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2.8 μm Er:ZBLAN Fiber Array Technology

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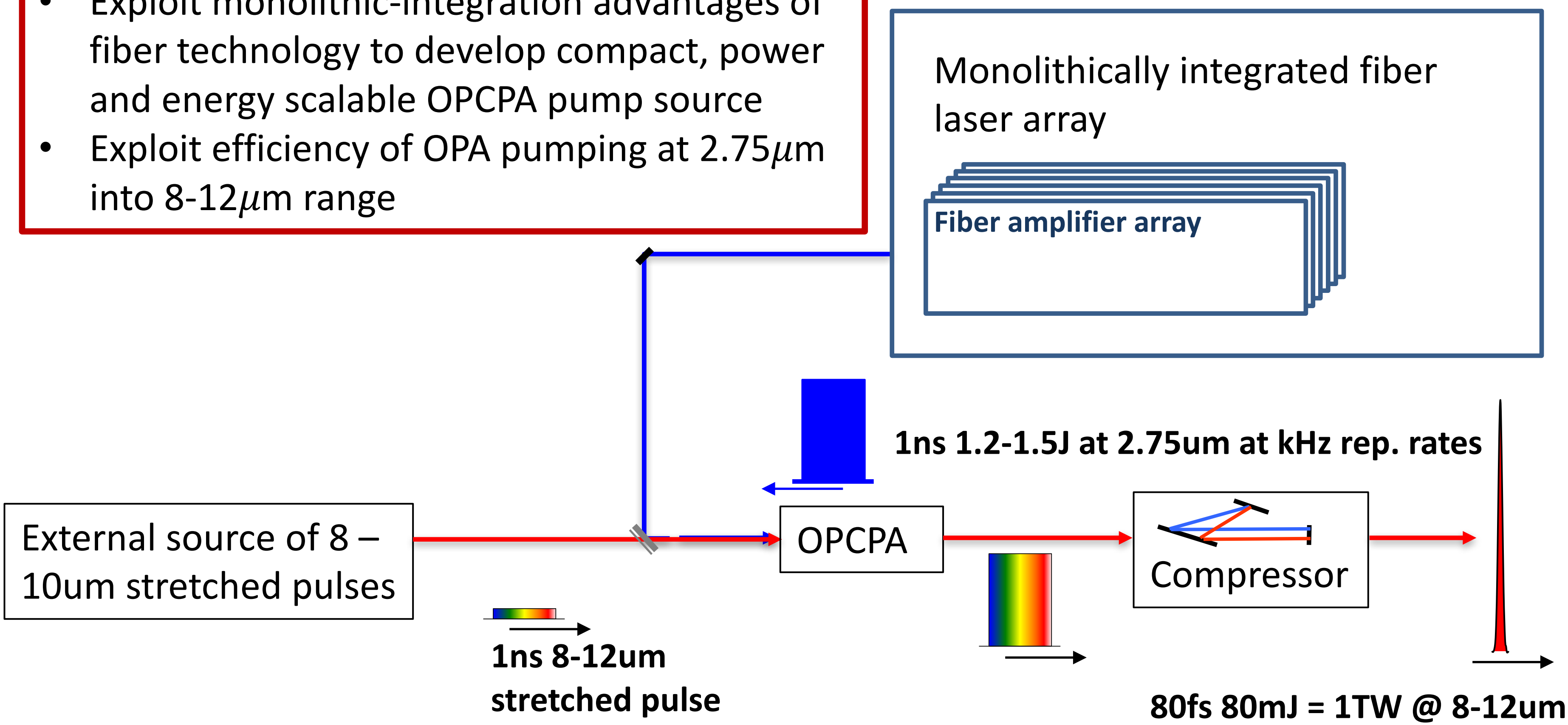
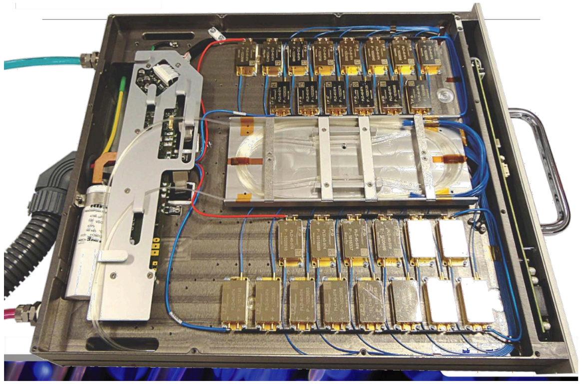
Motivation

Concept

- Exploit monolithic-integration advantages of fiber technology to develop compact, power and energy scalable OPCPA pump source
- Exploit efficiency of OPA pumping at 2.75μm into 8-12μm range



Example of fiber laser integration: 100kW modular-integrated industrial laser system

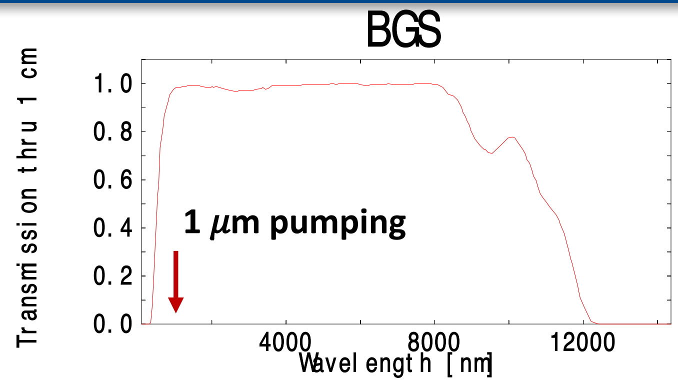


10kW cw fiber laser

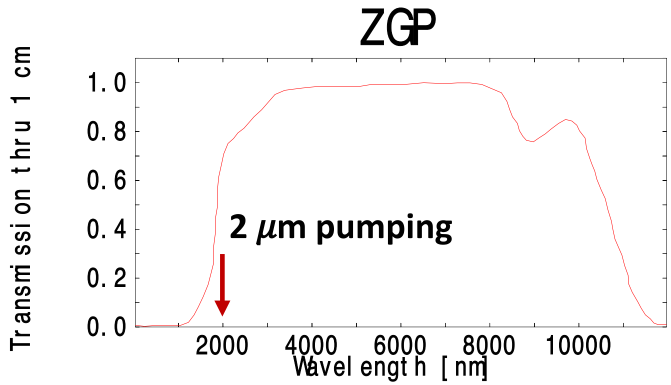
Commercial 100kW cw fiber laser!

37.5% Wall-plug efficiency!

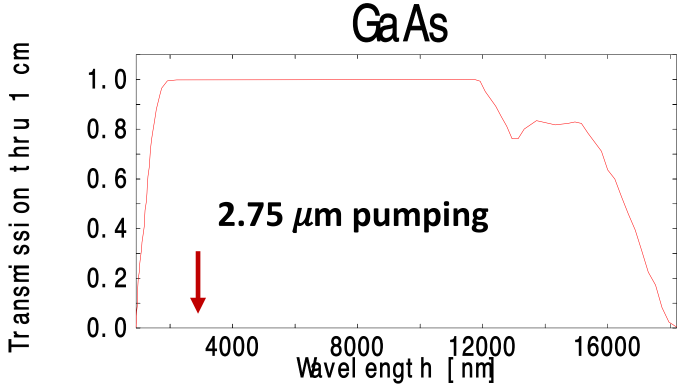
Why 2.75μm pumping?



- Quantum defect 11% (for 1 $\mu m \Rightarrow 9\ \mu m$)
- Signal losses at 8-12μm
- Relatively narrow signal bandwidth

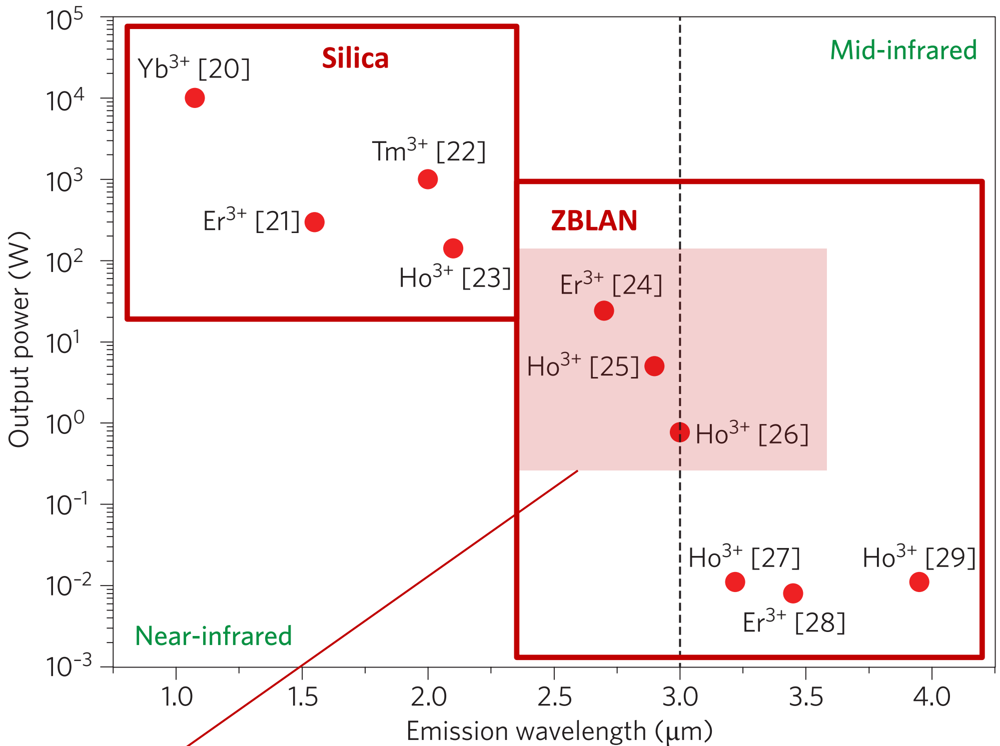


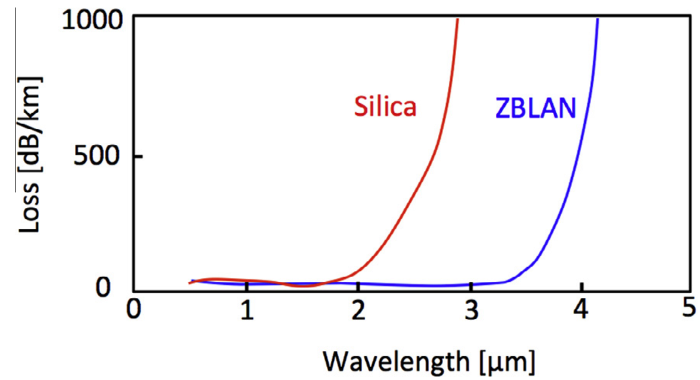
- Quantum defect 21% (for 2 $\mu m \Rightarrow 9\ \mu m$)
- Signal losses at 8-12μm
- Relatively narrow signal bandwidth



- Quantum defect 31% (2.75 $\mu m \Rightarrow 9\ \mu m$)
- No signal losses at 8-12μ
- Broadband signal covering 8-12μm

Why Er:ZBLAN fibers?



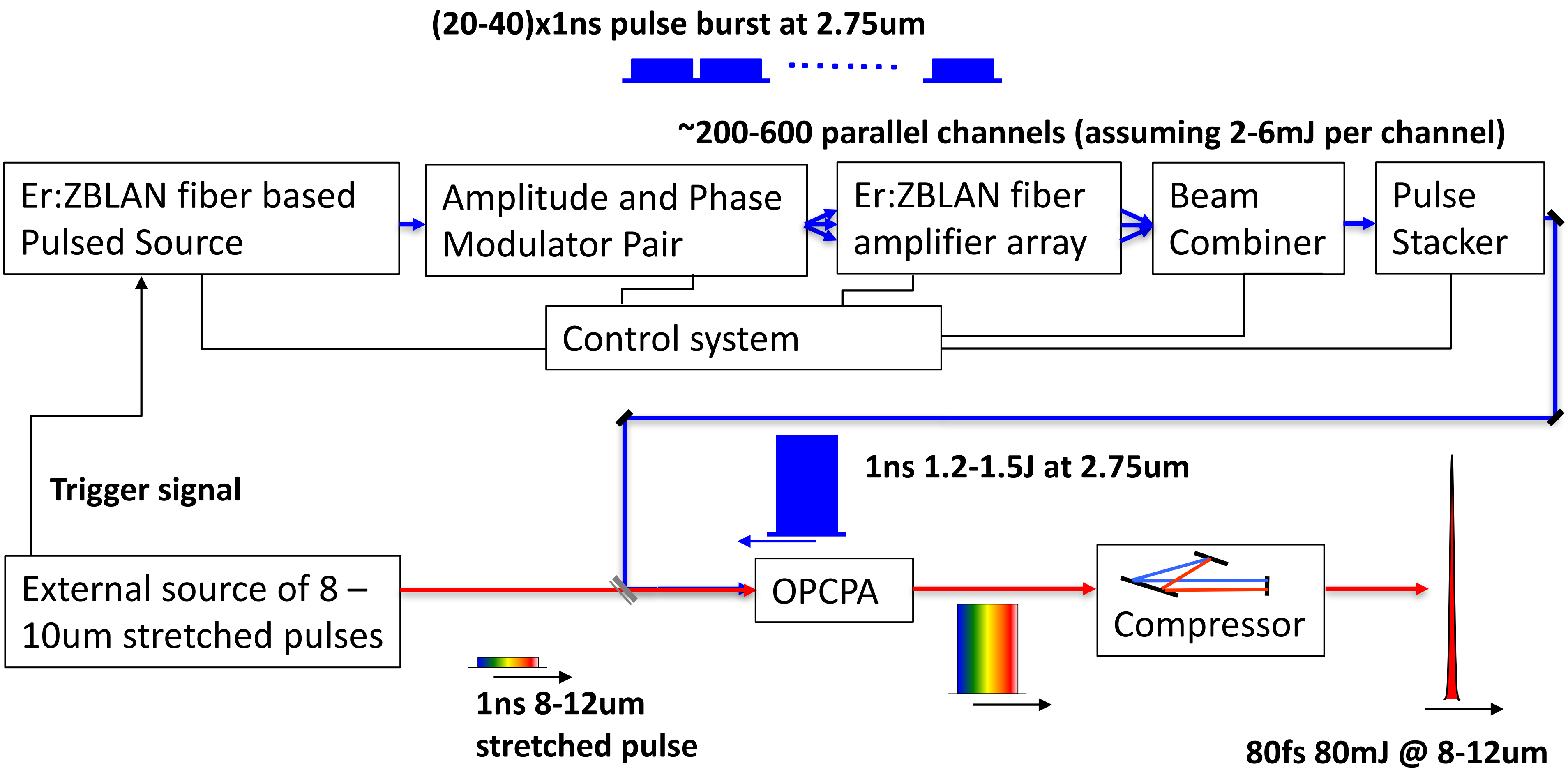


Dopant(s)	Host glass	Pump λ (μm)	Laser λ (μm)	Transition	Output power (W)	Slope efficiency (%)
Er^{3+}	ZBLAN	0.975	2.8	$^4I_{11/2} \rightarrow {^4I_{13/2}}$	~~24~~ **30W**	~~13~~ **35%**
Ho^{3+}, Pr^{3+}	ZBLAN	1.1	2.86	$^5I_6 \rightarrow {^5I_7}$	2.5	29
Dy^{3+}	ZBLAN	1.1	2.9	$^6H_{13/2} \rightarrow {^6H_{15/2}}$	0.275	4.5
Ho^{3+}	ZBLAN	1.15	3.002	$^5I_6 \rightarrow {^5I_7}$	0.77	12.4

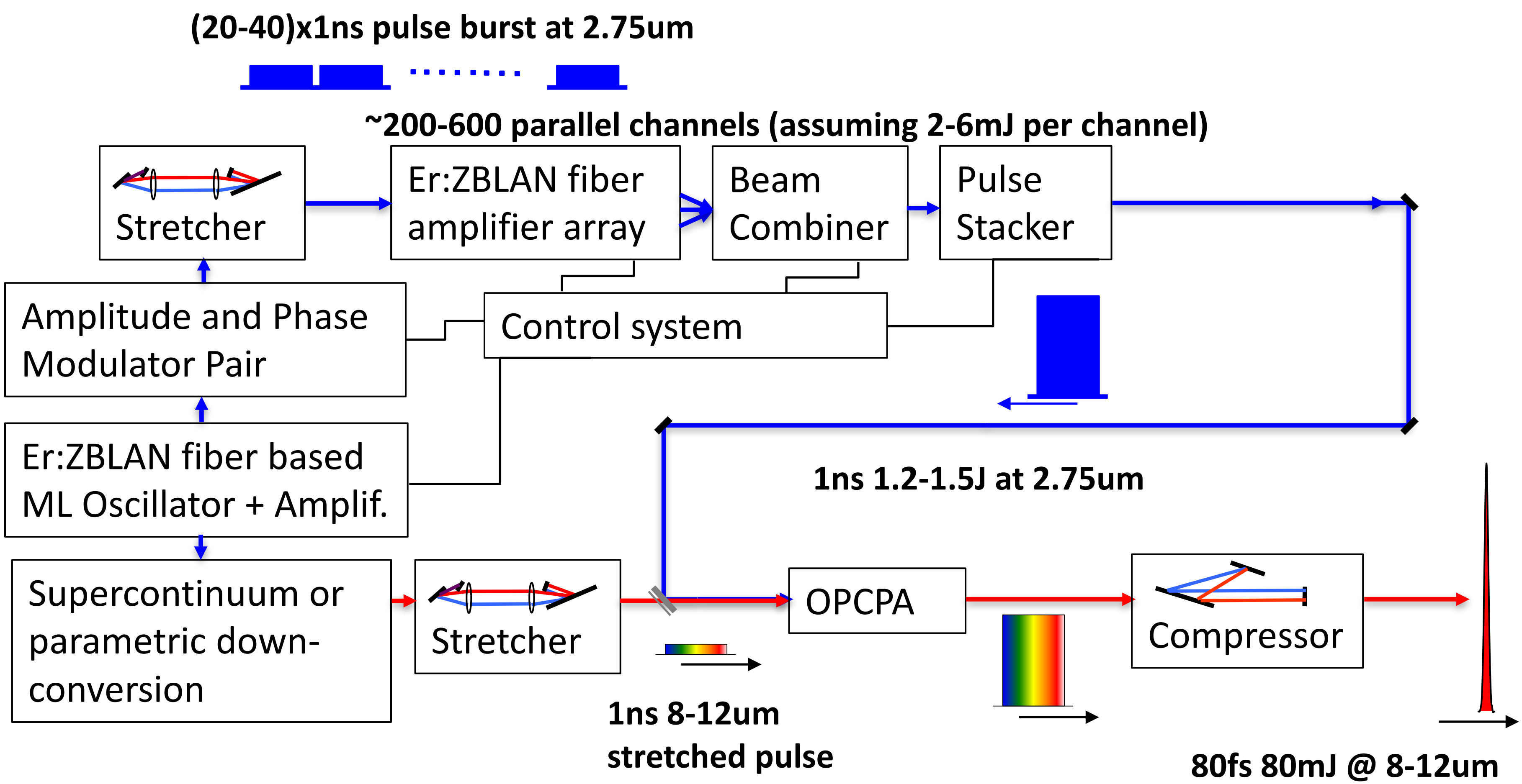
S.D. Jackson, Nature Photonics, vol. 6, 2012, p 423

Proposed architectures

Architecture 1:
OPCPA pump using a directly modulated source



Architecture 2: OPCPA pump using a mode-locked oscillator



Comparison of the two architectures

Architecture 1:

- Advantages:
  - Direct pulse forming by modulation
    - Electronic synchronization with OPCPA seed source
    - no stretcher
  - Simple source (single-frequency Er:ZBLAN cw laser)
- Challenges:
  - Speed of EOM modulators at 2750nm?
  - high gain pre-amplifier chain/ASE suppression?

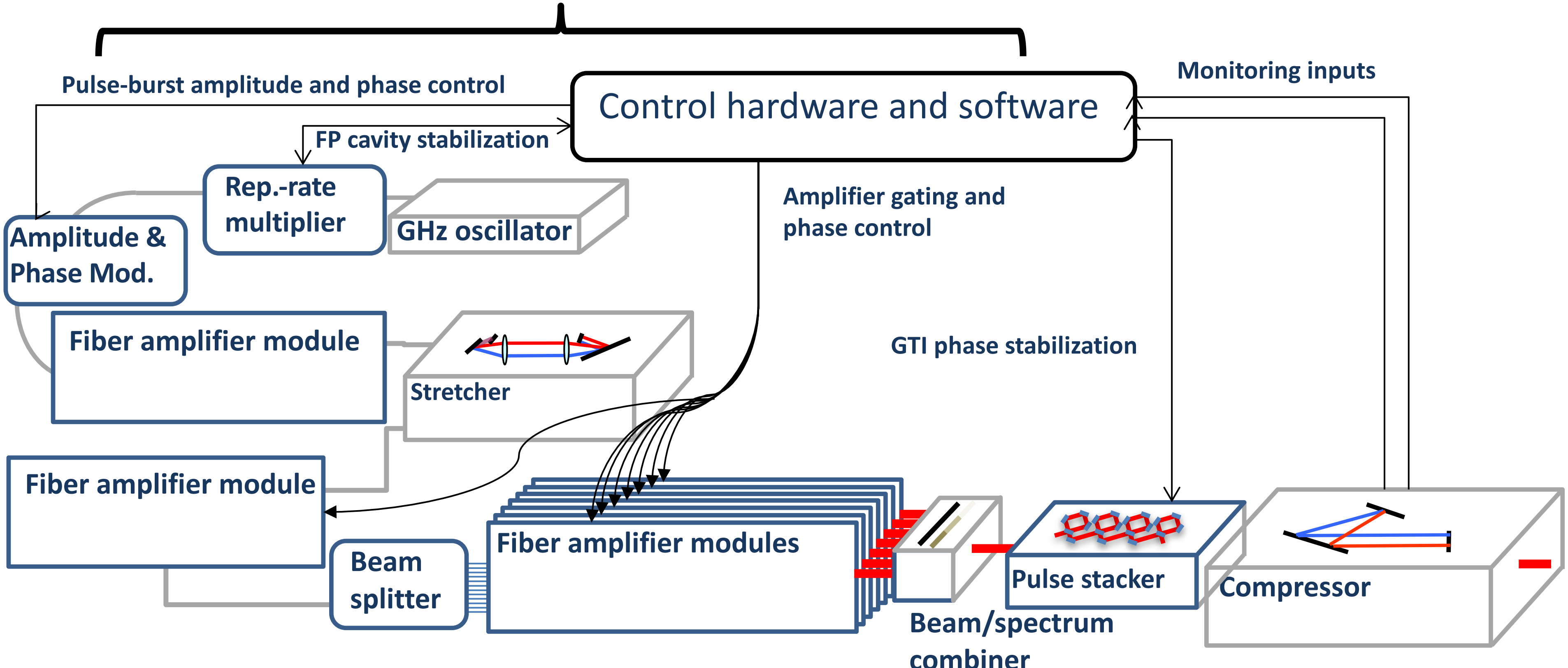
Architecture 2:

- Advantages:
  - Automatic synchronization with OPCPA seed
  - Low speed EOM at 2750nm are sufficient
- Challenges:
  - Stretcher is required
  - Low in-burst repetition rate – increases stacker size or reduces its efficiency

Current State-of-the-art in
Coherent Pulse Stacking Amplification

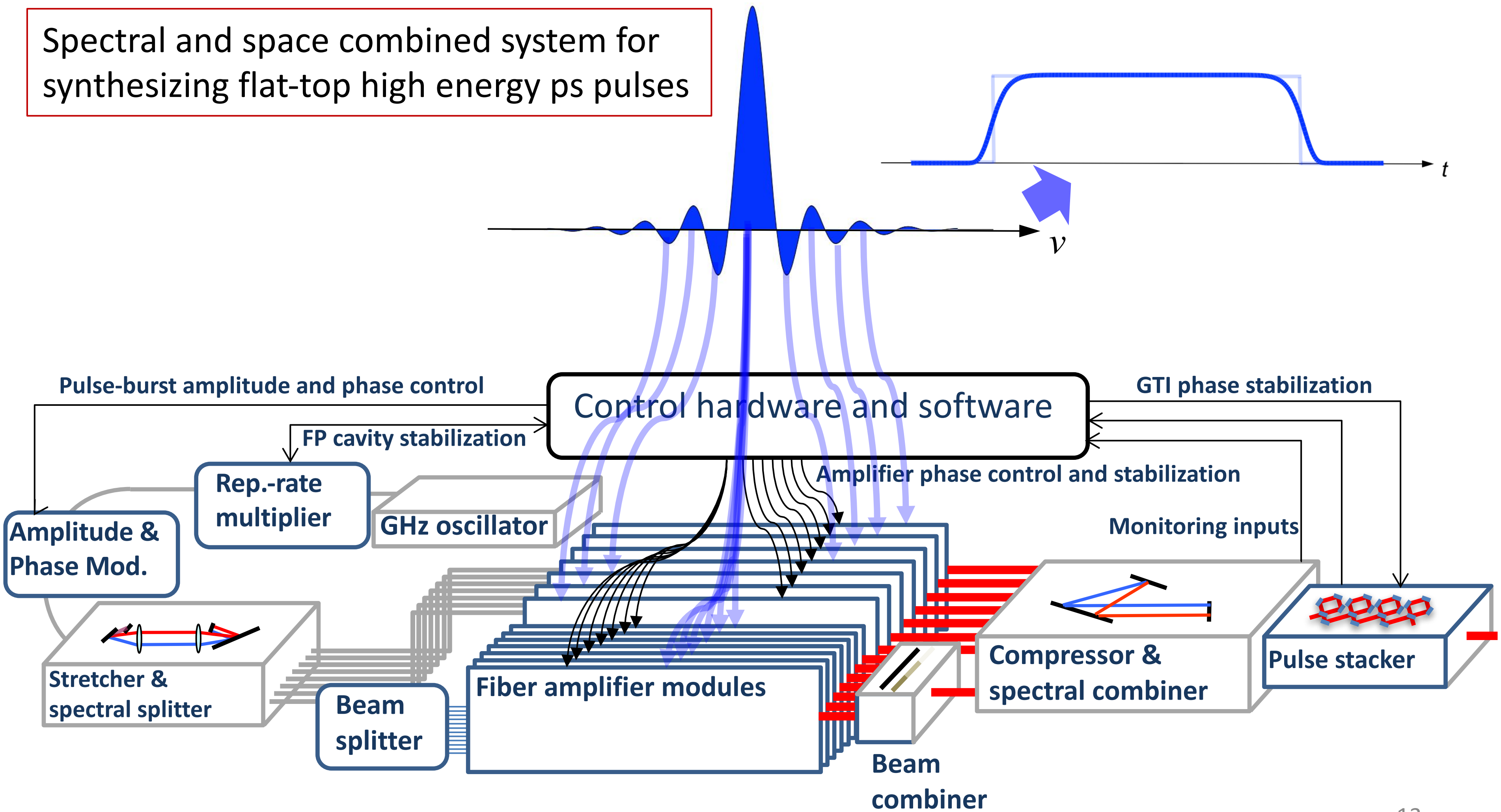
DOE funded LPA driver development of time- and spatially-combined Yb-fiber arrays at 1μm

- Bulk of the system is envisioned to be an integrated rack-mount assembly of multiple fiber-laser “circuit boards”
- Provides with a scalable architecture of >30% WPE laser drivers with E_{pulse} 0.1J - > 10J at kHz repetition rates



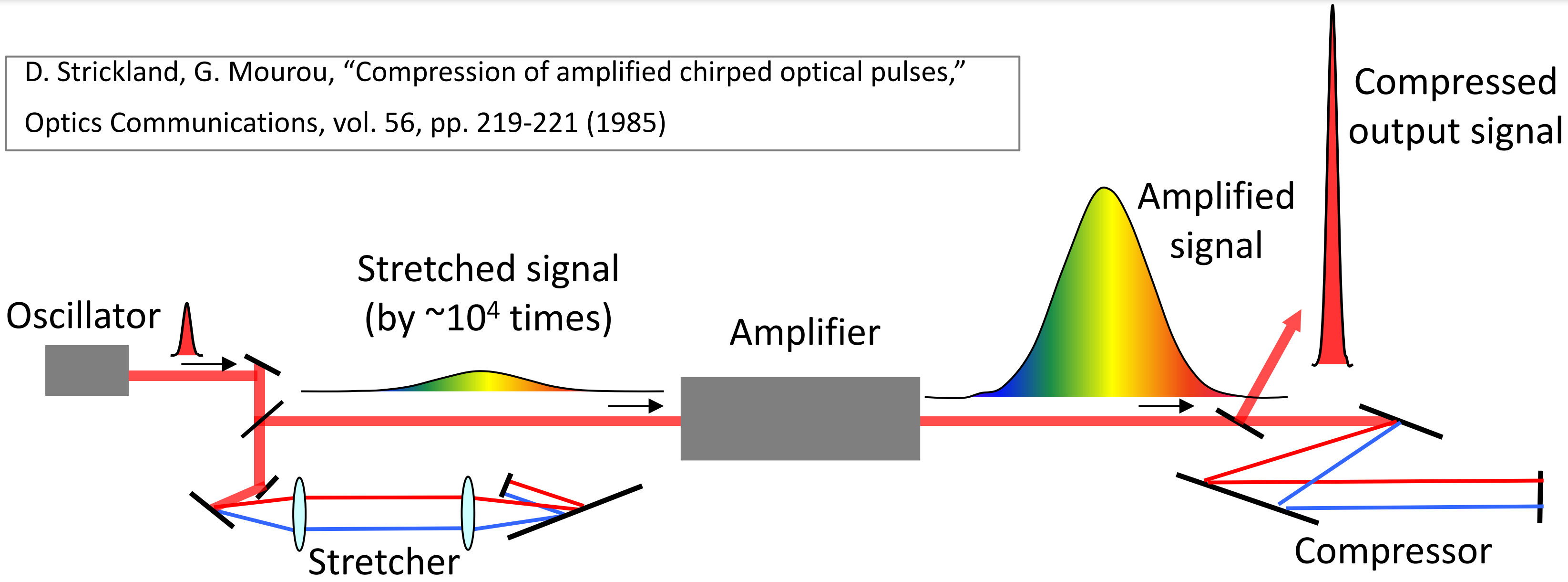
DNN and DHS funded high energy and power Thomson-scattering source for mono-energetic gamma rays

Spectral and space combined system for synthesizing flat-top high energy ps pulses



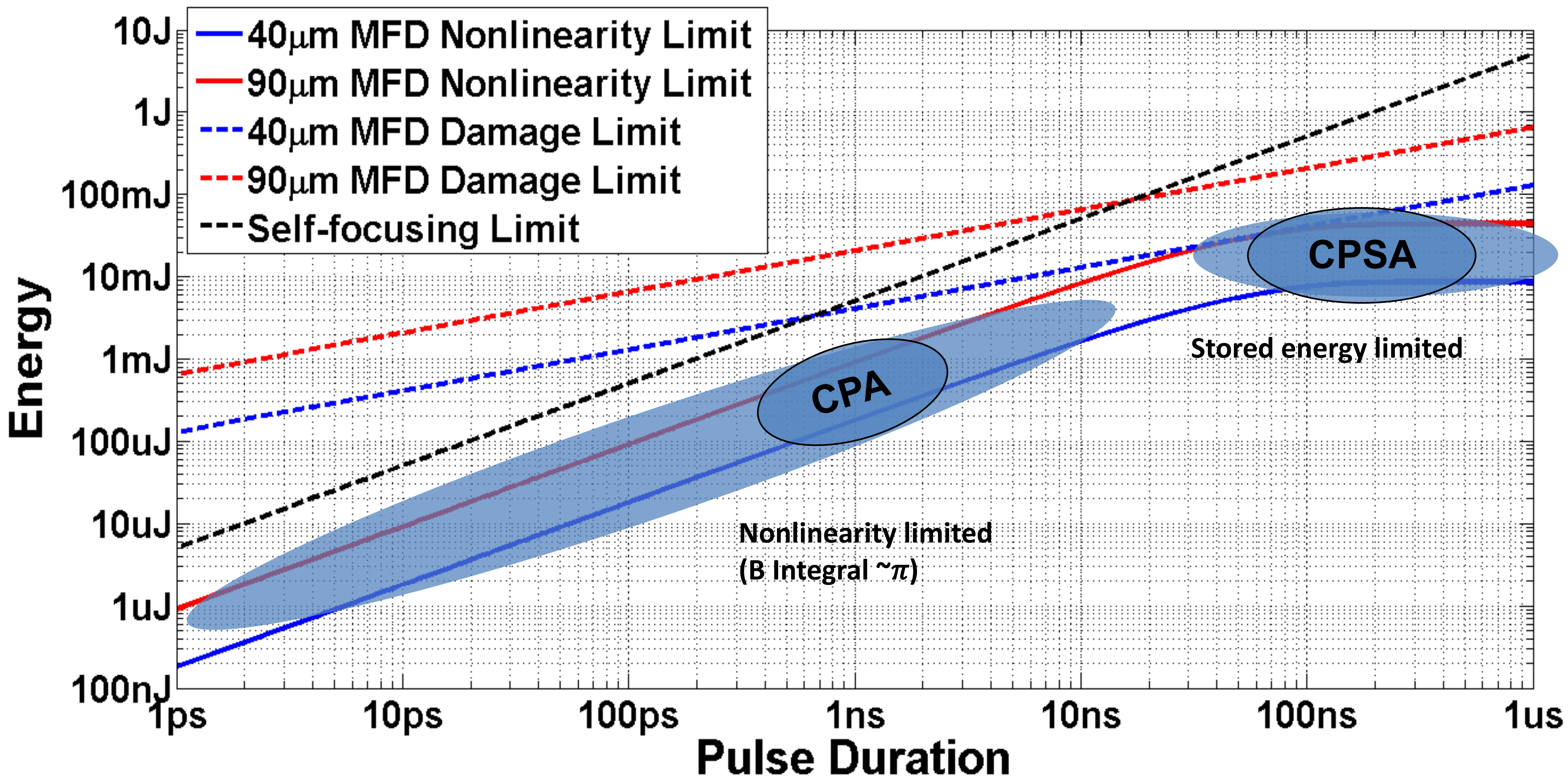
Chirped Pulse Amplification (CPA)

D. Strickland, G. Mourou, “Compression of amplified chirped optical pulses,” Optics Communications, vol. 56, pp. 219-221 (1985)



- CPA reduces peak power by ~10^5
  - ~10^4 to 10^5 energy increase comes from pulse stretching
- In a solid-state CPA - further 10^1 to 10^2 energy increase from transverse crystal size scaling
- In a fiber CPA:
  - Limited transverse aperture scaling - achievable energies are ~2 orders of magnitude below stored energy level
- **To extract full energy from a fiber: extend pulse duration by further ~10^2**

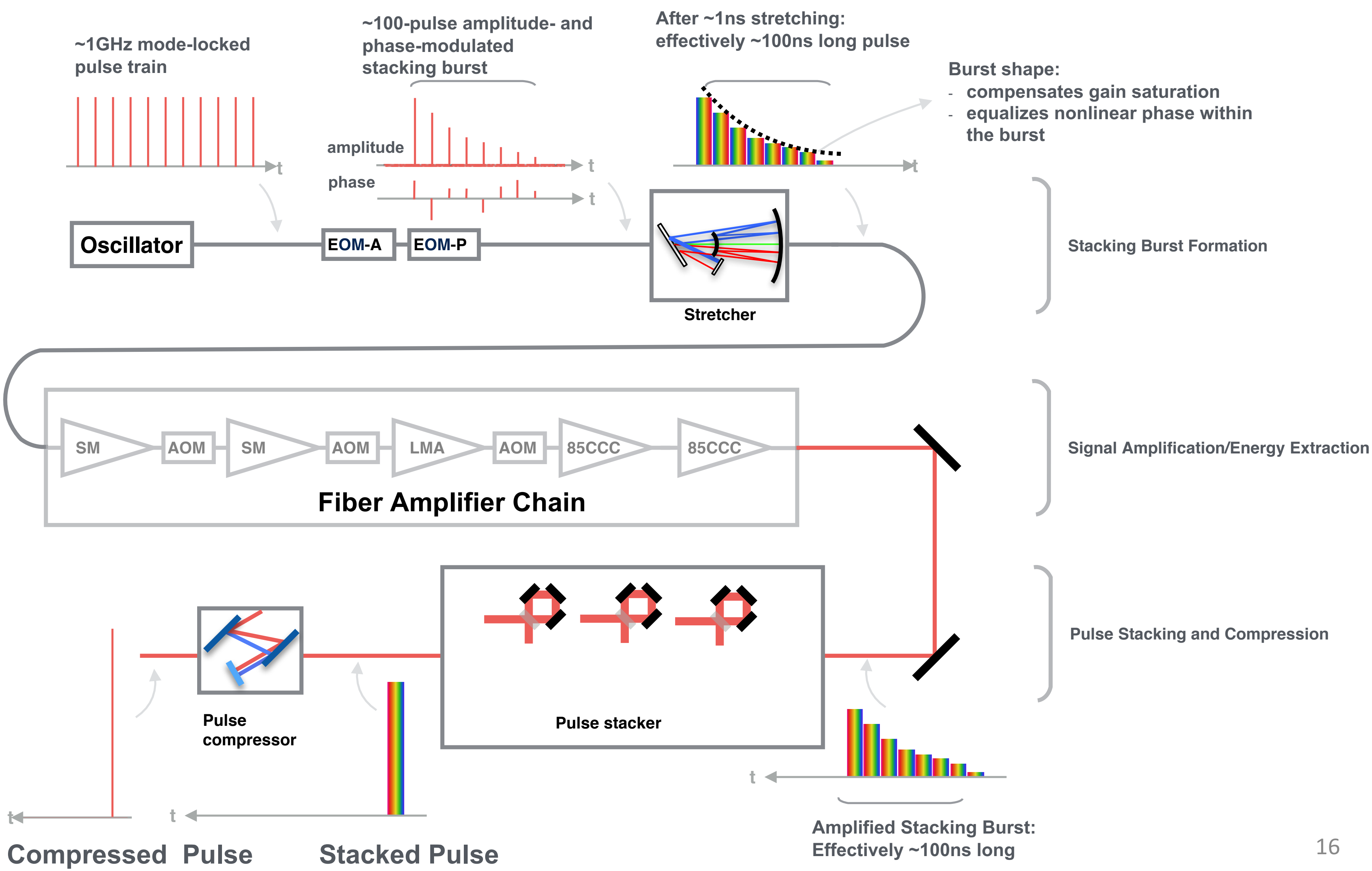
Energy Scaling of Fiber based CPA and CPSA Systems



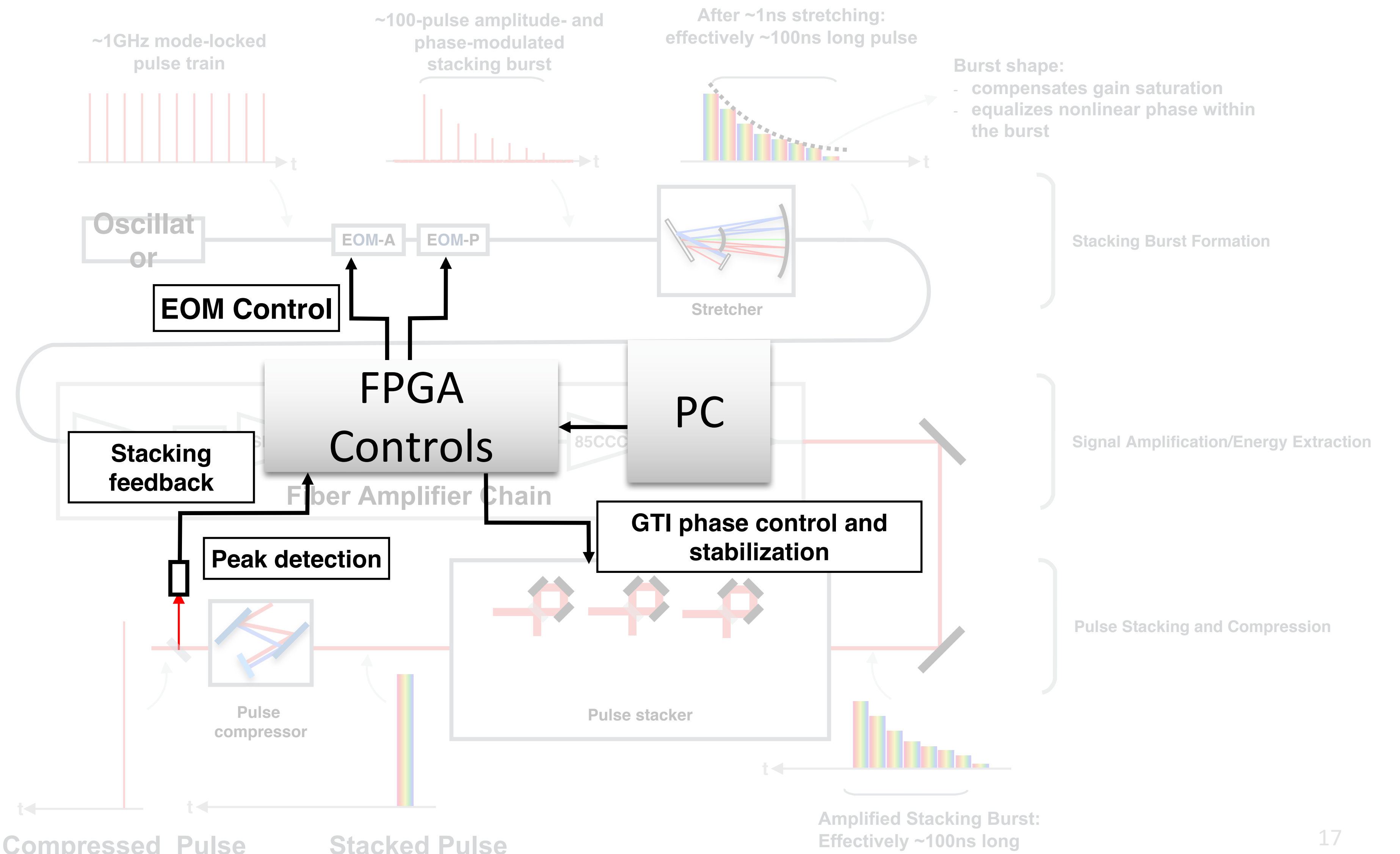
$$E_{\phi_{NL}\text{limited}}(\tau) = E_{stored}\left(1-\exp\left[\frac{-\phi_{NL}}{n_2 k_0 L U_{sat}}\tau\right]\right)$$

$$E_{stored} = U_{sat}\ln[G_0]A_{eff} = U_{sat} g_0 L A_{eff}$$

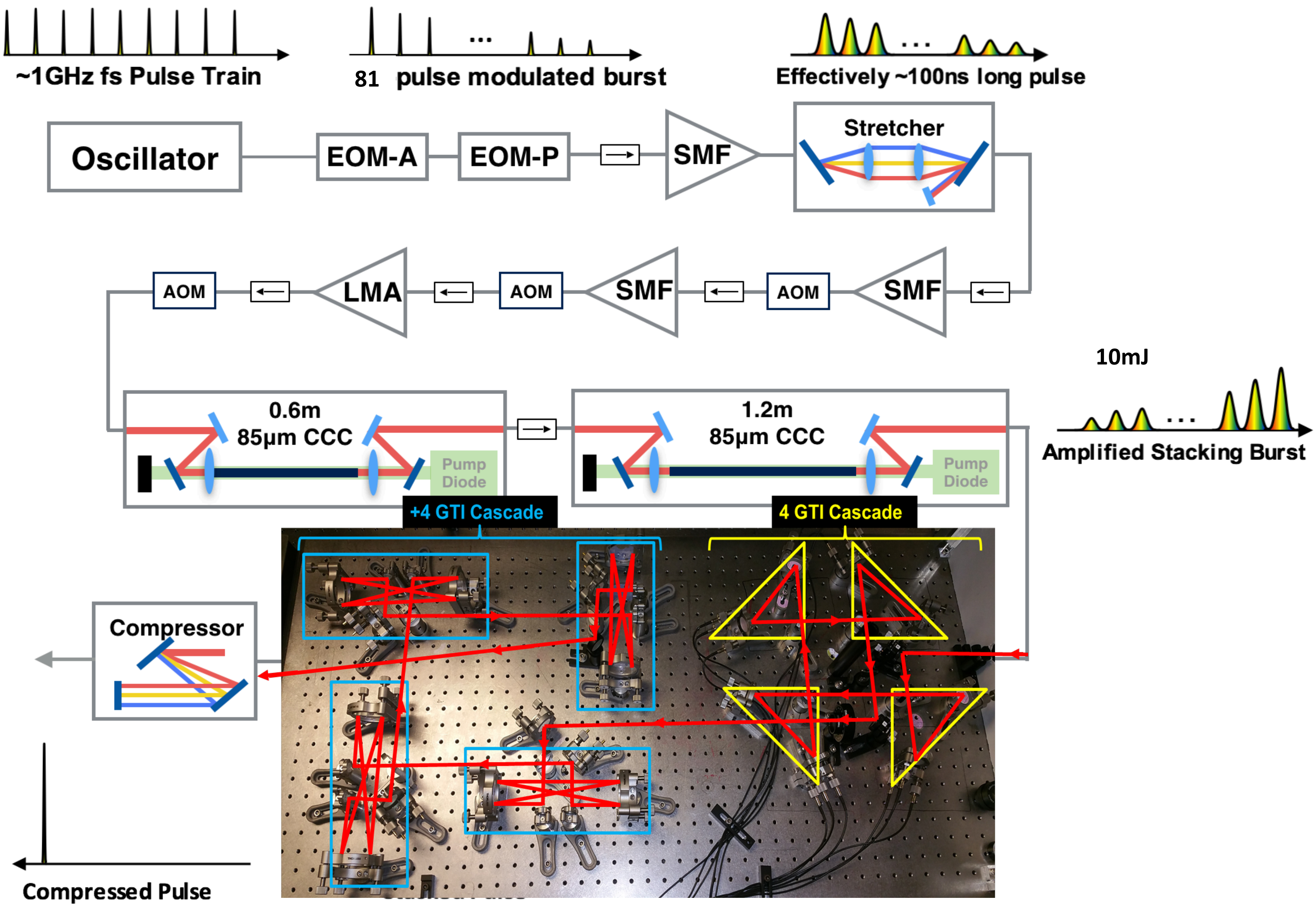
Coherent Pulse Stacking Amplification (CPSA)



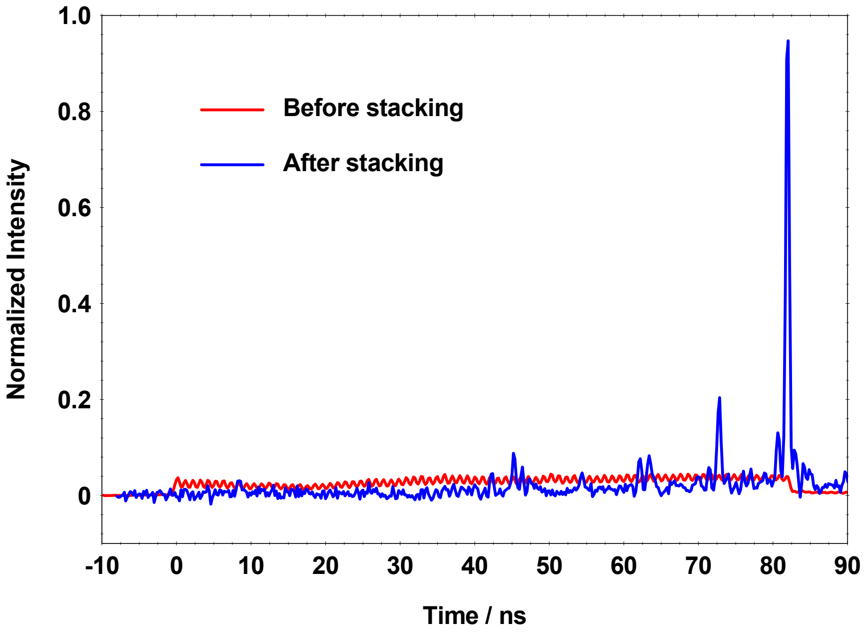
CPSA – is a Coherent Time-Domain Combining Technique

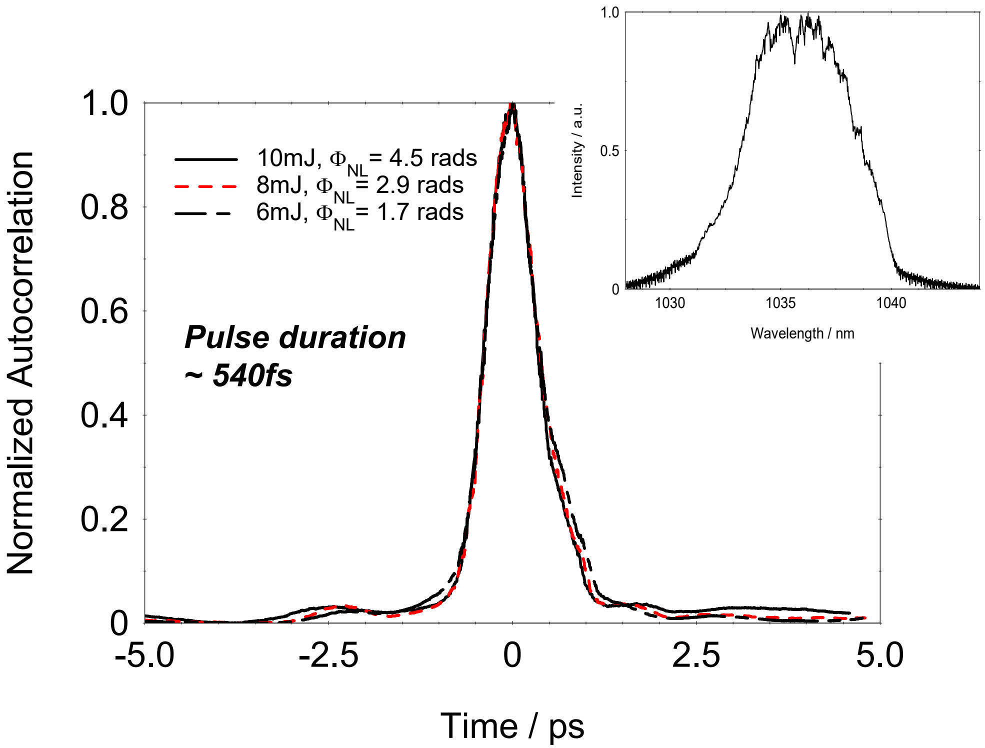


Current CPSA Experiment



4+4 GTI Cascade Stacking and compression of 81 Pulses





Er:ZBLAN properties, technical challenges, and proposed research directions

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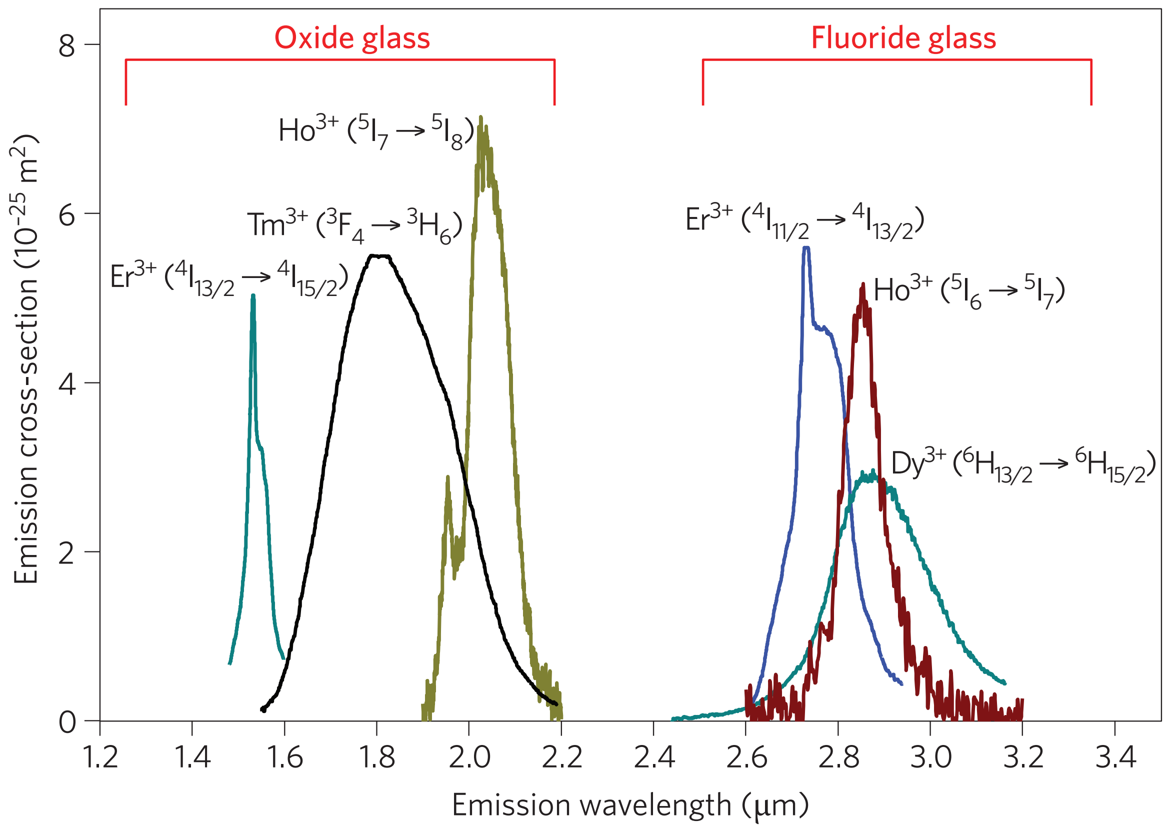
Spectroscopic properties

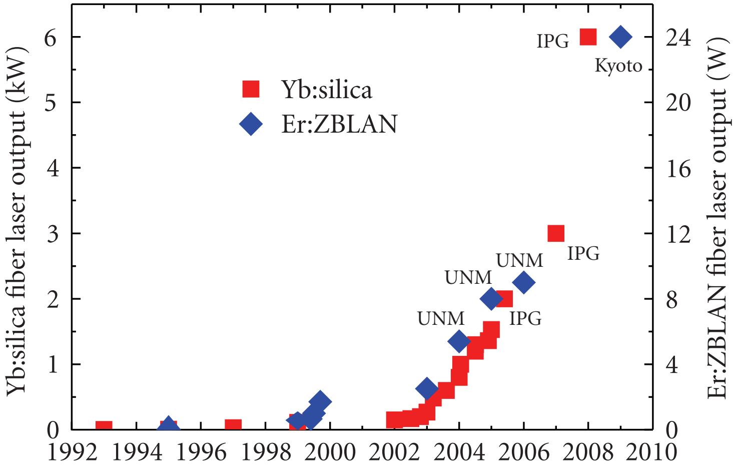


- Emission cross-section peak values are similar at various wavelengths
- However, since E_{sat} ~ 1/λ , achievable pulse energies tend to decrease with increasing wavelength

S. D. Jackson, Nature Photonics, vol. 6, 423 (2012)

Summary of Er:ZBLAN fiber laser results

- Max slope efficiency:
  - 35.4% with 20W cw output (air cooled)
    - Note: quantum defect is 35% for 980nm pumping!
- Max power:
  - 30W cw with 188W @ 980nm
- Max pulse energies:
  - 0.6 mJ in 50ns (Q-switched)
  - 1.9 mJ (pulse pumped)

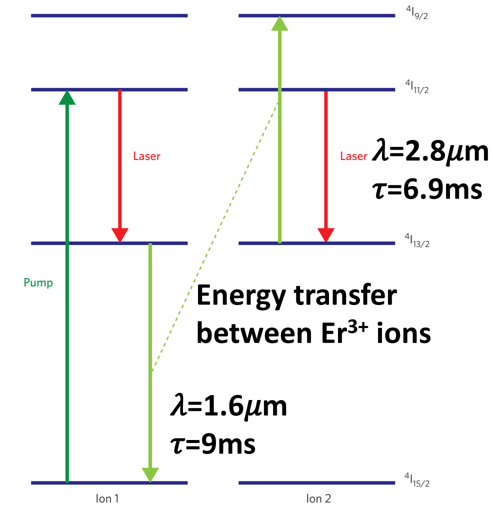


Advances in OptoElectronics, vol. 2010, p1

- Shortest pulse durations:
  - ~200fs at 55MHz from a NPE mode-locked laser
    - Note: Bandwidth-limit <100fs

Er:ZBLAN fiber laser challenges

- Multi-mJ pulsed energy extraction
  - Is 2mJ – 6 mJ per-burst achievable?
- Average power/thermal issues due to high QD
  - Air vs liquid cooling?
- Efficiency (i.e. bottlenecking in lower level)
  - Has been largely addressed by high Er^{3+} doping
- Modal properties
  - Lower V-numbers due to long wavelengths: LMA vs single-mode?
- Fiber end protection from degradation and damage
  - ZBLAN endcaps?
- Monolithic integration (crucial for fiber array combining)
  - Passive to active ZBLAN fiber splicing
  - Silica to ZBLAN splicing
  - ZBLAN fiber pump combiners*
  - ZBLAN fiber pigtailing of components (isolators, modulators, etc.)



Fusion-splicing of ZBLAN glass fibers

*first demonstration: "Towards a 20W-level industrial-grade Er:ZBLAN fiber laser at 2.8um" Paper JTu2A.38, in ASSL 2017, Nagoya, Japan, October 1-5 2017

Outline of Research Directions

2017 | 2018 | 2019 | 2020 | 2021 | 2022

Explore Er:ZBLAN gain-medium operation and performance of critical components at 2.75μm:

- Construct and explore mode-locked oscillator
- Explore ns-pulse modulated source: linewidth, pulse duration and shape, 2.75μm EOM speeds
- Explore single-mode and LMA amplifiers: pulse energies, powers; optical isolation and ASE gating between stages
- Explore fusion splicing ZBLAN: endcaps, fibers, etc.

Er:ZBLAN based time and space combined system design

Single-channel pulse stacking at mJ energies

2.75μm pulsed pump driven OPA/OPO at 8-12μm

2.75μm pumped OPCPA at 8-12μm

Summary

- Er:ZBLAN fiber platform offers an interesting "window" into mid-IR spectral range
  - Compatible with ultrashort pulses
  - Potentially compatible with high energies

- It is an "early stage" technology, which needs to be explored.
  - It has a significant potential for future mid-IR sources (direct and parametrically down-converted)