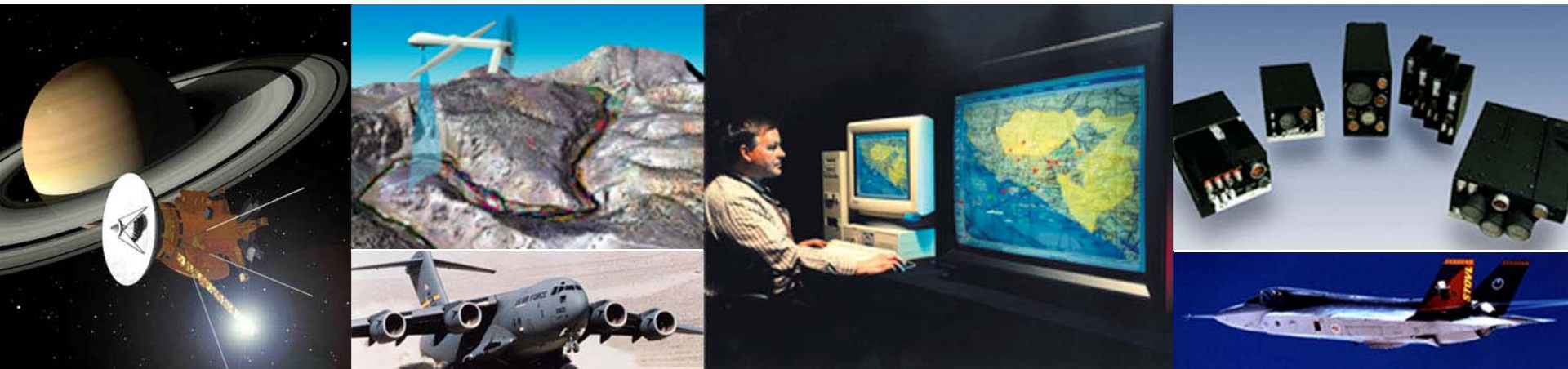


Silica Fiber Lasers and Amplifiers as Pump Sources for Frequency Conversion

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Outline

- Brief Overview of Nonlinear Conversion
 - Nonlinear materials, pump sources
- General fiber overview
- Design constraints and limitations
 - Nonlinear effects in fiber
- Considerations for fiber used in nonlinear conversion
 - Yb, Er, Er:Yb, Tm
 - Advantages and disadvantages
 - Fiber geometries
 - Architectures
- Summary
- General issues
- Moving forward

Mid-IR Generation

- Traditionally, Mid-IR light is frequency shifted from a laser pump
 - Diode-pumped solid-state laser converted in a nonlinear crystal
 - Typically ZGP, PPLN, OPGaAs
- How can we use fiber with Mid-IR light
 - We can use it to transport Mid-IR light over several meters
 - Fluorides and chalcogenides for power distribution
 - Advantages: only fibers which can transport MWIR light with low loss
 - Disadvantages: multimode output spoils beam quality
 - Not necessarily bad for most applications
 - However, we can use traditional fiber as a pump source
 - Take advantage of silica fiber technology
 - Transport the pump to nonlinear converter

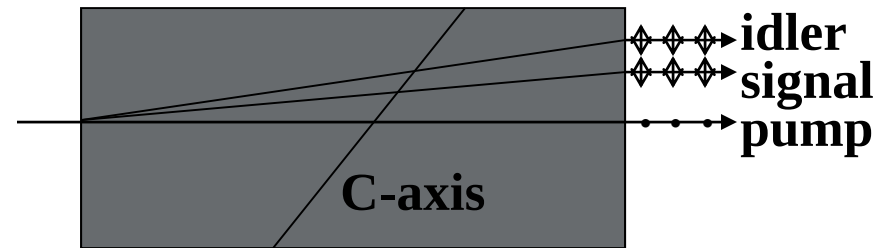
What is Needed For Mid-IR Generation?

- Pump source
 - Bright, single-mode laser
 - Generally need $M^2 < 2$
 - High peak power pulses
 - Generally several kW peak
 - Polarized output
 - For phase matching in nonlinear material
- Nonlinear material
 - Phase-matched to the pump and wavelengths to be generated
 - Conservation of energy and momentum
 - Critically phase-matched vs QPM materials
 - Conversion: methods: OPO, OPG, OPA

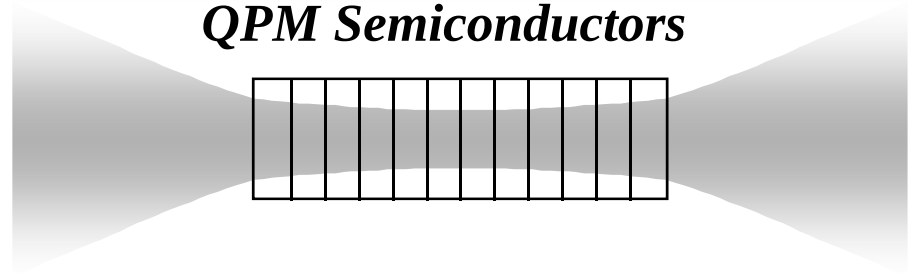
Nonlinear Optical Crystals – What Is Needed

- Higher efficiency and output power in the 2-8 μm spectral range
- Mid-IR crystals compatible with common pump lasers
- Better long-wavelength materials for CO₂ doubling and 8-12 μm generation
- Desirable material properties:
 - High nonlinear coefficient
 - Low absorption loss
 - High laser damage threshold
 - Low thermal lensing
 - Low/no walk-off
 - Non-critical phase matching (NCPM)

Birefringence Crystals

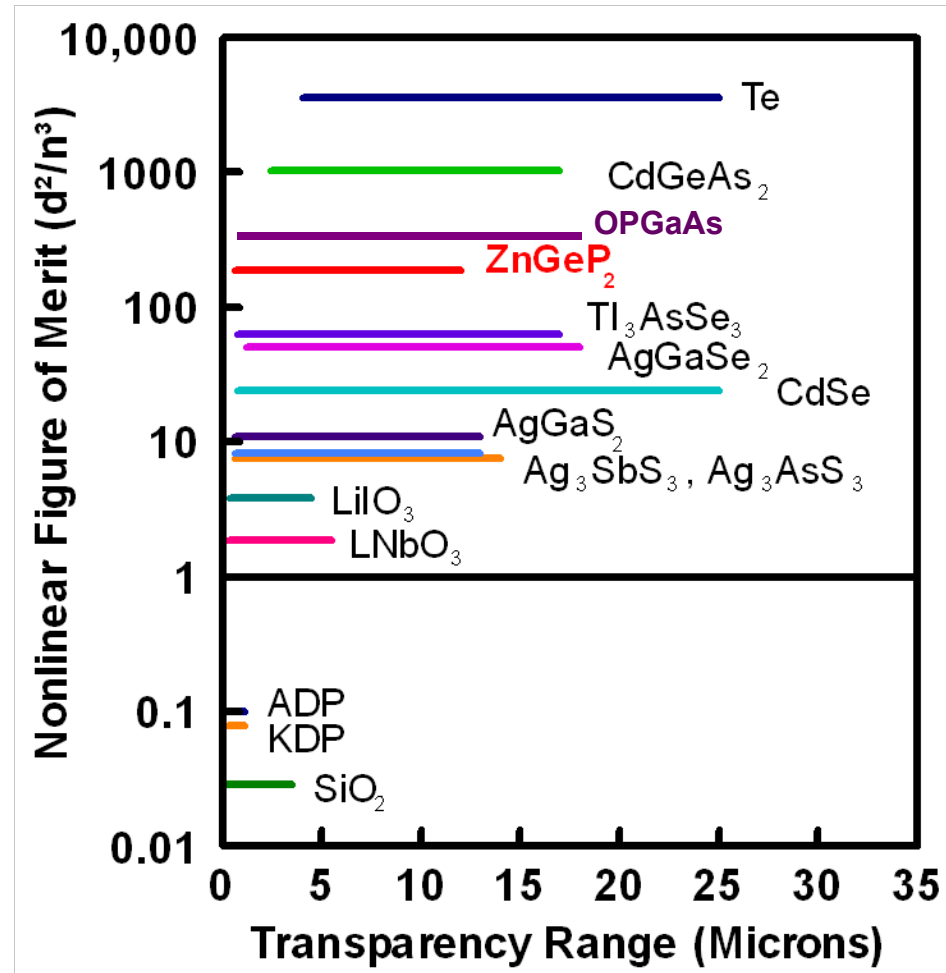


QPM Semiconductors



Common Nonlinear Materials for Mid-IR Conversion

- PPLN
 - Mature material, QPM
 - Limited transparency range in MWIR
- ZGP
 - High nonlinear coefficient
 - Critically phase-matched
- OPGaAs
 - QPM, high nonlinear coefficient
 - Large transparency range
 - Low absorption
 - High thermal conductivity



Solid-state vs. Fiber Pump Lasers

- Solid-state lasers
 - Q-switched
 - Good beam quality – M^2 : 1.2-2.0
 - Lower repetition rates, long pulse widths
 - Trade-off between pulse width and PRF
 - Generally high pulse energy with high peak power
 - Fiber lasers
 - Excellent beam quality – M^2 : 1.0-1.5
 - Efficient, compact
 - Minimal/no free-space optics
 - Variable rep rates and short pulse widths →
 - Low pulse energy with high (or low) peak power
 - Wavelength flexibility
 - Power scalable with beam quality
- Larger pump spots to mitigate NLO crystal damage
- Smaller pump spots for high peak intensities

So Why Bother With Silica Fiber?

- It can efficiently generate high powers and transport pump light
 - Transparent from near-IR (<800nm) up into mid-IR (2100nm)
- Gain length
 - Distribute the gain (lower gain per unit length, longer length)
 - Spread the heat load over long fiber length (surface area for heat removal)
- Frequency agility
 - Glass has a very chaotic structure
 - Broad absorption and emission features compared to crystals
- Efficient pump/signal overlap
 - Let the waveguide do the work
- It is inexpensive (in large quantities)
 - Leverage the telecom investments
 - Splicing, diodes, components, etc.
- The light is entirely confined to the fiber

For High Power Operation

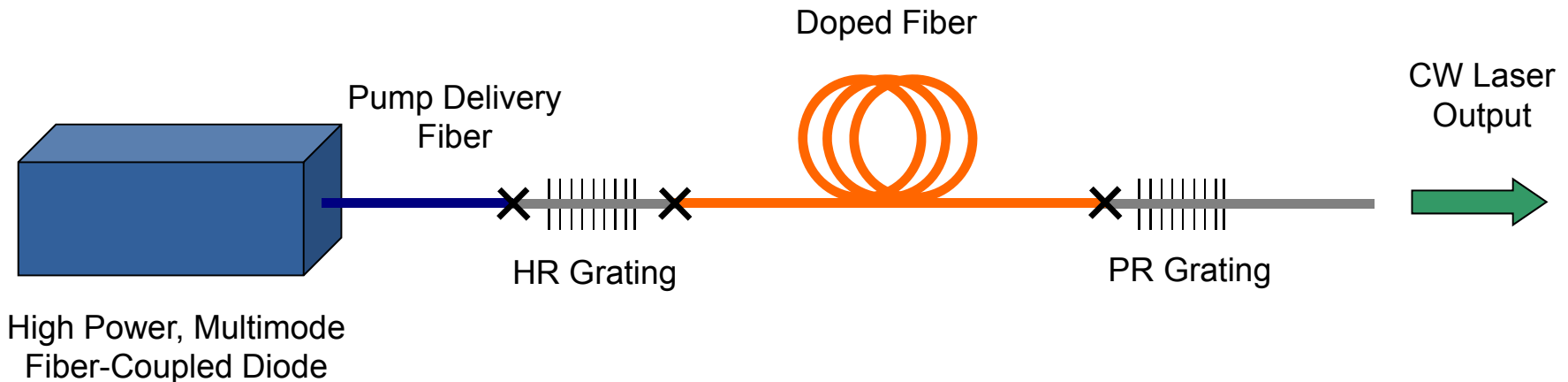
- DPSS crystal-based technologies
 - Thermal lensing in crystal
 - Beam distortions at high powers
 - Need significant waste heat removal
 - This requires a major engineering effort and increases size, weight, power
- Fiber
 - Pump absorption is spread over a few meters rather than a few centimeters
 - Fiber core is close to the heat-sink
 - Only a few hundred microns
 - Architectures can be power scalable without significantly impacting beam quality

Typical Fiber Dopants

- Erbium (Er)
 - Low gain, but eyesafe emission at $1.55\mu\text{m}$ → telecom wavelengths
 - Can pump at 980nm or resonantly at 1470-1532nm
- Ytterbium (Yb)
 - Very high gain, very efficient
 - Emission from 1000-1150nm (typically used from 1035-1080nm)
 - Can pump from 915nm-975nm
- Ytterbium-sensitized erbium (Er:Yb)
 - High power emission at $1.55\mu\text{m}$ → higher gain due to Yb ions
 - Pumped from 915nm-975nm
- Thulium (Tm)
 - 2-micron emission from 1850-2100nm
 - Pumped at 795nm or 1550nm
- Thulium-Holmium (Tm:Ho)

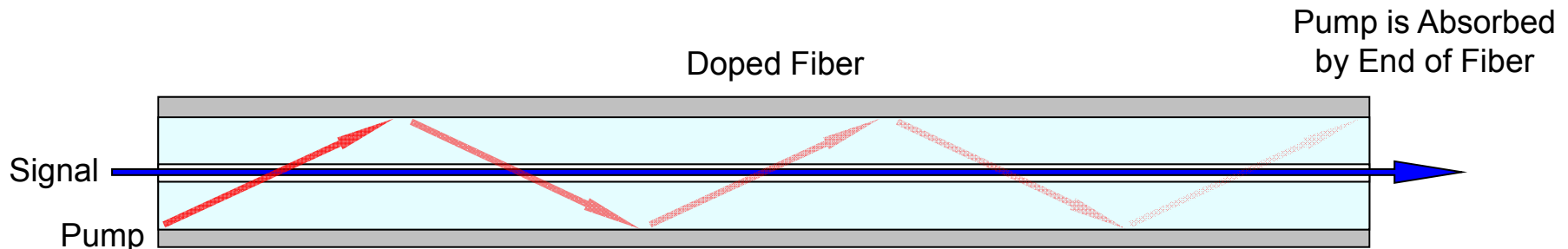
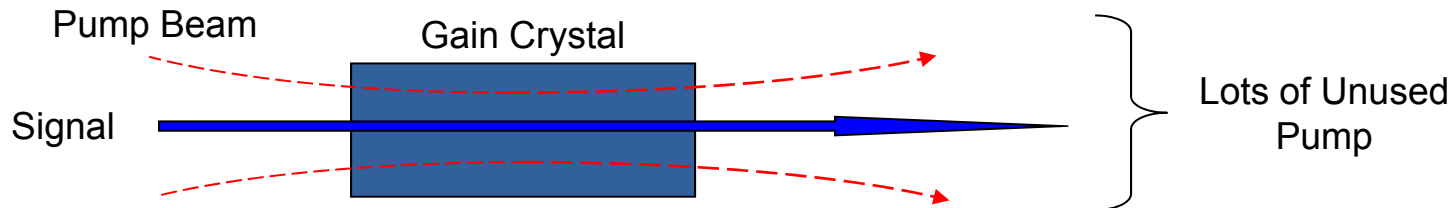
Fiber Lasers

- Just like a solid-state laser, but the fiber is the gain medium
 - Instead of a crystal and mirrors, we have a fiber and gratings
 - Diode pumps the fiber to excite the active ions
 - Gratings provide feedback at a specific wavelength for oscillation
 - Typically CW operation
 - But they can be q-switched or modulated
 - Have very closely spaced modes due to long cavity lengths
 - Typically several meters



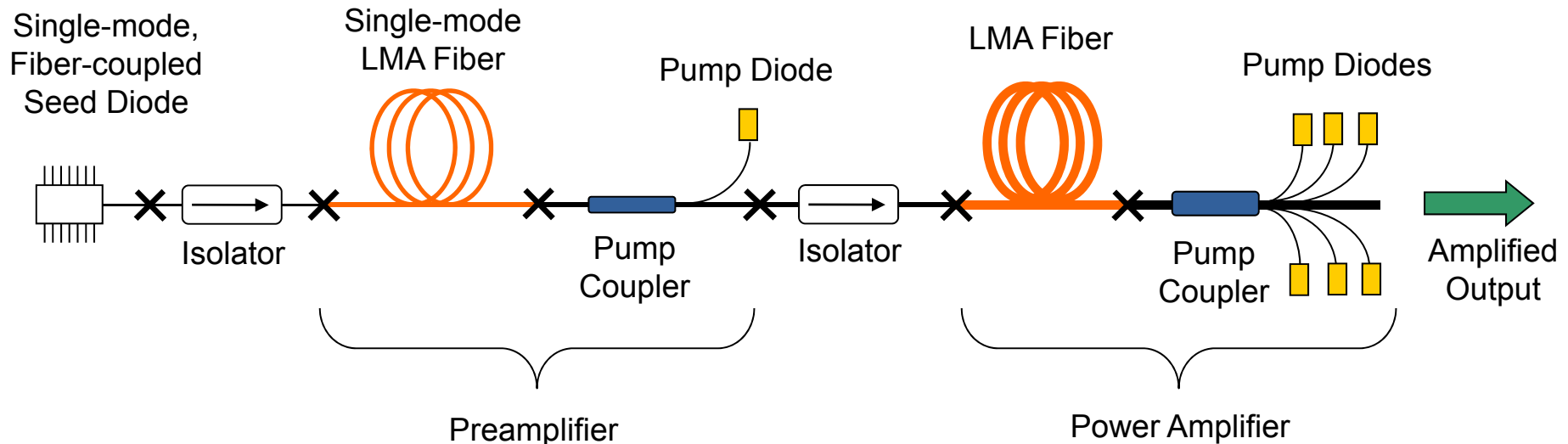
Amplifier Operation

- Just like a solid-state amplifier (all about overlap and saturation)
 - But you don't have to mode-match the signal and the pump
 - The waveguide does this for you
 - Length is determined by the core/clad area overlap
 - And thus, the pump/signal overlap



Fiber Amplifiers

- When seeded, fibers make very efficient amplifiers
 - Offer much more gain than crystal amplifiers
 - Due to length of gain medium
 - Fiber amplifier typically offer gains ranging from 5-20dB
 - The ability to generate pulsed output from a fiber
 - By seeding with a pulsed source (diode, microchip laser)



Performance

- Very high efficiency
 - Due to gain length and core/clad overlap (signal/pump overlap)
 - All of the pump is used (and all the gain is in the core)
- CW operation
 - Yb-doped CW fiber systems have demonstrated >75% optical efficiency
 - Er-doped systems are ~30% efficient (low power)
 - Er:Yb-doped are ~35% efficient (high power)
 - Tm-doped fibers are approaching 60% efficiency
- Pulsed operation
 - High peak-powers are achievable rather efficiently
 - Slightly less efficient than CW, but still much better than DPSS systems
 - Due to low duty cycles
 - Nonlinear effects become a major issue
 - This is where the engineering comes in

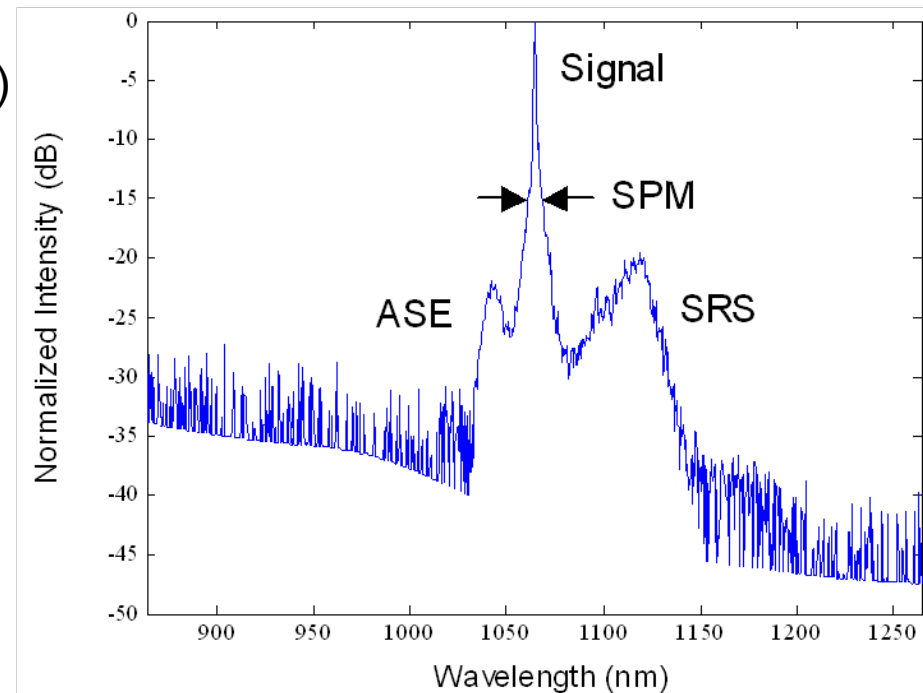
Limitations of Fiber Systems

Energy Scaling

- What are the limits?
 - Fiber core size - high powers do not like to be confined to such a small area
 - 10W average (10kHz, 10ns) in a 30um core = 14GW/cm²
- Self-focusing limit
 - High intensities modulate the nonlinear refractive index in the core
 - This can form a Kerr lens and focus the light until the fiber breaks
 - The limit for silica fiber is ~4.5MW of peak power at 1064nm
 - Does not depend on core size → we have length on our side again
- Surface damage
 - Occurs at the glass-air interface as the light exits the fiber
 - Depends on the surface quality and the pulse width but a good rule of thumb is <4GW/cm²
- Bulk damage
 - Depends on the peak power, pulse width, and core size (~600GW/cm²)
- Nonlinearities in the fiber

Nonlinear Effects

- Fibers have one particular “limitation”
 - Small cores yield very large optical intensities
 - Consequently, the good things about fiber are also bad
 - Small cores and long lengths may induce nonlinear effects
- What are these effects?
 - Stimulated Raman Scattering (SRS)
 - Stimulated Brillouin Scattering (SBS)
 - Single frequencies
 - Self-phase Modulation (SPM)
 - Optical Kerr effect
 - Nonlinear phase shift
 - Four-wave Mixing (FWM)
 - $\chi^{(3)}$ susceptibility
- Solutions?
 - “Short” fiber lengths, large cores
 - Novel fiber geometries



Now for the Math...

$$P_{SRS}^{thr}(\lambda) \approx \frac{16 \cdot A_{eff}}{g_R(\lambda) \cdot L_{eff}}$$

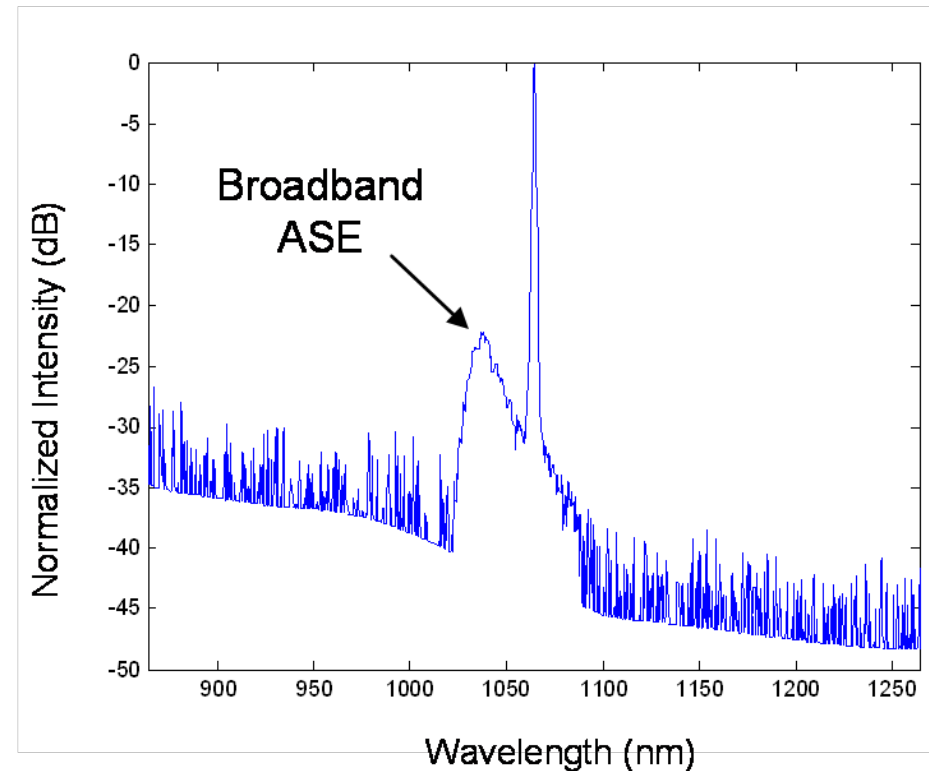
$$P_{SBS}^{thr}(\lambda) \approx \frac{21 \cdot A_{eff}}{g_B(\lambda) \cdot L_{eff}} \cdot \left(1 + \frac{\Delta \nu_s}{\Delta \nu_B(\lambda)} \right)$$

$$\Phi_{SPM} = \frac{2\pi n_2}{\lambda A_{eff}} P L_{eff}$$

- All effects are a function of fiber length, core size, and wavelength
 - Shorter fibers, larger cores increase the nonlinear thresholds
 - The longer the wavelength, the higher the threshold
- Example
 - Pulsed Yb-doped fiber amplifier at 1064nm (10kHz PRF, 10ns pulses)
 - Core diameter = 15um; fiber length = 5m; $g_R = 1 \times 10^{-13} \text{ m/W}$
 - $P_{SRS} = 6.5 \text{ kW} \rightarrow$ average power of 650mW is above the SRS threshold

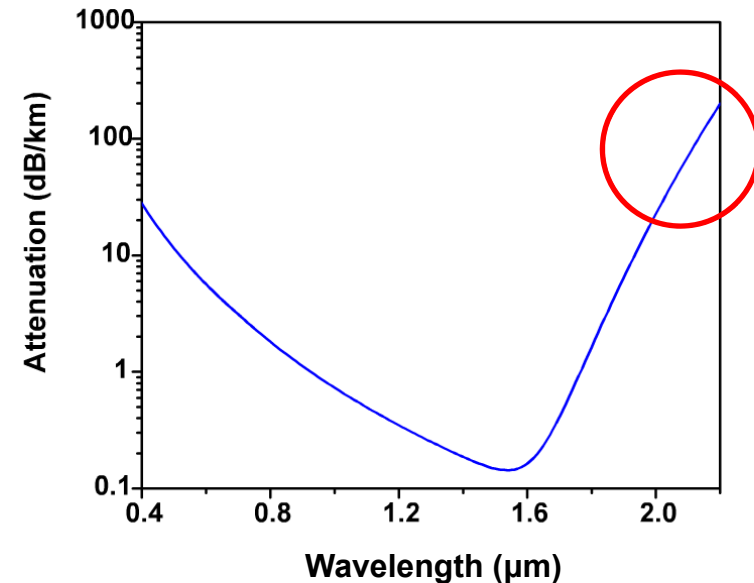
Amplified Spontaneous Emission (ASE)

- The excited ions have to go somewhere
 - If not extracted, the excited electrons decay and spontaneously emit
 - Unfortunately, there is gain at the emission wavelengths
 - So the spontaneous photons see gain and get amplified
 - This reduces the amount of gain seen by the signal, thus reducing efficiency
- Solution
 - Filter the out-of-band ASE
 - Saturate the gain so the signal extracts most of the pump



Background Losses in Silica

- Fibers have lowest loss in 1.55 μm window (telecom)
- Relatively low loss in 1.0 μm region
- Above 1.6 μm , losses are getting higher
- Above 2.1 μm , background loss is becoming significant ($>0.1\text{dB/m}$)
 - For lasing, this means higher threshold for lasers
 - Shorter fiber lengths would be required for efficient operation
 - Higher propagation losses in passive fiber
 - Limits propagation distances
 - 10m transport = 20% power loss



G. Frith, et al., Photonics
West (2008)

So What are Silica Fibers Systems Good For?

- High average power, low pulse energy output
 - With diffraction-limited performance
 - Higher repetition rates (<50kHz to >1MHz)
 - High efficiency → far better than DPSS lasers
 - Peak power output depends on pulse width and PRF
- Fibers make the perfect pump source for frequency conversion
 - Excellent beam quality
 - Determined by the fiber geometry
 - Wavelength agility (not offered in crystal systems)
 - Yb fiber offers more than 100nm of gain
 - Tm offers more than 200nm
 - Pulse flexibility
 - Pulse width and PRF variability
- Manufacturability
 - You can splice these fibers together and eliminate free-space transitions

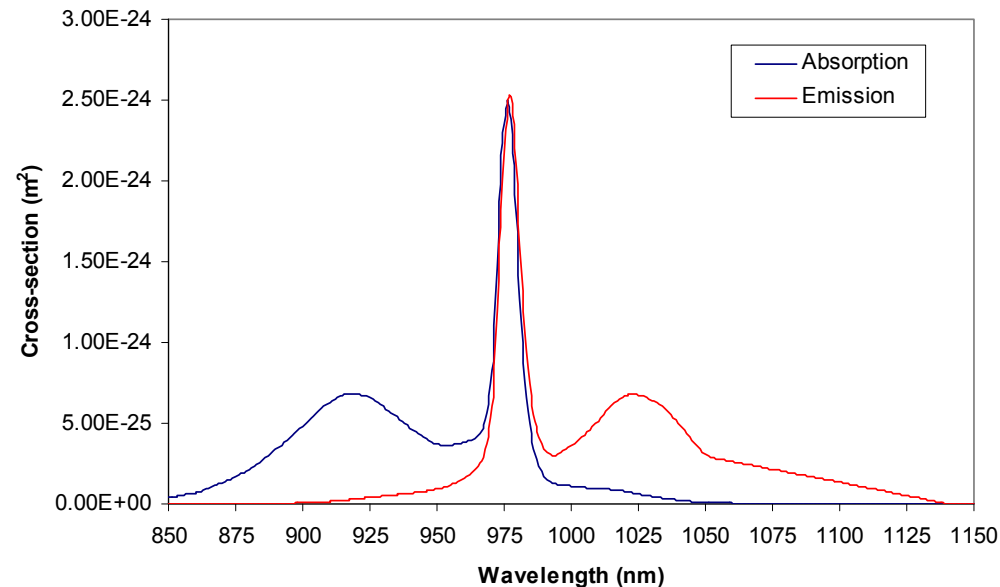
Considerations for Nonlinear Conversion

What are Needed from Fibers for Conversion

- Need to match the pump laser with nonlinear material
 - Gain region in fiber with the nonlinear material
 - Yb with PPLN
 - Er:Yb with PPLN
 - Tm with ZGP, OPGaAs
- Need energy and peak power for conversion
 - Nonlinear materials only care about peak intensity/energy
 - These are not energy storage devices
 - Conversion only occurs on a pulse-to-pulse basis
 - This translates to either high peak power or high intensities
 - By focusing tightly into nonlinear material

Ytterbium-Doped Fiber Systems

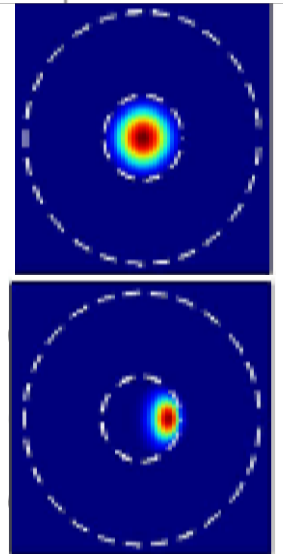
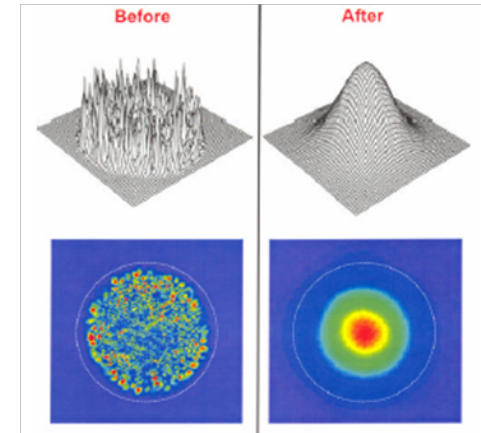
- Advantages:
 - High efficiencies (>70%)
 - Low quantum defect
 - Pumping from 915-976nm
 - Lasing from 1040-1080nm
 - Common wavelengths
- Primary Nonlinearities:
 - SRS, SBS, SPM, FWM
- Challenges:
 - Peak power scaling due to nonlinear effects
- How to get high peak power:
 - Large fiber cores, short fiber lengths
 - Novel fiber geometries



Ytterbium Fiber Geometries

- Large Mode Area (LMA)
 - Large core (15-30 μm) with low NA (0.06-0.1)
 - Up to 80 μm has been reported (U. Michigan)
 - Advantages:
 - Coiling promotes single-moded operation
 - HOMs get coupled into cladding
 - Conventional splicing technology can be used
 - Disadvantages:
 - Coiling can artificially reduce mode size in the core
 - Larger cores can support higher order modes
 - Even with coiling
 - Cannot scale to very large cores due to limited NA range
 - Difficult to reduce NA below 0.06
 - Splicing is difficult for cores above 25 μm diameters

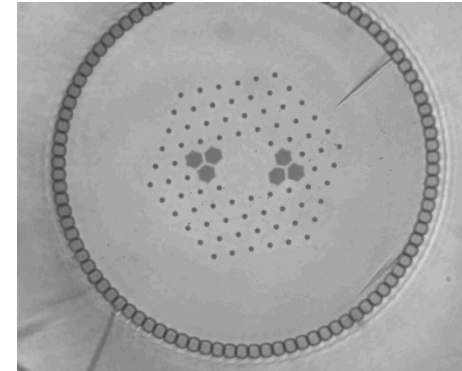
D. Kliner, et al., SPIE OE Magazine (2004)



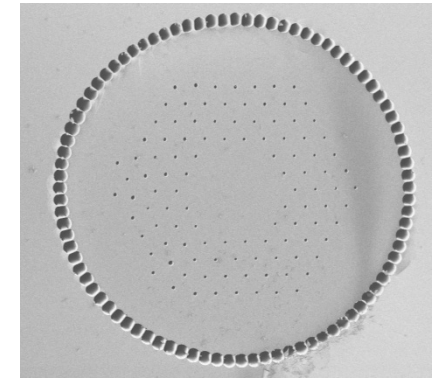
J.M. Fini, Opt. Exp. 14, 69 (2006)

Ytterbium Fiber Geometries

- Photonic Crystal Fiber (PCF)
 - Very large core ($>40\mu\text{m}$) with low NA (<0.03)
 - Air holes tailor the NA
 - Advantages:
 - “Endlessly” single-mode operation
 - Significantly larger core diameters than LMA fibers
 - Promotes power scaling with higher nonlinear thresholds
 - Disadvantages:
 - Coiling limitations
 - Low NA promotes significant bend-losses
 - For fundamental mode
 - Requires $>25\text{cm}$ bend radii
 - Air holes are present around the core
 - Cannot splice without collapsing air holes
 - Need free-space transition



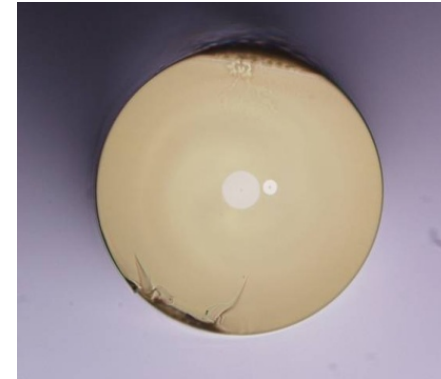
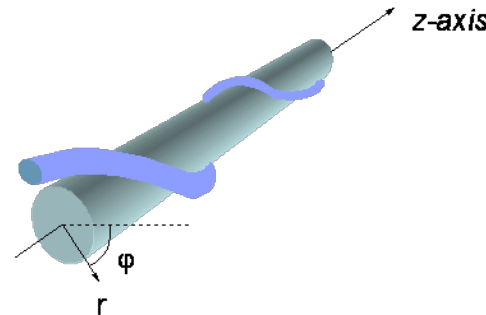
F. Di Teodoro and C. D. Brooks,
ASSP (2006)



J. Limpert, et al., Opt. Express 14,
(2006)

Ytterbium Fiber Geometries

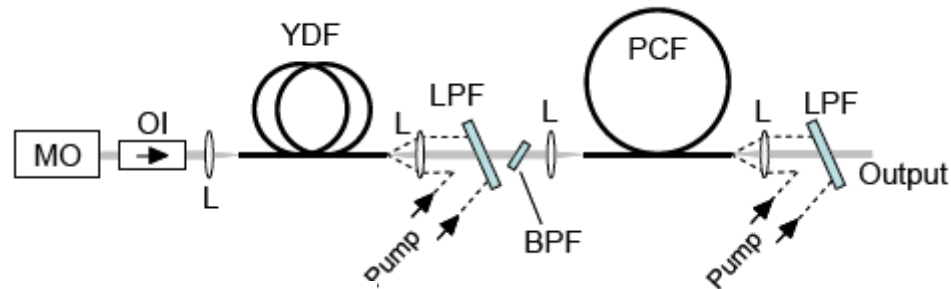
- Chirally-Coupled Core (CCC)
 - Large core with low-moderate NA
 - Helical coupled core
 - HOM suppression
- Advantages:
 - Higher order modes see loss due to CCC
 - Significantly larger core diameters are achievable than LMA fibers
 - Promotes power scaling with higher nonlinear thresholds
 - Can use with conventional splicing technology
- Disadvantages:
 - Relatively new technology
 - Need to develop components with matching passive fibers
 - Bend radii can be large (15cm for 35um core)
 - To avoid distortion in the fiber core
 - Results in larger packages



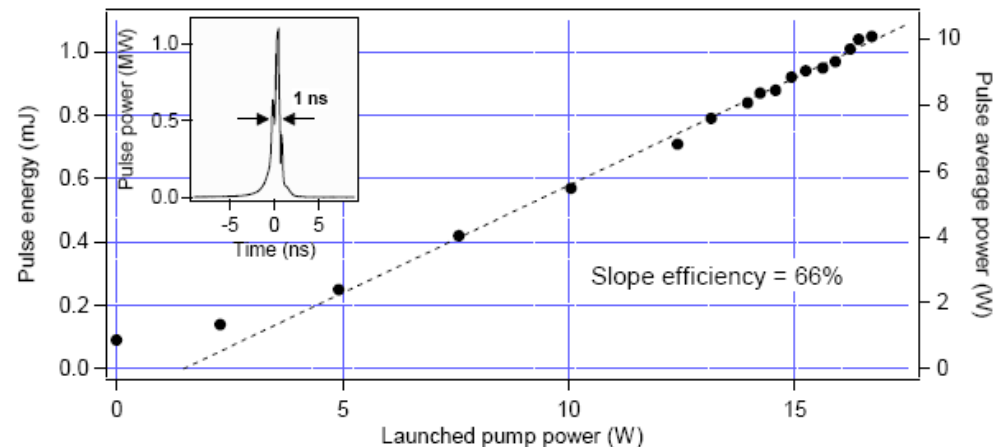
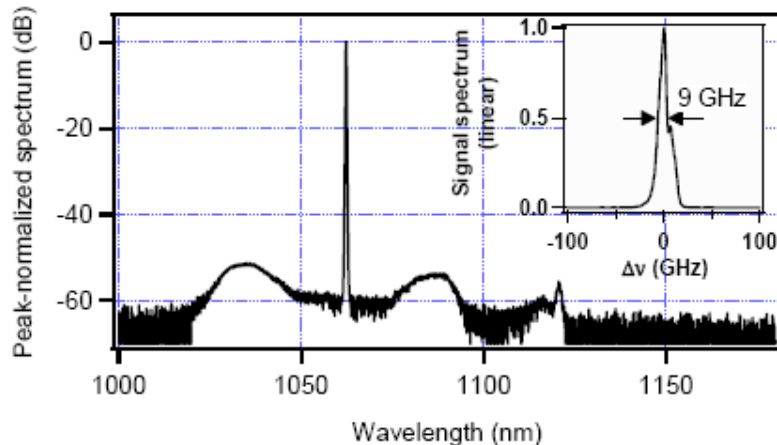
C. Liu et al., ASSP (2007)

High Peak Power YDFA

- MOPA architecture
 - Seeded by a microchip laser
- 10W average power, 9.6kHz PRF, 1ns PW
 - 1mJ pulse energy, 1MW peak power

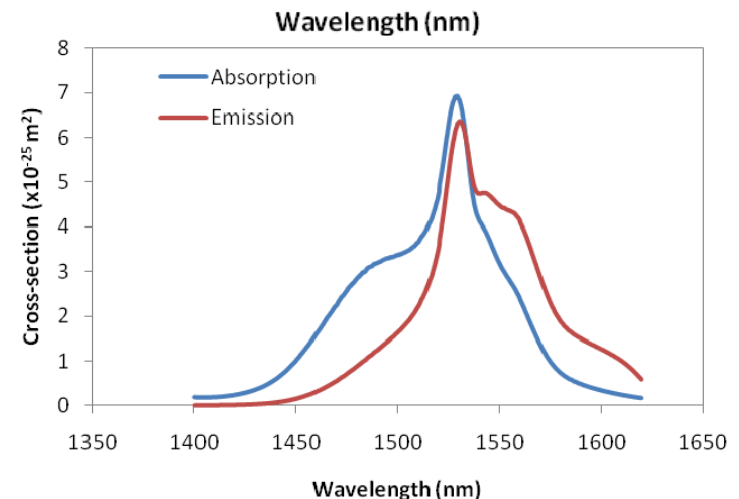
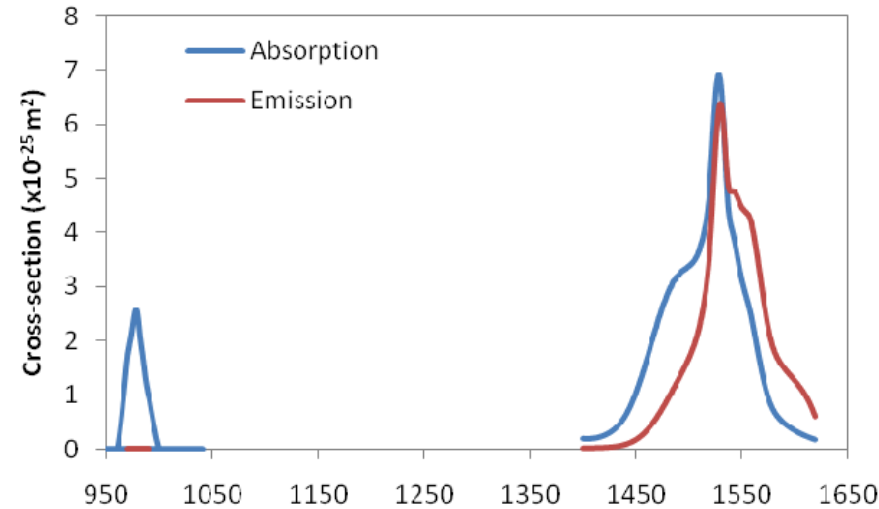


F. Di Teodoro and C. D. Brooks., ASSP (2006)



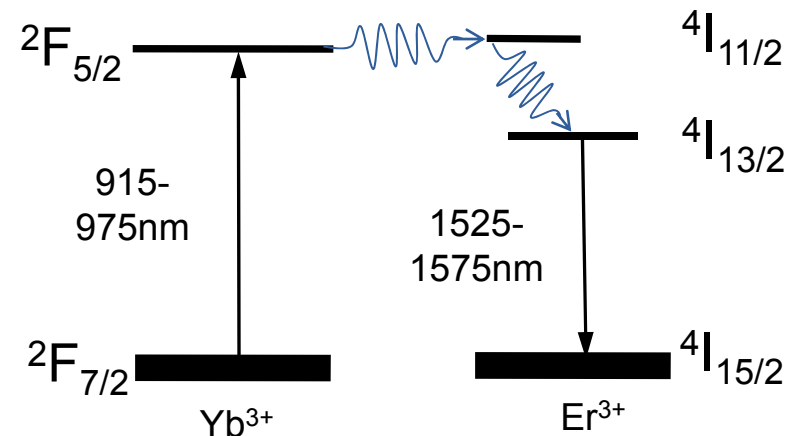
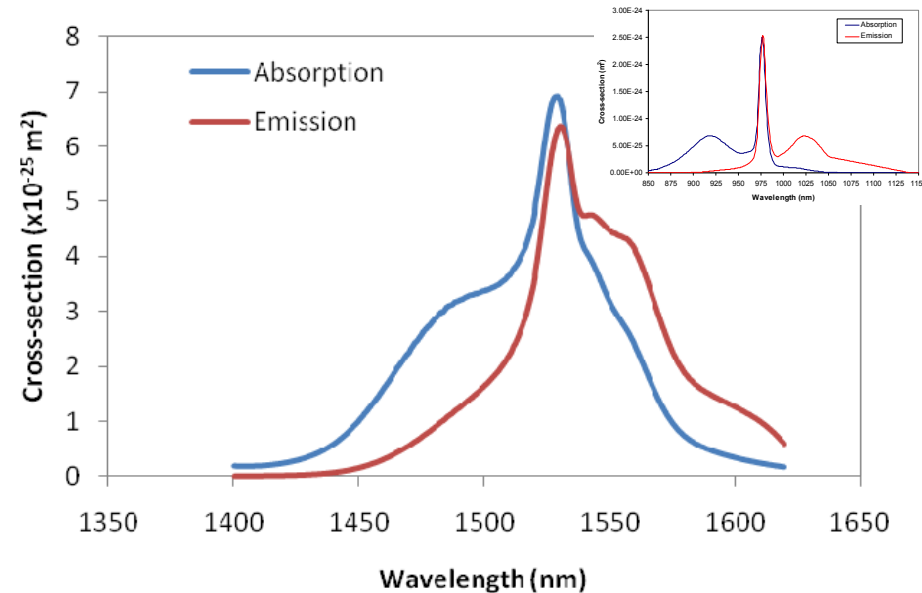
Erbium Fiber Systems

- Advantages:
 - Eyesafe output in the 1.55 μ m region
 - Lasing from 1525-1575nm
 - Leverage telecom technologies
- Primary issues:
 - Low gain
 - Doping is limited due to quenching
- Challenges:
 - Absorption is low at 980nm
 - Requiring long fiber lengths
 - Diode brightness limitations
 - Resonant pumping at 1470nm adds promise to Er-only fibers
 - But diodes are inefficient and not bright enough for high power



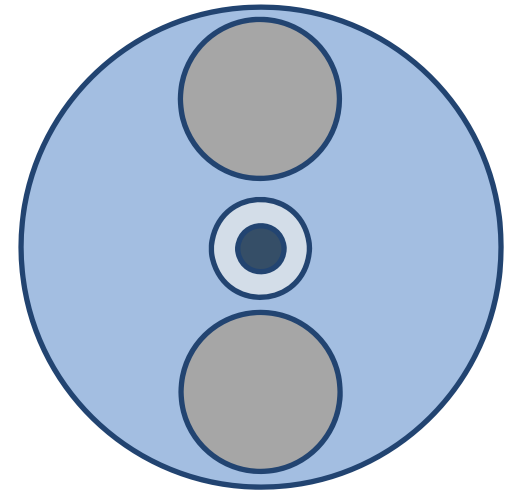
Erbium-Ytterbium Fiber Systems

- Advantages:
 - Eyesafe output in the 1.55 μ m region
 - Lasing from 1525-1575nm
 - Pump with diodes used in Yb
 - 915-975nm
- Primary issues:
 - Energy transfer from Yb to Er
 - 1-micron ASE and parasitic lasing
- Challenges:
 - Power scaling
 - NA limitations
 - Yb lasing



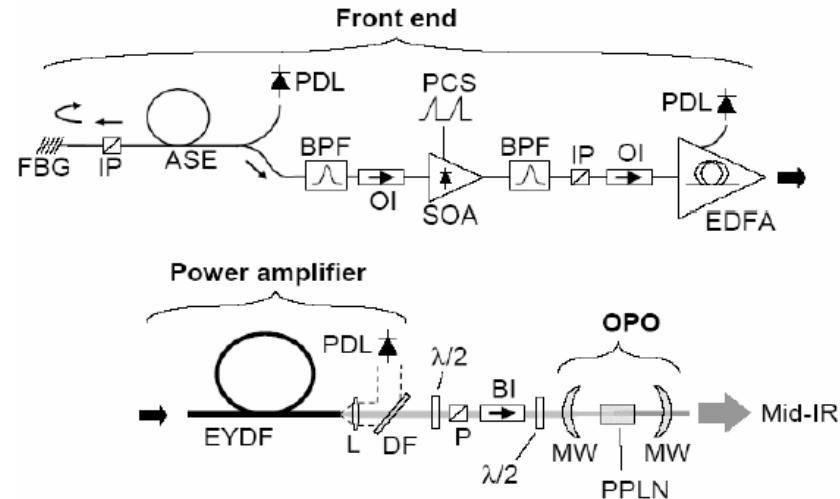
Erbium-Ytterbium Fiber Geometries

- Pedestal Fiber
 - Co-doping increases index in the fiber core
 - A “pedestal” surrounding the core can reduce the NA in the core
 - Advantages:
 - Lower NA core compared to non-pedestal LMA designs
 - NAs of 0.1 have been achieved
 - Disadvantages:
 - Additional glass material in the fiber
 - Fusion splicing issues
 - NA cannot be reduced indefinitely
 - Limits power scaling with SM operation

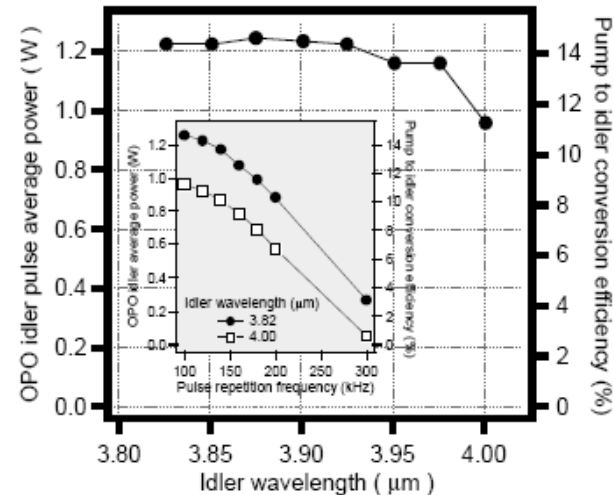
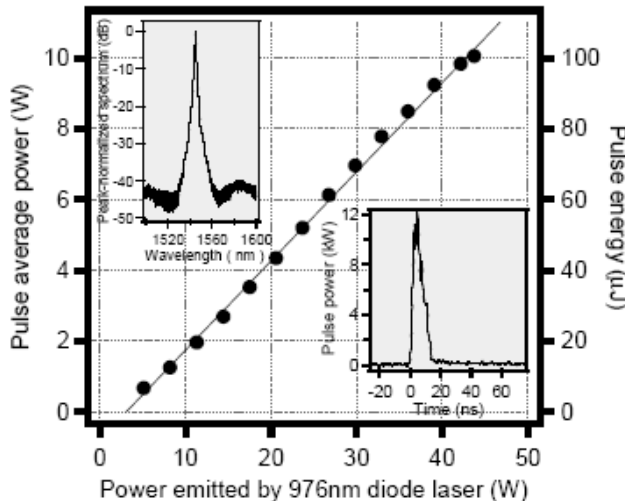


Pulsed Er:Yb Fiber Amplifier

- Pulsed MOPA
 - Generating 10W average output power
 - ~8ns pulses at 1545nm
- Converting to MWIR in PPLN
 - 10mm long crystal
 - 1.2W average MWIR power

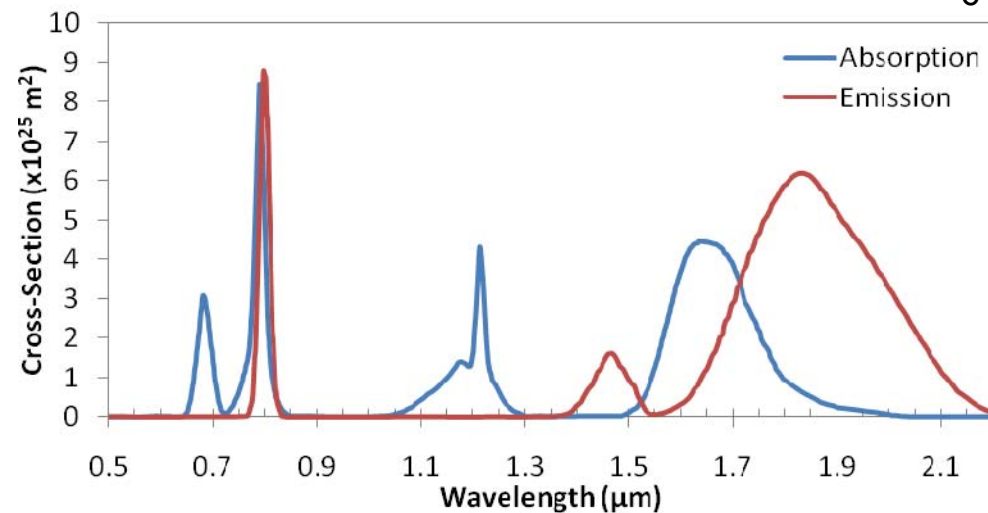
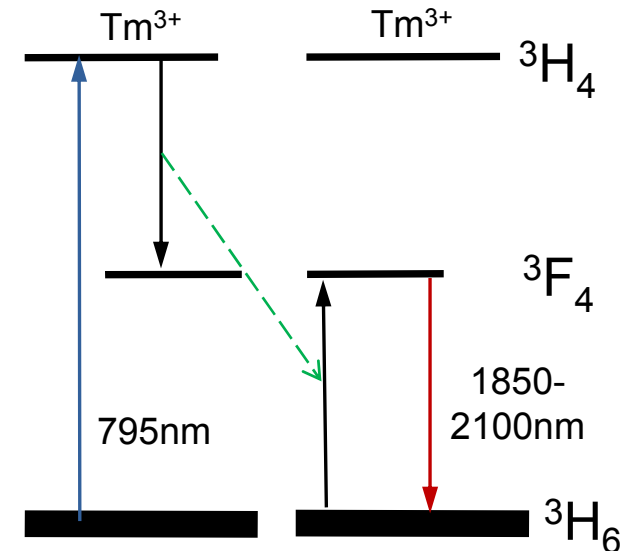


F. Di Teodoro and S. Desmoulin, CLEO (2007)



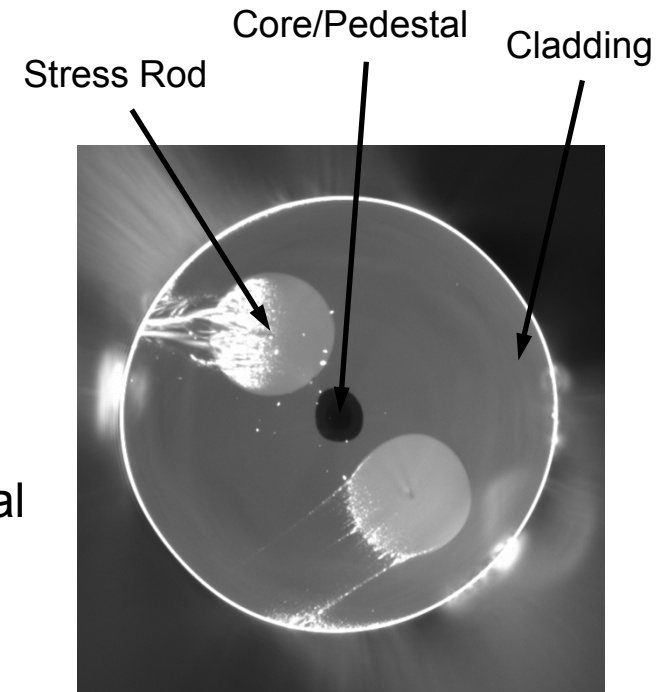
Thulium Fiber Systems

- Advantages:
 - High efficiencies
 - Due to 2-for-1 cross-relaxation
 - Pumping at ~795nm
 - Direct eyesafe output in the 2-micron region
 - 1850-2100nm
- Primary nonlinearities
 - FWM, SPM
- Challenges:
 - Power scaling
 - Due to NA limitations
 - Aluminum doping

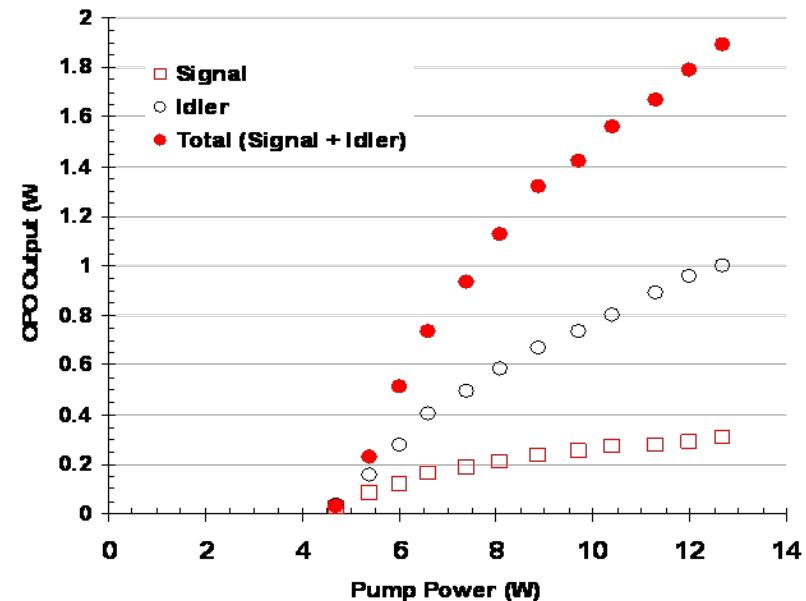
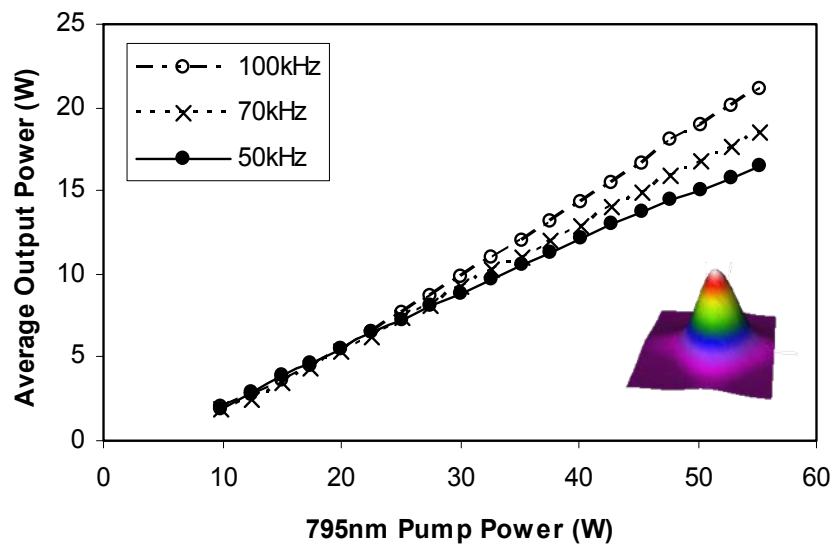
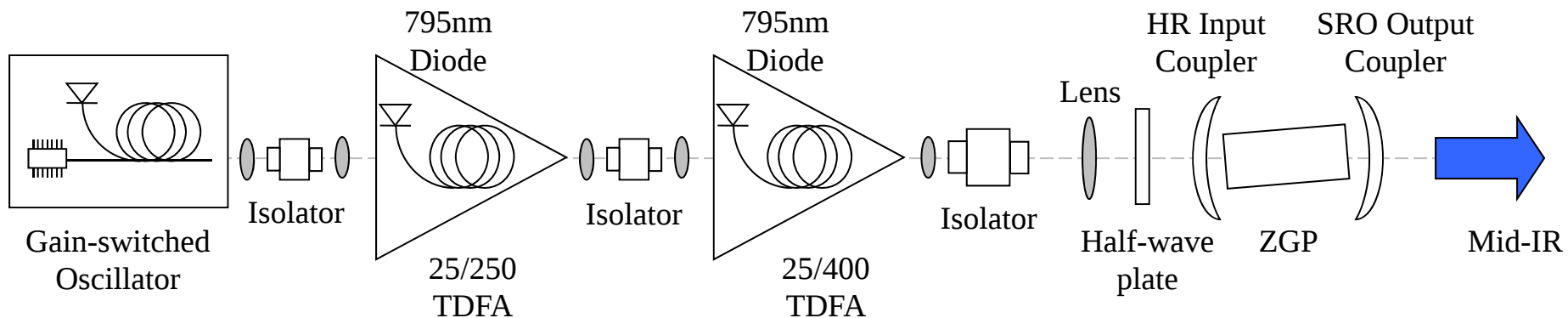


Thulium Fiber Geometries

- Tm fiber geometries
 - LMA-pedestal
- To get high efficiencies in thulium
 - Must get ions to cluster
 - Dope core with aluminum ions
 - Causes index/NA to increase
 - Surrounding the core with an undoped pedestal
 - Drops the NA of the core
 - With respect to pedestal
- Disadvantages:
 - Additional glass material in the fiber
 - Fusion splicing issues (4 glasses in a PM fiber)
 - NA cannot be reduced indefinitely
 - Limits power scaling with SM operation



TDFA Pumped Mid-IR ZGP OPO

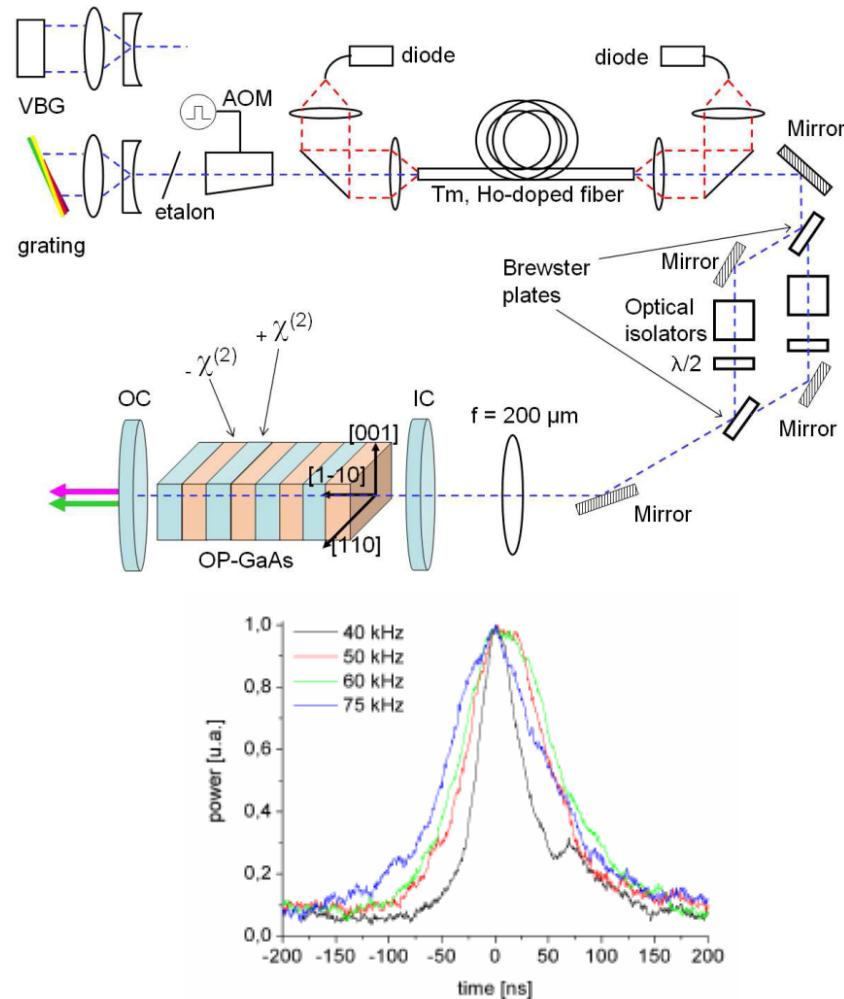
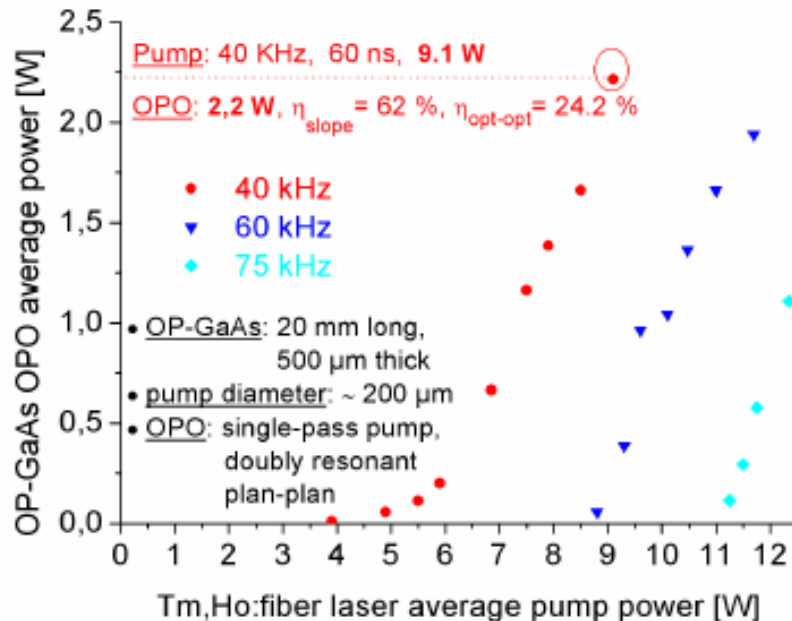


D. Creeden, et al., SPIE Defense and Security (2008)

D. Creeden, et al., Opt. Lett. **33**, 315-317 (2008)

TDFL Pumped Mid-IR OPGaAs OPO

- Q-switched Tm:Ho fiber laser
 - Grating used to narrow output spectrum
- Pumping OPGaAs for MWIR generation
 - 2.2W mid-IR output power



C. Kieleck, M. Eichhorn, et al., CLEO (2009)

Summary

- Must tailor the fiber pump to the nonlinear material
 - Nonlinear material will drive fiber dopant selection
- Must design fiber system around nonlinear effects
 - For nonlinear conversion, we must generate peak power
 - Without running into nonlinear effects in the fiber
 - Need novel fiber geometries or clever architectures
 - To achieve high enough peak powers to convert
- We are currently at the limit of conventional technology
 - Limited by components, doped fiber, free-space coupling
 - Ideally, we need all-fiber solutions

General Issues

- Nonlinear effects
 - Need to trade-off nonlinear thresholds in the fiber with the peak-power requirements of the frequency converter
- Brightness of pump sources
 - To keep gain lengths relatively short you need a high core/clad ratio
 - Either means large core or small cladding
- Beam quality from LMA fibers
 - LMA fibers cannot scale indefinitely
 - Eventually higher order modes will prevail
 - This leads to other fiber geometries (CCC, PCF)
 - But we need components and architectures which mate with these new fibers

General Issues

- Components
 - Passive fibers to match active fibers
 - Isolators, taps, pump combiners, diodes, etc.
- Fiber geometries
 - LMA fibers have scaling issues
 - The larger the core, the lower the NA
 - Limits coiling, mode can get distorted by coiling (reducing mode area)
 - Pedestal designs are difficult to splice to
 - 3-4 different glass compositions in a single fiber
 - Each with a slightly different melting point
- More research into other dopants
 - Ytterbium is very common, but is the farthest away from the mid-IR
 - Thulium and holmium are promising for mid-IR generation
 - Offering high efficiency with wavelength advantages

Path Forward

- More emphasis needs to be placed on component and fiber development
 - Currently there are few commercial vendors of specialty fibers
 - Especially for Thulium or Holmium-doped fibers
 - Also few vendors for components
- Every time a new fiber is made, new components need to be developed
 - Limits the turn-around time from new fiber development to its implementation in a system
 - Need pump combiners and isolators compatible with the fiber
- Ideally, everything needs to be fiber-coupled
 - To eliminate free-space coupling
 - Free-space coupling into small-core fibers is not practical in real-world systems