2.8 μm Er:ZBLAN Fiber Array Technology

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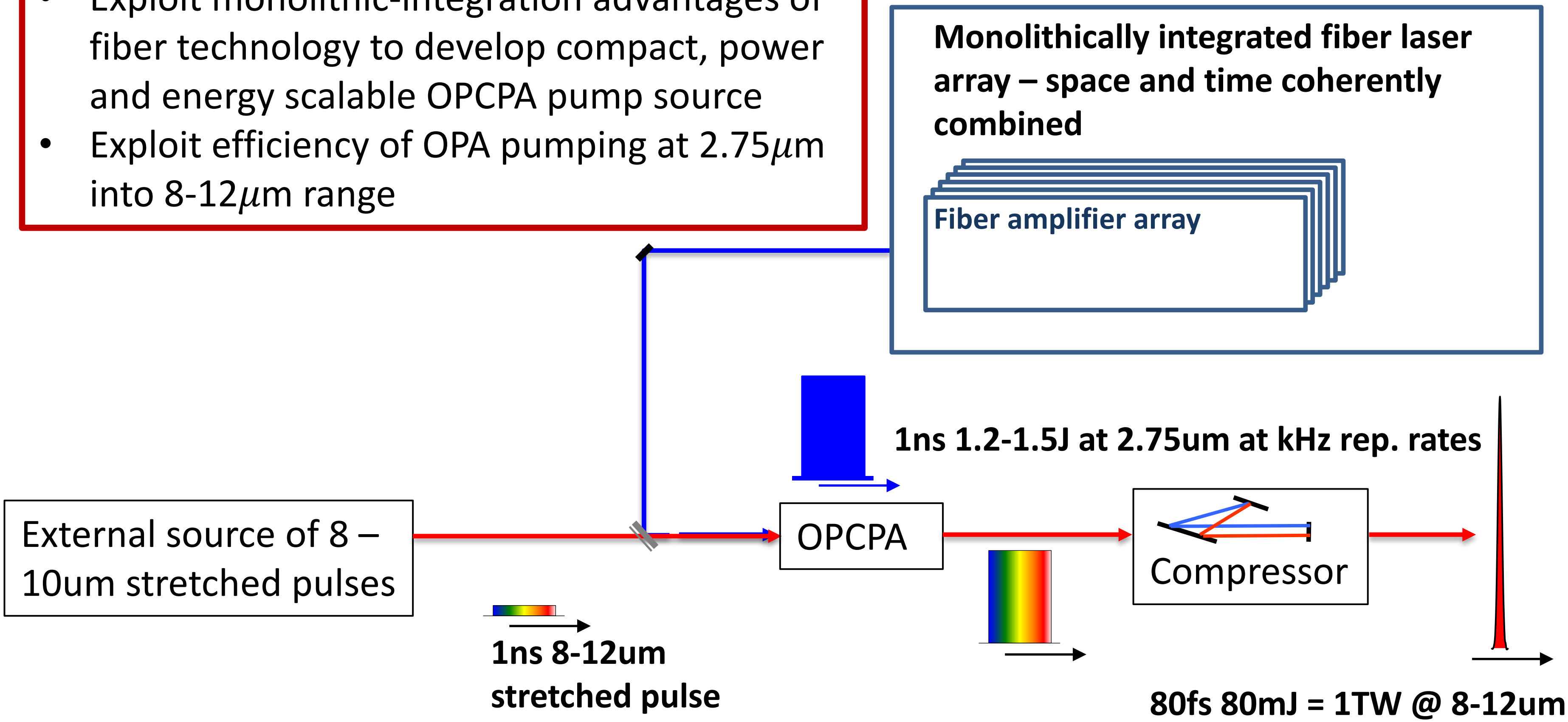
The Team

- Prof. A. Galvanauskas group:
  - Weizhi Du, PhD student **(100% on MURI – 1GSRA + supplementary equipment support)**
    - pulse amplification in Er:ZBLAN LMA fibers
  - Yifan Cui , PhD student **(part time on MURI)**
    - Mode-locking of Er:ZBLAN fiber lasers
  - Mingshu Chen, MS student **(part time on MURI)**
    - ZBLAN fiber processing and protective end-cap fabrication
- In collaboration with Prof. I. Jovanovic group:
  - Xuan Xiao, PhD student
    - OPO/OPA "surrogate" seed source for testing Er:ZBLAN amplifiers

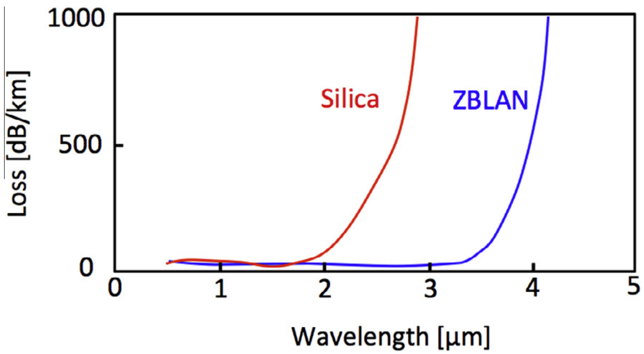
Proposed solid-state laser architecture for generating 8-12μm TW peak power ultrashort pulses

- 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

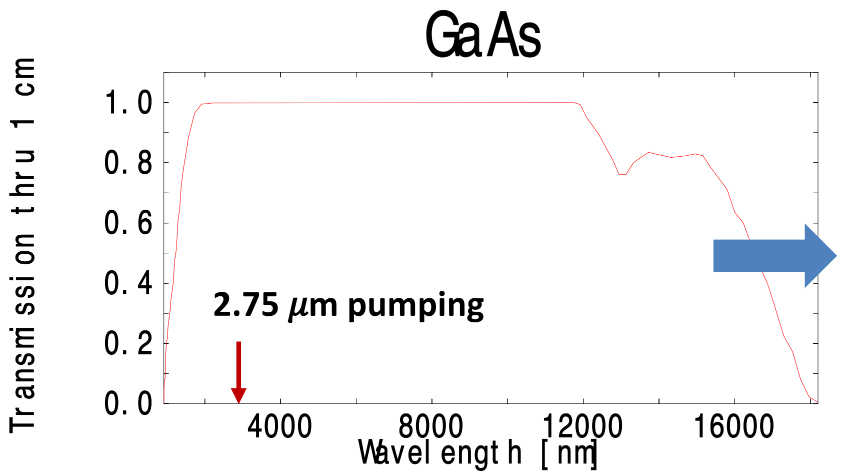


Why 2.75μm Er:ZBLAN fibers for ~10μm OPA pumping?

- **Er:ZBLAN fiber amplifiers**
  - Pumping @ 975nm – common telecom pump diodes
  - Signal @ 2.75µm
    - Option for 3.6µm signal (needs combined 975nm and 2µm pumping)
  - High power (per channel): max demonstrated cw power ~100W
  - Good mid-IR efficiency: max demonstrated slope efficiency - ~35%



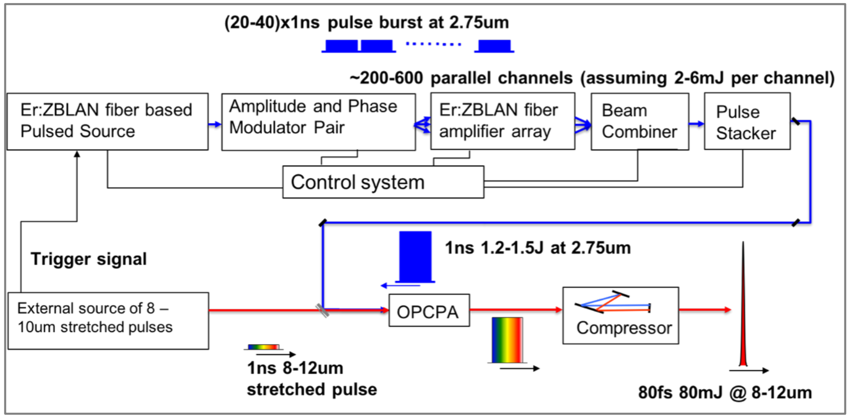
- **OP-GaAs OPA pumped at 2.75μm**



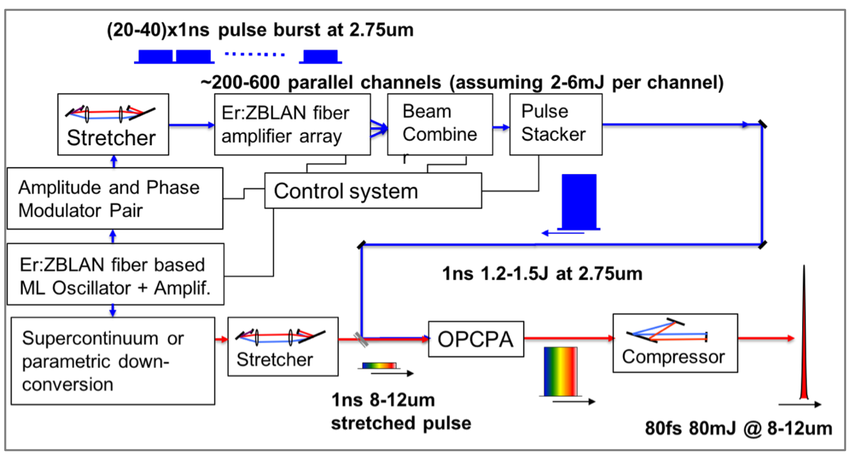
- Quantum defect 31% (2.75 μm ⇒ 9 μm)
- Low-loss signal and broadband at 8-12μm

Project Objectives

Example of a ns-pulse based source architecture



Example of a fs-pulse based source architecture



- Establish mid-IR fiber laser capability
- Explore key enabling factors of coherently-combined femtosecond fiber systems in Mid-IR:
  - Pulse generation and amplification technologies and achievable performance
  - Energy storage and extraction
    - Power and energy scaling potential
  - Monolithic integration
    - Possible with ZBLAN fibers, but splicing technology is incipient
  - …

Outline of Research Directions (Actual and Aspirational)

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

Current efforts

2017 2018 2019 2020 2021 2022

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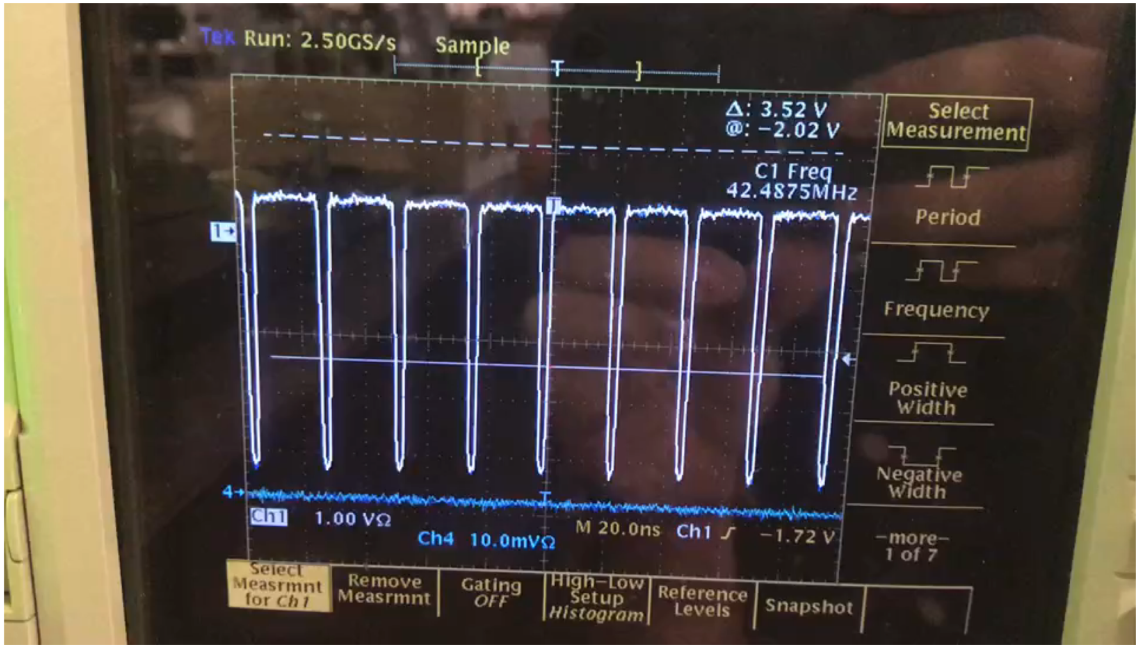
Mode-locked Er:ZBLAN fiber oscillator

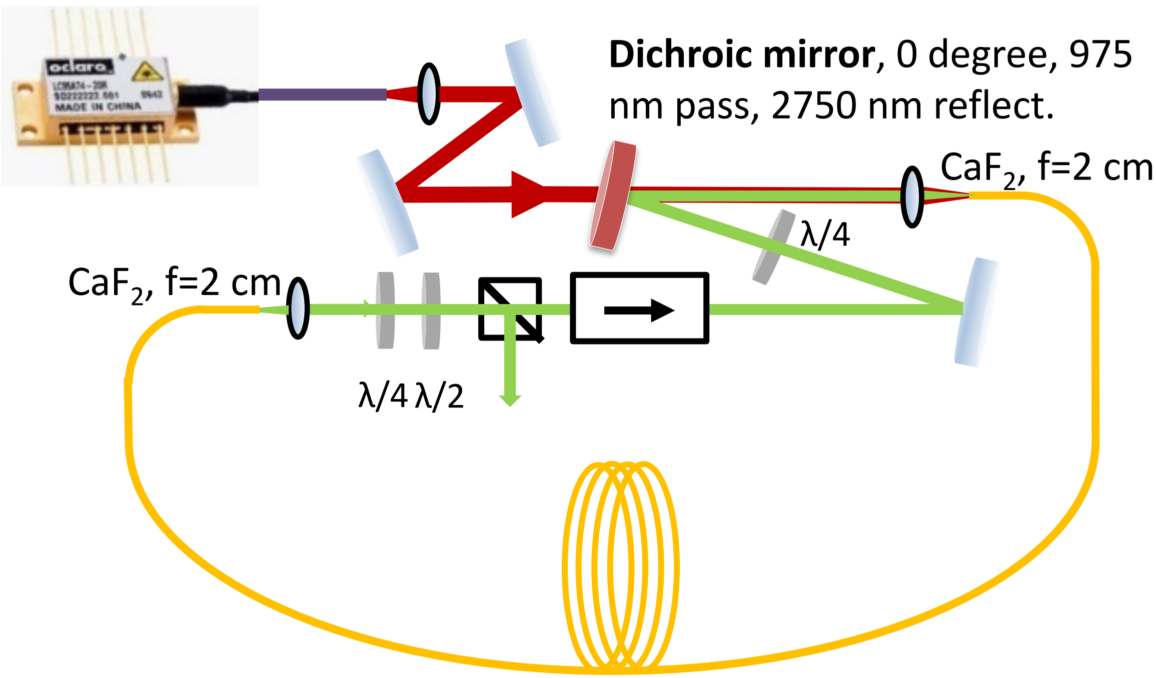
Yifan Cui

Oscillator is working!



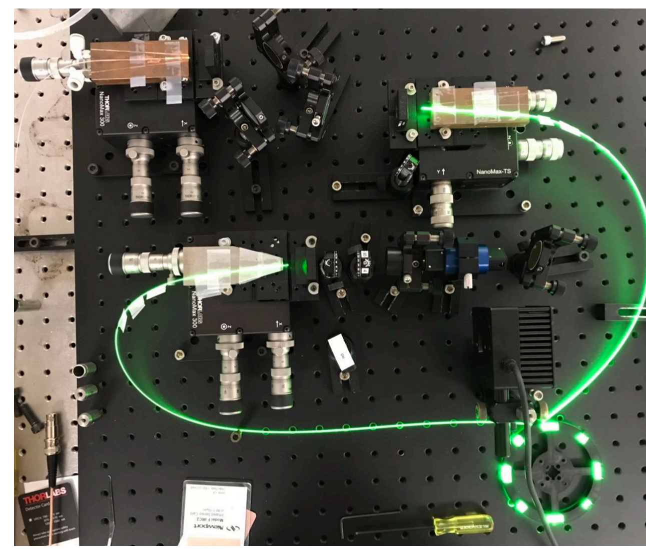
Mode-locked Er:ZBLAN fiber oscillator

NPE based Oscillator design and layout



Erbium doped ZBLAN fiber (3.9 m)

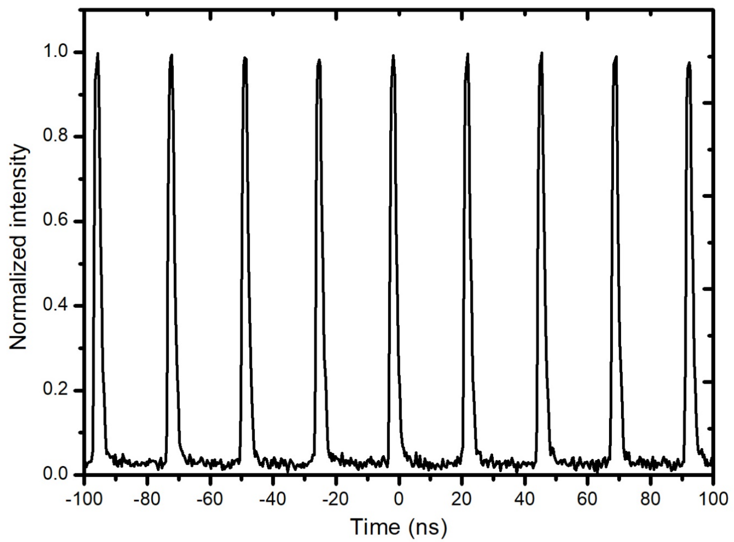
Gain fiber: Le Verre Floure
15µm/0.12 NA core, 240-290µm/0.5NA clad
Absorption @980 nm: 2.5 dB/m



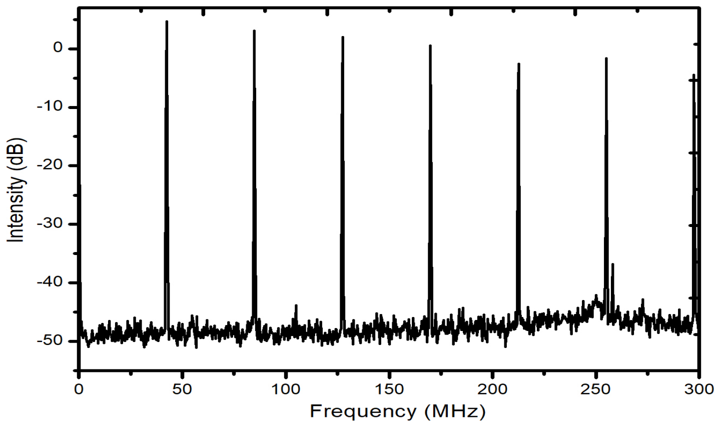
Mode-locked Er:ZBLAN fiber oscillator

- Operation parameters
  - Pump power at 975nm:
    - 2.04W (coupled)
  - Oscillator output at 2.75µm:
    - 87mW
  - Repetition rate:
    - 42.5 MHz
  - Pulse energy:
    - 2.05nJ
  - Pulse duration:
    - Expected ~100-200fs
    - Autocorrelator is currently under construction…

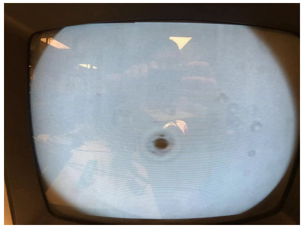
Mode-locked pulse train:



RF spectrum: measured 30kHz linewidth



Mode-locked Er:ZBLAN fiber oscillator

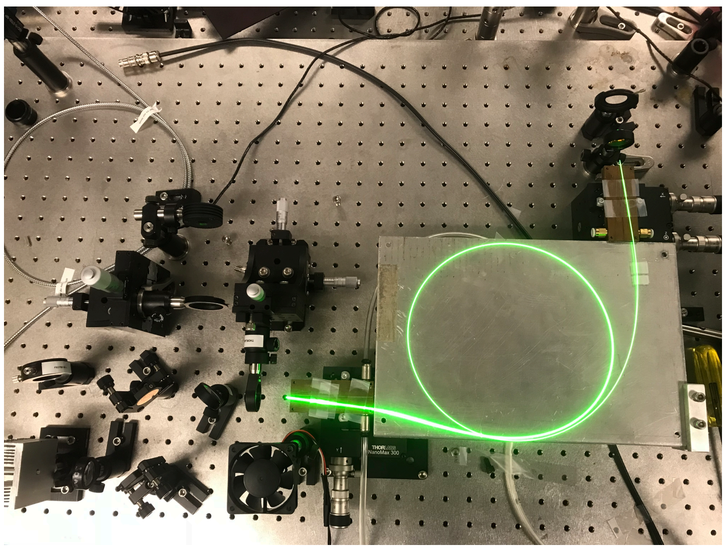
- Challenges:
  - Degradation of unprotected fiber ends: 
  - Necessary to develop endcap protection!

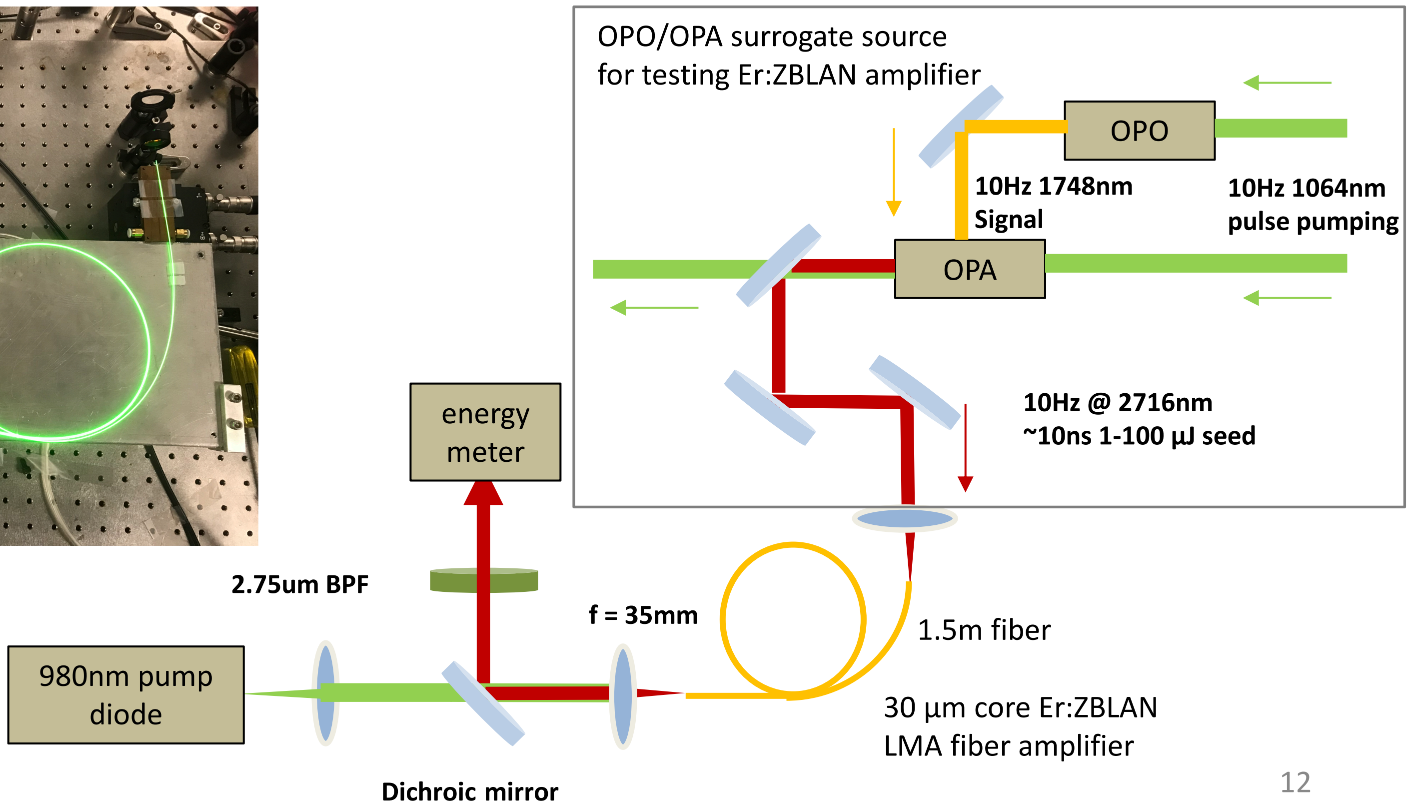
- Further plans:
  - Amplification in Er:ZBLAN fibers
  - Supercontinuum generation to ~4-5µm
    - OPA seed
  - Er:ZBLAN CPA?
  - Explore ~3.6µm mode-locked operation using combined 975nm and ~2µm pumping with Tm-doped fiber laser?

High energy amplification in Er:ZBLAN fiber amplifiers

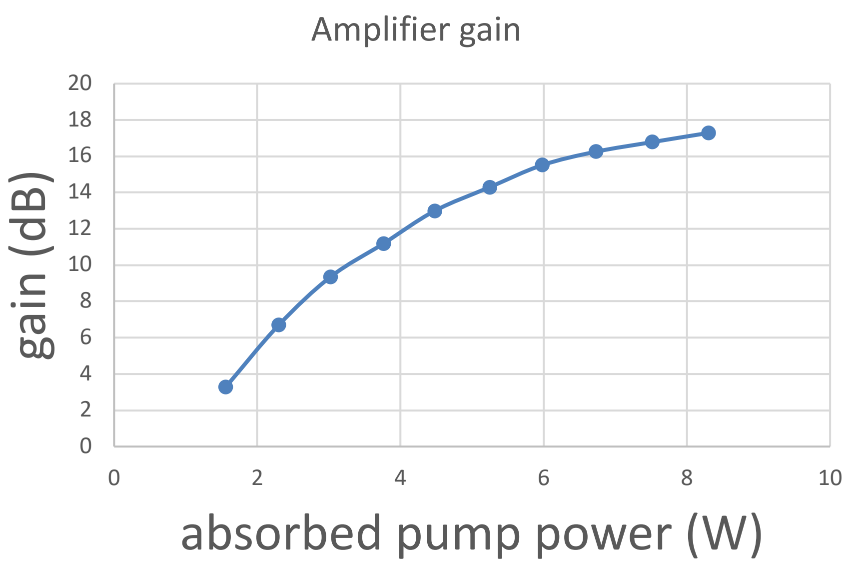
Weizhi Du (Er:ZBLAN amplifier) and Xuan Xiao (OPO/OPA source)

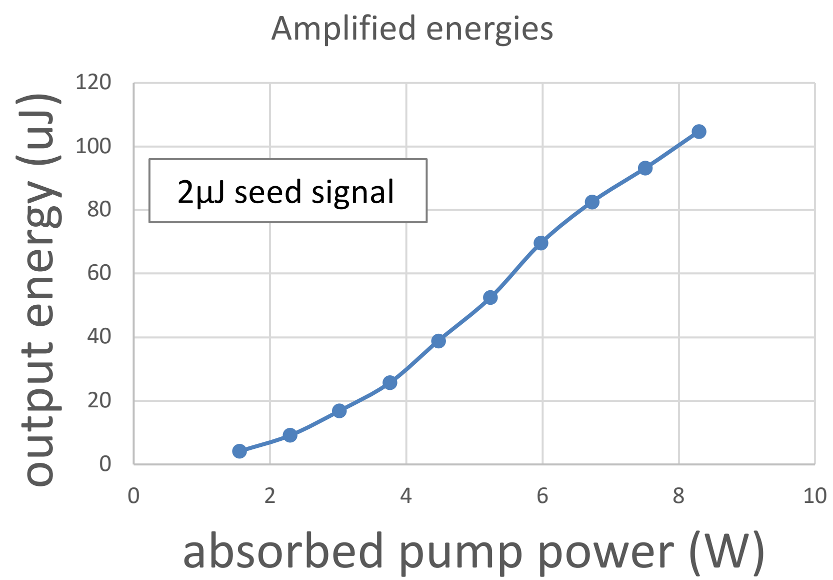
- Our objective is to explore feasibility of obtaining 2-5mJ ~100ns pulses from 30-50um core Er:ZBLAN fiber amplifier





High energy amplification in Er:ZBLAN fiber amplifiers



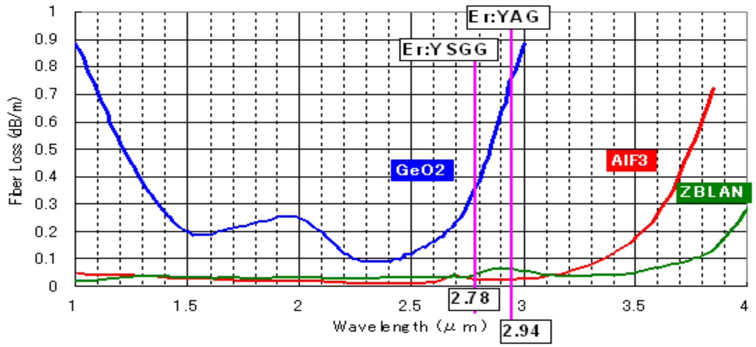


- These are initial results
  - More experiments and analysis needed, but it already indicates that mJ range is feasible with 30-70µm core Er:ZBLAN fibers
- To increase energies into ~mJ range it is necessary to protect fiber ends with spliced endcaps

Development of ZBLAN fiber splicing capabilities

Mingshu Chen, MS student

- Endcaps for fiber end protection from degradation and optical damage
  - At this point critical for
    - Reliable operation of the mode-locked oscillator
    - Er:ZBLAN LMA fiber end protection from optical damage and degradation



	ZBLAN	AlF_3
Glass transition temperature (Tg)	265 °C	367 ºC
Thermal expansion (a)	200 x 10-7 /°C	186×10-7 /ºC
Water solubility (Dw)	29.2w t %	0.27 wt%
Acid solubility (Da)	32w t %	0.69 wt%*
Young's modulus (E)	53 GPa	66 GPa
Knoop hardness (HK)	2.2 GPa	3.1 GPa

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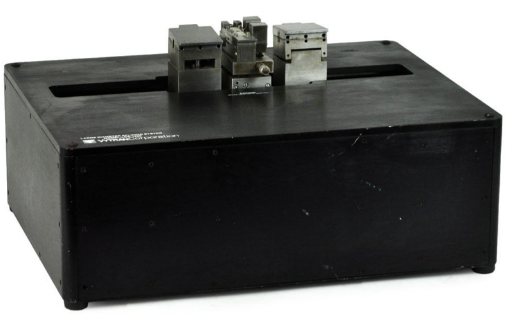
Development of ZBLAN fiber splicing capabilities

- Monolithic fiber-optic components – ZBLAN fiber splicing, pump combiners?
- Technical challenge: low splicing temperatures required by ZBLAN glass

- We are working with Vytran to develop low-temperature splicing processes

- (… old equipment we are using:
  - Vytran is no longer supporting this equipment (no replacement options for old iridium filaments, currently Vytran uses different type of filaments)
  - New splicing equipment is beyond current budget: LFS4100 splicer is optimized for low-T splicing but the cost is $48,200



Vytran LDS 1250

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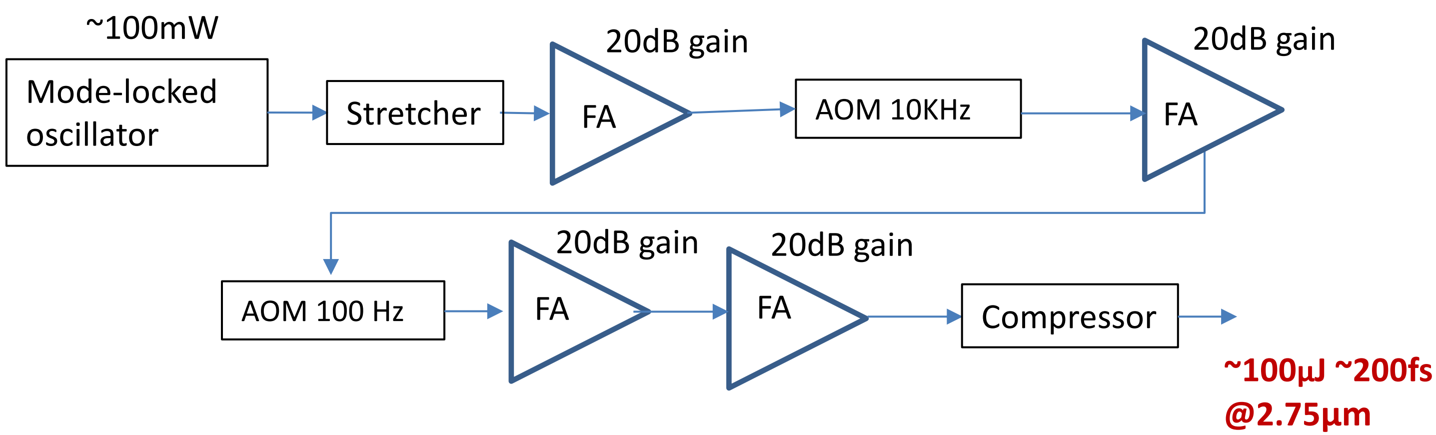
Summary and next steps

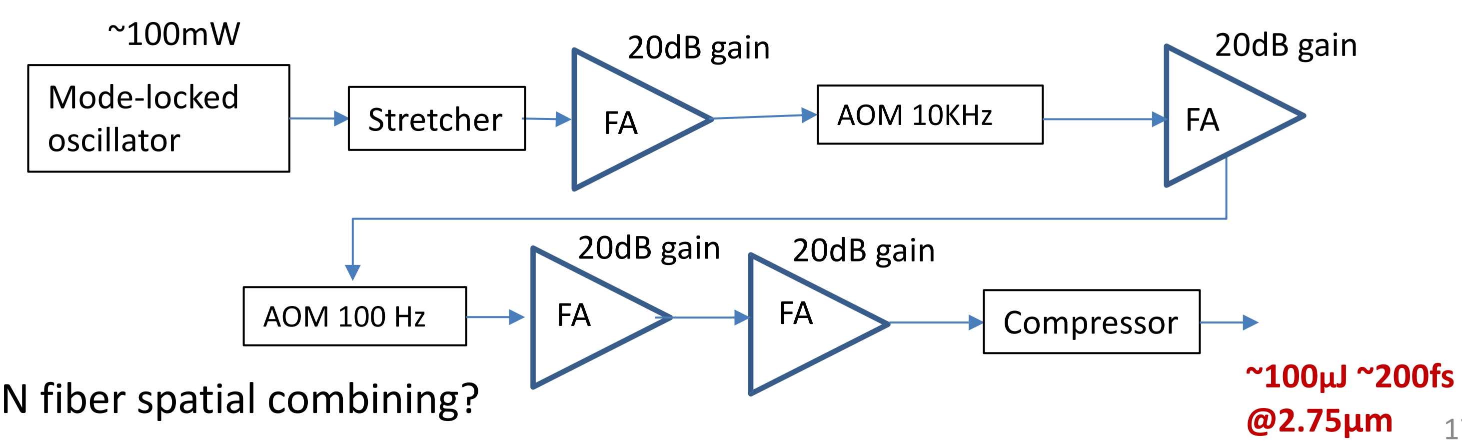
- Established critical mid-IR fiber laser exploration capabilities:
  - Mode-locked fs pulse source
  - High-energy amplification system
- Mode-locked oscillator:
  - Reliability (end protection), full characterization, etc…
  - Direct amplification
  - Extend mode-locked operation to ~3.6µm?
    - Will need construction of Tm-doped silica fiber laser pump
    - Contact with prof. S. Jackson's group at Macquarie University in Australia
- Amplification (using surrogate OPO/OPA seed source):
  - Measure stored energies in 30µm core Er:ZBLAN LMA amplifier and fully characterize it
    - End protection endcaps are critical
    - Need longer pulses
  - Explore high energy amplification in 50µm and 70µm core Er:ZBLAN LMA fibers
  - Explore ~3.6µm amplification?
    - Atmospheric transmission window
    - 30% higher OPA quantum defect/conversion efficiency

Possible future directions

- Er:ZBLAN fiber based CPA system



- Er:ZBLAN fiber based coherent pulse stacking amplification (CPSA) system



- Er:ZBLAN fiber spatial combining?