4.8kW pulsed laser for LC based on Yb fiber amplifier

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Requirements

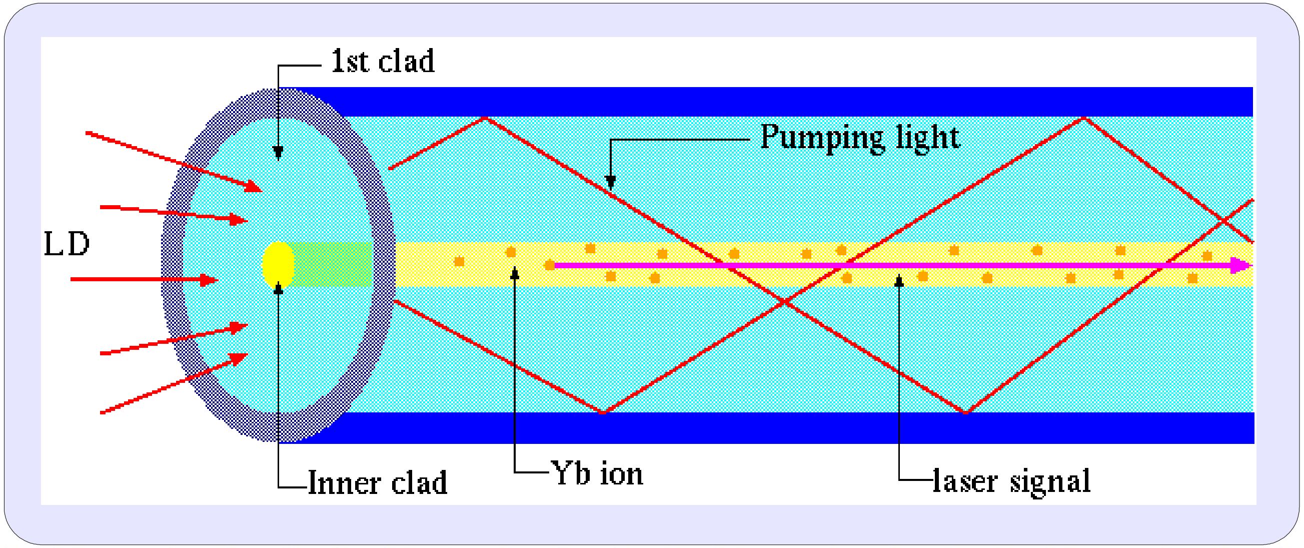
- ERL based Laser Compton ILC e+ source requires
  - **160MHz repetition**
  - **30μJ pulse energy**
  - **1ps or less pulse length**
- which has 4.8 kW average power and 30 MW peak power, which is quite challenging.
- This laser is not available at this moment and need our own efforts for
  - **Basic R&D,**
  - **System integration,**
  - **Demonstration.**

Fiber Laser Amplifier

- Among various laser technologies, Yb doped fiber laser amplifier has advantages
  - **Technology of fiber laser has made tremendous progress last few years.**
  - **Currently, the average power is limited only available power for pumping; further improvement is expected depending on the technology and cost performance of pumping.**
    - Laser Diode cost,
    - Laser Diode cooling technology,
    - Coupling to Yb fiber.
- Then, Yb fiber laser is one of the best candidate for the high power laser for Laser Compton.

Yb fiber laser

- Double clad-core optical fiber; Yb ion is doped in the inner core.
- InGaAs LD (940nm) is introduced into 1st core for pumping.
- Signal, who propagates only in the inner core, is amplified by stimulated emission.
- Typical core size is 6 – 40 μm.



Yb fiber laser Power Evolution

- ▶ 1989 DCFL (Double Clad Fiber Laser) is developed.
- ▶ 1999 >100W CW
- ▶ 2002 >1kW CW
- ▶ 2003 >10kW by fiber bundle. Fiber laser is introduce to Automobile industry
- ▶ 2004 >1kW by Single Mode.

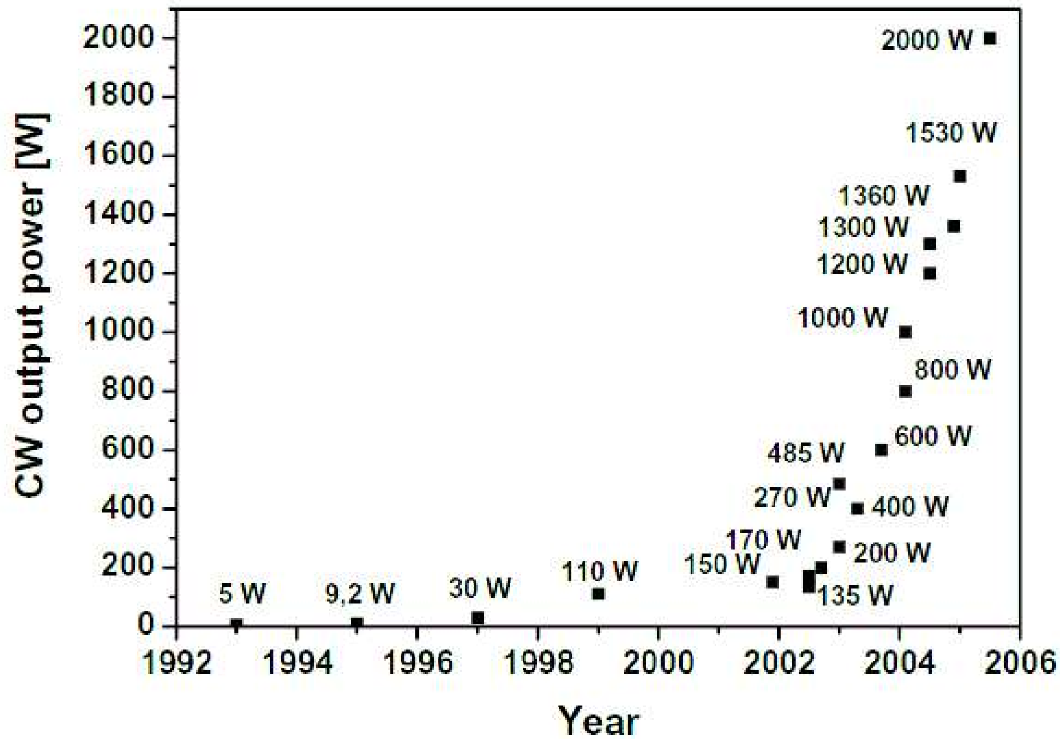


Fig. 4: Power evolution of cw double-clad fiber lasers with diffraction-limited beam quality over the last decade

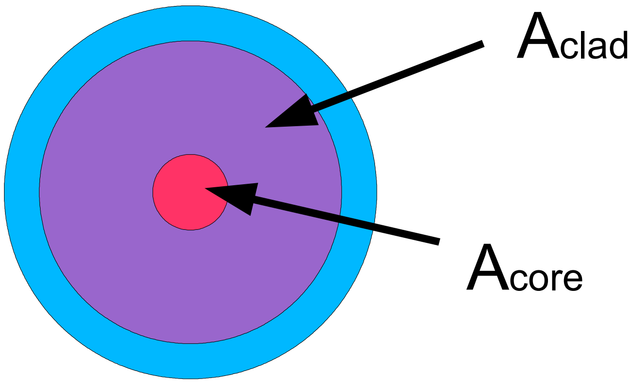
J. Limpert,T. Schreiber, and A. Tünnermann, “Fiber based high power laser systems"

Why Fiber Laser?

- High Power limit is determined primarily by thermal dissipation
  - **Cooling efficiency ~ surface area/volume is maximized by 1) large thin disk and 2) very long rod~fiber.**
- Yb3+ has unit quantum efficiency, which is an ideal dopant.
- Thermal damage threshold of an un-doped silica fiber is 2~5 GW/cm2 (CW) ; 10um core 1.5-4kW.
- The silica fiber has very low loss dB/km with dopant.
- Fiber itself is a wave-guide structure, which avoids any effects like thermal lends.

What is issue for higher power?

- Larger core area (A_{core}) is better to avoid non-linear effects.
- Small aspect ratio ~ $A_{clad}/A_{core} = (D/d)^2$ makes pumping efficiency lower, then the fiber length becomes longer.
- Non-linear effect is accumulated along the fiber length, then the shorter fiber length is desirable for less non-linear effects.
- As a result, larger A_{core} keeping A_{clad}/A_{core} is good for higher power operation. Not only the A_{core}, but also A_{clad} should be larger.



Large Fiber : LMA

- DCFL can be operated in high power by larger core size.
- Single mode lasing is ideal from technical points of view, e.g. the output laser quality, power efficiency, etc, but fiber with larger core size becomes MM (multi-mode).
- LMA (Large Mode Area) fiber with low NA, can be operated in SM with larger core area with the following treatments
  - **Low NA compensate the MM transmission.**
  - **MM is further removed by fiber bending due to the higher loss for MM.**

Large Fiber : PCFL

- Low NA LMA SM fiber is feasible for high power laser.
- Due to the low NA, loss for SM is also increased and fiber bending enhances this effect.
- Assuming step index fiber, SM condition is $V = \pi d NA_{core} < 2.405$. 50$\mu$m core requires NA~0.0152.
- To realize such low NA, the refractive index should be controlled in order of $\Delta n \sim 1E\text{-}3$, which is very difficult by impurity doping .
- PCF (Photonic Crystal Fiber) is a solution. LMA-PCFL (J. Limpert et al., Opt Exp 11(2003) 2982) generates 260W with 78% slope efficiency.

High Power Limits

- Non-linear effects like Stimulated Brillouin Scattering (SBS), Stimulated Raman Scattering (SRS), Self Phase Modulation (SPM) limit the high power operation. SRS case, the critical power P_{cr} is

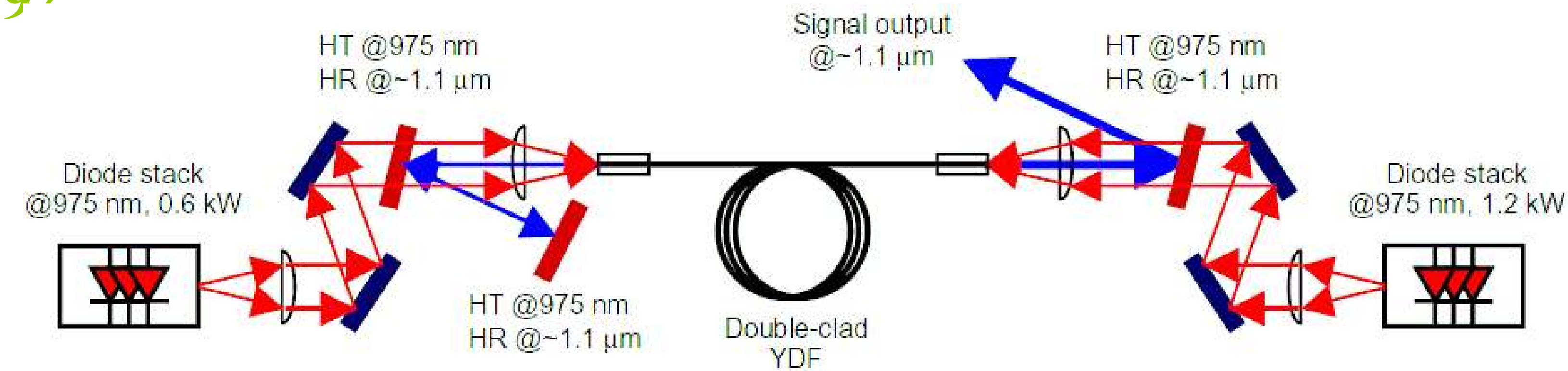
$$P_{cr} = \frac{16\, A_{eff}}{g_R\, L}$$

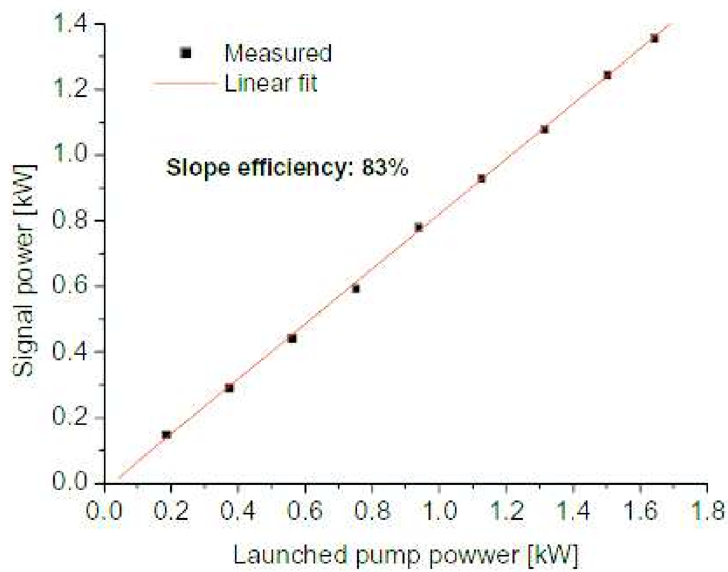
  - **A_{eff}: is effective mode area, g_R is Raman gain~ 1E-13m/W for Silica fiber at 1um, L is fiber length.**
  - **20μm core 10m fiber gives 5kW.**

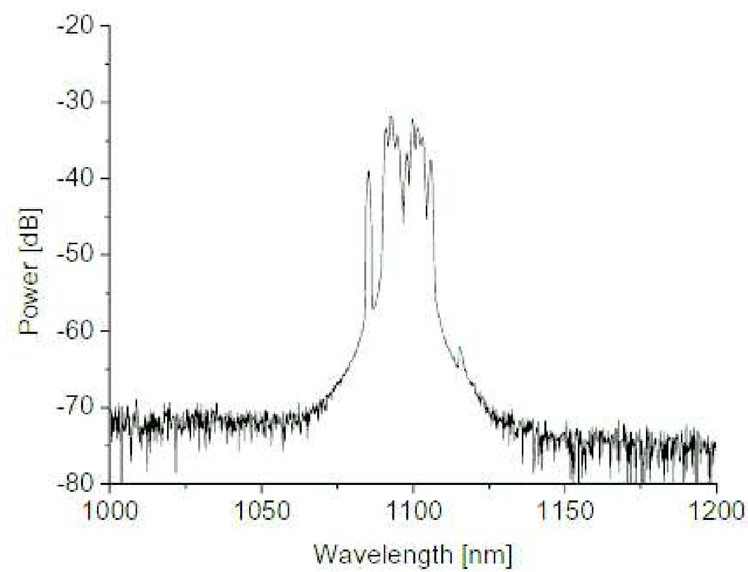
- Small L makes thermal load per length higher. Actual limit on the operation temperature is Tmax=600K.
  - **Power limit on d=50μm actively cooled fiber is > 10kW CW. (A. Shirakawa and K. Ueda, Journal of Japan Laser Society, Vol33, 4 (2005) 254)**

Yb fiber laser (CW)

- ► 1.36 kW CW at 1μm with 83% slope efficiency .
- ► The power is limited only by available pump power.
  - – **Y. Jeong et al., Optics Express, Vol. 12, Issue 25, pp. 6088-6092**



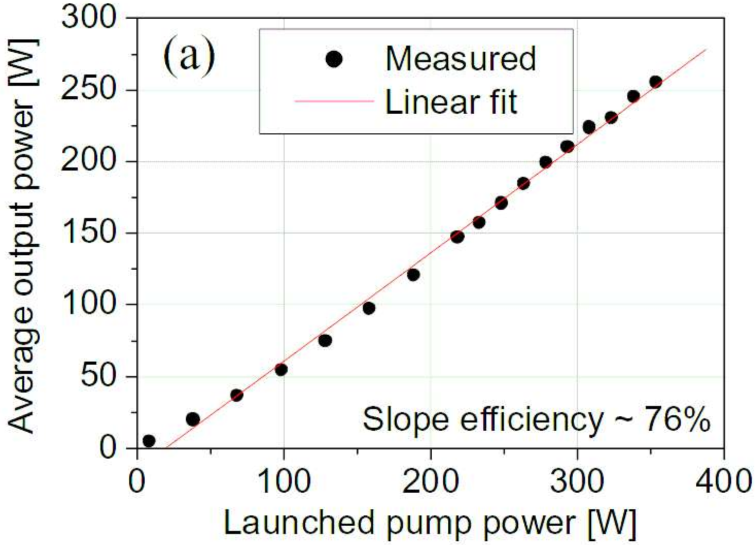


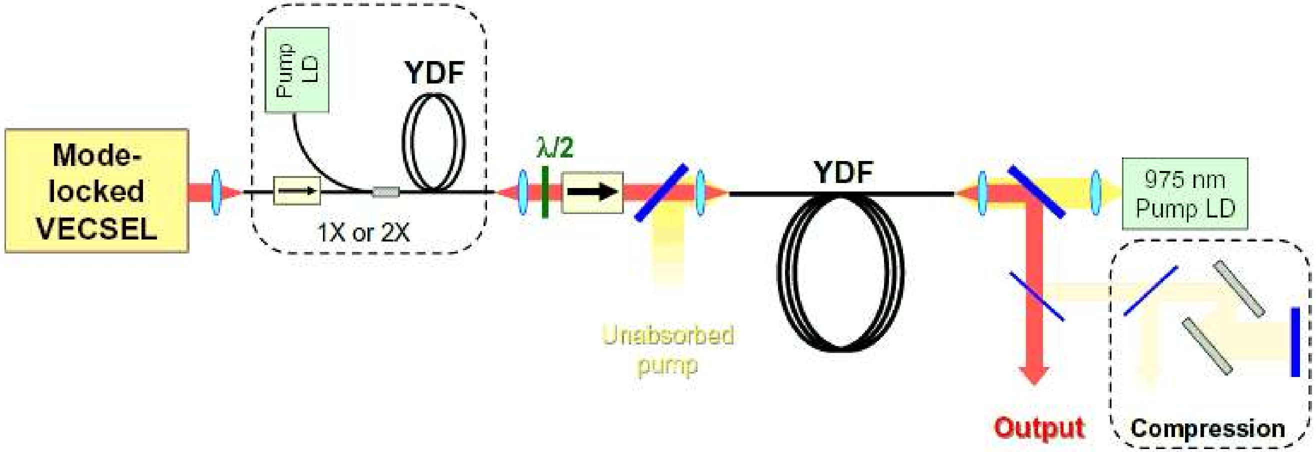


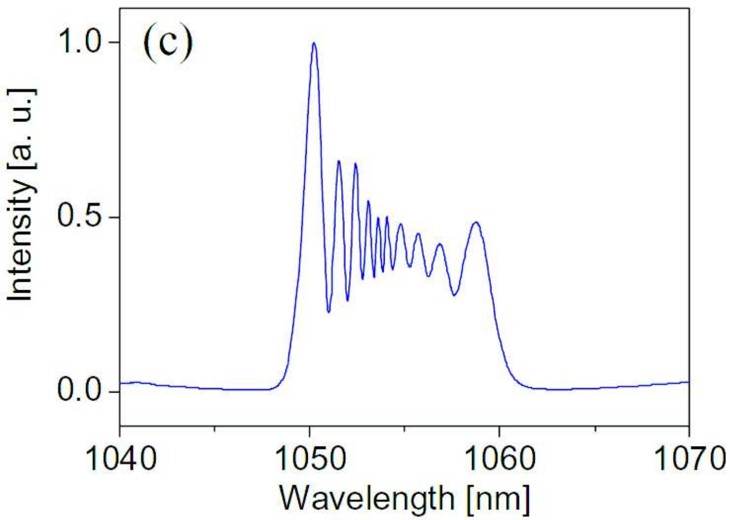
Yb fiber laser (ps pulse)

- 1GHz, 4.6ps -> 430fs, 200W pulse train with MOPA by passively mode-locked VECSEL and Yb fiber amplifier.
- 25μm inner core, 12m fiber.
- Peak power in fiber amp is 40 kW (8.8GW/cm^2), which is below SRS, but SPM is significant.

(P. Dupriez, et al., OPTICS EXPRESS 9611,
Vol. 14 - 21, 2006)

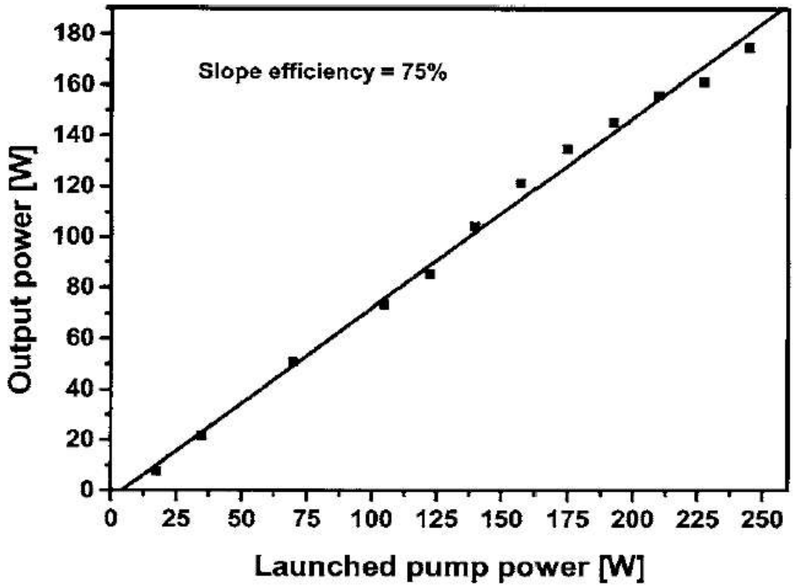




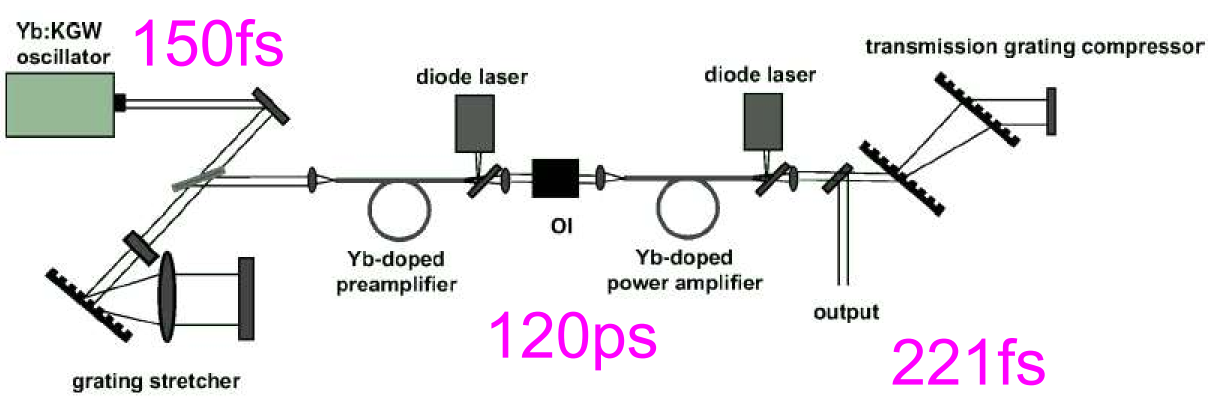


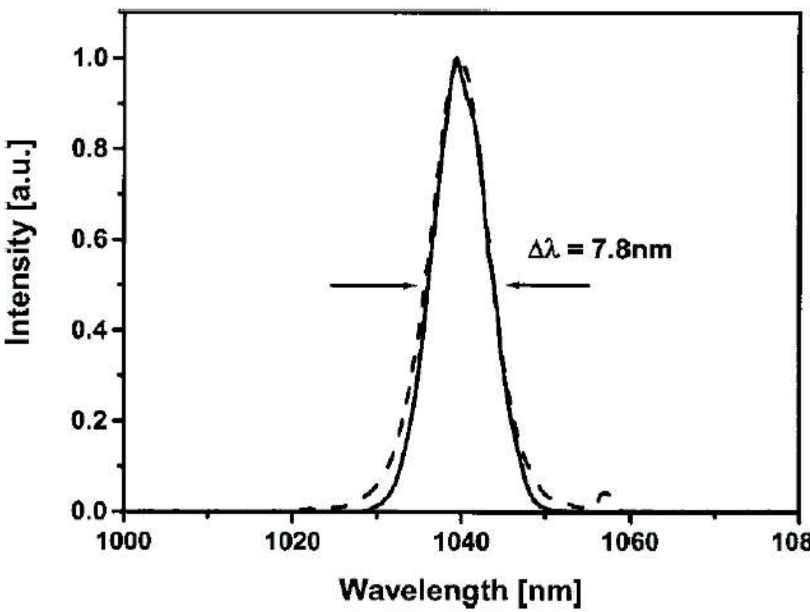
Yb fiber laser (CPA)

- ►73MHz 150fs pulse train is amplified by CPA up to 1.8μJ with 120ps, 131W.
- ►The pulse is compressed down to 221fs by de-chirping.
- ►40μm core, 1.2m fiber.



F. Roeser et al., OPTICS LETTERS, Vol. 30, No. 20 pp754-756, 2005





Scaling (1) ps pulse case

- 200W/1GHz/5ps=40 kW is peak power amplified in DCFL.
- Due to the SPM, linear dispersion is not preserved and the amplified pulse (200nJ) is compressed only down to 430 fs.
- If this pulse duration is scaled to 1ps by keeping the peak power (44kW in amp and 465kW after grating), 464nJ 10.7ps pulse after amp and then compressed down to 1ps.
- If the pulse repetition is 160MHz, the average power is 74W, which is 65 times smaller than our target.
- If we increase the power, the SPM will be more significant and pulse compression becomes much harder.
- It is very hard to achieve our goal by extending this scheme.

Scaling (2) CPA case

- If the pulse duration obtained in Roeser's article, is scaled from 221fs to 1ps,
  - **550ps in Yb fiber amp, 1ps after grating.**
  - **If the same peak power (15kW in fiber and 8.1 GW after grating), 8.1uJ/pulse is possible.**
- If the pulse repetition is 160MHz, the average power is
  - **8.1uJ x 160 MHz = 1.3 kW**
- This number is obtained from the demonstrated result by scaling on the pulse length with the same peak power.
- The power is limited by the pumping power. There is some possibility of more improvement up to 4.8kW.
- In addition, some improvements by optimizing on CPA are expected. Then, 4.8kW pulse laser based on Yb fiber amp is possible.

Pumping Power

- According to the power scaling from the demonstrated DCFL CPA pulse train generation, our goal is possible avoiding non-linear effects like SRS, SPM, etc.
- To realize this energy scaling, providing enough pumping power is another issue.
- Currently, DCFL pumped from both ends is emplyed and 1kW from each side, totally 2kw pumping is likely to be a practical limit.
- Multi-mode pumping, Side-pumping, Multi-fiber Pump Coupler (MFPC) are possible solution.
- Another solution is combining outputs from multi-fiber array: wave length beam combining, fiber coupler beam combining, etc.

Summary

- 4.8kW average power pulsed laser based on MOPA with Yb fiber amplifier is examined.
- By considering various theoretical and technical limits, our goal is even possible integrating the latest laser and optical technologies.
- According to the past experiments, pulse amplification with CPA technique is possibly a solution, but preserving a good linear chirping avoiding SPM during the amplification is an issue.
- More fancy technique to ease the non-linear effects are possible, LMA, LMA-PCFL,etc.
- Providing enough pumping power to Yb fiber is also a technical challenge; New pumping methods should be developed for 4.8kW laser.

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