High Power All-Fiber Lasers at AFRL

AFRL/UNM Directed Energy Day

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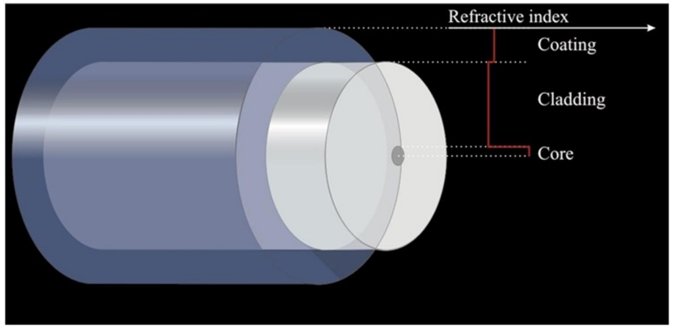
Fiber Lasers for Beam Combining

Fibers: promising laser sources for Directed Energy (DE) applications

- Power scaling of single fibers limited by nonlinear (NL) and thermal effects
  - Beam Combining Required for Further Power Scaling
- HP Industrial Fiber Lasers: broad bandwidth (~5-10nm) -> not beam combinable; or multi-mode fibers (reduced intensity) -> poor beam quality (BQ)/brightness
- **Beam combinable fibers: req. narrow linewidth & single-mode BQ**

Double Clad Fiber



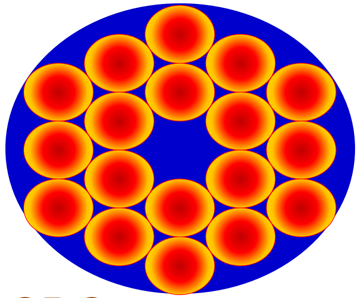
Fiber Laser Advantages:

- Compactness ~3.5 kg/kW
- High efficiency: 90% O-O, 45% E-O
- All fiber configuration; Graceful degradation

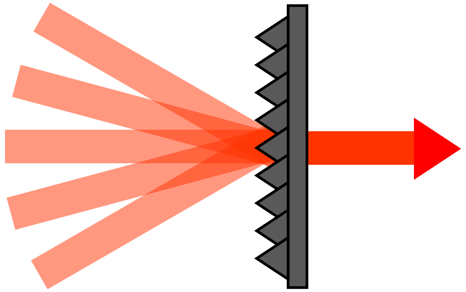
Fiber Challenges:

- NL: Stimulated Brillouin and Raman scattering (SBS, SRS); Kerr nonlinearity- self phase modulation
- Thermal: Heating and modal interference; modal instability (MI)

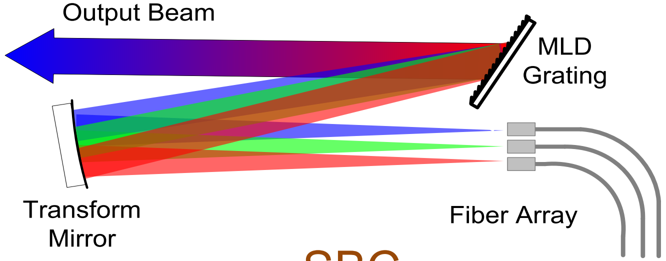
Prevalent Beam Combining (BC) Architectures



Tiled CBC



Filled CBC

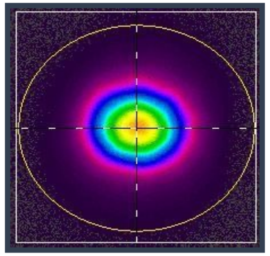


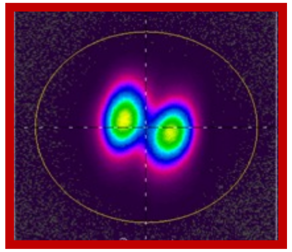
SBC

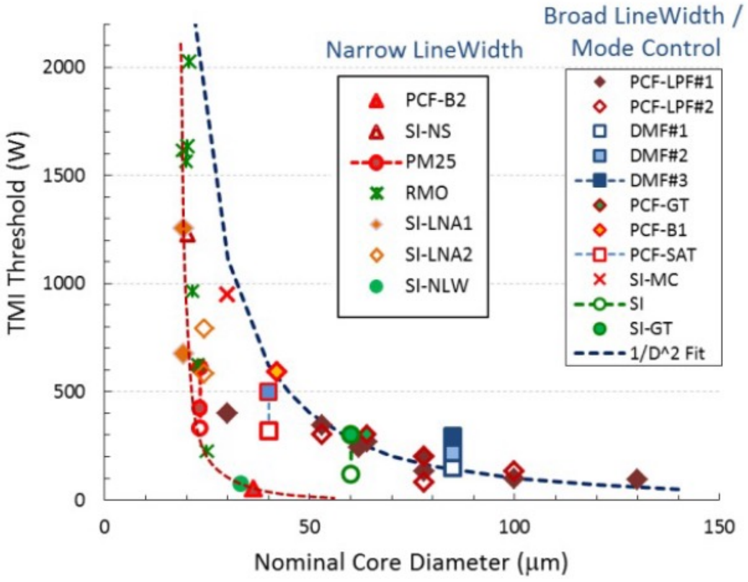
High Power Fiber Amplifiers: Thermal Limits

Thermal Mode Instability (TMI)

Interplay of modal interference and heating leading to degradation of beam quality







Zervas, et al. Proc. SPIE 10083 2017

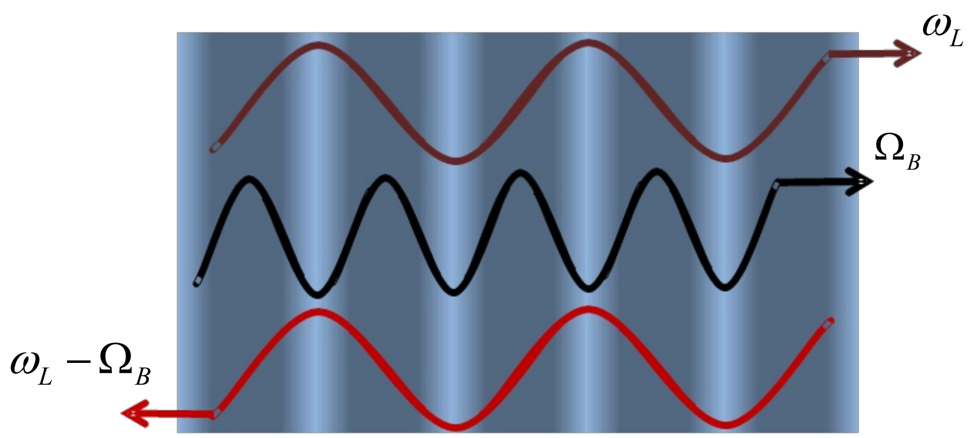
MI suppression techniques

Mitigation Strategies	Potential Limitations
Gain tailoring	Longer length: lower SBS threshold
Higher seed power	Add'tl preamp stage; HP isolator; complexity
Counter-pumping; Bi-Directional	Power handling capability of combiners (rapidly maturing)
Tandem pumping	SWaP
Shorter seed wavelength	ASE, photodarkening
Smaller core size	***Lower SBS threshold***

- **Thermal effect limiting diffraction limited output at high average powers**
  - Thermal grating scatters the fundamental mode into a higher order mode, reducing beam quality
    - ***Inversely proportional to the core diameter: Critical for other nonlinear effects***
  - *Smaller core sizes increase higher order loss in fiber*

Trade space between TMI and nonlinear effects must be optimized to produce narrow linewidth fiber amplifiers

Nonlinear Effects: Stimulated Brillouin Scattering



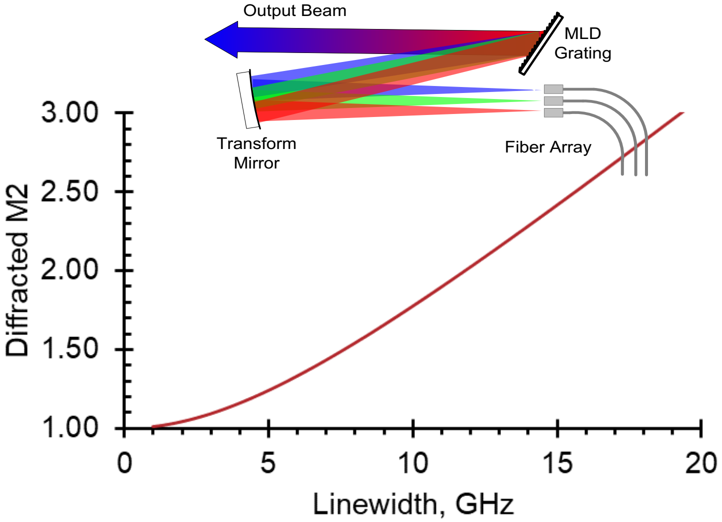
$$P_{thresh} = 21\frac{A_e}{g_b L_e}\left(1 + \frac{\Delta\nu}{\nu_B}\right)$$

SBS suppression techniques

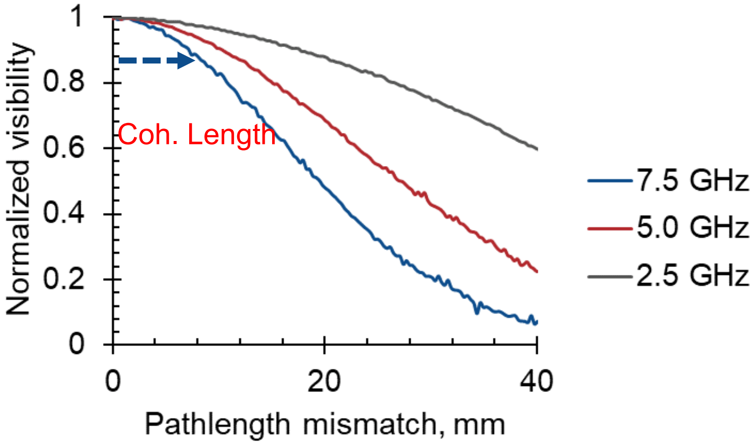
Mitigation Strategy	Parameter	SBS Threshold Increase	Potential Limitations
Large core	A_e	>100x	Single mode operation; MI
Lower Intrinsic Brillouin gain	G_b/v_b	10x?	Fiber fabrication; comp. w/ phase modulation?
Laser gain competition	L_e	2-2.5x	Higher order nonlinearities
Higher Yb concentration	L_e	1.5-2x	Photo-darkening, high heat load
Phase modulation	***Δv***	***>100x***	***Beam combinability***

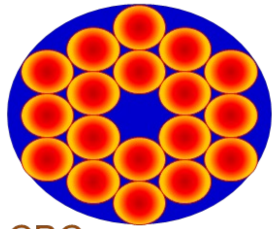
- **1st Nonlinear effect encountered in narrow-linewidth, combinable fiber amplifiers**
- **Creates a backwards propagating wave at a lower frequency (~16 GHz @ 1 μm)**
  - Characterized by a nonlinear increase in the backwards propagating signal
  - SBS thres. prop. to mode area (Ae) and inv. prop. to eff. fiber length (Le)
- **Large Mode Area (LMA) fibers and RF phase modulation prevalent approaches for SBS suppression**

SBC/CBC Compatible Fiber Amplifiers

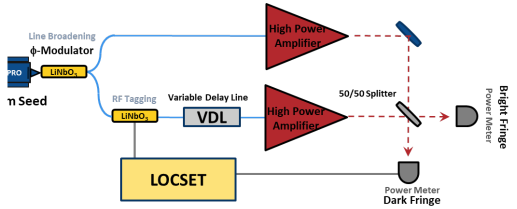


SBC: Increased bandwidth reduces beam quality; angular dispersion of gratings





Tiled CBC



CBC: Increased bandwidth creates strict path length matching requirements; reduced coherence length

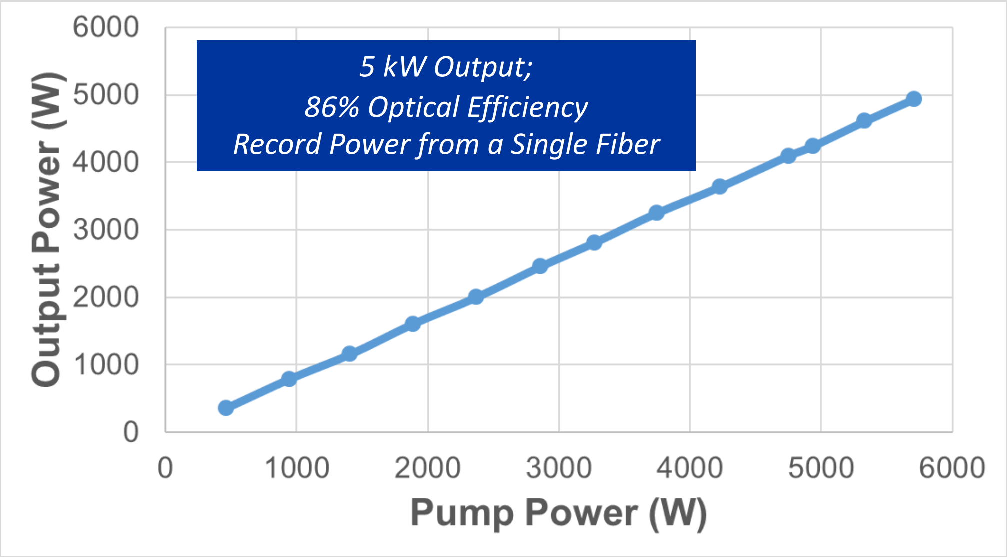
- CBC: Potn'l atm. turbulence compensation thru tiled array; broader linewidths feasible; N^2 intensity scaling
  - Reqs phase, polarization, and path length control; increased complexity
- SBC: incoherent combining; minimal ctrl loops; reduced system complexity
  - SBC challenging narrow linewidths (<12GHz) req. due to grating dispersion (reduced BQ)
- ***Good BQ ($M^2 \leq 1.2$) and narrow linewidths <12 GHz (0.04nm) req for compatibility w/ all BC systems***

AFRL Goal: Develop high power fiber laser sources suitable for incorporating into both SBC & CBC architectures

AFRL 1μm Fiber Amplifier Research

- Initial high power fiber amp research focused on Ytterbium (Yb)-doped fibers operating at ~1μm
  - Semiconductor diodes commercially available at peak Yb absorption (976 nm); pump diode wavelength near 1μm signal wavelengths-low quantum defect
  - Favorable Yb doping properties in silica & low quant. defect lead to high optical effic. (~80-90%)
- Beam combinable, Yb-doped fiber amps prev. limited to kW class power levels (nonlinear/thermal effects)
- ***AFRL/RD, AFOSR, DE-JTO co-investments led to key breakthroughs for 1μm fiber amps***

- **2012 (AFOSR PO: Dr. Nachman):** AFRL dev. time-dependent nonlinear (SBS) model for fiber amps; enabled investigation of var. phase modulation schemes for optimal nonlinear mitigation; *[Zeringue, Dajani, et al Opt. Exp 20 (2012)]*
- **2014 (AFOSR POs: Dr. Schlossberg, Dr. Luginsland):** 1.2kW Fiber Amp (3 GHz~0.01nm linewidth); record narrow linewidth (3-5x linewidth reduction); *[Flores, Robin, et al Opt Exp 22 (2014)]*
- **2016-2017 (AFOSR PO: Dr. Luginsland):** 1) Dev. novel phase mod. technique for enhanced nonlinear supp.; 2) 1st Multi-kW Beam Combining of Phase Mod. Fiber Amps; *[Flores, Dajani, et al Opt Eng 55 (2016) & Anderson, Flores, et al Opt Exp 25 (2017)]*

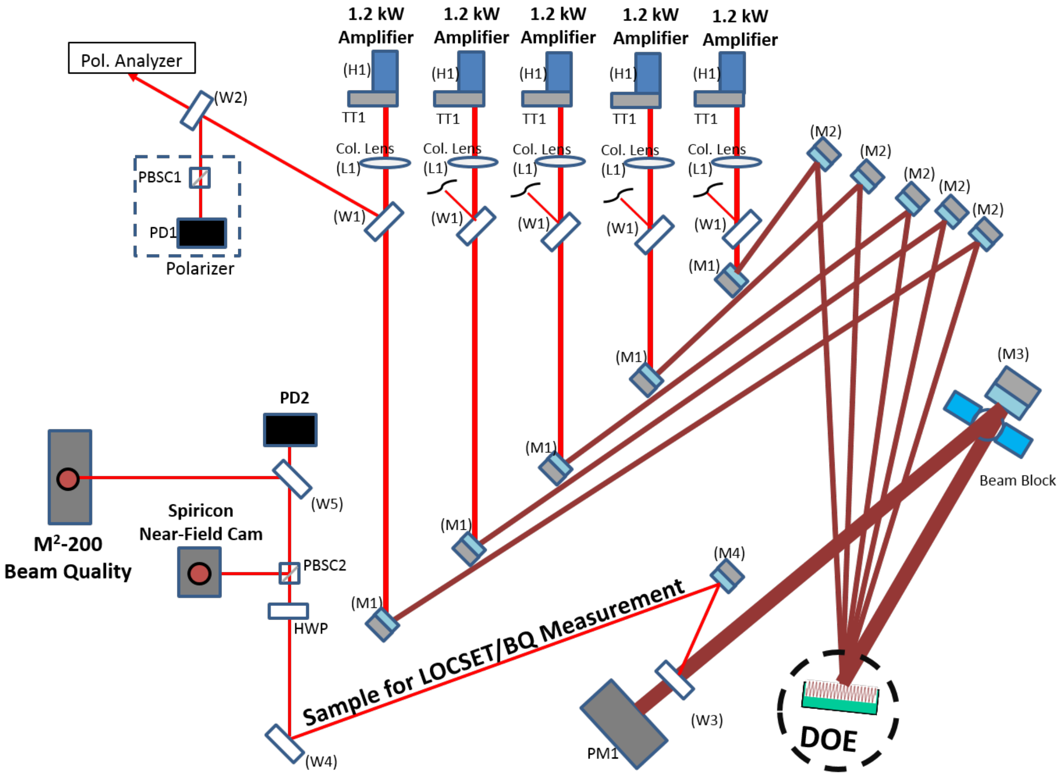


AFOSR, RD, & JTO Investments led to Demonstration of 1st Multi-kW, Beam Combinable Fiber Amplifiers
Major Breakthrough For Next Gen High Power Fiber Laser Systems

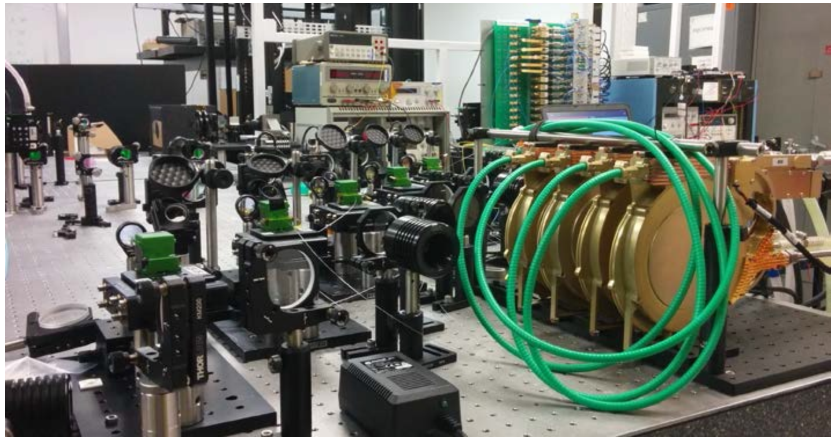
Multi-kW Coherent Beam Combining

Multi-kW class CBC

- Validate beam combinability of PRBS modulated fibers
- 5 commercial Nufern amplifiers
- Filled aperture beam combining: 1x5 Diffractive Optical Element (DOE)

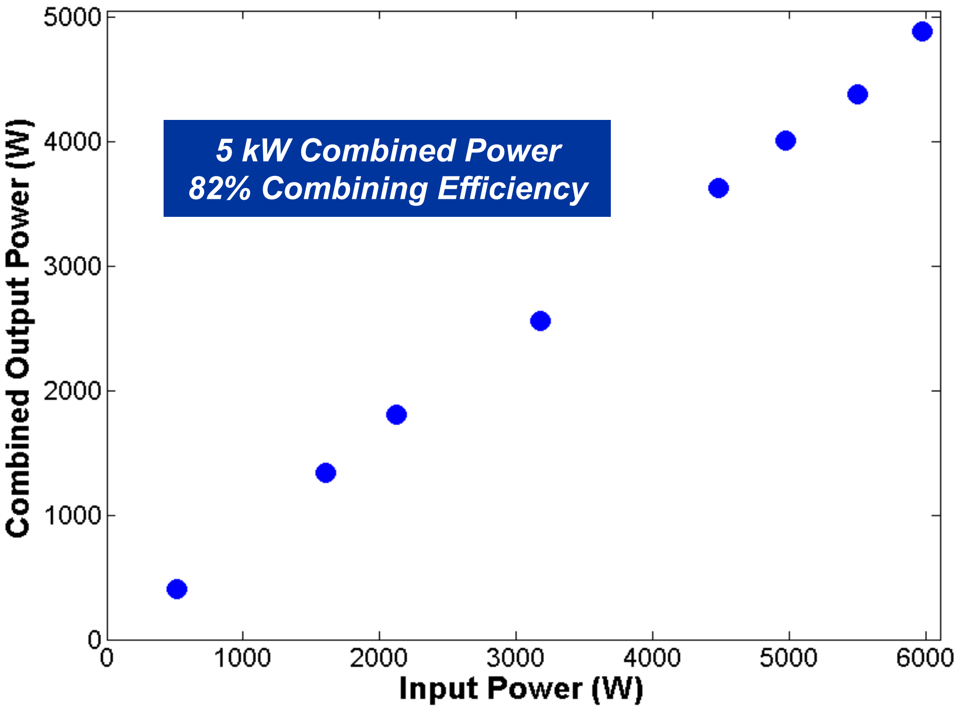


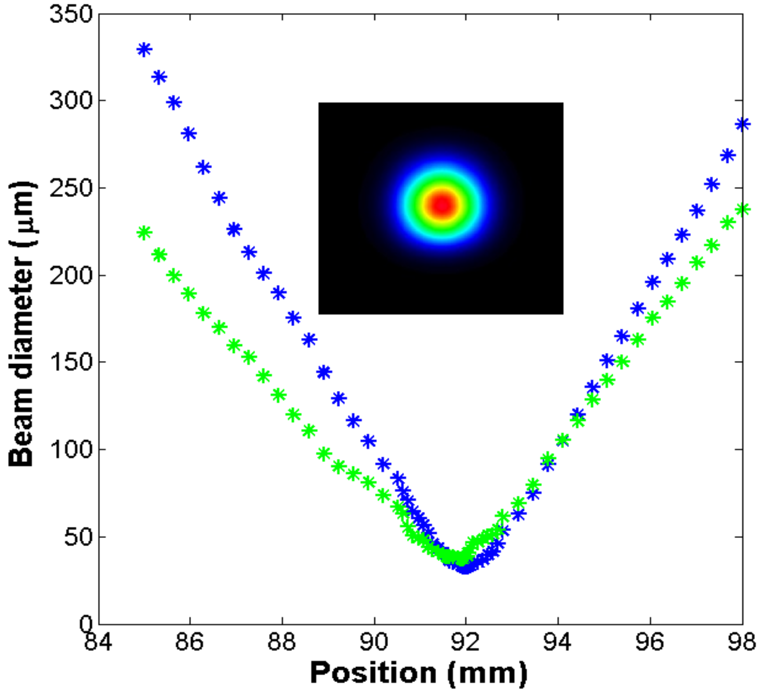
AFRL DOE (1 x 5) Beam Combining Setup



5kW Coherent Beam Combining

- Phase modulation via PRBS (n = 7 pattern) at clock rate of 10 GHz
- **Phase locking via AFRL patented LOCSET, used extensively worldwide for coherent combining**
- **Total Combined Output Power: ~5 kW; Combining Efficiency: 82%**
- Diffraction Limited Beam Quality: $M^2 = 1.06$





Fiber laser nonlinear suppression schemes can be efficiently combined in multi-kW regime

Conclusions

- Narrow linewidth fiber amplifiers are required for efficient beam combination
- AFRL developing fiber amplifiers compatible with prevalent SBC and CBC architectures
- AFRL demonstrated 1st beam combinable, multi-kW fiber amplifiers
- Demonstrated Multi-kW Class Coherent Beam Combining
  - Combined Output Power: 5 kW; Efficiency: 82%; Beam Quality: M2 = 1.06

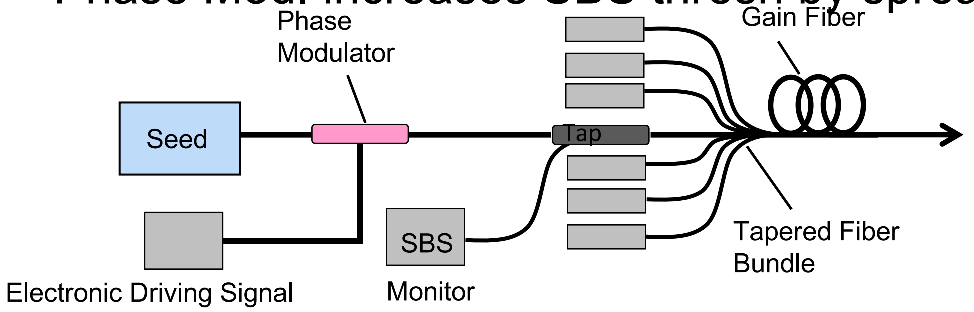
Scaling output power of narrow linewidth (beam combinable) fiber amplifiers for DE applications

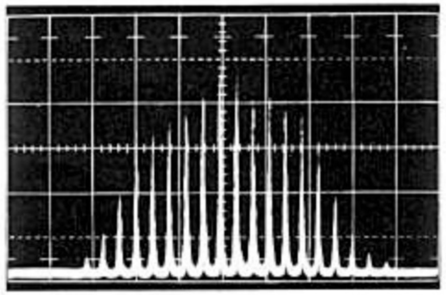
The authors would like to thank AFRL/RD, the Air Force Office of Scientific Research (AFOSR) and the DE Joint Technology Office (DE-JTO) for funding this research.

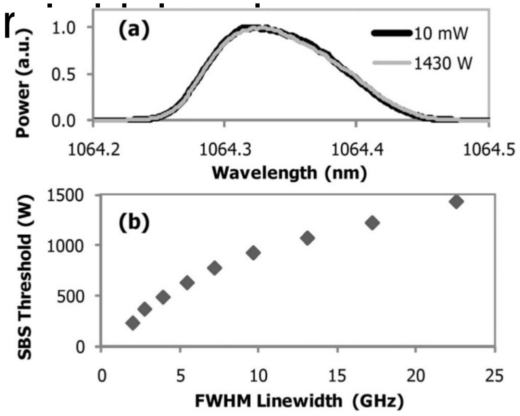
BACKUP

SBS Suppression: Phase Modulation

- Power Scaling: 2 Approaches – Increase Fiber Channels or Increase Power Per Fiber Channel
- Phase Modulation: RF driving signal utilized to modulate optical signal; broaden spectral linewidth
- Phase Mod. increases SBS thresh by spreading optical intensity among sever

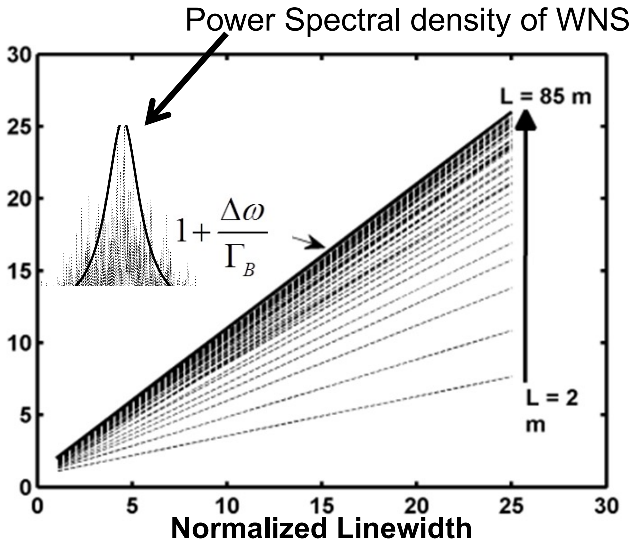






G. D. Goodno, S. J. McNaught, et al, Opt. Lett. 35, 1542 (2010).

C. Zeringue, I. Dajani, et al, Opt. Express 20 (2012)



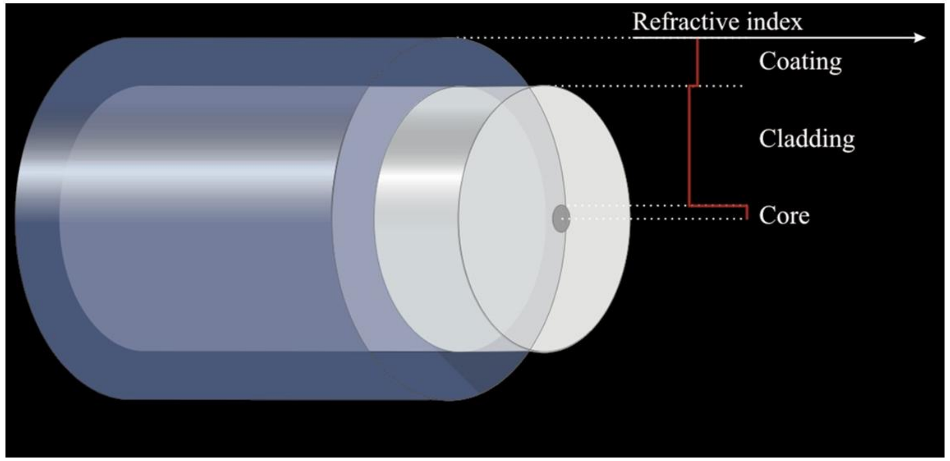
$$P_{th}(\Delta v) = P_o\left(1+\Delta v/\Delta v_B\right)$$

- Deviation from exp. linear broadening/SBS thresh relationship
- Developed time-dependent SBS model w/ phase mod effects included
- WNS: enhancement factor approaches theory

Novel time-dependent nonlinear model enabled investigation of various modulation schemes for optimal SBS suppression

Key Technological Advances

Double-Clad Fiber



Pump guided in multi-mode cladding waveguide

Seed guided in core

- Single-clad, single-mode fiber requires single-mode pump

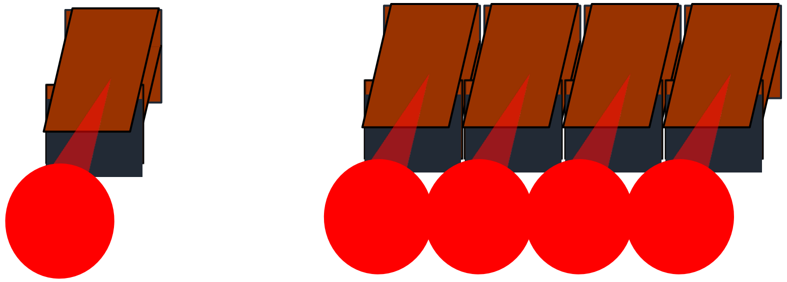
Laser Diode Pumping

Single Emitter

P_{max} ~ 8-10 W

Laser Diode Bars

P_{max} limited by Brightness requirements



Prior lasers, used flash lamps (poor eff. & lifetime)
Efficient pump coupling to double-clad fiber requires brightness conservation

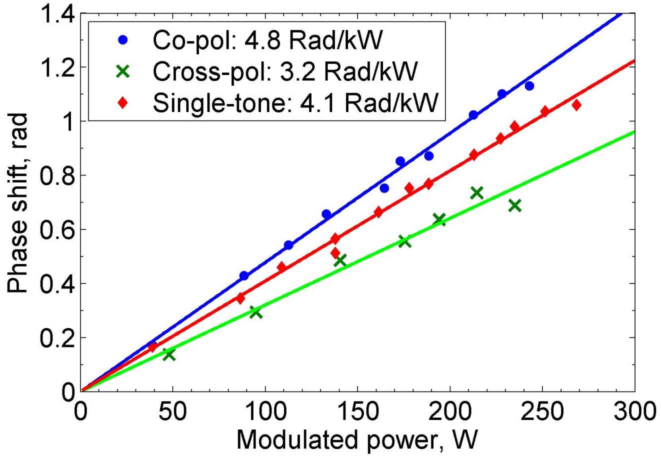
$$D_{fiber} \cdot NA_{fiber} \geq D_{pump} \cdot NA_{pump}$$

Fiber amplifier is a brightness converter:

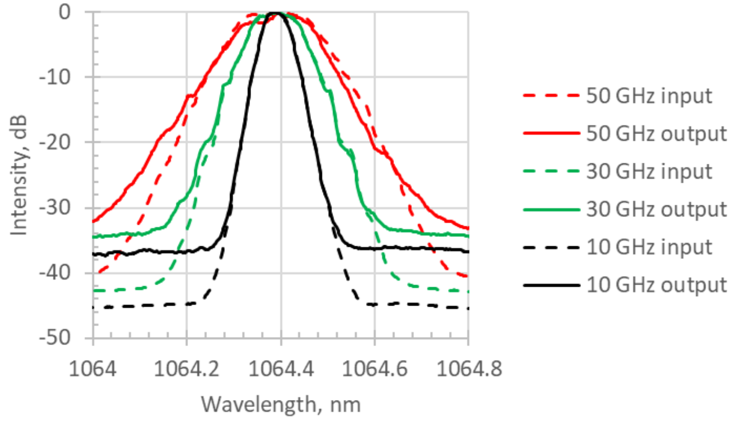
Multi-mode pump → Single-mode signal

Kerr nonlinearity:

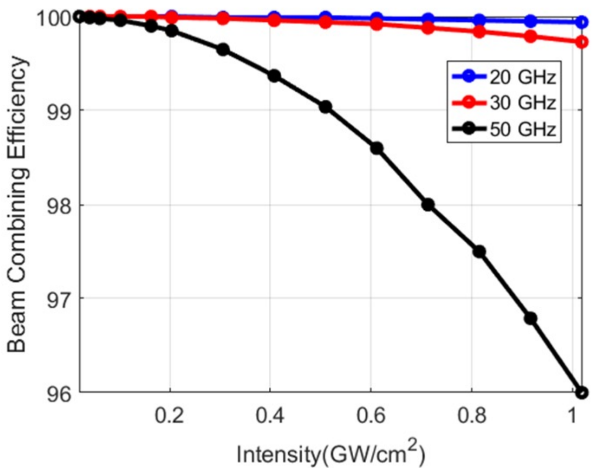
Nonlinear phase shift



SPM



Loss in beam combining efficiency



- **Kerr nonlinearity limits beam combinability at high powers**
  - Amplitude noise from GVD, combines w/ Kerr nonlinear to produce SPM broadening
    - ***→Drop in beam combining efficiency, reduced coherence length***
  - kW-class fiber amplifier: ~4 rad/kW, higher power amplifiers: 11 rad/kW
- **Mitigation:** Use narrower linewidths to reduce amplitude noise