U.S. ARMY RESEARCH, DEVELOPMENT AND ENGINEERING COMMAND

LASERS FOR DEW BASED ON FULLY CRYSTALLINE FIBERS

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ASSL – DISRUPTIVE TECHNOLOGIES

ARL's Advanced Solid State Laser (ASSL) Team:

- Develops disruptive technologies
- Supports CFT Priorities:
  - Army Air and Missile Defense (AMD)
    - HEL Enabling/Support Technologies w/SMDC for DEW systems development
  - Future Vertical Lift (FVL)
    - Aircraft Survivability w/CERDEC

ARMY RELEVANCE

- **Mission: Develop compact and reliable high power laser sources (HELs) for Counter-Rocket/ Artillery/Mortar (C-RAM) applications**
- **Challenge: Reduce system Size Weight and Power (SWaP) and complexity for smaller platforms**
- **ARL Essential Research Program (ERP) "Distributed & Cooperative Engagements in Contested Environments"**
    - **"HEL with Low SWAP-C" Technology Gap**

Current State of the Art

High Energy Laser Mobile Test Truck (HELMTT)

- **60 kW HELMTT Master Laser with 58 individual spectrally combined ~1kW fibers**
- **Next short term Army goal – 100 kW class Master Laser on Stryker Combat Vehicle**

KEY TECHNICAL CHALLENGES

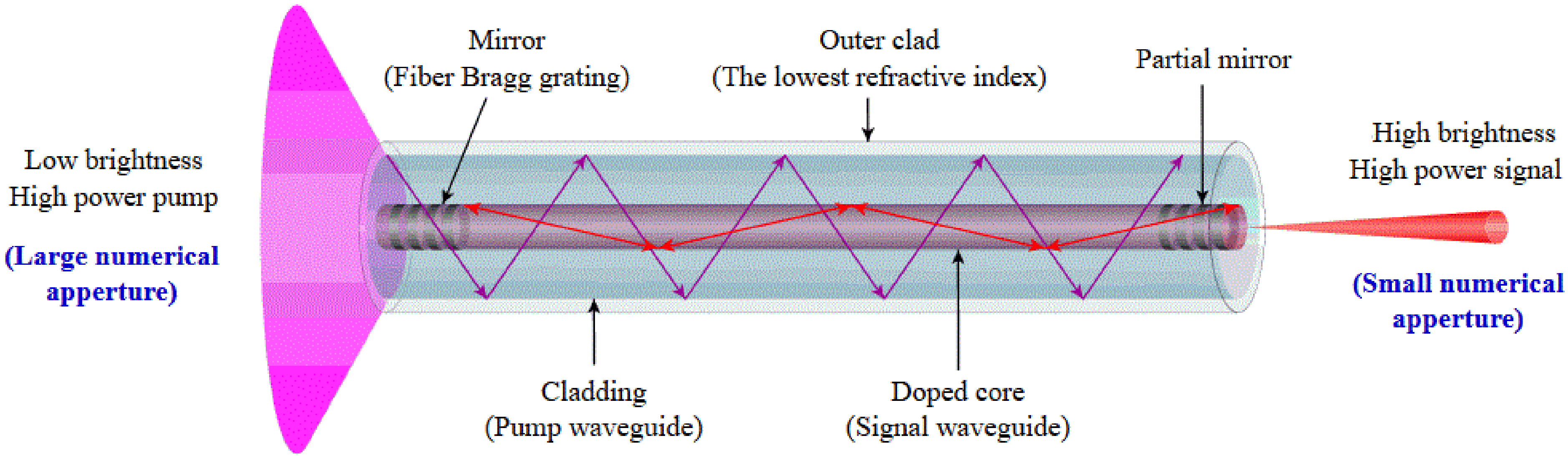
- Current System Limitations
  - Laser DEW based on current SOA in fiber lasers
  - Must combine multiple fibers to increase power
  - HELMTT Master Laser: 58 individual 1kW fibers
  - Too big for small Army platforms
- Major SWAP Reduction Needed
  - Increase power per fiber 10-50X
  - Only 2 lasers to be combined - to get 100 kW
- ARL approach – explore laser power scaling based on fully crystalline gain fibers
  - Theoretical predictions from 2010 [1,2]
  - First laser demonstrations based on fully crystalline double-clad fibers [3,4]

Smallest Army Platforms

BLUF: Laser power out of a single fiber can be scaled by a factor of 10-50X

DOUBLE CLAD FIBERS

How does the double clad fiber work:



'All-Glass' Fiber or **'Fully Crystalline' Fiber**

a.k.a. "crystalline core/crystalline cladding" (CCCC = C4) fiber

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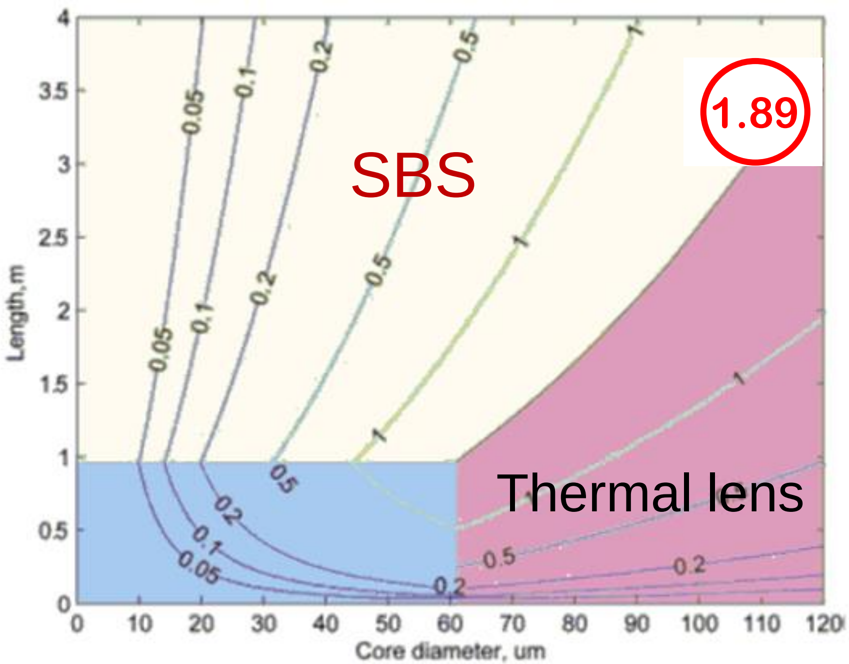
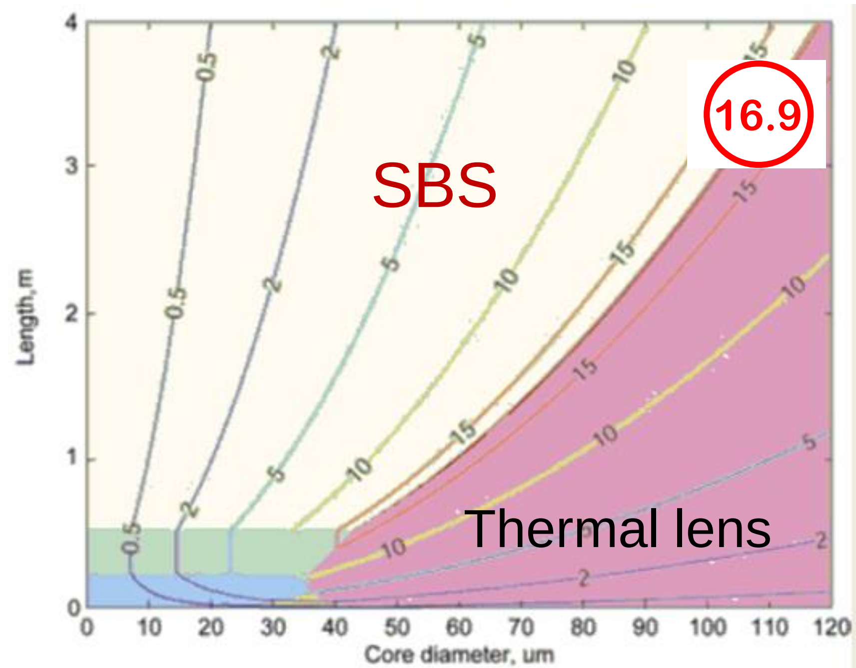
POWER SCALING POTENTIAL OF C4 FIBERS OUT OF A SINGLE FIBER APERTURE

Maximum laser power in Yb-doped C4 YAG-fiber case is (conservatively) 10X the maximum expected power in the Yb^{3+} doped silica fiber



'All-Glass' Fiber



REF(1)

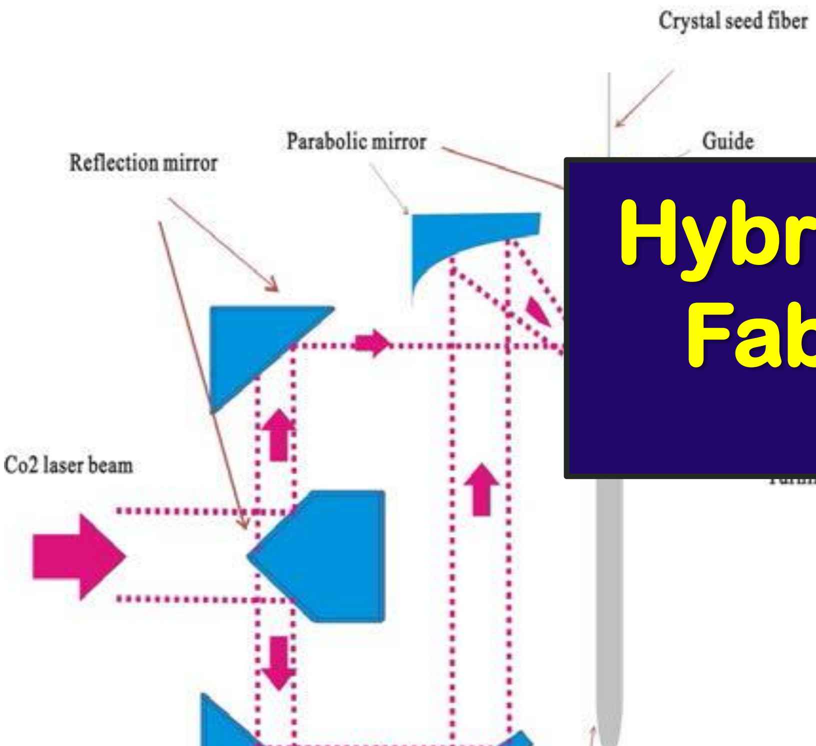
'Fully Crystalline' Fiber

SBS – Stimulated Brillouin Scattering
YAG – Yttrium Aluminum Garnet crystal

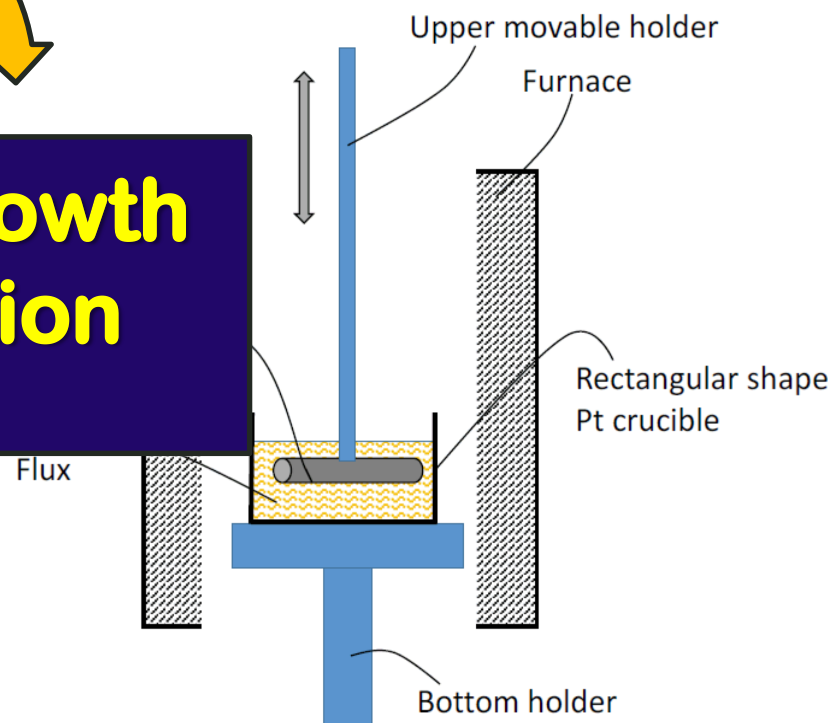
Pump diode brightness | Damage limited

C4 FIBER VIA HYBRID GROWTH FABRICATION APPROACH (HGFA)

Laser heated pedestal growth (LHPG) for core fabrication



Liquid Phase Epitaxy (LPE) for cladding fabrication



Hybrid Growth Fabrication

RESULT

Length-scalable and coilable C4-design low-loss laser fibers

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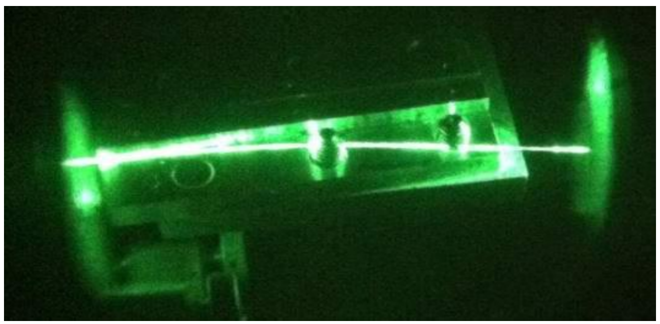
FIRST STEPS IN FABRICATION AND TESTING

Highly efficient waveguided laser operation of RE-doped cores:

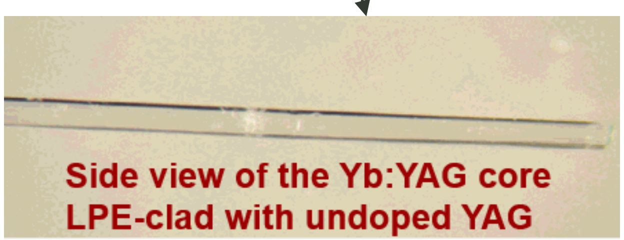
Core composition	Pump source, wavelength	Slope efficiency	Laser wavelength	Fiber dimensions	Straight or bent
Yb^{3+}(1%):YAG (Ref. [2])	Multimode laser diode module, 969 nm	58.3% -- (published) **Most recent results: 78%**	1030 nm	100 mm, dia. 100 µm	Both straight, and bent to a dia. of ~30 cm

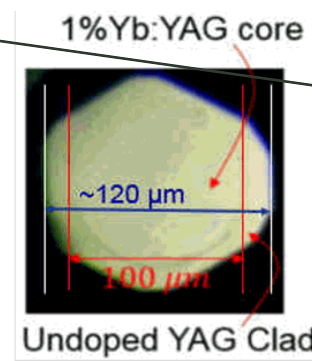


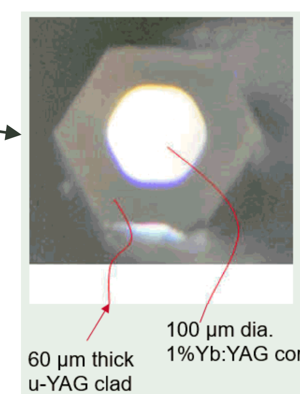
Waveguided laser operation of intentionally bent unclad Yb:YAG core. Observed with the same slope efficiency as with the straight core

LHPG-grown YAG cores are good enough for fabrication of C4 DC fibers

Fabricated double-clad C4 fibers

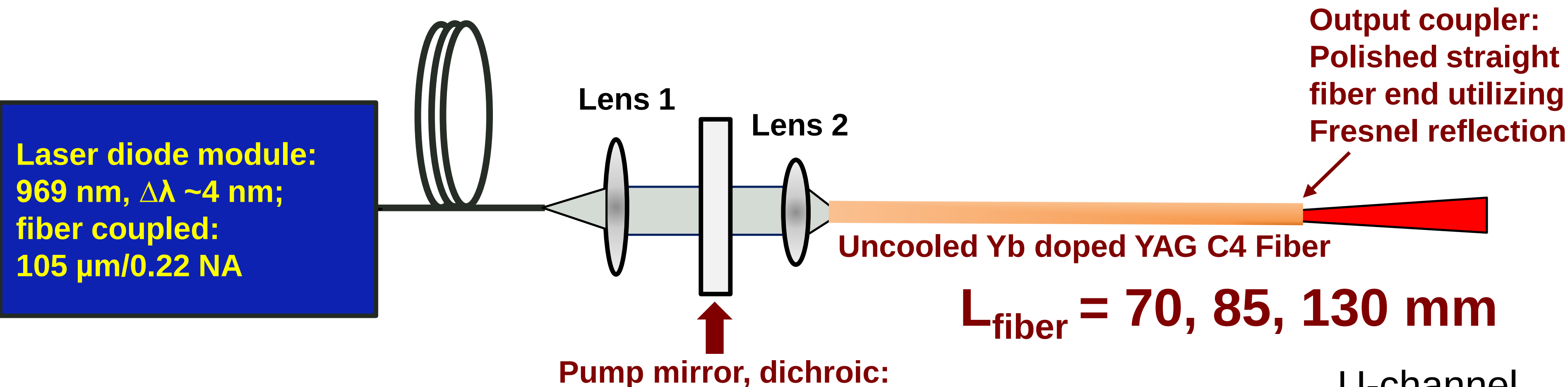


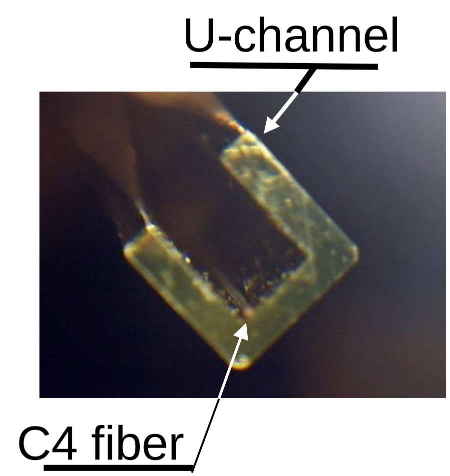




EXPERIMENTAL LASER SETUP

Co-pumped C4 fiber laser setup

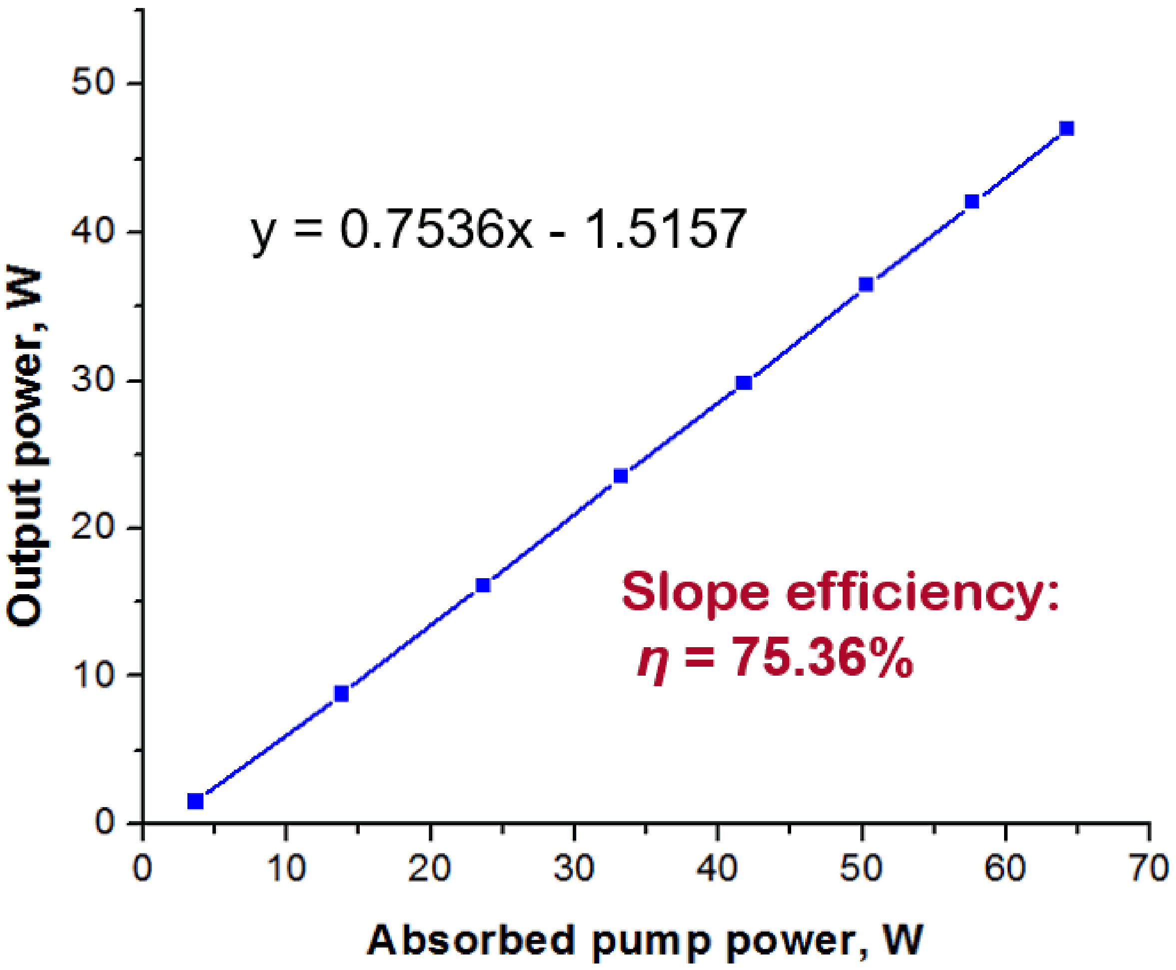




Q-CW pump regime of testing:
1 ms pump pulse duration, 1% duty cycle.

BEST LASER EFFICIENCY SO FAR

Results after pump mode and cavity optimization



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CONCLUSIONS

- Power scaling in crystalline-based fibers shown to be theoretically feasible
- Fabrication of the ‘crystalline core/crystalline cladding’ (C4) fibers was demonstrated using the Hybrid Growth Fabrication as a combination of LHPG and LPE
- Demonstrated ~50 W of Q-CW power from an uncooled ‘Yb:YAG core/undoped-YAG clad’ C4 fiber with ~70% optical-to-optical efficiency and over 75% slope efficiency
- Improvements in the quality of a double-clad C4 fiber will yield greater power and efficiency
- C4 fiber design upgrades for true CW operation are in progress
- This work demonstrates a viable pathway to major SWaP and complexity reduction of laser DEW systems in support of AMD

Backup slides

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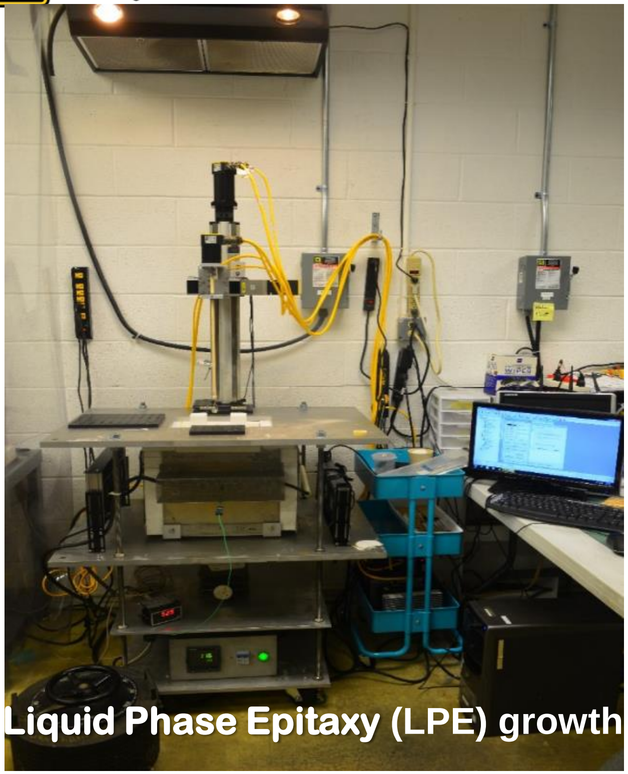
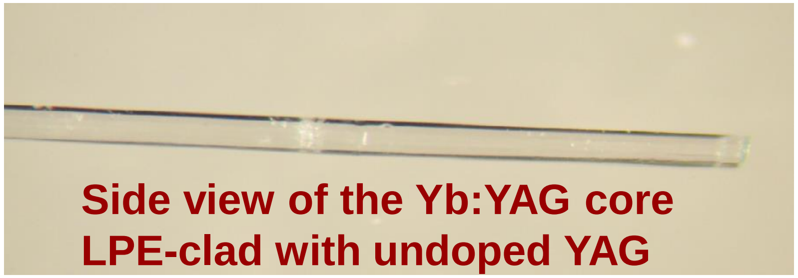
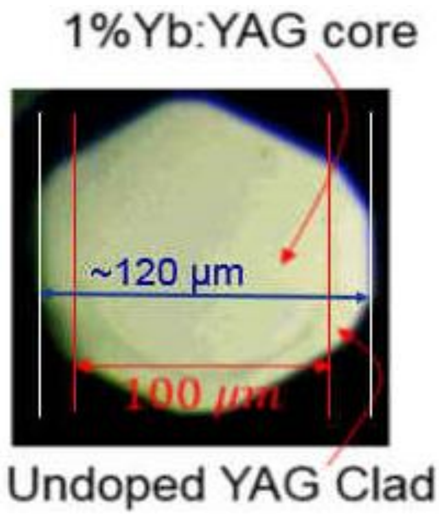
YB:YAG/YAG C4 FIBER – LPE CLAD



Liquid Phase Epitaxy (LPE) growth



Side view of the Yb:YAG core LPE-clad with undoped YAG



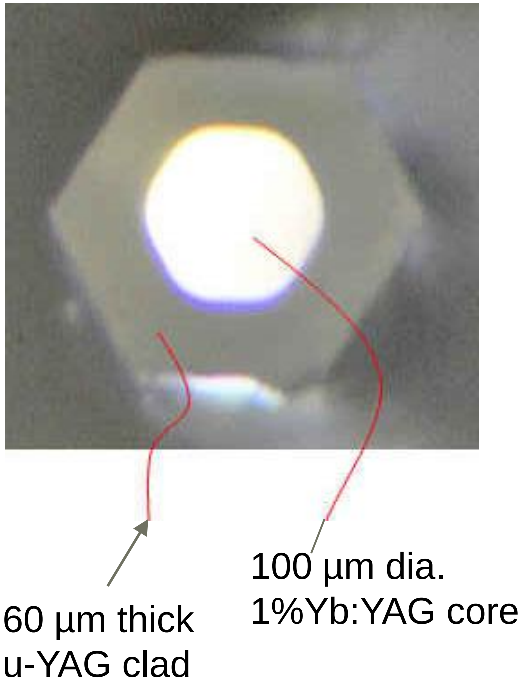
n_{YAG} (1030 nm) = 1.8153

$n_{Yb(1\%):YAG}$ (1030 nm) = 1.8155

Core NA = 0.027

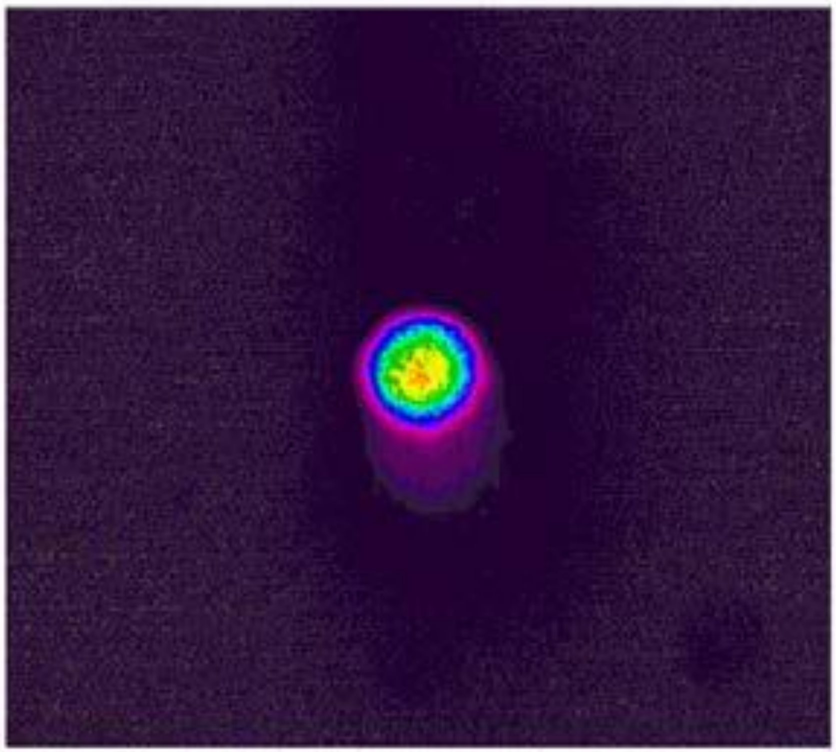
V number = 8.22

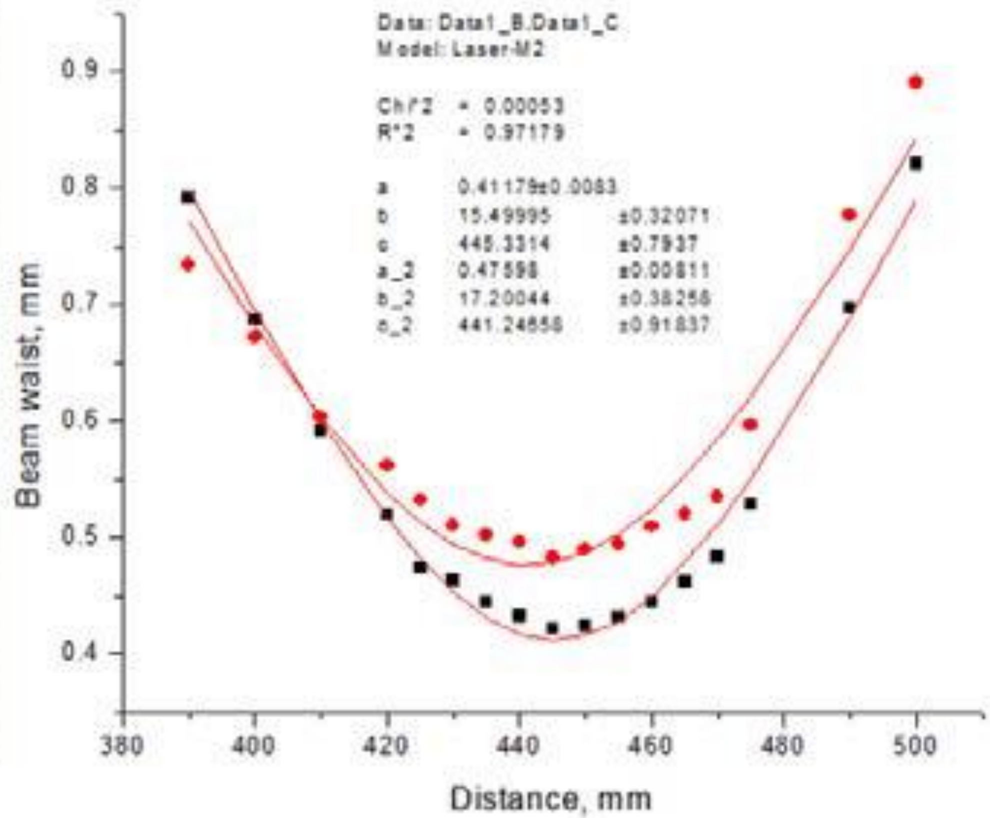
So this fiber core was never meant to be a singe-mode one



Growing thicker cladding is possible, but we do not currently specifically push for it

EXPERIMENTAL RESULTS - BEAM QUALITY

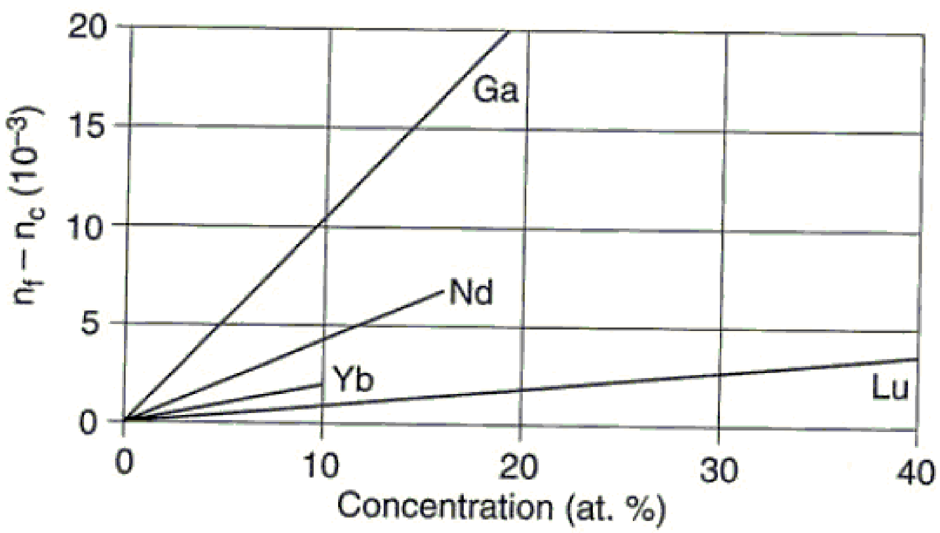




Far field laser output spatial power distribution

M^2 measurement results: M^2_x~15, M^2_y~17

HOW DO WE DESIGN THE C4 FIBER FOR A SINGLE-MODE OPERATION



M. Malinowski, J. Sarnecki, R. Piramidowicz, P. Szczepanski, and W. Wolinski, "Epitaxial Re3+:YAG planar waveguide lasers," Opto-Electronics Review 9, 67-74, 2001.

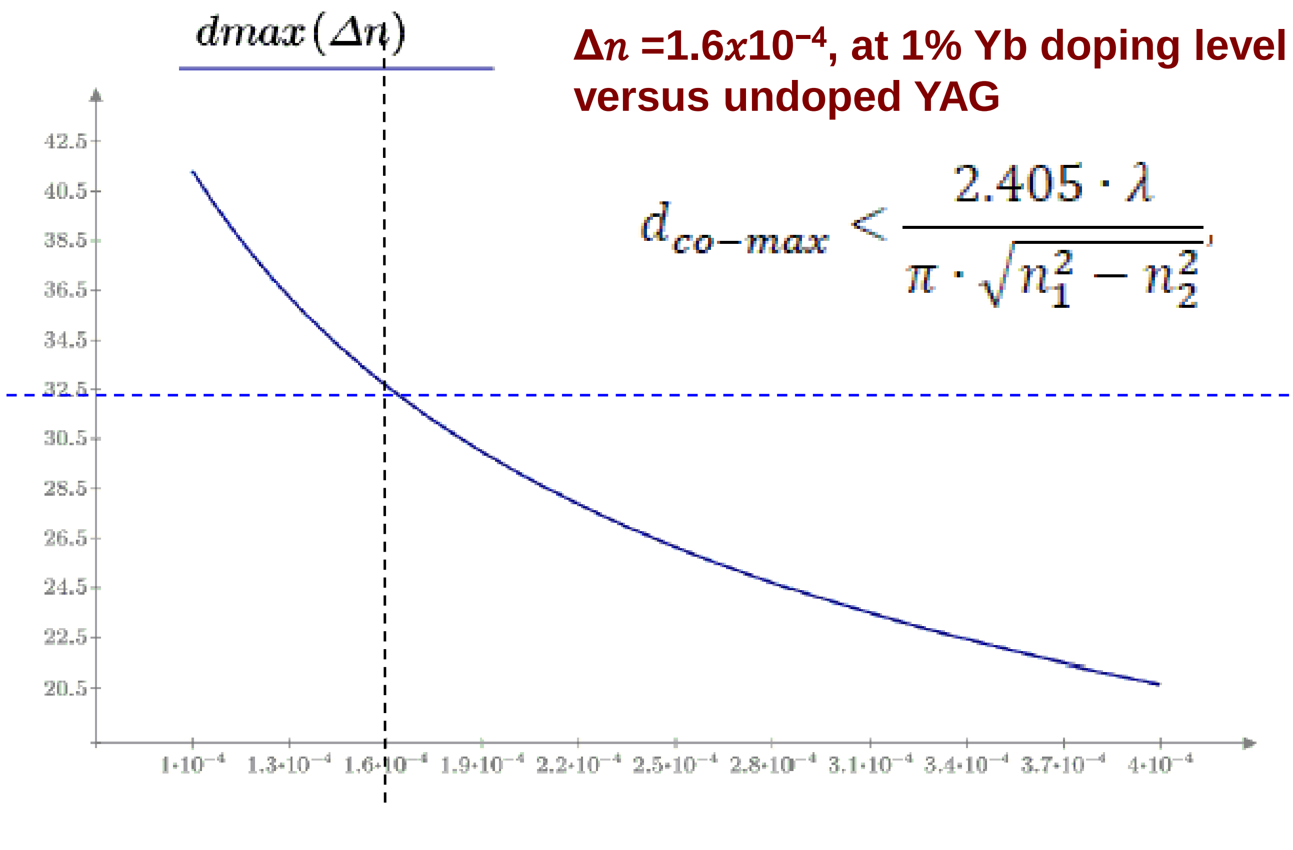
Refractive index change rate in commonly used RE-doped YAG crystals.

RE dopant	Lu	Yb	Tm	Er	Ho	Nd
$\Delta n(\times 10^{-4})/1\%$	0.96	1.60	2.08	2.10	2.44	4.74

X.Mu, H.Meissner, H-C.Lee, M.Dubinskii, "True Crystalline Fibers: Double-Clad LMA Design Concept of Tm:YAG-Core Fiber and Mode Simulation", Proc. of SPIE Vol. 8237, 82373M (2012)

CAN WE TURN THIS LASER INTO A SINGLE TRANSVERSE MODE DEVICE?

Calculated maximum core diameter as a function refractive index difference between core and cladding



$\Delta n = 1.6x10^{-4}$, at 1% Yb doping level versus undoped YAG

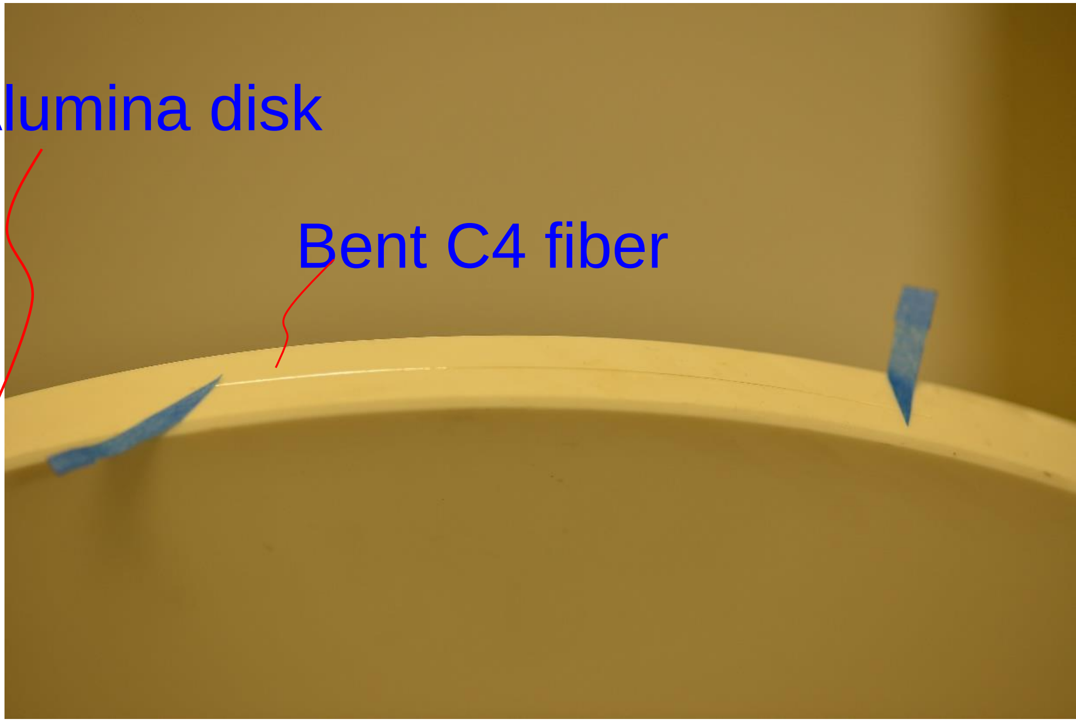
$$d_{co-max} < \frac{2.405 \cdot \lambda}{\pi \cdot \sqrt{n_1^2 - n_2^2}},$$

All we need to do (for Yb^{3+} 1% doping in YAG vs undoped YAG) is to go to a core diameter of ~30 µm, which is shown to be very feasible for LHPG-grown cores

C4 FIBER - BENDABILITY

We demonstrated the bending (or coiling) capability of our C4 fiber, enabling future operation when the length extents to over 0.5 m, or so

Shown to the right is the C4 fiber bent on an alumina disk with a diameter around 30 cm



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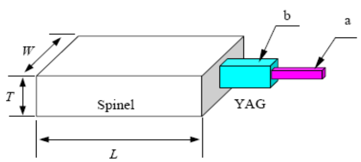
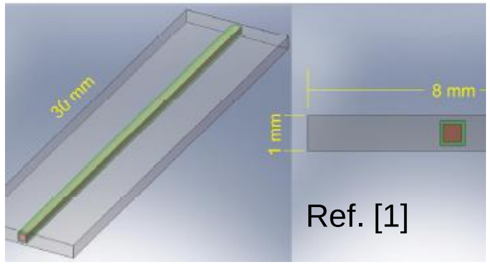
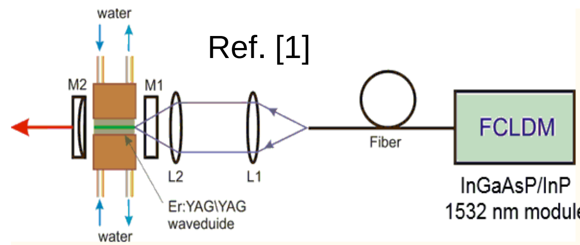
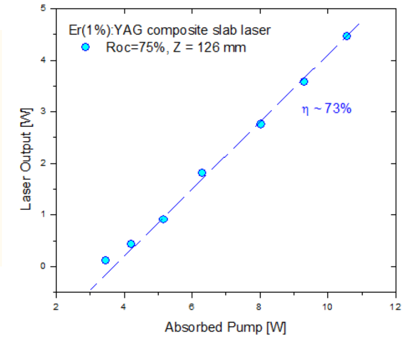
SMALL CRYSTALLINE WAVEGUIDING STRUCTURES: OUR EARLY ANALOG OF CCCC (C4) FIBER



Fully crystalline double-clad fiber design based on diffusion bonding

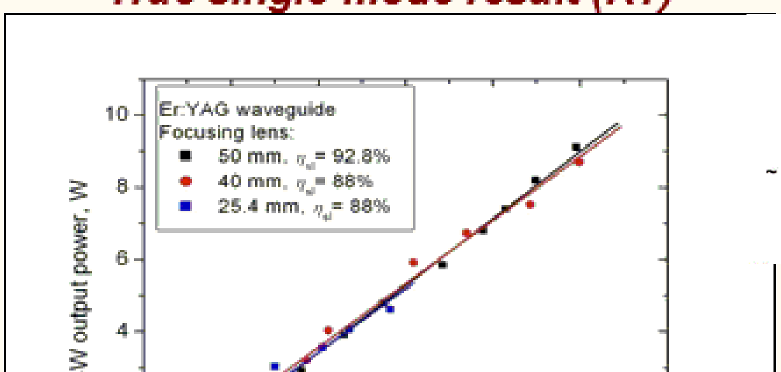


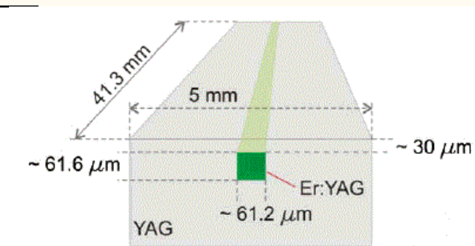




[1] N. Ter-Gabrielyan, V. Fromzel, X. Mu, H. Meissner, and M. Dubinskii, "High efficiency, resonantly diode pumped, double-clad, Er:YAG-core, waveguide laser," Opt. Express 20 (23), 25554-25561 (2012) .

True single-mode result (RT)

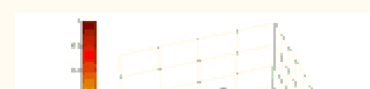




Composite "Er:YAG/YAG" buried channel waveguide

(60 x 60) μm SC core

Ref. [2]



First experiments with fully-crystalline fiber-like double-clad structures in bulk crystalline materials provided a proof-of concept, but, based on fabrication technique, are not amenable either to major length scaling, or fiber coiling