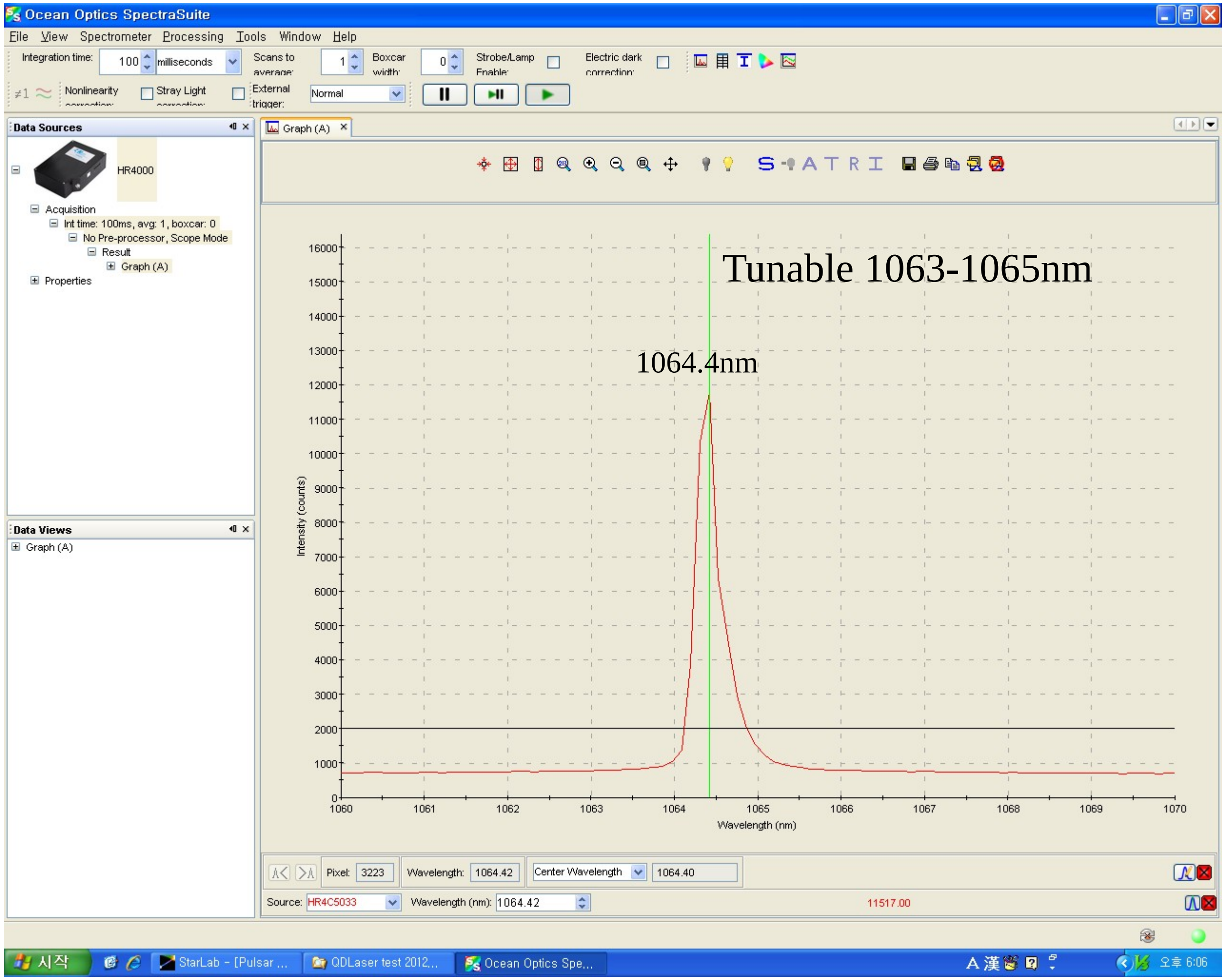
*Arbitrary waveform generator

Pulsed Master OSC

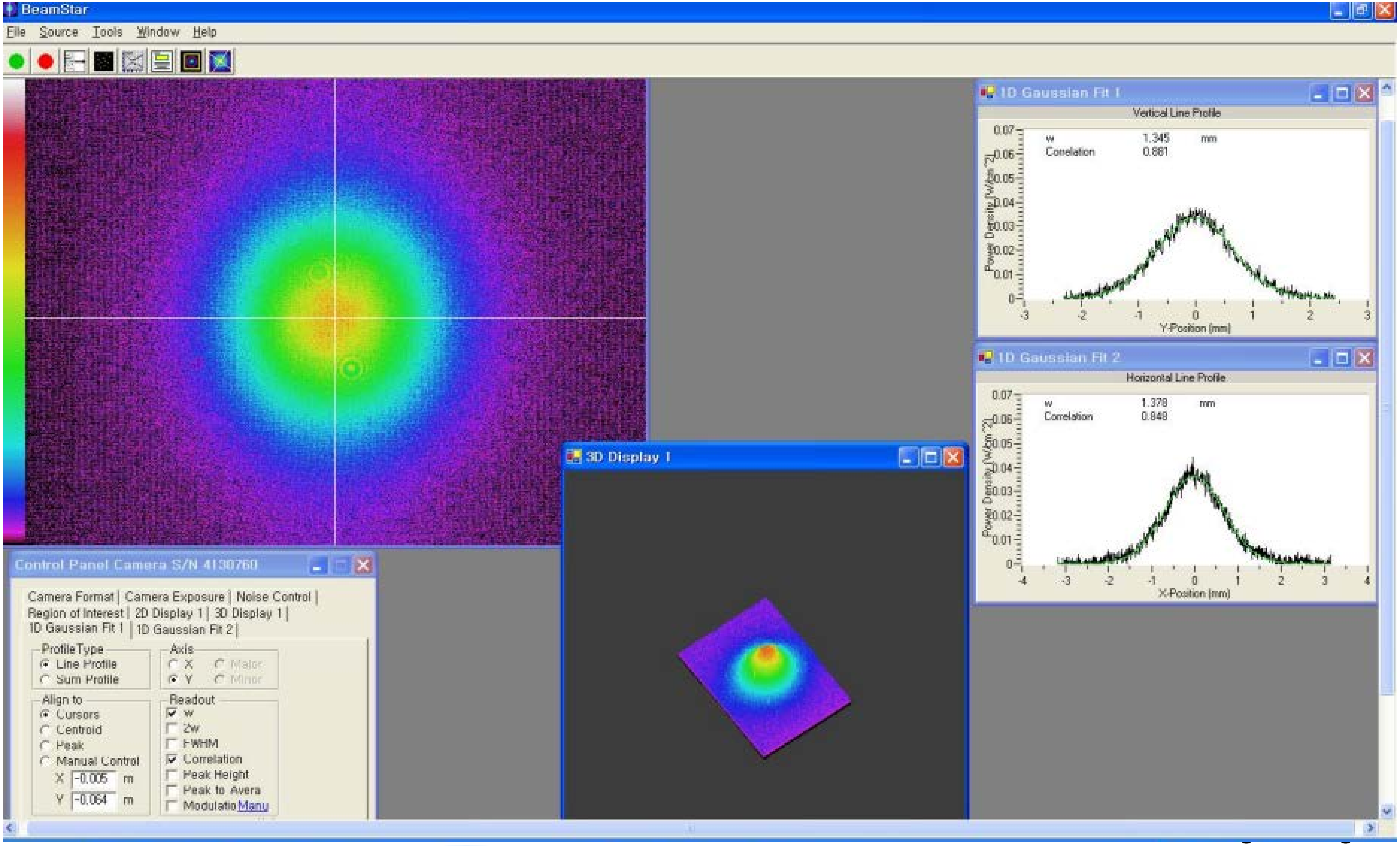


****AOM1-Pulse modulation, AOM2-CW reduction**

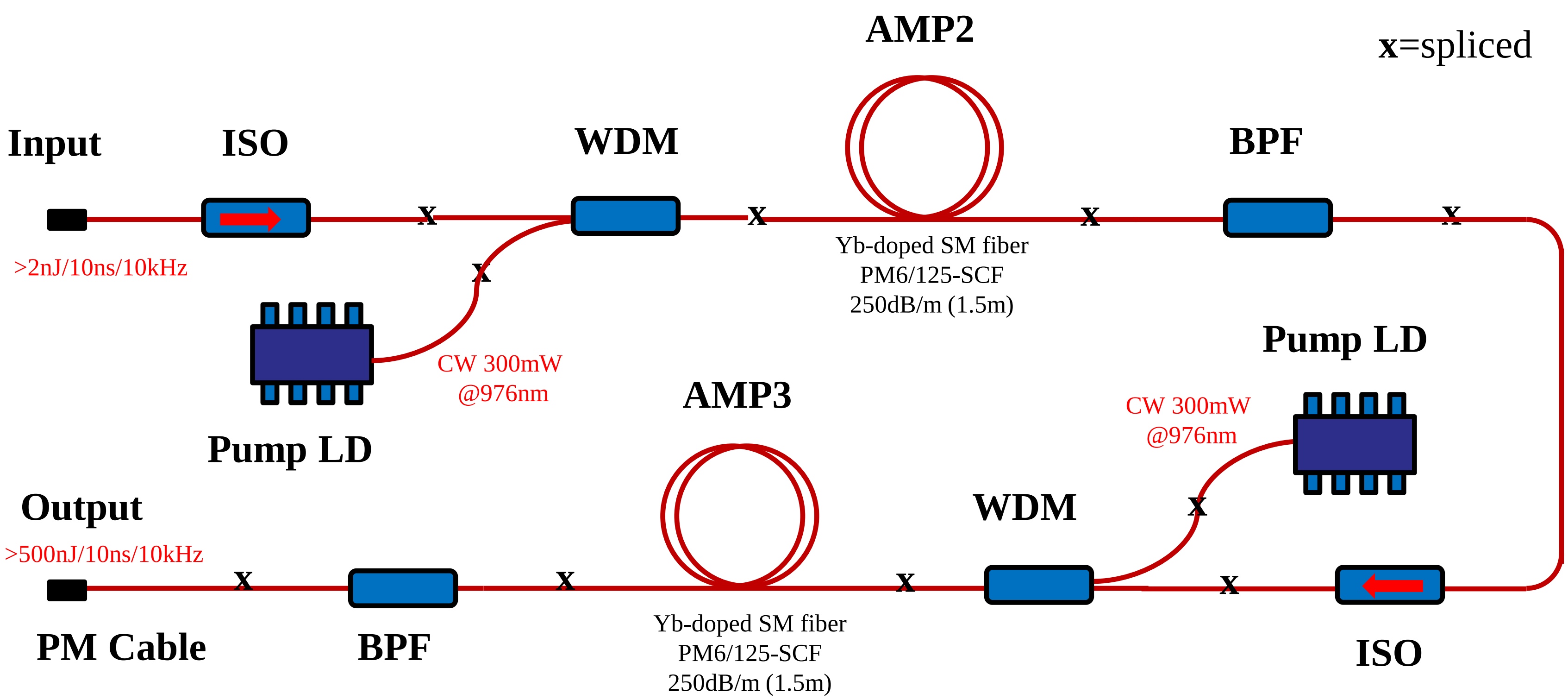
Pulsed Master OSC



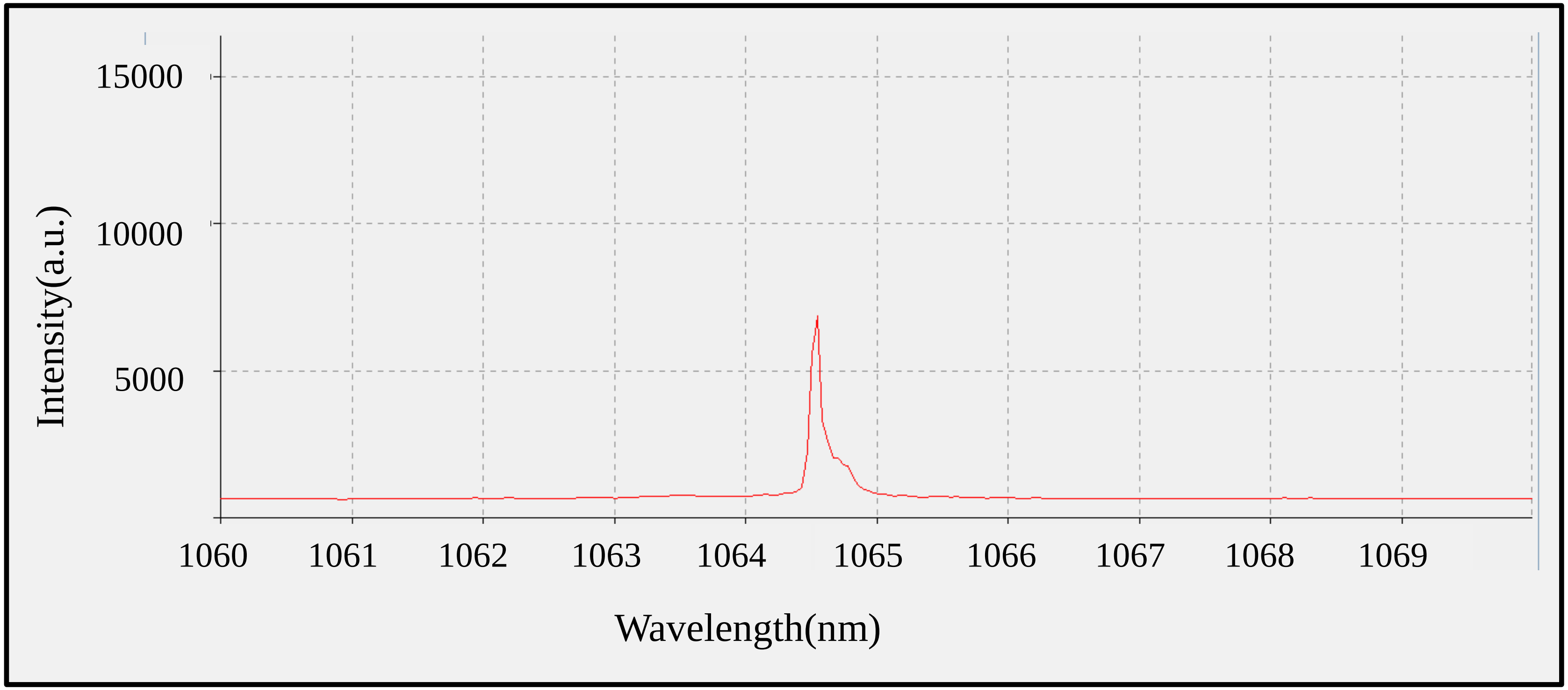
Pulsed Master OSC



Fiber Pre Amp

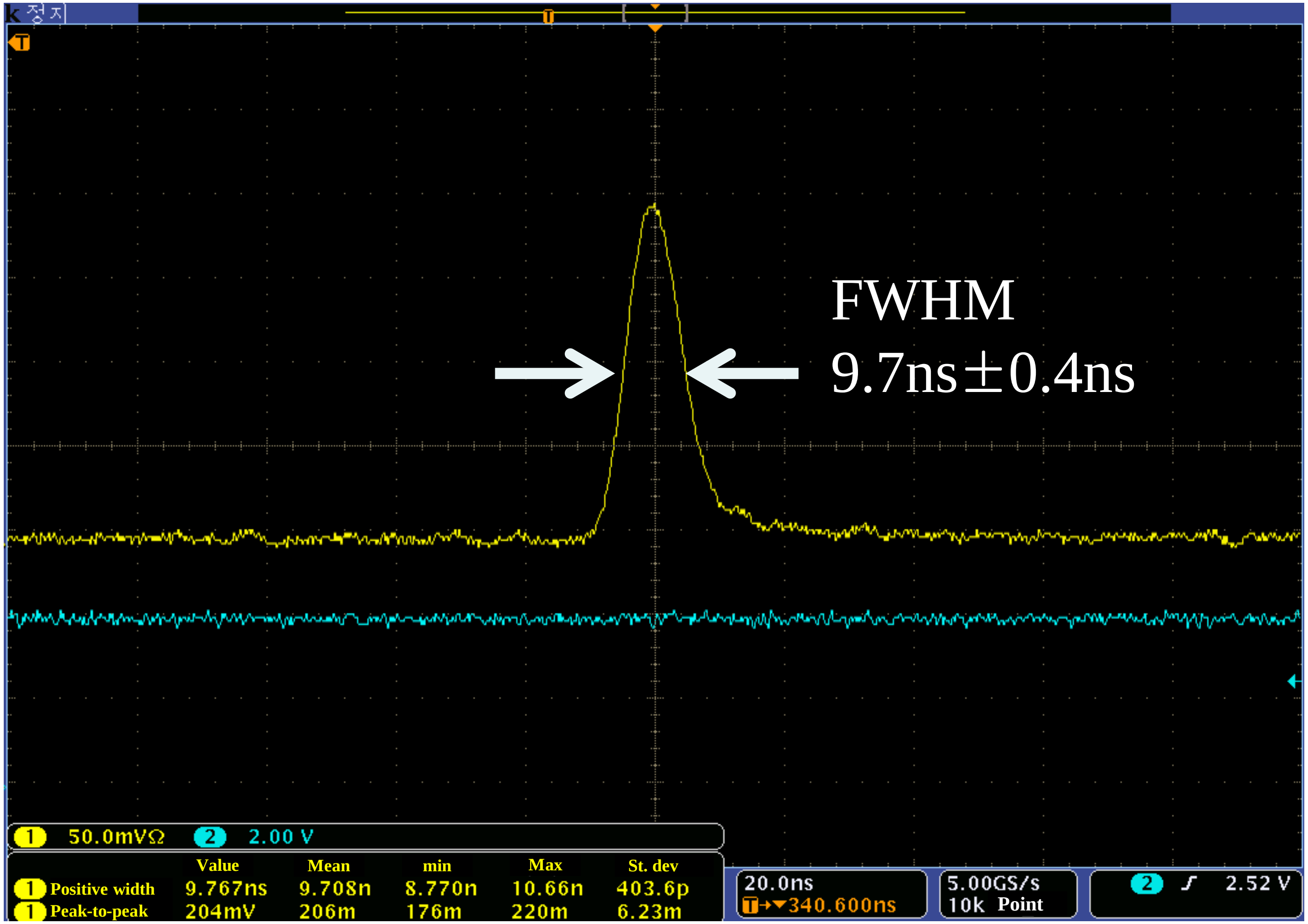


Output beam spectrum @10kHz

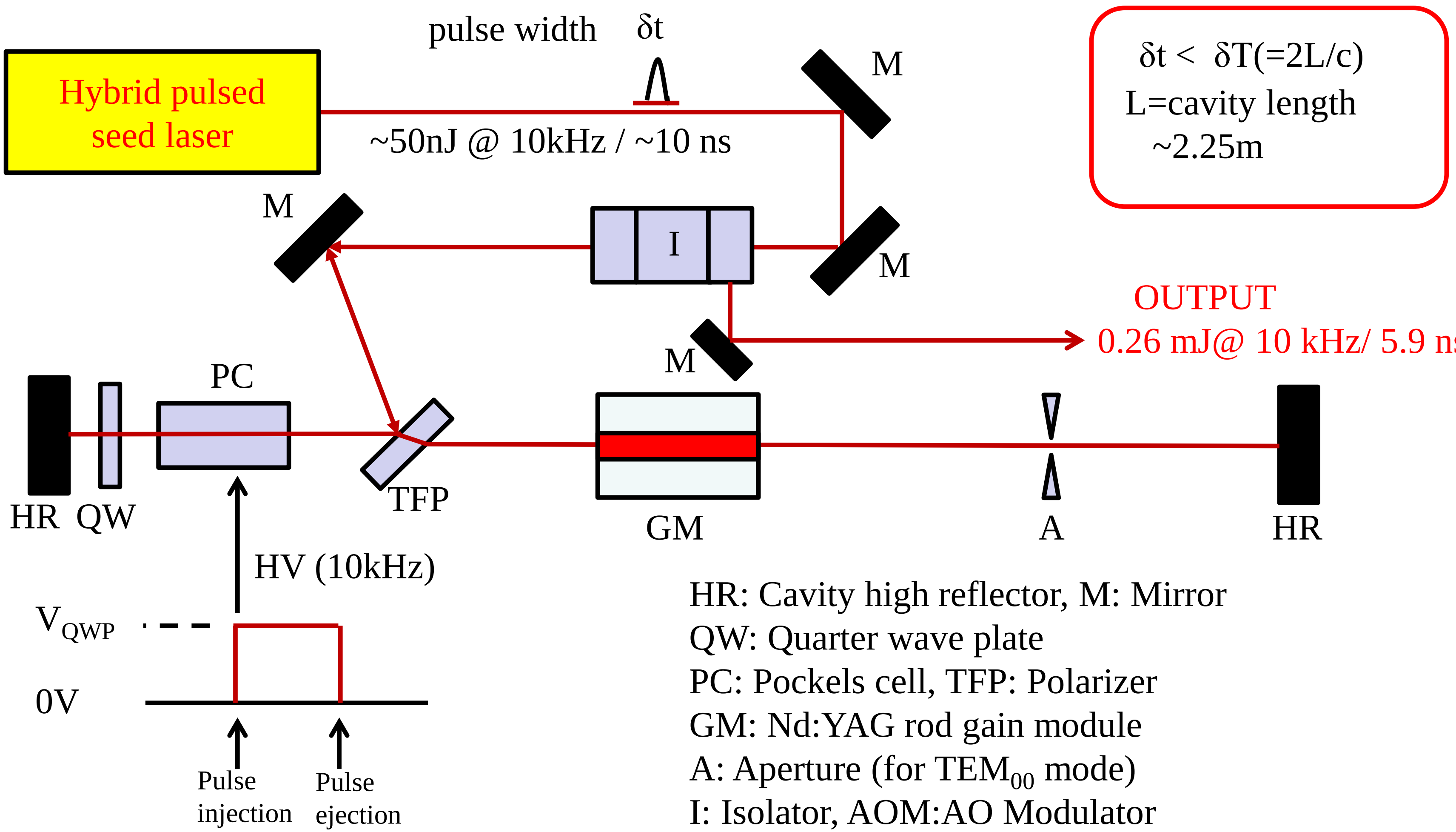


Central wavelength= 1064.6nm

Output pulse shape @ 10kHz

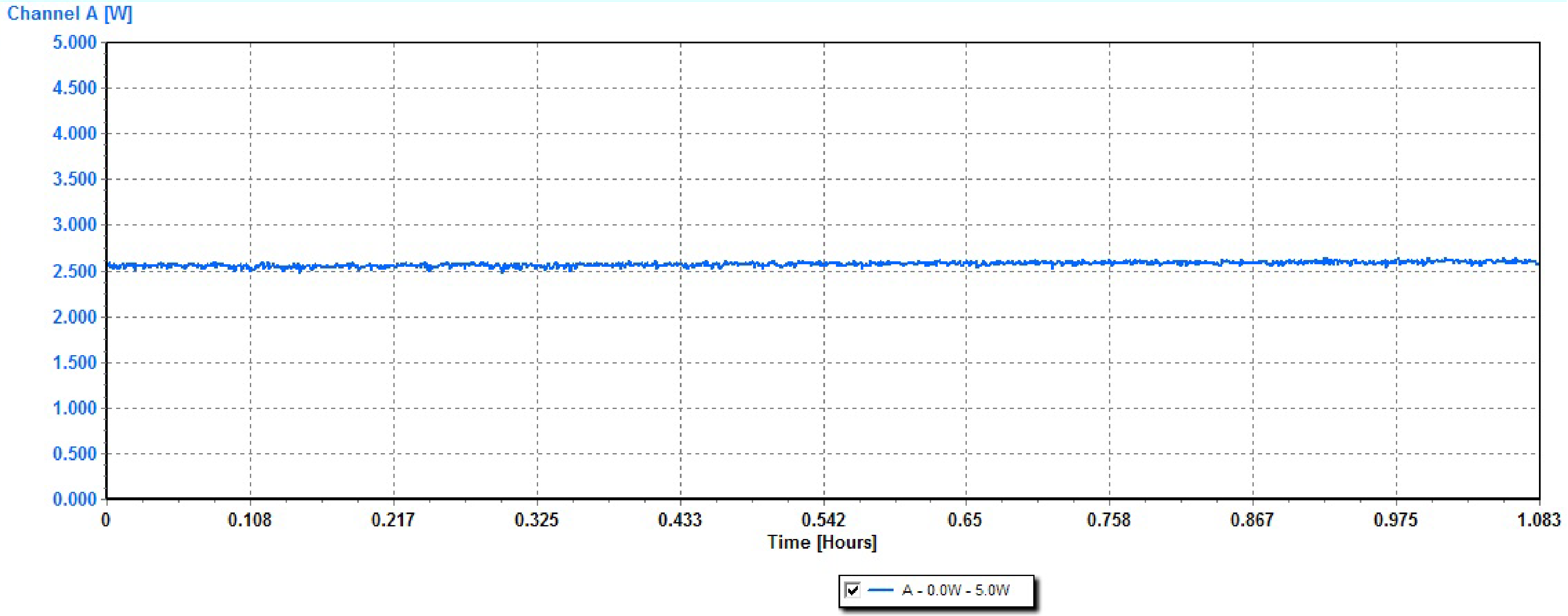


10kHz Regenerative Amplification



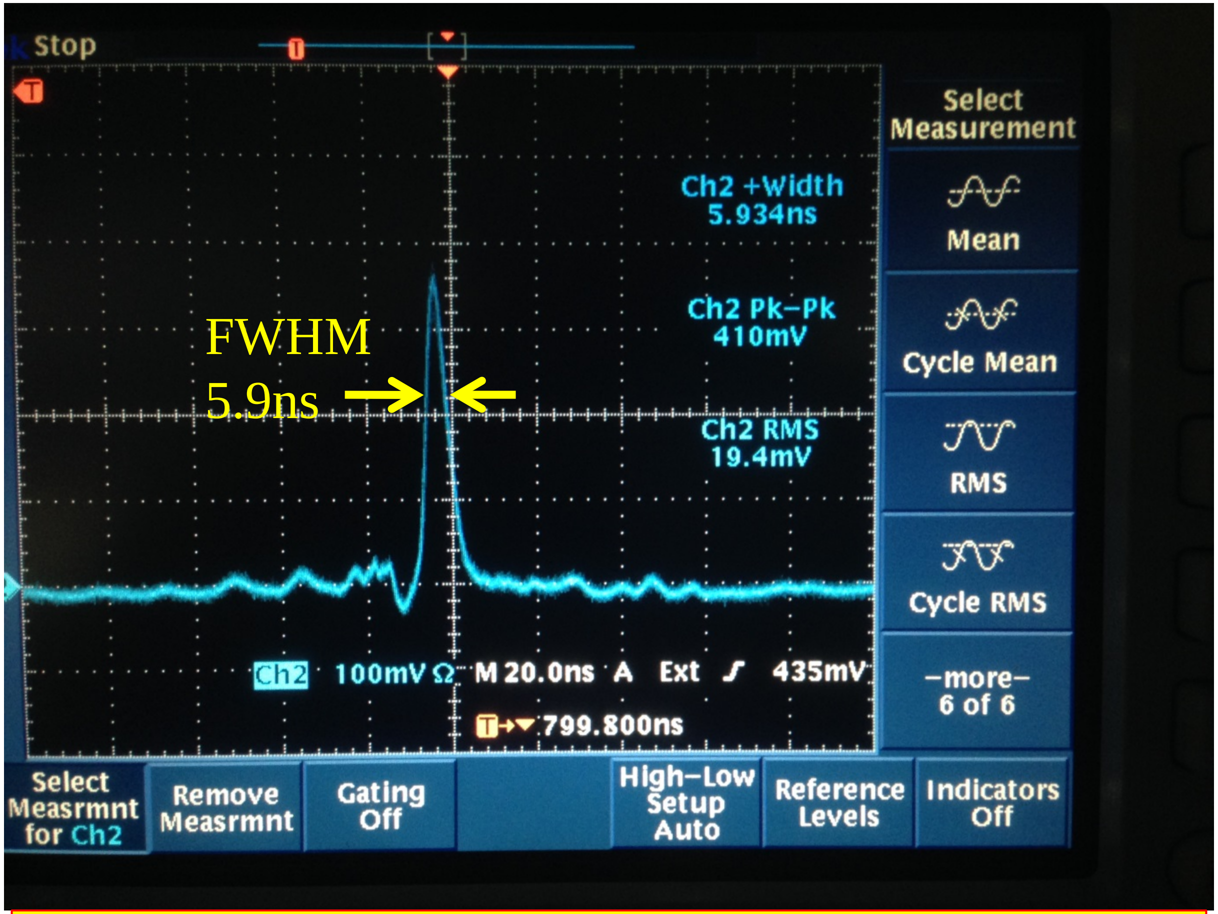
HR: Cavity high reflector, M: Mirror
QW: Quarter wave plate
PC: Pockels cell, TFP: Polarizer
GM: Nd:YAG rod gain module
A: Aperture (for TEM_{00} mode)
I: Isolator, AOM:AO Modulator

Output power stability after regenerative amplification



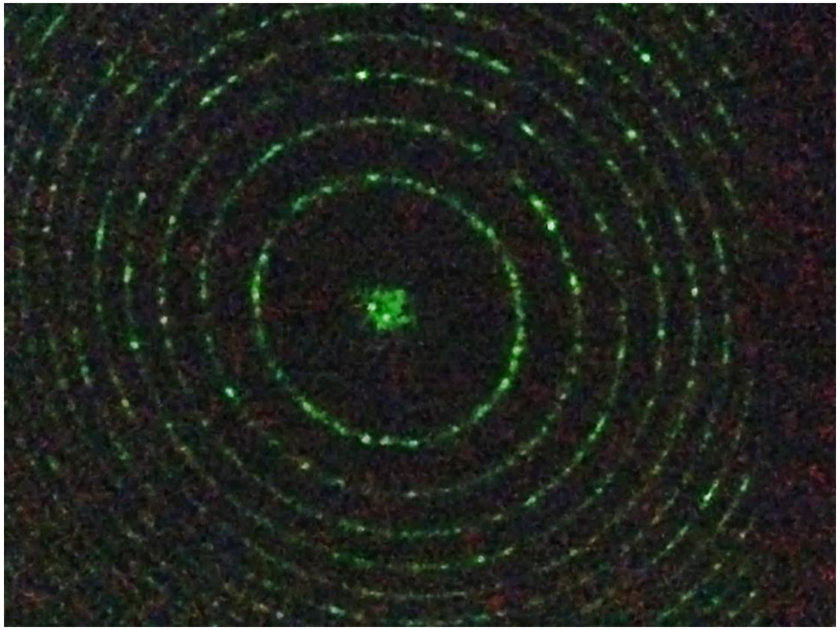
Output power P_{out} = 2.576 W ± 26.45 mW
(≒1% standard deviation, during 1 hour)

Output beam pulse width



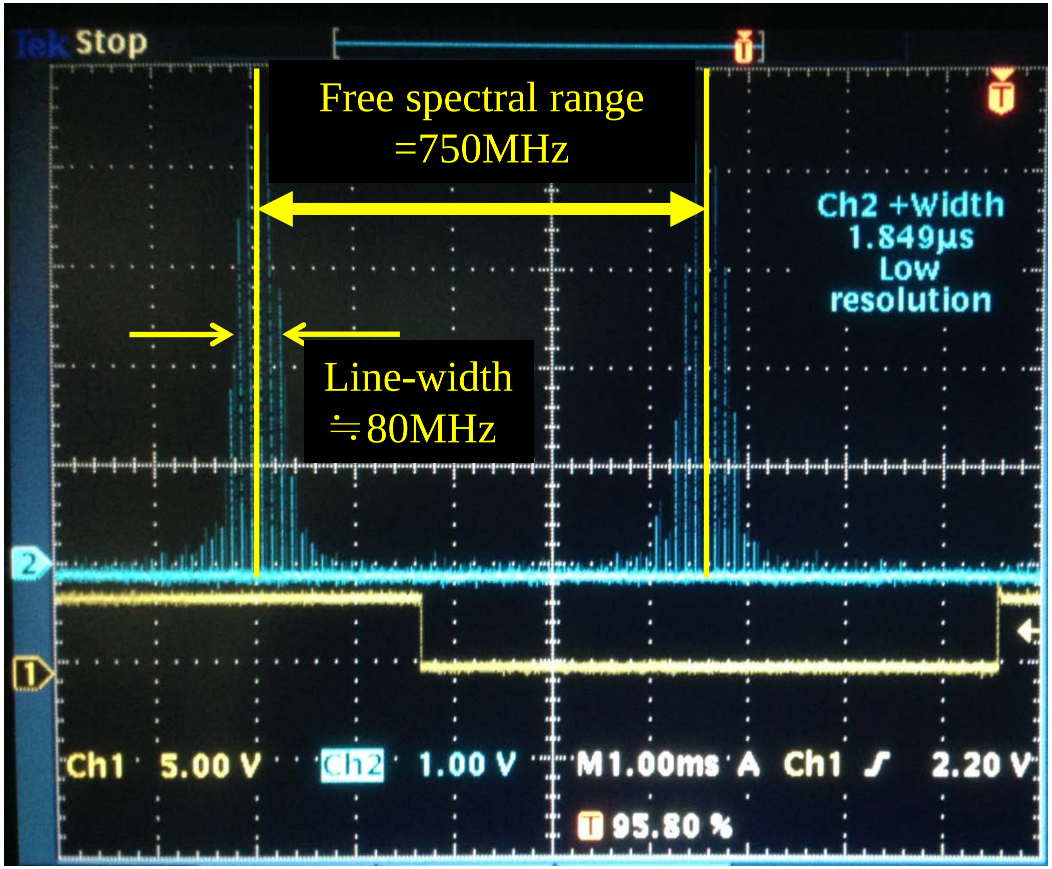
Output beam pulse width ≒ 5.9 ns

Output beam interferogram using Fabry-Perot interferometry



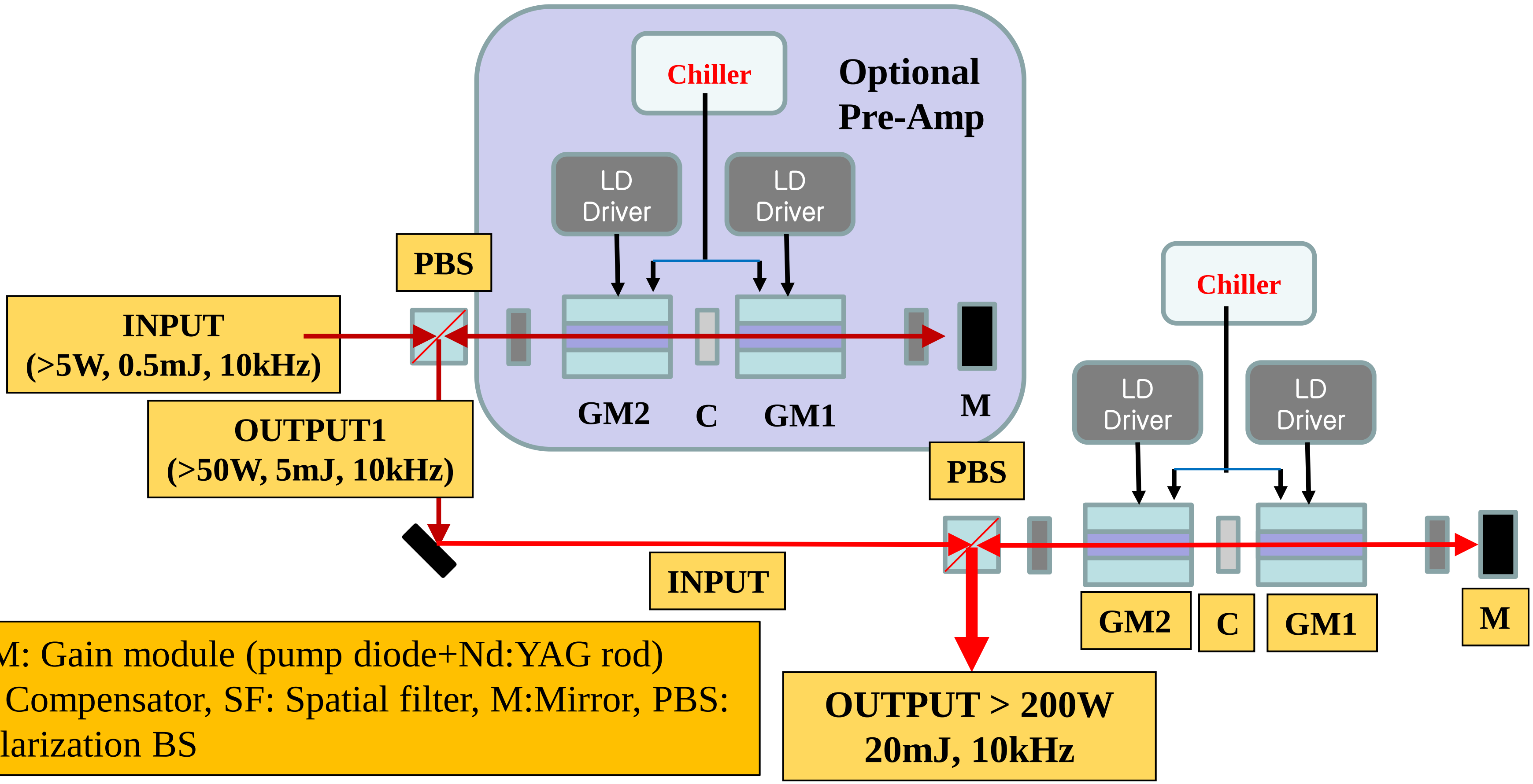
- There's no sub-fringes between the fringes
  - At the multi-mode operation, sub-fringes are shown between the fringes
- Therefore, the output beam is considered as single mode

Output beam line-width measured by scanning Fabry-Perot interferometry



Output beam line-width≒80MHz

Rod Pre-Amp Module



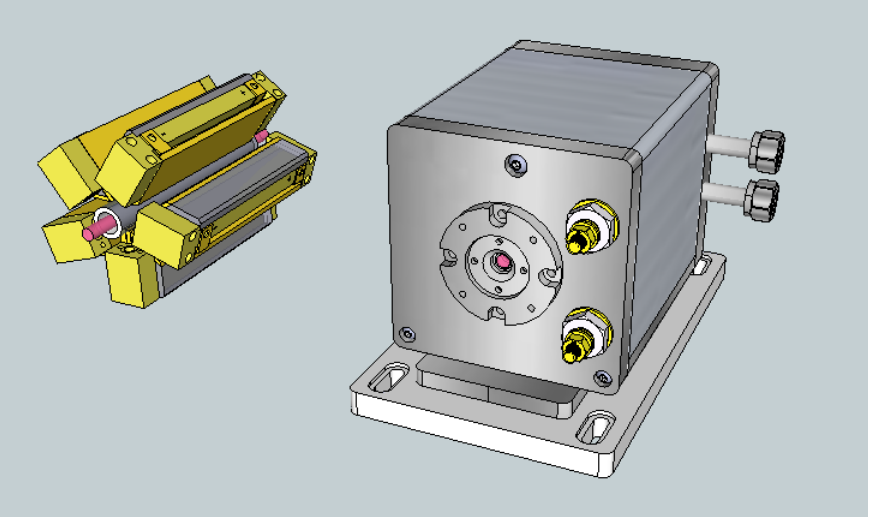
GM: Gain module (pump diode+Nd:YAG rod)
C: Compensator, SF: Spatial filter, M:Mirror, PBS: Polarization BS

2 or 4 xGM Two Pass Pre-amplifier

Gain Module: Design

HiWatt-Series GM4.5 Gain Module (GM) for Pre-AMP

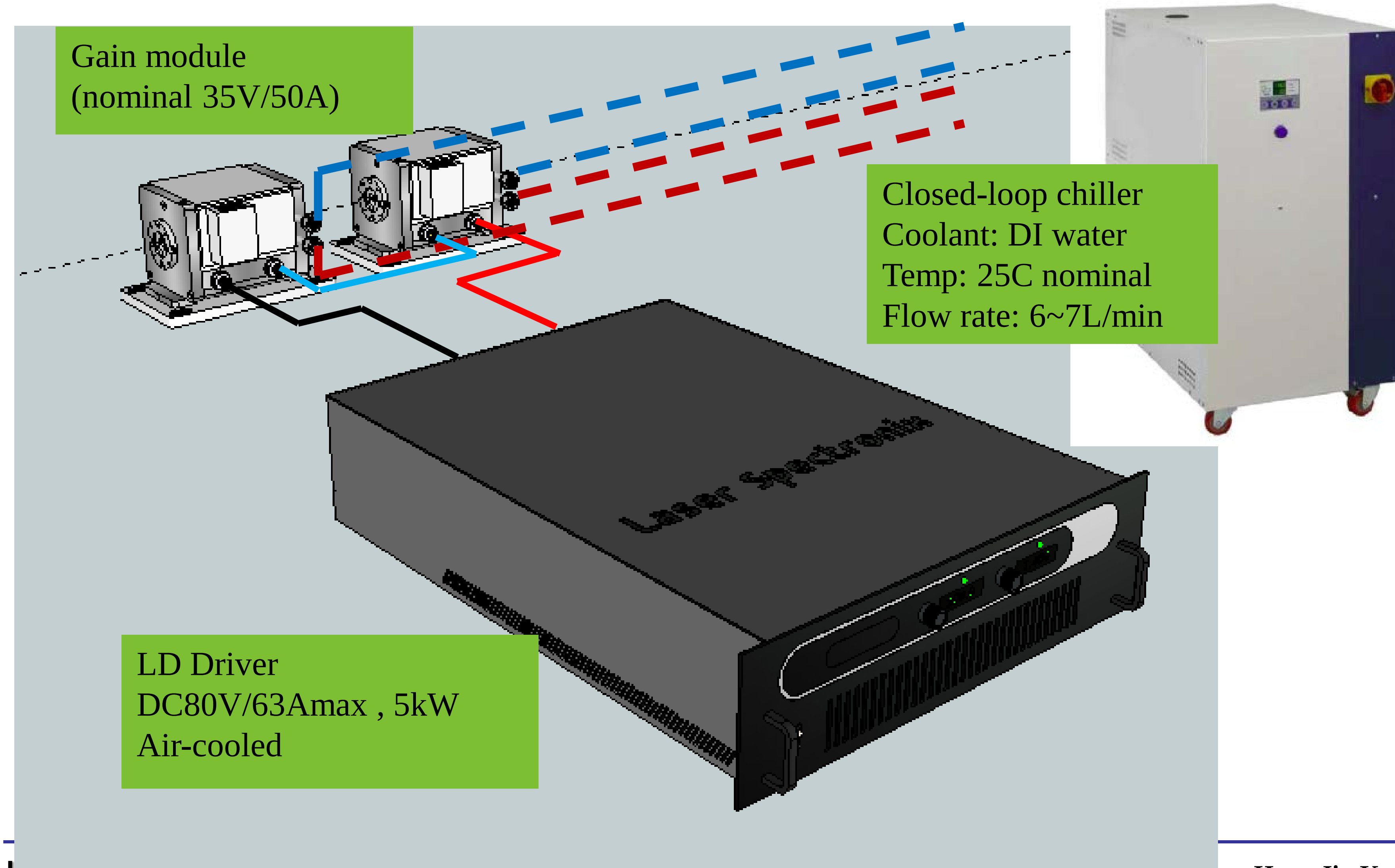
- Wavelength 1064nm
- Nd:YAG rod- ϕ4.5mm x 96mm
- CW diode-stack side-pumped
- Pump power 1kW max @808nm
- CW output power>350W*
- DI water-cooled, flow 7L/min
- Single LD driver of 5kW drives two GMs in series



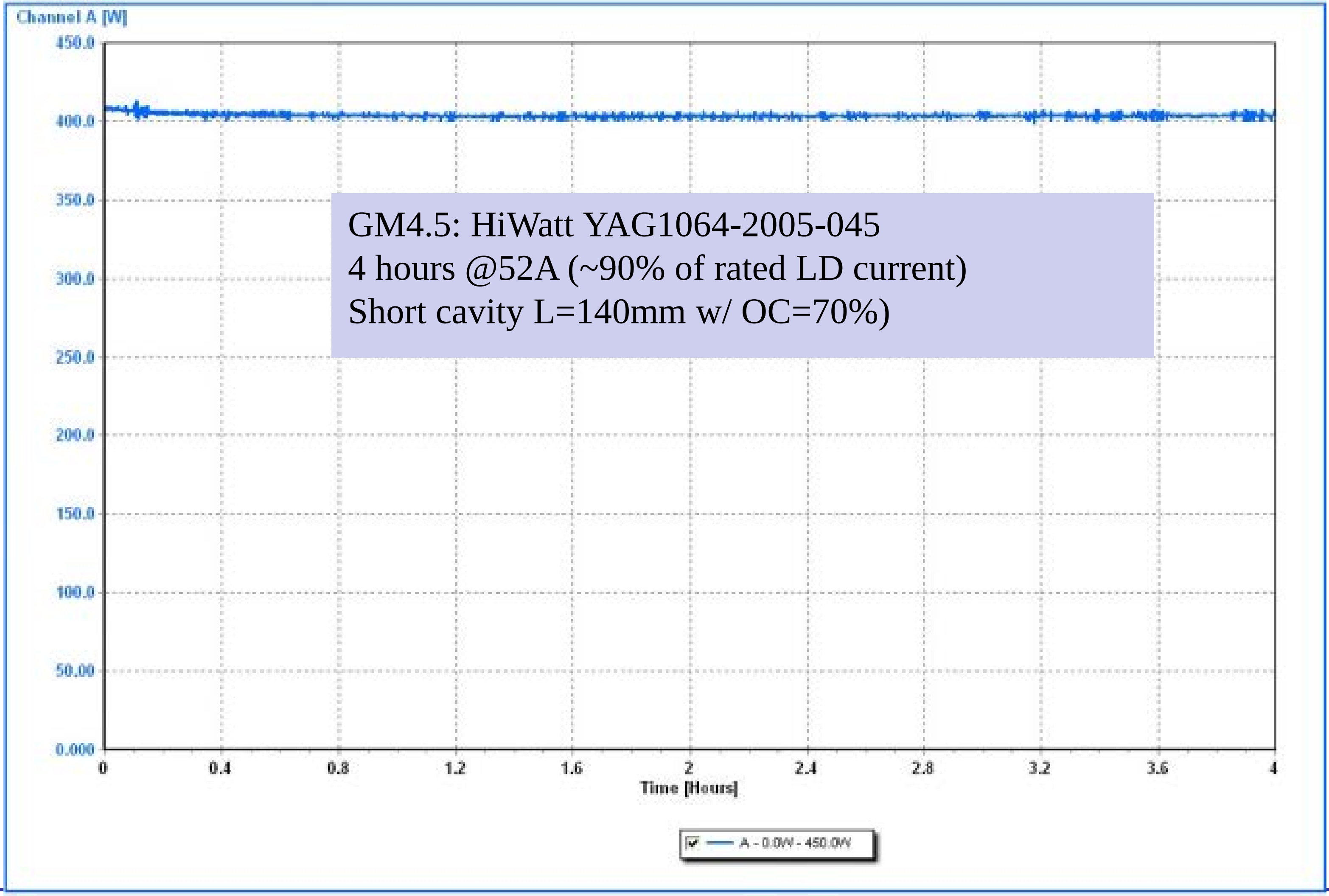
GM4.5 @1064nm	Nd:YAG Rod	Pump LD (max Power)	CW Output*
HiWatt-YAG1064-2005-045	f4.5mm, 0.6%	200W x 5ea (1kW)	>350W, MM

*short cavity, unpolarized

Gain Module: Drive & Cooling

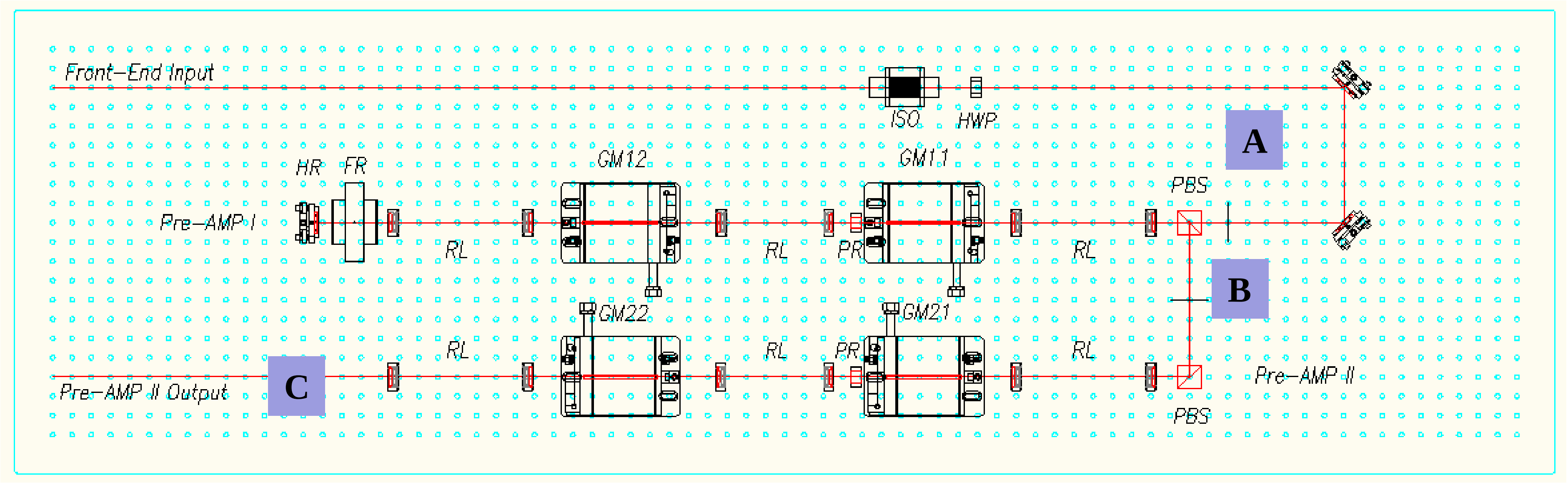


Gain Module: CW Burn-in Test



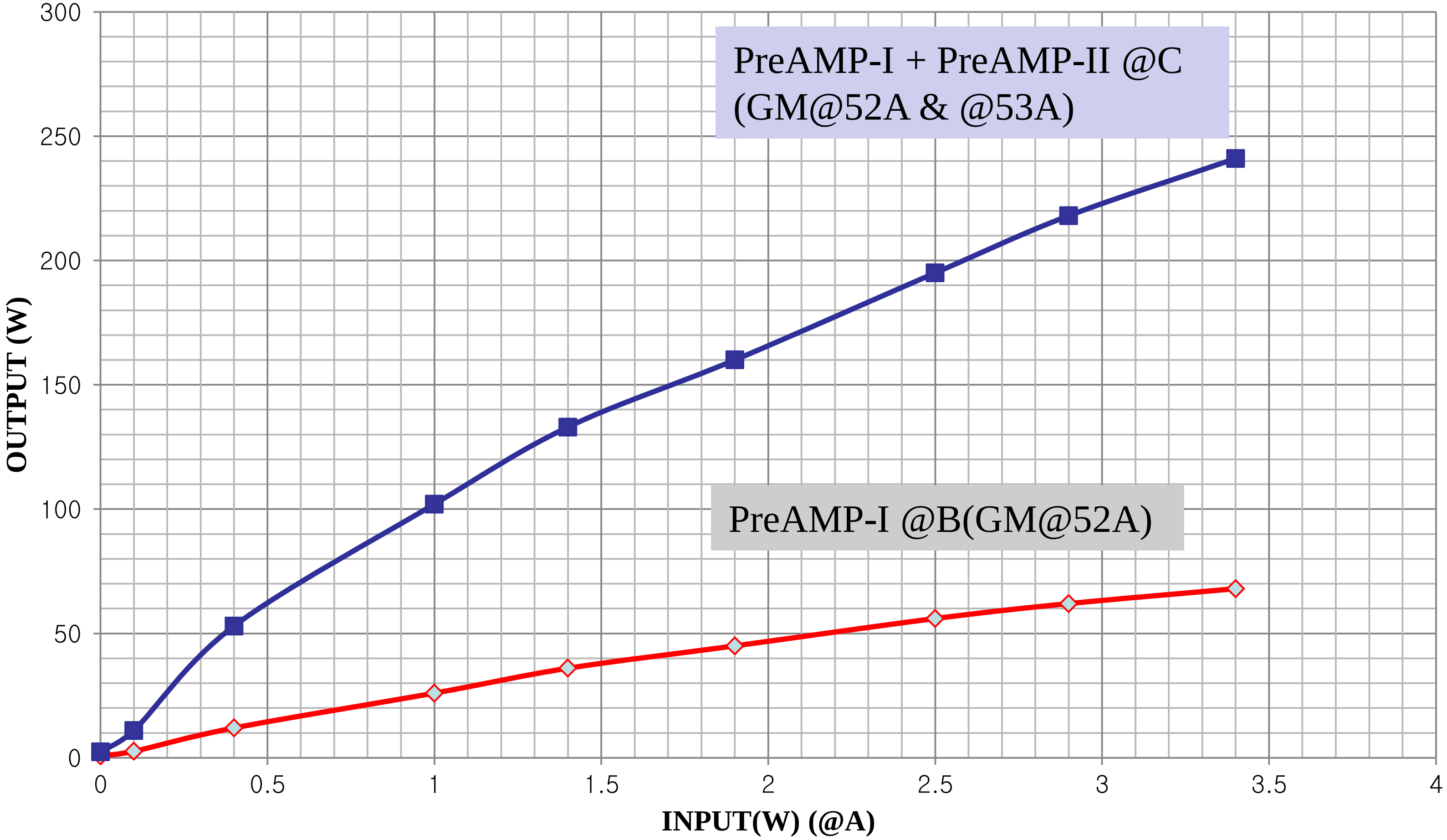
Pre-AMP Configuration

PreAMP-I Double pass + PreAMP-II Single-pass
(thermal lensing and birefringence compensation)

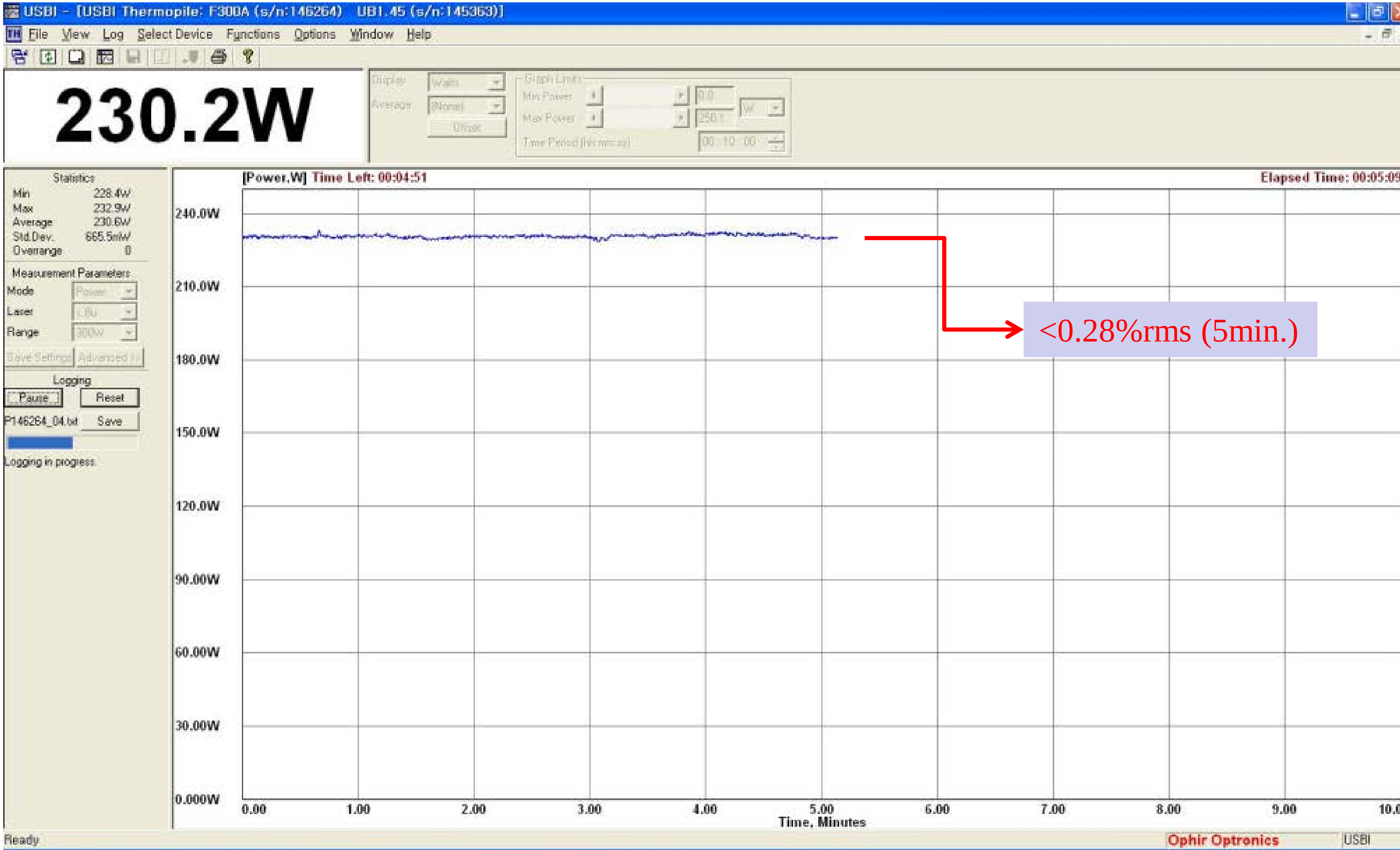


GM1-4: Gain module(GM4.5), RL: Relay image lens, PR: Polarization rotator
FR: Faraday rotator, PBS: Polarization beam splitter, ISO: Isolator
A,B,C: measurement positions

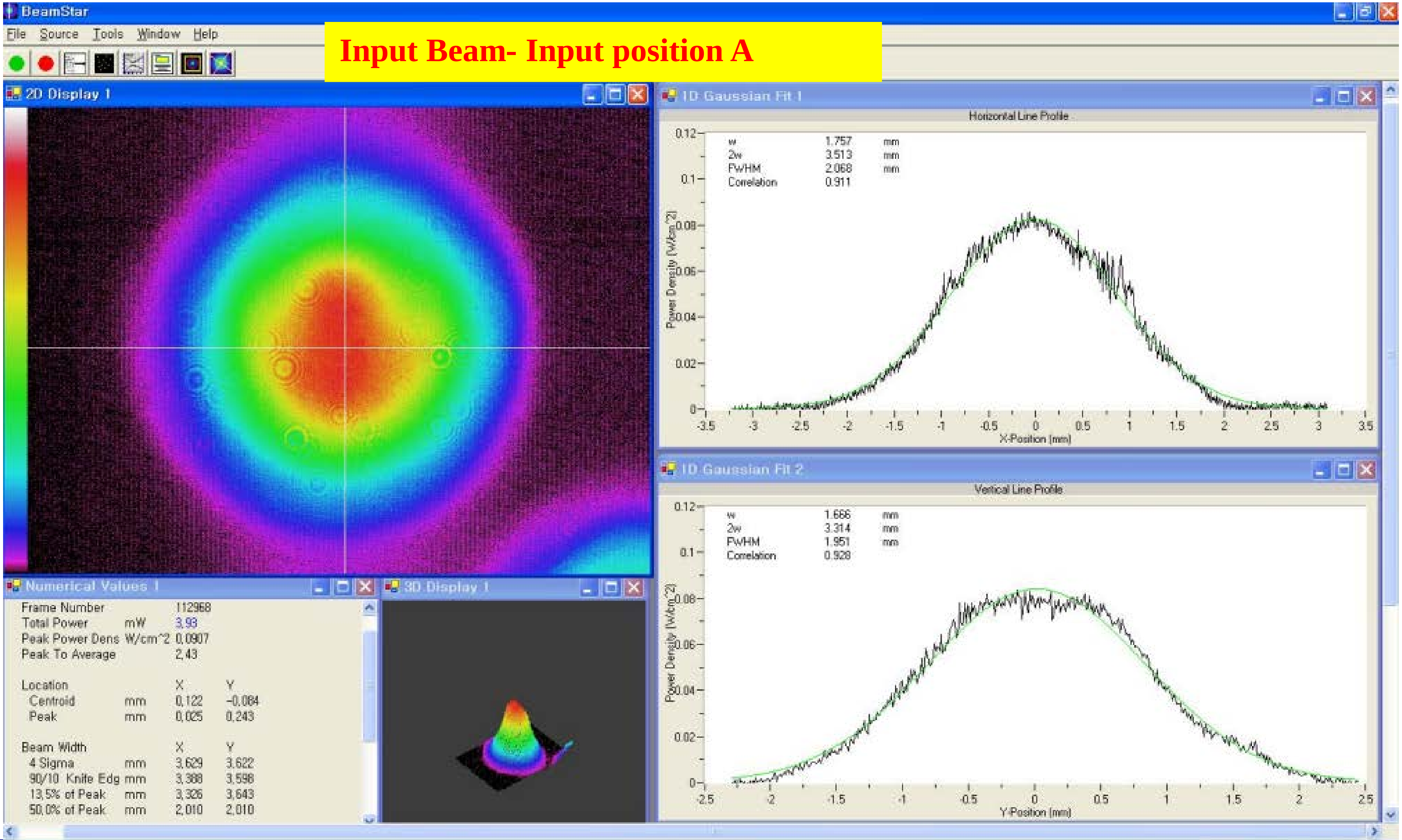
Pre-AMP: Input vs. Output



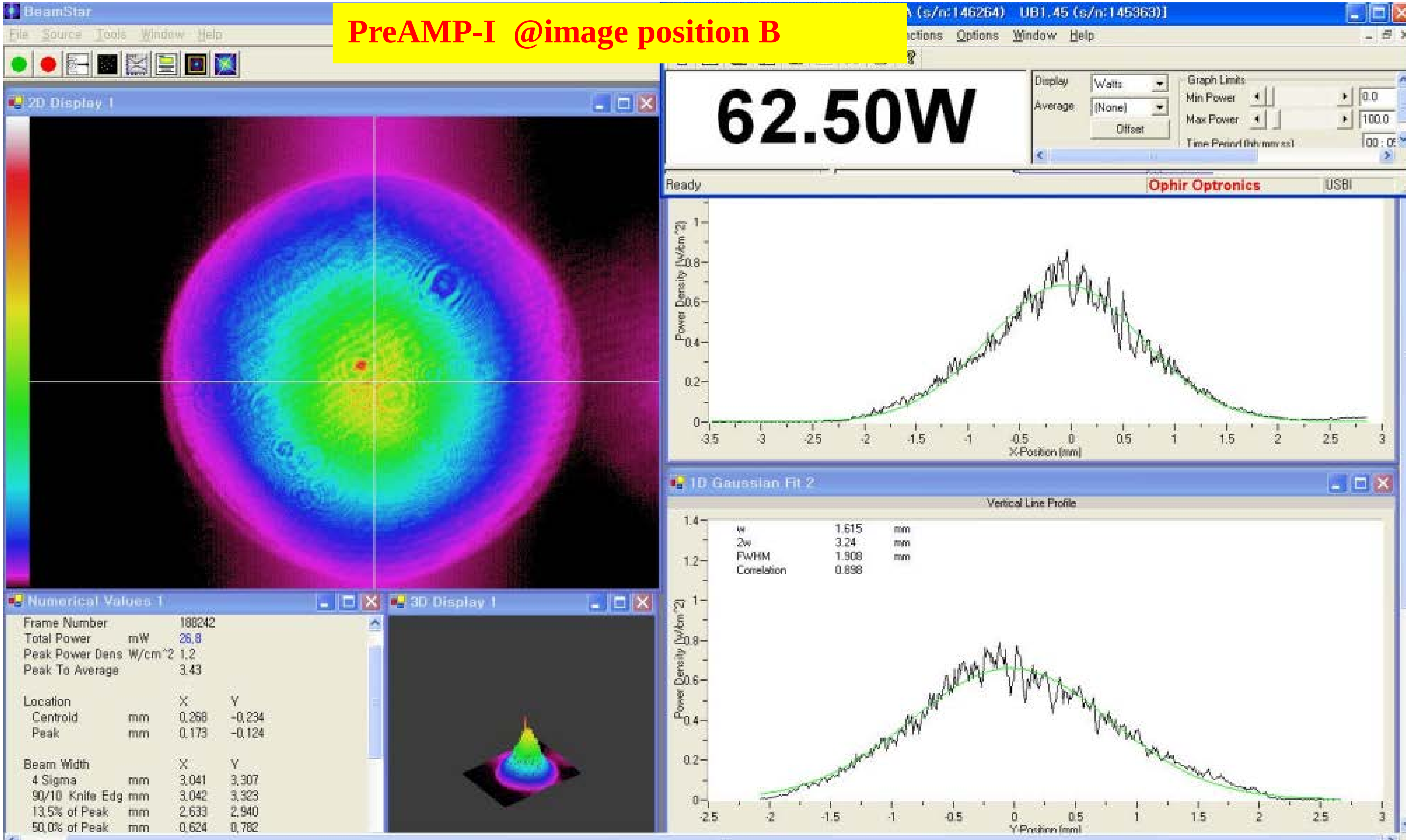
Pre-AMP: Power stability



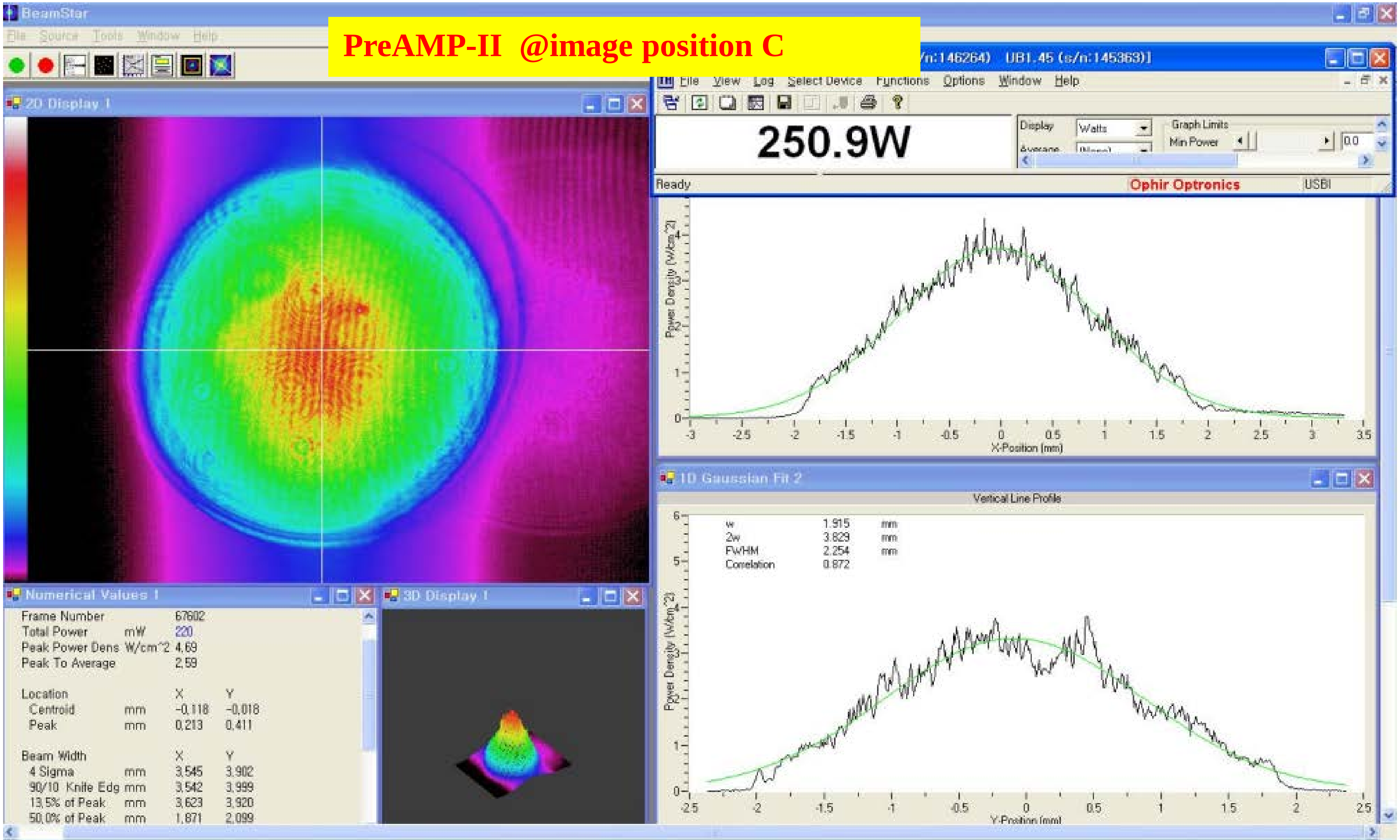
Pre-AMP: Input beam profile



Pre-AMP: Output beam profile

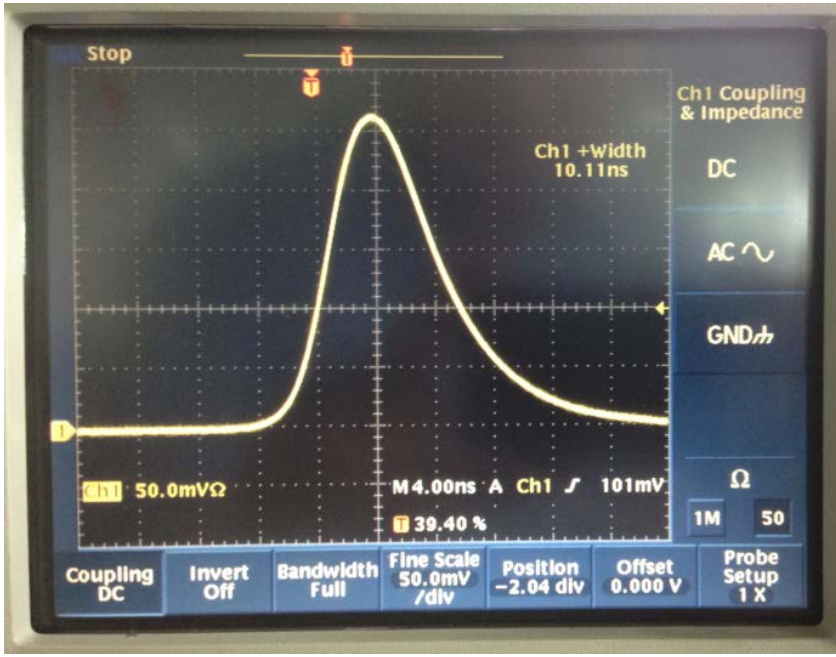


Pre-AMP: Output beam profile

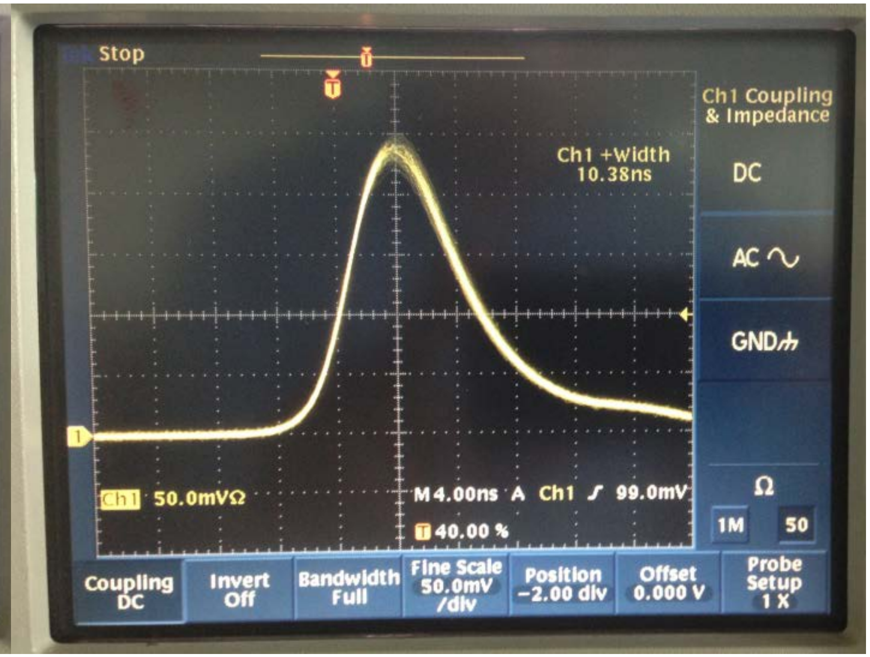


Pre-AMP: Pulse width & profile

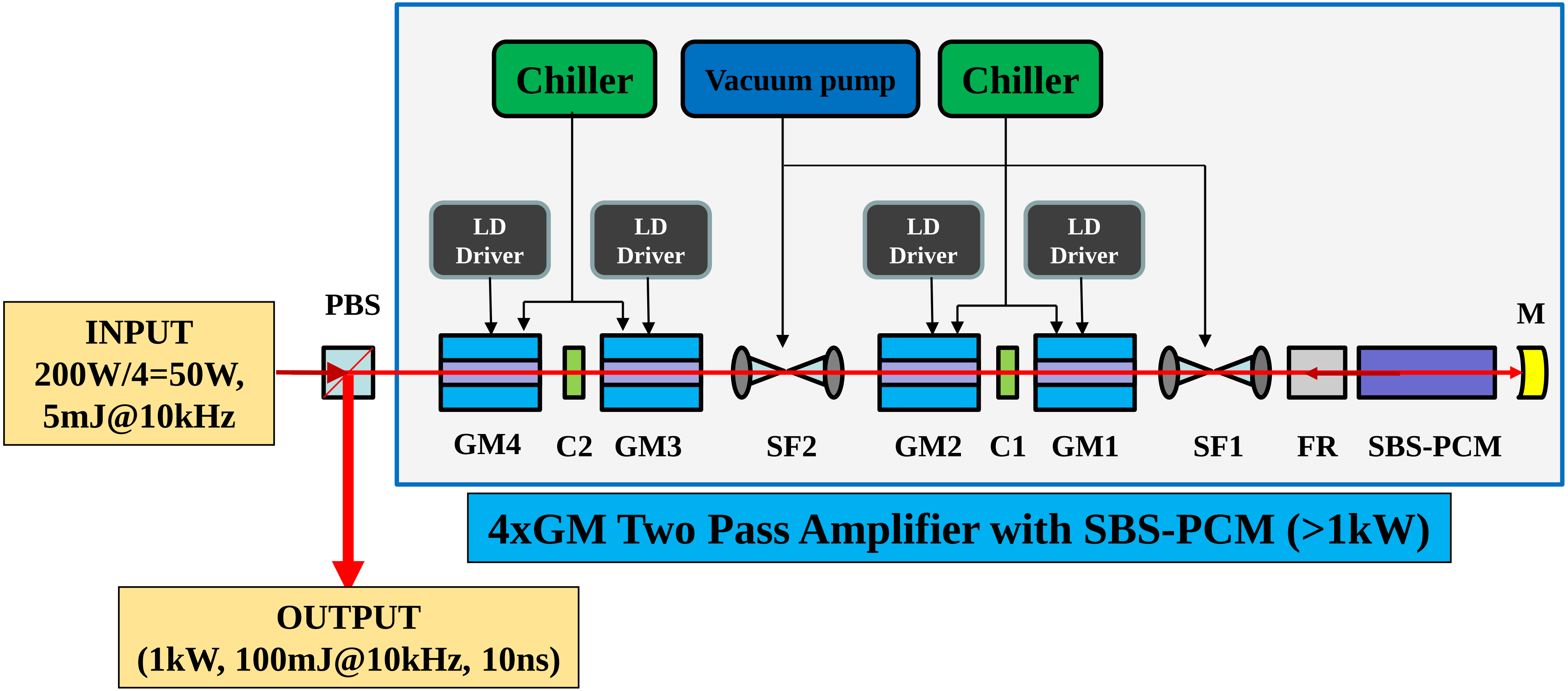
Input pulse (10ns)



Output pulse



Rod Main Amp Module



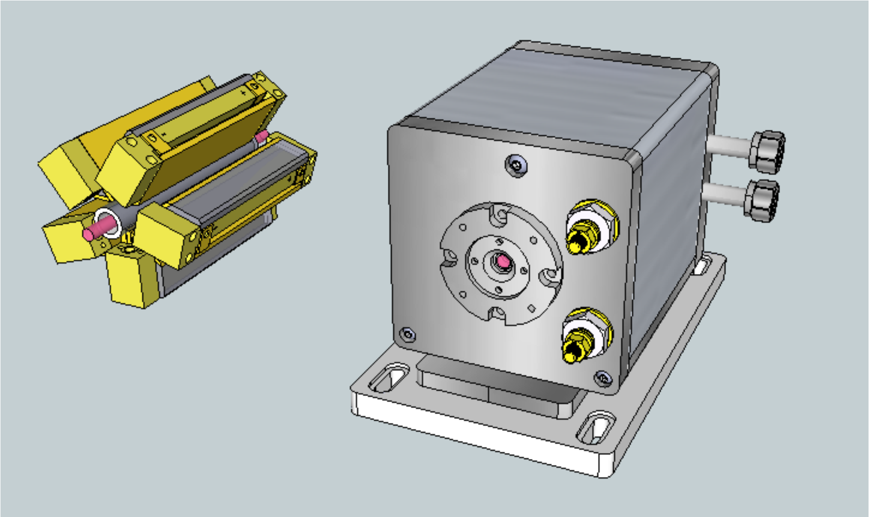
4xGM Two Pass Amplifier with SBS-PCM (>1kW)

GM: Gain module (pump diode + Nd:YAG rod, Gain > 1.5)
C: Compensator, SF : Spatial filter, FR : Faraday rotator
M : Mirror, PBS : Polarization BS (TFP)

Gain Module: Design

HiWatt-Series GM6.3 Gain Module (GM) for Main-AMP

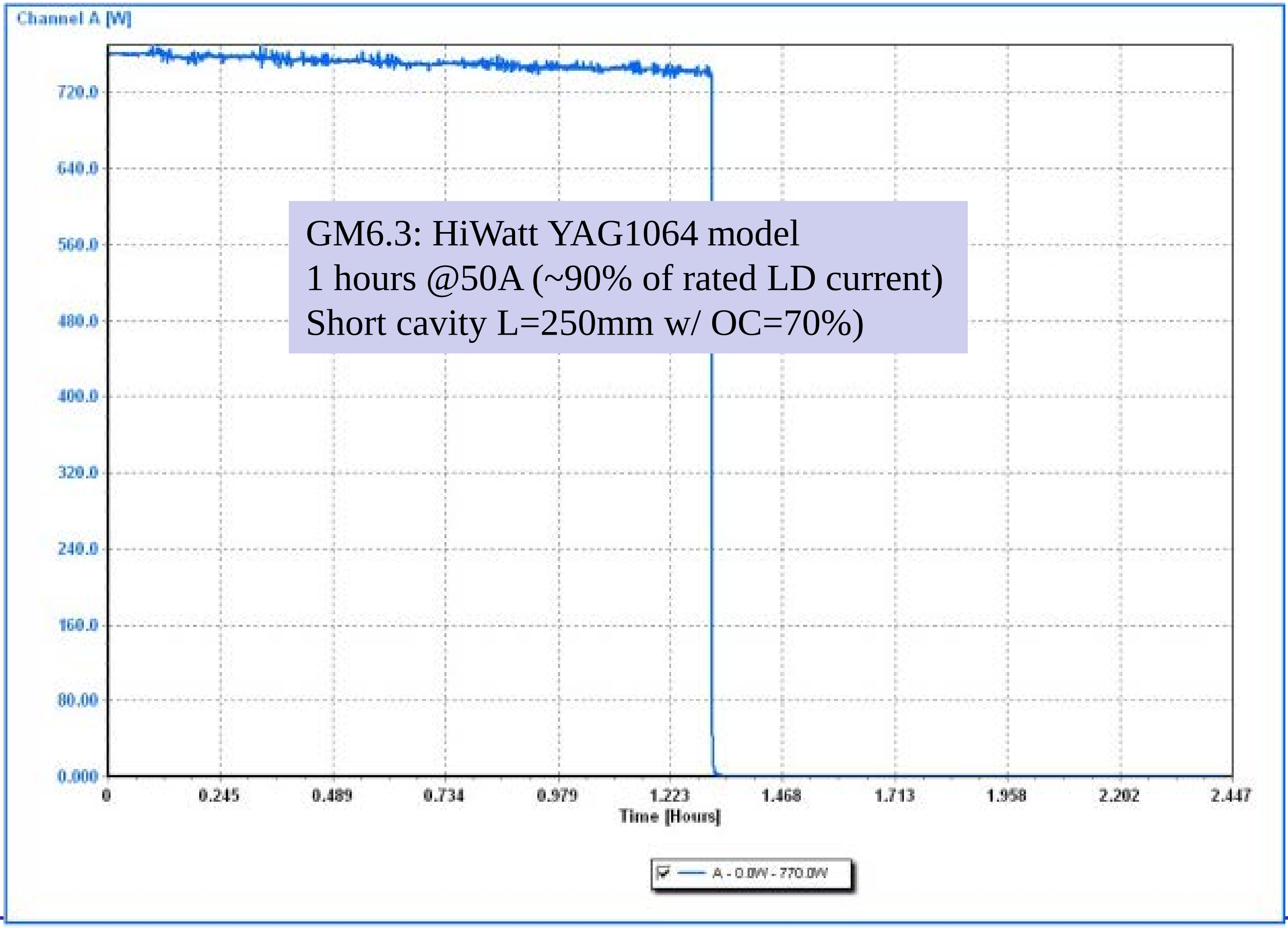
- Wavelength 1064nm
- Nd:YAG rod- ϕ6.3mm x 146mm
- CW diode-stack side-pumped
- Pump power 2kW max @808nm
- CW output power>880W*
- Single LD driver of 5kW drives one GM



GM4.5 @1064nm	Nd:YAG Rod	Pump LD (max Power)	CW Output*
HiWatt-YAG1064-2005-045	ϕ6.3mm, 0.6%	400W x 5ea (2kW)	>880W, MM

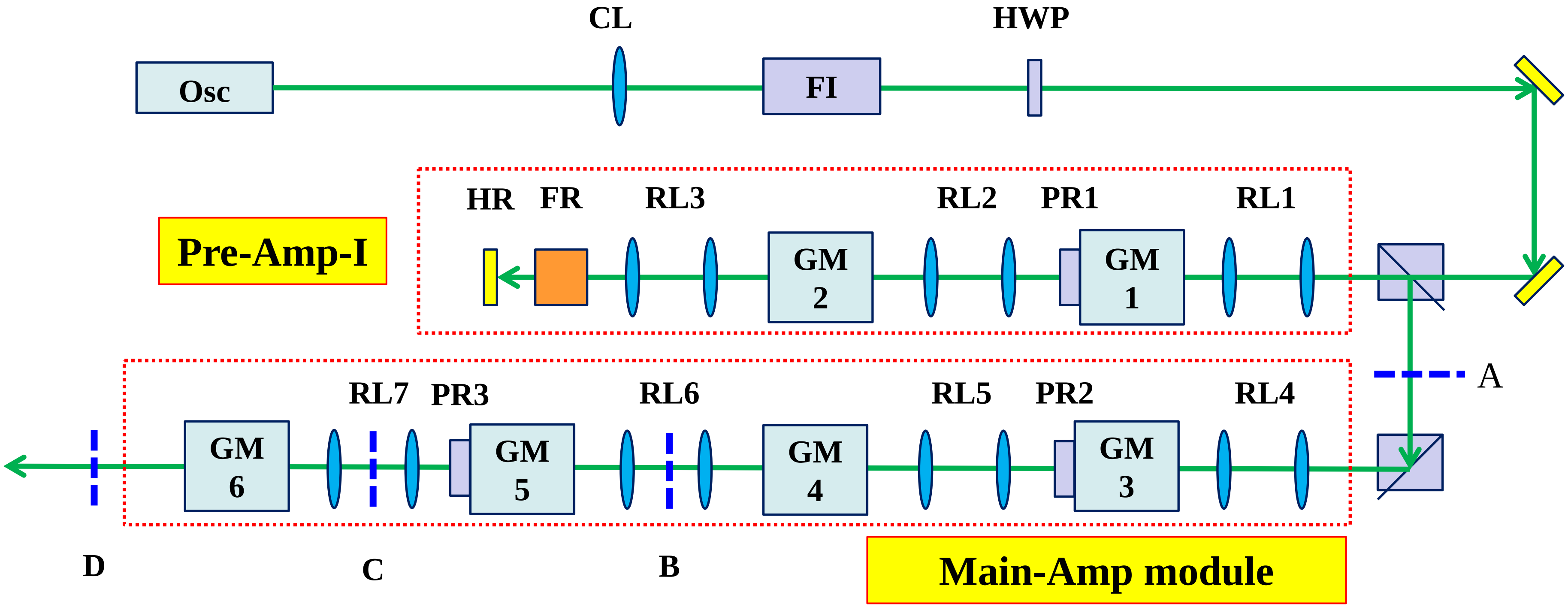
*short cavity, unpolarized

Gain Module: CW Burn-in Test



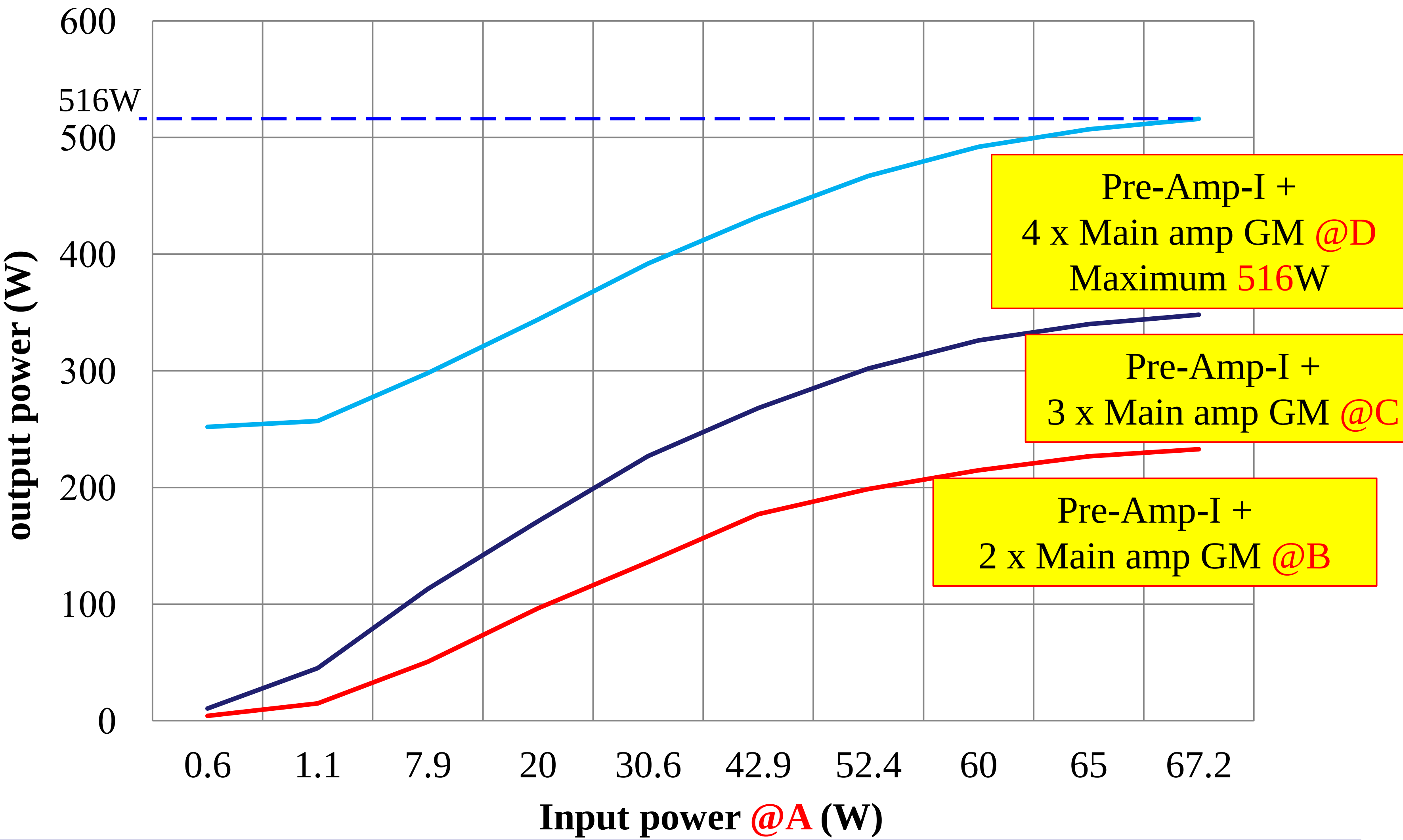
Main-AMP test (single pass) : configuration

Pre-Amp-I Double pass + Main-Amp Single pass

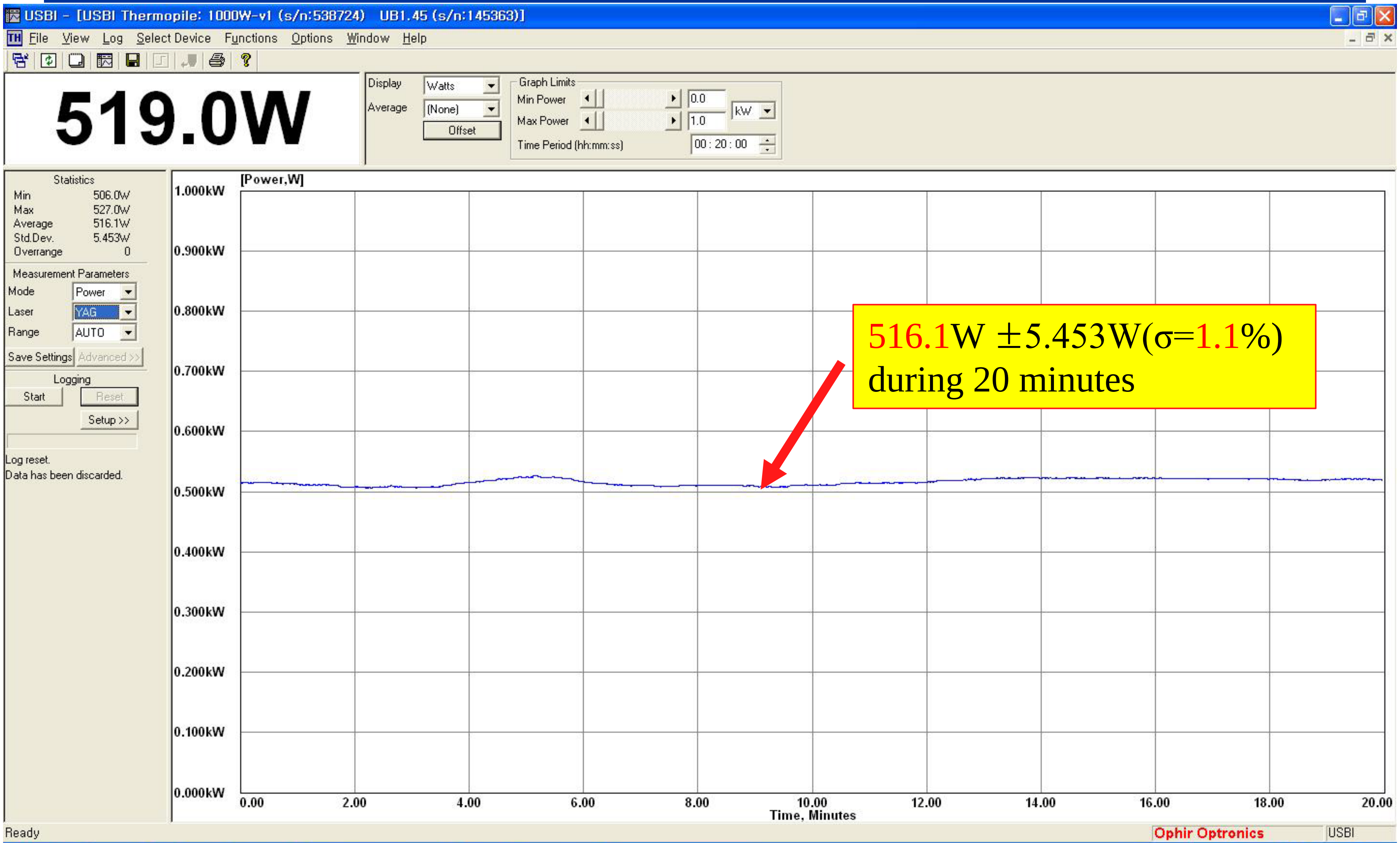


CL, collimation lens,	FI, Faraday isolator,	HWP, half wave plate,
RL1~7, Relay image lenses,	GM1~6, Gain module,	PR1~3, Polarization rotator
FR, Faraday rotator,	HR, high reflector,	A~D, measurement point

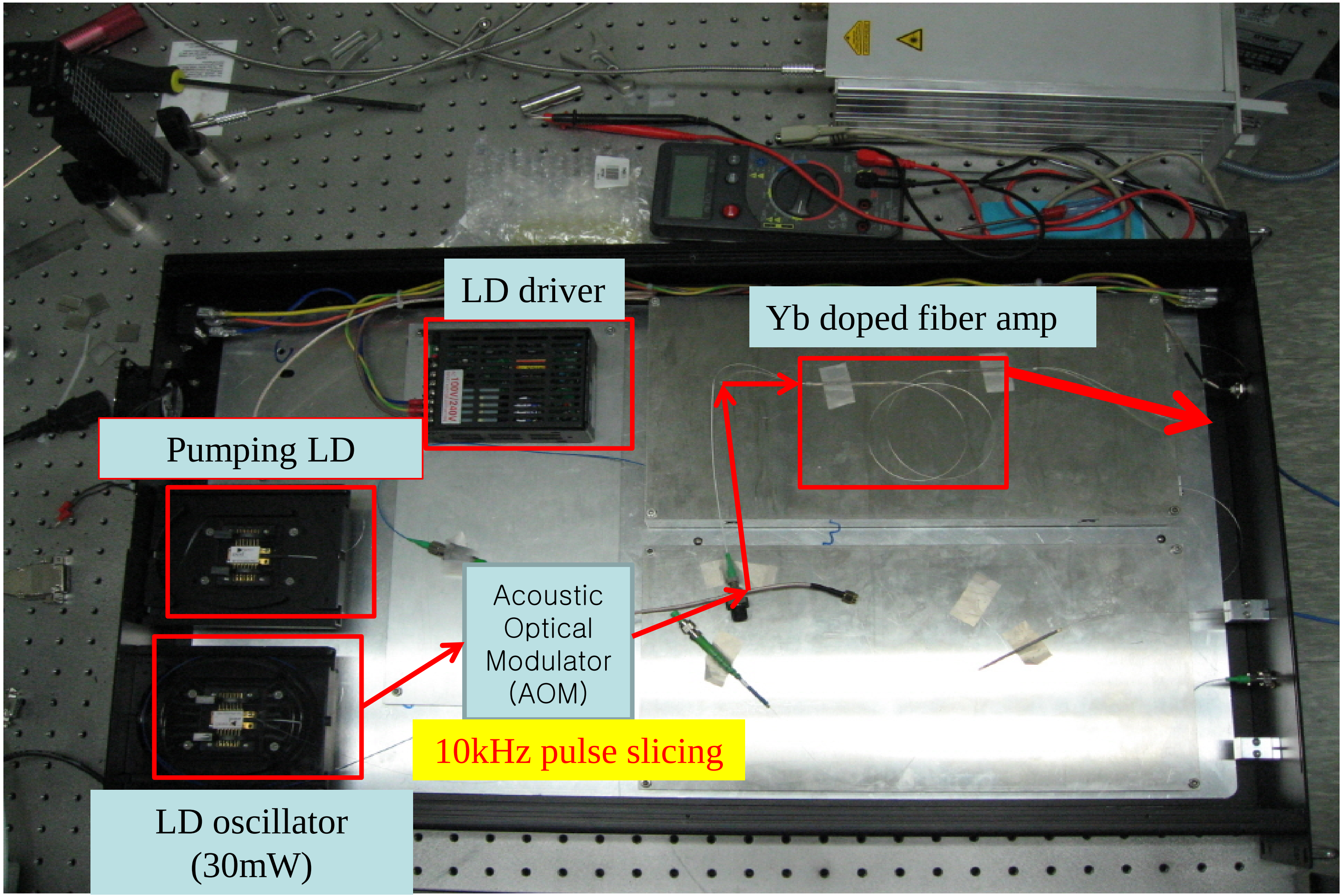
Main-AMP (single pass): Input vs. Output



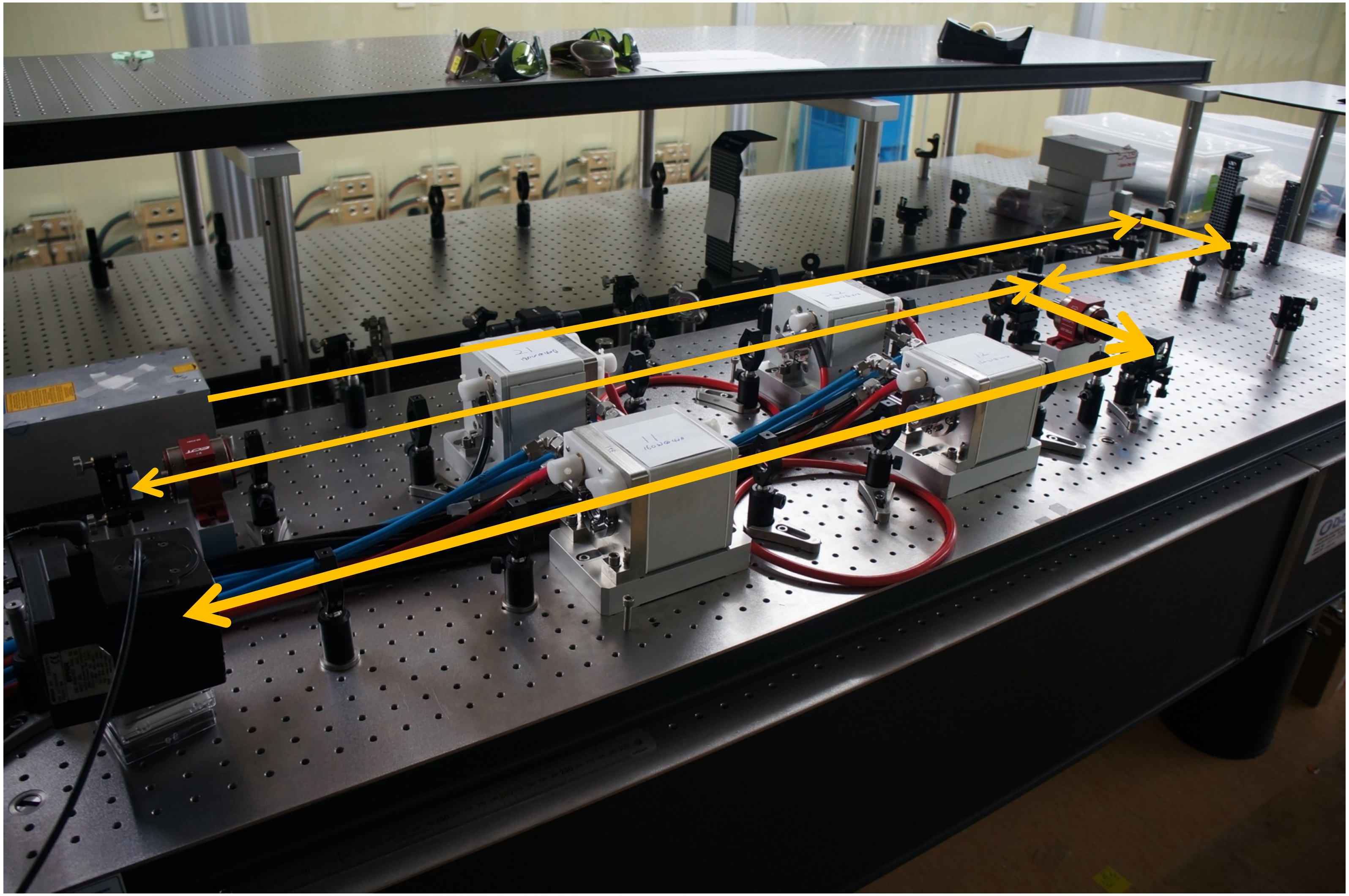
Main-AMP: Power Stability

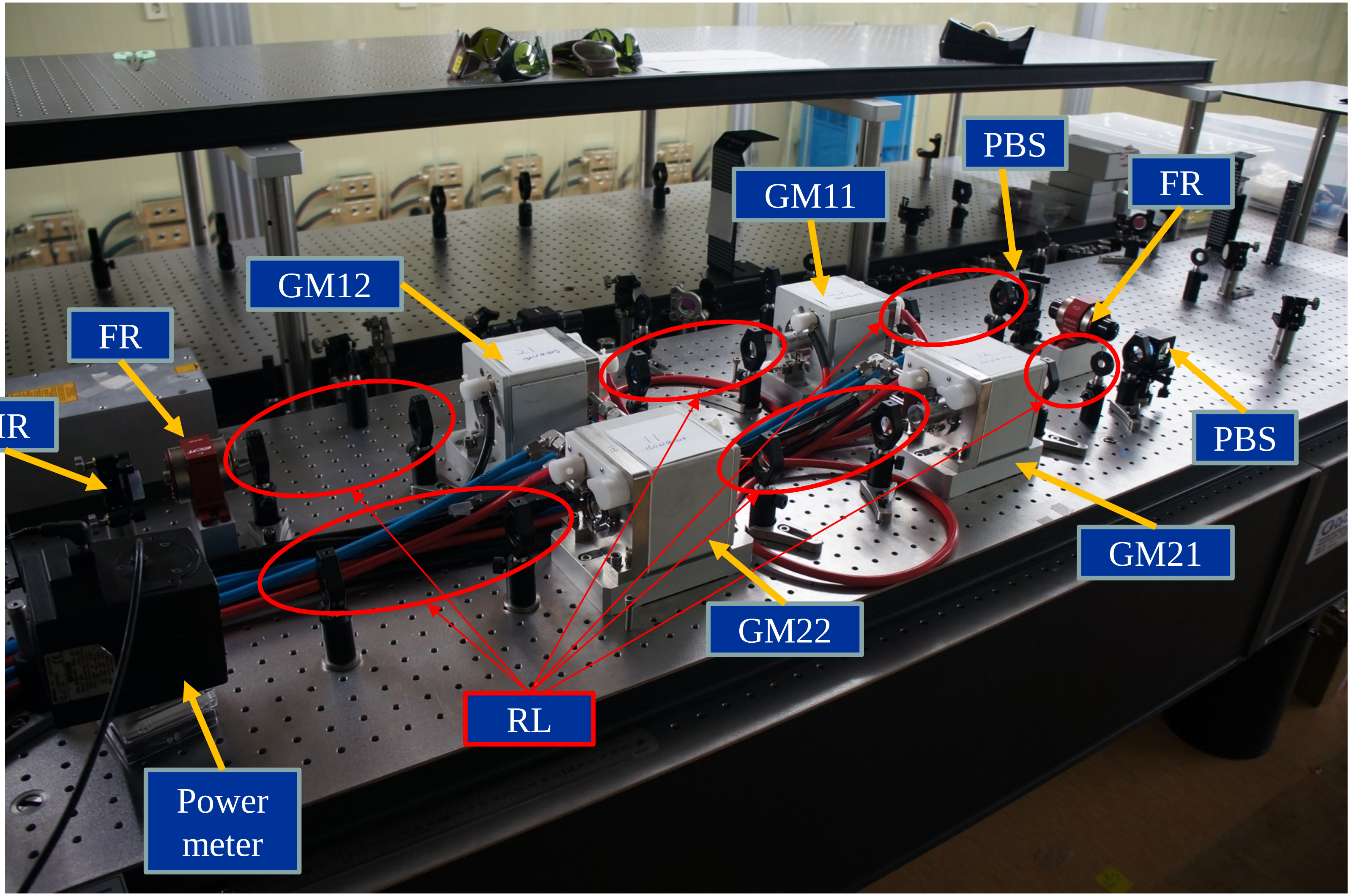


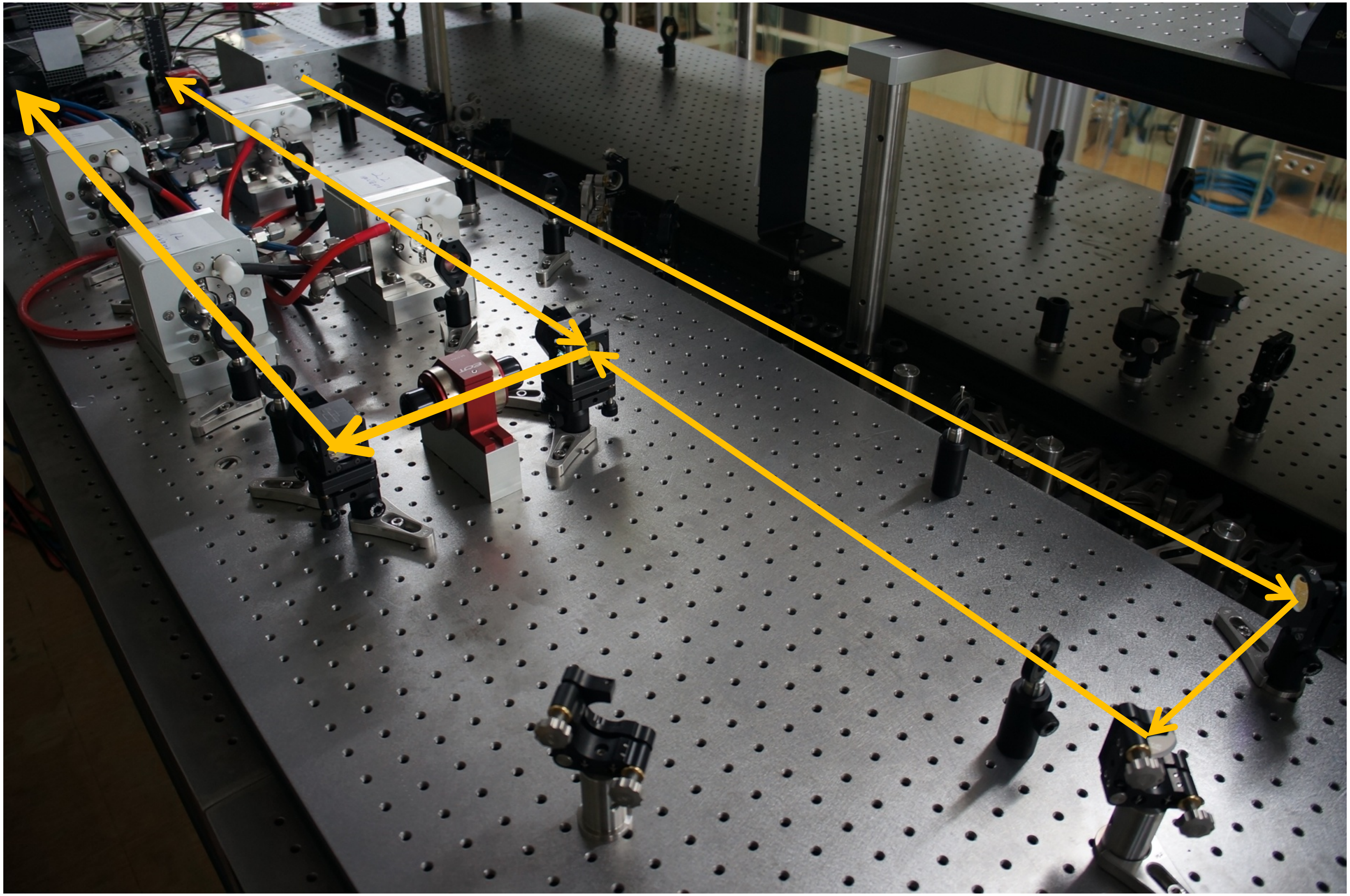
LD laser oscillaotor module

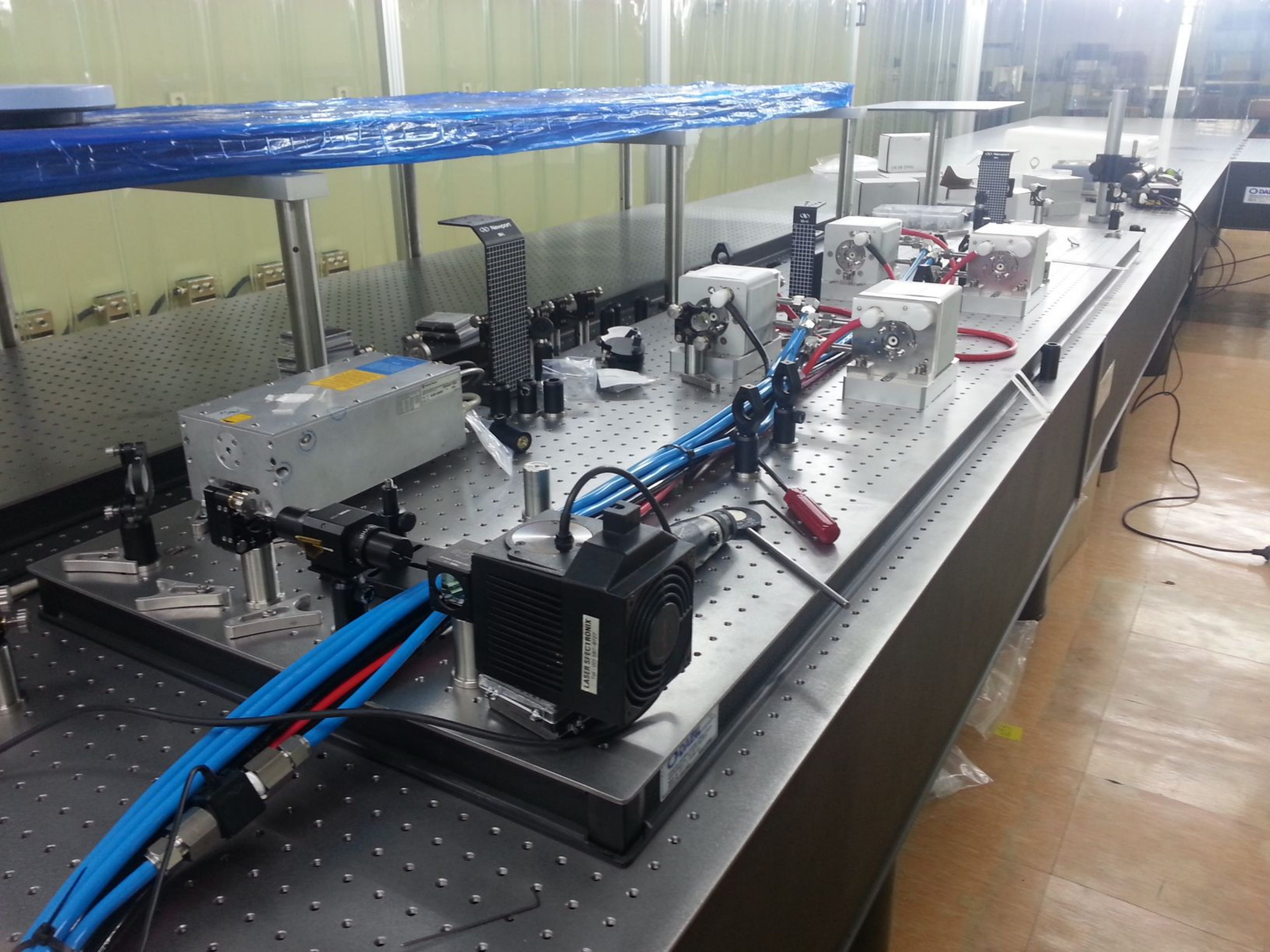


Pre-AMP setup



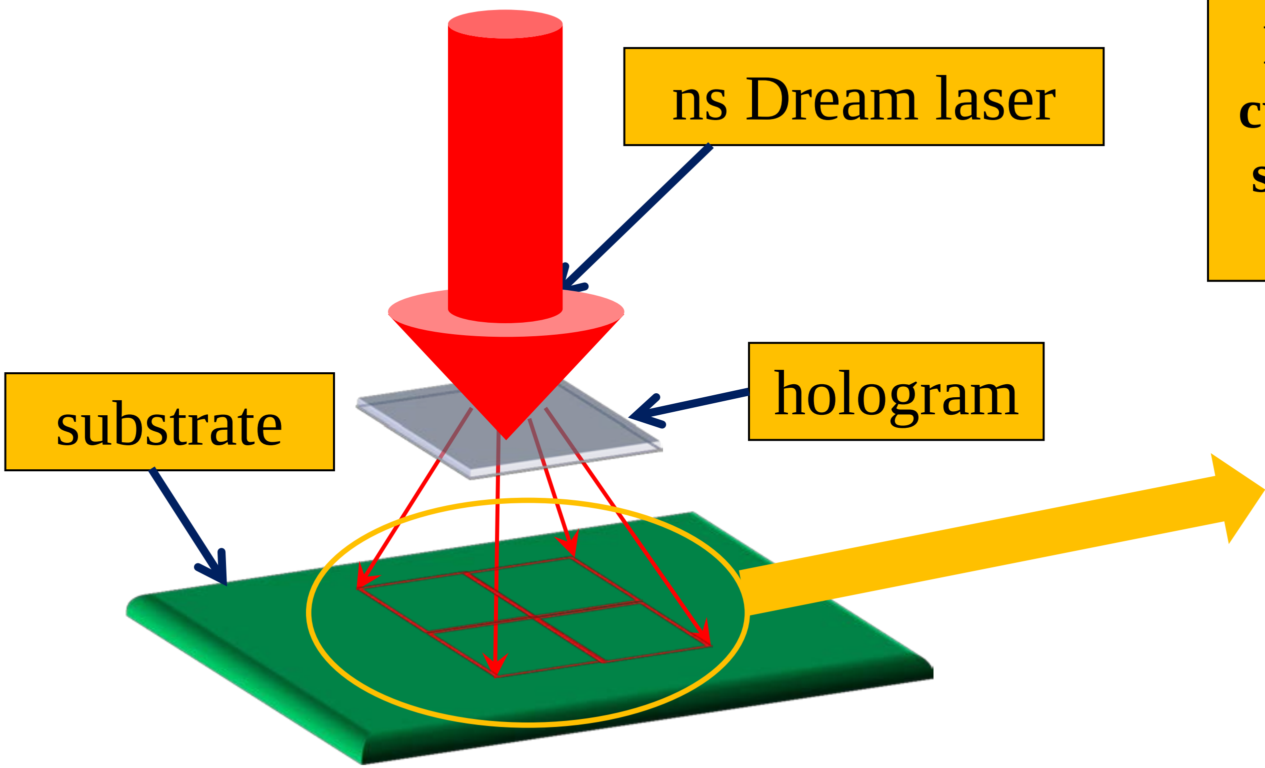

PBS
FR
GM11
GM12
FR
HR
PBS
GM21
GM22
RL
Power meter

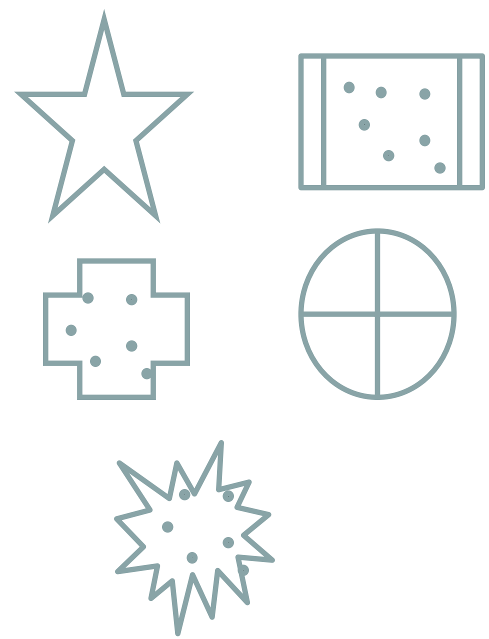



Newport
LASER SPECTRONIX

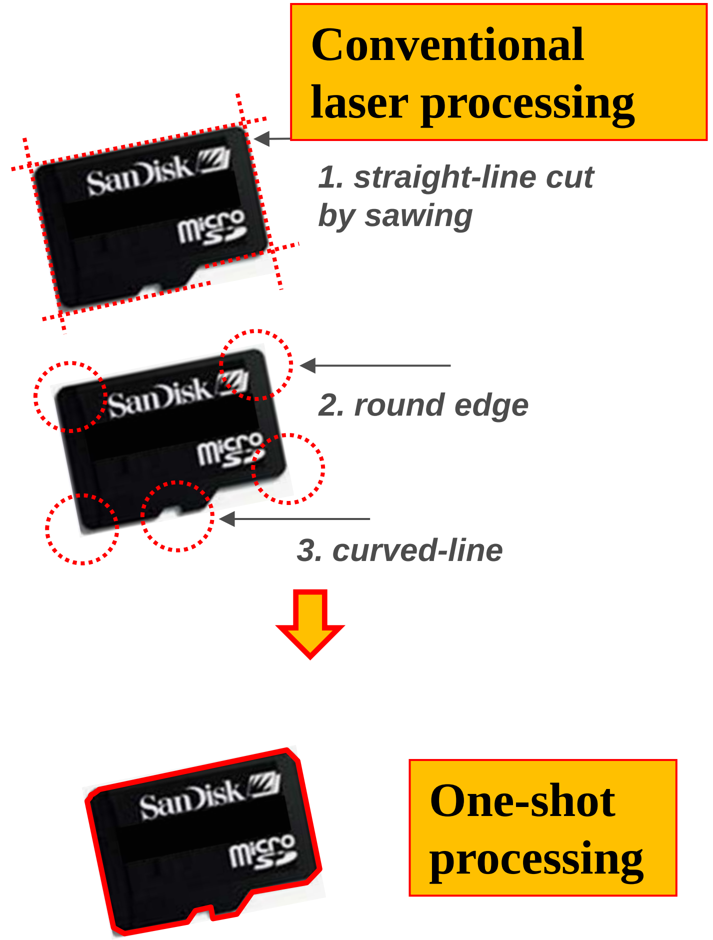
2D Laser machining by hologram

Any Patterns and many holes can be machined, cutting, welding, drilling, surface treating without scanning

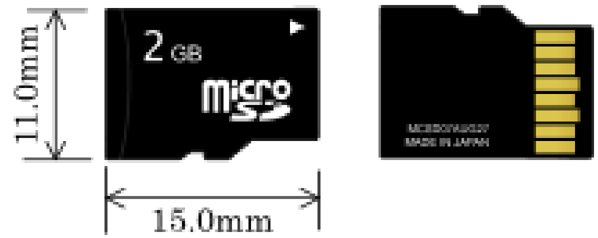


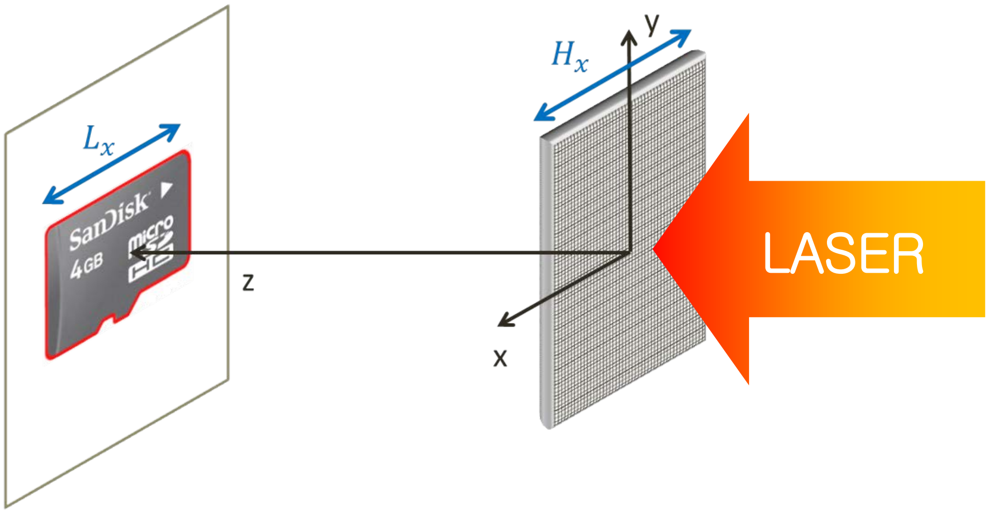


Laser machining by hologram pattern

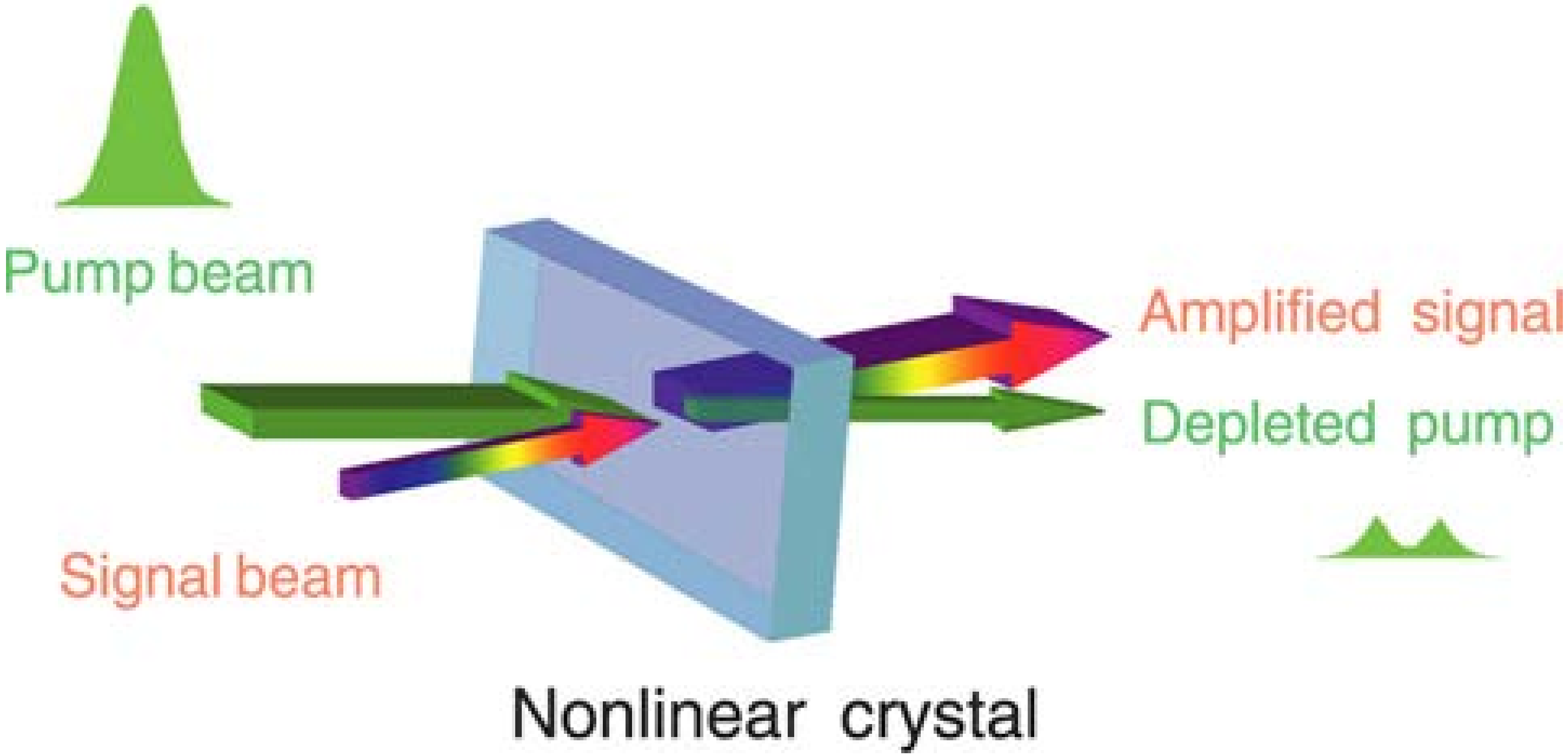


Laser machining of μ-SD card by hologram

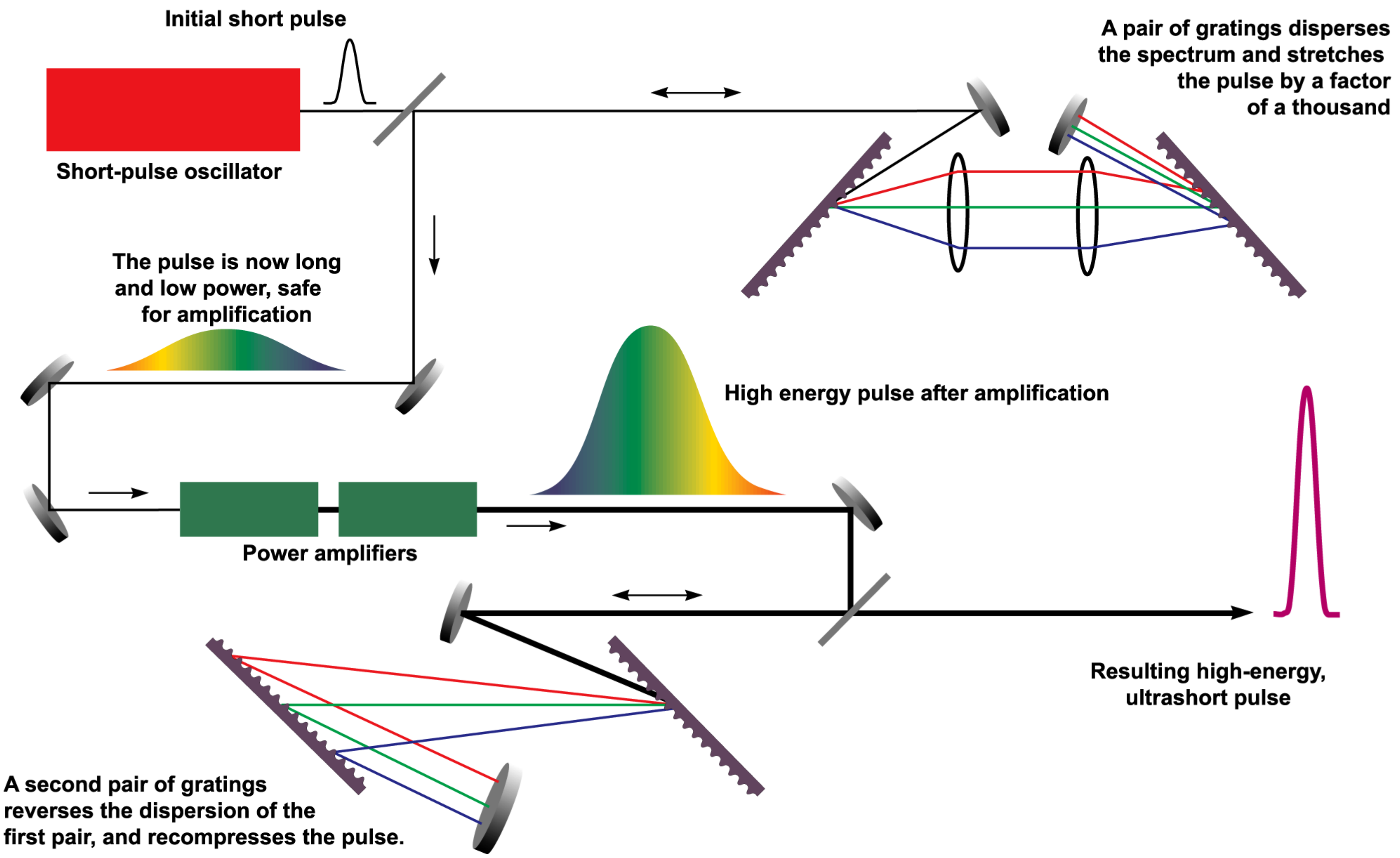




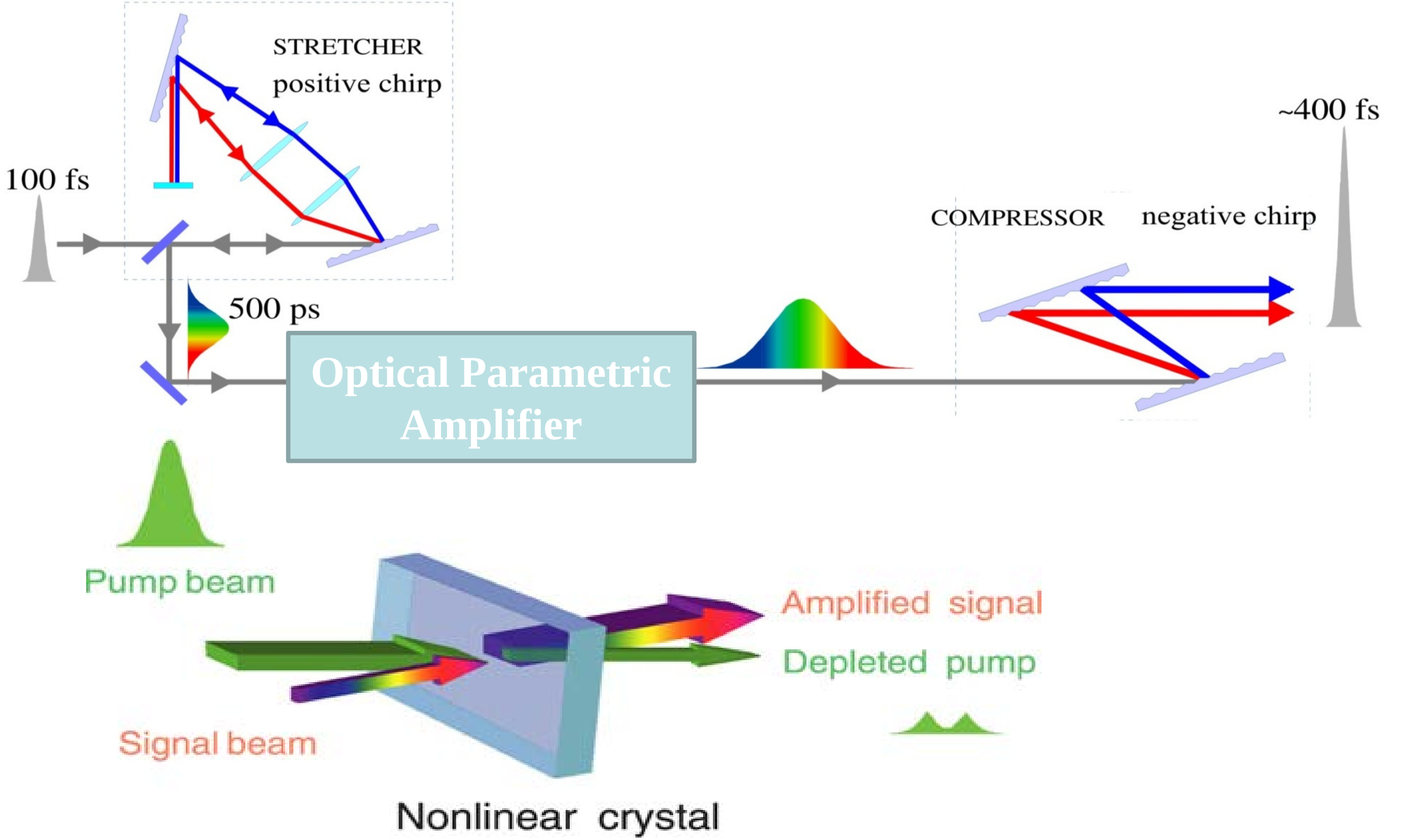
OPA: Optical Parametric Amplification



CPA

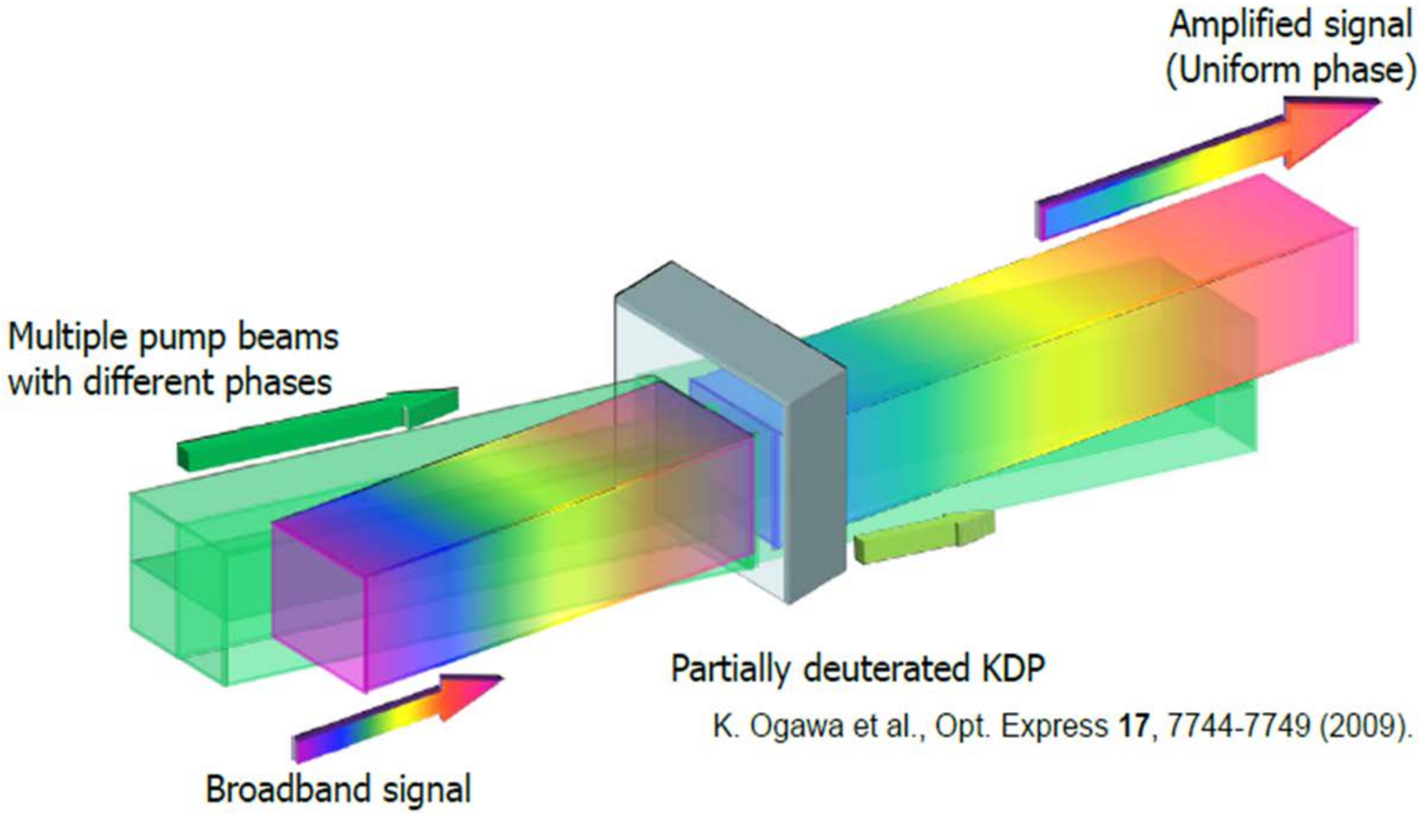

Initial short pulse
Short-pulse oscillator
A pair of gratings disperses the spectrum and stretches the pulse by a factor of a thousand
The pulse is now long and low power, safe for amplification
High energy pulse after amplification
Power amplifiers
Resulting high-energy, ultrashort pulse
A second pair of gratings reverses the dispersion of the first pair, and recompresses the pulse.

OPCPA = OPA + CPA



High rep rate high energy fs/ps laser by OPCPA

Exa-watt laser concept based on broadband OPA pumped by multiple beams



K. Ogawa et al., Opt. Express **17**, 7744-7749 (2009).

Future Plans

1st step ($5M, 3.5years from Sept. of 2012)

- 0.1J@10kHz
- 4 Beam combination
- 0.4J@10kHz

2nd step (3 years)

- 10 X 10 Beam combination
- 10J@10kHz 100kW

Applications:

- ✓ Laser machining by Hologram
- ✓ EUV source
- ✓ Etc.

3rd step (3 years)

- 100J~1kJ@10Hz
- 4 Beam combination
- 400J~4kJ@10Hz

4th step (3 years)

- 10 X 10 Beam combination
- 10kJ~100kJ@10Hz

Applications:

- ✓ Laser machining by Hologram
- ✓ Laser peening
- ✓ n/p generator
- ✓ **Laser Fusion**
- ✓ Etc.

Conclusion

- **0.1J@10ns@10kHz** laser modules has been designed and is being tested.
  - Pre-Amp module: 23mJ@10kHz/10ns
  - Main-Amp module: 51.6mJ@10kHz/10ns (single pass)
- Beam combination will be done by a **serrated aperture** or a **VBG** (Volume Bragg Grating)
- The system will be completed by Feb. 2016.
- The success of research is expected to be a **critical point for the future laser technology**.
- This beam combination can be applied to **WD** and **AD** schemes depending on the demands.
- This project is very important step for future development of **Dream Pulsed Lasers**.

Thank you for your attention.

Future Works

- With new amplifiers, the 4 beam combined output energy is expected to be around 2,000mJ (4×500mJ) at 10 Hz repetition rate.
  - ✓ For AD and WD
- For the WD beam combination
  - ✓ Beam-quality improvement by
    - ➢ image relays,
    - ➢ serrated apertures

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13. H. J. Kong, J. W. Yoon, D. W. Lee, S. K. Lee, and M. Nakatsuka, “Beam combination using stimulated Brillouin scattering phase conjugate mirror for laser fusion driver,” Journal of the Korean Physical Society **49**, S39-S42, 2006.
14. S. K. Lee, H. J. Kong, J. W. Yoon, M. Nakatsuka, D. K. Ko, and J. Lee, “Beam combined IFE driver using phase controlled stimulated Brillouin scattering phase conjugation mirrors”, Journal De Physique IV France **133**, 621-625, 2006.
15. H. J. Kong, J. W. Yoon, D. H. Beak, J. S. Shin, S. K. Lee and D. W. Lee, “Laser fusion driver using stimulated Brillouin scattering phase conjugate mirrors by a self-density modulation,” Laser and Particle Beams **25**, 225-238, 2007.
16. H. J. Kong, J. W. Yoon, J. S. Shin, and D. H. Beak, “Long-term stabilized two-beam combination laser amplifier with stimulated Brillouin scattering mirrors,” Applied Physics Letters **92**, 021120, 2008.
17. H. J. Kong, D. H. Beak, J. W. Yoon, and J. S. Shin, “Principle of the phase controlling of the SBS wave and its application to the beam combination laser for the laser fusion driver,” The Review of Laser Engineering **36**, 1164-1167, 2008.

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23. H. J. Kong, J. S. Shin, J. W. Yoon, and D. H. Beak, “Phase stabilization of the amplitude dividing four-beam combined laser system using stimulated Brillouin scattering phase conjugate mirrors,” Laser and Particle Beams **27**, 179-184, 2009.
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28. M. Kalal, O. Slezak, M. Martinkova, H. J. Kong, and J. W. Yoon, "SBS PCM Technique Applied for Aiming at IFE Pellets: First Tests with Amplifiers and Harmonic Conversion," Journal of the Korean Physical Society **56**, 184-189, 2010.
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