Pulse duration tunable and high-brightness unstable cavity microchip laser

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Outline

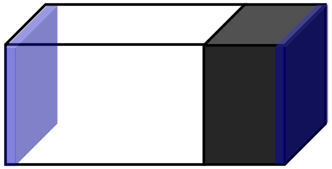
1. Introduction

2. Pulse duration tunable MCL

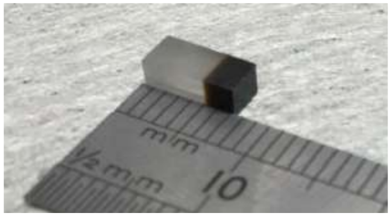
3. High brightness unstable cavity MCL

4. Summary

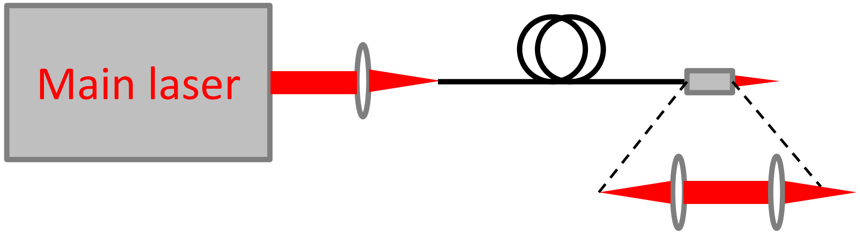
Introduction



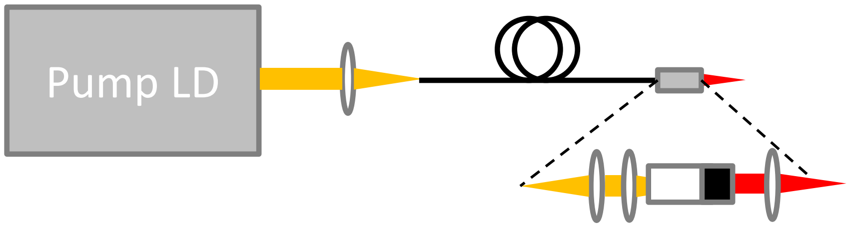
- ▶ Compact
- ▶ Stable
- ▶ Short pulse (< 1 ns) → >MW peak power
- ▶ Single axial frequency

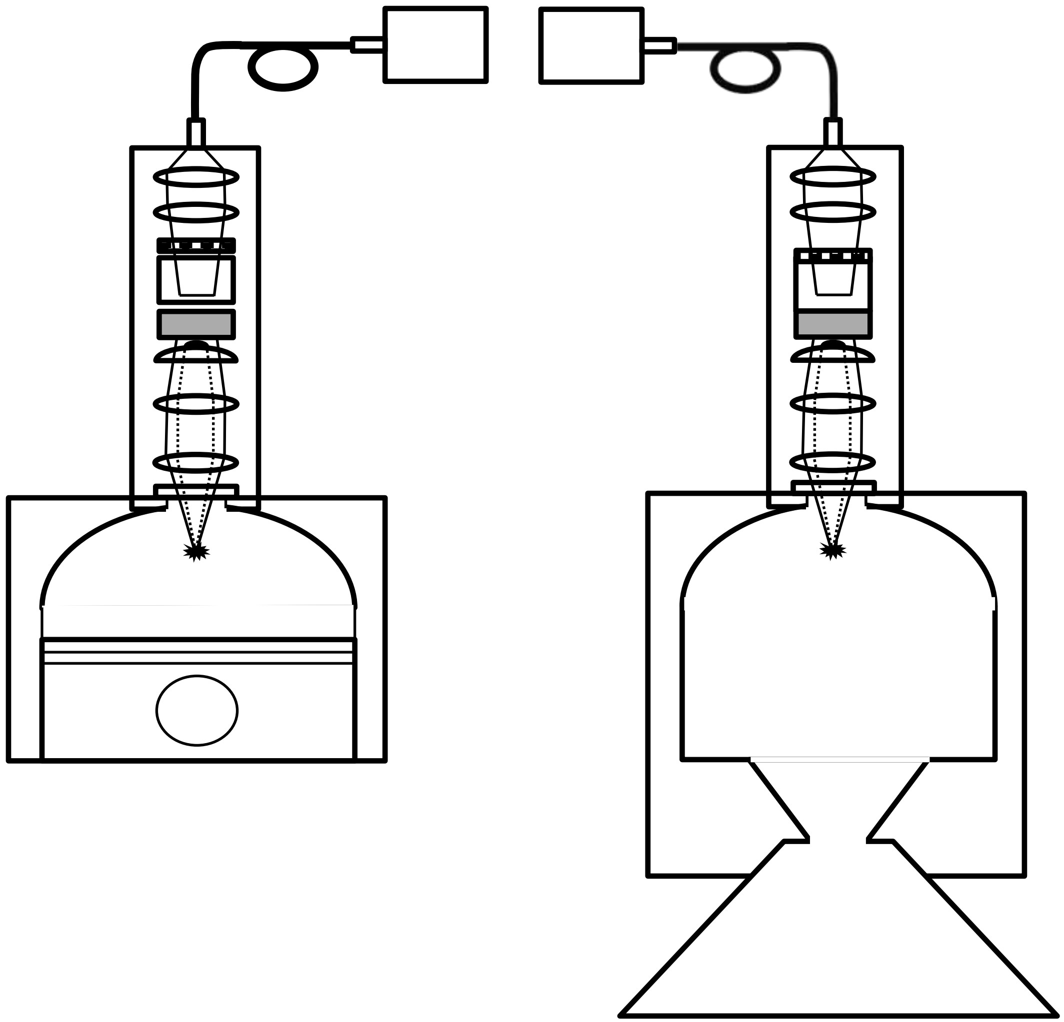


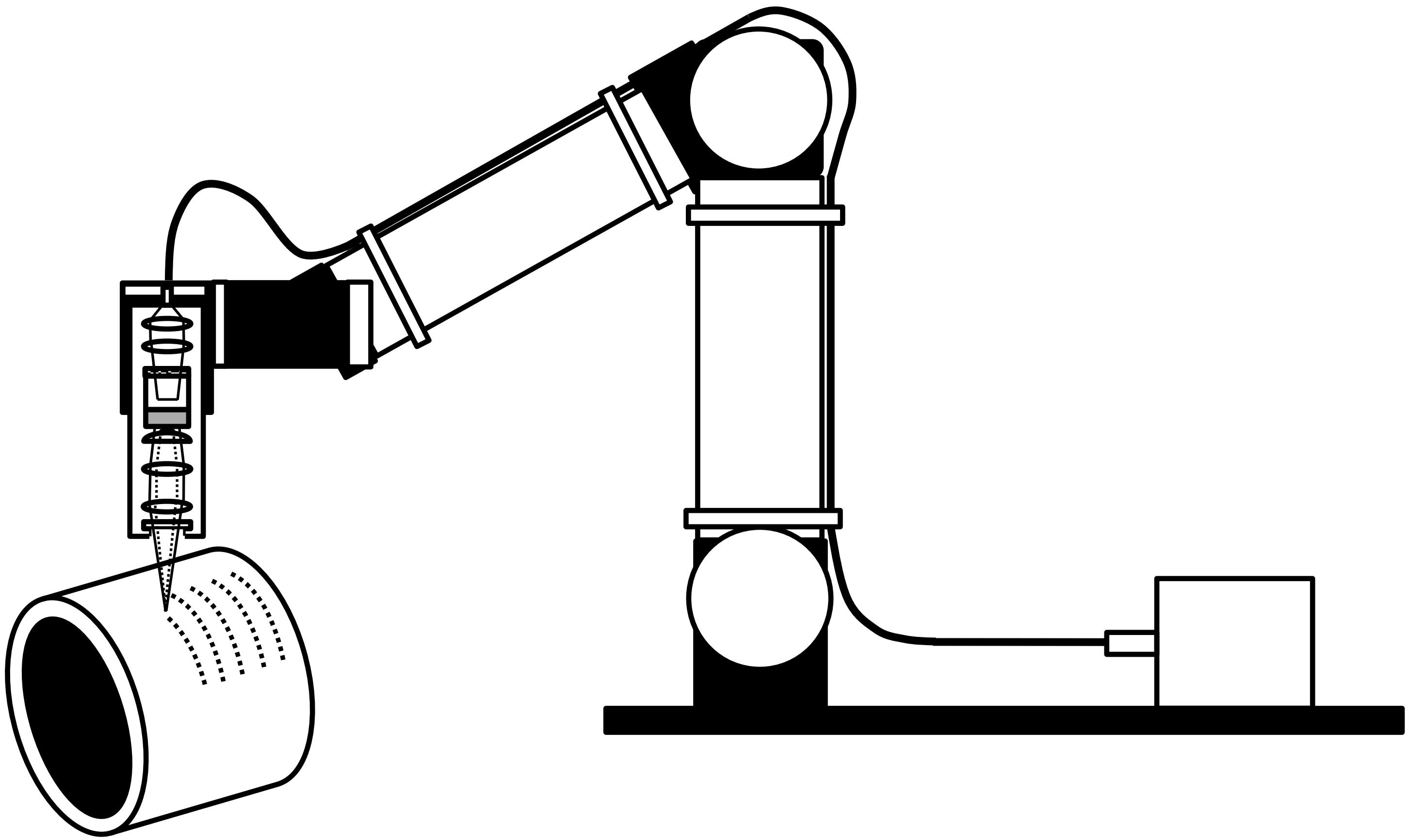
Fiber delivery laser

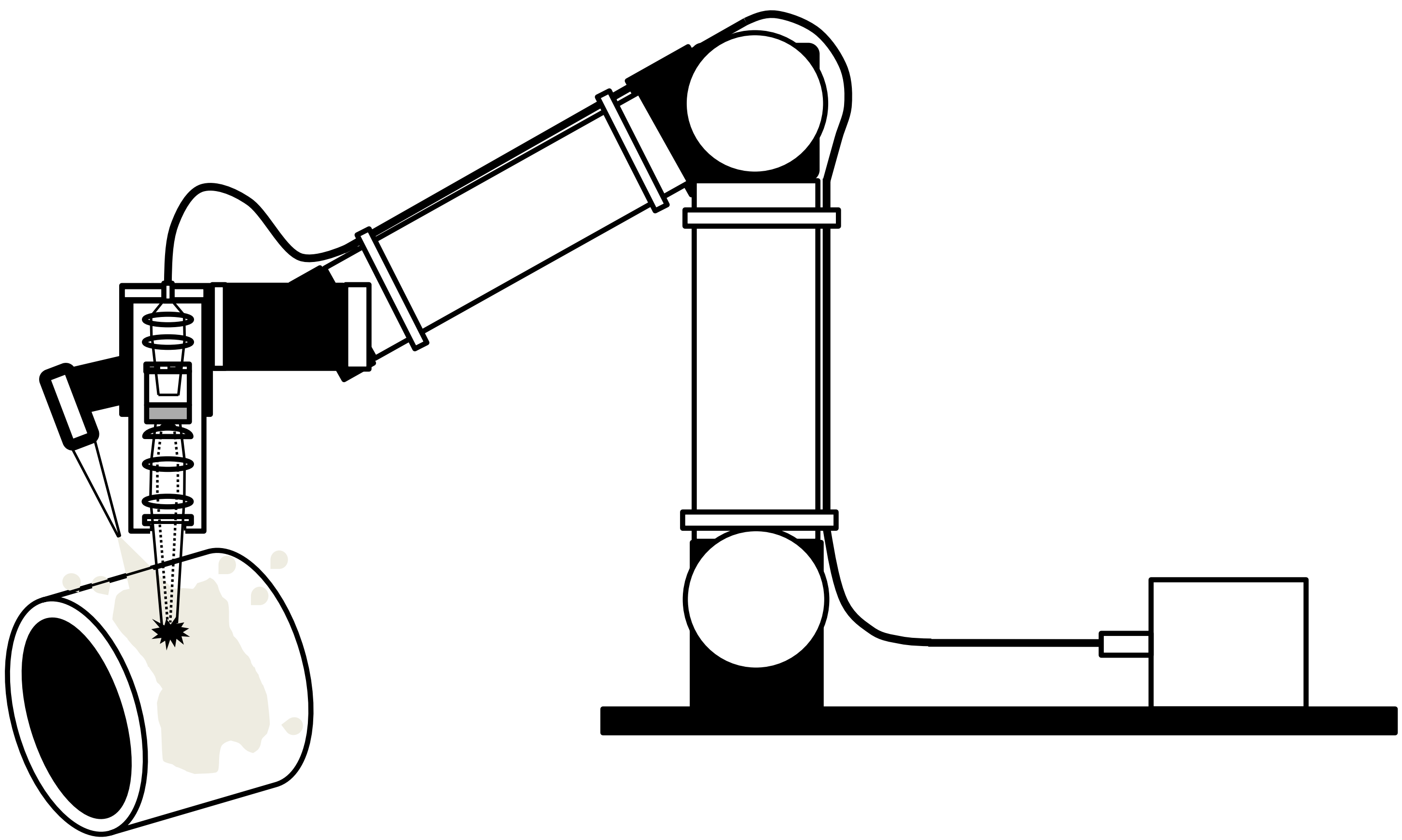


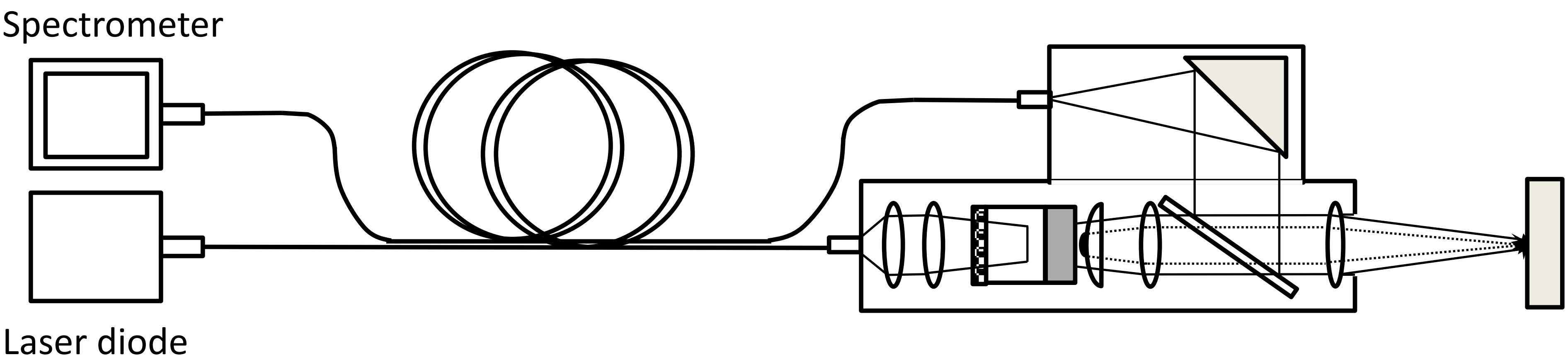
Microchip laser



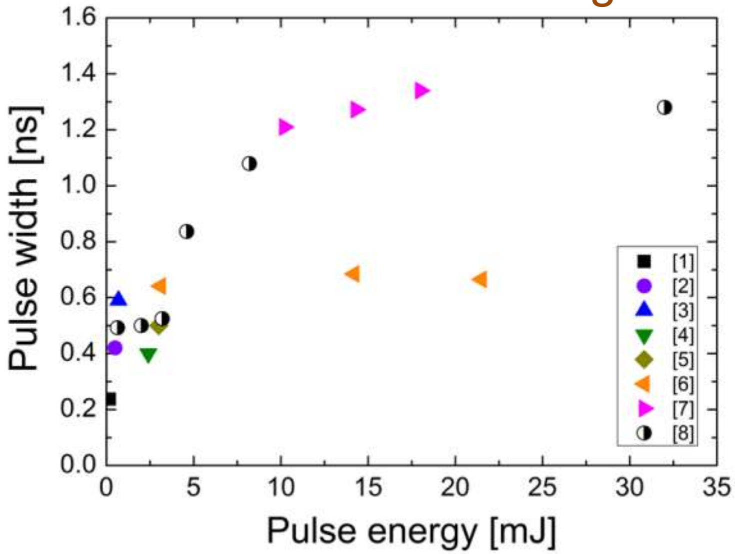




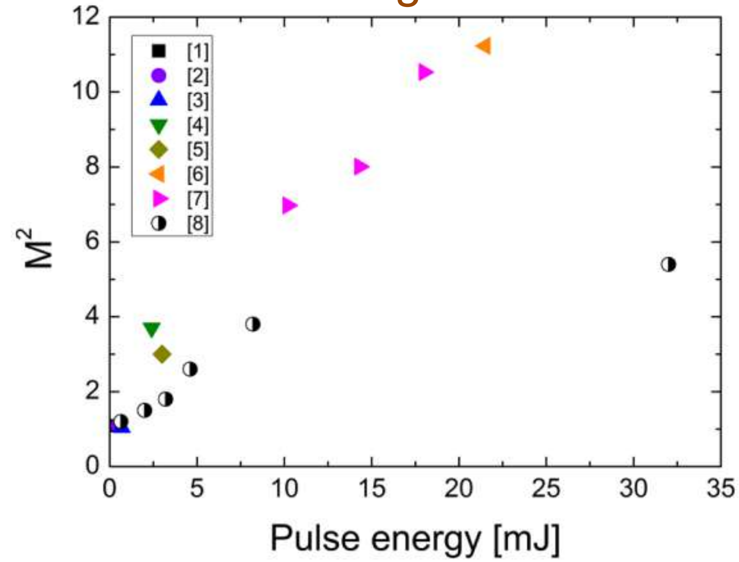



Spectrometer
Laser diode

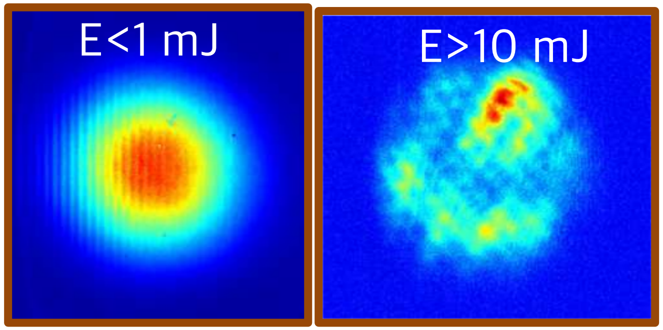
► Pulse broadening



► M² degradation



► Beam pattern degradation



[1] J. Dong, et al., Opt. Express **15**, 14516 (2007).

[2] A. Agnesi, et al., Appl. Phys. Lett. **89**, 101120 (2006).

[3] H. Sakai, et al., Opt. Express **16**, 19891 (2008).

[4] N. Pavel, et al., Opt. Express **19**, 9378 (2011).

[5] H. H. Lim and T. Taira, Opt. Express **25**, 6302 (2017).

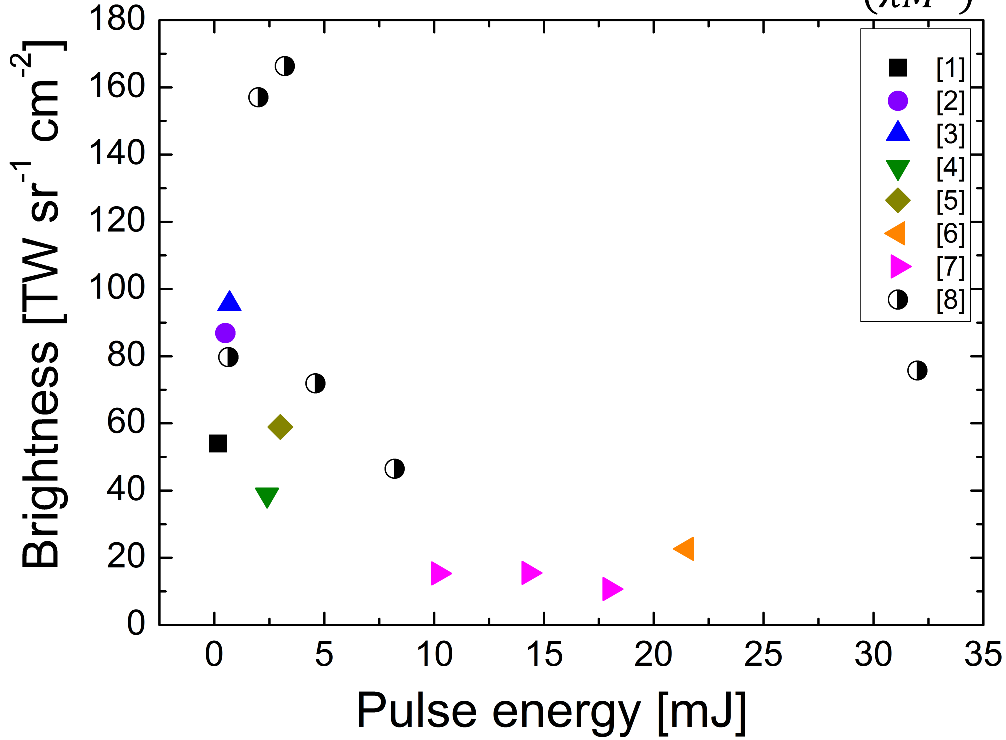
[6] L. Zheng, et al., Opt. Express **27**, 30217 (2019).

[7] H. H. Lim and T. Taira, Opt. Express **27**, 31307 (2019).

[8] X. Guo, et al., Opt. Express **27**, 45-54 (2019).

▶ Poor brightness

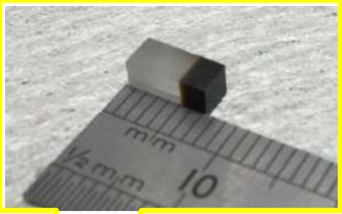
$$B = \frac{P_0}{(\lambda M^2)^2}$$

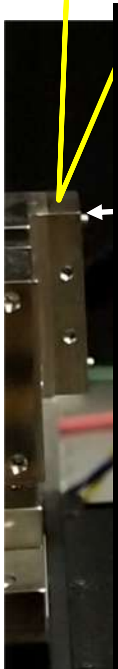


[1] J. Dong, et al., Opt. Express **15**, 14516 (2007).
[2] A. Agnesi, et al., Appl. Phys. Lett. **89**, 101120 (2006).
[3] H. Sakai, et al., Opt. Express **16**, 19891 (2008).
[4] N. Pavel, et al., Opt. Express **19**, 9378 (2011).
[5] H. H. Lim and T. Taira, Opt. Express **25**, 6302 (2017).
[6] L. Zheng, et al., Opt. Express **27**, 30217 (2019).
[7] H. H. Lim and T. Taira, Opt. Express **27**, 31307 (2019).
[8] X. Guo, et al., Opt. Express **27**, 45-54 (2019).

Pulse duration tunable laser

Nd:YAG/Cr:YAG ceramic
3 X 3 X 7 mm^3





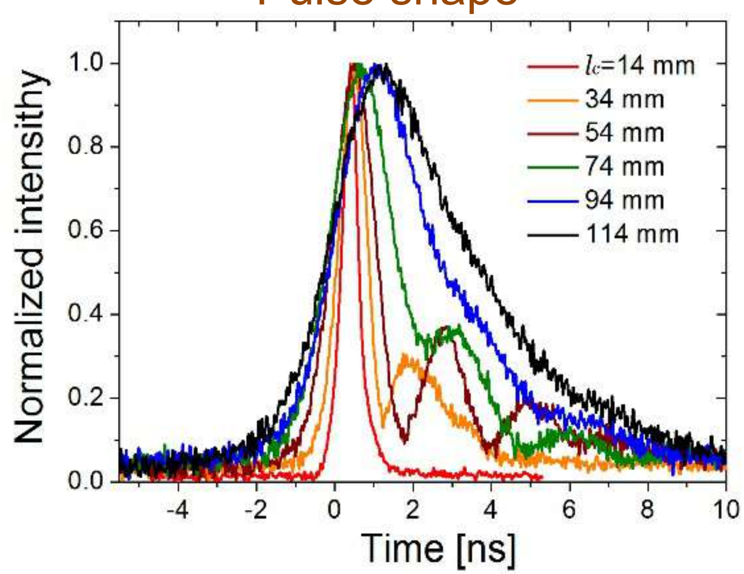
Q-switched pulse duration ∝ cavity length

$$\tau_p \approx \frac{r\eta(r)}{r-1-\ln r}\tau_c$$

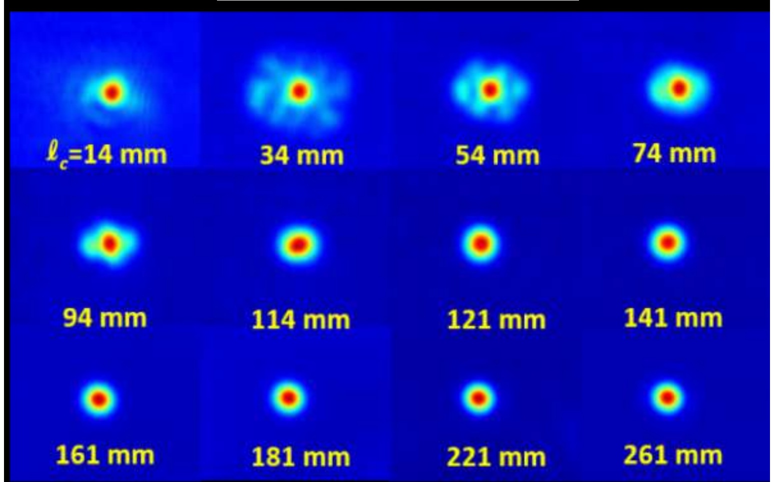
τ_c : the cavity lifetime
r : the initial inversion ratio
η : the energy extraction efficiency

Cavity length dependent characteristics

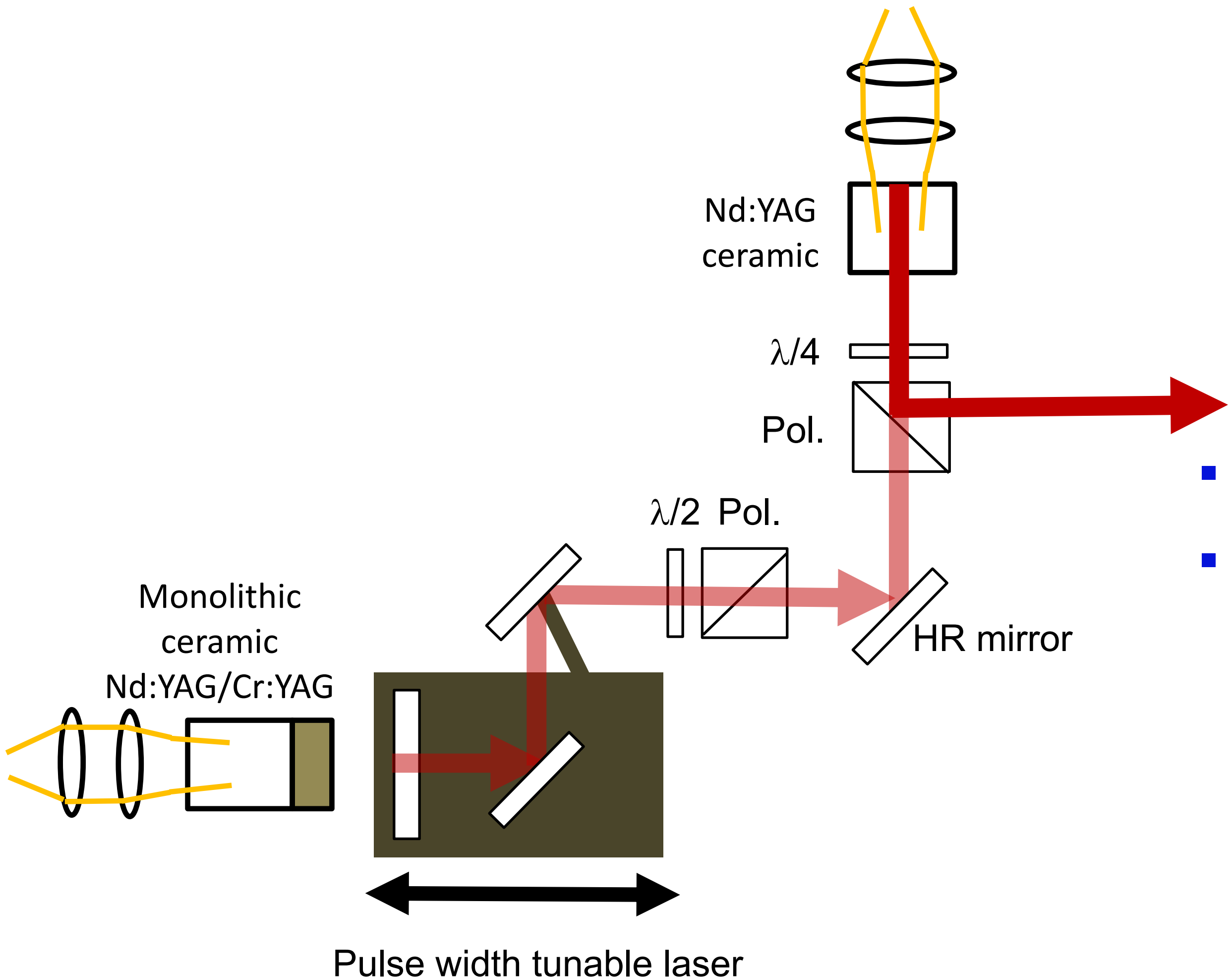
Pulse shape



Beam pattern

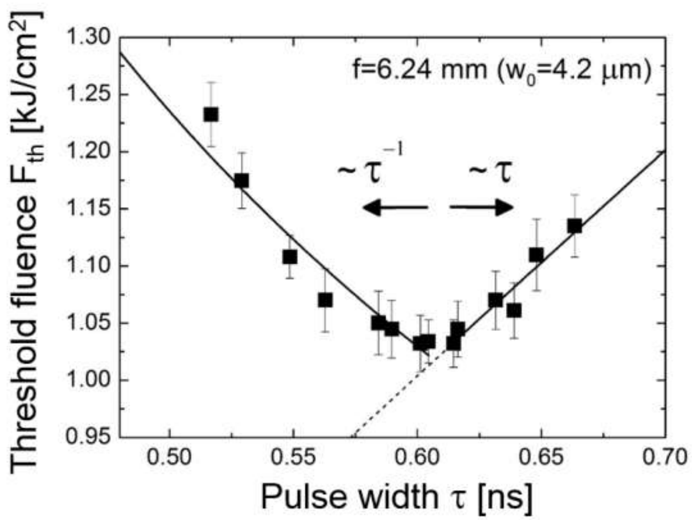


Pulse width tunable MOPA



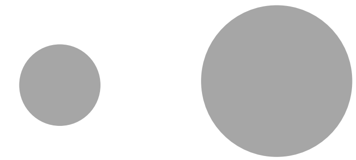
- >2 times energy amplification
- Beam quality improvement
  (M^2=1.3 for short cavities)

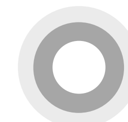
Application examples

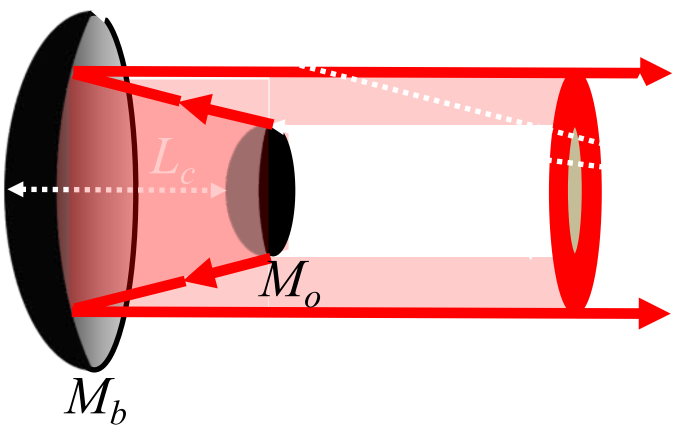


High brightness unstable cavity MCL

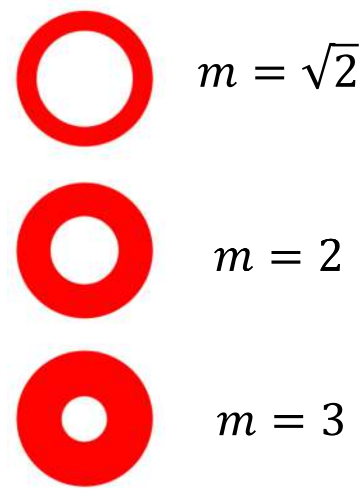
- Wider and controllable mode volumes
- Uniform beam pattern of doughnut shape
  - No beam pattern degradation for energy scaling
- A good focusability of doughnut beam as a Bessel-like beam



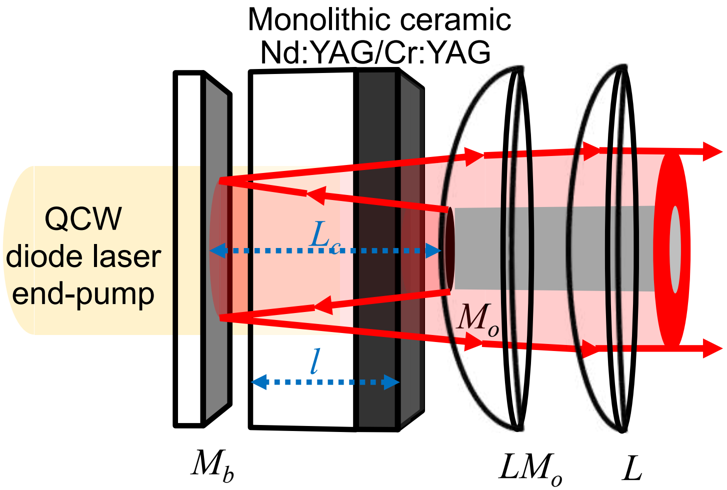




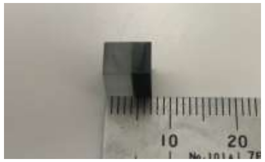
Positive branch confocal cavity



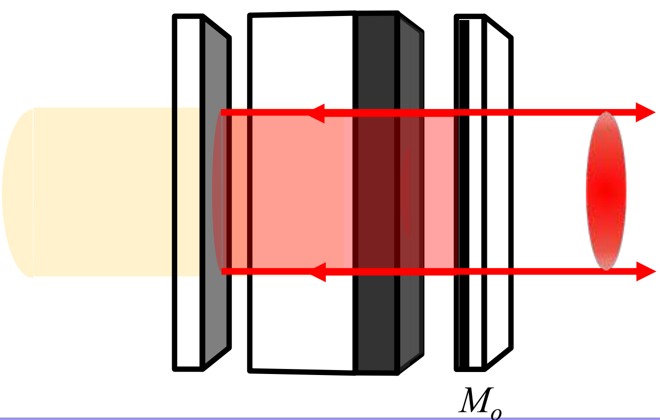
Experimental setup



- 700 W pump diode @ 808 nm, 10 Hz during <400 μs
- Monolithic ceramic with a dimension of 6 X 6 X 7(l) mm^3
- 1.1 at.% Nd^{3+} doping and 30% of initial transmittance of Cr^{4+}:YAG

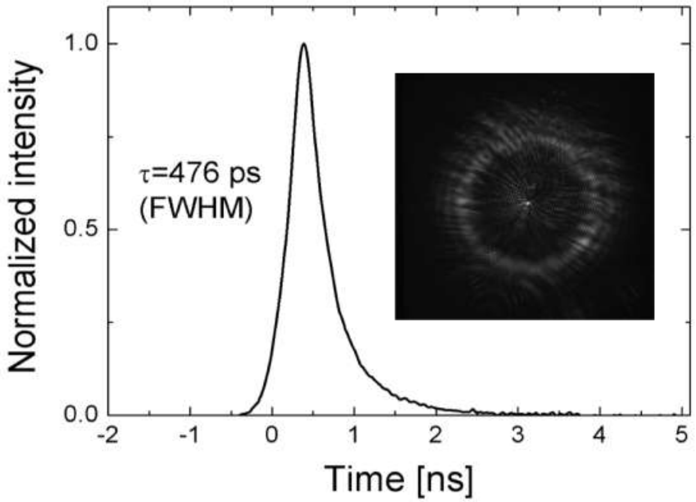


- Flat back cavity mirror M_b
- A half inch plano-convex lens LM_0 with a radius of curvature of 52 mm (for m of $\sqrt{2}$ for the confocal cavity)
- Output coupler (OC) M_0, HR coated on the center part of LM_0 in a spot diameter of 2 mm
- Collimation lens L with a focal length of 50~150 mm in case of the lens position

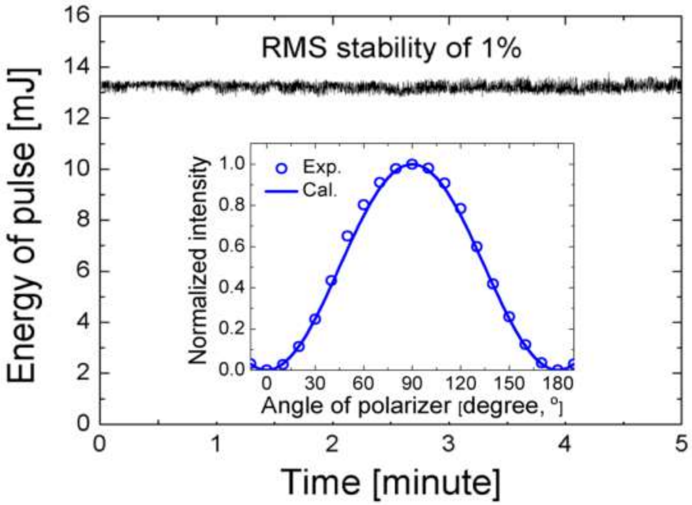


- Comparison of laser performance for brightness scaling
- Replacement of the curved OC, M_0 with a flat mirror
- Identical all other conditions (pumping, cooling, and so on) for both resonators
- A flat mirror with a reflectance of 50% (the same round-trip loss for an ideal confocal cavity with m of $\sqrt{2}$)

Laser characteristics



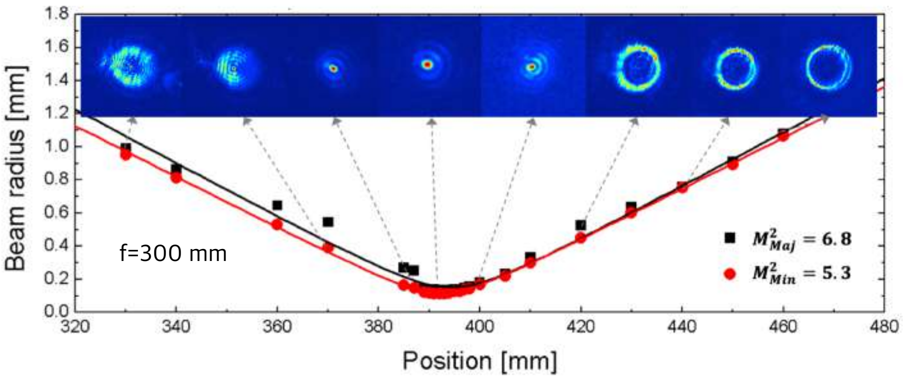
- ▶ Doughnut beam pattern with a center Poisson spot
- ▶ Pulse energy of 13.2 mJ @ 10 Hz
- ▶ Pulse width of 476 ps



- ▶ Short term RMS stability <1%
- ▶ Linear polarization @ 10 Hz

(may be pump power induced birefringence and depolarization due to stress and heat)

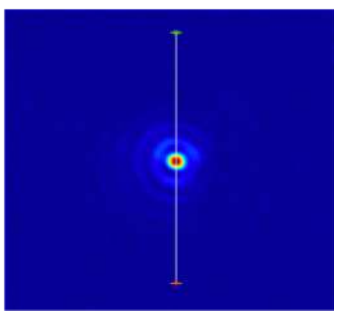
Laser characteristics

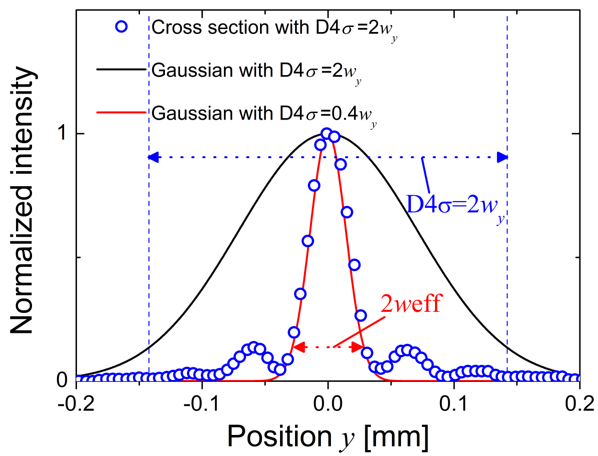


► , second-moment based M^2 and 86.5% power-content based M^2_{pc}

$$M^2_{ave} = \sqrt{M^2_{maj} M^2_{min}}$$

►





►The center part (red line) of Bessel-like beam has (black line).

►The small center part can increase focusability substantially.

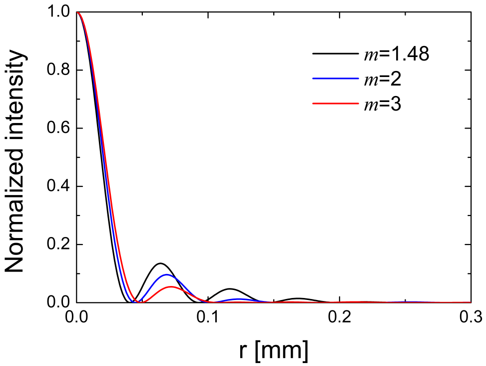
$$M^2_{eff} = \frac{\pi w_{0,eff}}{\lambda}\theta = \frac{\pi w_{0,eff}}{\lambda} \cdot \frac{\lambda M^2}{\pi w_0} = \frac{w_{0,eff}}{w_0} M^2 = 0.2 \times 6 = 1.2.$$

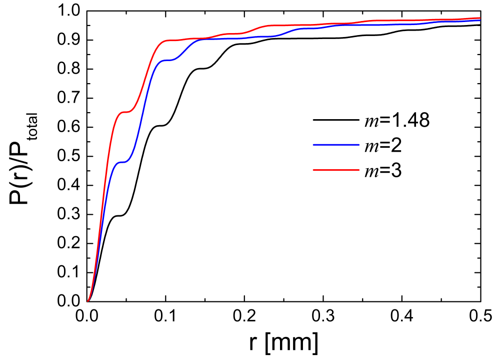
M^2_{eff}: effective M²

$w_{0,eff}$: effective beam waist

θ: half angle divergence

Laser characteristics



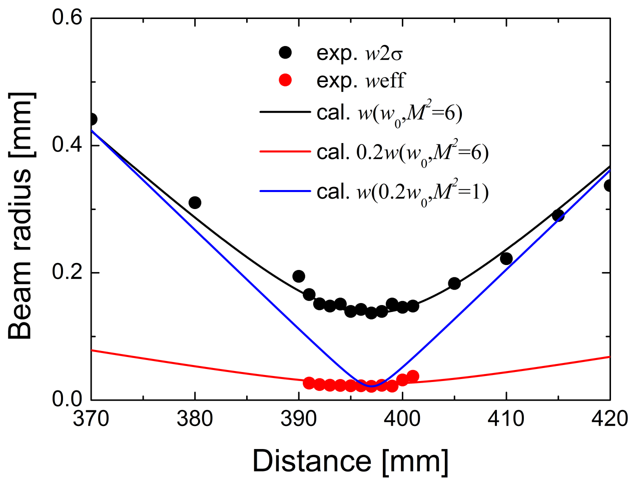


$E_{eff} \approx 30\%$

Intensity distribution of plane wave focused by an annular aperture at the focal plane

$$I(r,f) = \frac{4\,I(0,f)}{(1-1/m^2)^2}\left[\frac{J_1(kr\,b/f)}{kr\,b/f} - \frac{1}{m^2}\frac{J_1(kr\,a/f)}{kr\,a/f}\right]^2, \qquad (1)$$

where $m = b/a$ is the ratio of the outer radius b and the inner radius a of the aperture, $S = \pi a^2(m^2-1)$ is the annular area, J_1 is the first-order Bessel function, $k = 2\pi/\lambda$ is the wave number, f is the focal length, and $I(0,f) = S^2/(\lambda^2 f^2)$ is the peak intensity at the focal plane. [1] B. Lu, et al., J. Mod. Opt. **48**, 1171 (2001).



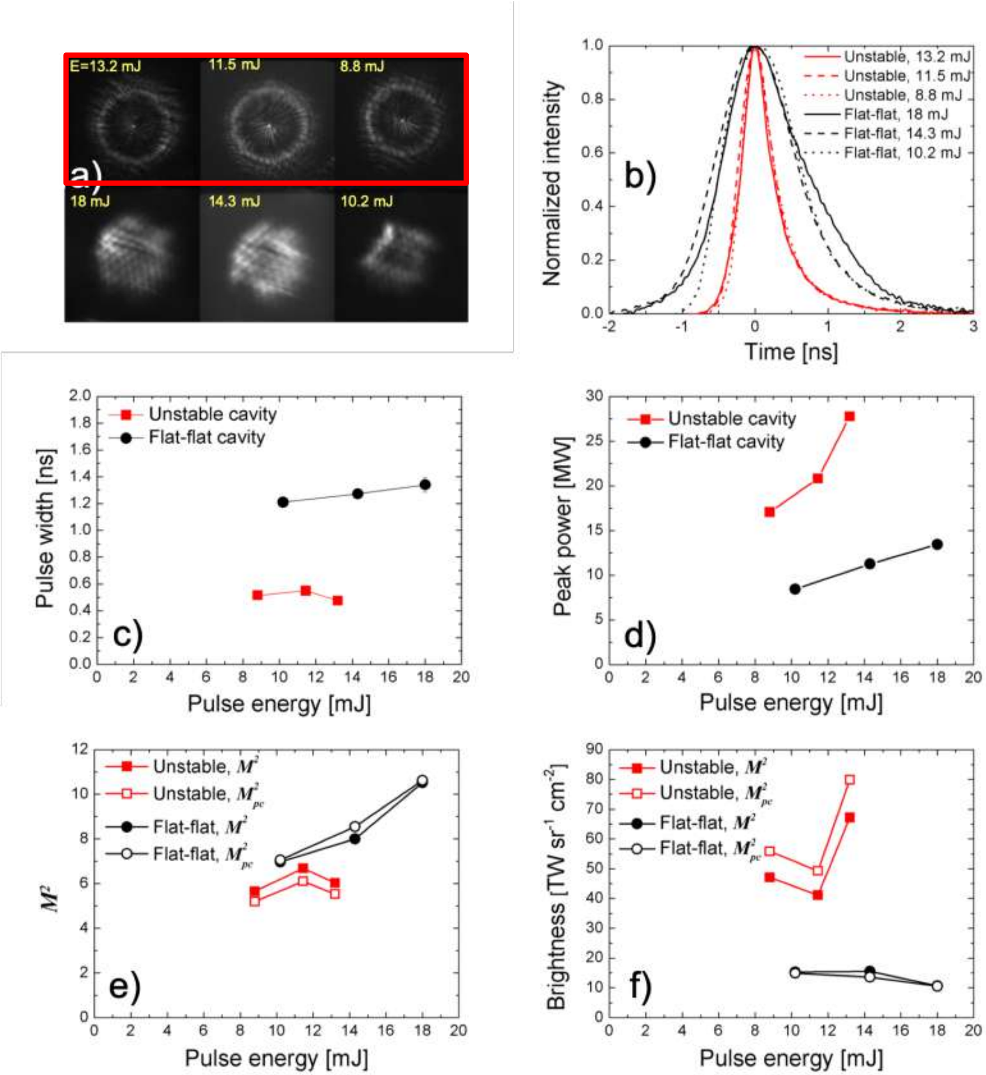
$z_{R,eff}$

(Red line)

$z_{R,G(M^2=1)}$

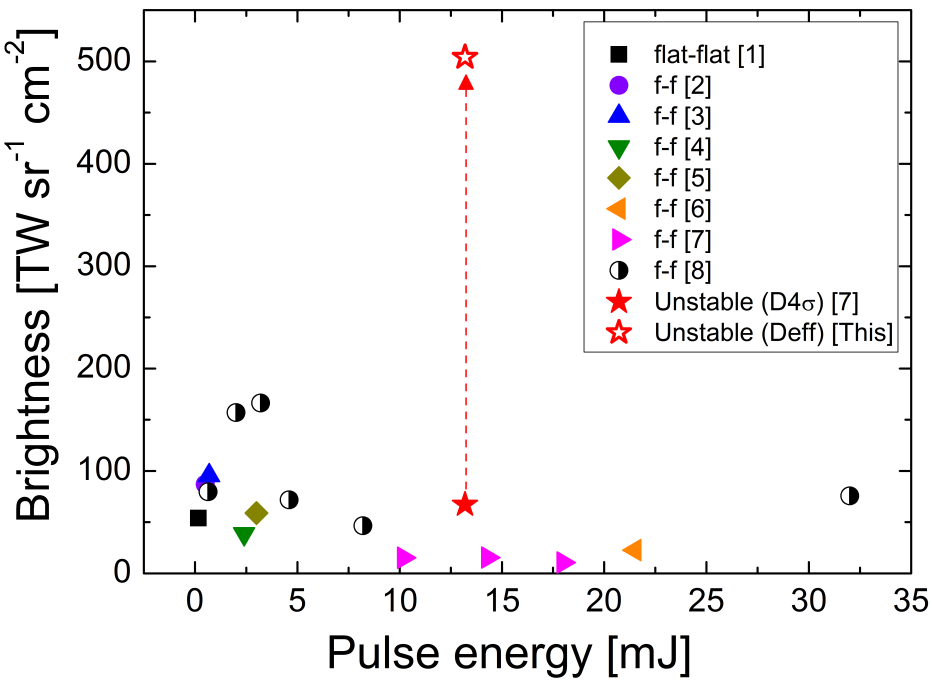
(Blue line)

Comparison with flat-flat cavity



- The energies of 8.8, 11.5, and 13.2 mJ for unstable cavity are paired with 10.2, 14.3, and 18 mJ for flat-flat cavity by every pump condition, respectively.
- No degradation of pulse width and M^2 due to the uniform doughnut pattern for energy scaling.

Comparison with other works



[1] J. Dong, et al., Opt. Express **15**, 14516 (2007).

[2] A. Agnesi, et al., App. Phys. Lett. **89**, 101120 (2006).

[3] H. Sakai, et al., Opt. Express **16**, 19891 (2008).

[4] N. Pavel, et al., Opt. Express **19**, 9378 (2011).

[5] H. H. Lim and T. Taira, Opt. Express **25**, 6302 (2017).

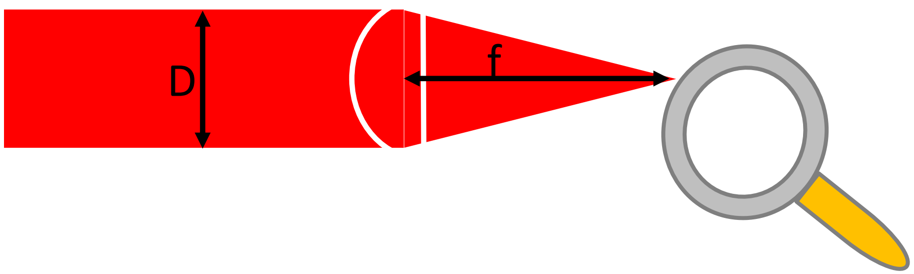
[6] L. Zheng, et al., Opt. Express **27**, 30217 (2019).

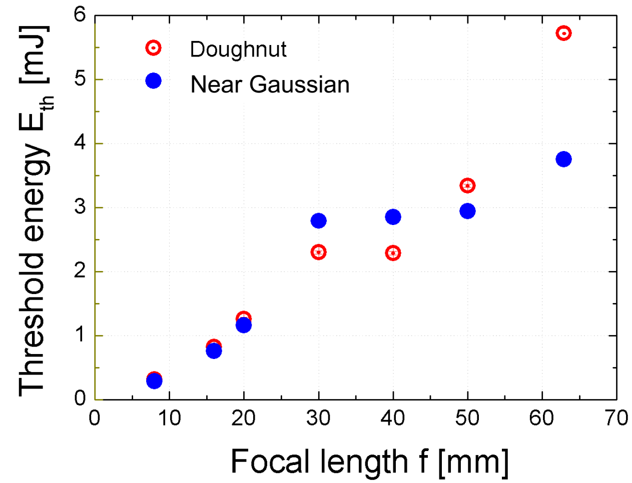
[7] H. H. Lim and T. Taira, Opt. Express **27**, 31307 (2019).

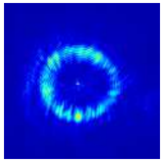
[8] X. Guo, et al., Opt. Express **27**, 45-54 (2019).

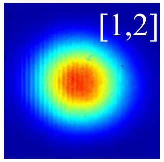
- $E_{eff} = 30\%$
- $M^2_{eff} = 1.2$
- Highest effective brightness of over 0.5 PW/(sr·cm^{-2})

Laser induced breakdown (LIB) in air

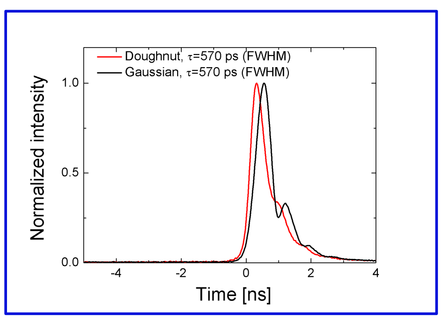






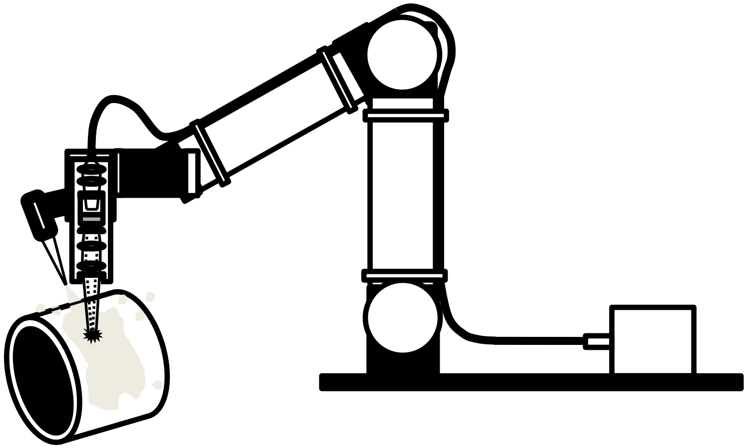


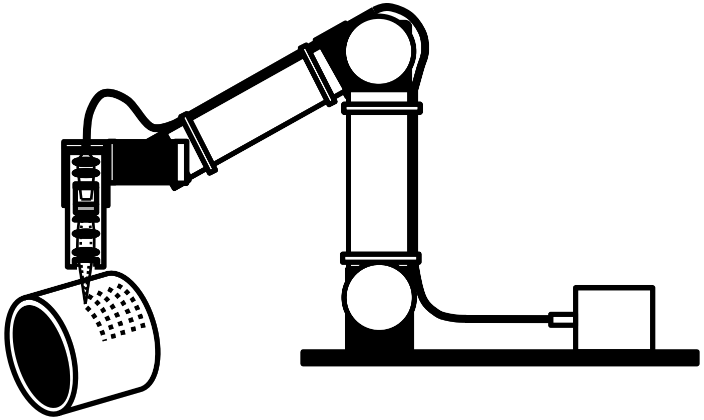
D=7.5 mm	D=7.5 mm
τ=0.57 ns	τ=0.57 ns
M^2=	M^2=



[1] H. H. Lim and T. Taira, Opt. Express **25**, 6320 (2017).
[2] H. H. Lim and T. Taira, Opt. Express **27**, 31307 (2019).

Application examples

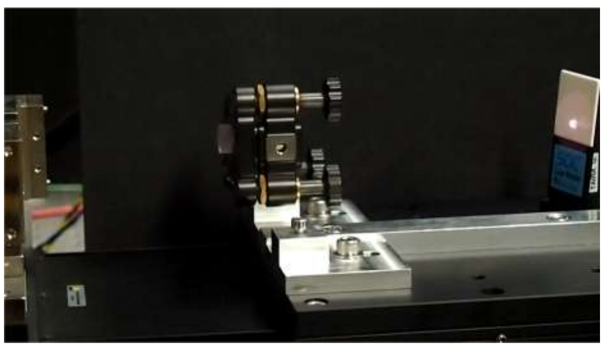


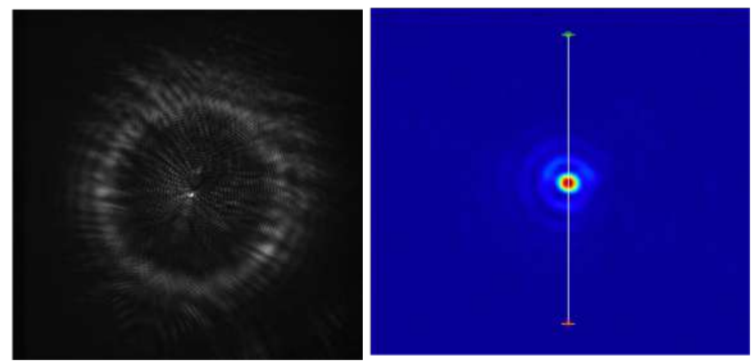


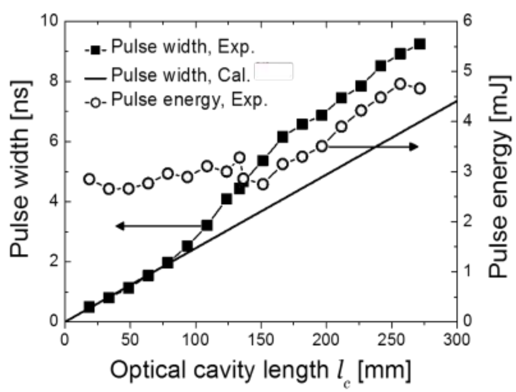
Summary

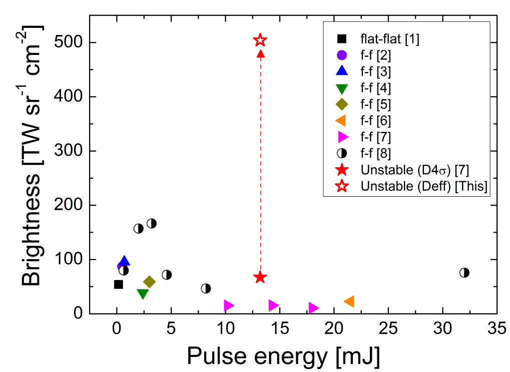
► Pulse duration tunable laser: 0.5-9 ns, ~1 MW

► High brightness doughnut laser: 0.5 $sr^{-1} cm^{-2}$, 28 MW, 13.2 mJ



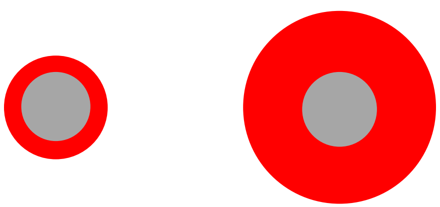


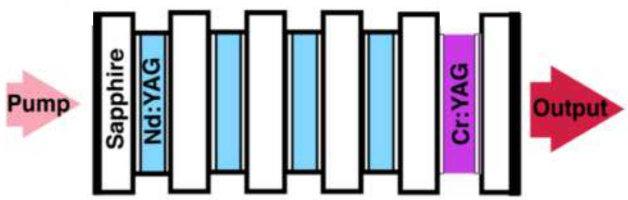


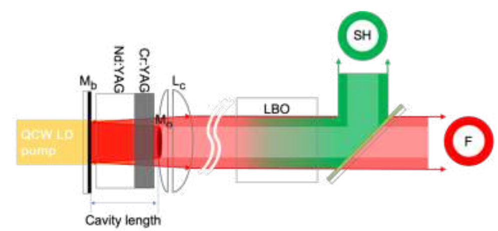


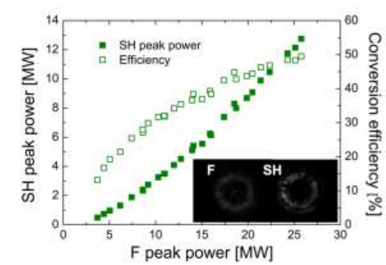
Future works

- ► Brightness scaling up
- ► Higher repetition rate
- ► Frequency conversion by NLO









Acknowledgement

Support:

TILA
Tiny Integrated Laser

JST MIRAI 未来社会創造事業

Impulsing Paradigm Change through Disruptive Technologies Program ImPACT

NEDO New Energy and Industrial Technology Development Organization