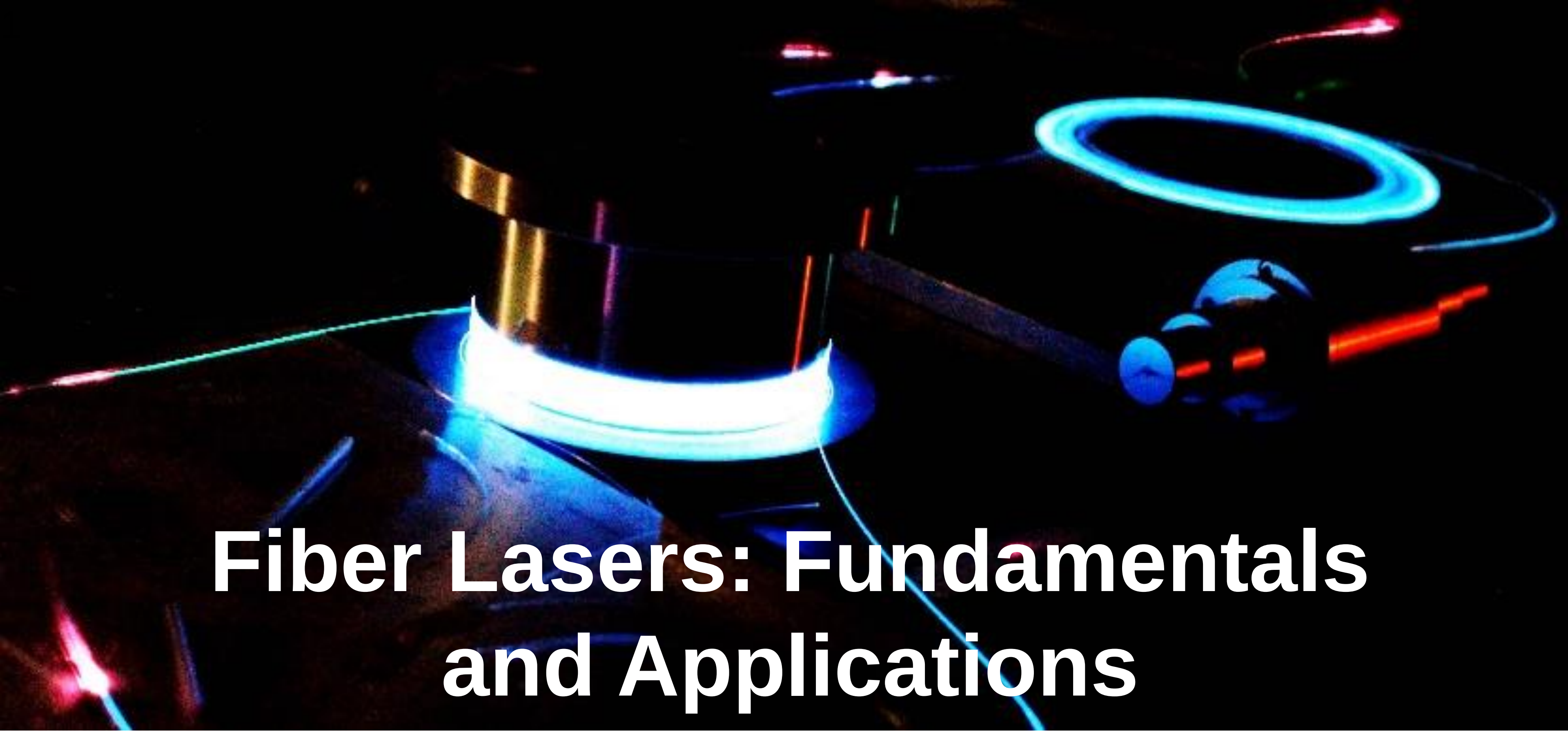

Fiber Lasers: Fundamentals and Applications

Lecture 6

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onlinear
otonics

Lasers for Directed energy

- High energy military lasers used in weapon systems
- "*Introduction of energy weapons is a game changer comparable to missiles, aircraft carriers and GPS technology" -Navy League Exposition 2013*
- 2013- US Navy to deploy first laser on a ship capable of disabling an aircraft
- Competing technologies: Free Electron (FEL) and Solid State Slab lasers

Requirements

50kW – 100kW class Lasers necessary

Excellent beam quality and pointing stability

LAWS Short Range Laser System

Limits of power scaling

IPG

• **Single mode CW fiber lasers with output power of upto 10kW has been demonstrated**

  • **More akin to power combing, multiple fiber laser modules pumping a large-mode area double clad fiber)**

• **Practically, individual single mode fiber laser modules have power levels in the level of 2-3kW**

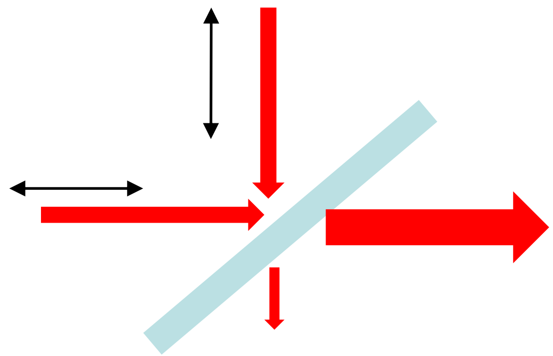
• **The limits of single mode output power from a fiber laser is expected to be ~ 10kW** **(J. W. Dawson et al, IEEE Leos 2008)**

  • **Limited by effects such as optical damage, core melting, thermal lensing, thermal rupture etc**

Overcoming power scaling limitations

- **Power combining needs to enhance brightness. Broadly divided into**
  - **Coherent beam combining**
    - **One spatial mode and one spectral mode**
  - **Spectral beam combining**
    - **One spatial mode but multiple spectral modes**

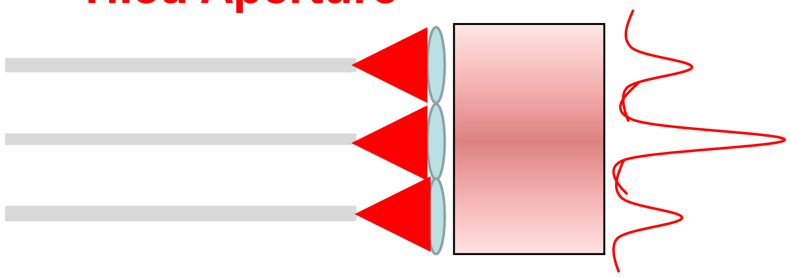
Coherent Combining

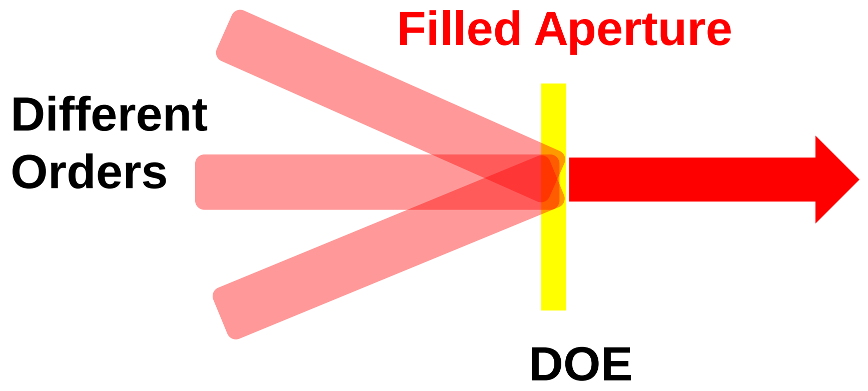


All laser sources originating from the same seed source (same common mode noise)

Why narrow linewidth – path length accuracy needs to be significantly better than coherence length

Tiled Aperture





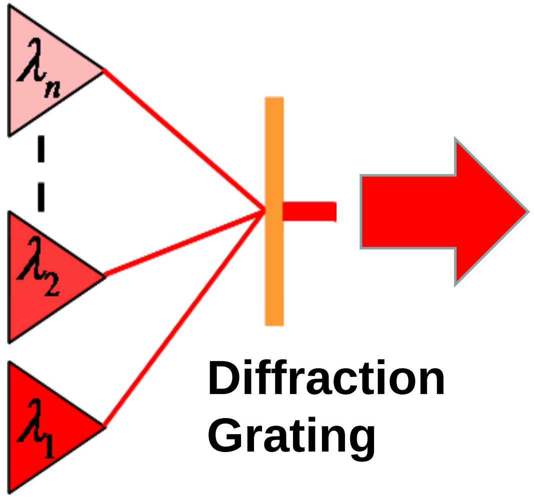
Pros

- Single seed source

Cons

- Complex system and control
- Degradation not graceful on individual module failure

Wavelength Combining



Individual seed laser sources locked precisely in wavelength

Why narrow linewidth – Angular spread due to Diffraction effects needs to be small within each channel

Pros

- Simplified control system
- Graceful degradation

Cons

- Multiple seed sources locked to wavelength grid

Power Combinable Fiber Lasers

General Requirements

- High gain single stage amplifier (15-dB +)
  - To minimize system complexity
  - Power handling of standard isolators decided need for Gain

- High output power per amplifier module
  - Higher the power, the better

- linewidth of < 10GHz at 1kW
  - Power linewidth compromise

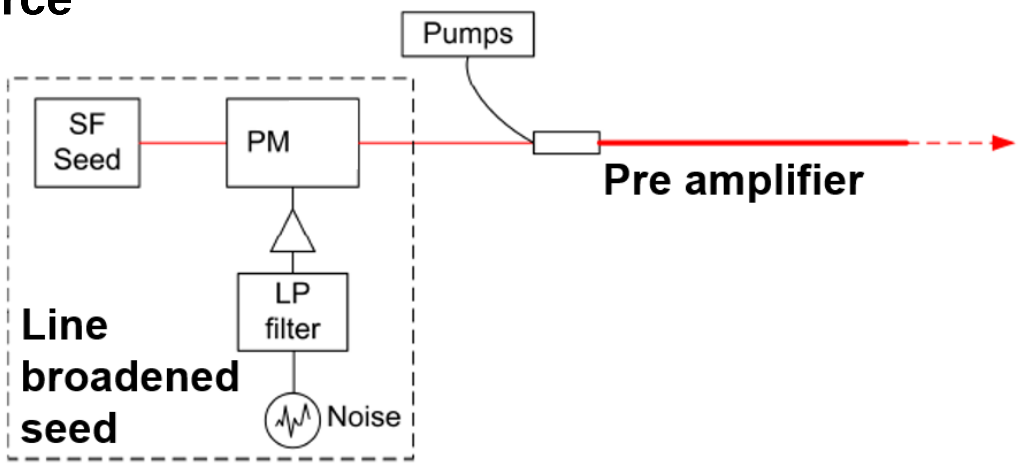
- $M^2 \leq 1.1$

- $\eta \geq 75\%$

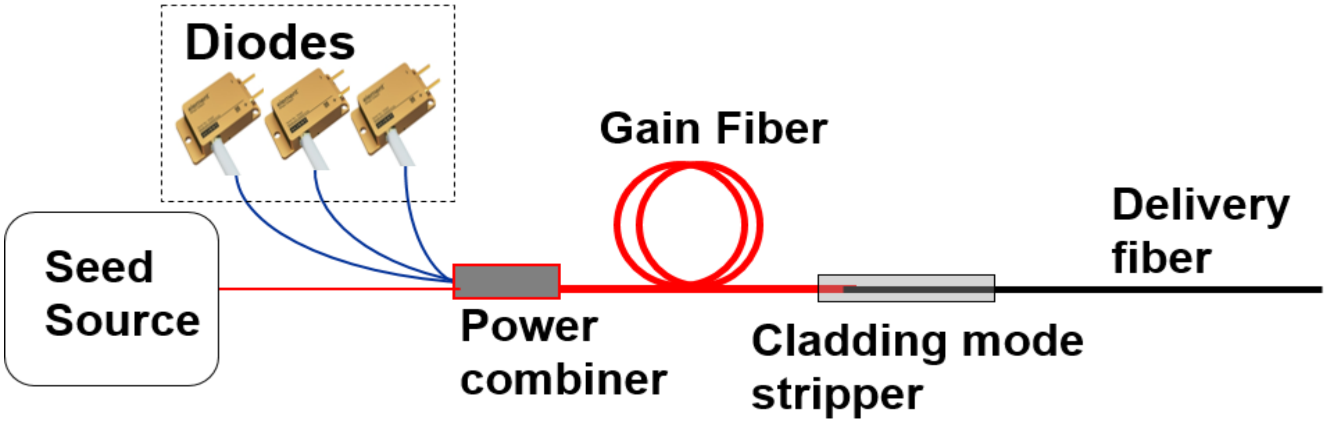
- Preferably Linearly Polarized Architecture (PER > 13dB)

Module Schematic

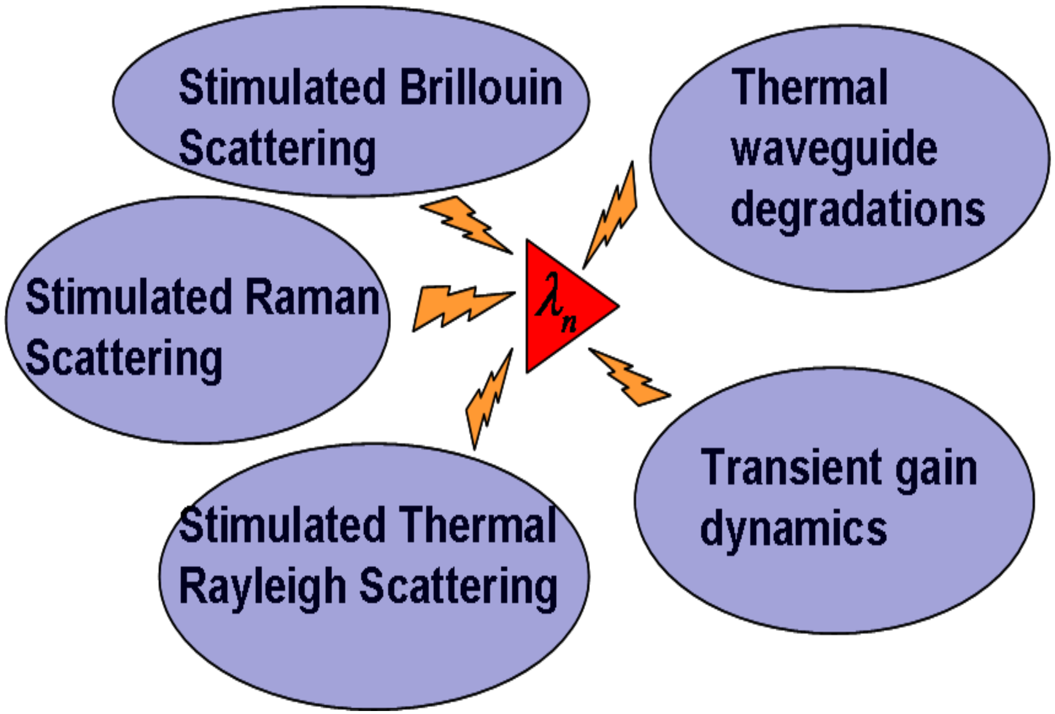
Seed Source



Power Amplifier



Nonlinear Limitations

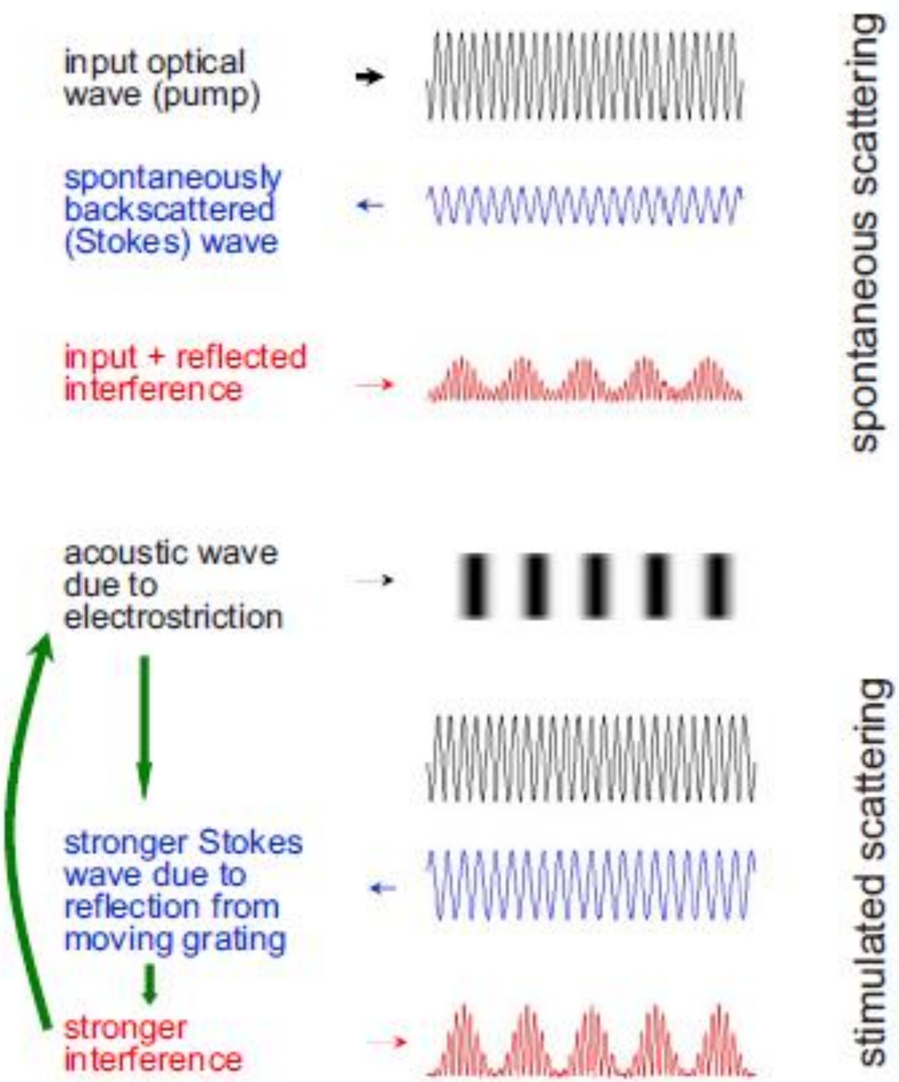


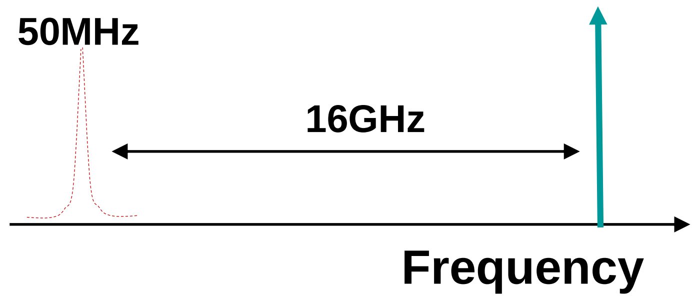
Key limiting factors

- **Stimulated Brillouin scattering**
- **Modal instability (Stimulated thermal Rayleigh scattering)**
- **Thermal waveguide degradations**

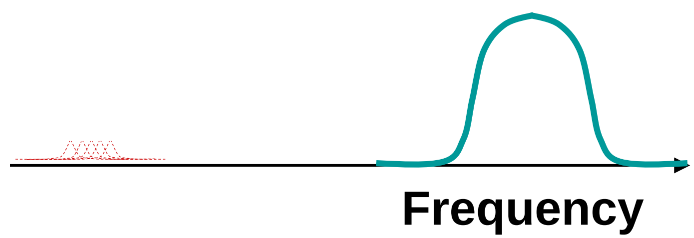
Stimulated Brillouin Scattering

Stimulated Brillouin Scattering





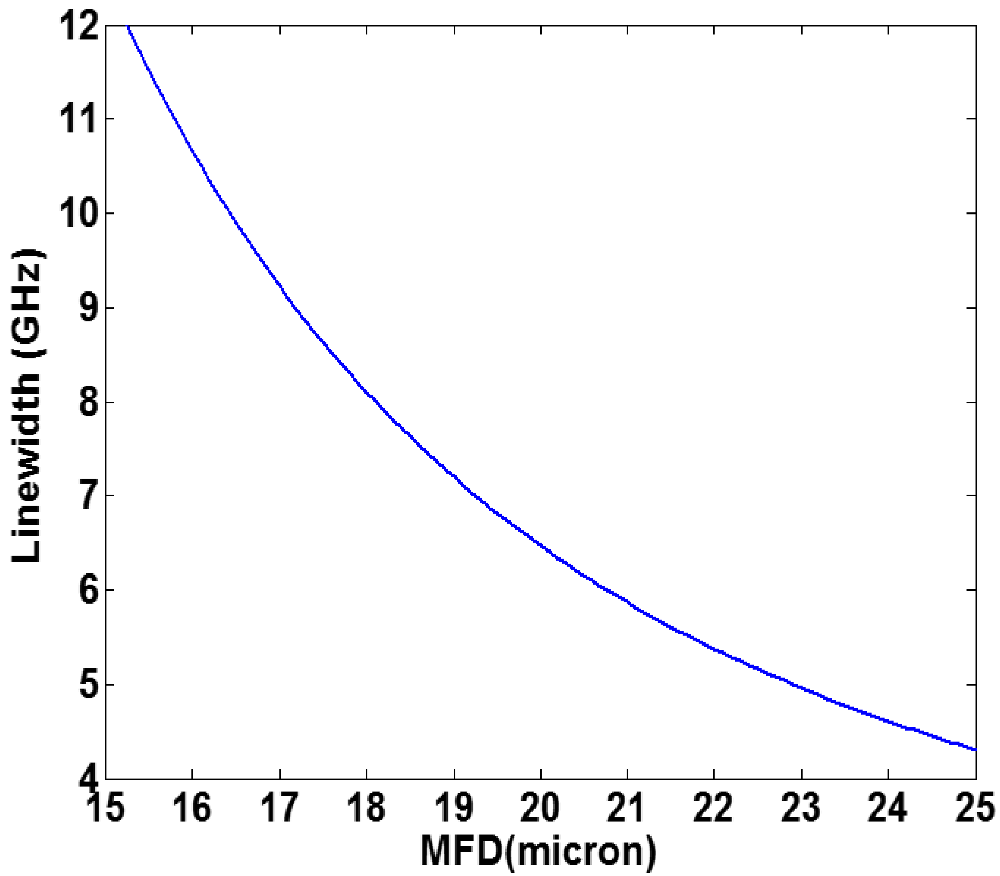
- **Narrow gain bandwidth ~ 50MHz**
- **Reducing optical intensity reduces SBS**



Enhancement factor

$$EF = 1 + \frac{\Delta f}{\Delta \upsilon_B}$$

Design of SBS compensated Laser Modules



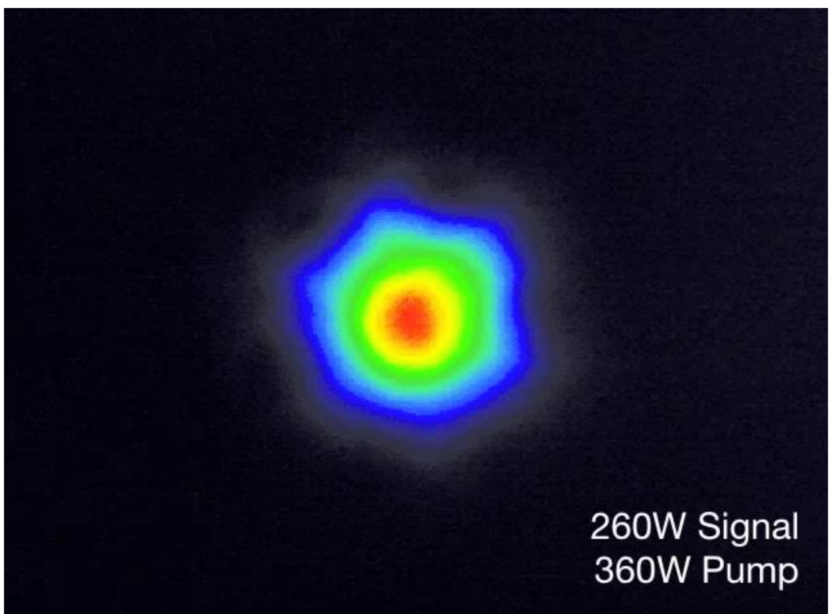
Anticipated linewidth as a function of fiber MFD at 1kW

Modal Instability

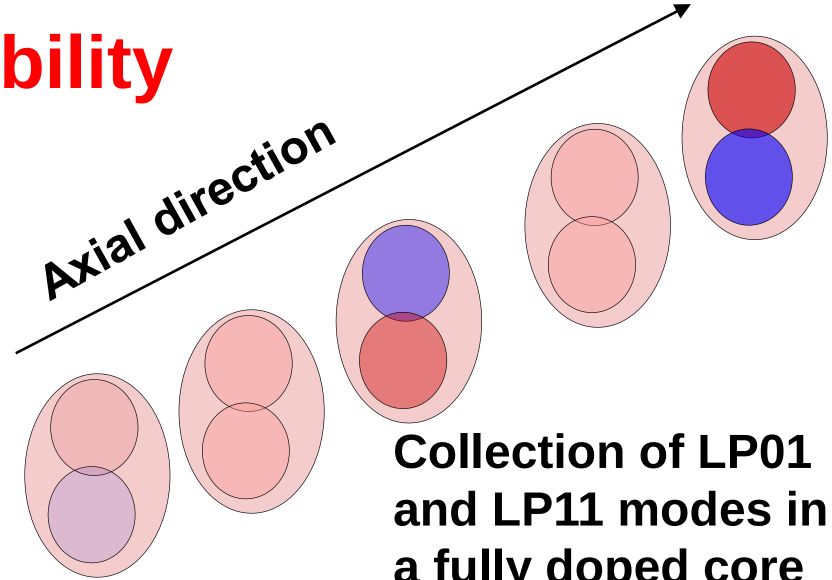
Modal Instability

• Coherent phenomenon occuring primarily in narrow linewidth fiber lasers with multimoded behavior.

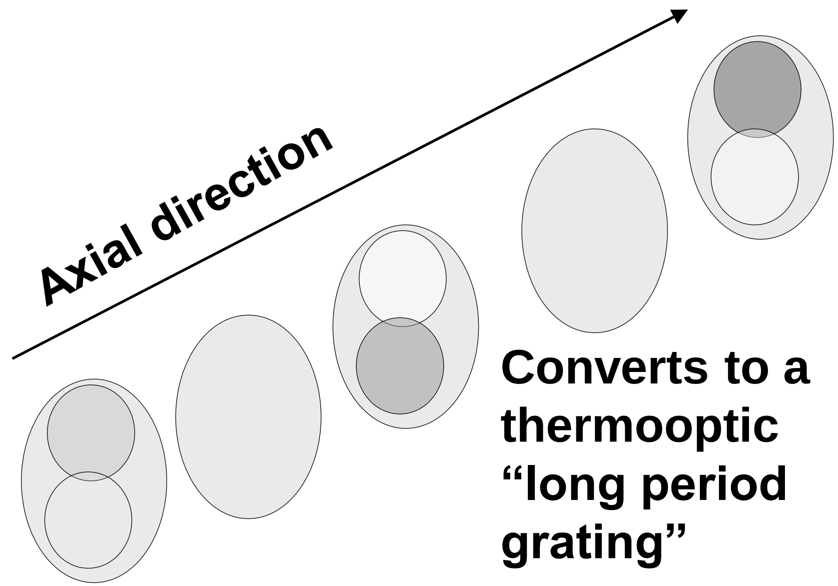
• Due to differential heat load in the coherent interference pattern between different modes, thermo-optic grating forms.



(From Jena)

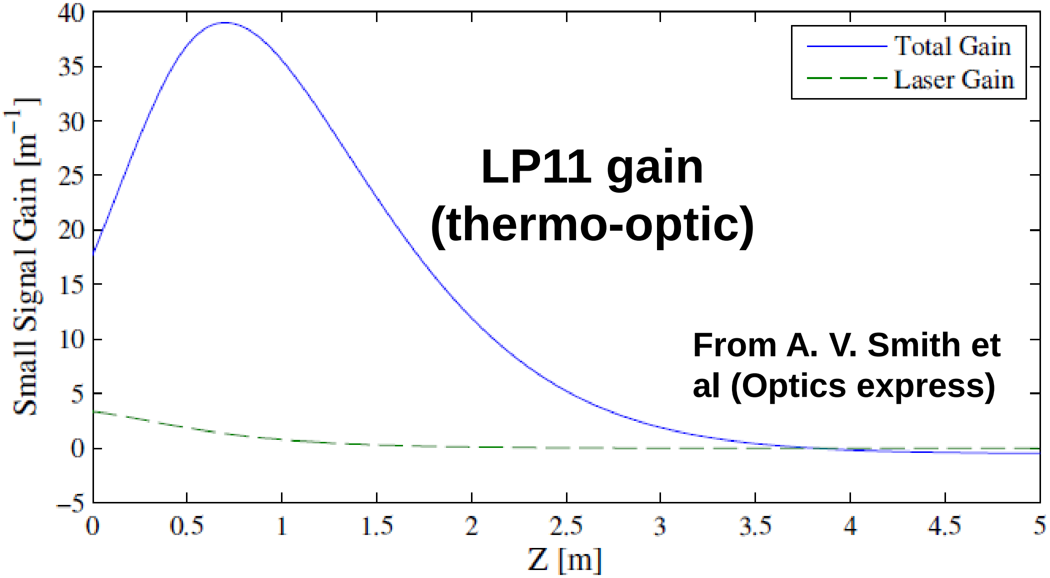


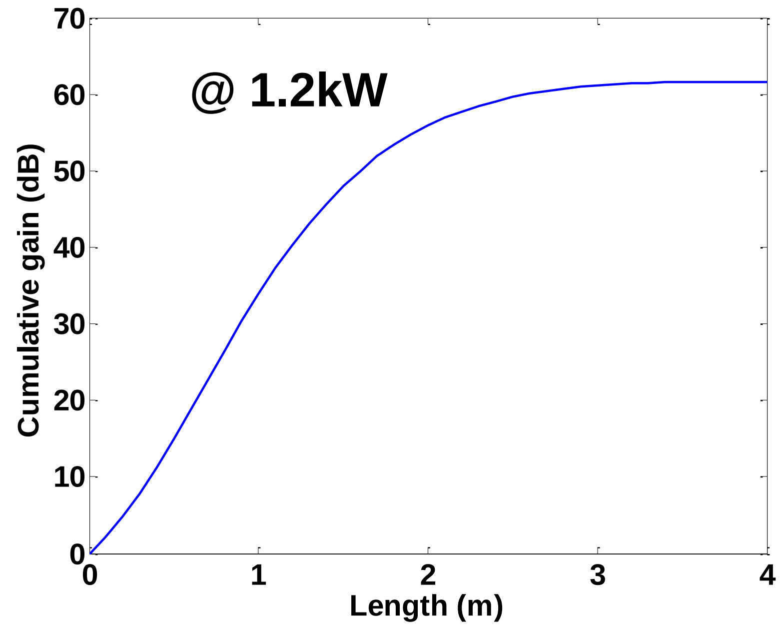
Collection of LP01 and LP11 modes in a fully doped core

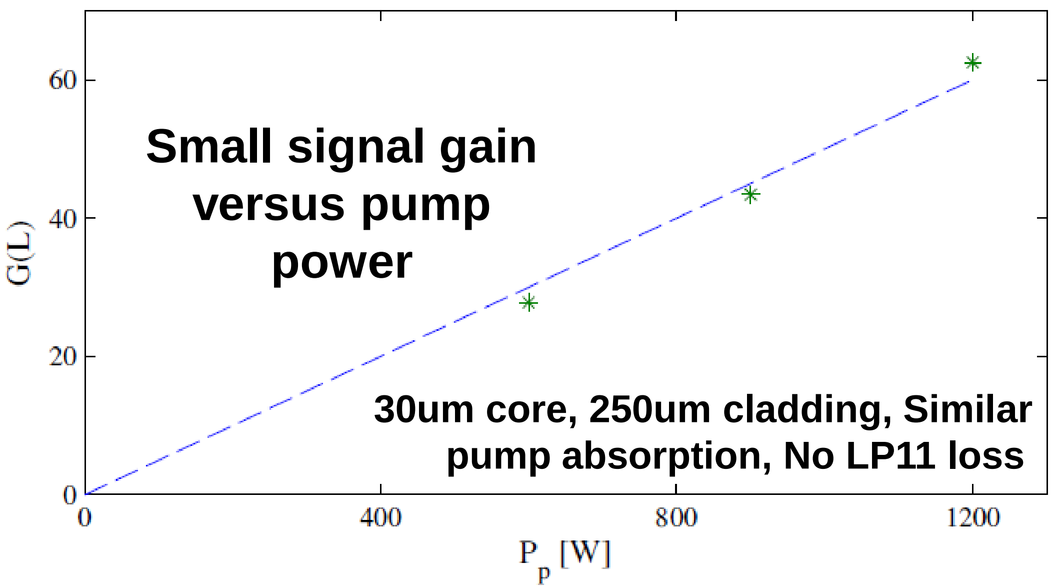


Converts to a thermooptic “long period grating”

Modal Instability





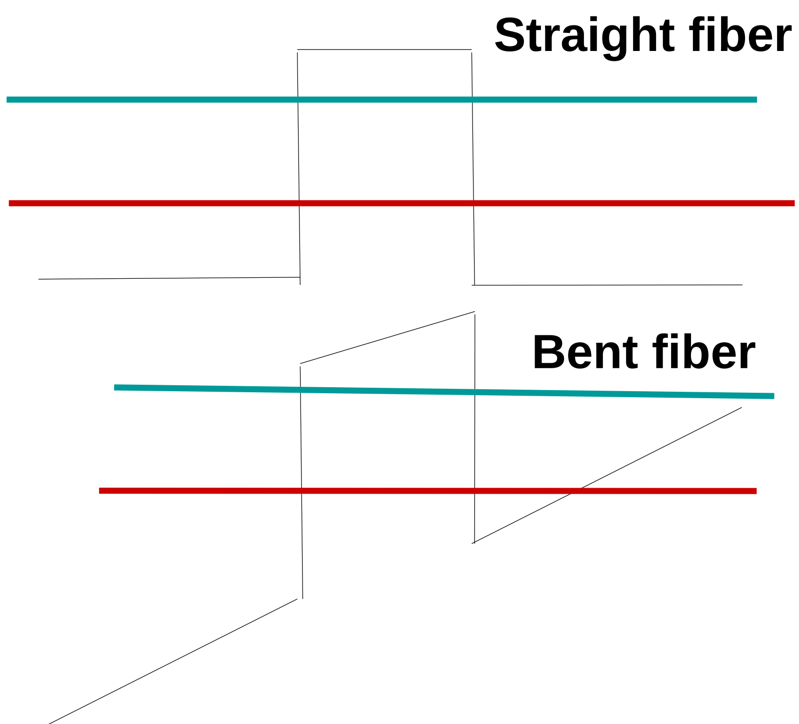


- **Failsafe option to suppress modal instability – Loss for higher order mode > Nonlinear gain**
- **Highly single-moded LMA fibers necessary**

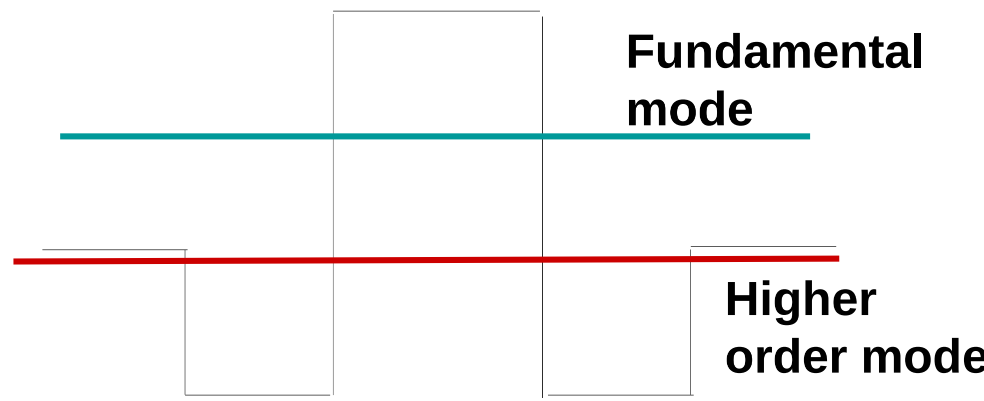
Novel Fiber designs for suppressing Modal Instability

- **Goal:** Achieving large mode field areas while preserving effective single-modedness (only fool proof method to suppress modal instability)

Step-index fiber

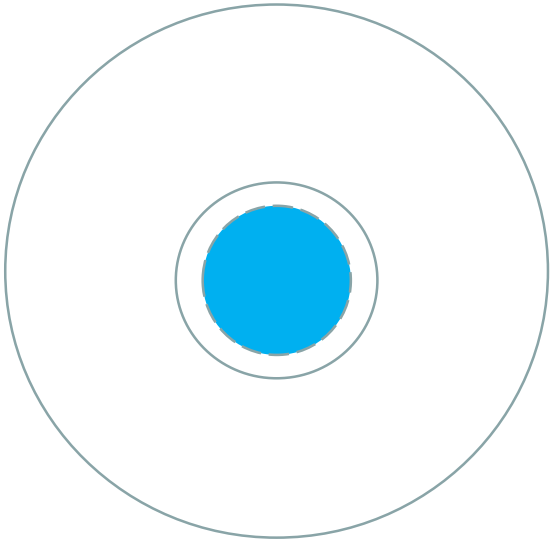


W-Fibers



Novel Fiber designs for suppressing Modal Instability

- **Confined Doping**

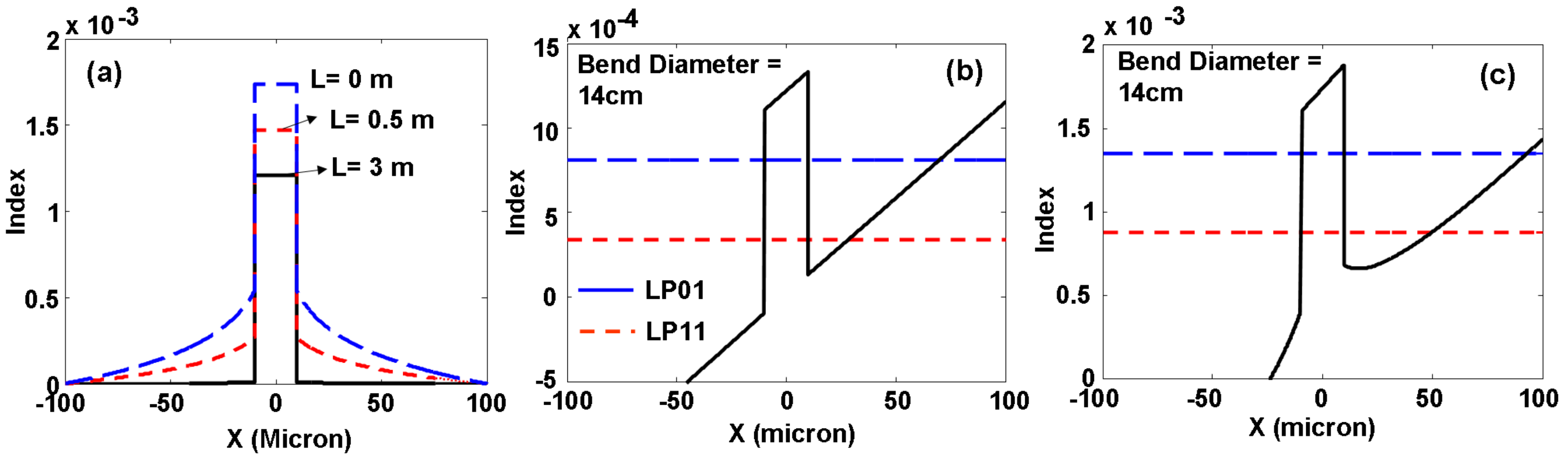


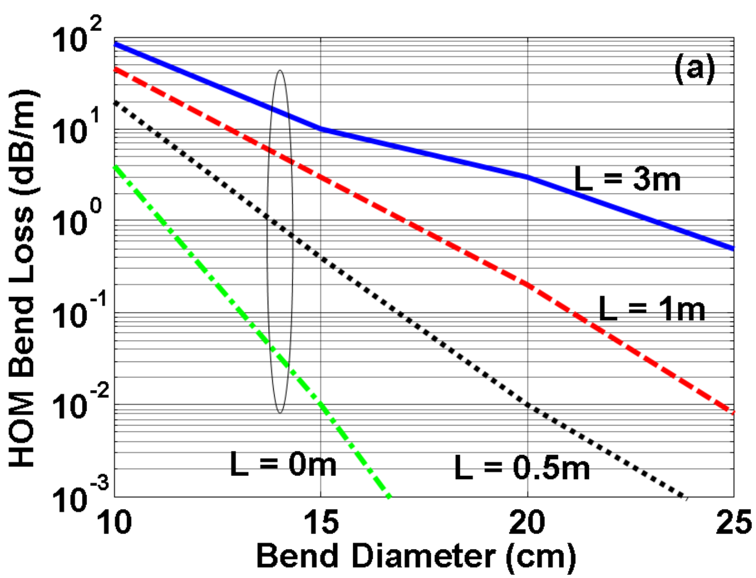
Core index enables large mode area

Confined doping reduces overlap with higher order modes

Thermal Waveguide Degradations

Loss of single modedness in active fibers

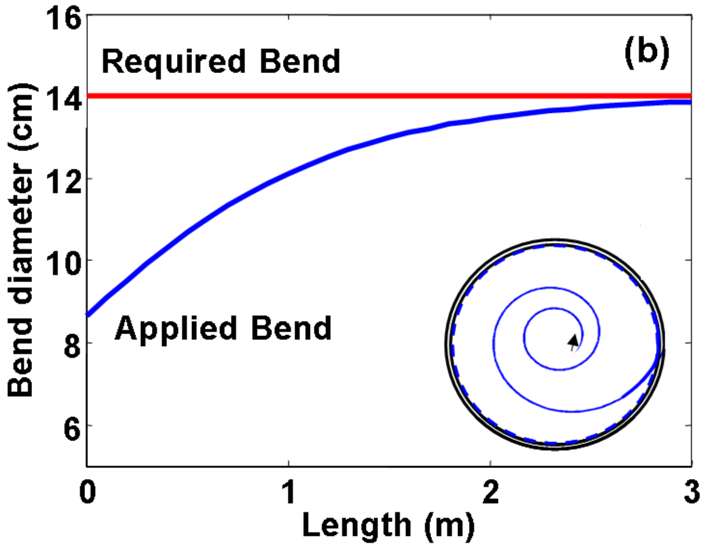


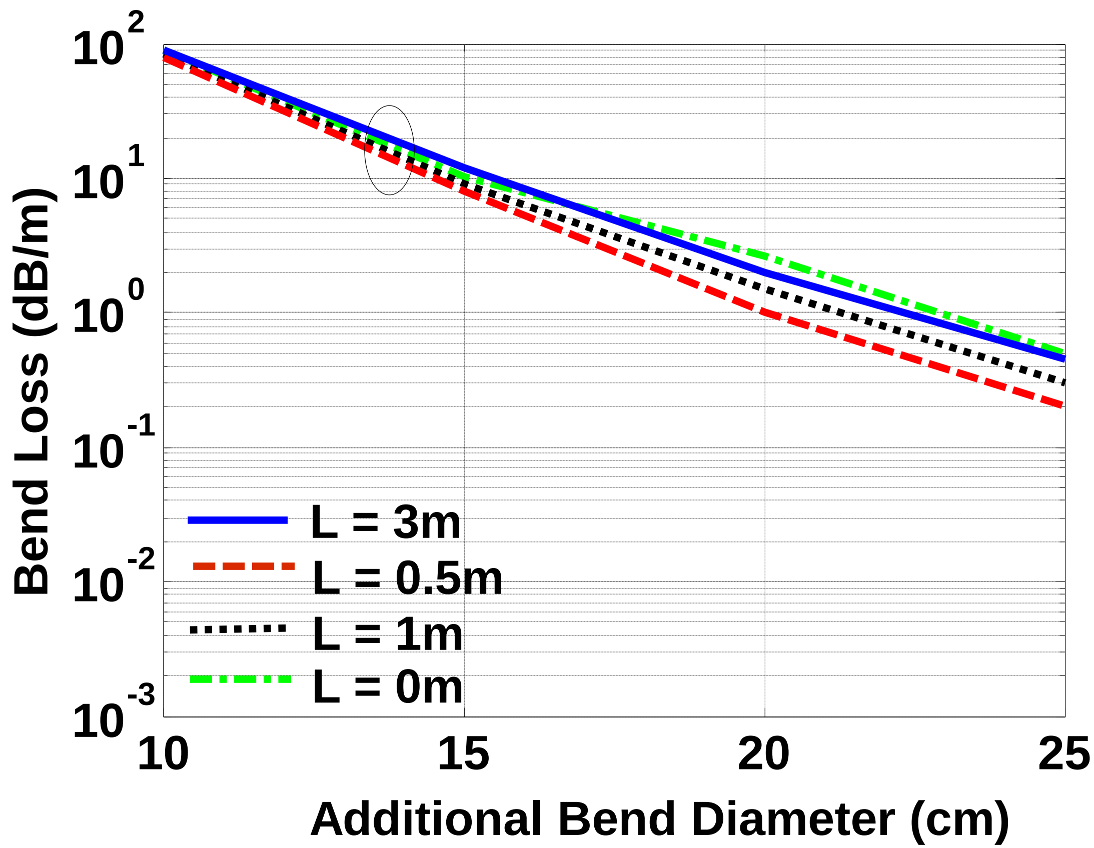


Compensation Mechanisms for thermal waveguide degradations

Goal

- **Simple and elegant methods to overcome thermal waveguide degradations**

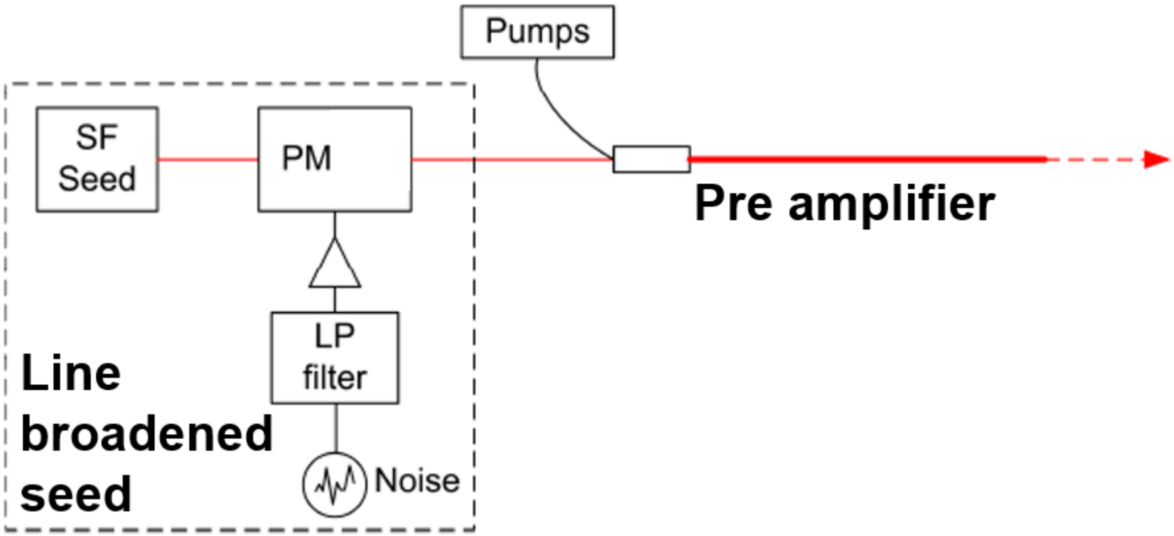




Supradeepa et al, CLEO 2015, Optics Express (Submitted)

Narrow Linewidth Laser Module

Pre-amplifier



- Output power – 20W
- Linewidth - < 1GHz to > 10GHz
- Polarization maintaining design

Isolator availability limits maximum power out of the pre-amplifier

Line Broadening

Necessary Linewidths –

Coherent combining – GHz class linewidths (< 0.04nm) corresponds to path length accuracies of several mm.

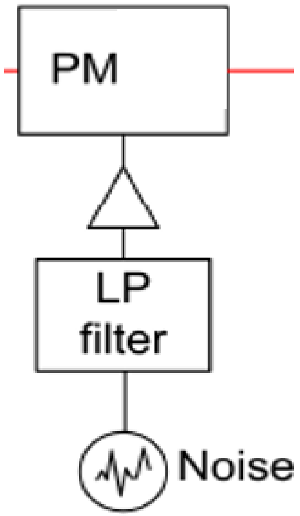
- Achievable in practice.
- Lower linewidths than this – largely unnecessary

Spectral combining – Intrachannel spectral dispersion needs to be low, intra-channel spectral dispersion needs to be high.

- Assuming 50 channels in high Yb gain bandwidth of 25nm, corresponds to channel spacing of 0.5nm. Desired, linewidth less than 10% of that < 0.05nm
- With increasing number of channels, this scales appropriately

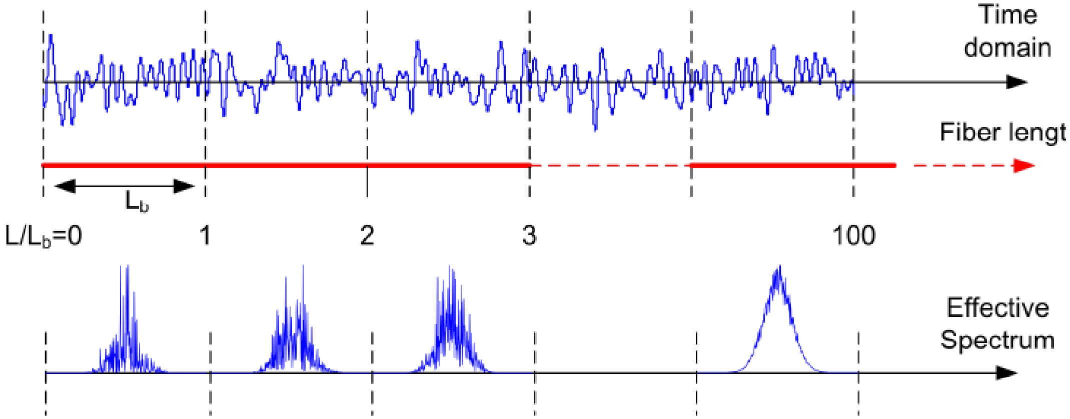
Line Broadening Mechanisms

- Sinusoidal tones –
  - Strongly driving a phase modulator with sinusoids.
  - Results in uneven lines, SBS suppression per spectral width not optimal
- Chirp –
  - Works well for small bandwidths, but not GHz class
- Filtered Noise –
  - Easy to implement, most common
  - Results in length dependent effects

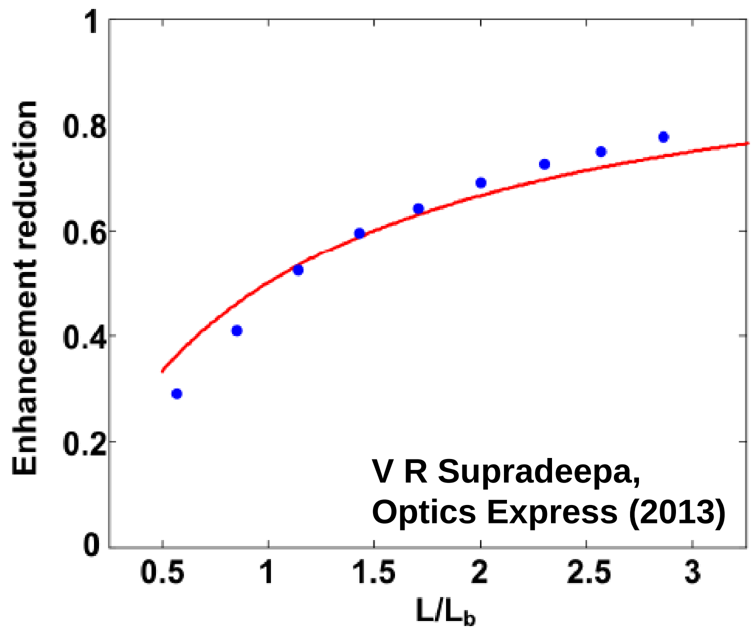


Line Broadening with Noise – Length dependent effects

$$EF = \frac{(L/L_B)}{(L/L_B)+1} EF_{ideal}$$

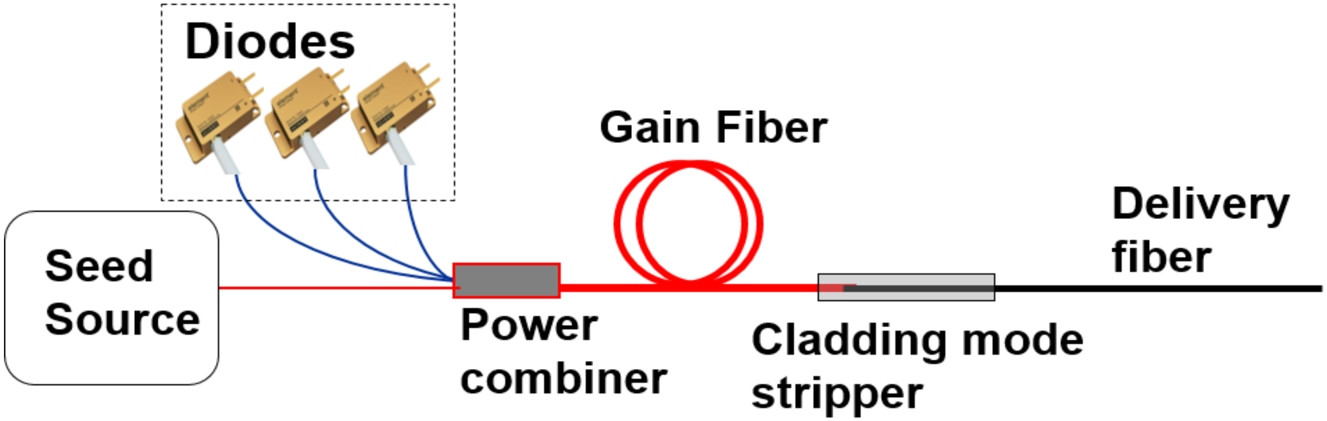


L_b ~ 4m, Length scale originating from Brillouin gain bandwidth



- **Short length effects need to be compensated**
- **Goal - Suppressing SBS in the systems perspective (SBS as a signal processing problem)**

Amplifier architecture

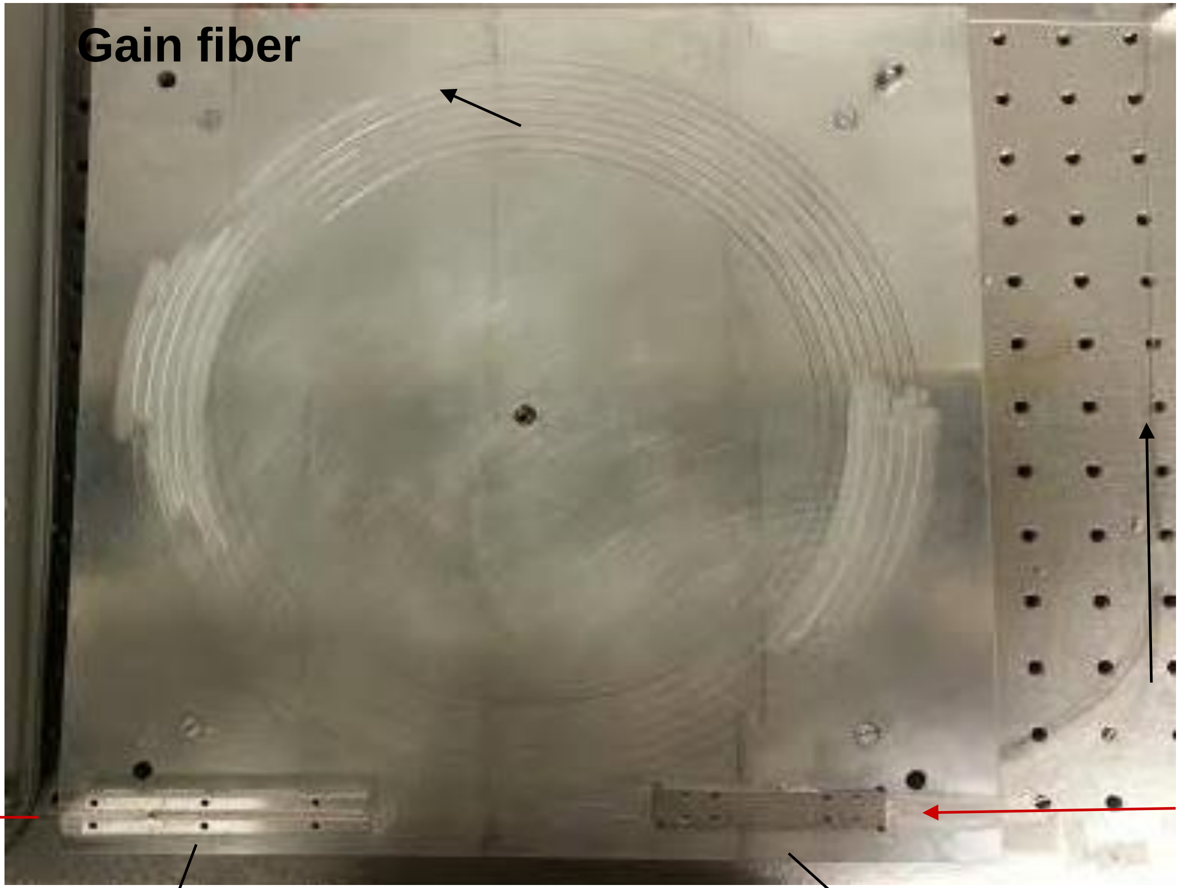


- Fiber – Effectively single-moded with MFD > 15micron

- Delivery fiber need not be the same – can be bigger (needs tapered splice)

- Polarization maintaining – PANDA design

Amplifier Module: Layout



Mode converter +
Cladding mode stripper

TFB

Setup and Characterization (Testbench)