0.4J/10ns/10kHz-4kW coherent beam combined laser using Stimulated Brillouin Scattering Phase Conjugate Mirrors for industrial applications

Hong Jin Kong, Sang Woo Park, and Seongwoo Cha

Department of Physics, KAIST, Republic of Korea

Contents

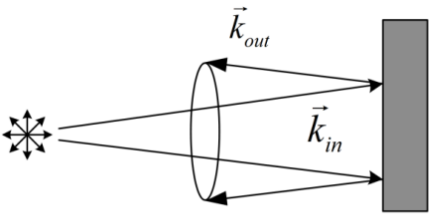
1. Motivation
2. SBS-PCM(stimulated Brillouin scattering)
3. Beam combination using SBS-PCMs
4. Previous phase locking techniques
5. Self phase control technique of SBS wave
6. Long-term phase stabilization
7. 4 beam combination
8. fs/ps dream laser system by OPCPA pumped by ns dream laser
9. Laser machining by hologram
10. 4 beam combination laser system of 0.1J@10kHz@10ns modules
11. Future plan
12. Conclusions

Motivation

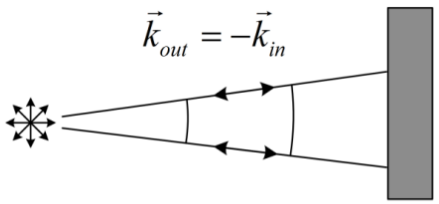
- **High repetition rate/High Energy/High Power lasers are strongly required for**
  - **Laser peening**
  - **2-D laser machining by holography**
  - **Laser n/p accelerator**
  - **Laser fusion driver**
  - **…**
- **Solutions to increase the output energy/power :**
  - LD pumping
  - High thermal conductivity laser media (Ceramic laser materials)
  - **Cryogenic 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 ; extend the attainable energy/power :**

>>>> Dream Laser

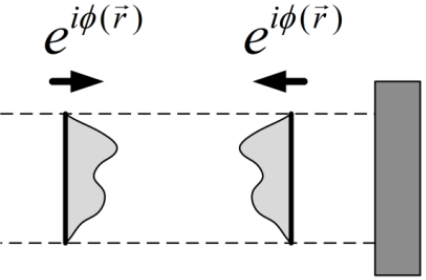
Phase conjugate mirror



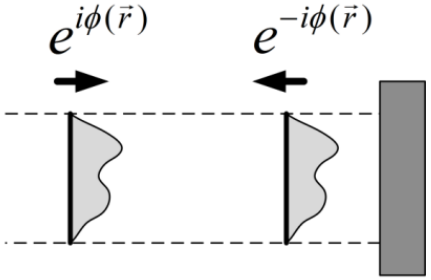
Conventional mirror



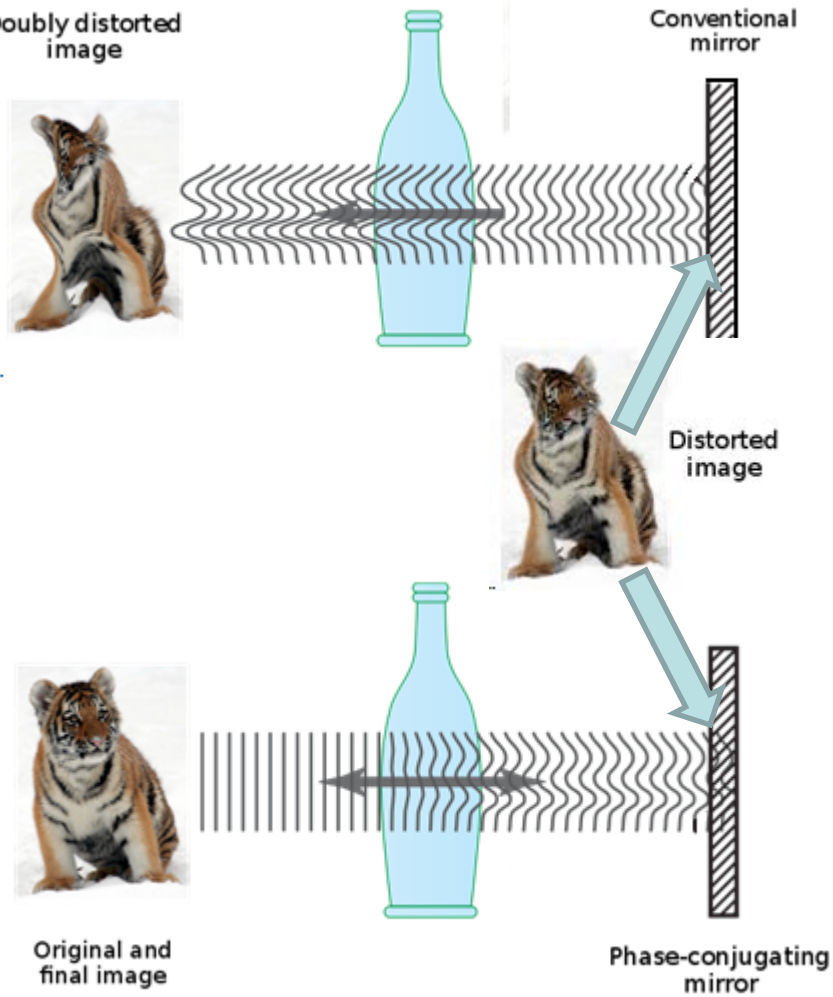
Phase conjugate mirror



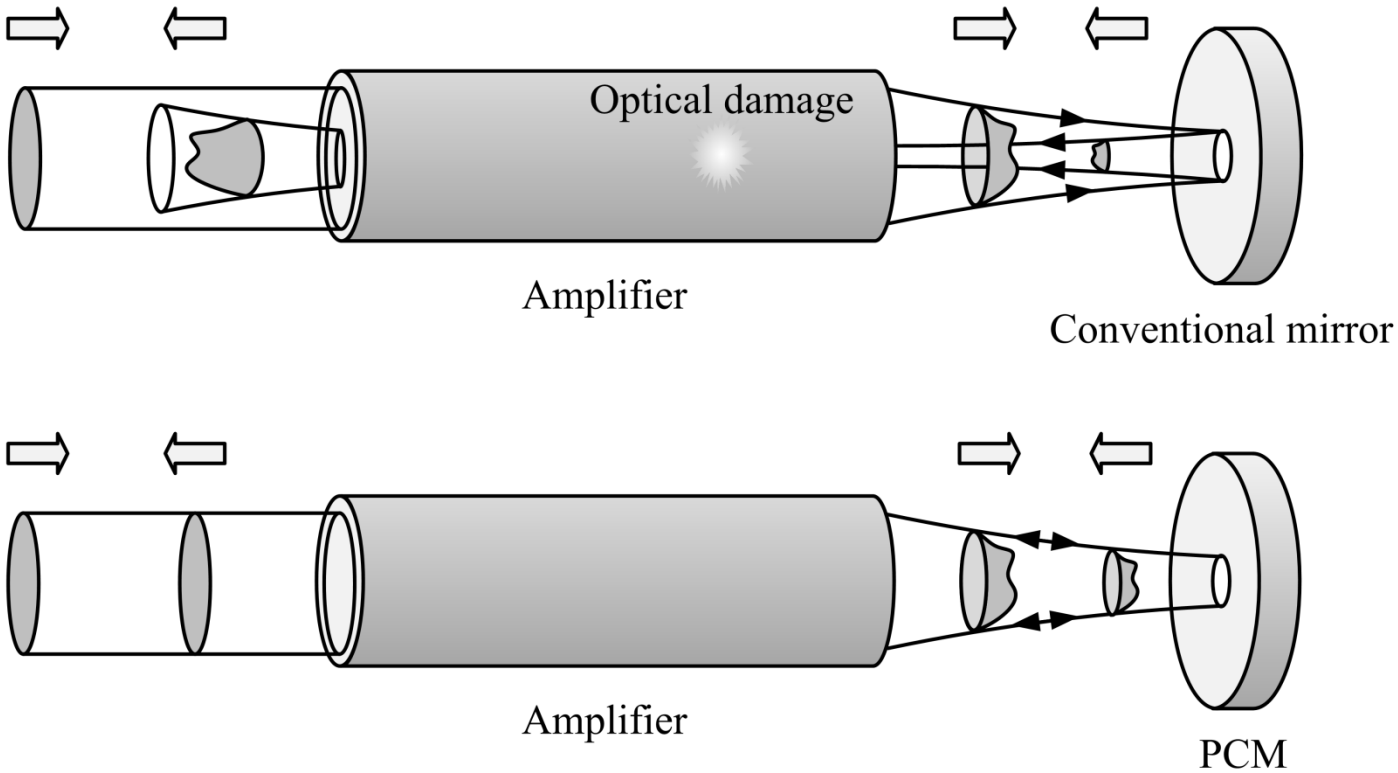
Conventional mirror



Phase conjugate mirror

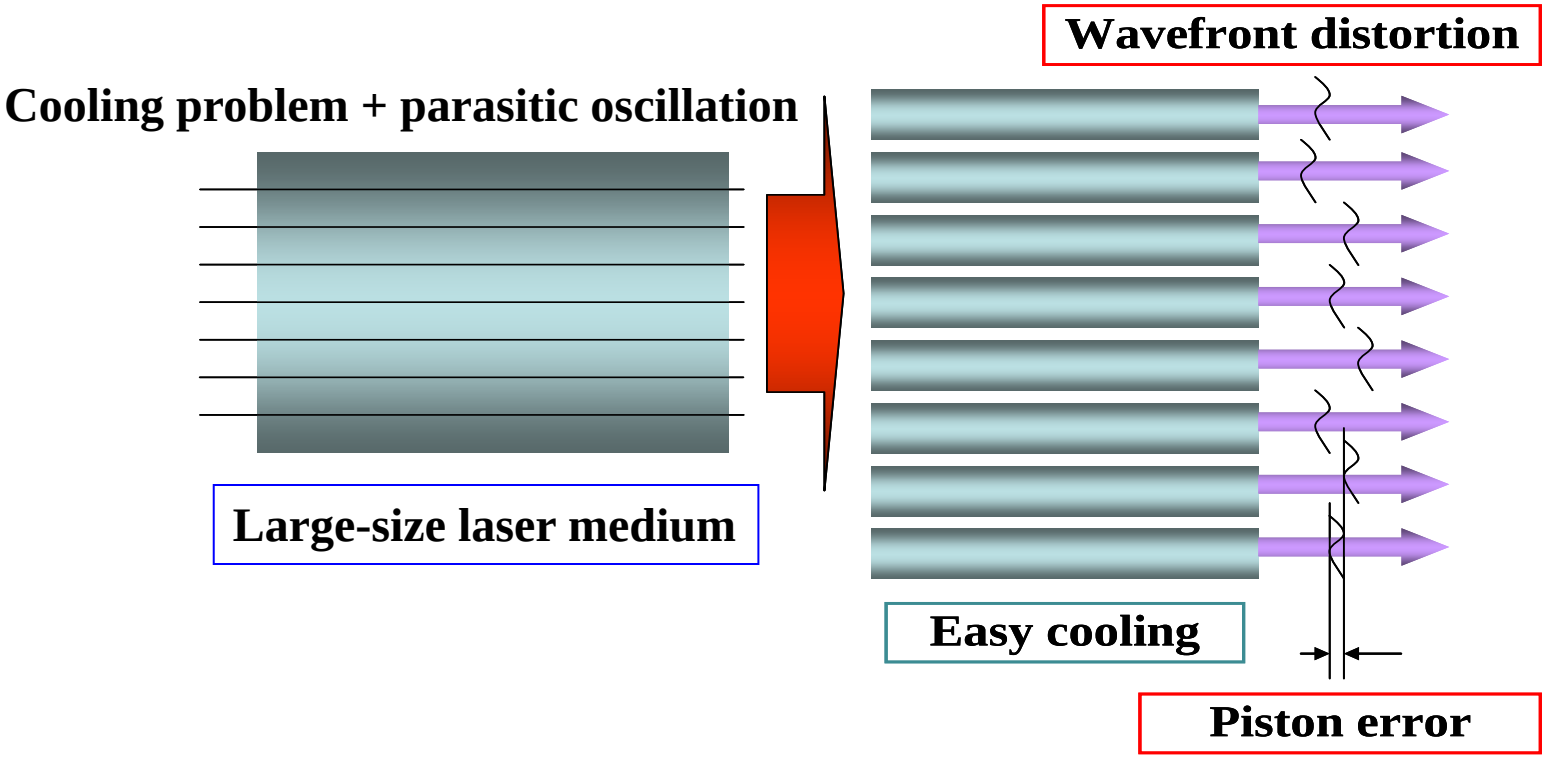


Practical Application of SBS-PCM



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

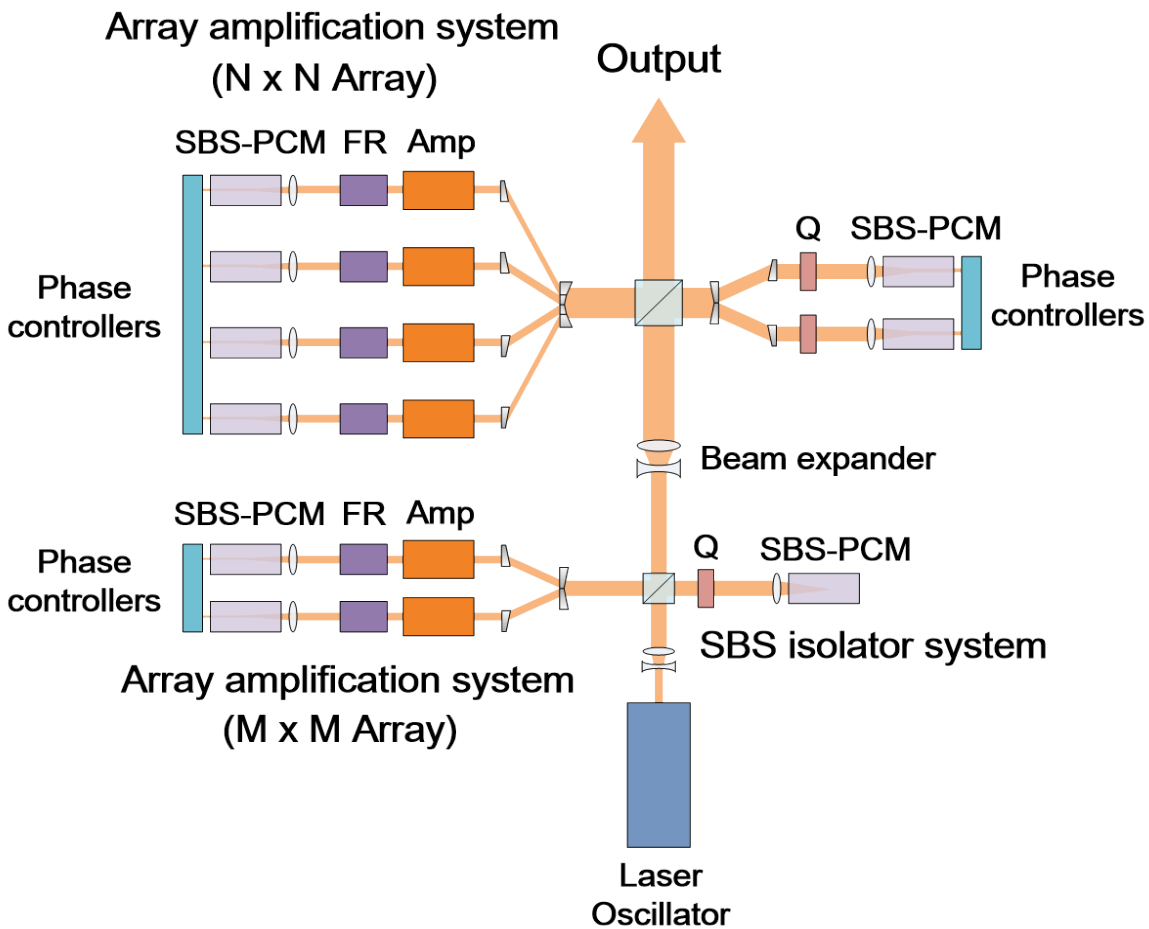
Beam combination and its problems



- **Wave-front distortion :** by **stimulated Brillouin scattering (SBS) phase conjugate mirrors** with the double-pass amplification
- **Piston error :** inherent problem of SBS, but it has been resolved by a new technique, **the self-phase-control technique** invented by H. J. Kong

Beam combination laser system using SBS-PCMs

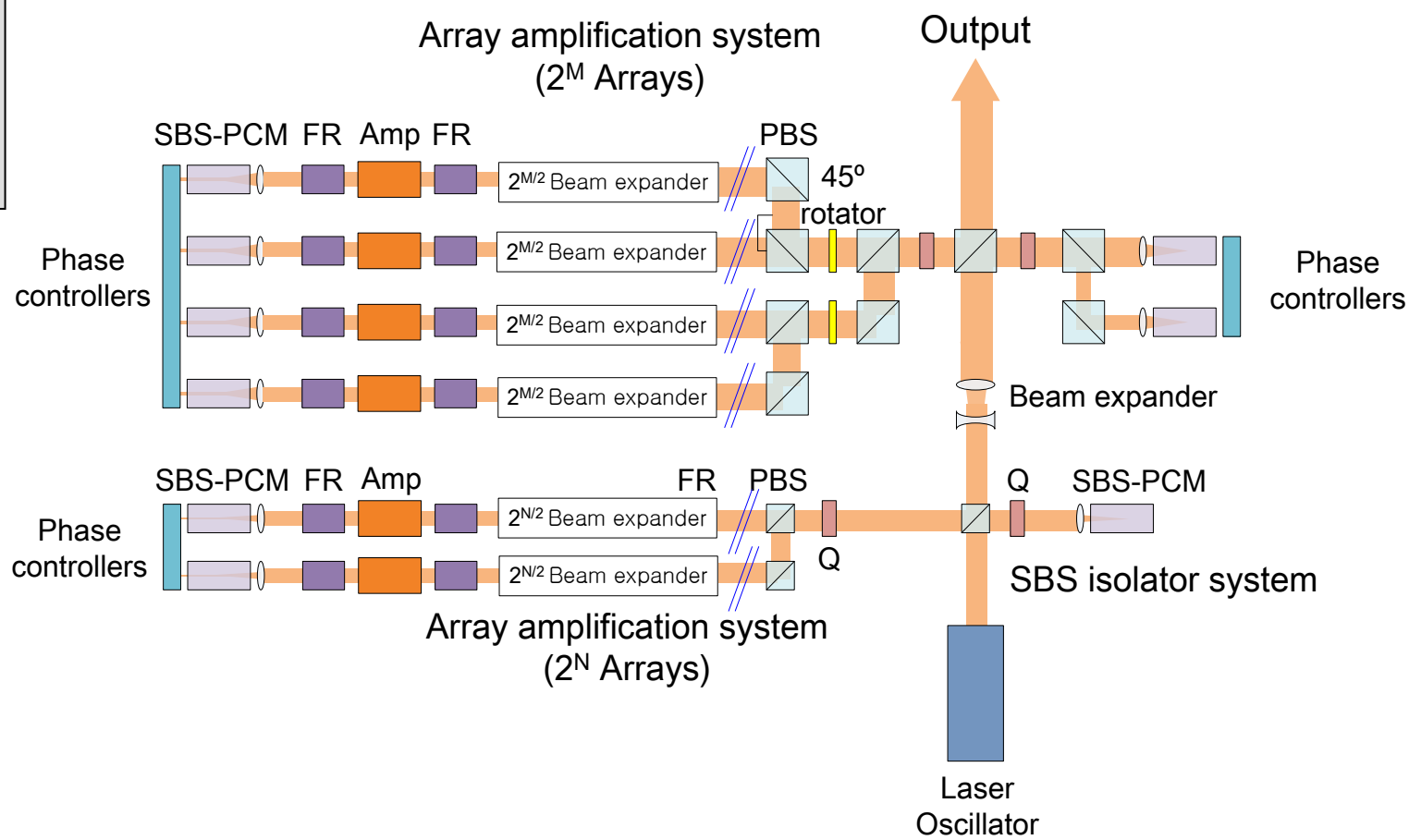
Wave-front dividing method



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

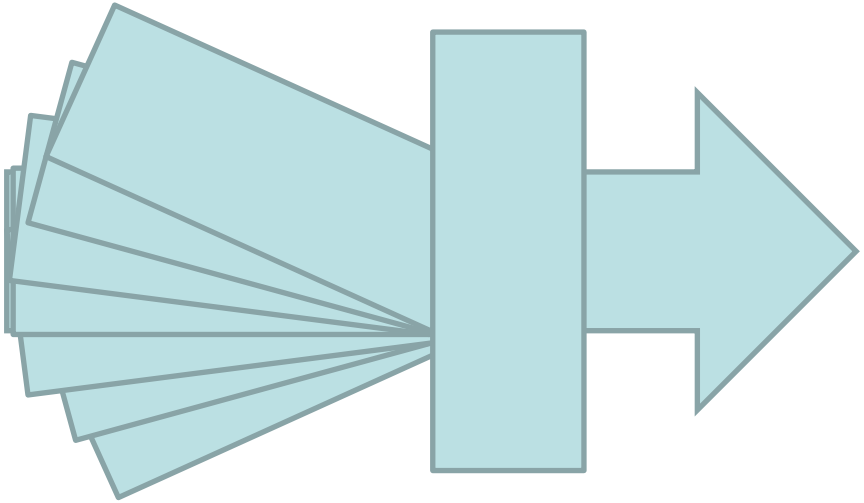
Beam combination laser system using SBS-PCMs

Amplitude dividing method



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

Amplitude Dividing scheme



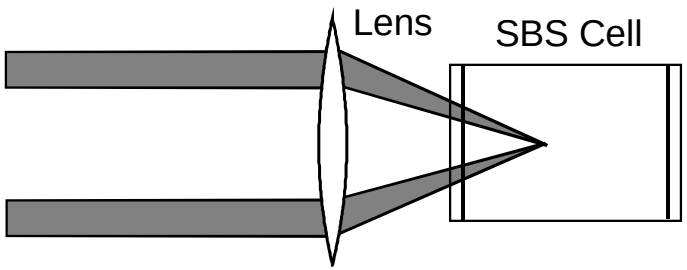
Good for 10kHz repetition rate (LOCSET)

How to measure and control the Phases for low repetition rate???

Previously developed phase control methods

1. Overlapping the SBS focal points locks the phases of the beams.

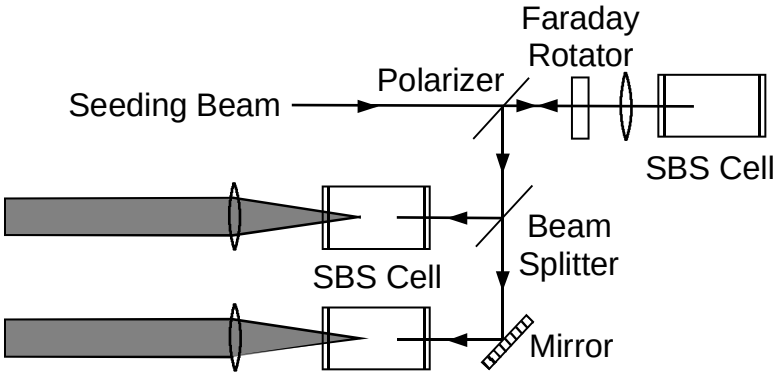
2. Phase locking by back seeding the Stokes shifted beam, which locks the phase of the PC wave.



a) Overlap of two focal points

D.A.Rockwell and C.R.Giuliano, Opt. Lett. 11, 147 (1986)

Impractical for many beams > 4



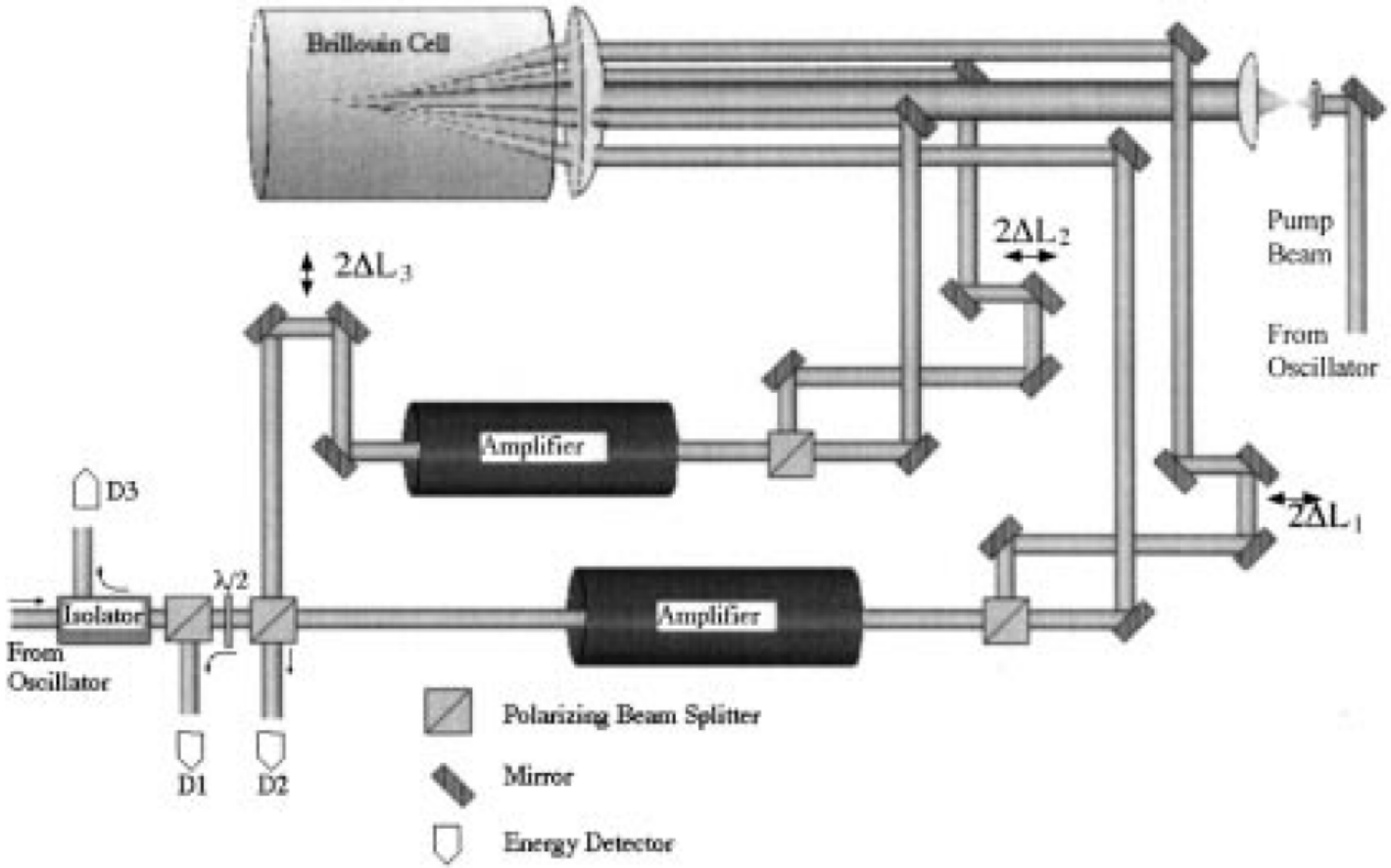
b) Back-seeding of Stokes wave

R.H.Moyer, et. al., J.Opt.Soc.Am.B, 5, 2473 (1988)

PC can be broken by back seeding beam
No PC anymore

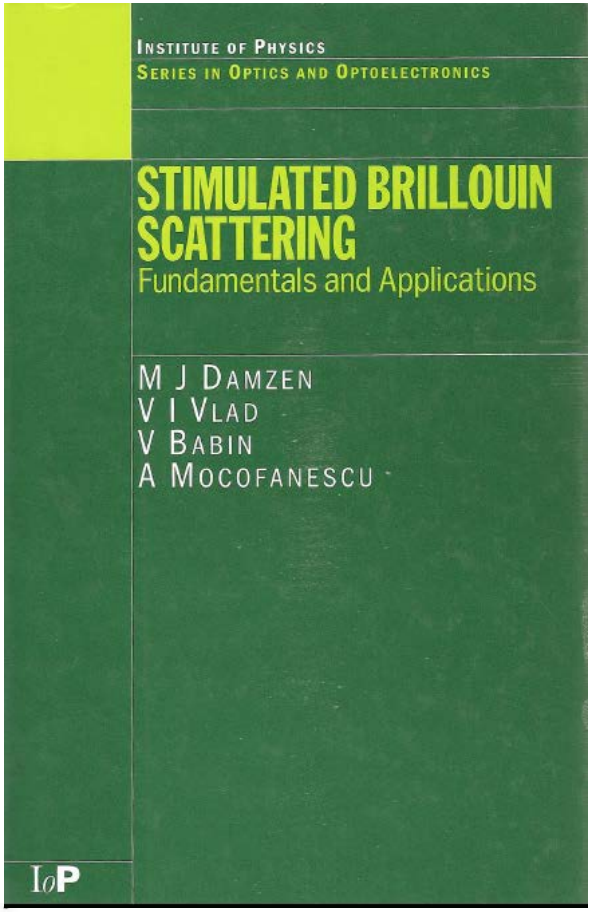
Brilloun-enhanced four-wave mixing (BEFWM)

M.Bowers and R.Boyd, “Phase locking via Brillouin-enhanced four-wave mixing phase conjugation”, **IEEE QE-34**, 634(1998)



Good for controlling phase

Too complicated optics



pulse duration to be long compared with the SBS onset time and intercell transit time. Similarly, for a coherent interaction it is necessary for the laser-coherence length to be at least twice the total length of the two-cell system. If the intercell transit time is long, then there will be a lengthy delay before the amplifier is seeded and power limiting becomes effective. For this reason it is desirable to use a relatively compact two-cell geometry.

A further feature demonstrated by the simulations but also observed experimentally at high powers is the ability to achieve greater than unity reflectivity on a transient basis. This overshoot by the Stokes radiation can be explained by storage of radiation in the two-cell system. The excess of Stokes power over the input pump will only be temporary since the severe depletion of the pump will reduce the seeding signal, resulting in an overshoot for a time of the order of twice the intercell transit time. The amount of overshoot is dependent on the gain of the amplifier and on the intercell losses. For low losses, the seeding level can be high, leading to a substantial overshoot.

The performance of the generator cell could be improved by the introduction of optical feedback, which has been shown to reduce the threshold and increase the phase conjugate fidelity of the SBS process [7.6], as described previously.

7.5 Laser beam combining using SBS

In the normal SBS configuration a single pump beam is incident upon the SBS medium, and the Stokes scattered output beam is generated by amplification of noise. This SBS scattered field will have a random overall phase since it starts from statistical noise and, in addition, this phase has been shown to fluctuate randomly in a time of the order of several times the phonon lifetime [7.14]. The SBS reflection, therefore, has no absolute temporal phase reference. As a consequence, if two beams are conjugated by SBS in separate interaction volumes the two Stokes beams will have a phase difference that is random and unrelated to the phase difference of the pump beams. Basov *et al* [7.15] first predicted this random phase difference and several groups demonstrated its existence [7.16–7.18]. If the random phase difference in the Stokes beams is to be avoided an absolute phase reference must be created. This can be accomplished by several methods.

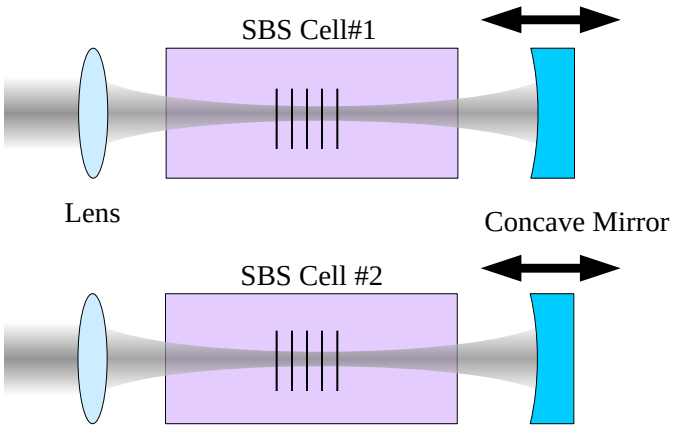
7.5.1 Laser beam combining using spatial overlap in SBS

Consider the case where two or more pump beams are overlapped in the same interaction volume. They appear to the SBS process as a single, but highly aberrated, beam with the relative phase between the beams appearing as an aberrated wave front. The standard mechanisms that phase conjugate a

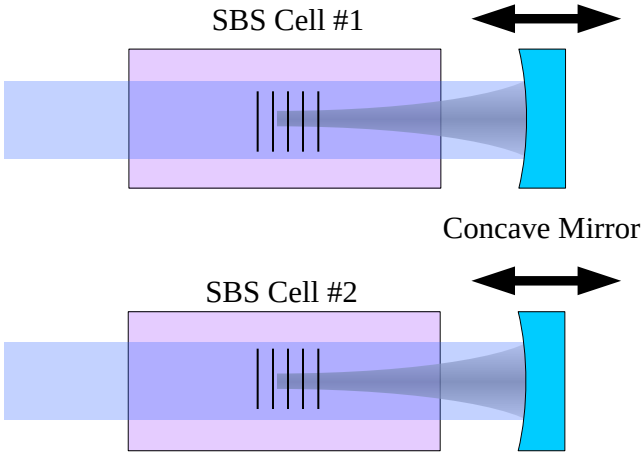
cation of noise. This SBS scattered field will have a random overall phase since it starts from statistical noise and, in addition, this phase has been shown to fluctuate randomly in a time of the order of several times the phonon lifetime [7.14]. The SBS reflection, therefore, has no absolute

“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.**

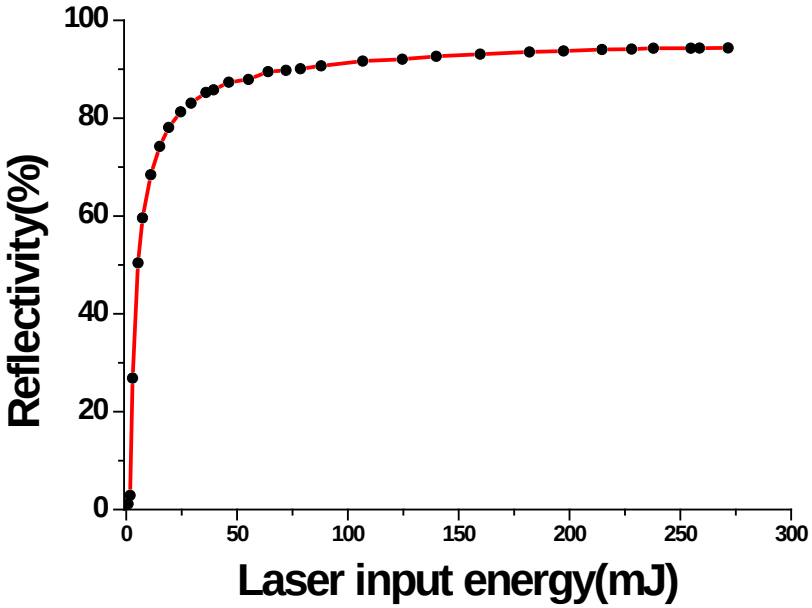


(a)Concentric type

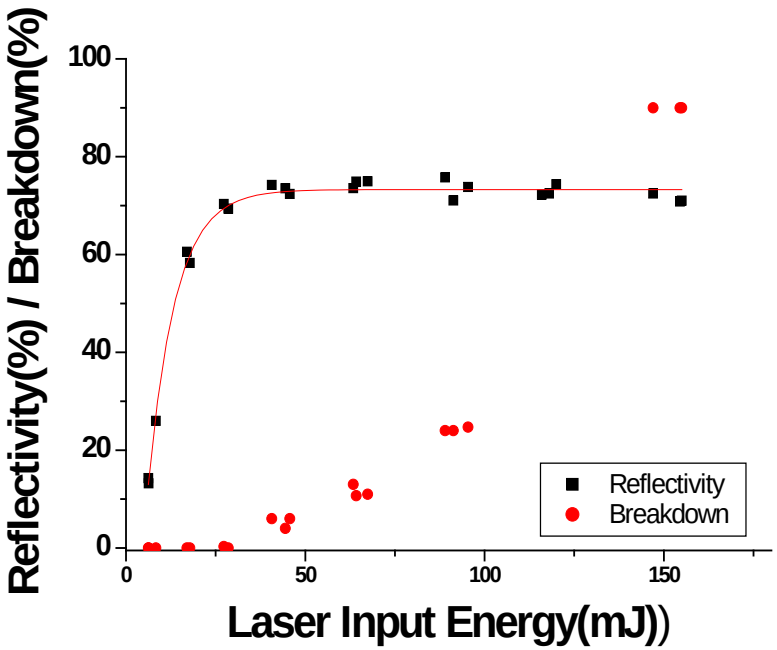


(b) Confocal type

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



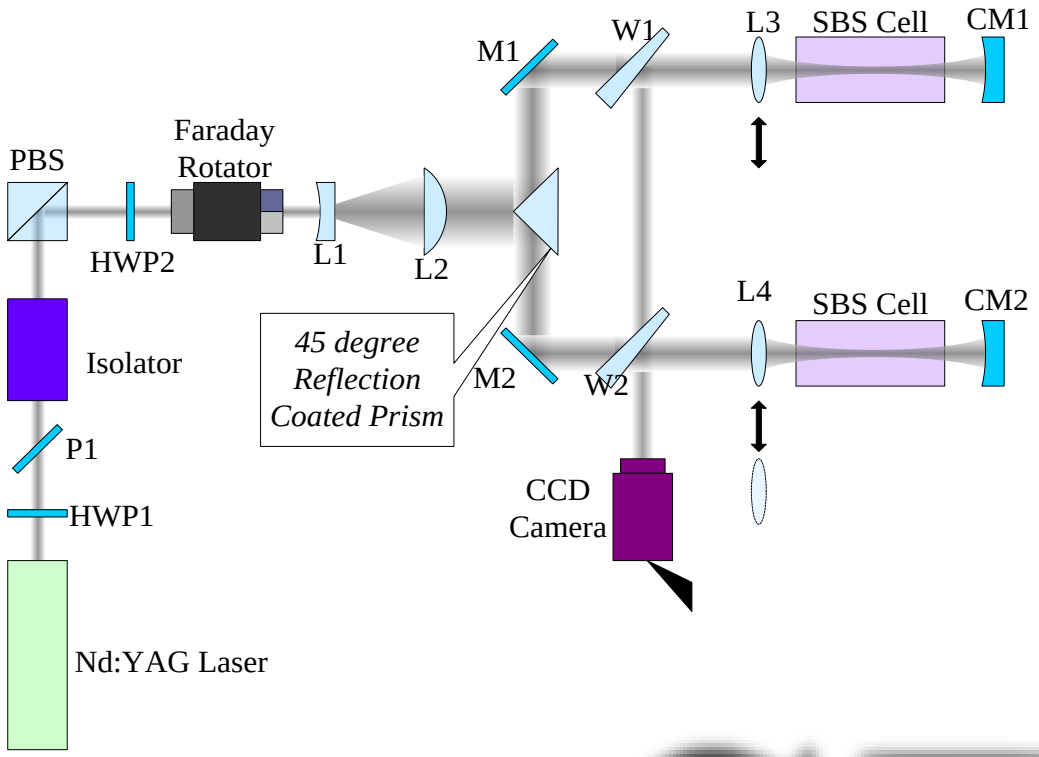
Single mode pumping
($\Delta\nu$~120MHz, Γ=350MHz)
(No break down)



Multi mode pumping
($\Delta\nu$~30GHz, Γ=350MHz)
(Break down occurs)

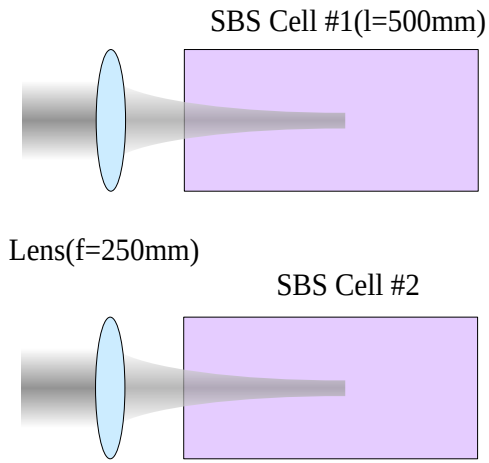
Seong Ku Lee, et. al, JKPS 46, pp.443~447, 2005.

wave-front division

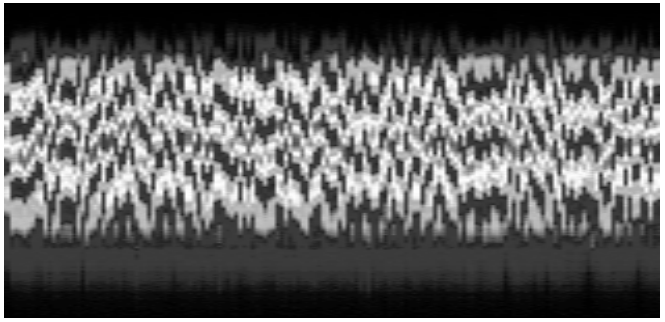


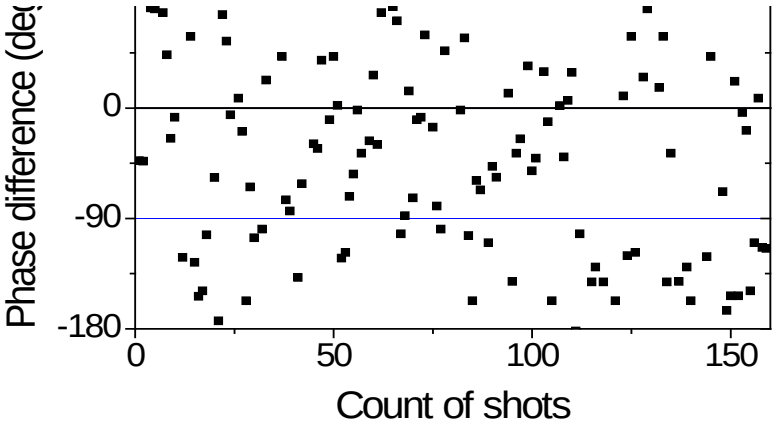
M1&M2, mirrors; W1&W2, wedges; L1&L2, cylindrical lenses; L3&L4, focusing lenses; CM1&CM2, concave mirrors; HWP1&HWP2, half wave plates; P1, polarizer; PBS, polarizing beam splitter.

S. K. Lee, H. J. Kong, and M. Nakatsuka, Applied Physics Letters 87, 61109 (2005).



Intensity profile of interference for 160 shots





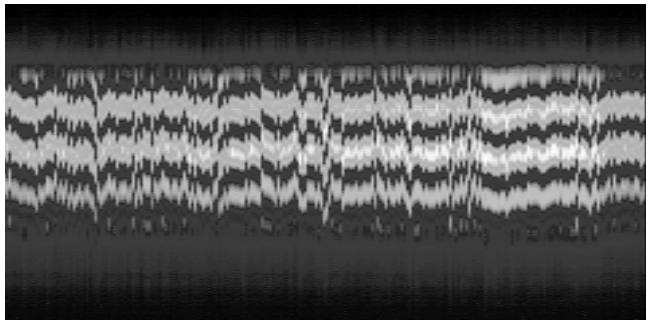
Intensity profile of interference

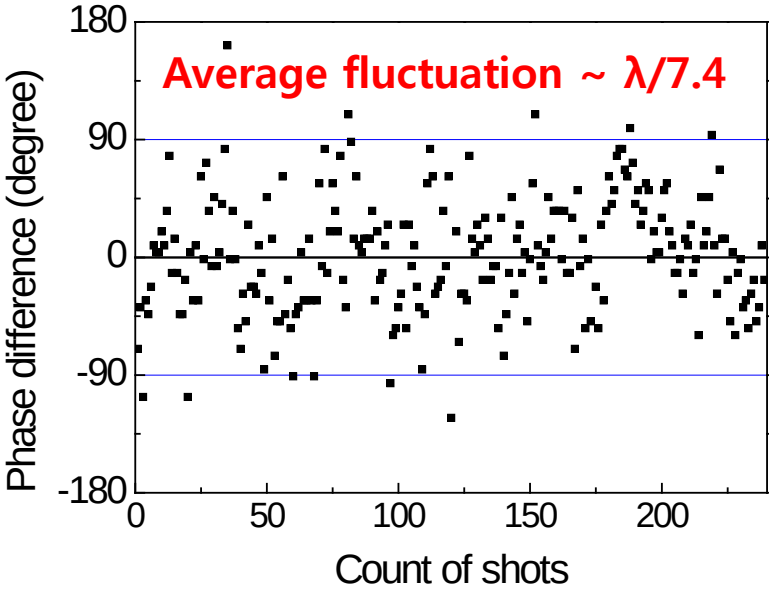
H. J. Kong, S. K. Lee, and Y. S. Kim, "Phase locking of two beams using stimulated Brillouin phase conjugate mirrors, LO2003, XIth Conference on Laser Optics, St. Petersburg, Russia (June 30 – July 04, 2003).

Wave-front division

Confocal type

Intensity profile of interference for 239 shots

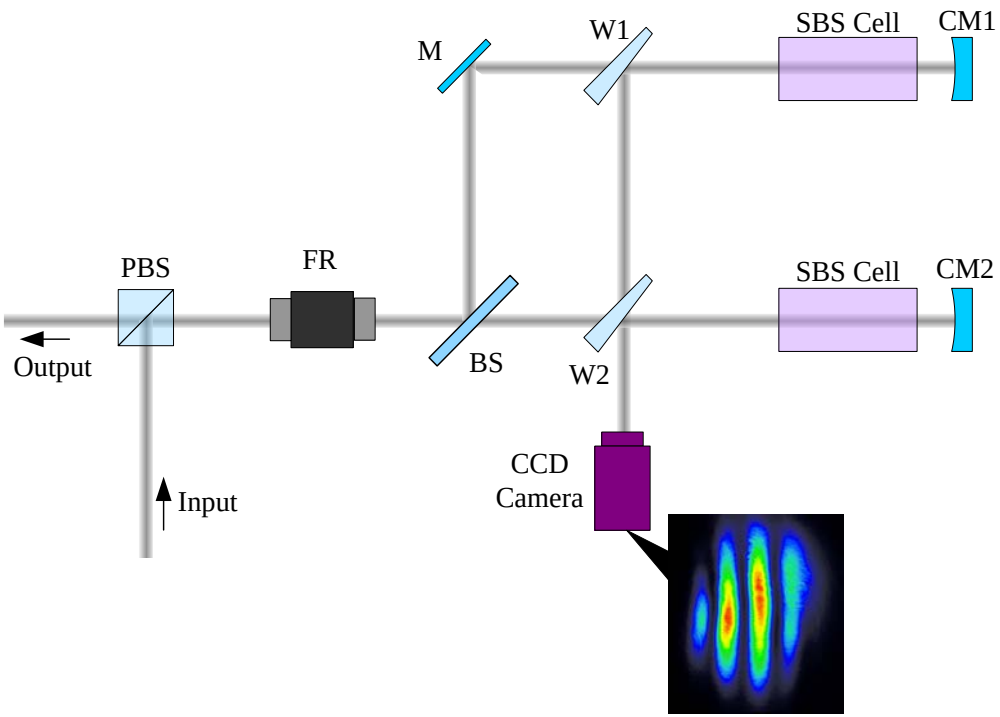




H. J. Kong, S. K. Lee, and Y. S. Kim, "Phase locking of two beams using stimulated Brillouin phase conjugate mirrors, LO2003, XIth Conference on Laser Optics, St. Petersburg, Russia (June 30 – July 04, 2003).

SBS phase control with the amplitude division

Insensitive to beam pointing effect → keep energy balance → Phase stability
Kong's theory

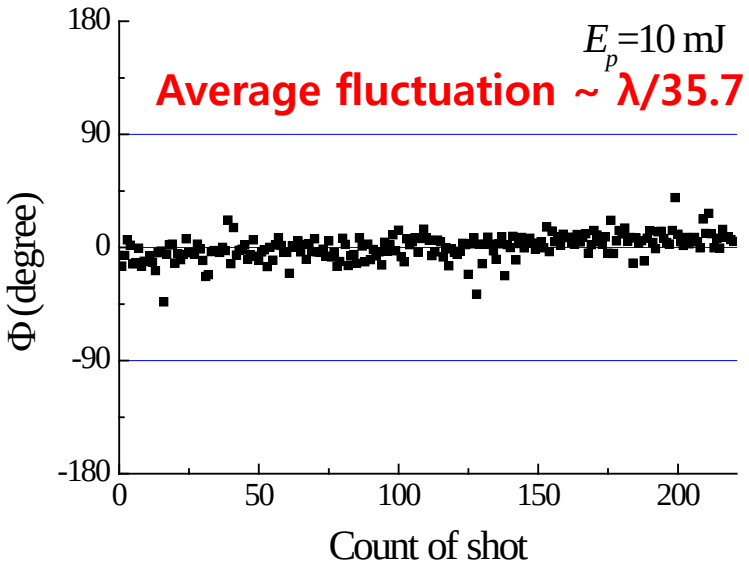


M, mirror; BS, beam splitter; W1&W2, wedges; CM1&CM2, concave mirrors.

H. J. Kong, S. K. Lee, and D. W. Lee, Laser and Particle Beams 23, 55-59 (2005).
S. K. Lee, H. J. Kong, and M. Nakatsuka, Applied Physics Letters 87, 161109 (2005).

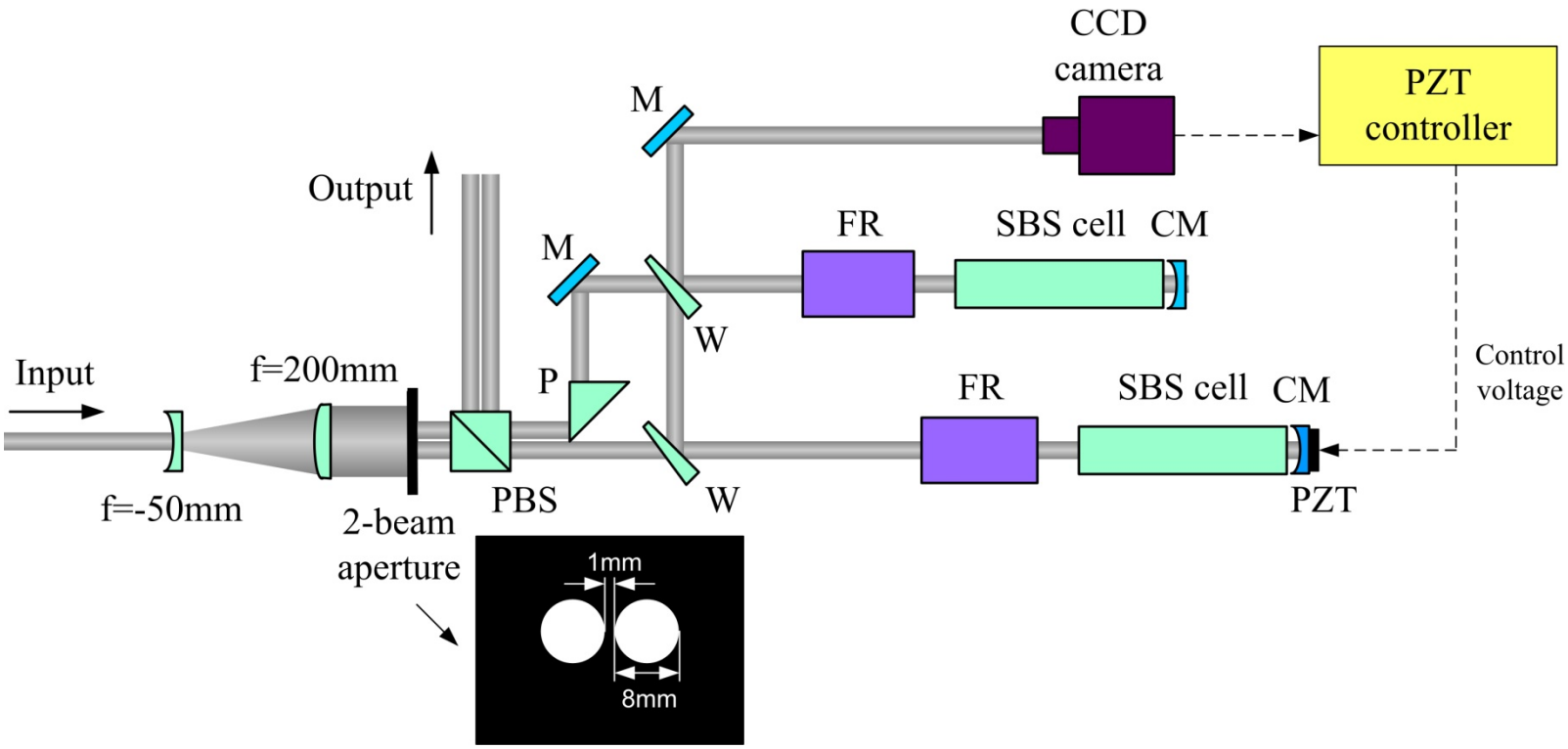
Amplitude division

Intensity profile of interference for 220 shots



S. K. Lee, H. J. Kong, and M. Nakatsuka, Applied Physics Letters 87, 161109 (2005).

SBS phase control experiment with the wave-front division using the expanded input beam

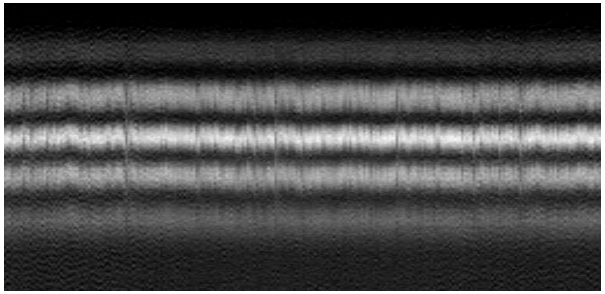


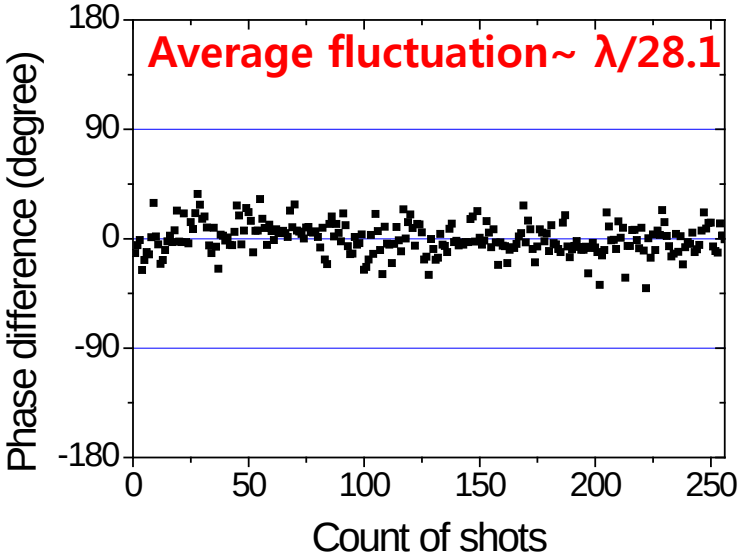
PBS, polarizing beam splitter; M, mirror; W, wedged window; FR, Faraday rotator; CM, concave mirror; PZT, piezoelectric translator.

H. J. Kong, J. S. Shin, J. W. Yoon, and D. H. Beak, Nuclear Fusion 49, 125002 (2009).

Short-term phase fluctuation

Intensity profile of interference for 256 shots



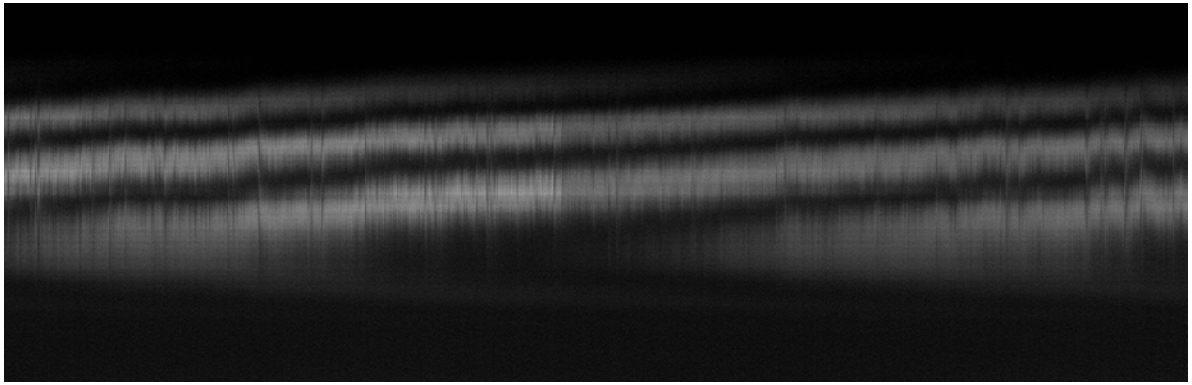


4 X more stable than before for the **beam expansion**

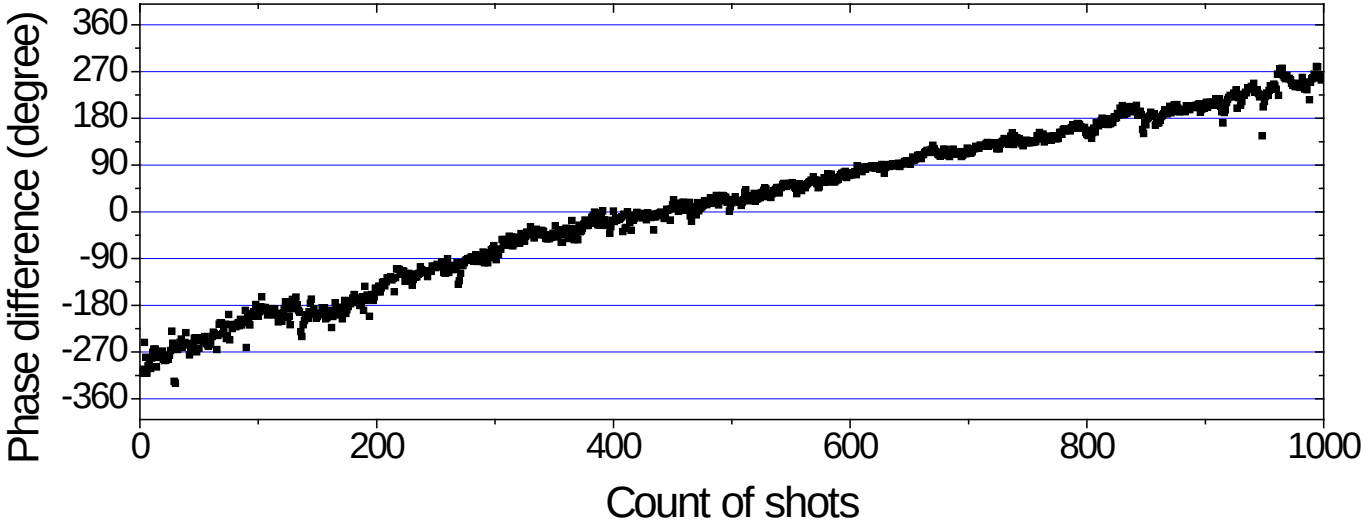
H. J. Kong, J. S. Shin, J. W. Yoon, and D. H. Beak, Nuclear Fusion 49, 125002 (2009).

Experimental result – Long-term phase fluctuation

[Mosaic intensity profile of the horizontal lines from interference patterns]



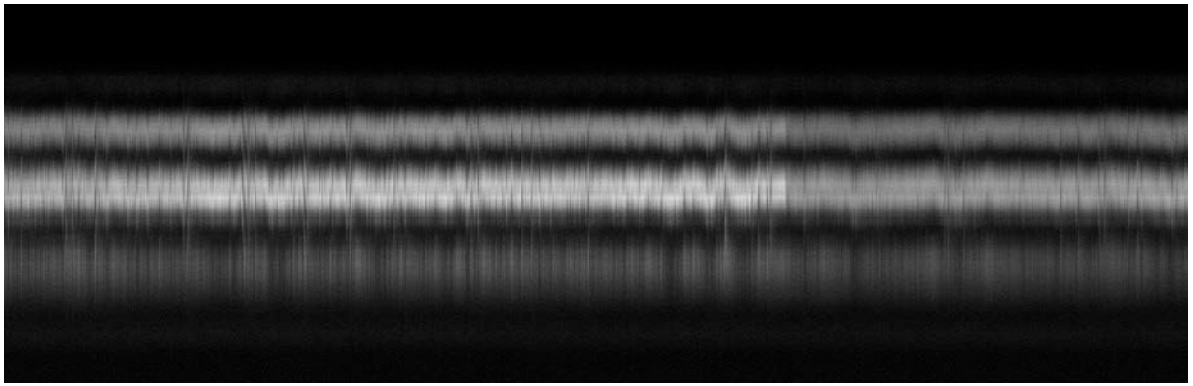
[Measured phase difference from interference patterns]



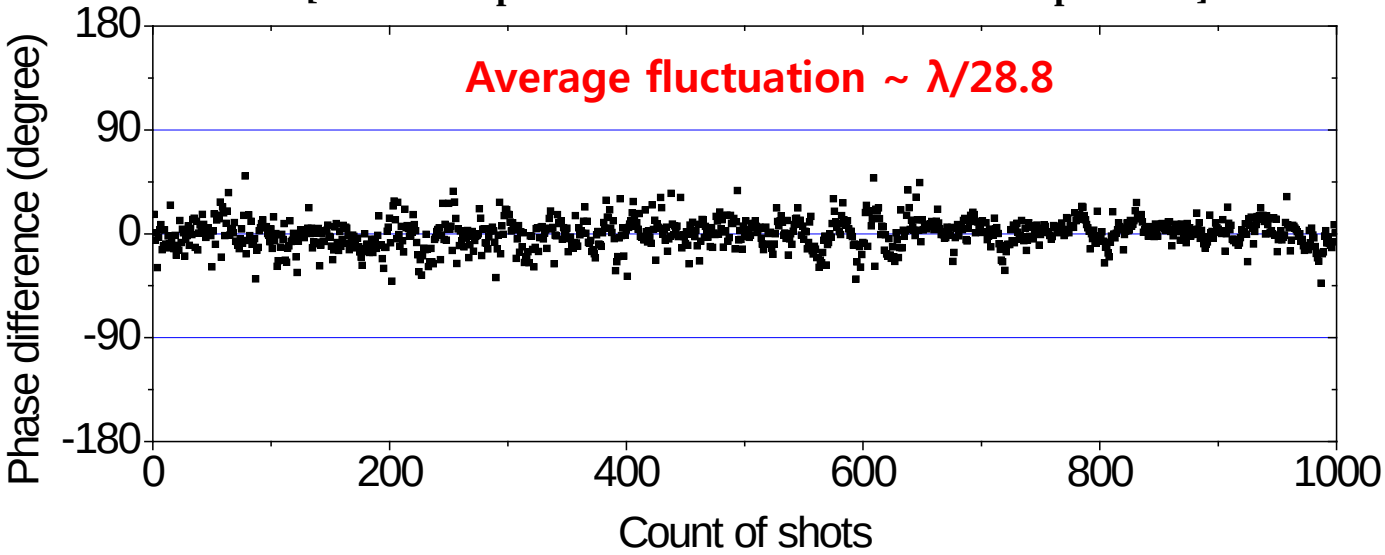
H. J. Kong, J. S. Shin, J. W. Yoon, and D. H. Beak, Nuclear Fusion 49, 125002, 2009.

Long-term phase stabilization with PZT control

[Mosaic intensity profile of the horizontal lines from interference patterns]

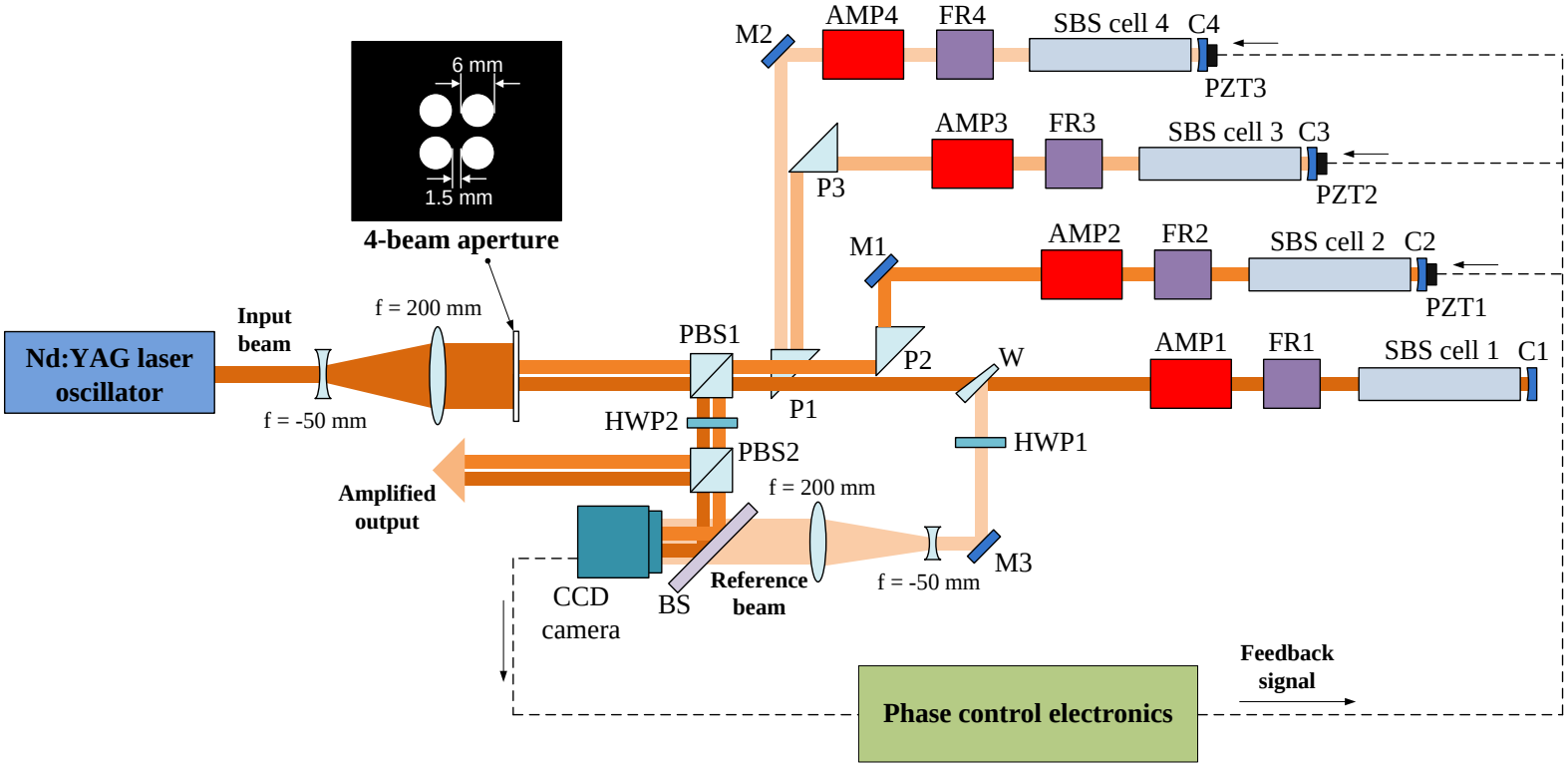


[Measured phase difference from interference patterns]



H. J. Kong, J. S. Shin, J. W. Yoon, and D. H. Beak, Nuclear Fusion 49, 125002, 2009.

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

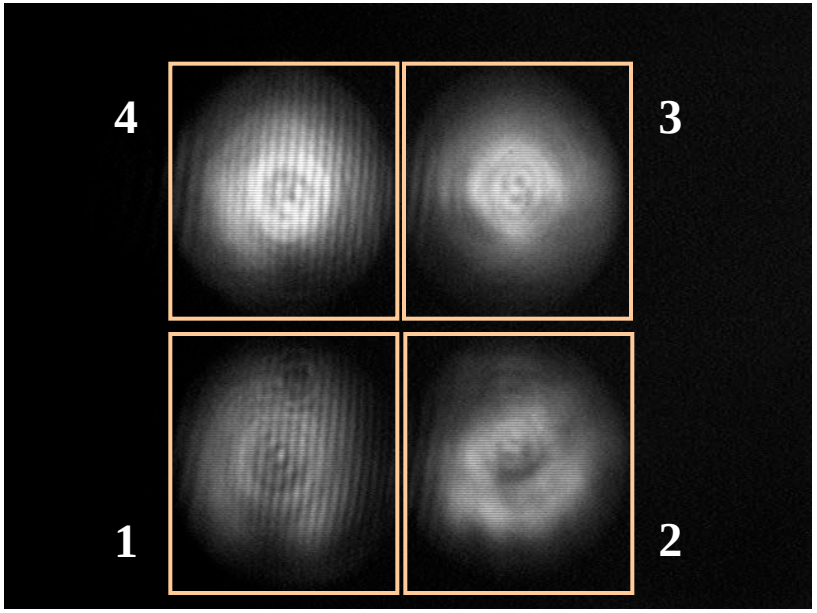


PB1&PBS2, polarizing beam splitters; HWP1&HWP2, half wave plate; P1, P2&P3, 45 degree prisms; BS, beam splitter; W, wedged window; FR1, FR2, FR3&FR4, Faraday rotators; C1, C2, C3&C4, concave mirrors; PZT1, PZT2&PZT3, piezoelectric translators.

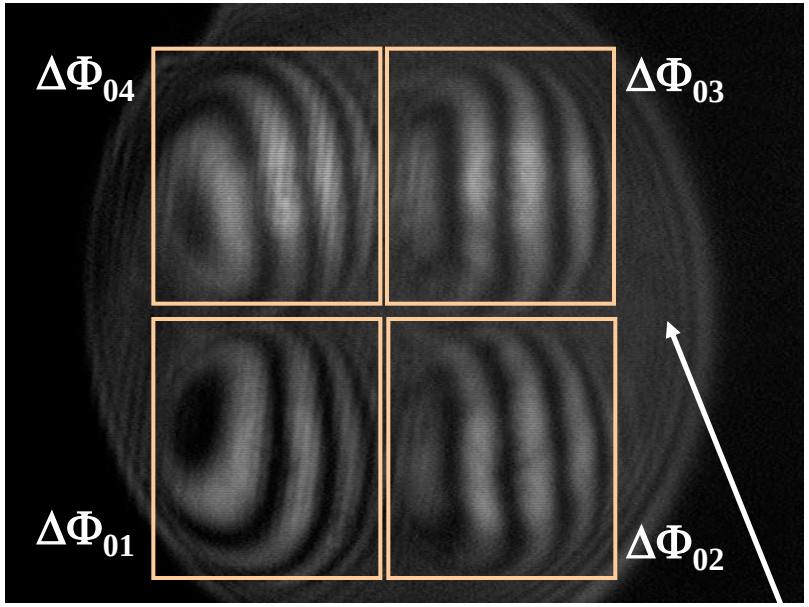
J. S. Shin, S. Park, H. J. Kong, and J. W. Yoon, Applied Physics Letters. 96.131116, 2010.

4-beam output profile & Interference patterns

4-beam combined output profile



Interference patterns at CCD camera



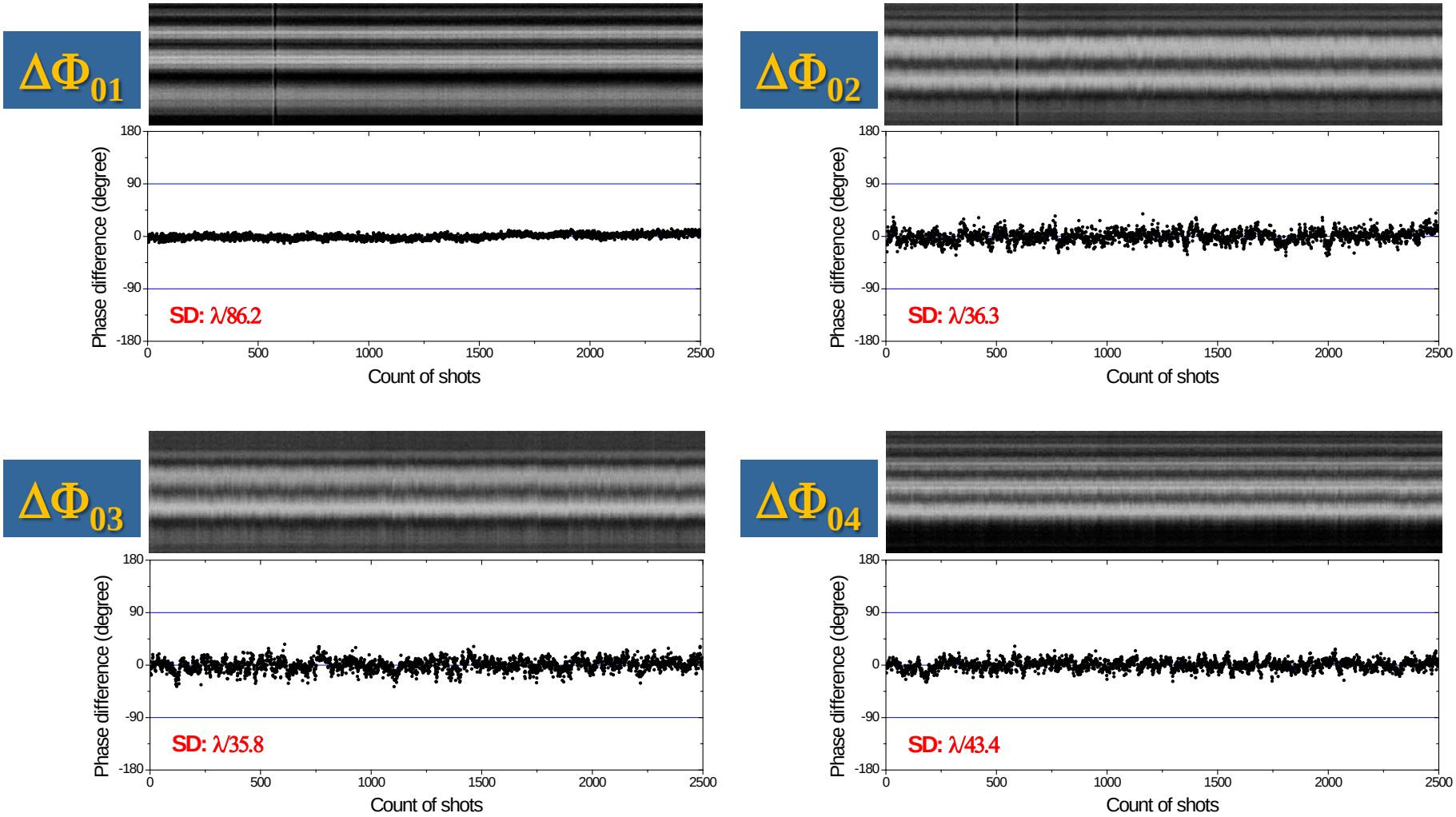
0: Reference beam

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



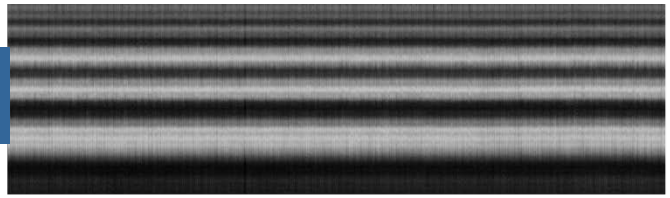
J. S. Shin, S. Park, H. J. Kong, and J. W. Yoon, Applied Physics Letters. 96.131116, 2010.

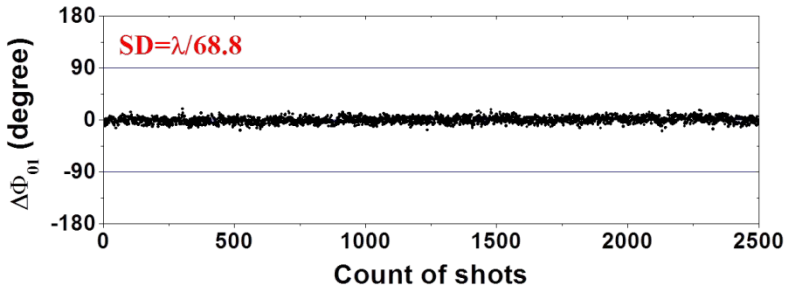
Beam Energy – AMP on case

- **Input energy :** 32.2 ± 0.3 mJ
- **Output energy**
  - AMP off : 169 ± 6 mJ (gain : 5.3)

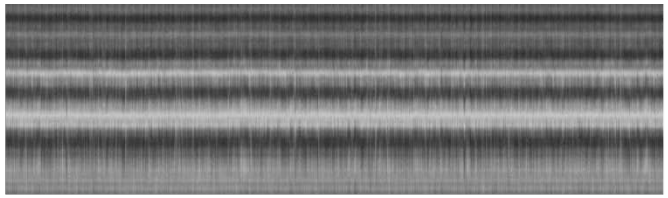
Phase fluctuation with amplifier operation

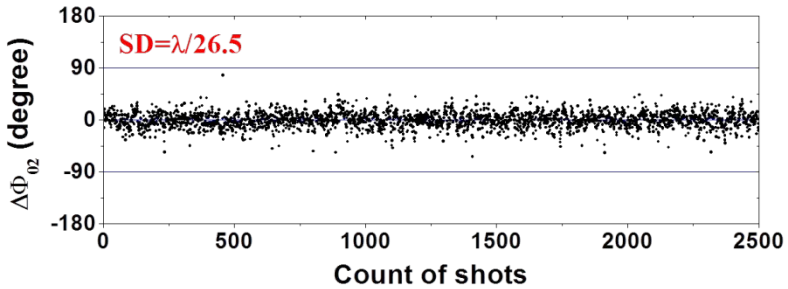
$\Delta\Phi_{01}$



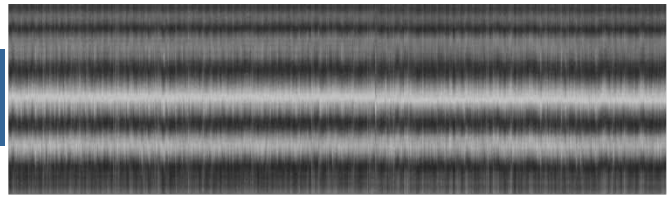


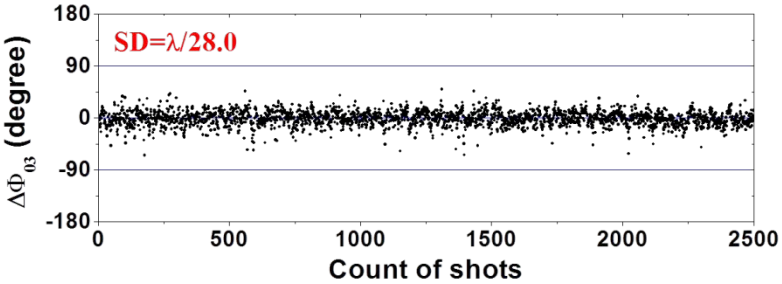
$\Delta\Phi_{02}$



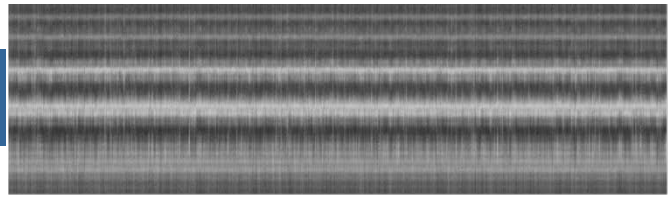


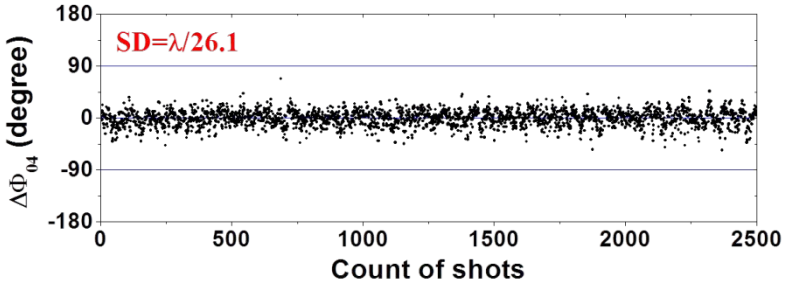
$\Delta\Phi_{03}$



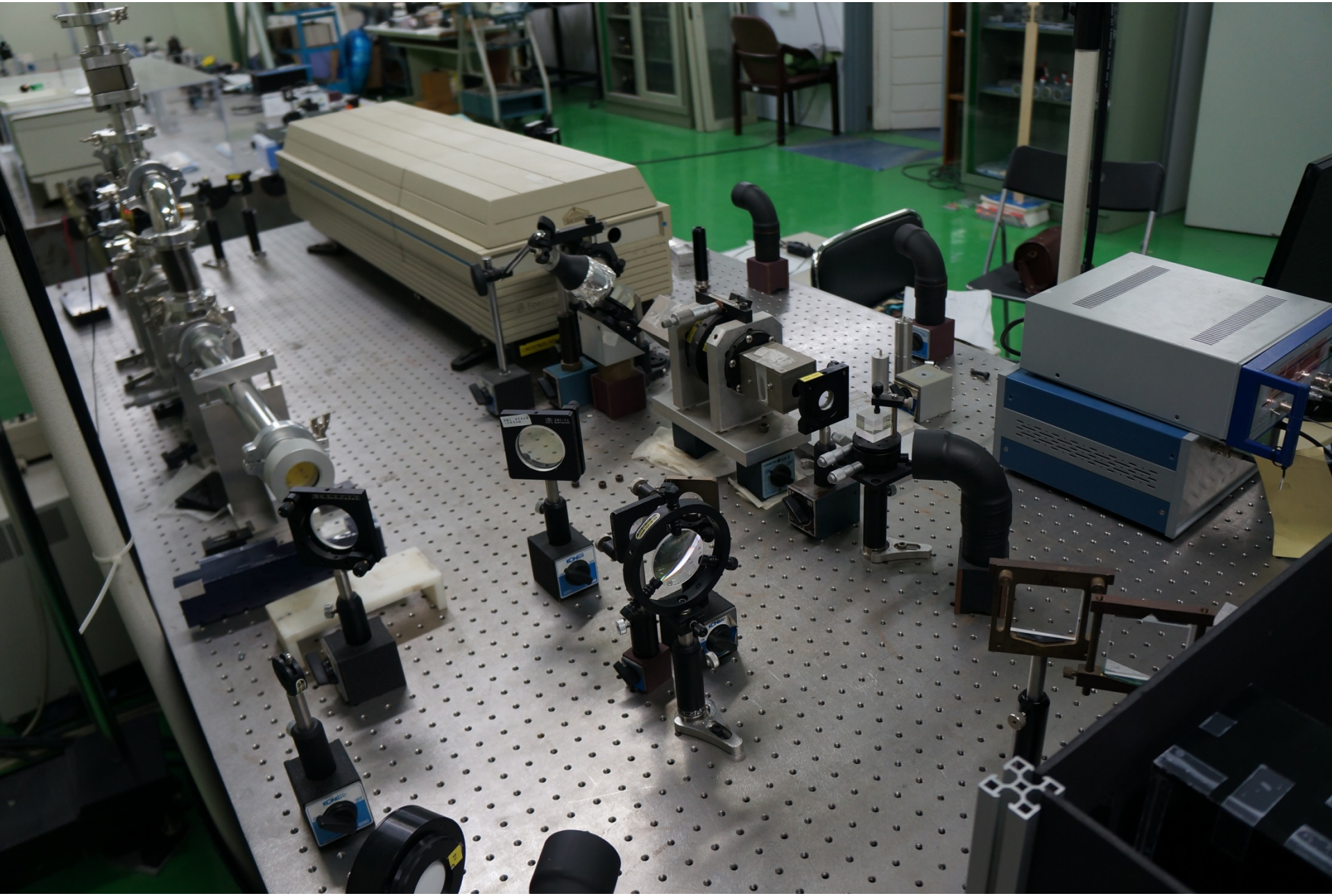


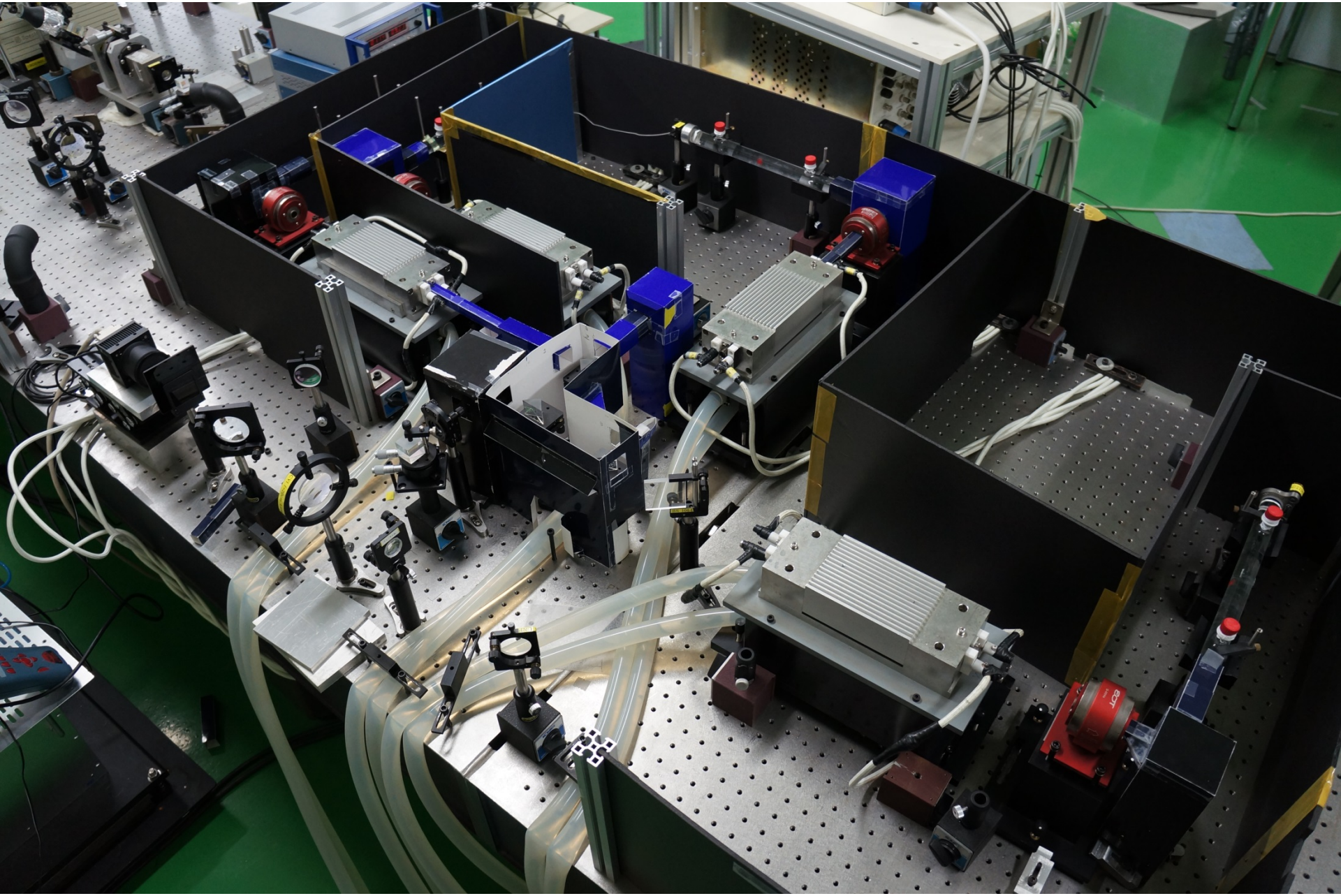
$\Delta\Phi_{04}$

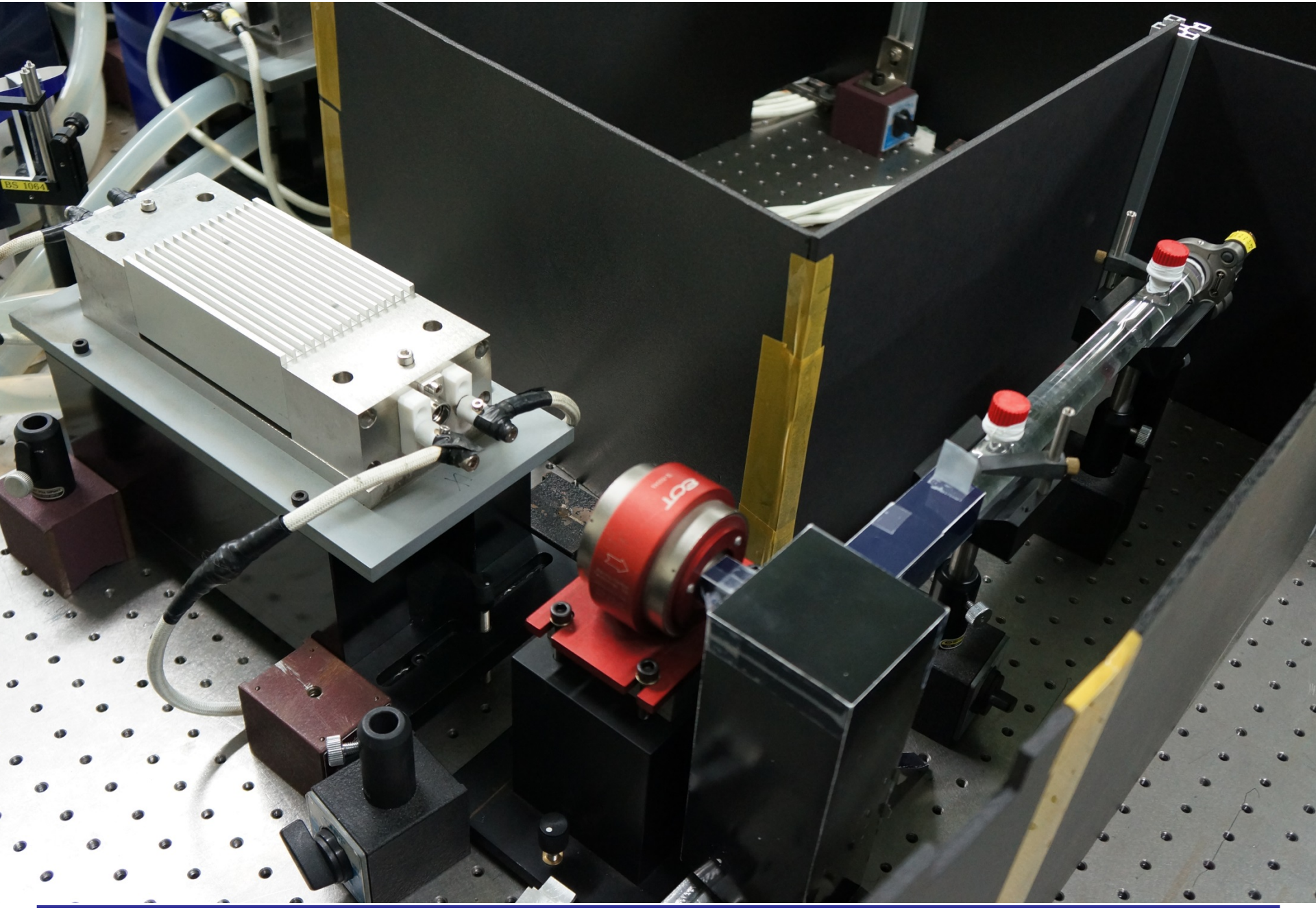


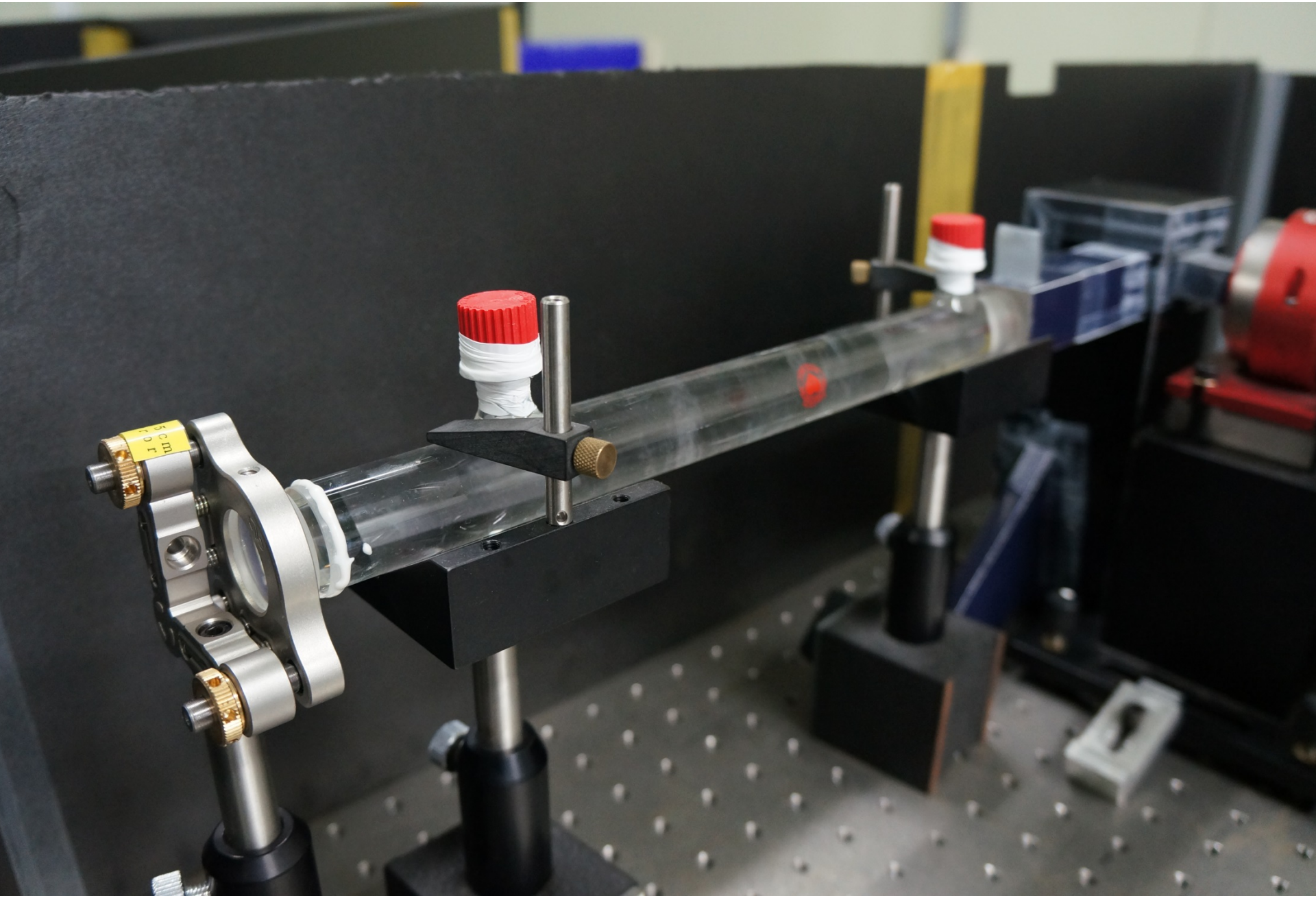


J. S. Shin, S. Park, H. J. Kong, and J. W. Yoon, Applied Physics Letters. 96.131116, 2010.

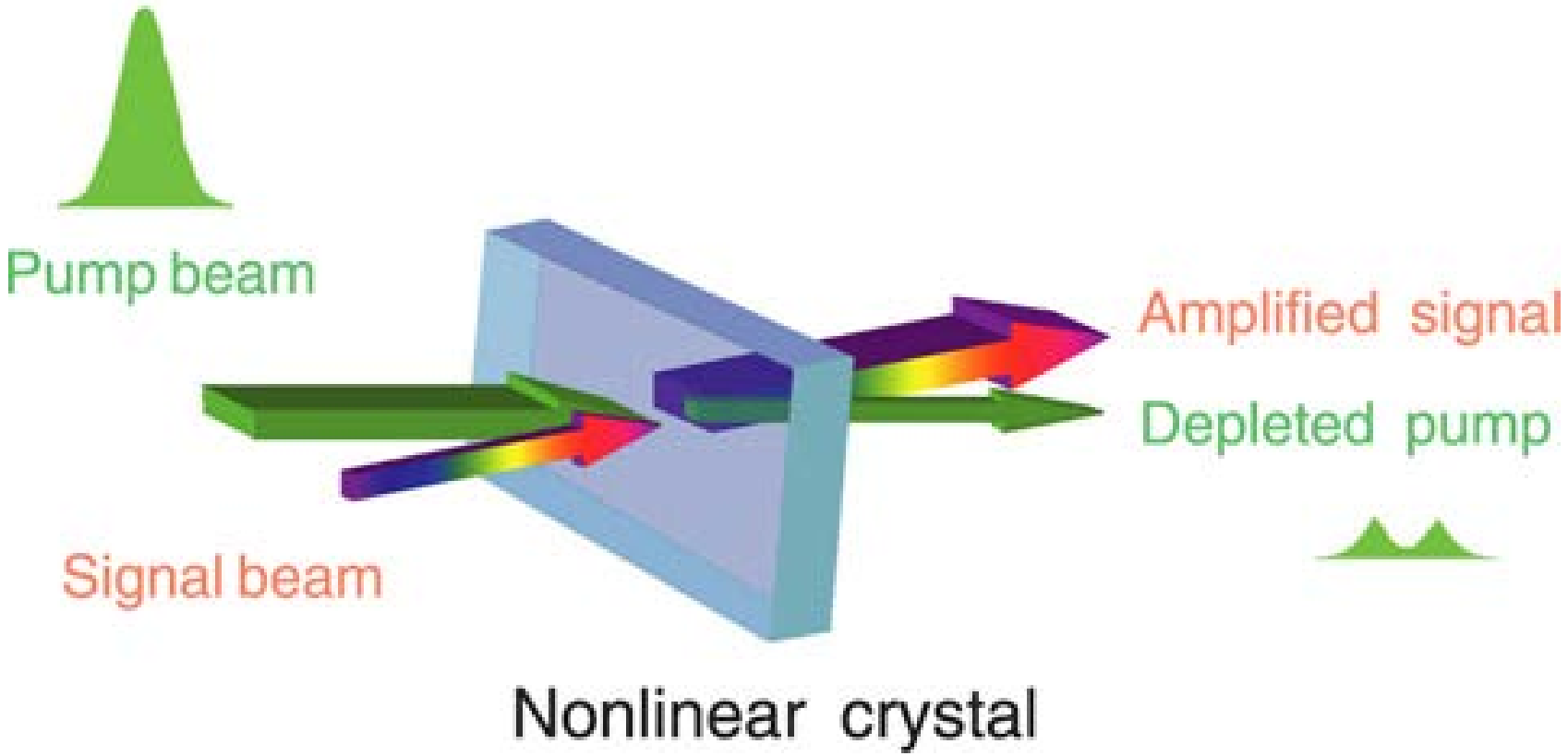




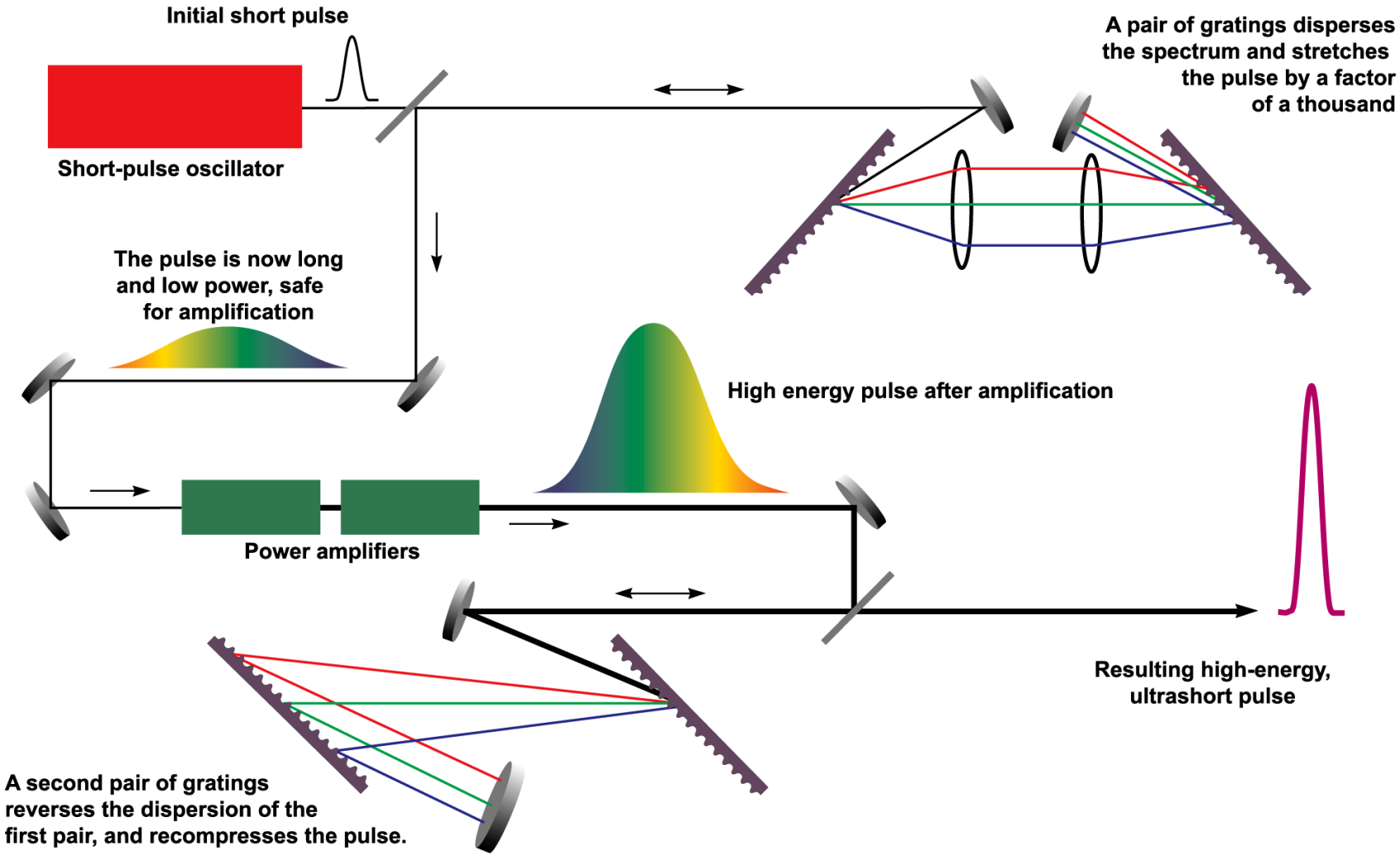




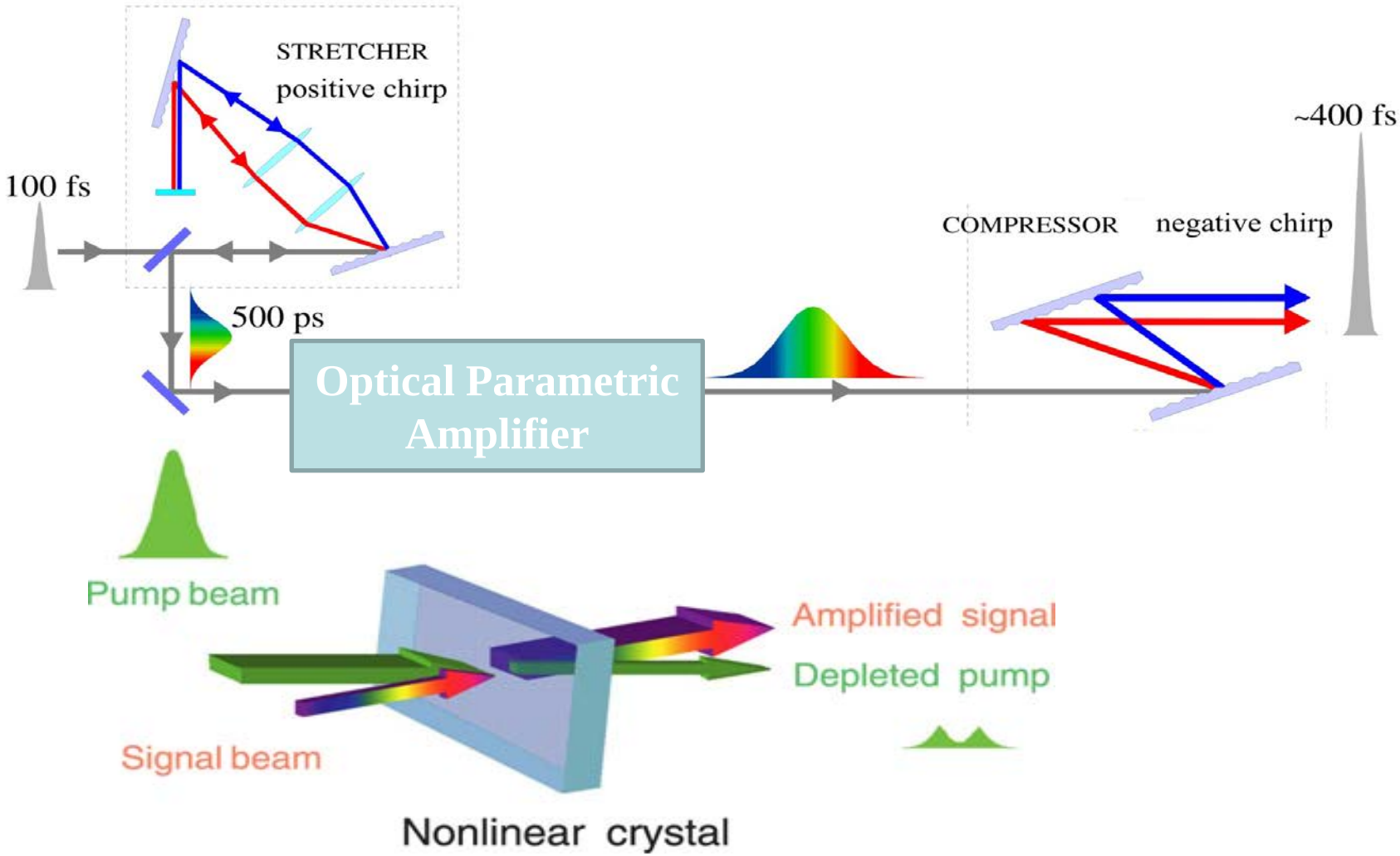
OPA: Optical Parametric Amplification



CPA

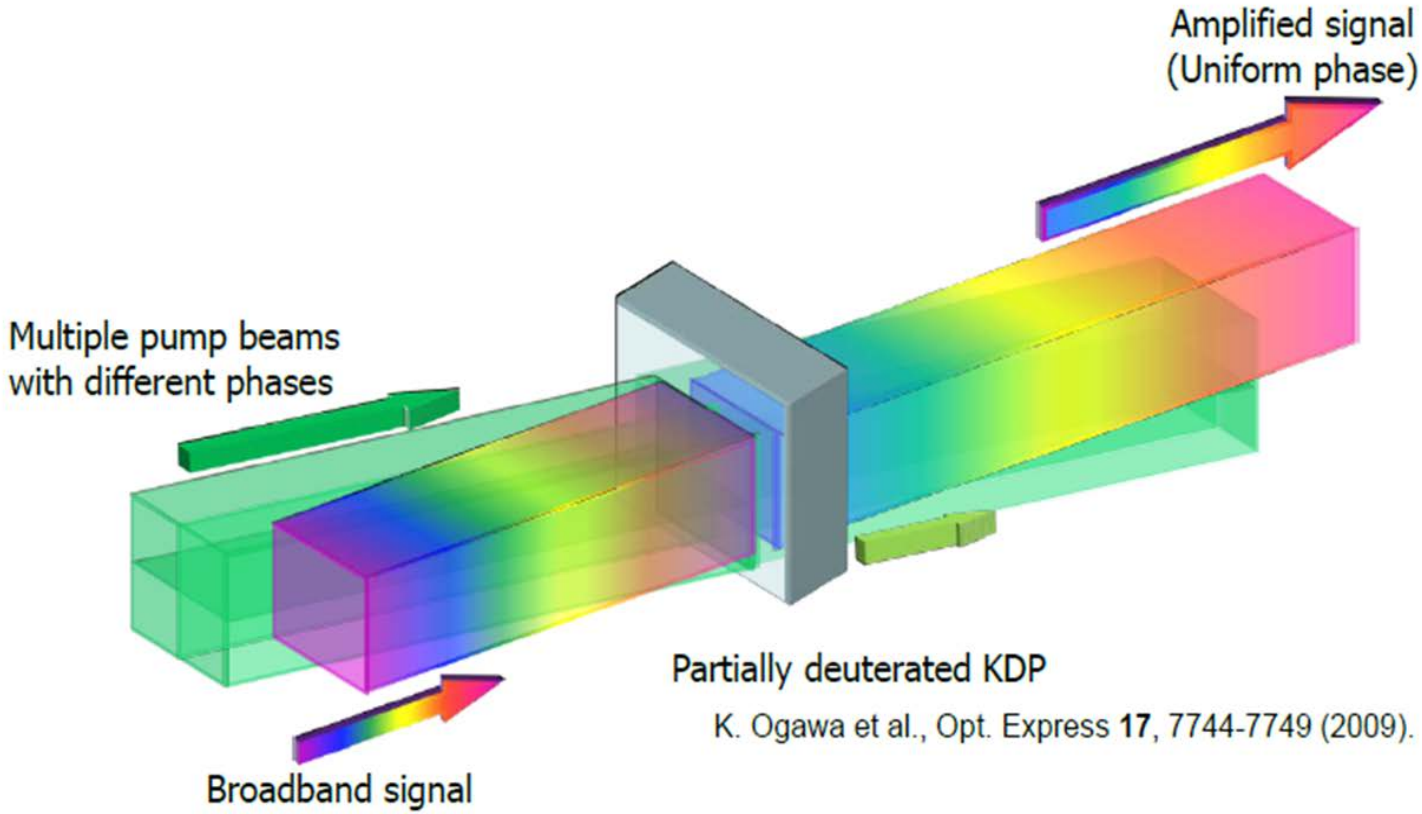

Initial short pulse
Short-pulse oscillator
A pair of gratings disperses the spectrum and stretches the pulse by a factor of a thousand
The pulse is now long and low power, safe for amplification
High energy pulse after amplification
Power amplifiers
Resulting high-energy, ultrashort pulse
A second pair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

10 X 10 Beam combination

10J@10kHz

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

2nd step ($25M, 5years from June of 2013)

10J@10Hz

4 Beam combination

40J@10Hz

10 X 10 Beam combination

1kJ@10Hz

>100J@10Hz

4 Beam combination

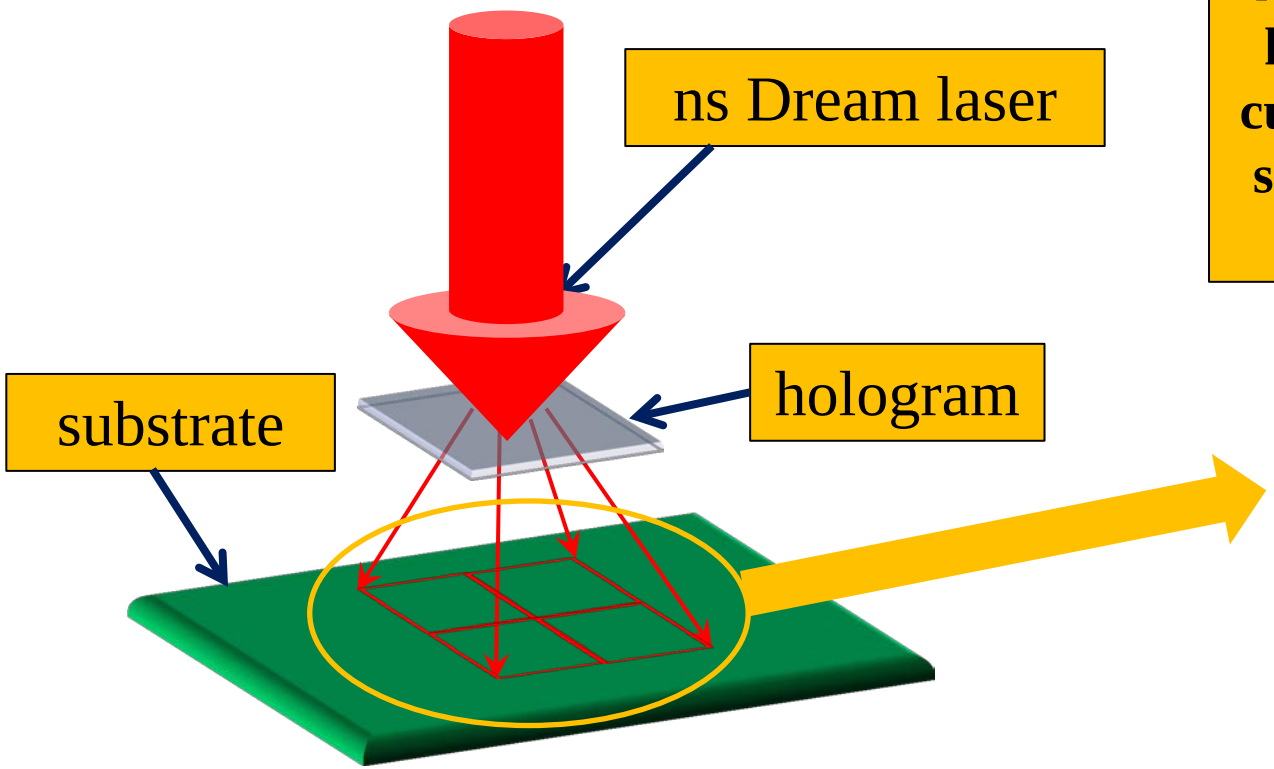
>400J@10Hz

10 X 10 Beam combination

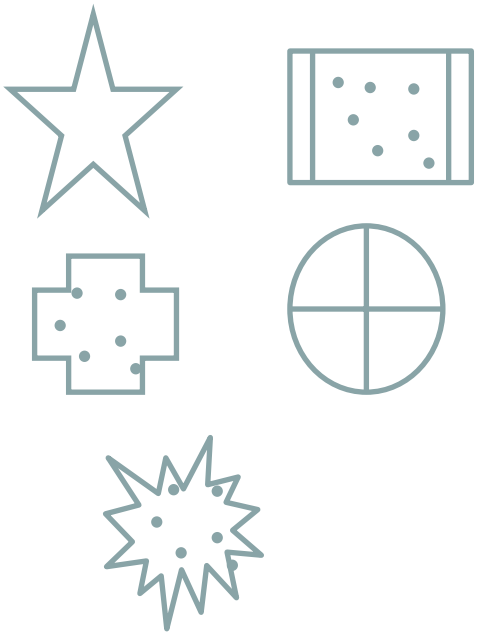
>10kJ@10Hz

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

2D Laser machining by hologram

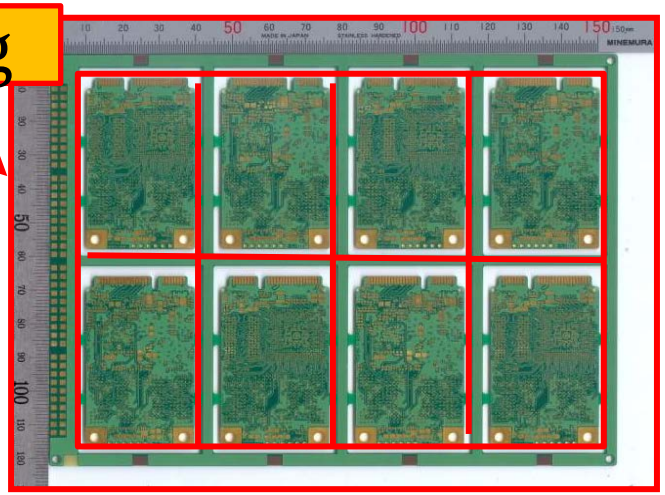


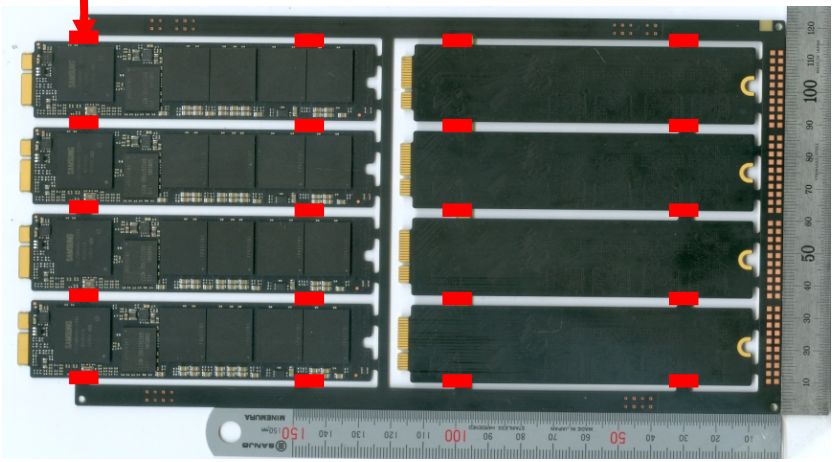
Any Patterns and many holes can be machined, cutting, welding, drilling, surface treating without scanning



Laser machining by hologram pattern

cutting





Conventional laser processing

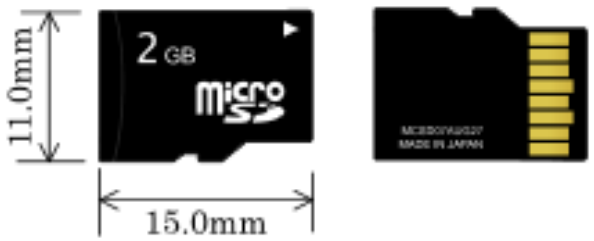
1. straight-line cut by sawing

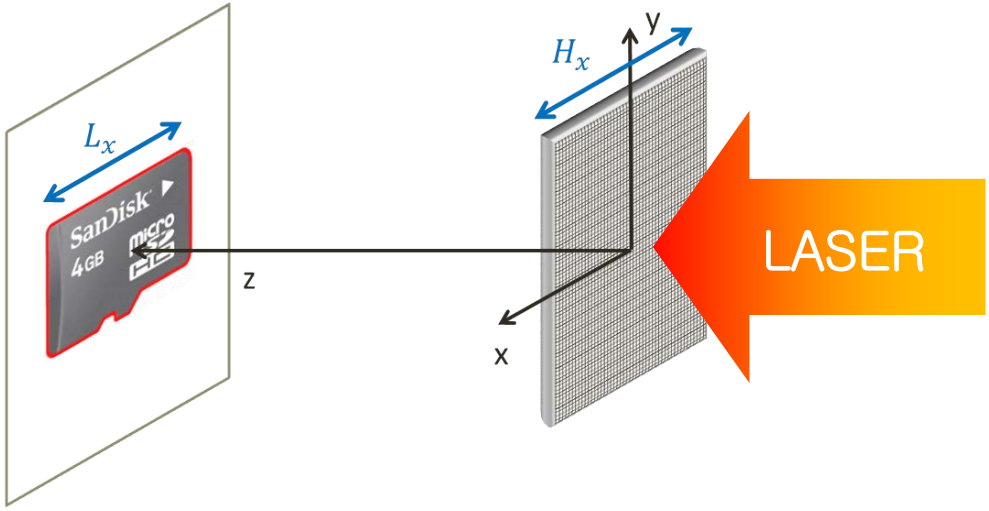
2. round edge

3. curved-line

One-shot processing

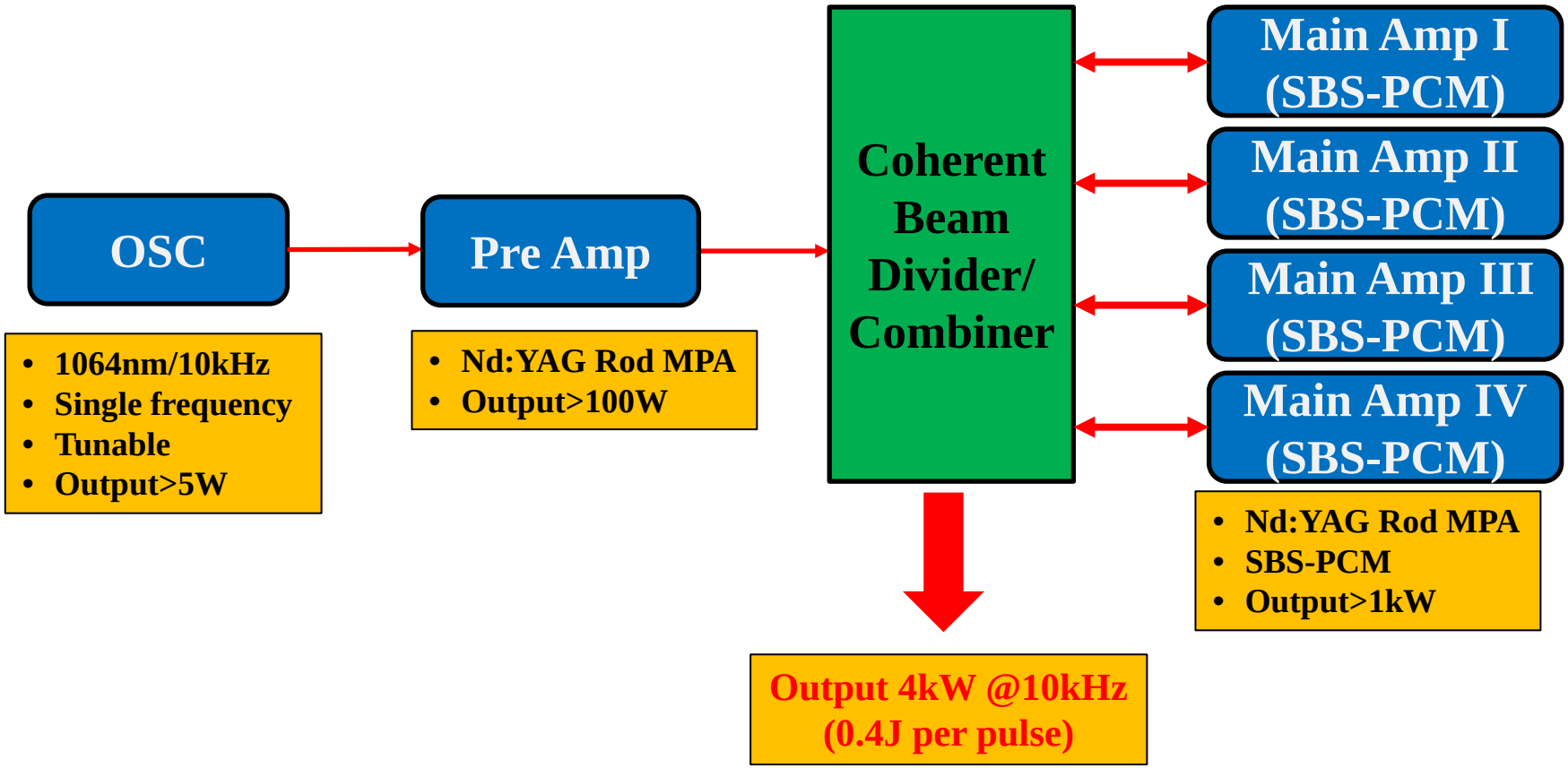
Laser machining of μ-SD card by hologram





4 beam combination of 0.1J@10ns@10kHz laser modules

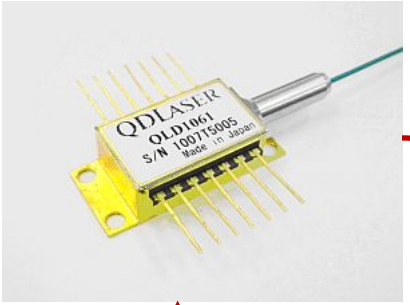
Laser System Configuration



Front-End system

CW Diode Oscillator

CW Oscillator
(30mW @1064nm, <1MHz)
(0.08nm/K, 0.008nm/mA)

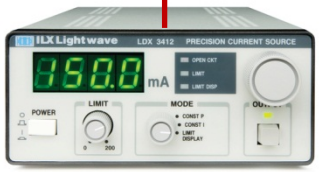


AOM

To Yb-fiber pre-amp

10ns @10kHz
Duty cycle=0.01%
Ave power=0.2uW
0.02nJ/pulse

Driver



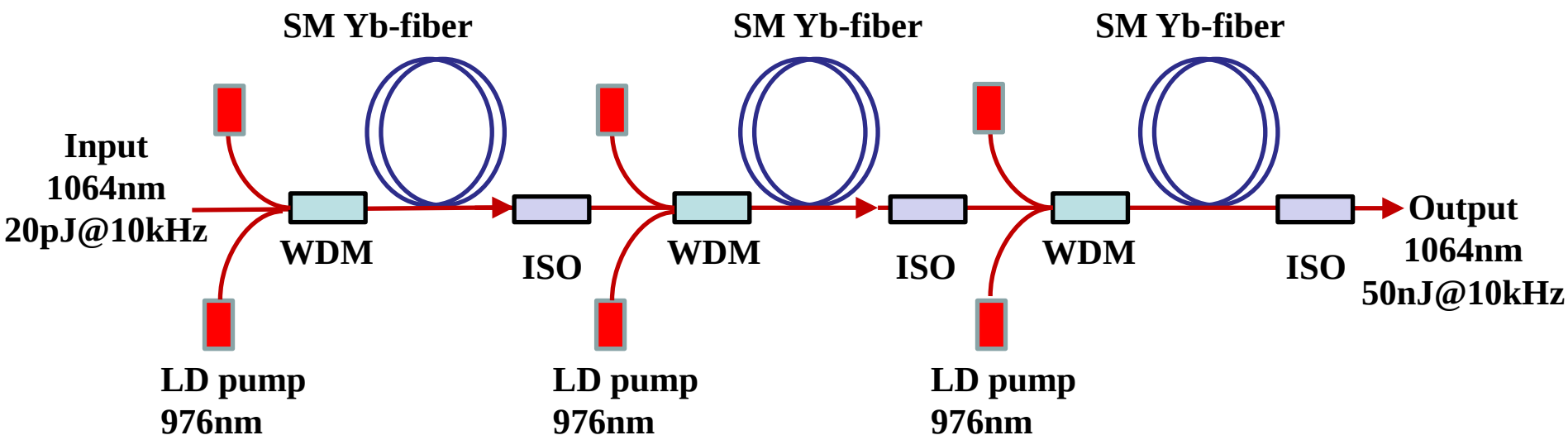
RF Driver

TEC

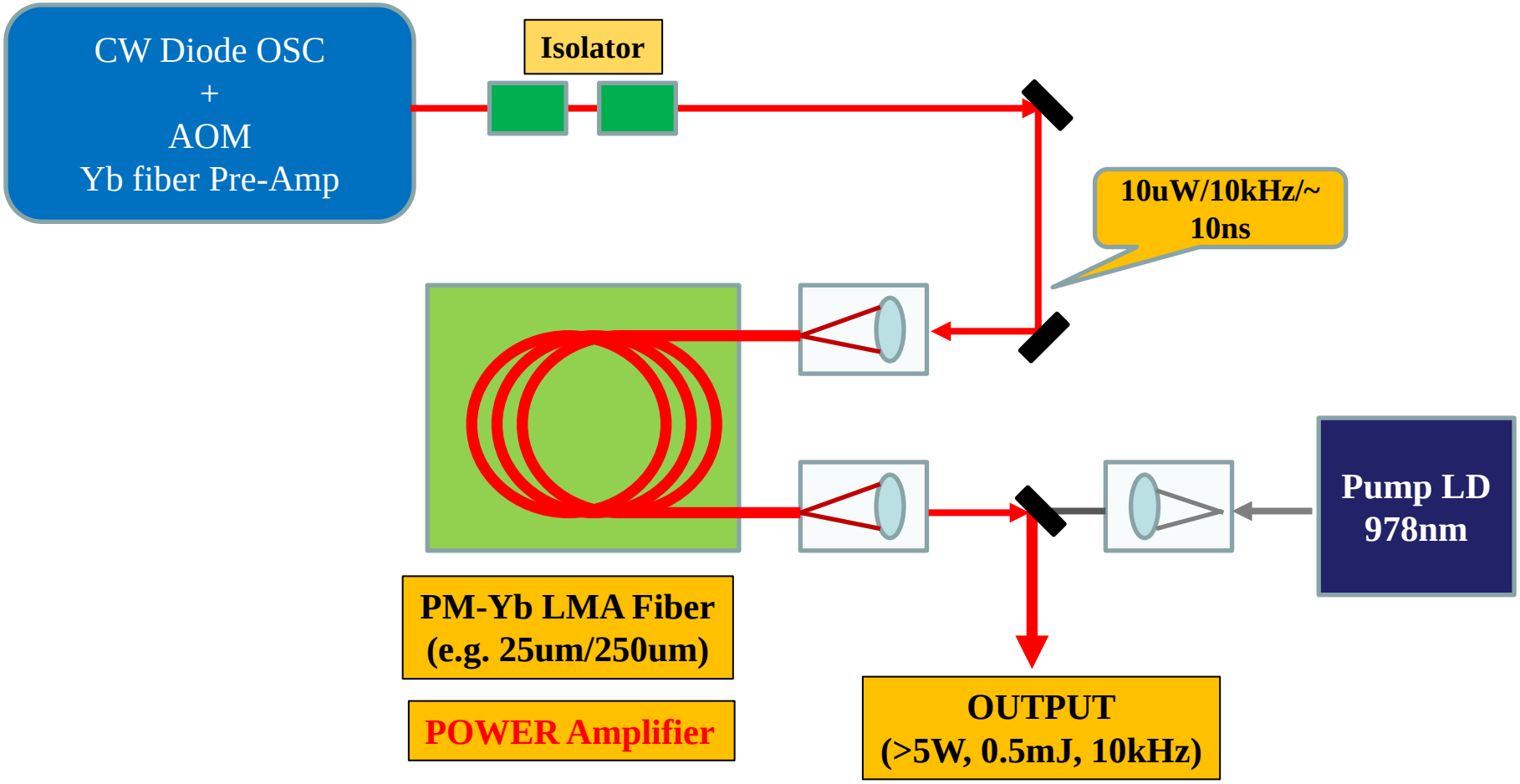
AWG

*Arbitrary waveform generator

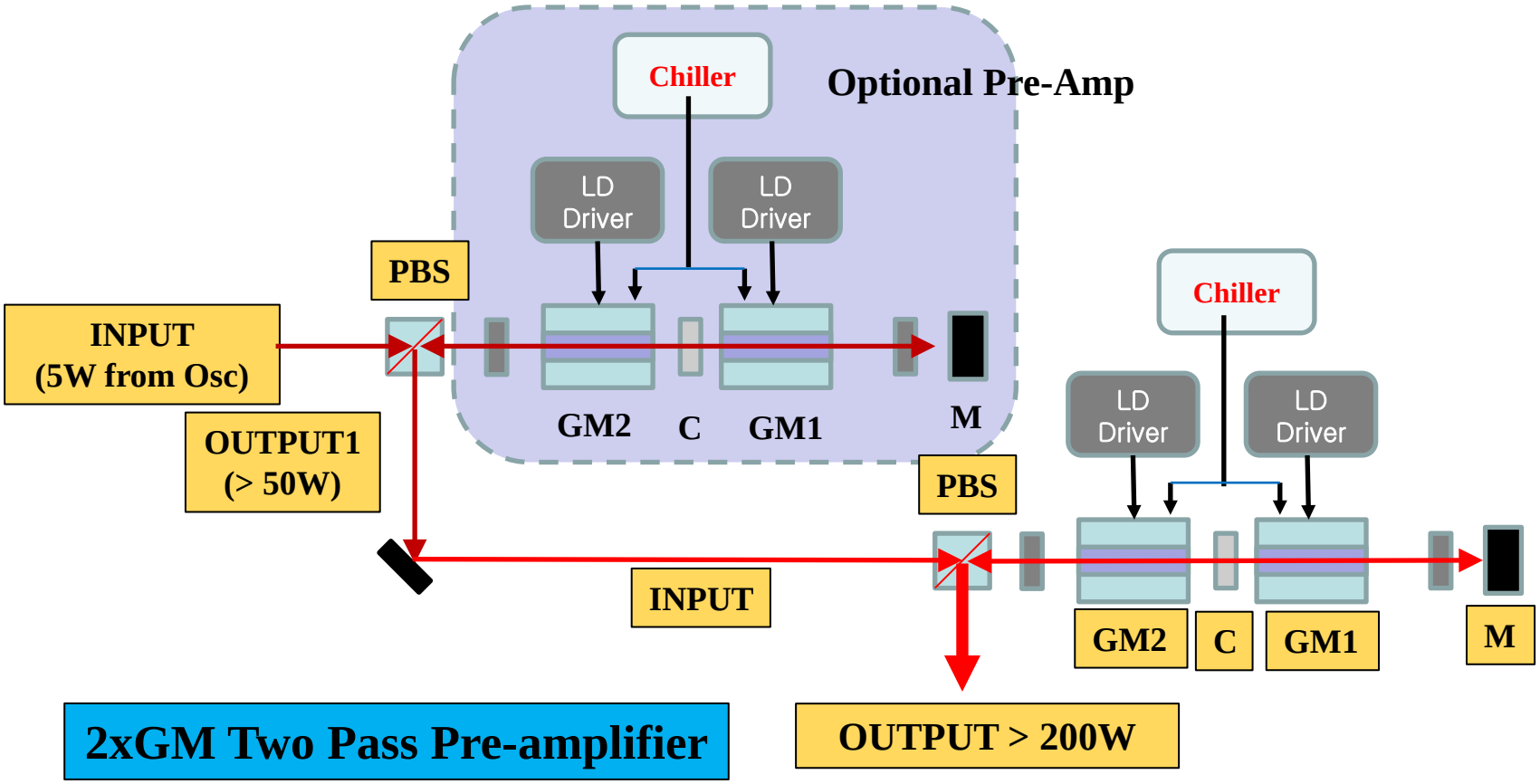
Fiber pre-Amp



Yb Fiber Power Amp

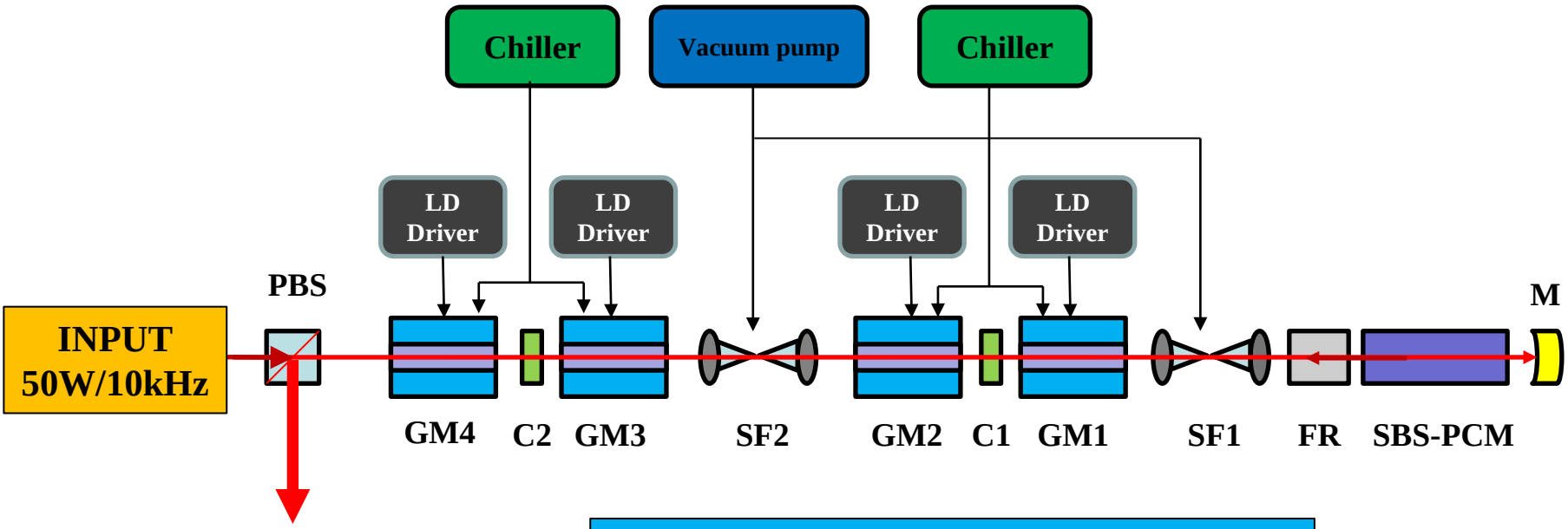


Rod Pre-Amp Module



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

Rod Main Amp Module (x1)



OUTPUT
(1kW, 01.J@10kHz, 10ns)

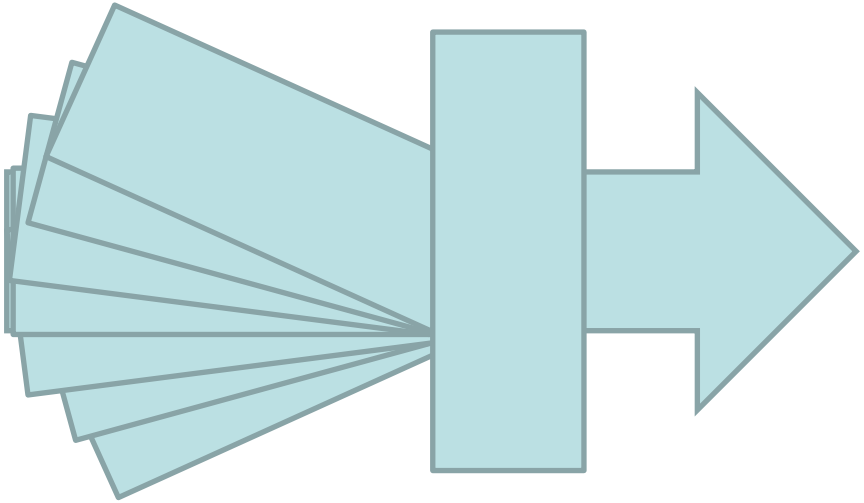
4xGM Two Pass Amplifier (>1kW)

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)

Conclusion

- **0.1J@10ns@10kHz** laser modules has been designed and is being tested.
- 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.

Amplitude Dividing scheme



Good for 10kHz repetition rate (LOCSET)

How to measure and control the Phases for low repetition rate???

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

Publications

1. H. J. Kong, J. Y. Lee, Y. S. Shin, J. O. Byun, H. S. Park, and H. Kim, “Beam recombination characteristics in array laser amplification using stimulated Brillouin scattering phase conjugation,” Optical Review **4**, 277-283, 1997.
2. H. J. Kong, Y. G.. Kang, A. Ohkubo, H. Yoshida, M. Nakatsuka, “Complete isolation of the back reflection by stimulated Brillouin scattering phase conjugation,” Review of Laser Engineering (Reza Kenkyu) **26**, 138-140, 1998.
3. H. J. Kong, Y. S. Shin, and H. Kim, “Beam combination characteristics in an array laser using stimulated Brillouin scattering phase conjugation mirrors considering partial coherency between the beams,” Fusion Engineering and Design **44**, 407-417, 1999.
4. H. J. Kong, S. K. Lee, J. J. Kim, Y. G. Kang, and H. Kim, “A cross type double pass laser amplifier with two symmetric phase conjugation mirrors using stimulated Brillouin scattering,” Chinese Journal of Lasers **B10 Supplement**, I5-I9, 2001.
5. H. J. Kong, Y. J. Kwon, S. K. Lee, J. J. Kim, and Y. G. Kang, “The dependence of the reflectivity of a stimulated Brillouin scattering phase-conjugate mirror on the pumping laser mode", Chinese Journal of Lasers **B10 Supplement**, III20-III23, 2001.
6. S. K. Lee, D. W. Lee, H. J. Kong, and H. Guo, “Stimulated Brillouin scattering by a multi-mode pump with a large number of longitudinal modes,” Journal of the Korean Physical Society **46**, 443-447, 2005.

Publications

7. H. J. Kong, S. K. Lee, and D. W. Lee, “Beam combined laser fusion driver with high power and high repetition rate using stimulated Brillouin scattering phase conjugation mirrors and self-phase-locking,” Laser and Particle Beams **23**, 55-59, 2005.
8. H. J. Kong, S. K. Lee, and D. W. Lee, “Highly repetitive high energy/power beam combination Laser: IFE laser driver using independent phase control of stimulated Brillouin scattering phase conjugate mirrors and pre-pulse technique,” Laser and Particle Beams **23**, 107-111, 2005.
9. S. K. Lee, H. J. Kong, and M. Nakatsuka, “Great improvement of phase control of the entirely independent stimulated Brillouin scattering phase conjugate mirrors by balancing the pump energies,” Applied Physics Letters **87**, 161109, 2005.
10. H. J. Kong, D. H. Beak, and D. W. Lee, “Waveform preservation of the backscattered stimulated Brillouin scattering wave by using a prepulse injection,” Optics Letters **30**, 3401-3403, 2005.
11. H. J. Kong, S. K. Lee, J. W. Yoon, and D. H. Beak, “Beam combination using stimulated Brillouin scattering for the ultimate high power-energy laser system operating at high repetition rate over 10 Hz for laser fusion driver,” Optical Review **13**, 119-128, 2006.
12. H. J. Kong, J. W. Yoon, J. S. Shin, D. H. Beak, and B. J. Lee, “Long term stabilization of the beam combination laser with a phase controlled mirrors for the laser fusion driver,” Laser and Particle Beams **24**, 519-523, 2006.

Publications

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.

Publications

18. M. Ostermeyer, H.J. Kong, V.I. Kovalev, R.G. Harrison, A.A. Fotiadi, P. Mégret, M. Kalal, O. Slezak, J.W. Yoon, J.S. Shin, D.H. Beak, S.K. Lee, Z. Lü, S. Wang, D. Lin, J.C. Knight, N.E. Kotova, A. Sträßer, A. Scheikh-Obeid, T. Riesbeck, S. Meister, H.J. Eichler, Y. Wang, W. He, H. Yoshida, H. Fujita, M. Nakatsuka, T. Hatae, H. Park, C. Lim, T. Omatsu, K. Nawata, N. Shiba, O.L. Antipov, M.S. Kuznetsov and N.G. Zakharov, "Trends in stimulated Brillouin scattering and optical phase conjugation", Laser and Particle Beams **26**, 297-362, 2008.
19. D. H. Beak, J. W. Yoon, J. S. Shin, and H. J. Kong, "Restoration of high spatial frequency at the image formed by stimulated Brillouin scattering with a prepulse," Applied Physics Letters **93**, 231113, 2008.
20. H. J. Kong, D. H. Beak, J. W. Yoon, and J. S. Shin, "Proposal of the practical laser fusion driver operating at high repetition rate over 10Hz by a beam combination technique using phase controlled stimulated Brillouin scattering mirrors," Journal of Physics: Conference Series **112**, 032034, 2008.
21. M. Kalal, M. Martinkova, O. Slezak, H. J. Kong, and N. B. Alexander, "SBS PCM technique and its possible role in achieving IFE objectives," Journal of Physics: Conference Series **112**, 032049, 2008.
22. J. W. Yoon, J. S. Shin, D. H. Beak, and H. J. Kong, "Piston error characteristics of the self-phase-controlled stimulated Brillouin scattering phase conjugate mirrors," Optics Communications **282**, 1000–1003, 2009.

Publications

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.
24. H. J. Kong, J. S. Shin, J. W. Yoon, and D. H. Beak, “Wave-front dividing beam combined laser fusion driver using stimulated Brillouin scattering phase conjugation mirrors,” Nuclear Fusion **49**, 125002, 2009.
25. J. W. Yoon, J. S. Shin, H. J. Kong, and J. Lee, “Investigation of the relationship between the prepulse energy and the delay time in the waveform preservation of a stimulated Brillouin scattering wave by prepulse injection,” Journal of the Optical Society of America B **26**, 2167–2170, 2009.
26. J. S. Shin, S. Park, H. J. Kong, “Compensation of the thermally induced depolarization in a double-pass Nd:YAG rod amplifier with a stimulated Brillouin scattering phase conjugate mirror,” Optics Communications **283**, 2402-2405, 2010.
27. H. J. Kong, J. S. Shin, D. H. Beak, and S. Park, “Current Trends in Laser Fusion Driver and Beam Combination Laser Systems Using Stimulated Brillouin Scattering Phase Conjugate Mirrors for a Fusion Driver,” Journal of the Korean Physical Society **56**, 177-183, 2010.

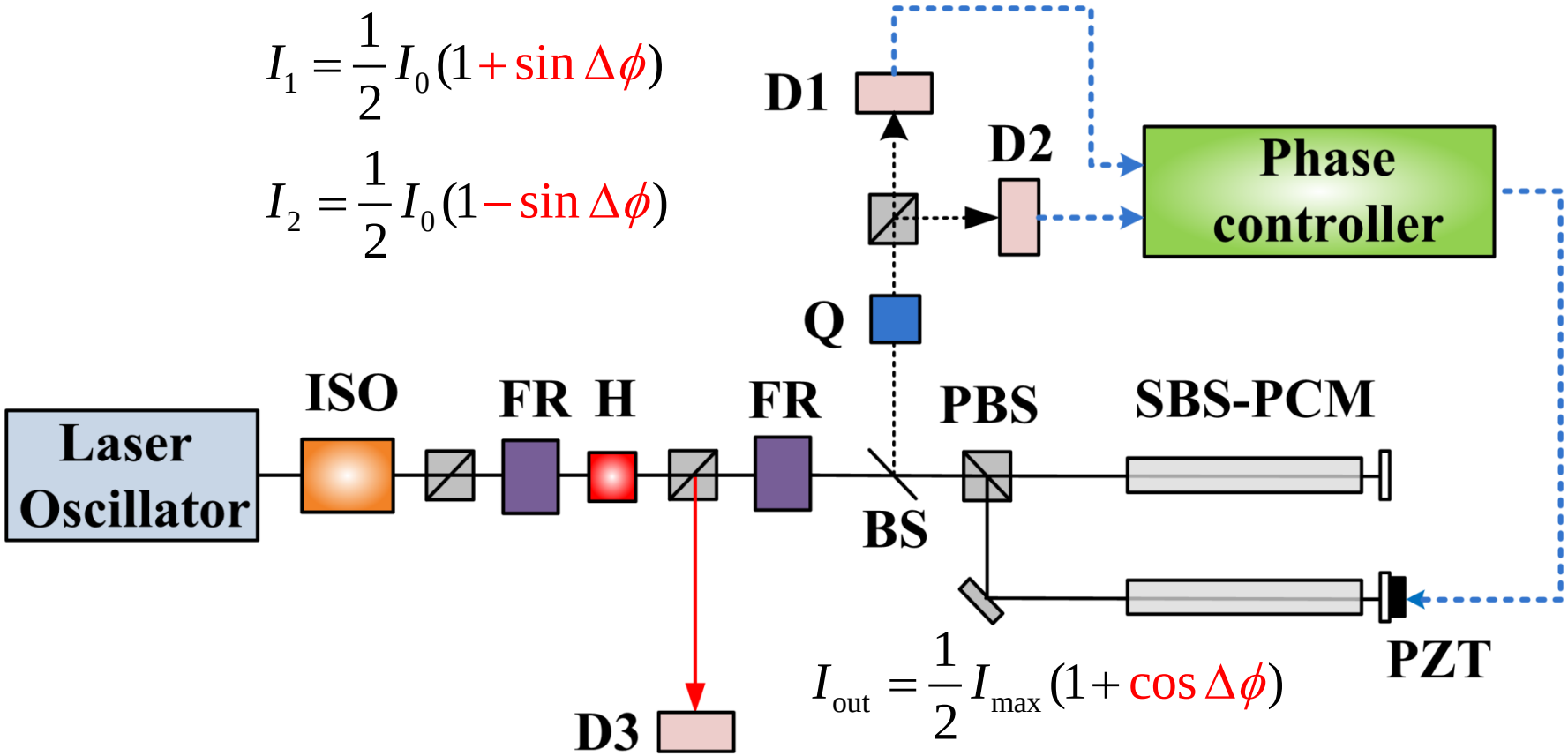
Publications

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.
29. J. S. Shin, S. Park, H. J. Kong, and J. W. Yoon, “Phase stabilization of a wave-front dividing four-beam combined amplifier with stimulated Brillouin scattering phase conjugate mirrors”, Applied Physics Letters **96**, 131116, 2010.
30. M. Kalal, H. J. Kong, O. Slezak, E. R. Koresheva, S. Park, S. A. Startsev, “Recent Progress Made in the SBS PCM Approach to Self-navigation of Lasers on Direct Drive IFE Targets”, J. Fusion Energ., **29**, 527–531, 2010
31. O. Slezak, M. Kalal, and H. J. Kong, “Phase control of SBS PCM seeding by optical interference pattern clarifed: Direct applicability for IFE laser driver”, Journal of Physics: Conference Series, **244**, 032026, 2010
32. M. Kalal, M. Martinkova, O. Slezak, H. J. Kong, J. W. Yoon, J. S. Shin, E. R. Koresheva and S. A. Startsev, “Current status of the SBS PCM approach to self-navigation of lasers on injected IFE pellets”, Journal of Physics: Conference Series, **244**, 032034, 2010

Experimental setup for the long-term phase stabilization

$$I_1 = \frac{1}{2} I_0 (1 + \sin \Delta\phi)$$

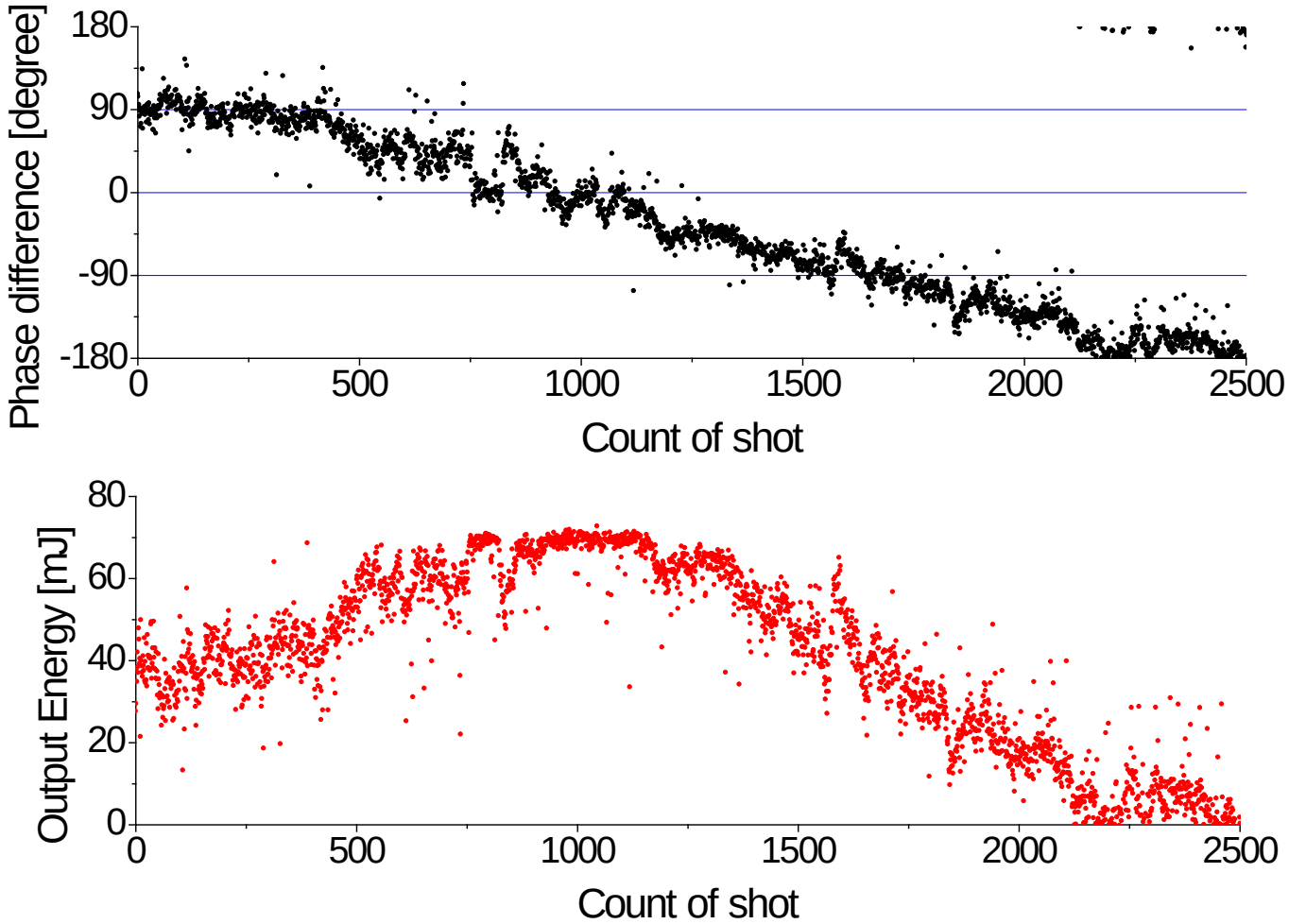
$$I_2 = \frac{1}{2} I_0 (1 - \sin \Delta\phi)$$



$$I_{out} = \frac{1}{2} I_{max} (1 + \cos \Delta\phi)$$

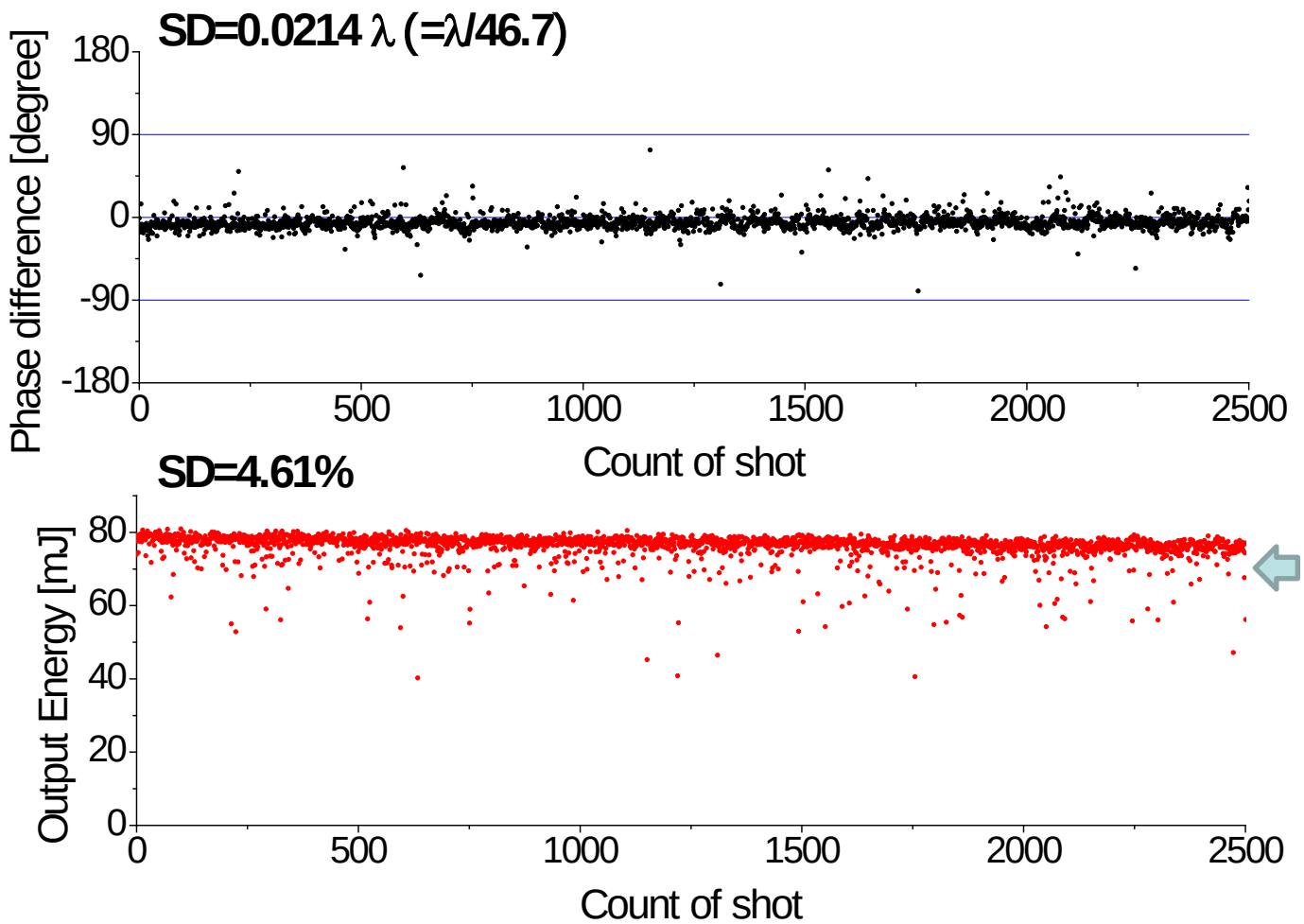
H. J. Kong, J. W. Yoon, J. S. Shin, and D. H. Beak, Applied Physics Letters 92, 021120, 2008.

Long-term phase fluctuation – No PZT control case



H. J. Kong, J. W. Yoon, J. S. Shin, and D. H. Beak, Applied Physics Letters 92, 021120, 2008.

Long-term stabilized result – PZT control case

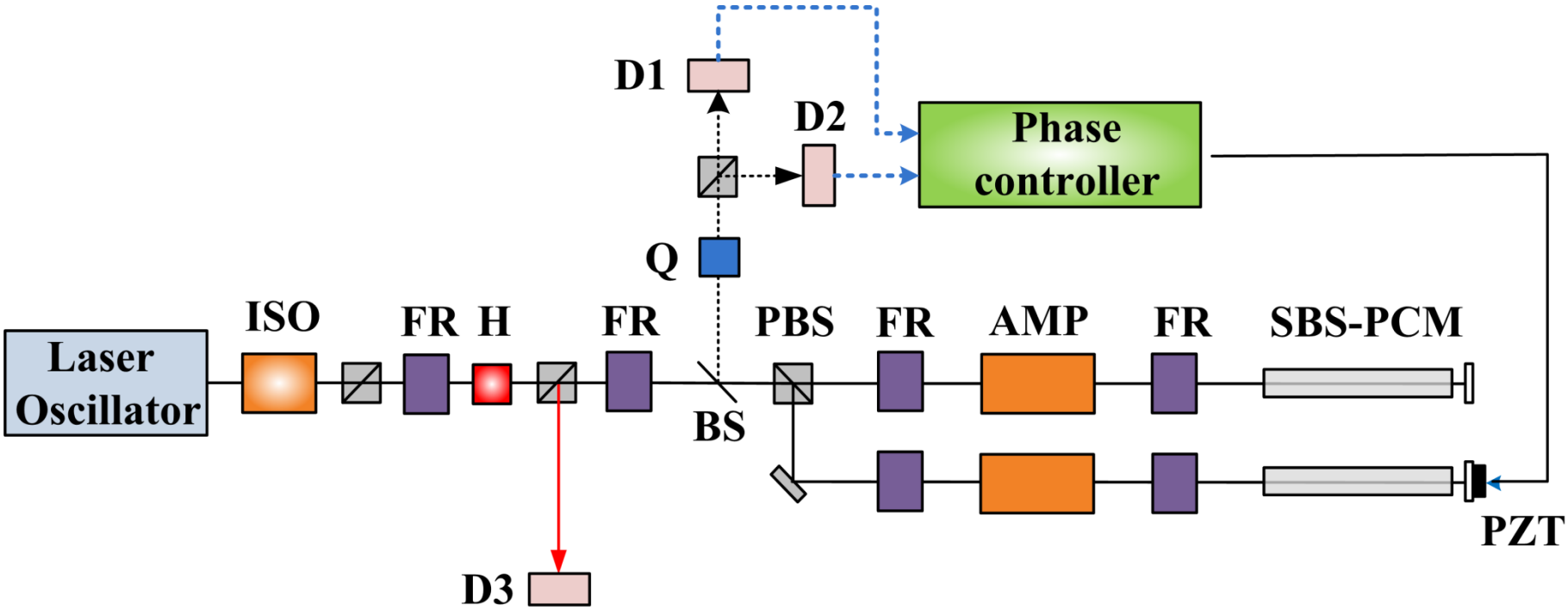


Max: 80.9mJ
Med: 77.1mJ
Mean:76.3mJ

(Reflectivity fluctuation: 1.34% & 1.42%)

H. J. Kong, J. W. Yoon, J. S. Shin, and D. H. Beak, Applied Physics Letters 92, 021120, 2008.

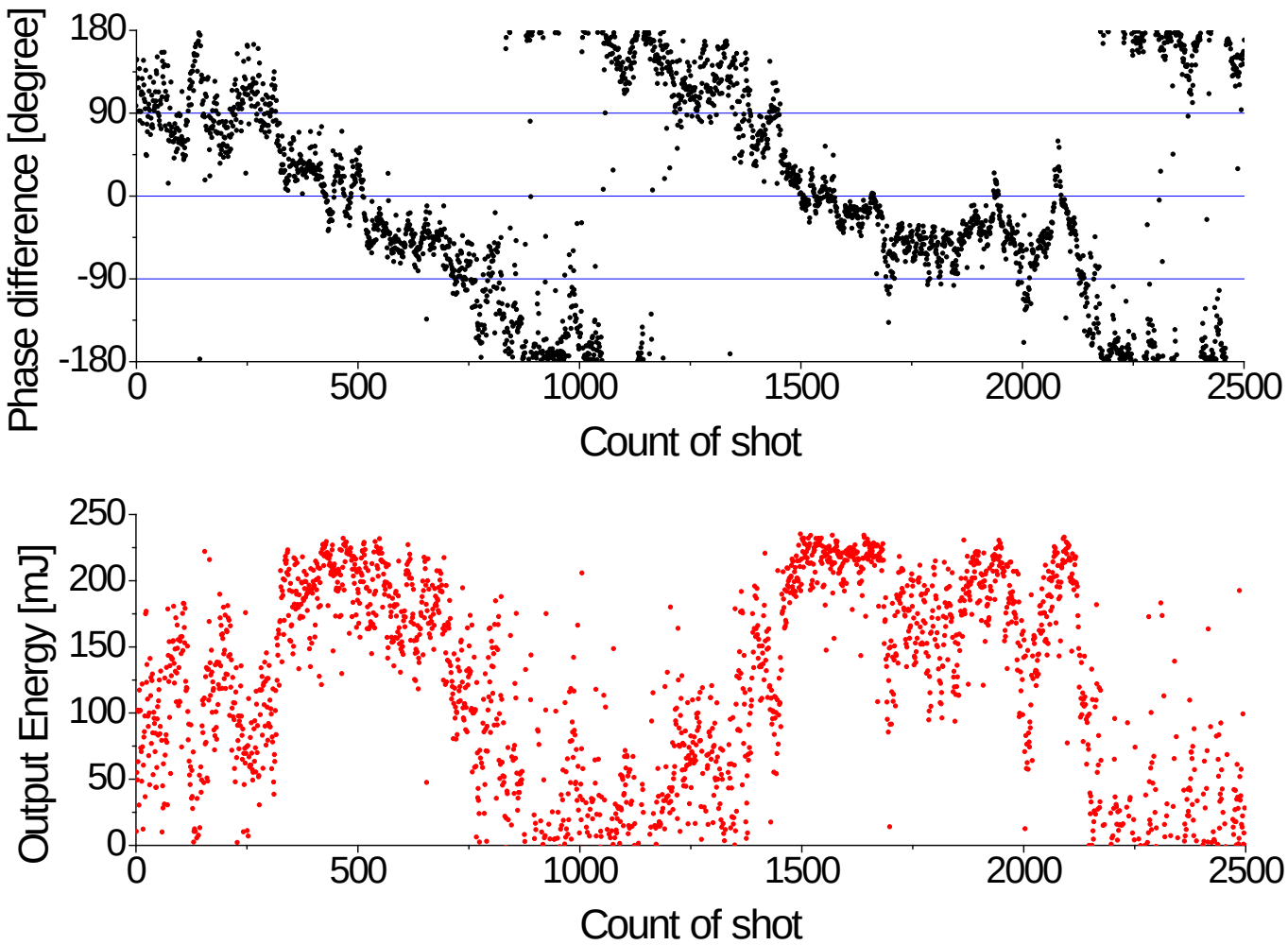
Experimental setup for the long-term phase stabilization with amplifiers



Experimental Setup for the Long Term Phase Stabilization (Amp operation case)

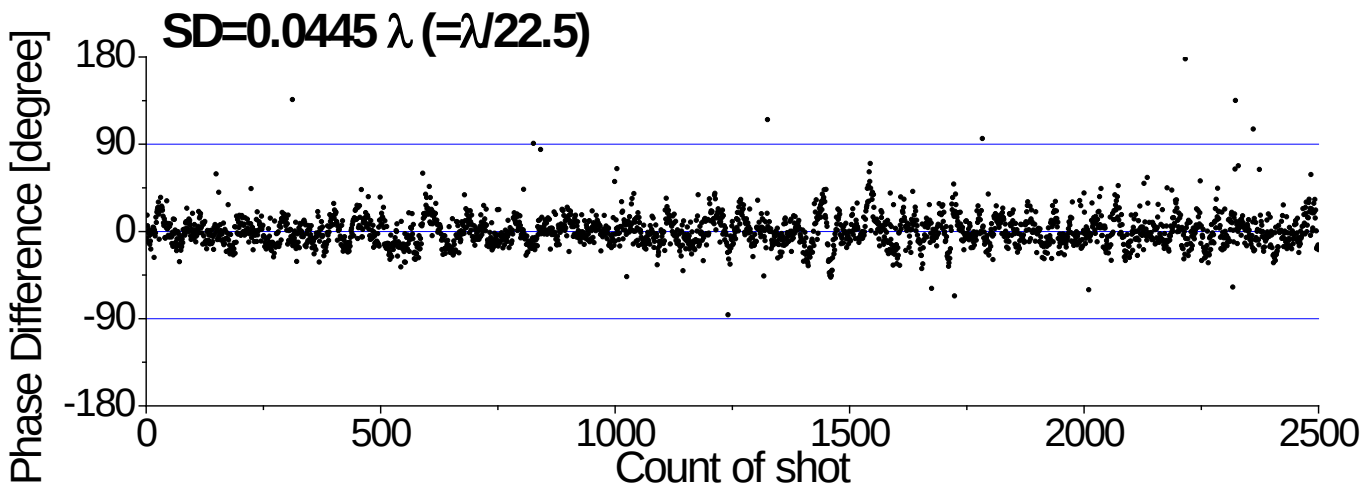
H. J. Kong, J. W. Yoon, J. S. Shin, and D. H. Beak, Applied Physics Letters 92, 021120, 2008.

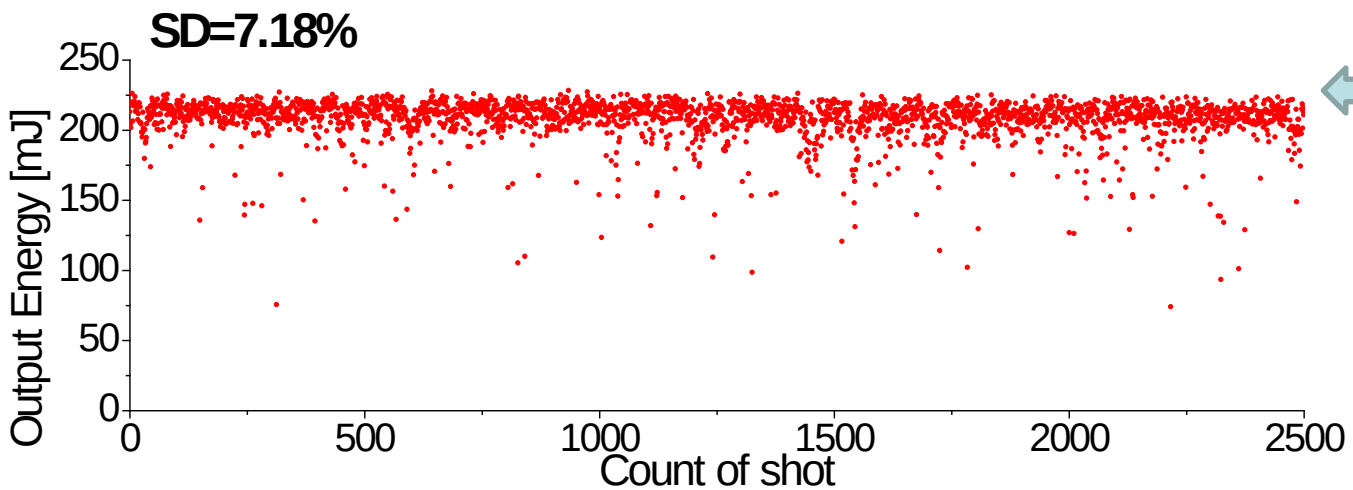
Long-term phase fluctuation – No PZT control case



H. J. Kong, J. W. Yoon, J. S. Shin, and D. H. Beak, Applied Physics Letters 92, 021120, 2008.

Long-term stabilized result – PZT control case

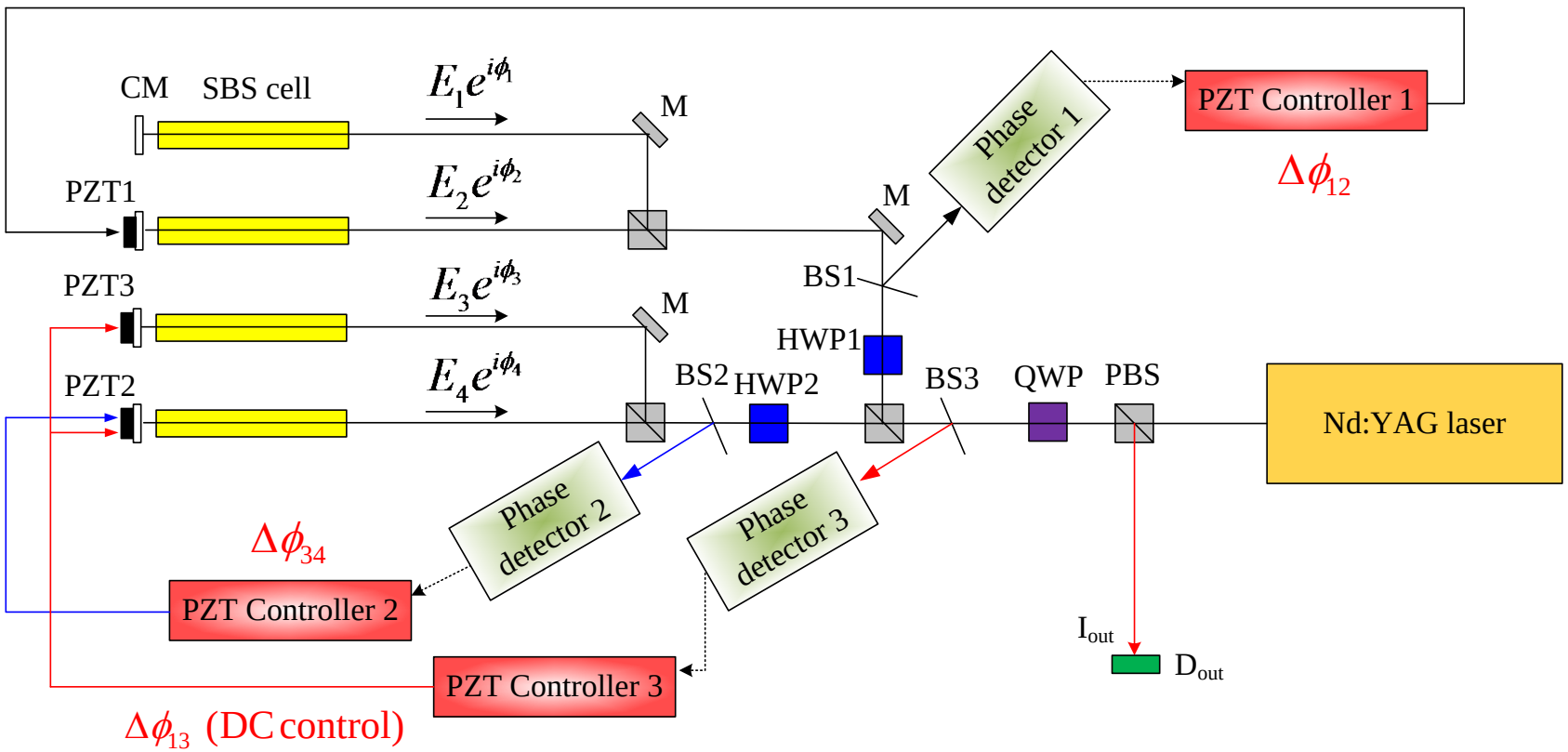




Max: 228 mJ
Med: 211 mJ
Mean: 208mJ

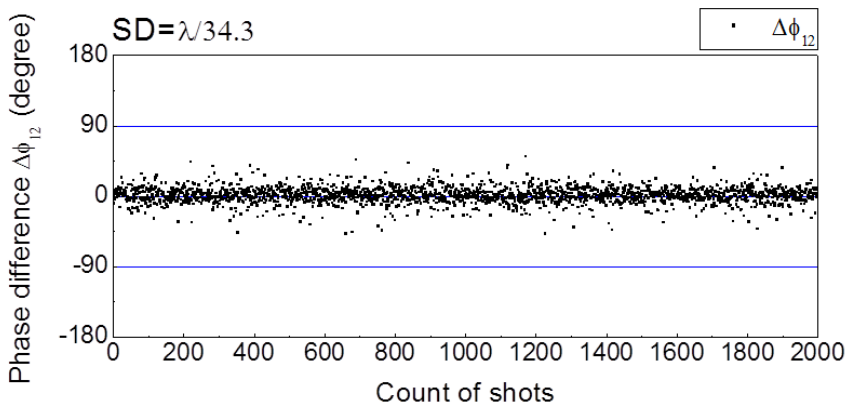
H. J. Kong, J. W. Yoon, J. S. Shin, and D. H. Beak, Applied Physics Letters 92, 021120, 2008.

Experimental setup for the amplitude dividing 4-beam combination

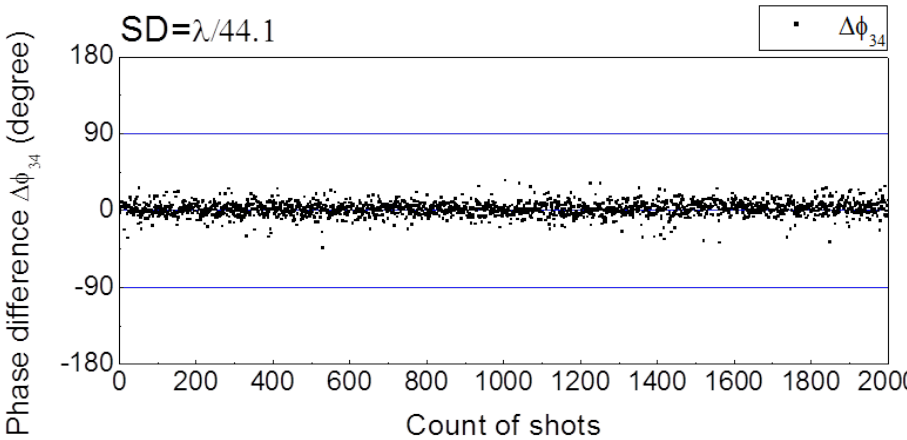


H. J. Kong, J. S. Shin, J. W. Yoon, and D. H. Beak, Laser and Particle Beams 27, 179-184, 2009.

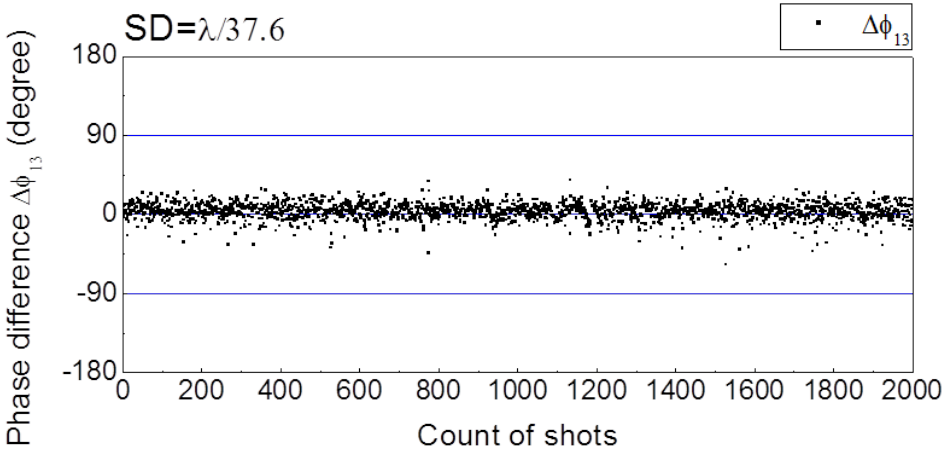
$\Delta\phi_{12}$



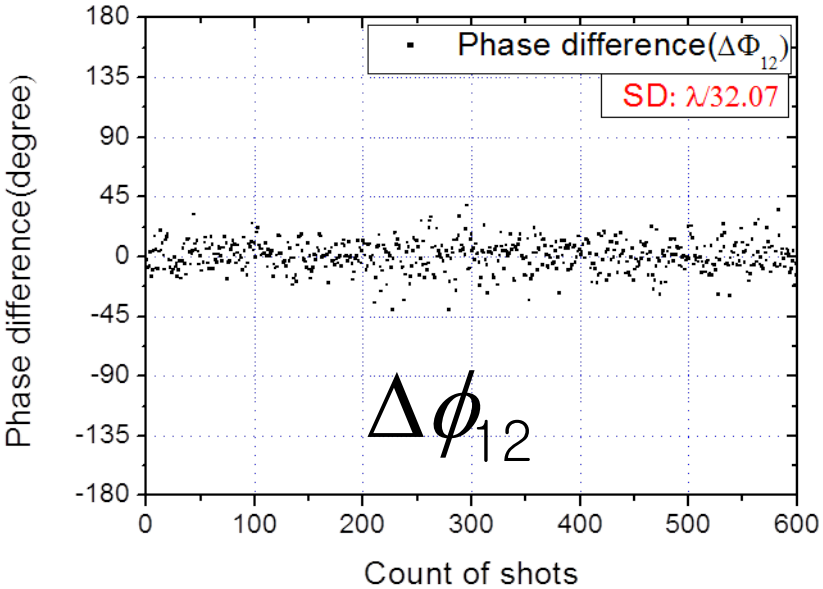
$\Delta\phi_{34}$

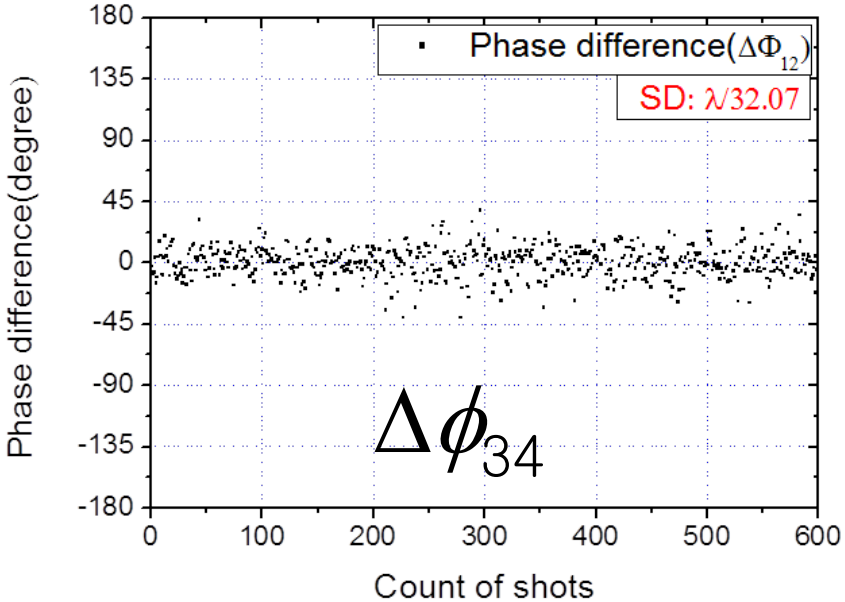


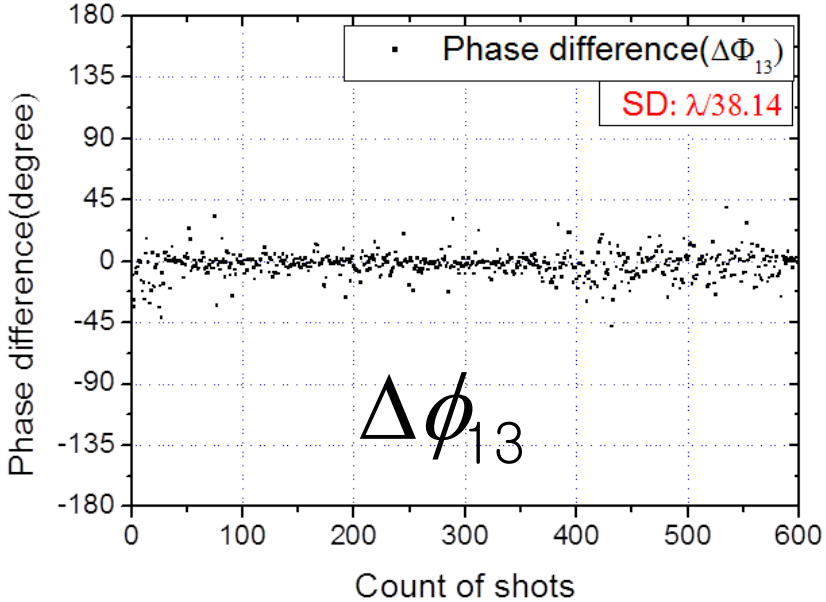
$\Delta\phi_{13}$



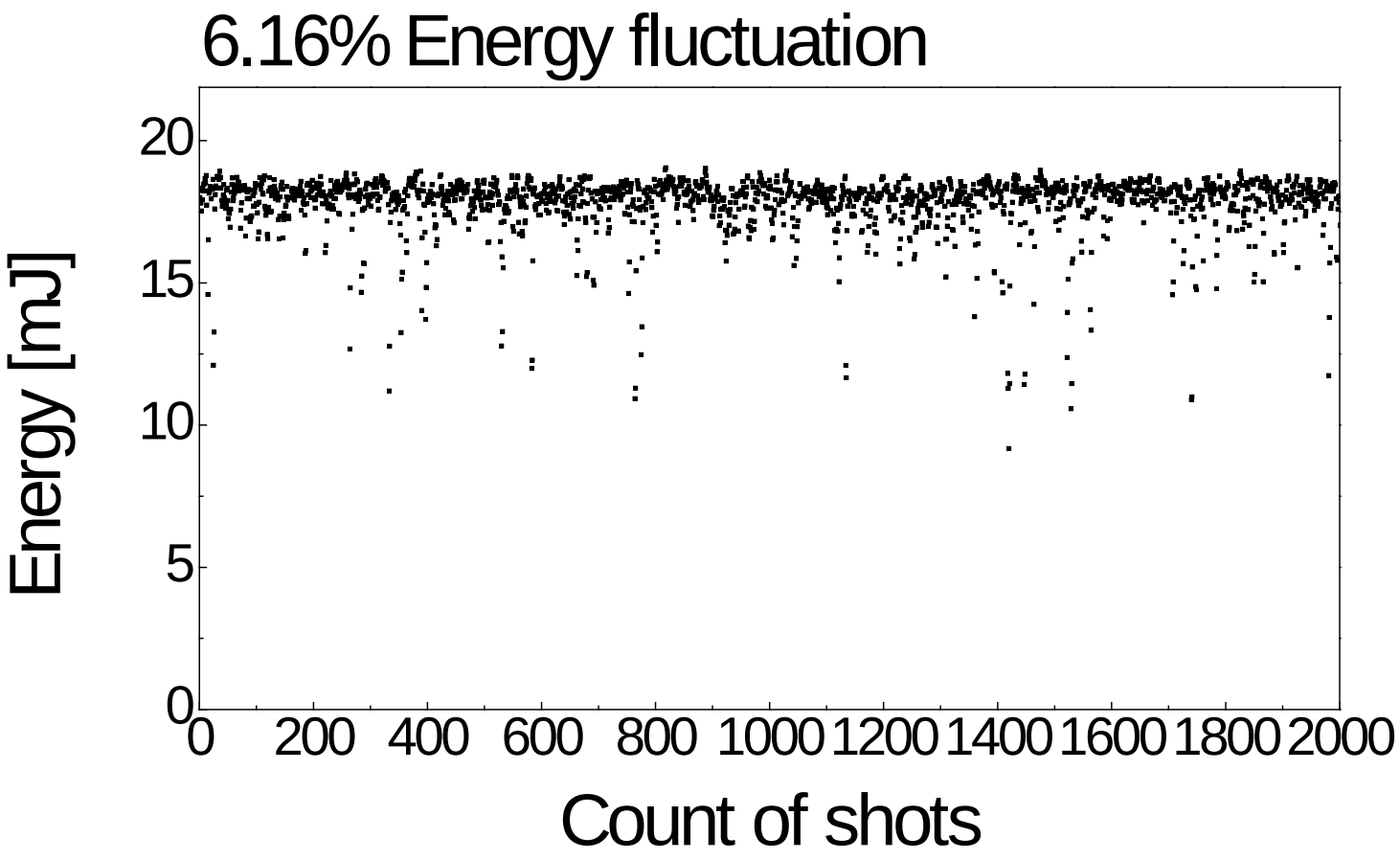
H. J. Kong, J. S. Shin, J. W. Yoon, and D. H. Beak, Laser and Particle Beams 27, 179-184, 2009.


Phase difference(ΔΦ12)
SD: λ/32.07
Δϕ12
Phase difference(degree)
Count of shots
180
135
90
45
0
-45
-90
-135
-180
0
100
200
300
400
500
600


Phase difference(ΔΦ12)
SD: λ/32.07
Δϕ34
Phase difference(degree)
Count of shots
180
135
90
45
0
-45
-90
-135
-180
0
100
200
300
400
500
600


Phase difference(ΔΦ13)
SD: λ/38.14
Δϕ13
Phase difference(degree)
Count of shots
180
135
90
45
0
-45
-90
-135
-180
0
100
200
300
400
500
600

4-beam combined output energy



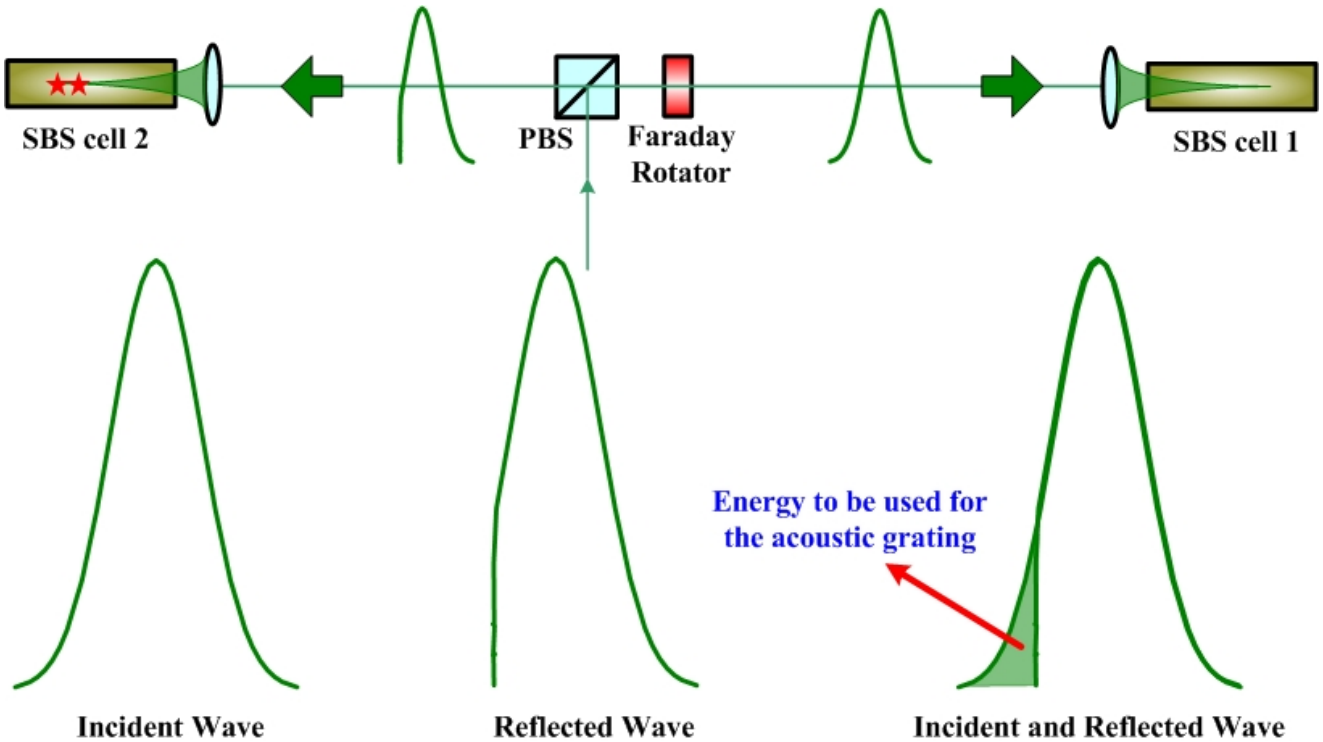
H. J. Kong, J. S. Shin, J. W. Yoon, and D. H. Beak, Laser and Particle Beams 27, 179-184, 2009.

Pre-pulse technique for waveform preservation of SBS waves

Pre-pulse technique

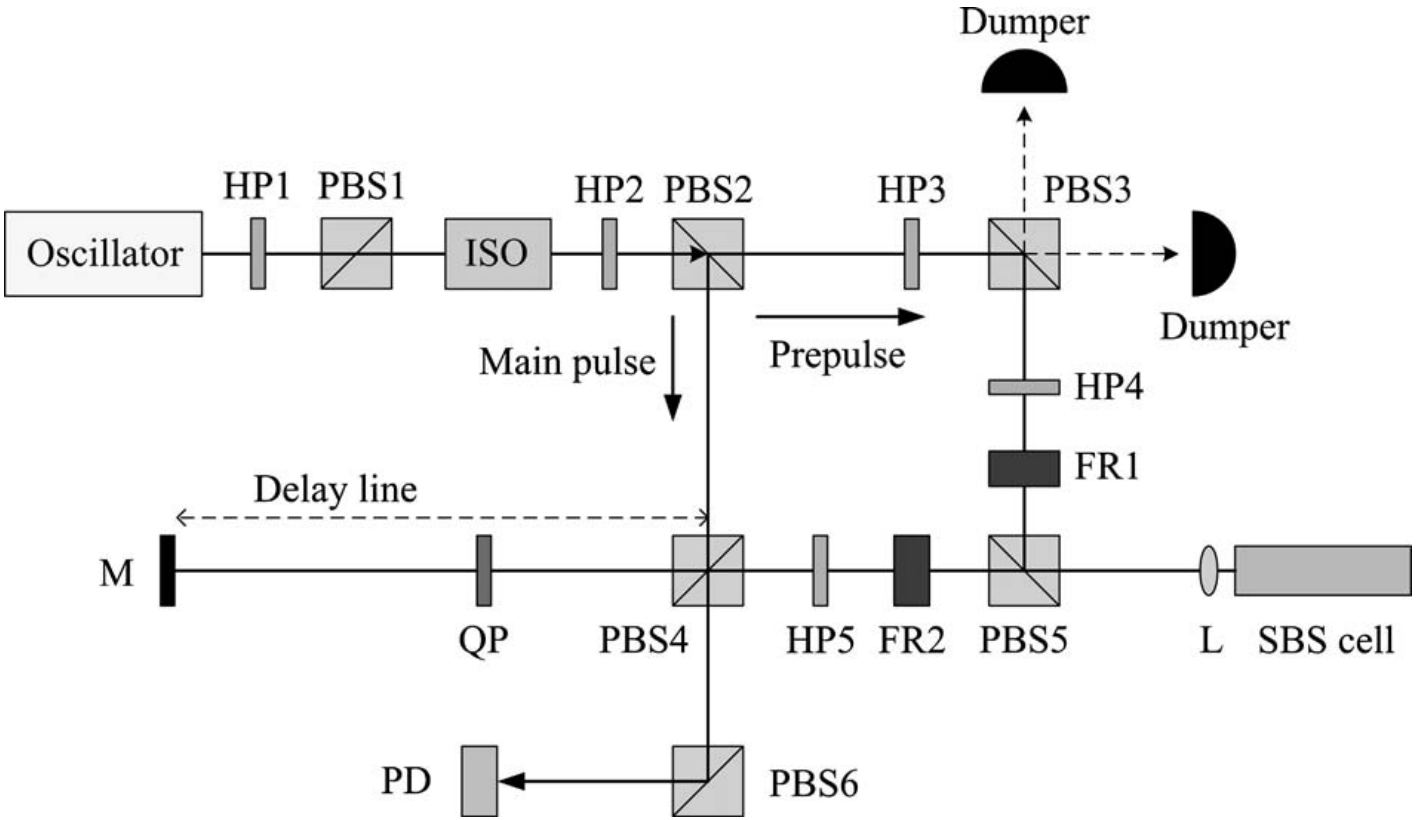
1. To avoid the deformation of the waveform, the pre-pulse technique has been developed.
2. At first, the laser pulse is divided into two pulses with delay time. (main pulse + pre-pulse, $E_{main\ pulse} > E_{pre\text{-}pulse} \sim E_{threshold}$)
3. Pre-pulse which is incident on the SBS cell prior to the main pulse creates the acoustic grating.
4. Therefore, the main pulse does not lose its energy for the acoustic grating generation.
5. Waveform of the reflected main pulse can be preserved.

Pulse shape deformation of the SBS wave



- The SBS wave has a steep rising edge because it consumes its front part energy to generate the acoustic grating.
- This steep rising edge causes the optical breakdown in the SBS cell 2.

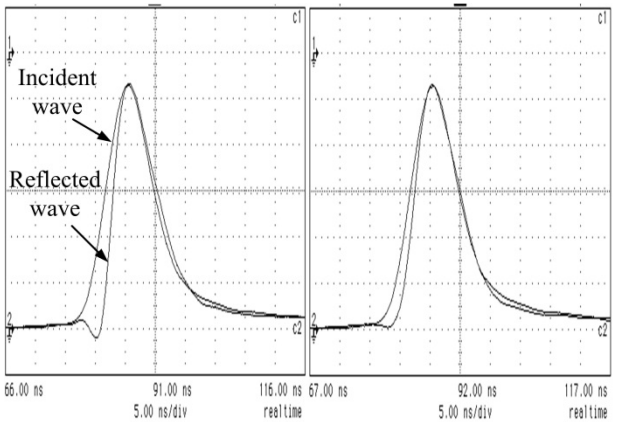
Pre-pulse technique



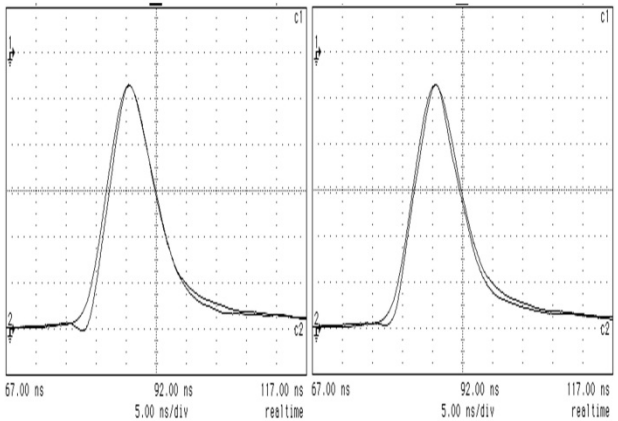
- HPs, half-wave plates; PBSs, polarizing beam splitters; ISO, optical isolator; FRs, Faraday rotators; QP, quarter-wave plate; M, mirror; L, focusing lens; PD, photodiode

Waveforms of the SBS wave according to the pre-pulse energy

Delay time: 3 ns

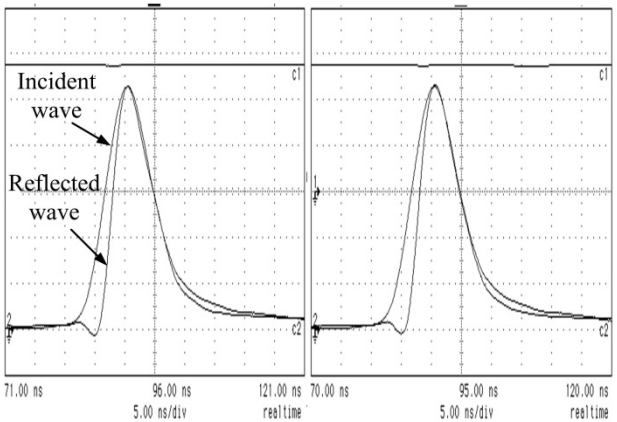


(a) E_{pre}=0 (b) E_{pre}=6mJ

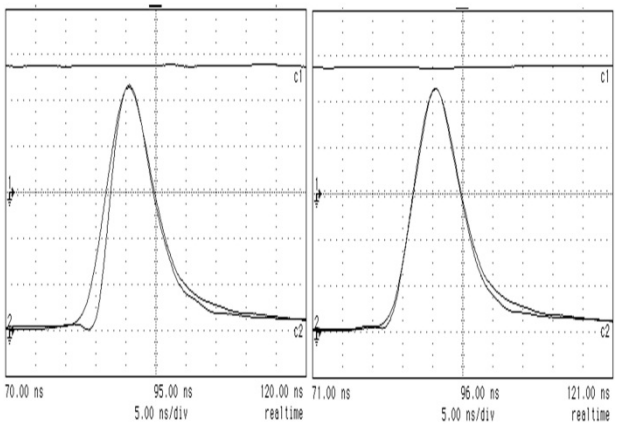


(c) E_{pre}=7mJ (d) $E_{pre} \geq$ 8mJ

Delay time: 8 ns



(a) E_{pre}=0mJ (b) E_{pre}=2mJ

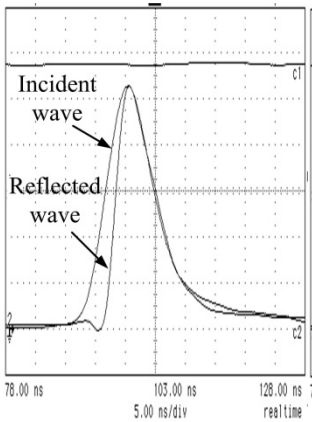


(c) E_{pre}=2.5mJ (d) $E_{pre} \geq$ 3mJ

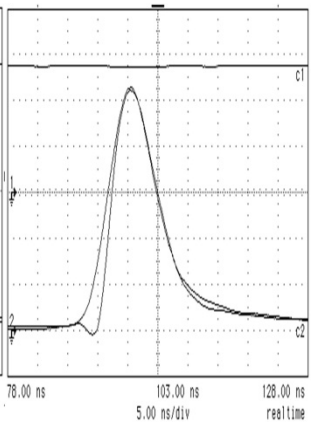
J. W. Yoon, J. S. Shin, H. J. Kong, and J. Lee, Journal of the Optical Society of America B 26, 2167–2170, 2009.

Waveforms of the SBS wave according to the pre-pulse energy

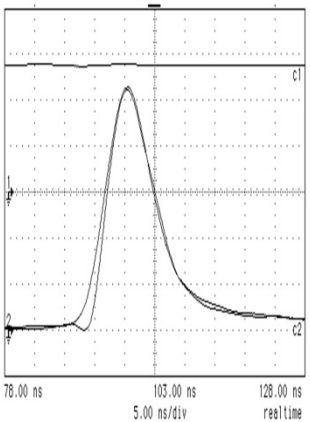
Delay time: 15 ns



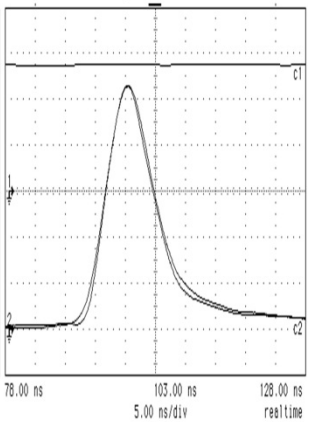
(a) E_{pre}=0mJ



(b) E_{pre}=1.5mJ

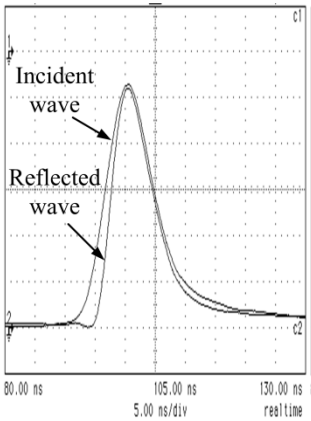


(c) E_{pre}=1.8mJ

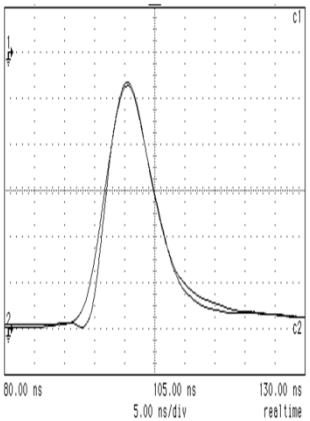


(d) $E_{pre} \geq$ 2mJ

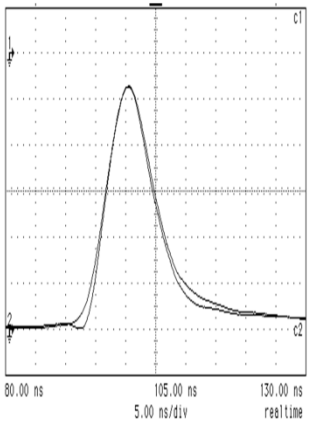
Delay time: 17 ns



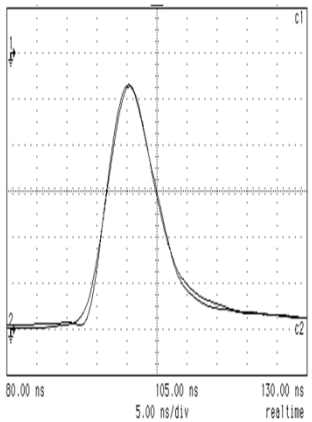
(a) E_{pre}=2mJ



(b) E_{pre}=2.5mJ



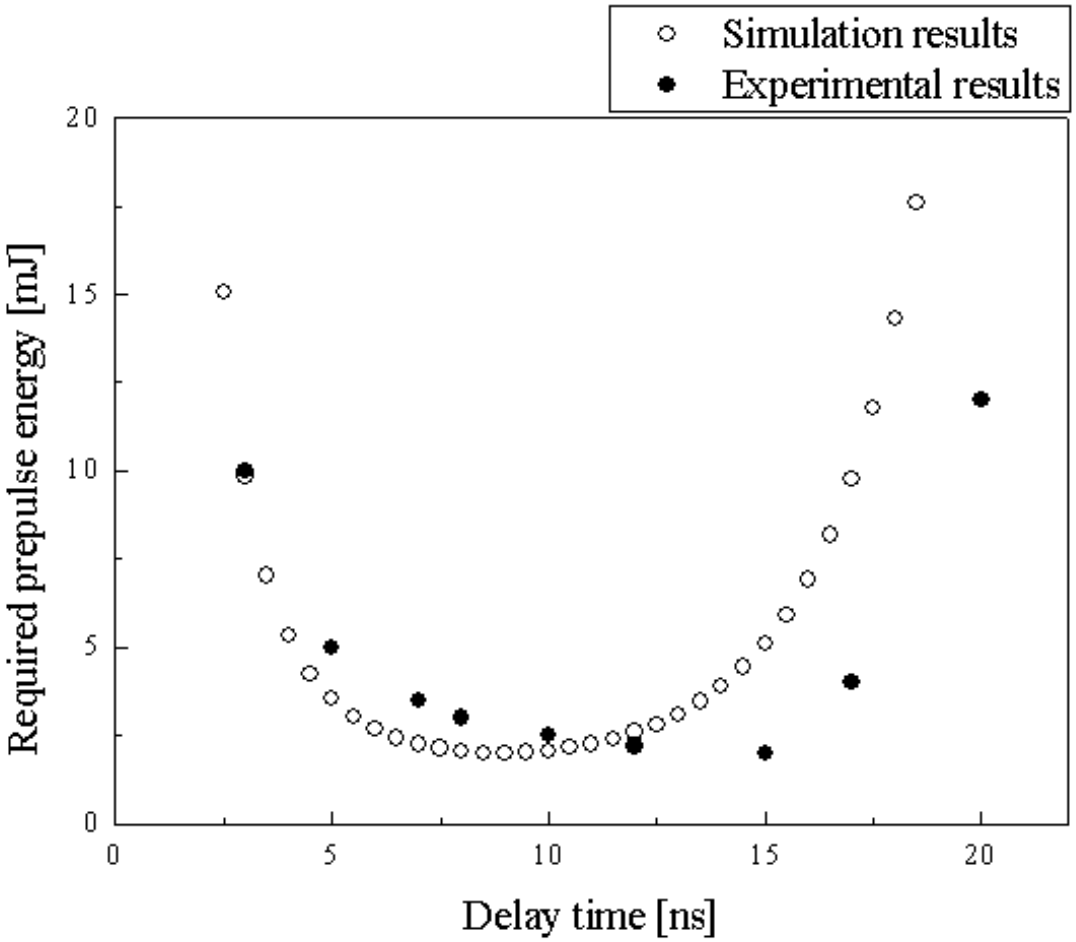
(c) E_{pre}=3mJ



(d) $E_{pre} \geq$ 4mJ

J. W. Yoon, J. S. Shin, H. J. Kong, and J. Lee, Journal of the Optical Society of America B 26, 2167–2170, 2009.

Required pre-pulse energy vs. the delay time



J. W. Yoon, J. S. Shin, H. J. Kong, and J. Lee, Journal of the Optical Society of America B 26, 2167–2170, 2009.