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Advanced Fiber Laser Concepts for Future Accelerator Technology

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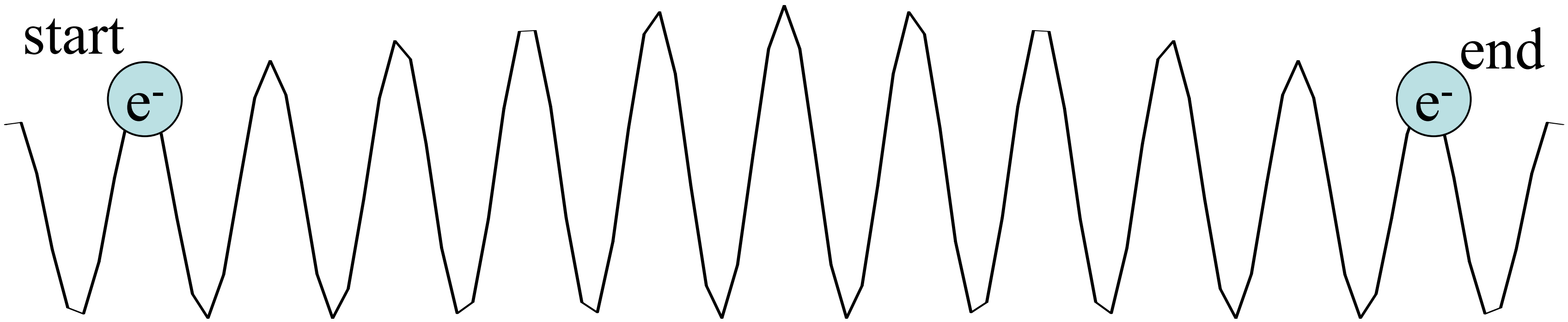
Acknowledgements: Ingmar Hartl, Lawrence Shah, Robert Siemann

Principle of photonic electron acceleration



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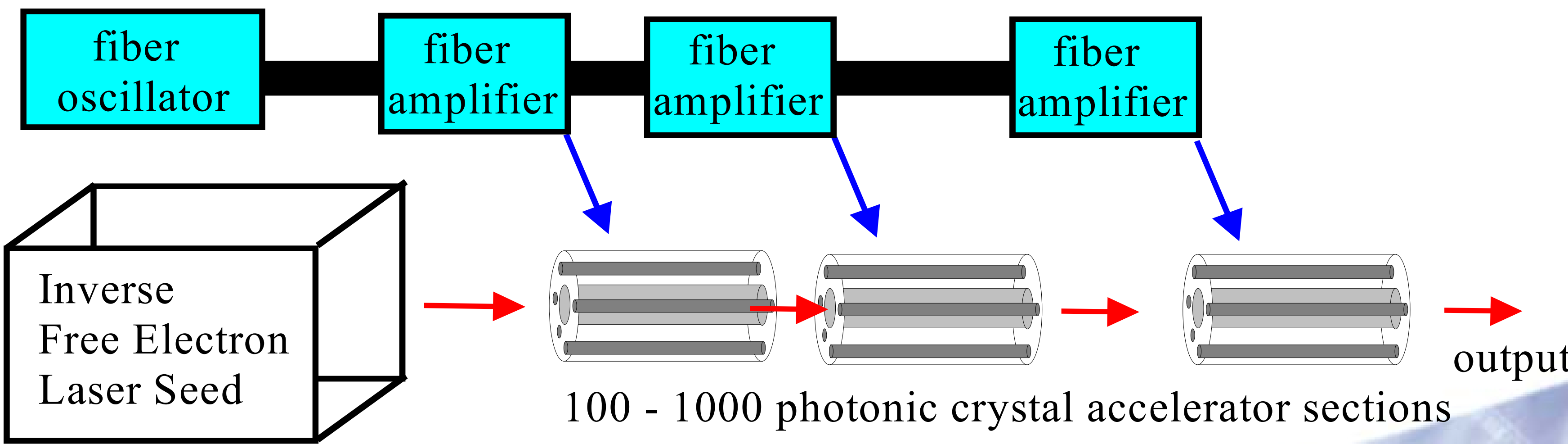

Ref. Benjamin Cowan, working group #7, Friday

Outline

- Fiber lasers as high power sources of photons
- Fiber based accelerator structures
- Phase stable fiber lasers
- Short wavelength sources without accelerators
- Conclusions

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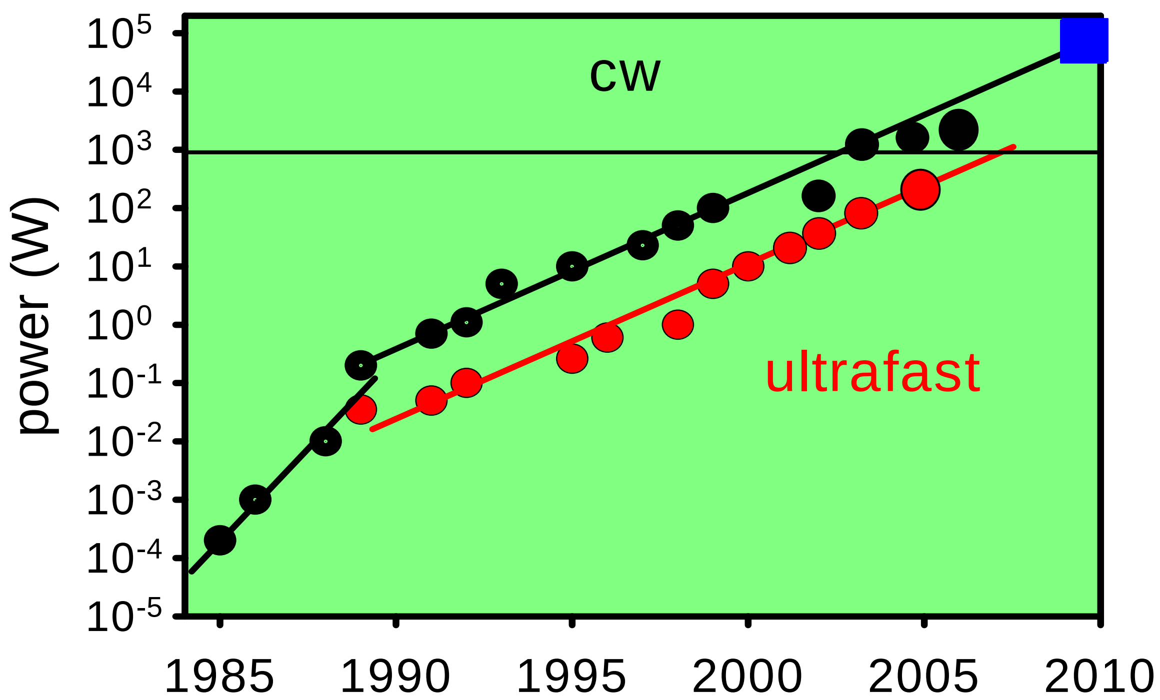
Basic Capabilities of Fiber Lasers



Since 1985 power level from SM fiber lasers went up 7 orders of magnitude,

- Currently 3 kW is record for diffraction-limited power
- 100 kW expected in 2010
- 1 MW expected in 2015

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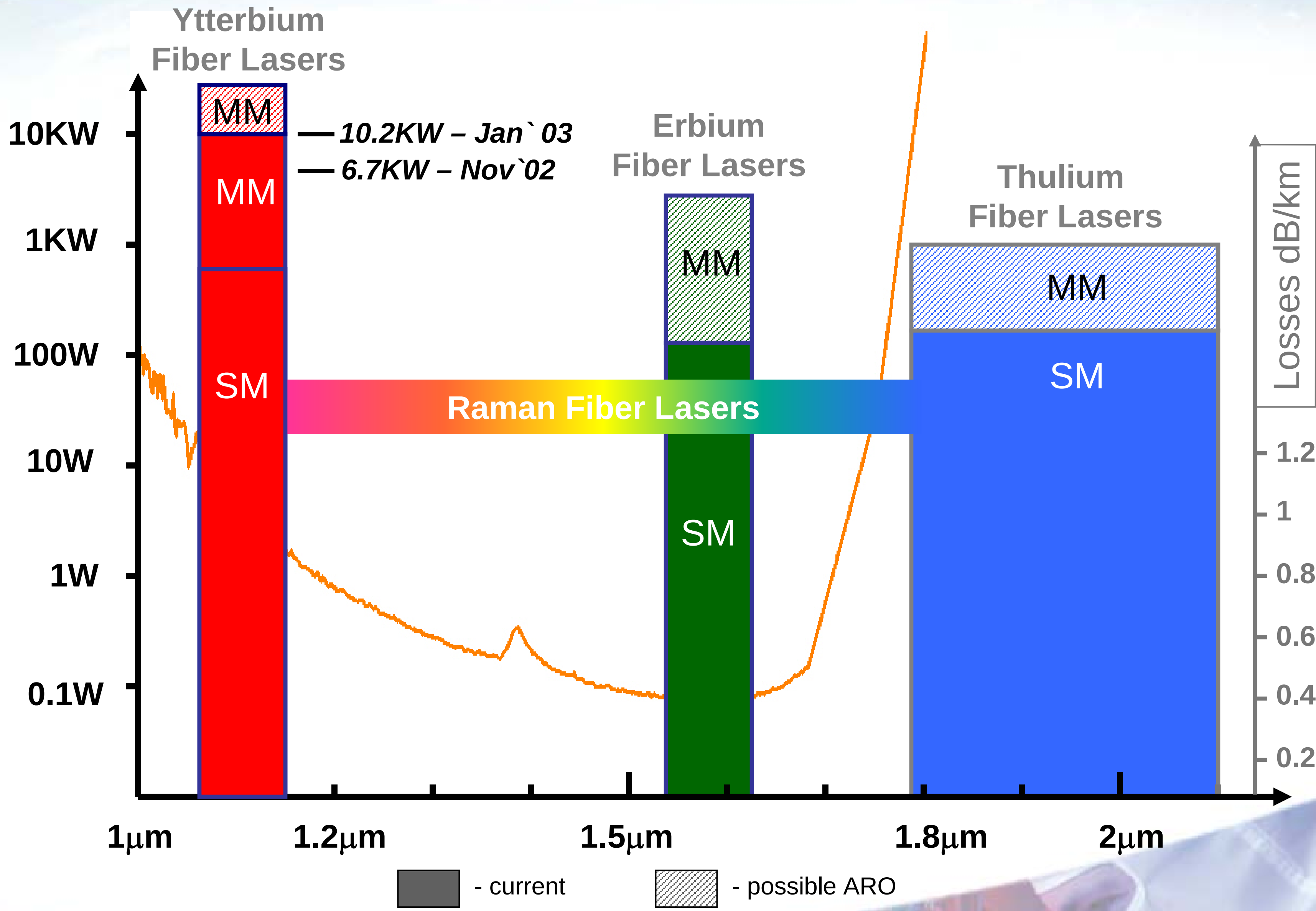
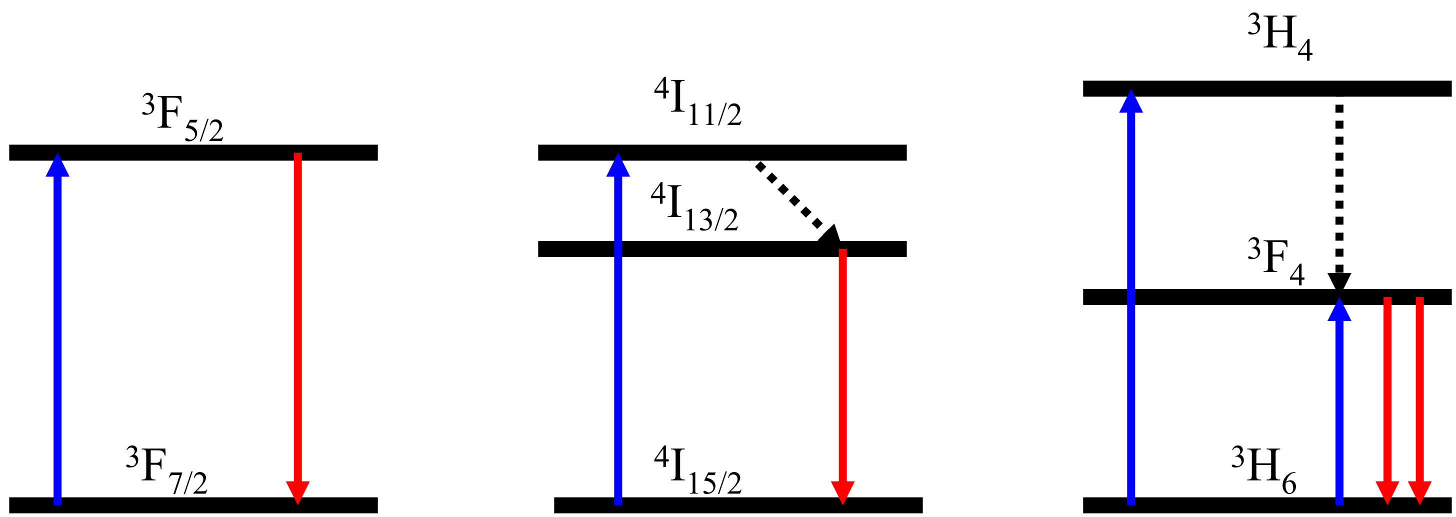
Commercial Fiber Lasers Spectral Range

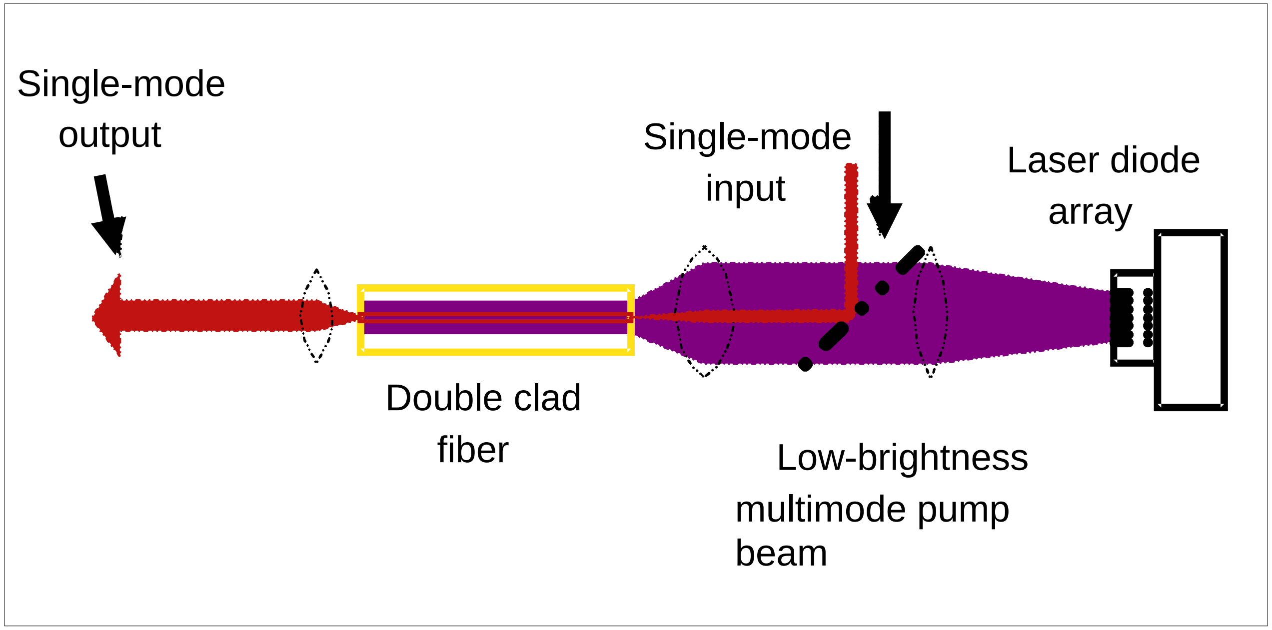


Efficient Fiber Laser Systems



Yb^{3+}	Er^{3+}	Tm^{3+}
Emission: 1040 nm	Emission: 1530 nm	Emission: 2000 nm
Efficiency: 95%	Efficiency: 60%	Efficiency: 70%

Pumping of fiber lasers



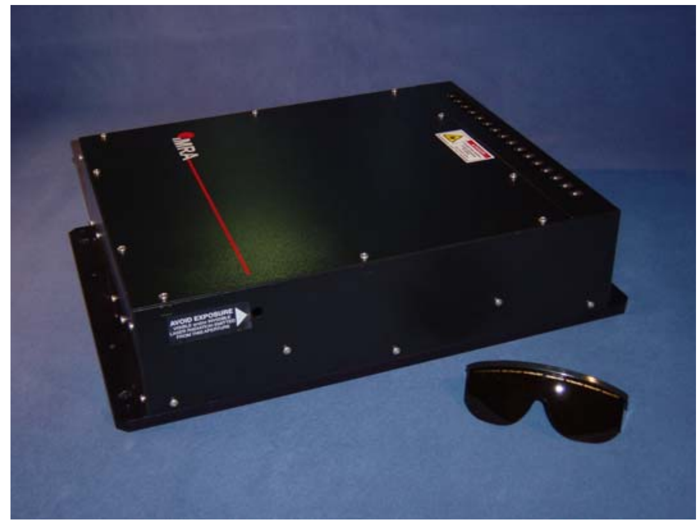
ref.: H. Po et al., OFC, paper PD7 (1989)

$$P_{pump} = Bd^2 NA^2$$ with $B_{max} = 10\ MW/cm^2$

P_{pump} = 5 - 8 kW into 600 μm diameter fiber!

Industrial fiber lasers

4 kW average power fiber laser (IPG)



10 uJ, 700 fs fiber laser,
Peak power = 15 MW
P_{av} = 1 W
(IMRA)

Dielectric breakdown in silica

Pulsed:

optical damage fluence: $F = 300\ \text{J/cm}^2 \times (\tau/1\ \text{ns})^{1/2}$

$$E_{damage} = \sqrt{\frac{2F}{\sqrt{\varepsilon_r \tau}} Z_0}$$

= 1.9 GV/m for 100 ps pulses

= 3.3 GV/m for 10 ps pulses

$E_{damage} = E_0/\tau^{1/4}$

Accelerating gradients up to 1.6 GeV/m may be available

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DC breakdown

Optical DC-facet breakdown = 2 GW/cm^2, not much Increase of damage fluence for τ > 150 ns

For 1 μm core diameter fiber, a dc power of 20 W may lead to DC breakdown,

For state of the art 30 μm core fiber, DC breakdown = 20 kW

→ To maximize DC breakdown, operation at 2 μm preferred,

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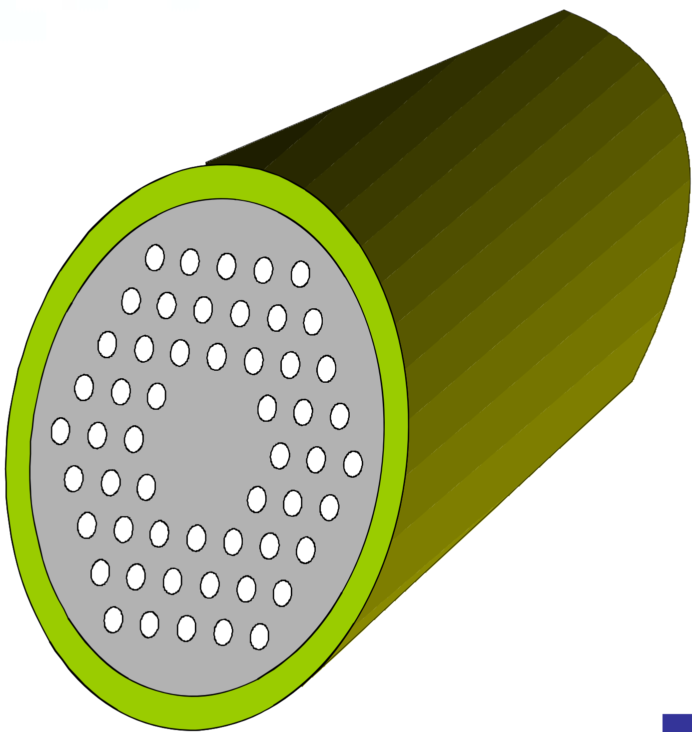
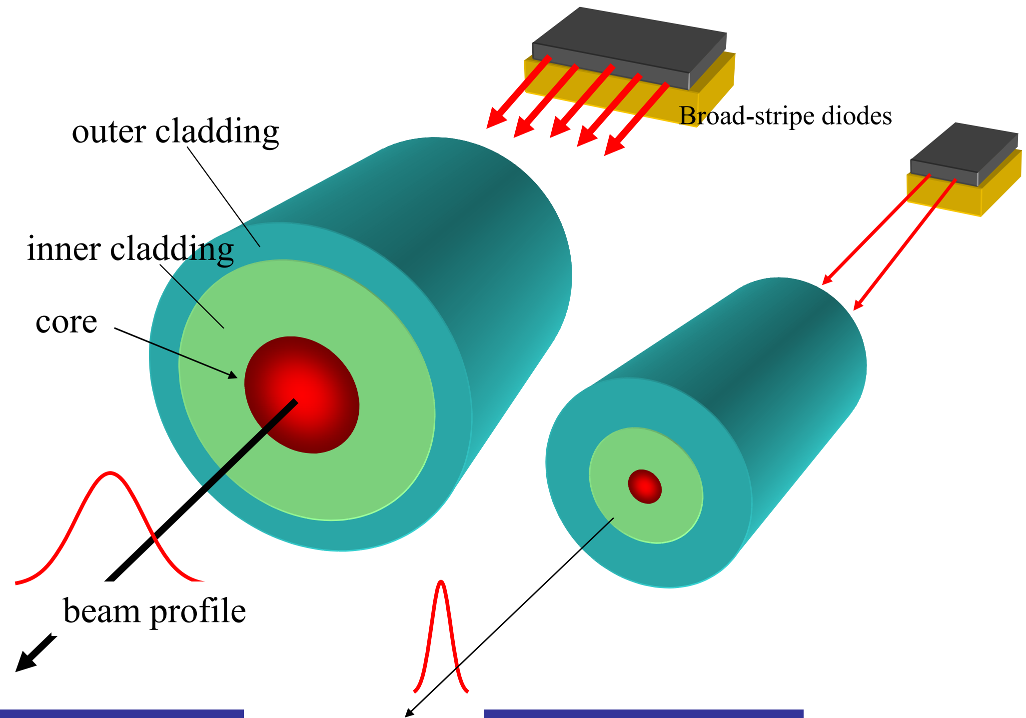
Maximize DC breakdown by use of large-core fibers





Up to 60 micron core

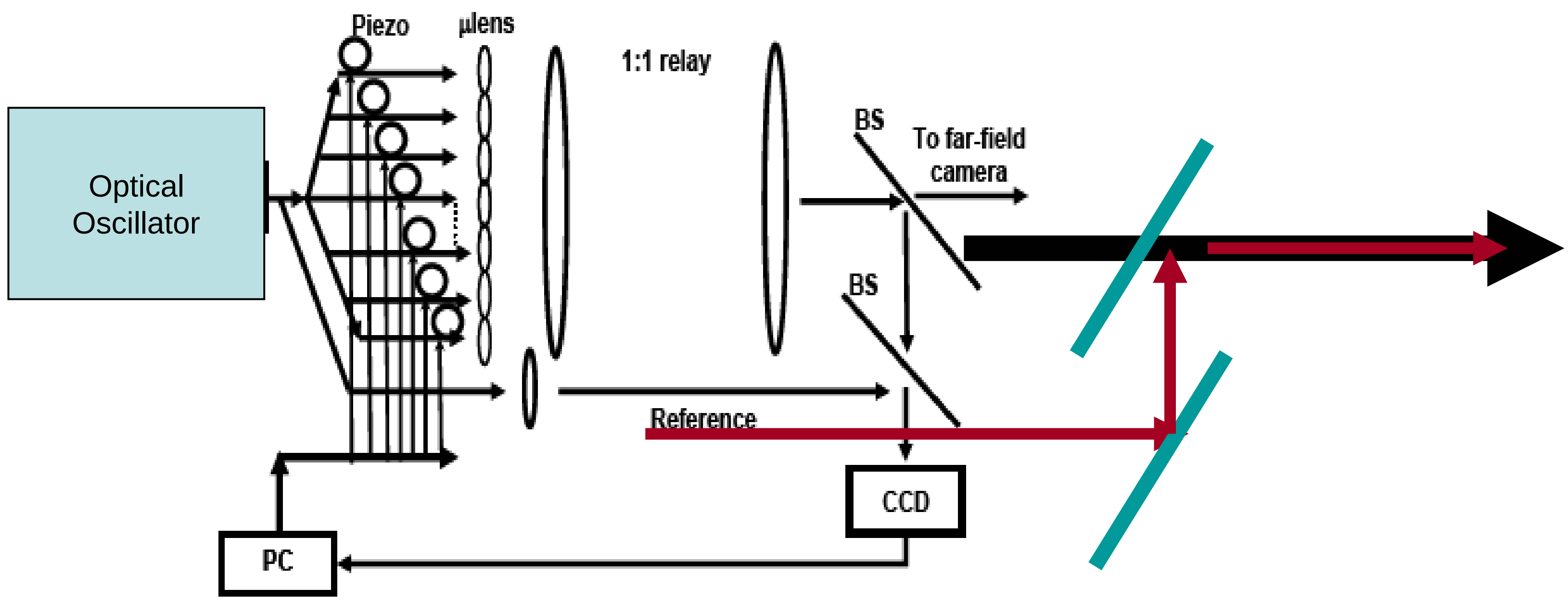
Standard 6 micron core

Limpert et al., 2006:
60 um crystal fiber rod

Fermann et al., 1997
US patent# 5,818,630

If 20 kW, DC limit for fiber lasers, how can we get to 1 MW?

Answer: fiber phased arrays



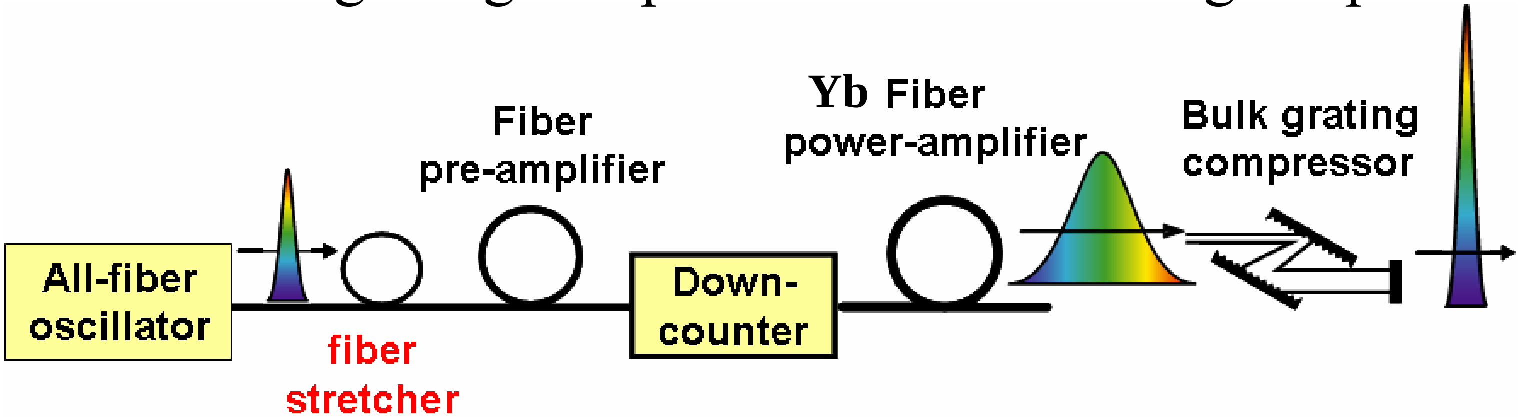
Coherent combination of up to 1000 separate kW level fiber lasers

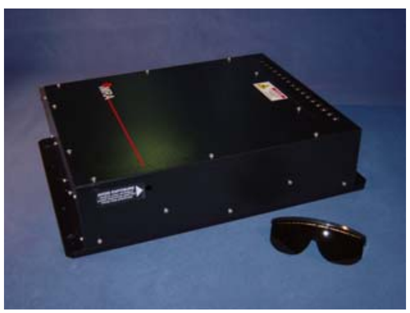
Ref. S. J. Augst et al., Opt. Lett., vol. 28, pp. 331 (2003)

So far up to 40 ‘cold’ fibers have been coherently combined, with phase stability < 1 rad/30 **,questionable whether economical approach**

High peak power fiber amplifiers chirped pulse amplification

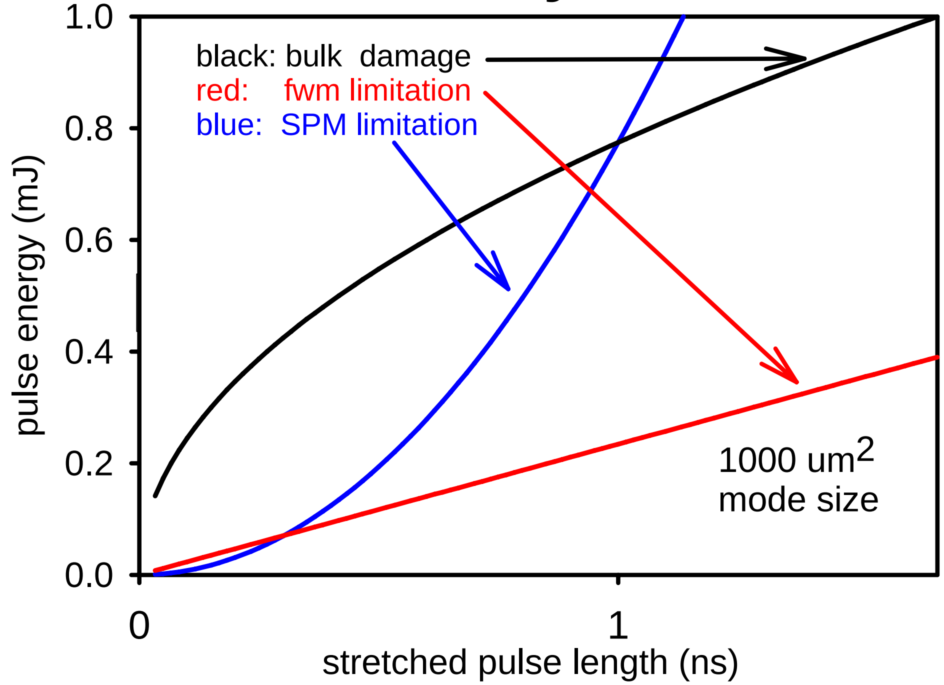
- generation of ultimate peak power
- bulk grating compressor to avoid damage in power amp





Can: generate: 100 μJ, 400 fs pulses at 1 MHz rep. rate with 100 W average power;
kW systems in progress;

Pulse energy limitations for fiber CPA systems

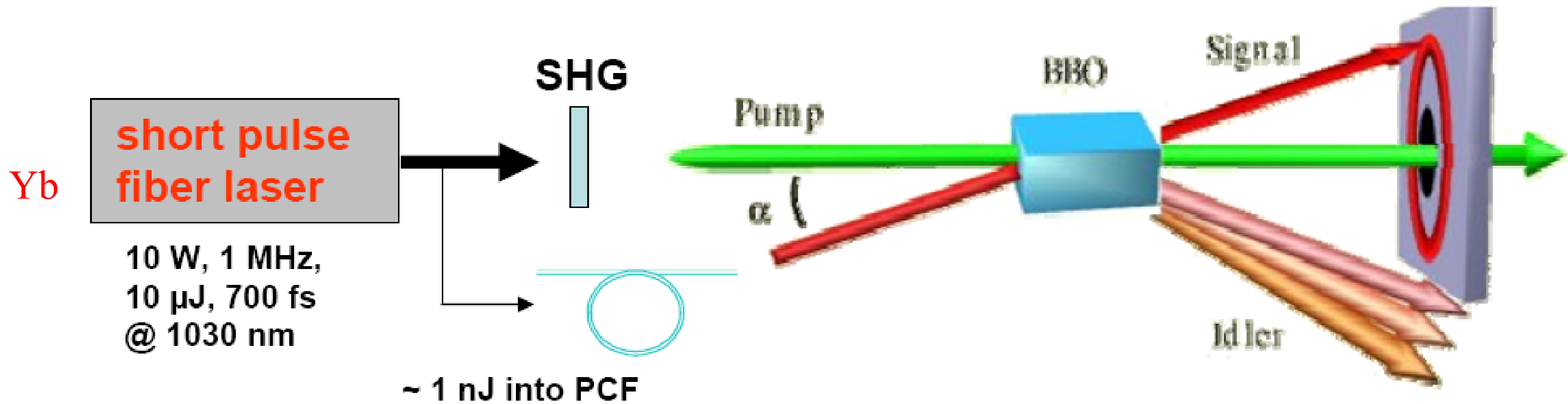


1 mJ pulse energy, 500 fs pulse width
reachable with 1 ns stretched pulse length

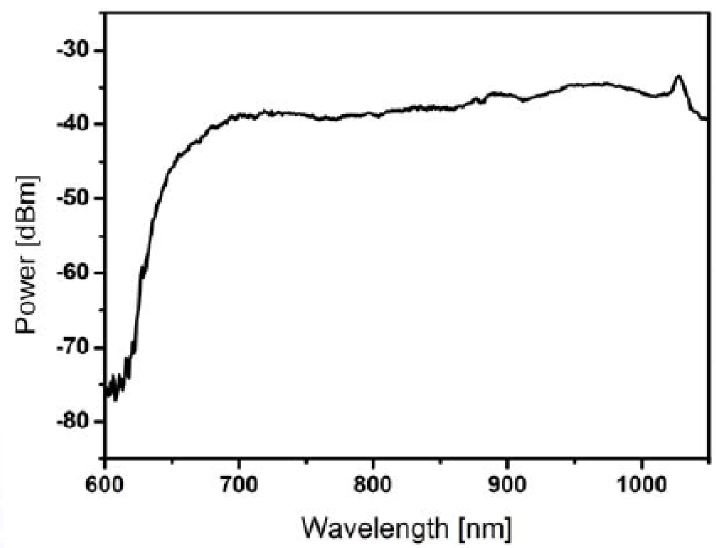
Maximum peak power from fiber chirped pulse amplifier:
10 GW

Coherent combination not practical yet for pulsed systems

Fiber Laser Pumped Ultrafast Parametric Amplification



Generated continuum in 80 cm PCF



Potentially achievable

10 fs	pulse width
500 uJ	pulse energy
10 – 100 W	average power
50 GW	peak power

Limpert et al.,
CLEO 2006

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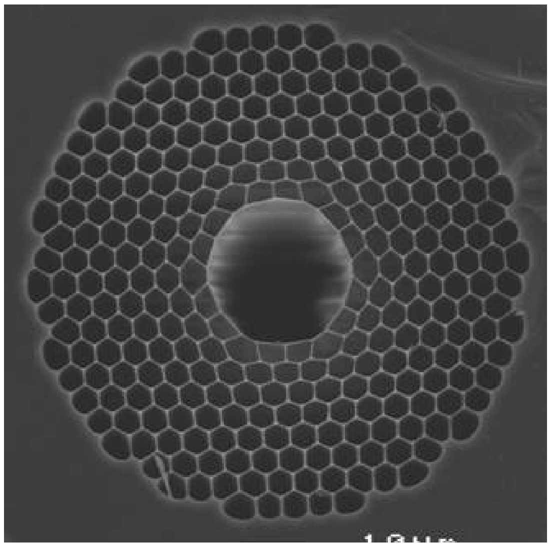
Summary of high peak power fiber laser

- CPA limit: 1 – 10 GW for 500 fs pulses
  optical efficiency > 90%
- PCPA limit: 10 – 50 GW for 10 fs pulses
  optical efficiency> 20%

- TW systems will require further amplification in bulk solid-state amplifiers

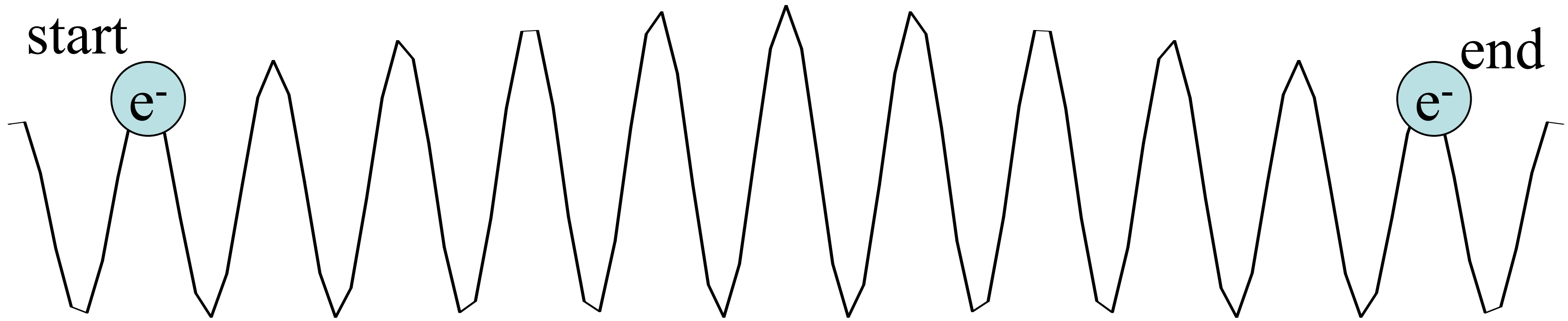
Photonic Crystal-Accelerator Structures



Photonic Crystal Fibers

Ref.: P.St. Russell et al., Science, vol. 299, 358 (2003)

Principle of photonic electron acceleration



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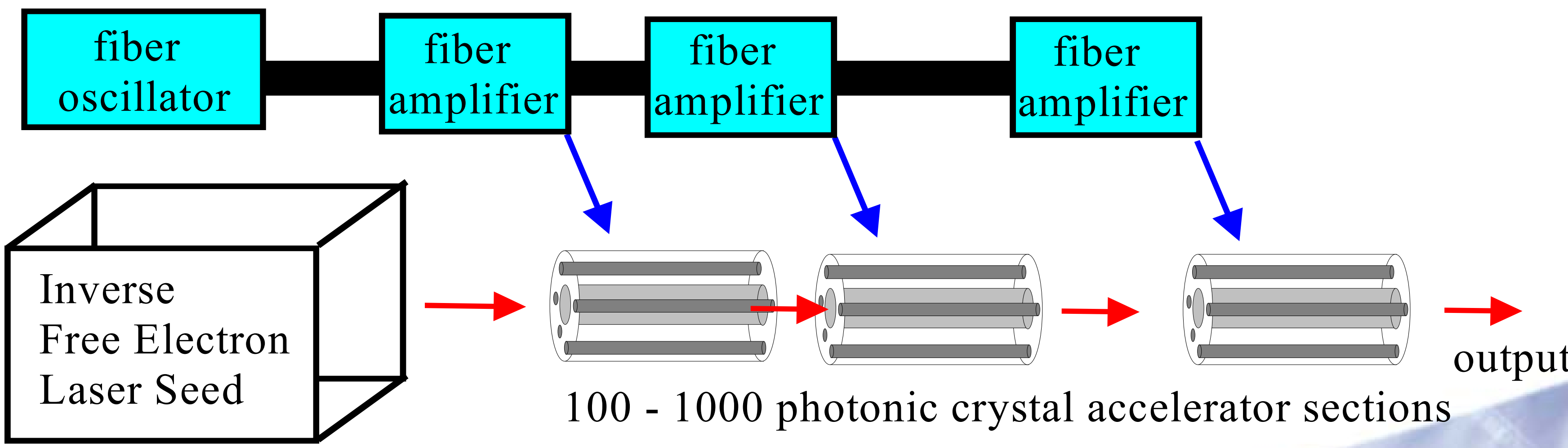
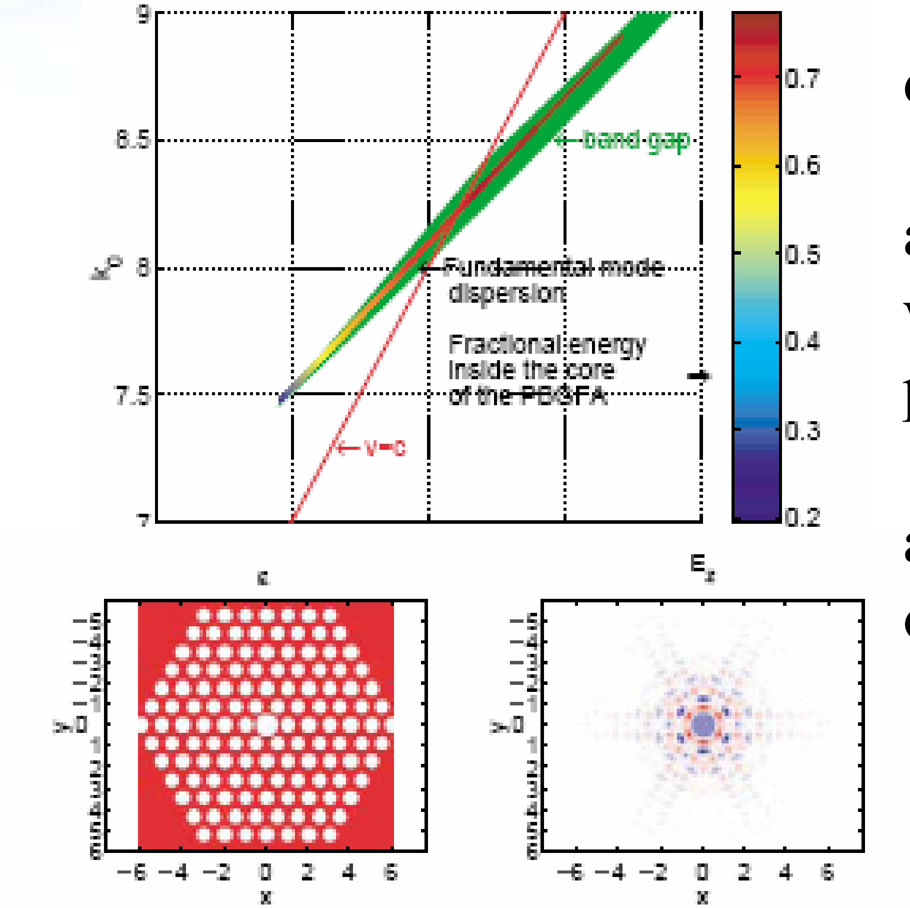


Ref. Benjamin Cowan, working group #7

Fiber based accelerator structures



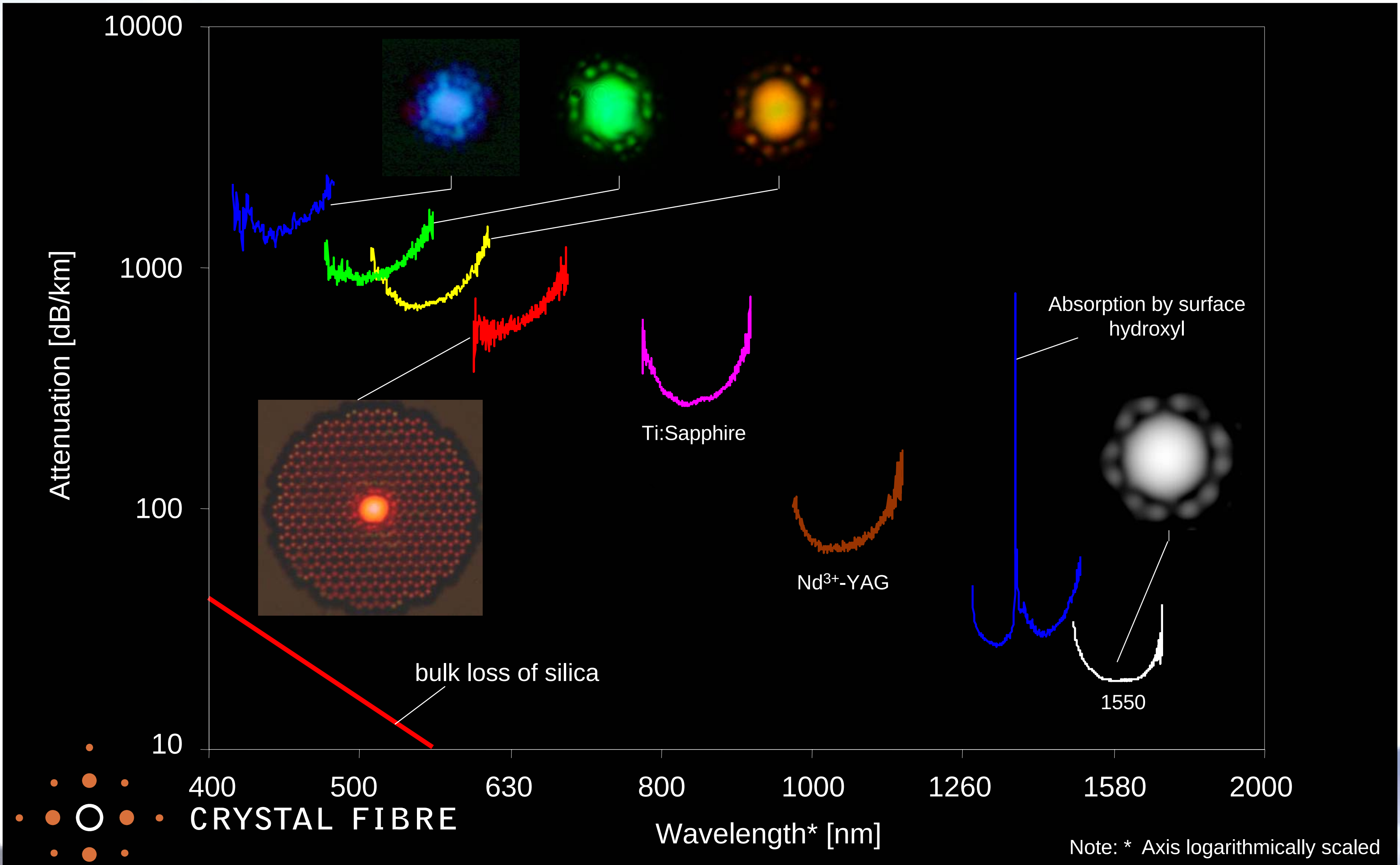
defect size ≈ pump wavelength

accelerating fiber TM modes with longitudinal E-field& phase velocity = c

accelerating field limited by optical damage, i.e. 1 - 2 GeV/m

Ref.: X. E. Lin, Phys. Rev. Special Topics-Accelerators and Beams, Vol. 4, 051301 (2001)

Transmission properties of air-guiding fibers



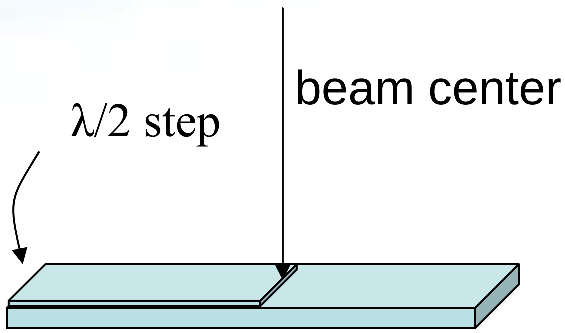
CRYSTAL FIBRE

Photonic crystal accelerator structures

Various problems:

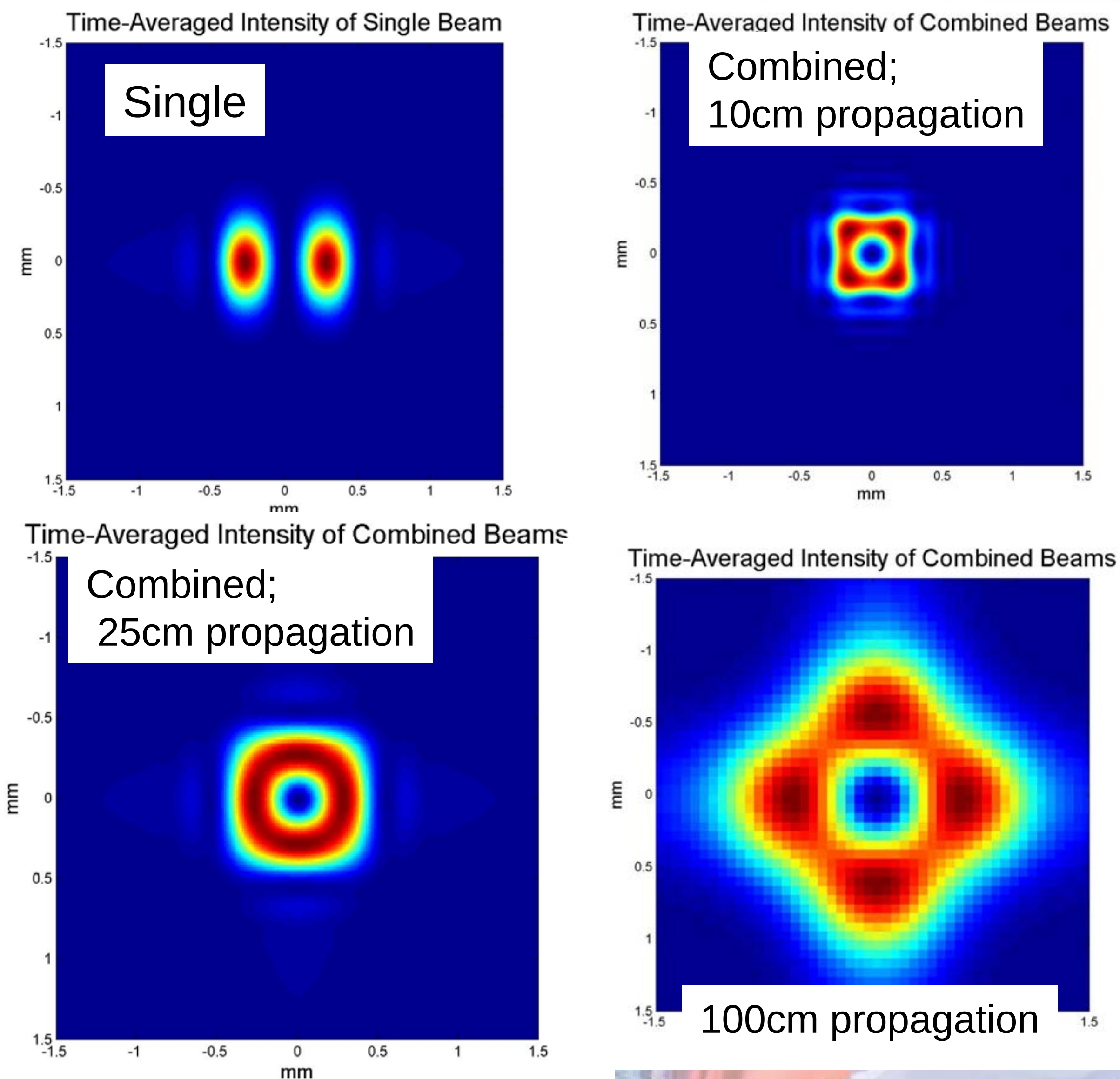
•generation of ultra-short electron bunches
•radiation damage to optical fiber
•simultaneous coupling of e-beam & optical beam
•coupling of optical beam into TM modes of photonic crystal fiber
•remote phase-control of photonic accelerator sections
•absolute phase stability of optical beam

Coupling of TM modes into PBG fiber

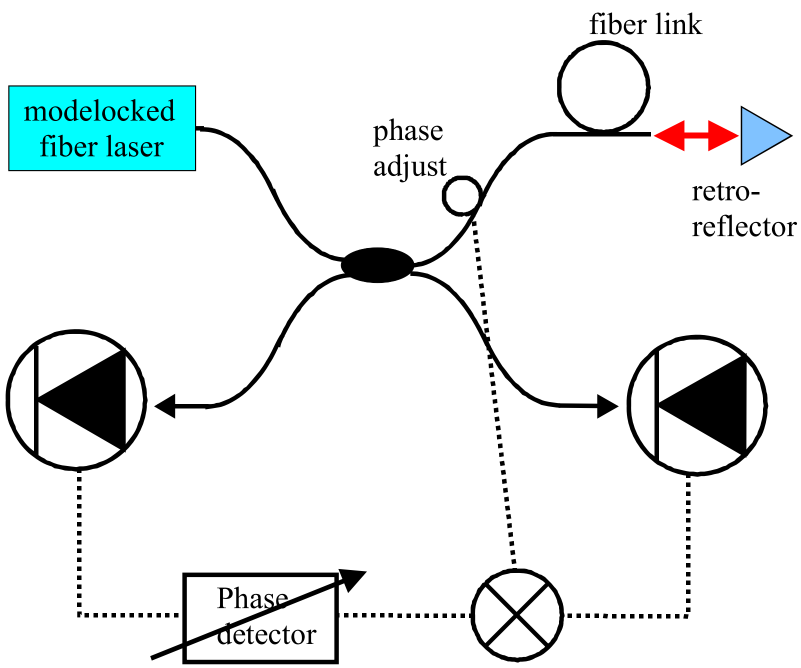


simplier than spiral wave plate. Only need 1 interferometer to make donut mode

Ref. Patrick Lu Stanford



Remote transfer of high-stability ultra-low jitter timing signal



Remote phase of fiber link can be controlled precisely using homodyne detection

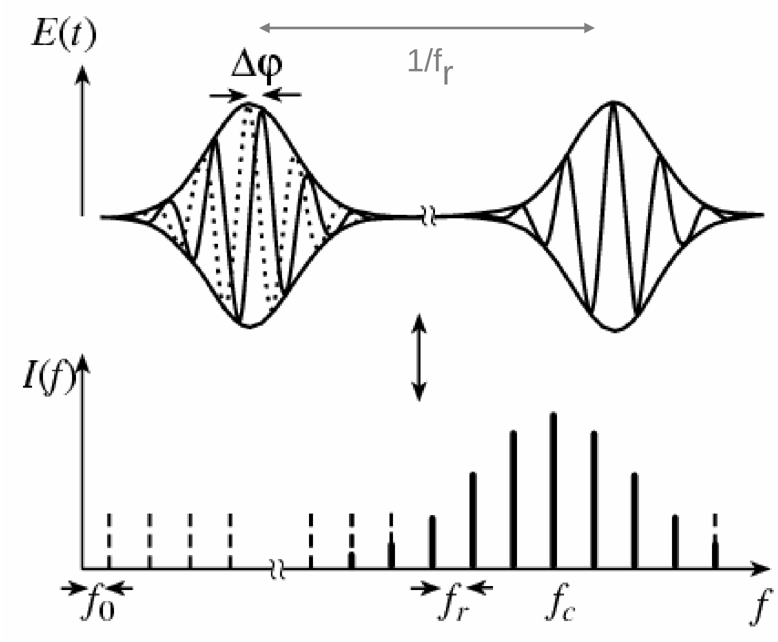
Ref. K. Holman et al., Opt. Lett., vol. 30, 1225 (2005)
J. Ye et al., J. Opt. Soc. Am. B, vol. 20, 1459 (2003)

Fiber lasers with absolute phase stability

Frequency combs

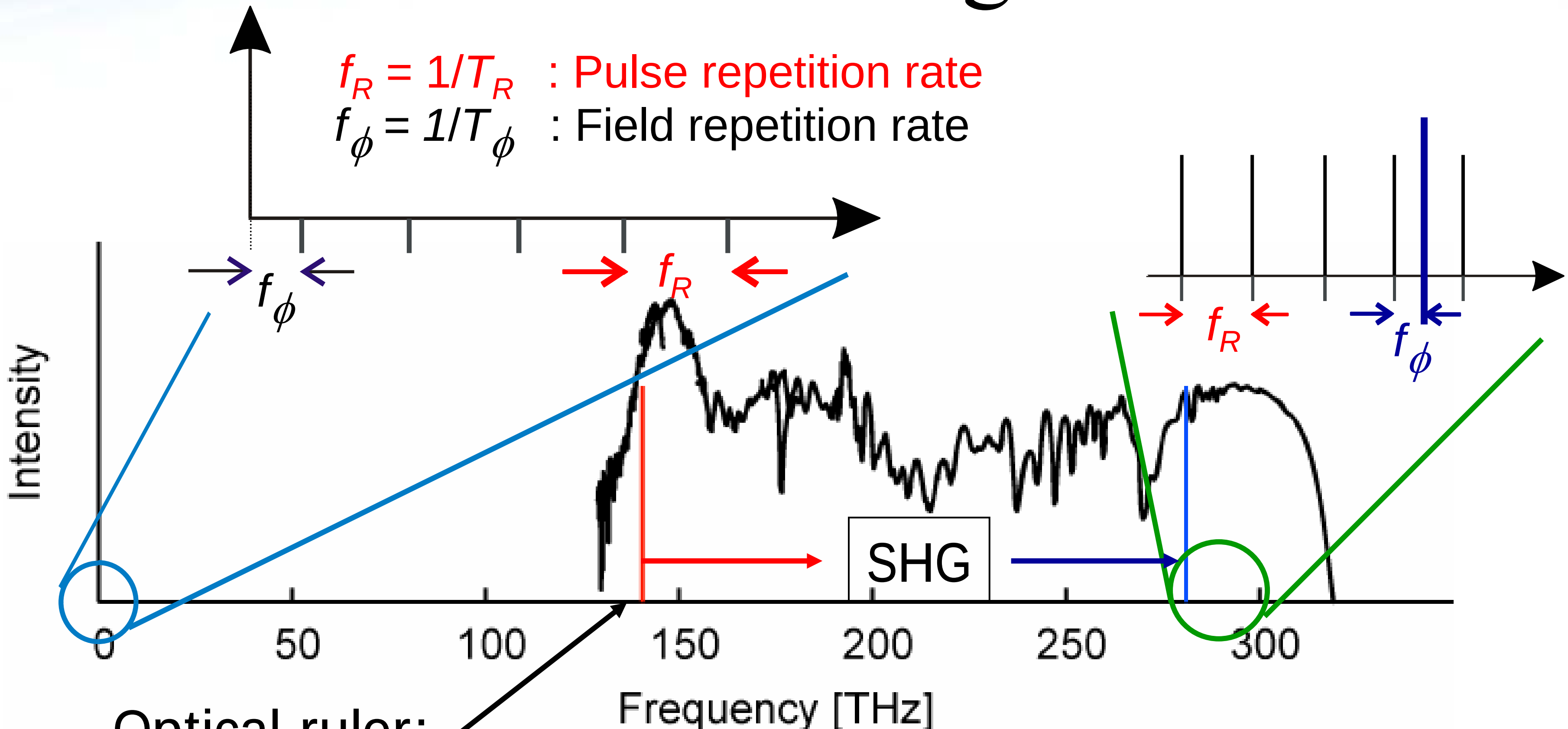
Time Domain

Frequency Domain



E. V. Baklanov (1977), T. Hänsch (1978),
V. P. Chebotaev (1988), Th. Udem, PRL **8**2, 3568 (1999).

Self Referencing Comb

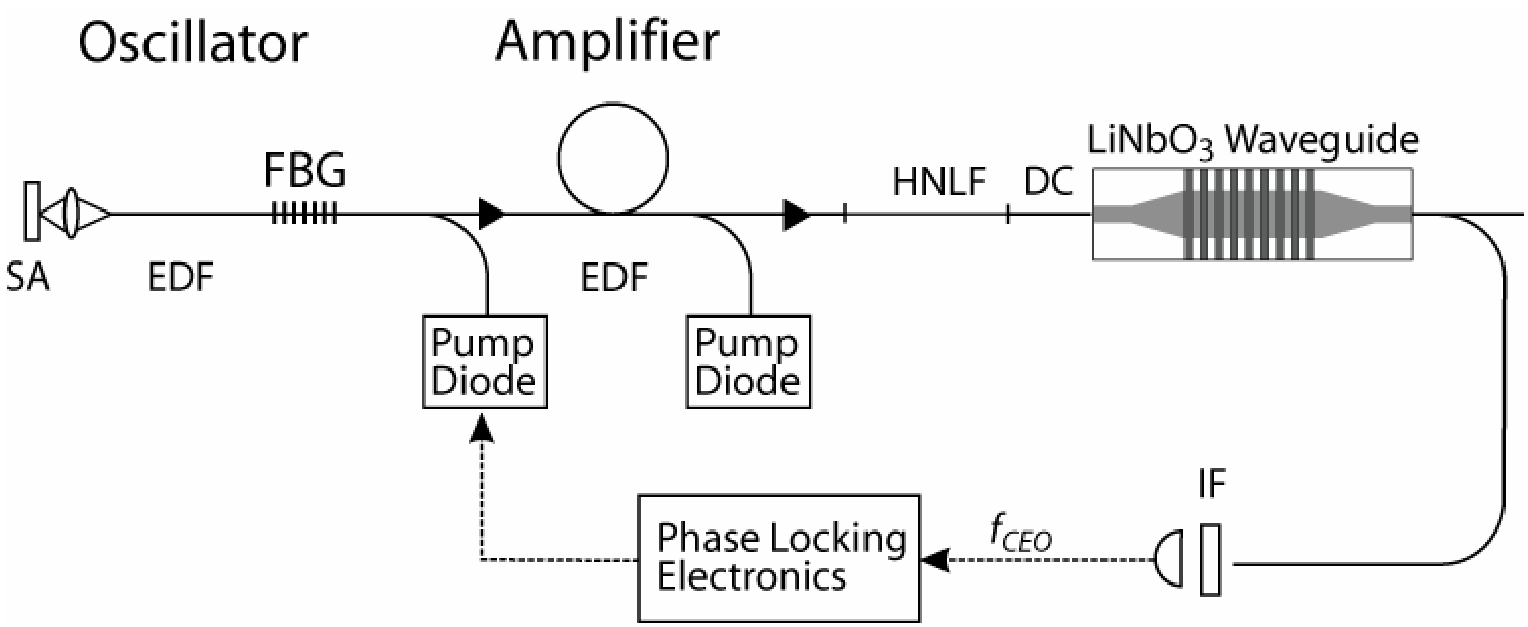


Optical ruler:

$$f_m = f_\phi + m f_R$$

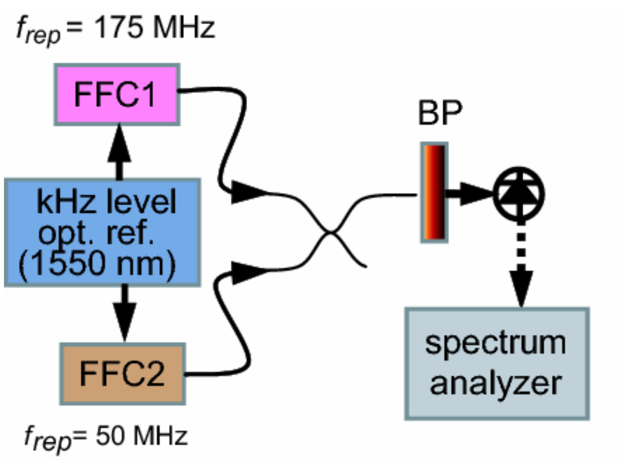
$$f_\phi = 2(f_\phi + mf_r) - (f_\phi + 2mf_r)$$

Optically Integrated, all Guided Wave Frequency Comb Laser

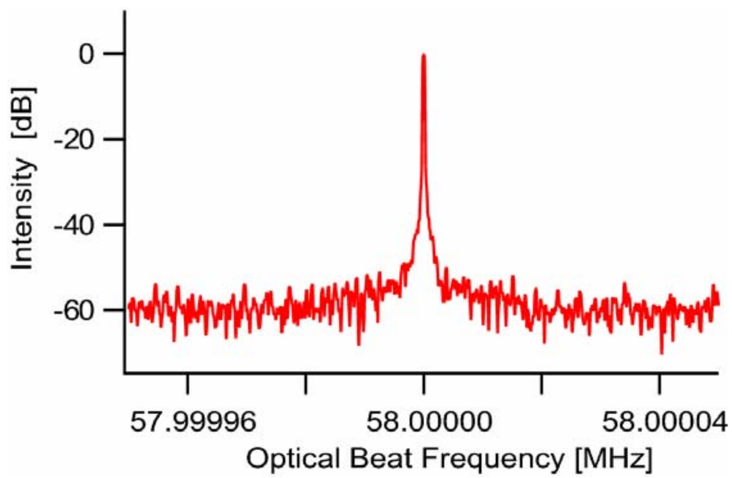


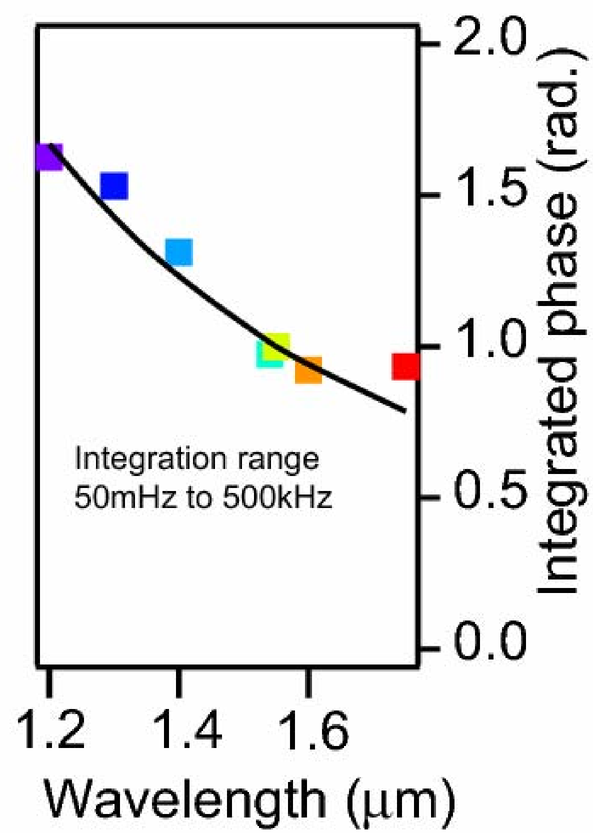
Ref. I. Hartl et al., '170 MHz spaced, self-referenced fiber frequency comb', CLEO 2006

Phase stability of fiber lasers



- Phase noise governed by phase locks
- No measured excess phase noise
- Implies timing jitter between combs of ~1fs

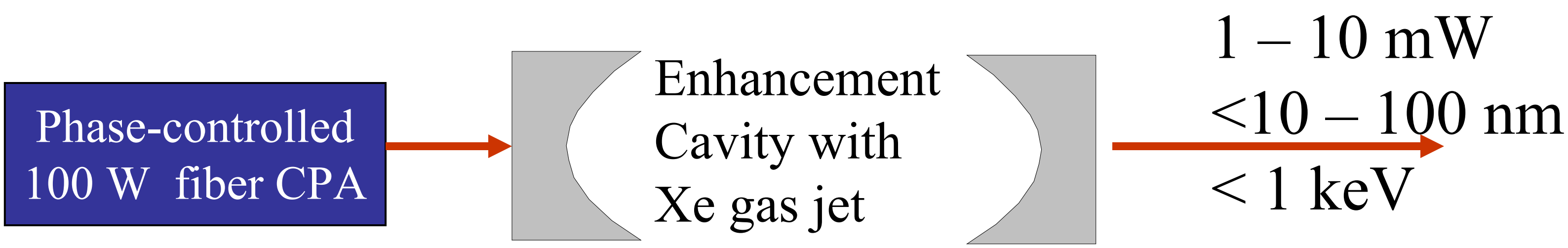




Ref.: I. Hartl et al., CLEO, (2006), PDL

Low fluence soft-X-ray source without accelerators;

High harmonic generation in enhancement cavity



- Enhancement = $1/(1 - L_{cav})$; 3000 times enhancement possible
- > 10 GW peak power inside cavity
- High power EUV generation via ultra-high power fiber laser
- keV emission will require new physics

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Conclusions

- Fiber lasers can potentially reach peak power levels of tens of GW at kW average power, solutions for TW lasers at kW average power still elusive
- Phase stable MW-peak power fiber lasers can be constructed; cavity enhancement can produce > 10 GW;
- Phase stability can be transferred along extended fiber length
- Most components for single-section photonic crystal electron accelerating structure exist
- Multi-section PBG structures and high average power operation remain very challenging