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Rare Earth Doped Fibers for Use in Fiber Lasers and Amplifiers

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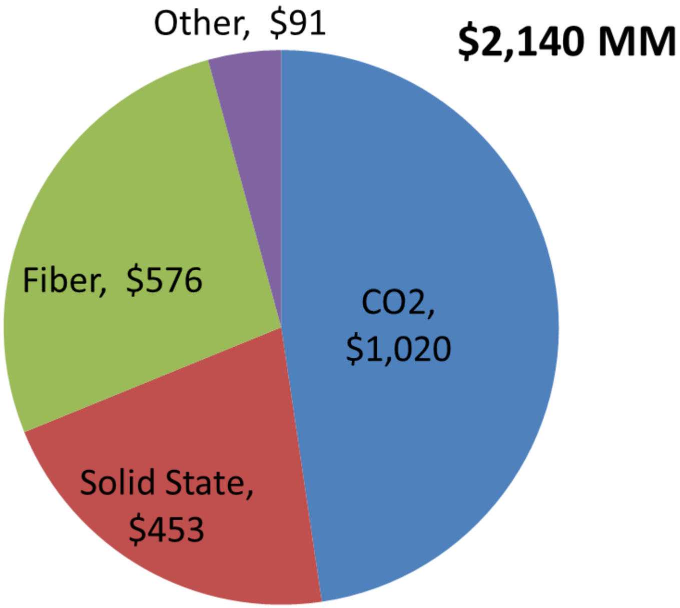
Outline

- Introduction
- Part I: Fiber basics
- Part II: Rare earth doped double-clad fibers
- Part III: Example fiber laser and amplifier platforms
- Part IV: Conclusion
- Q&A

Introduction

- Overall the laser market was worth >$2B/year in 2012
- Fiber lasers have ~25% of the market
- In 2012 fiber lasers had the highest growth (16%) of all categories
- Fiber lasers will continue to grow in 2013 with expectation of 7% growth (vs. 2% for lasers overall)

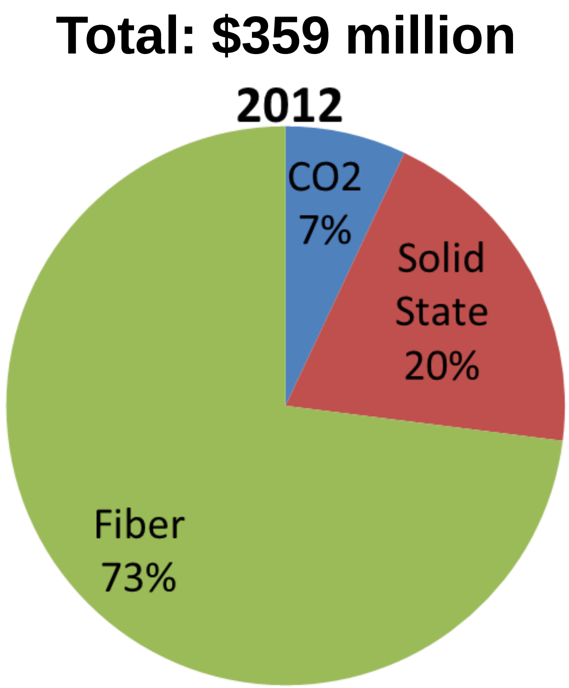
Output power:	1kW cw
Pulse duration:	cw....100µs
Beam quality:	M^2 < 1,3
Delivery fiber:	20µ opt. 50, 100, 200µ
Fiber length:	10m, Optoskand QBH
Beam switch:	opt. up to 4x
Op. temperature:	5..40°C
Op. humidity :	5..85% (non condensing)
Input voltage:	400V (AC), 50..60Hz
Dimensions:	1160x900x1480mm



Source: David Belforte, ILS, PW Marketplace Seminar

Introduction

- In some markets fiber lasers are the dominant laser technology, one example is the marking and engraving segment (~$360M in 2012)
- Overall market share for fiber lasers was ~75%
- This is primarily pulsed fiber lasers competing against DPSSL and CO2 lasers



Source: David Belforte, ILS, PW Marketplace Seminar

Introduction

- This $570M market for fiber lasers covers a wide range of suppliers and fiber laser technologies including:
  - kW CW fiber lasers
  - nsec pulsed fiber lasers
  - ps & fs ultra-fast fiber lasers
- Few things are in common between the companies making and selling this wide range of fiber lasers
- The one things all these have in the common? They all use rare earth doped fibers as the gain medium for the device!!

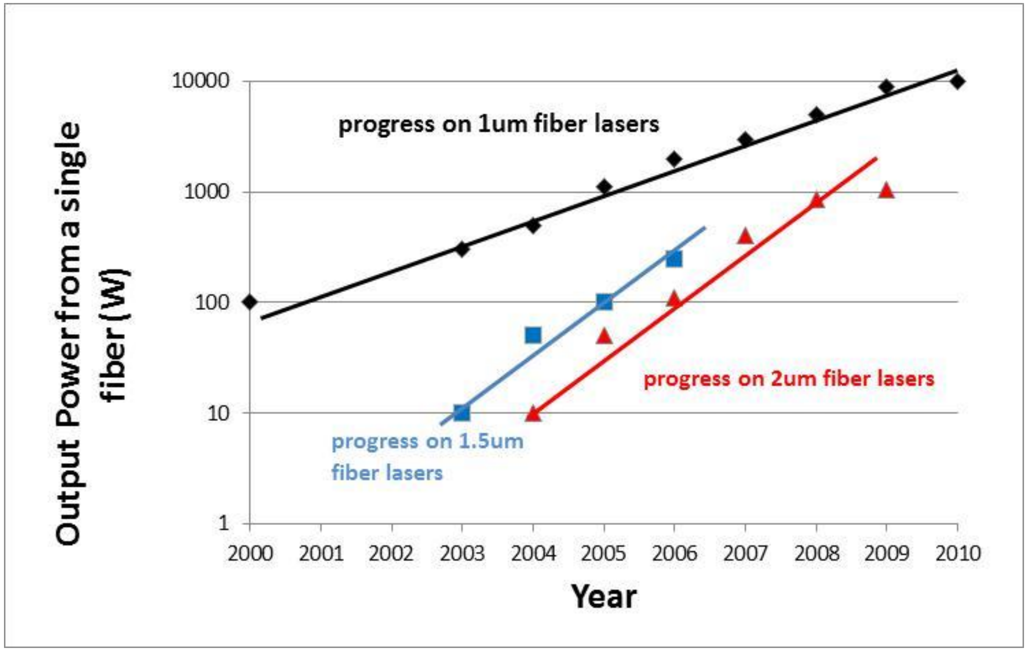
Splice between two fibers used in a typical fiber laser

Introduction

- Some intrinsic advantages of fiber lasers are also common across these multiple markets
- Fiber laser efficiency is very high, requiring less diode pump power than most other solid state lasers
  - Less diode power means lower cooling requirements and lower cost
  - The thermal load is distributed over the length of the fiber
- Beam quality from the fiber laser is determined by the fiber waveguide rather than the laser cavity optics
  - Making stable single mode operation a function of the fiber design
- All Monolithic designs using spliced components removes the need for free space optics and re-alignment
  - This greatly helps with reliability and reduces the need for servicing

Introduction

- Technologically there has been a revolution in power scaling from CW fiber lasers, partly enabled by the high efficiency of the fiber
  - Output power from a near single mode fiber "laser" increased from ~100W to >10kW in ~10 years
- Output power at "eye-safer" wavelengths has started to catch up….~1kW at 2μm

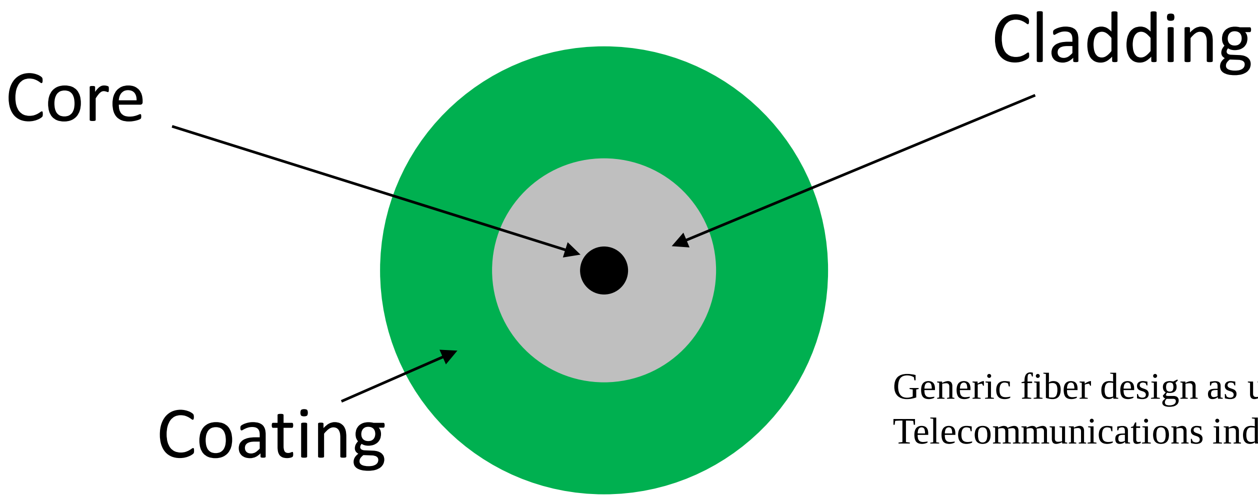


Part I: Fiber Basics

- Guiding light in optical fibers
- Some important properties of optical fibers
- Types of optical fibers
- Examples of fiber laser results

Part I: Fiber Basics

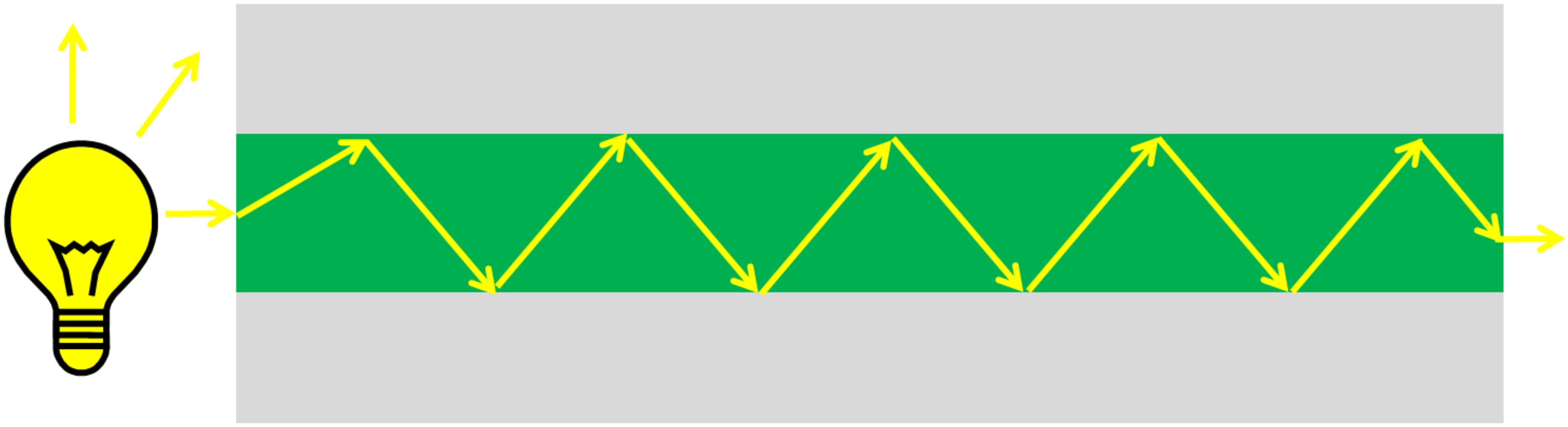
- Core = Glass, carries light/signal, typical size: 10-200μm
- Cladding = Glass, helps define optical characteristics, makes fiber bigger & stronger for handling, typical size: 80-400 μm (~diameter of human hair)
- Coating = Plastic / Acrylate, for protection & handling, typical size: 140-550μm (typically 2 different layers)



Generic fiber design as used in Telecommunications industry

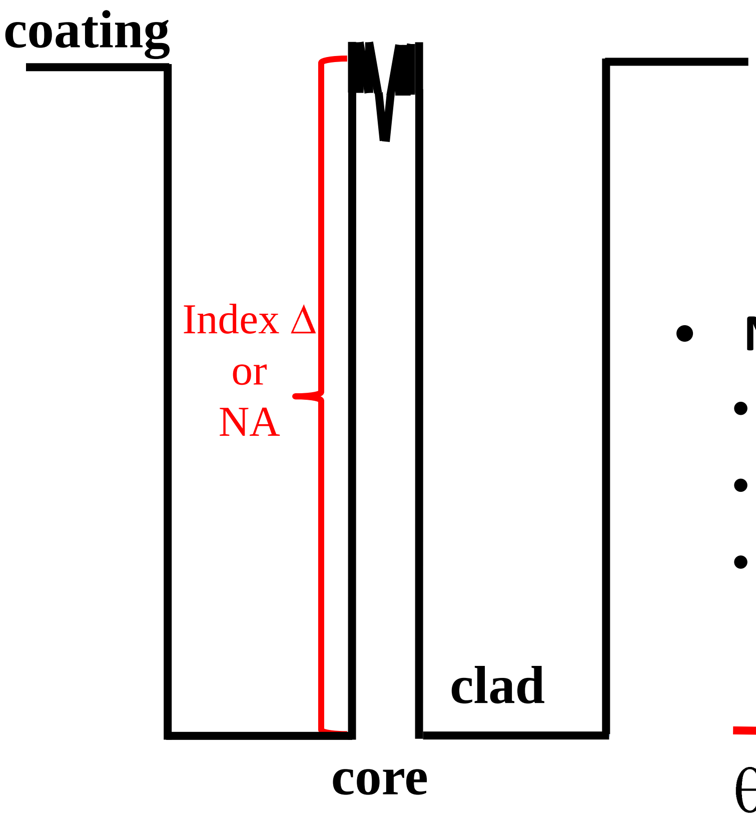
Part I: Fiber Basics

- Total internal reflection driven by refractive index difference between the core glass and the cladding glass
- Light gets trapped in core is reflected at the core/clad boundary and exits at the other end
- Because the fiber is ultrapure the loss of light as it propagates is extremely low (~0.3 dB/km)

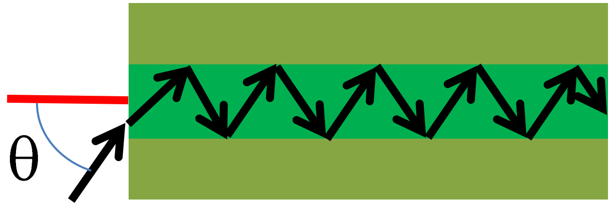


Part I: Fiber Basics

The difference in the optical property called **refractive index** is what confines the light in the core and prevents it from leaking into the cladding.



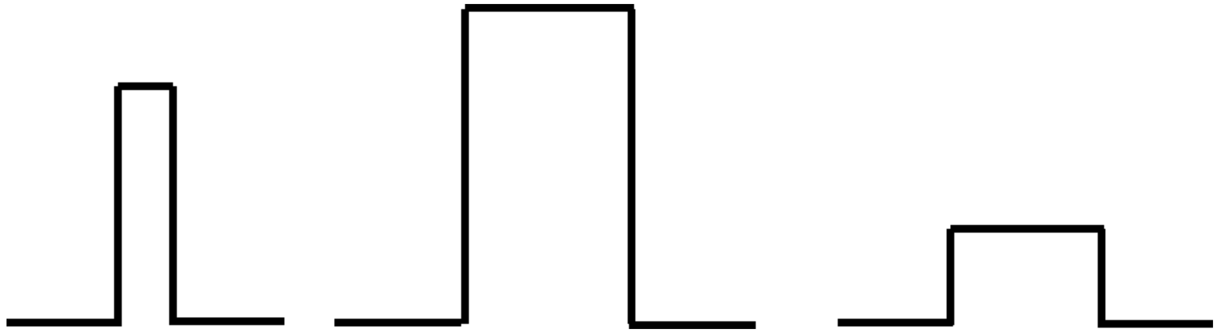
- **Index difference between core & cladding is important design parameter:**
  - Typical number is 0.0055
  - Range from 0.001 to 0.05
- **NA (Numerical Aperture)**
  - Calculated from the index of core & cladding
  - Typical number is 0.12; Range from 0.05 to 0.45
  - Defines the acceptance angle



$$NA = n \sin\theta$$
$$= \sqrt{}$$

Part I: Fiber Basics

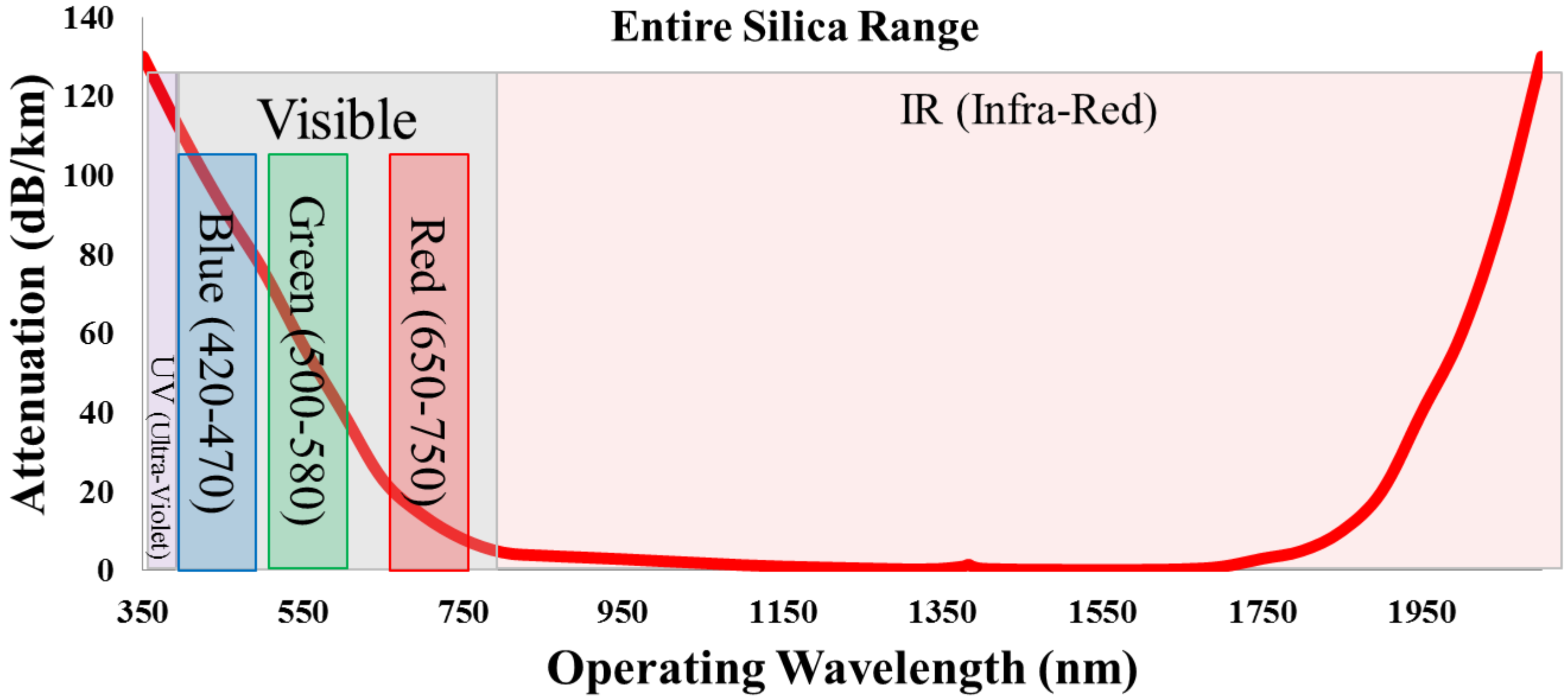
- Fibers with different core sizes and NA



	Singlemode “SM”	Multimode “MM”	Large Mode Area “LMA”
# of Modes	1	~ 1000	2 to 5
Core Size (microns)	3 – 10	50 – 150	15 - 50
NA	0.12 – 0.20	0.20 – 0.35	0.05 – 0.10
% of Fiber Worldwide	90%	9%	<1%
Used in Fiber Lasers	Yes, low power lasers	Yes, used in pump delivery	Yes, high power lasers

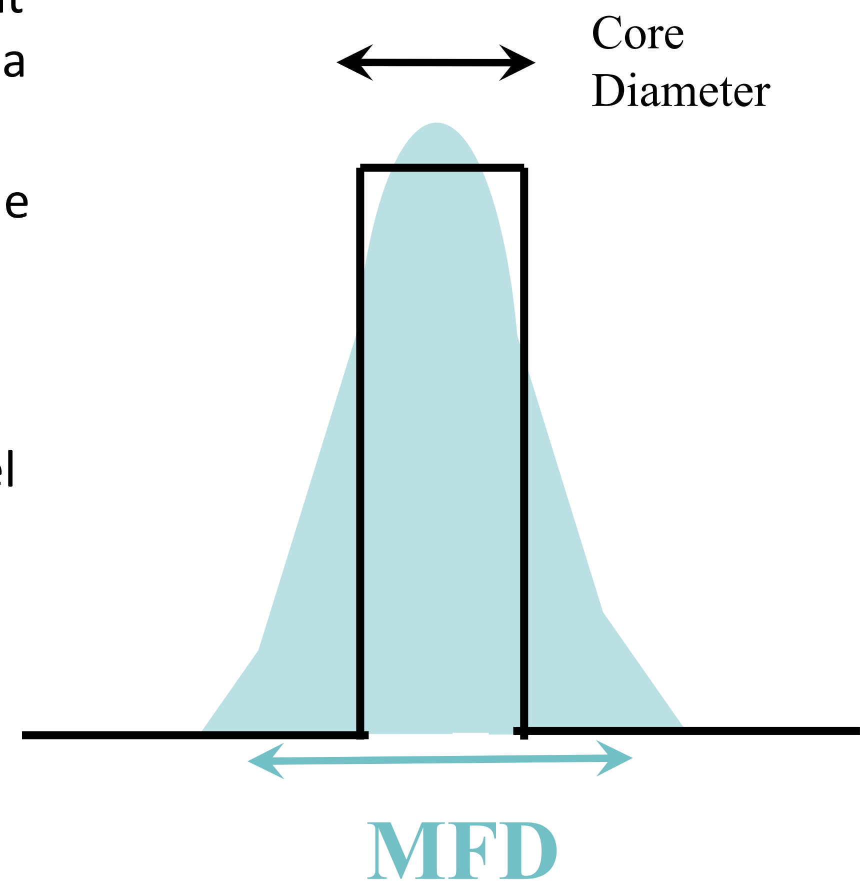
Part I: Fiber Basics

- Attenuation limits the operating wavelength for silica optical fiber between ~350nm and ~2100nm
  - 350-1500nm loss dominated by Rayleigh scattering
  - >1600nm loss dominated by IR absorption of silica
- At shorter wavelength glass composition can affect the attenuation



Part I: Fiber Basics

- The core is physically & optically different than the cladding, because it is made of a different type of glass.
- However, the light does not exactly fit the core, it travels slightly outside. The effective area in which it travels is called the ***Mode Field Diameter (MFD).***
- For SM fibers ~30% of the light can travel outside the core in the cladding.
- For MM fibers very little light travels in the cladding since the NA is high.
- LMA fibers are few-moded, but behave more like SM fibers and <10-20% of the signal light can travel in the cladding.



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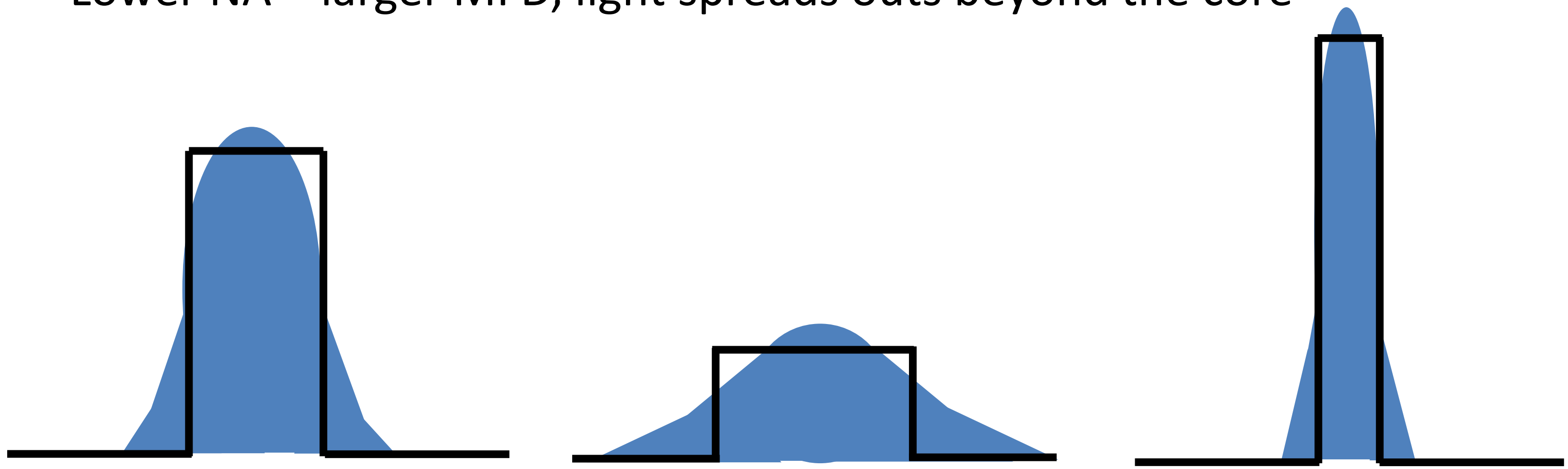
Part I: Fiber Basics

- MFD determined by index profile & NA
  - Higher NA = smaller MFD, light tightly confined in core
  - Lower NA = larger MFD, light spreads outs beyond the core



- MFD varies with wavelength – shorter wavelengths behave more like a stream of photons and longer wavelengths have more wave-like behavior.

8.8 mm core has 9.1 mm MFD @ 1310 nm,; but 10.5 mm MFD @ 1550 nm

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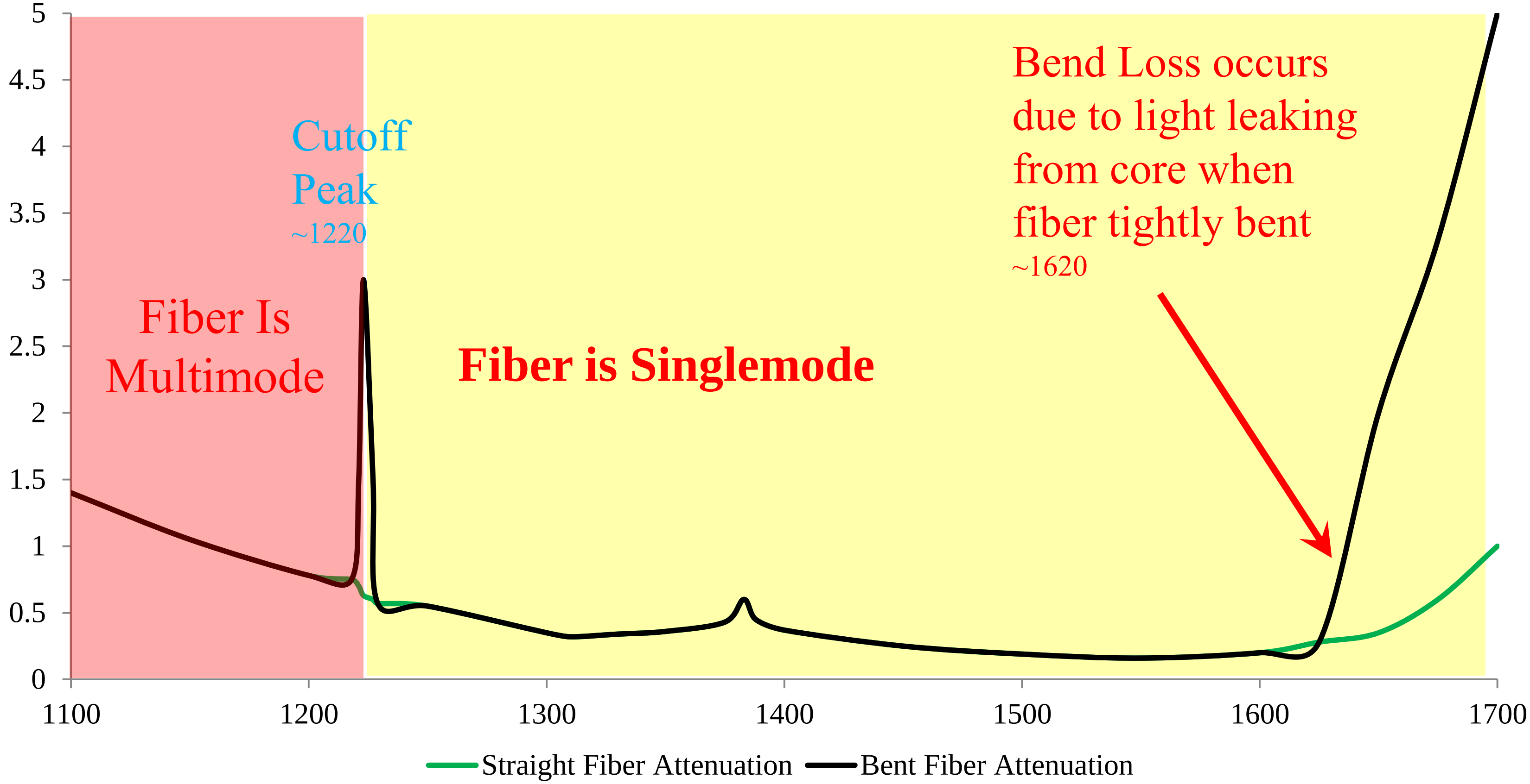
Part I: Fiber Basics

- Cutoff defines where the single mode operating window starts
- Bend-edge defines where operating bandwidth ends.



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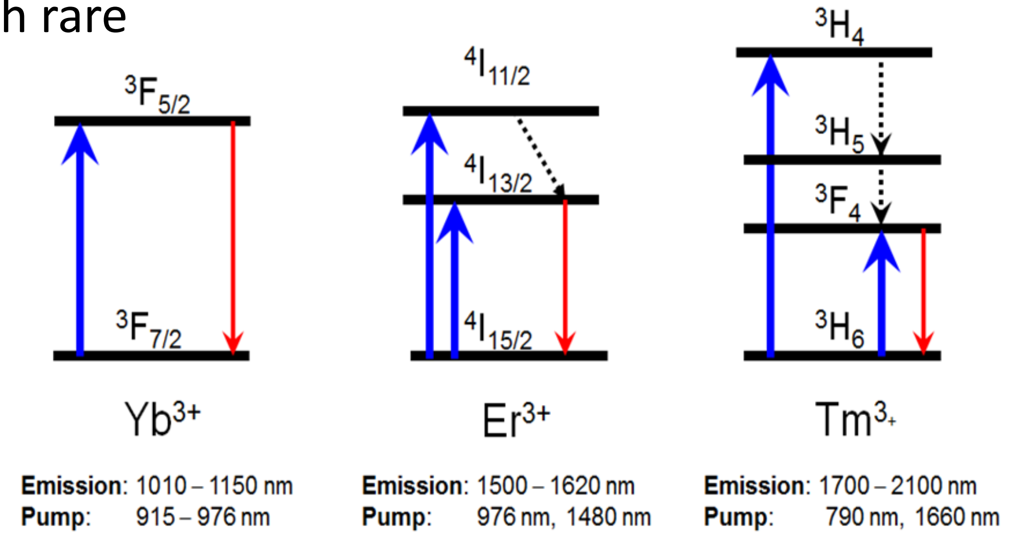
Part II: Rare Earth Doped Fibers

- Doping the optical fiber with rare earth ions such as:
  - Ytterbium (Yb^{3+})
  - Erbium (Er^{3+})
  - Thulium (Tm^{3+})
  - Holmium (Ho^{3+})



- The fiber becomes an active medium with gain rather than passive transmission medium.
- In order for the gain to be efficient and deliver high power, optimization of the fiber design is required.
- First, how to optically pump or excite the rare earth doped fiber?

Part II: Rare Earth Doped Fibers

- Rare earth is doped into the core of the optical fiber along with the modifier element (Al, Ge, P, etc)
- Create two waveguide regions: the core and the inner cladding – both guide light.
- Inner cladding waveguide created by making lower index region outside of inner cladding (double-clad) by replacing the coating with a fluoropolymer low-index coating.

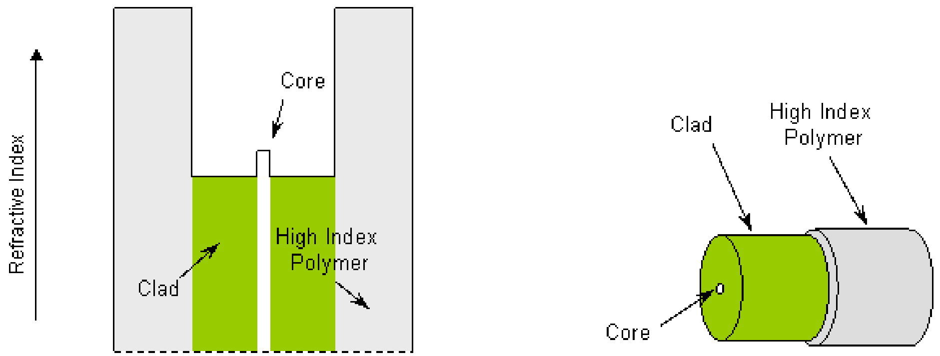


Figure 1a: Traditional Optical Fiber Design

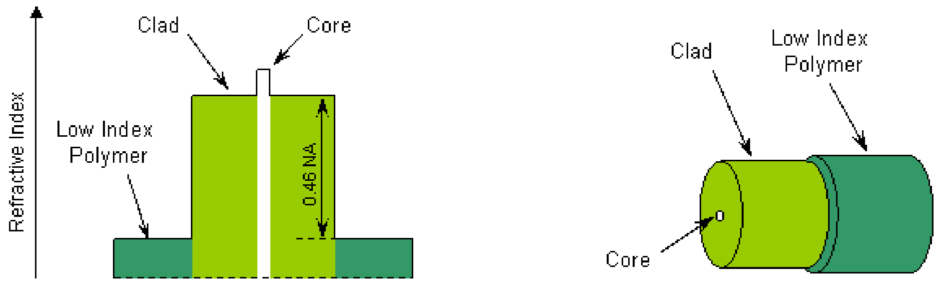
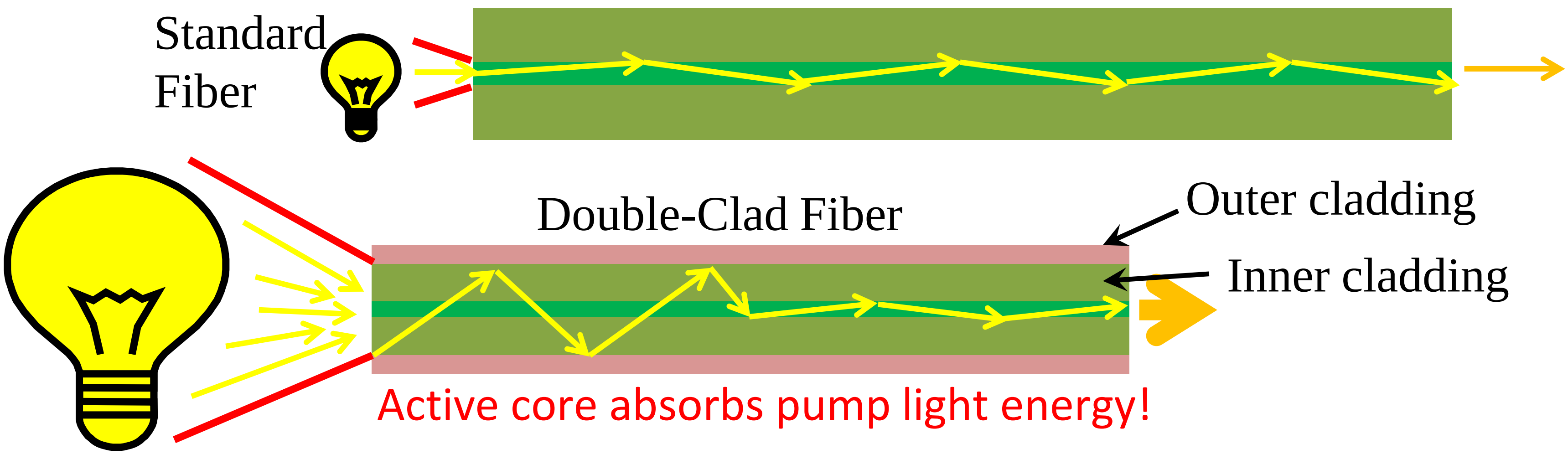
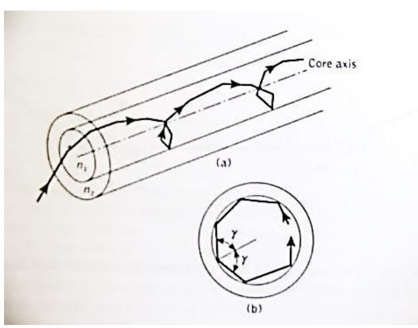


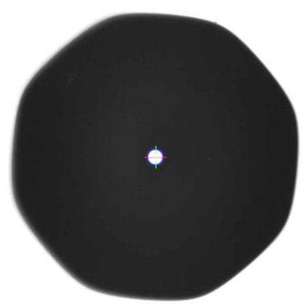
Figure 1b: Double Clad Optical Fiber Design

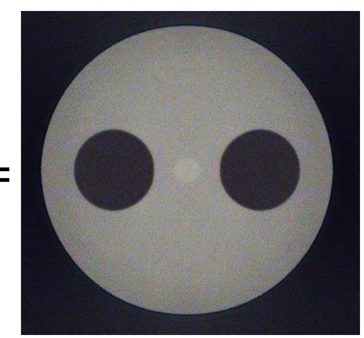
Part II: Rare Earth Doped Fibers

- Double-clad fibers increase the ability of the core to absorb light by allowing higher input pump powers enhancing interaction between active ions in the core and the pump light. Shaped cladding used to increase light-ion interaction.



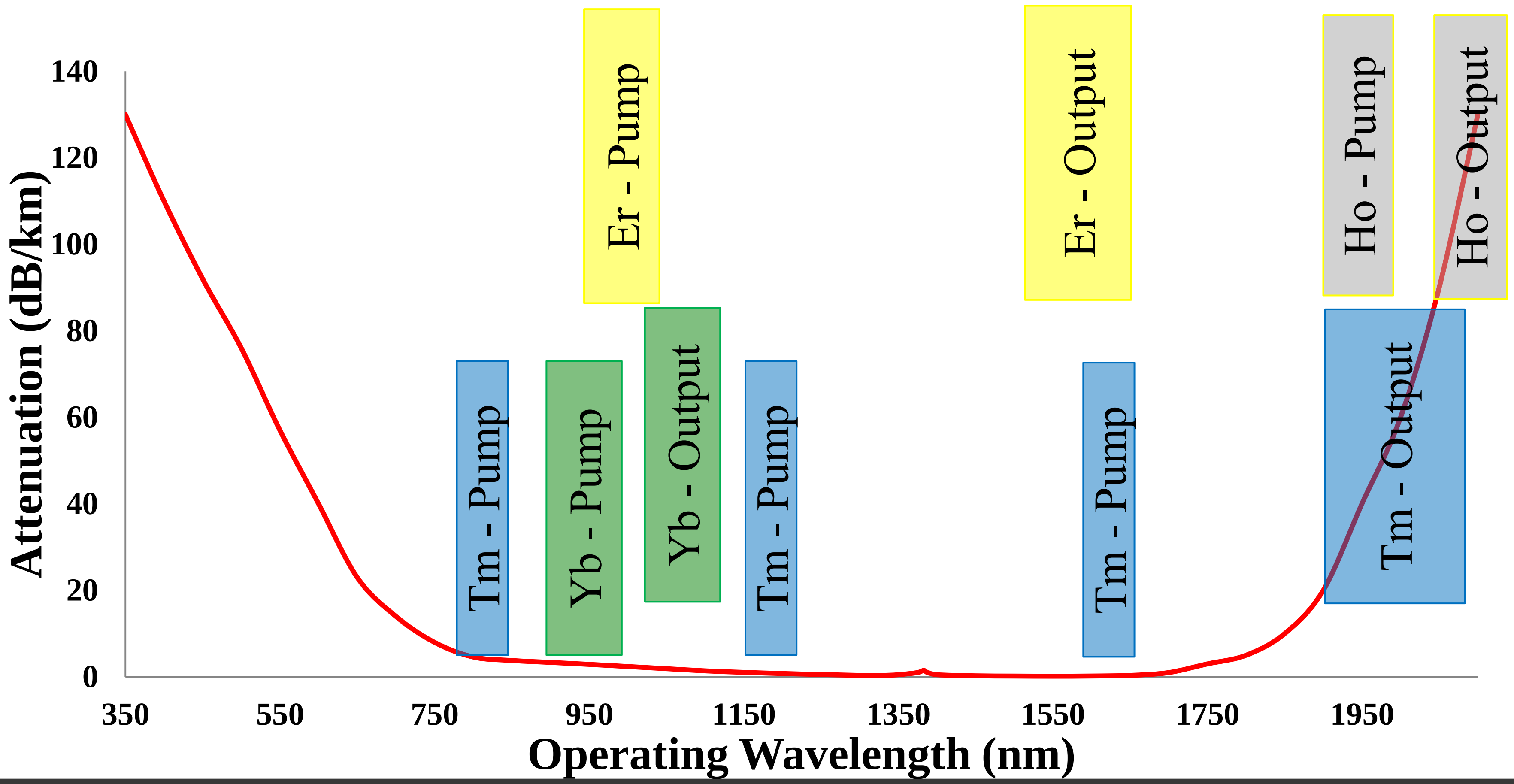


LMA = 

PLMA = 

Part II: Rare Earth Doped Fibers

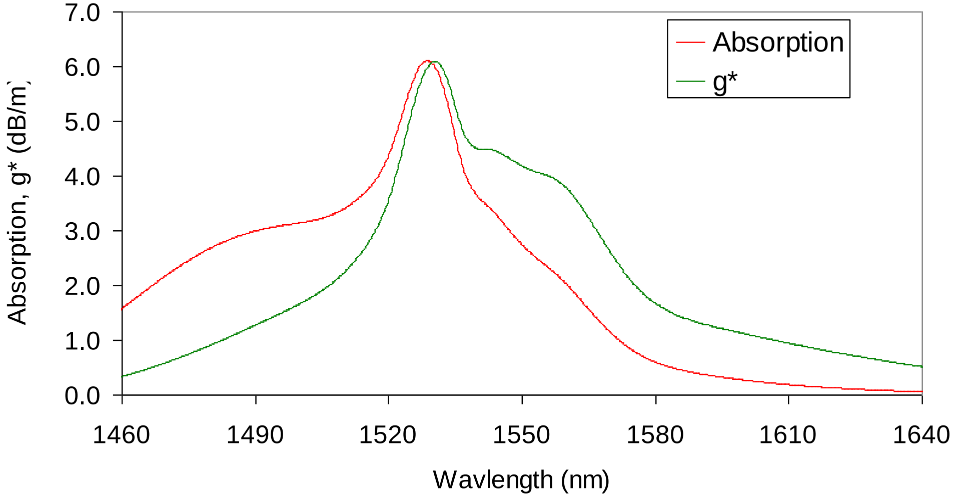
- Each active fiber works within a specific wavelength range determined by the RE ion and the pump light is a shorter wavelength than the lasing wavelength



Part II: Rare Earth Doped Fibers

- Unlike in crystals, the absorption and emission spectrum are very broad in doped silica fibers
- Compared with many crystal hosts, the rare earth doping levels in fibers are low because of the solubility issue (clustering)
- However, in a fiber, the length can be much longer to overcome the lower absorption
- Fiber may be ~10m in length compared with a crystal of a few cm's.

Absorption, g* For a Typical Nufern EDFC-980-HP Fiber



Part II: Rare Earth Doped Fibers

- The detailed pump absorption cross section and emission cross section also depend on the details of the glass composition.
- Solubility of the rare earths is not high in silica and can be different for each rare earth
  - To increase solubility in the silica glass a co-dopant is added, usually Al, often referred to as the glass modifier
- In Yb-doped fibers the lasing/amplification occurs between 1030-1100nm depending on the inversion (ratio of high energy ions to lower energy ions).

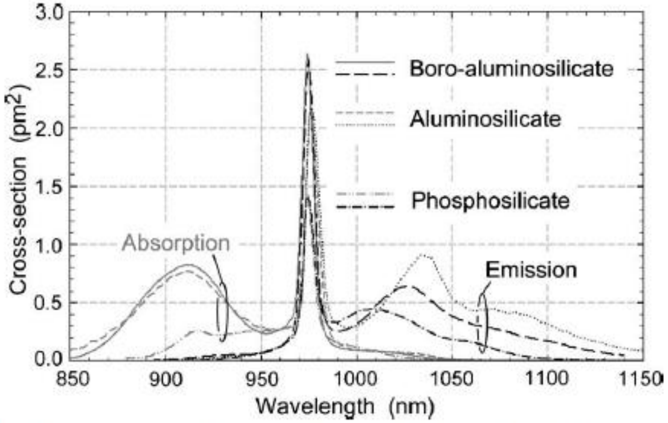
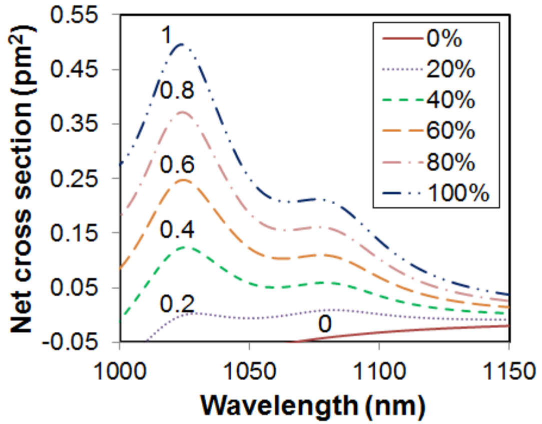


Fig. 2. Emission and absorption spectrum of ytterbium ions in different silica hosts.



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Part II: Rare Earth Doped Fibers

- In many applications it is desirable to use a few-moded fiber with larger core diameter
  - Has an increased mode field for LP01 mode
  - Also reduces the fiber length (large core to clad ratio)
  - Increases energy storage in the fiber
- Lower limit of RE doped, step-index large mode area (LMA) fibers is ~0.06NA
  - Difficult to control the profile of the deposited silica glass below this value
  - Based on this NA, the **limit of a single mode fiber is ~12mm core diameter** before the fiber core supports >1 mode at 1080nm (V<2.4)

$$V = \frac{\pi d_{core} NA_{core}}{\lambda}$$

Assuming 0.06 NA

CoreØ	**[µm]**	**12**	**15**	**20**	**25**	**30**	**35**
MFD@1080nm	**[µm]**	**13**	**15**	**18**	**21**	**25**	**28**
# of modes		**1**	**2**	**2**	**4**	**6**	**7**
MF-area	**[µm^2]**	**142**	**176**	**255**	**356**	**476**	**616**

Part II: Rare Earth Doped Fibers

- Typical fiber lengths assuming 13dB pump absorption (95%) for standard Yb-doped fibers pumped at 915nm
- For 975nm pumping use 3x short lengths

Core/Clad diameter	5µm	10µm	15µm	20µm	25µm	30µm
130µm	24m 0.55dB/m	10m 1.3dB/m	7m 1.8dB/m	4.5m 2.8 dB/m	N/A	N/A
250µm	N/A	N/A	N/A	N/A	8m 1.6 dB/m	7.5m 1.7 dB/m
400µm	N/A	65m 0.2dB/m	N/A	33m 0.4 dB/m	22m 0.6dB/m	

Part II: Rare Earth Doped Fibers

- In order to operate these LMA fiber based lasers at >1kW, careful optimization of the different fibers along the amplifier chain is necessary
  - **The splice loss between the active and passive fibers, can lead to failure of splices at high power and deterioration of beam quality at high power levels**
  - **This has led to a "matched" series of LMA fibers for high power operation**

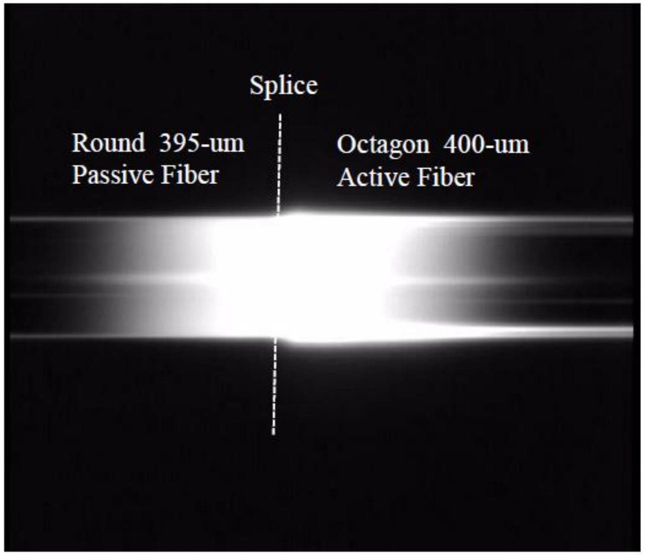


Figure 2: Image showing splice of passive fiber to active fiber.

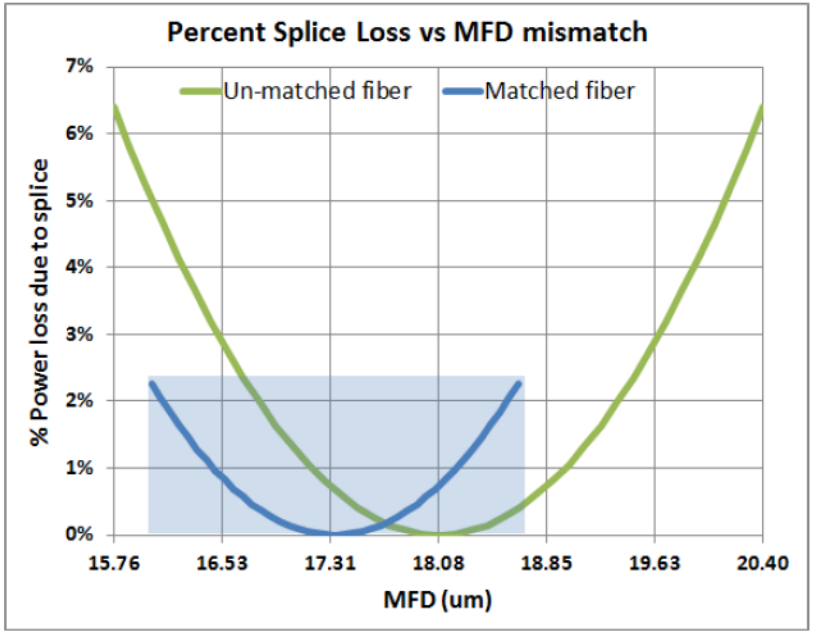


Figure 3: Relative splice loss dependence as a function of MFD equivalence.

Part II: Rare Earth Doped Fibers

- 1.5µm and 2µm have become important wavelengths of operation because of the need for eye-safer operating wavelengths in some cases (>1400nm)

- 2µm fiber lasers based on Tm-doped fibers are seeing significant growth

- Applications include medical, sensing and materials processing as well as military and defense

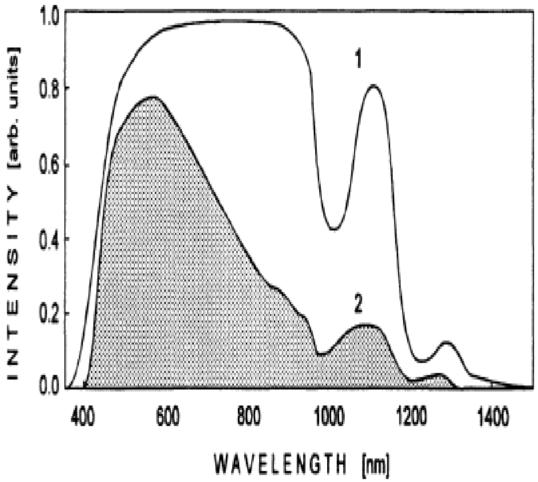
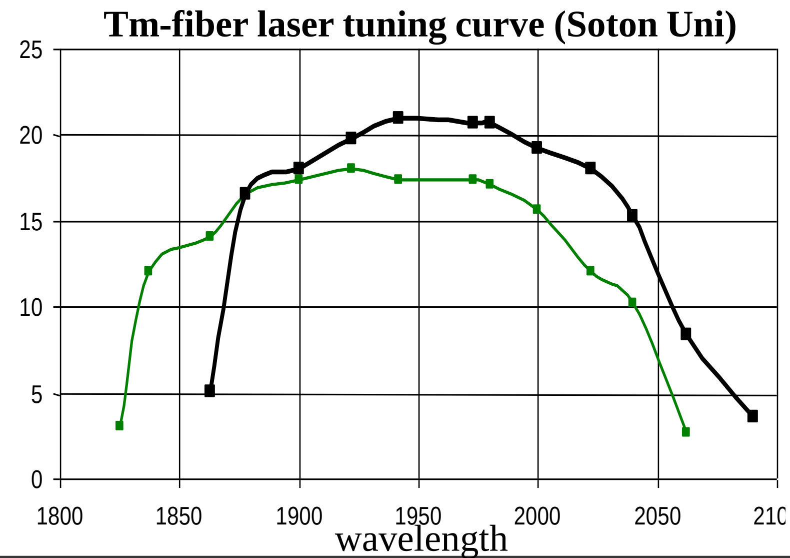
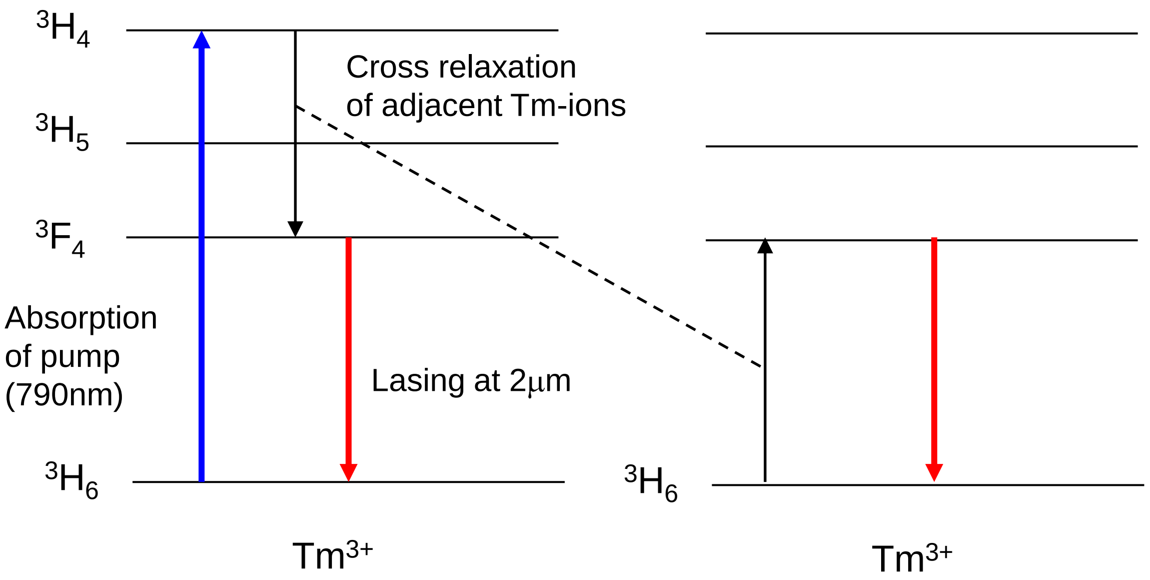


Fig.1. Penetration of radiation into the eye:
1 - eye transmission to the retina,
2 - radiation absorption in the retina.



Part II: Rare Earth Doped Fibers

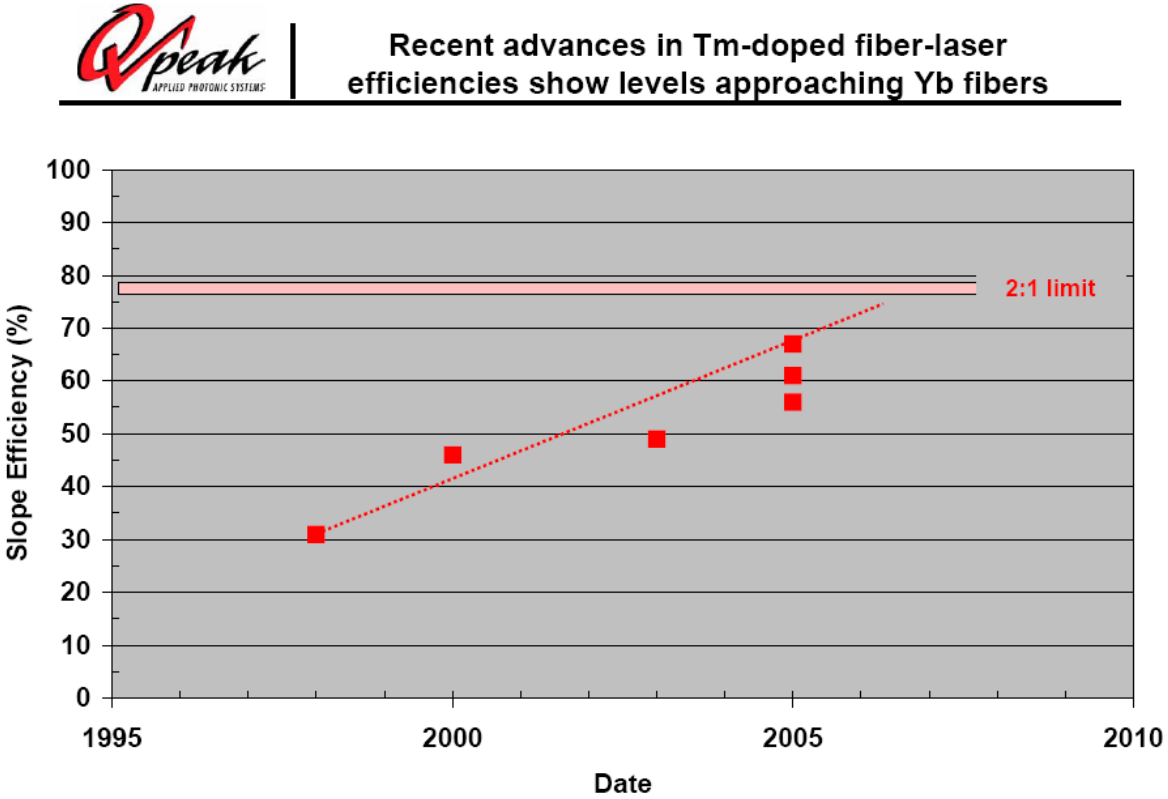
- Current generation of Tm-doped fibers is pumped at 790nm
- Cross relaxation of excited Tm-ions in highly doped fibers leads to increased slope efficiency for ~790nm pumping compared with the quantum limit (~40%)



Increasing the Tm^{3+} concentration decreases the ion-ion separation to enhance the cross-relaxation process.

Part II: Rare Earth Doped Fibers

- By optimizing the fiber composition, efficiencies of 790nm pumped Tm-fibers have steadily improved over the last 10 years
- Efficiency for 790nm pumping of Tm-doped silica is now typically around 60%



Part II: Rare Earth Doped Fibers

- A range of standard Tm-doped LMA fibers (10-25μm core) are available from suppliers using a pedestal core design (-P)

Eye Safe 10P/130 Thulium-I Single-Mode Double Clad Fi

Nufern Thulium-doped double clad fiber utilizes a glass composition specifically optimized for high around the important 2 μm wavelength when pumped at ~793 nm. These small core low NA fibers single-mode operation while the telecom-like 130 μm cladding diameter makes handling, including simple as possible.

Typical Applications

- Low to mid power CW and pulsed Eye Safe 2 μm lasers & amplifiers
- Eye Safe industrial & medical lasers
- Military and commercial LIDAR
- 2 μm output TEM_{00} fiber lasers for pumping solid state crystal lasers

Features & Benefits

- NuCOAT™ fluoroacrylate coating — Greater fiber durability in extreme environmental operatin
- LMA single mode core design and short amplifier length — Useful for generating high peak po
- Easy to maintain single-mode LP01 beam through fiber & components
- PANDA-style stress structure for increased birefringence — Superior optical performance and
- All fiber proof tested to > 100 kpsi — Critical for ensuring long term reliability when coiling

Optical Specifications	SM-TDF-10P/130-HE	PM-TDF-10P/130-HE
Operating Wavelength (nominal)	2000 nm	2000 nm
Core NA	0.150	0.150
First Cladding NA (5%)	≥ 0.46	≥ 0.46
Cladding Attenuation	≤ 15.0 dB/km @ 860 nm	≤ 15 dB/km @ 860 nm
Cladding Absorption	1.00 ± 0.30 dB/m at 1180 nm 3.00 dB/m at 793 nm	1.60 ± 0.30 dB/m at 1180 nm 4.70 dB/m at 793 nm
Birefringence	N/A	nominal 1.5×10^{-4}
Geometrical & Mechanical Specifications		
Cladding Diameter	N/A	130.0 ± 1.0 μm
Cladding Diameter (flat-to-flat)	130.0 ± 2.0 μm	N/A
Core Diameter	10.0 ± 1.0 μm	10.0 ± 1.0 μm
Coating Diameter	215.0 ± 10.0 μm	215.0 ± 10.0 μm
Coating Material	Low Index Polymer	Low Index Polymer
Prooftest Level	≥ 100 kpsi (0.7 GN/m²)	≥ 100 kpsi (0.7 GN/m²)

EyeSafe 25 Micron Core Thulium-Doped LMA Double Clad Fibers

True LMA fiber featuring a unique low NA (< 0.1) high concentration Tm-doped core design. It is fully optimized for high slope efficiency (composition has demonstrated > 130% quantum efficiency) when pumped at 793 nm. This extraordinary efficiency is due to composition enabled cross relaxation of Thulium ions in the core. The high Tm concentration allows short device lengths and high pump conversion efficiency while the low NA (few moded) core design is ideal for application where robust single-mode beam quality is critical. The high NA (0.46) large pump cladding waveguide allows for efficient coupling of high pump powers. The large core diameter (25 μm) maintains a large mode field diameter and short device length, thereby minimizing non-linear effects such as SBS and SRS.

Typical Applications

- High power 2 μm CW and pulsed EyeSafe lasers & amps
- EyeSafe industrial & medical lasers
- Military and commercial LIDAR
- 2 μm TEM_{00} fiber lasers for pumping crystal lasers

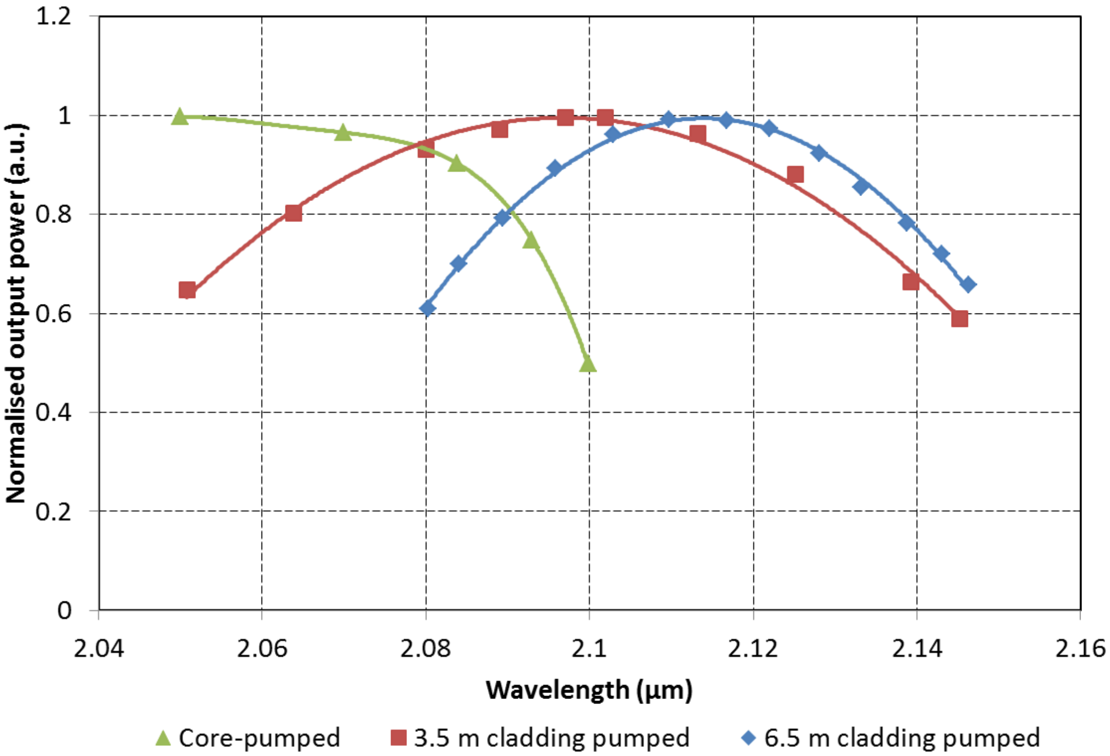
Features & Benefits

- Unique low NA Tm-doped core design — Robust single-mode beam quality
- Optimized composition for 793 nm pumping — Very high conversion efficiency
- High pump absorption — Short fiber length, efficient lasing in the ~2 μm window

Optical Specifications	PLMA-TDF-25P/400-HE	LMA-TDF-25P/400-HE
Operating Wavelength (nominal)	2000 nm	2000 nm
Core NA	0.090	0.090
First Cladding NA (5%)	≥ 0.460	≥ 0.460
Cladding Attenuation	≤ 15.0 dB/km @ 860 nm	≤ 15.0 dB/km @ 860 nm
Cladding Absorption	0.80 ± 0.10 dB/m at 1180 nm 2.40 dB/m at 793 nm	0.60 ± 0.10 dB/m at 1180 nm 1.80 dB/m at 793 nm
Birefringence	nominal 2.5×10^{-4}	N/A
Geometrical & Mechanical Specifications		
Cladding Diameter	400.0 ± 15.0 μm	N/A
Cladding Diameter (flat-to-flat)	N/A	400.0 ± 15.0 μm
Core Diameter	25.0 ± 2.5 μm	25.0 ± 2.5 μm
Coating Diameter	550.0 ± 20.0 μm	550.0 ± 20.0 μm
Coating Material	Low Index Polymer	Low Index Polymer
Prooftest Level	≥ 100 kpsi (0.7 GN/m²)	≥ 100 kpsi (0.7 GN/m²)

Part II: Rare Earth Doped Fibers

- Recently interest has grown in the properties of Holmium doped silica fibers
- Tuning results for Holmium doped silica shows better operation at longer wavelengths >2.1μm than Tm-fibers



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(*A. Hemming et al, CLEO 2013*)

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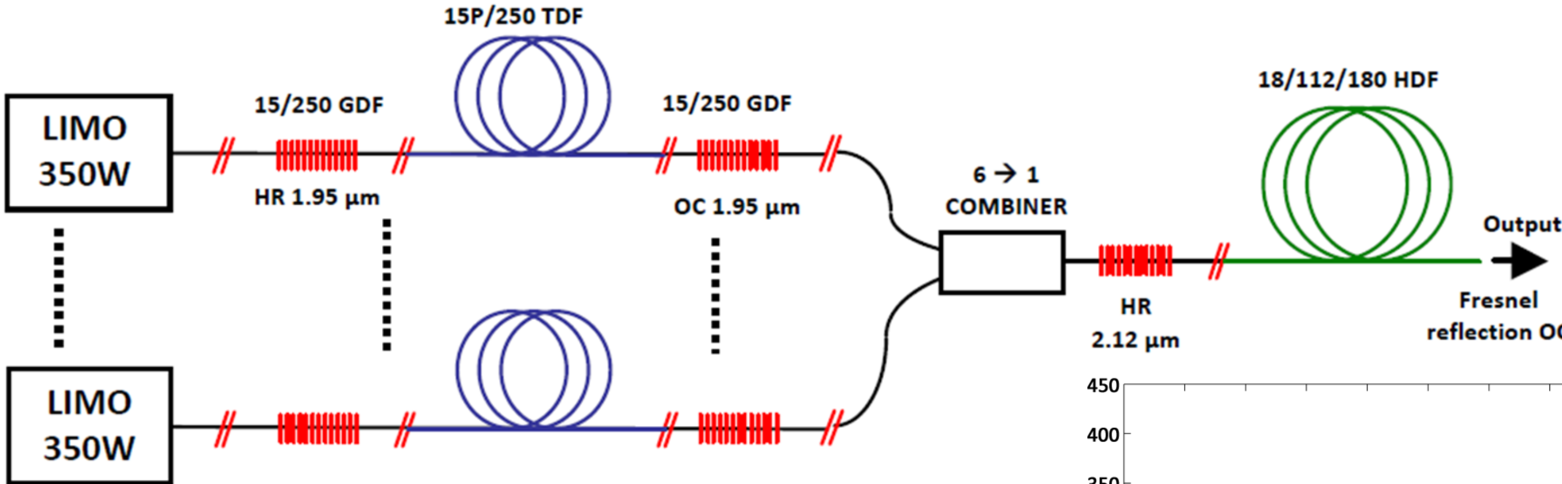
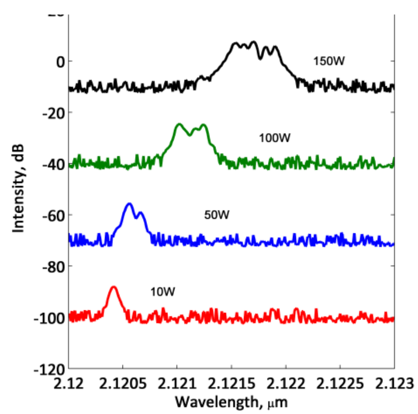
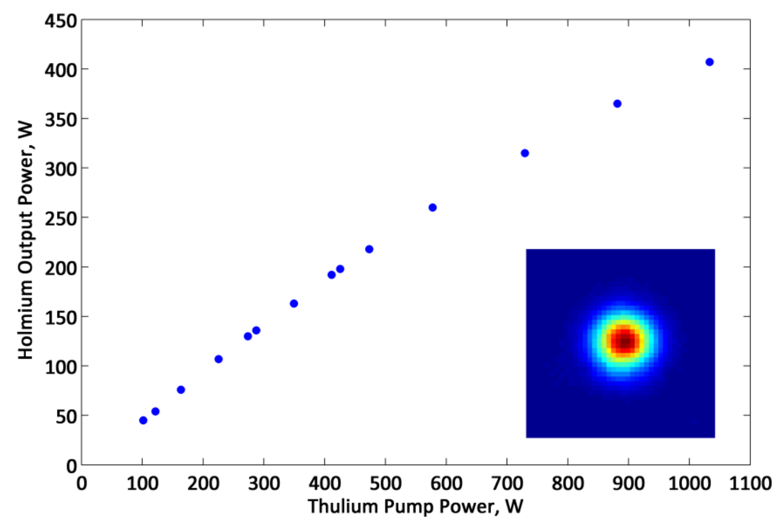
Part II: Rare Earth Doped Fibers

- In addition, the resonant pumping of Ho-doped fibers shows promise for power scaling to very high power levels (*A. Hemming et al, CLEO 2013*)







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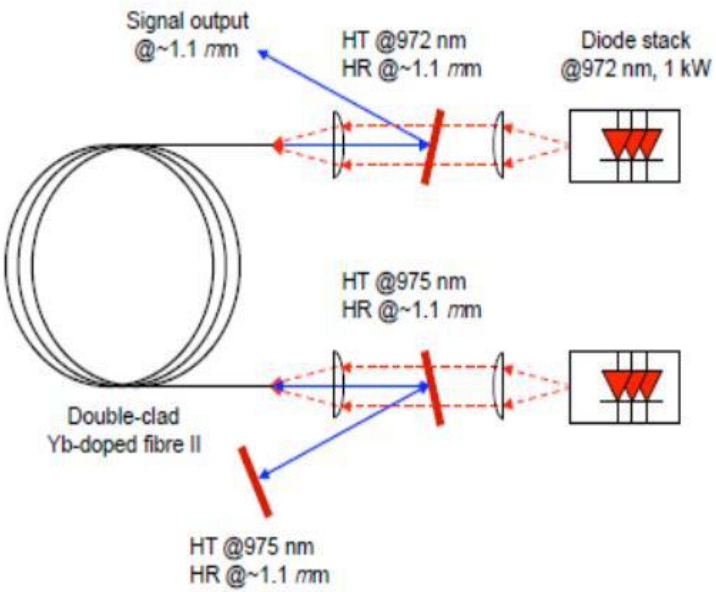
Part III: Example fiber laser and amplifier platforms

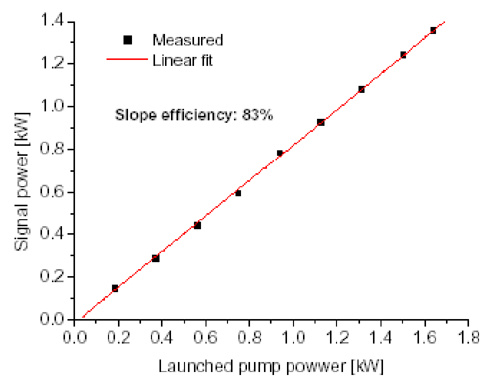
- Monolithic fiber lasers
- FBGs for making lasers
- Pump laser diodes
- Combiners for pumping fibers
- High power MOPA systems
- Tm-doped fiber lasers

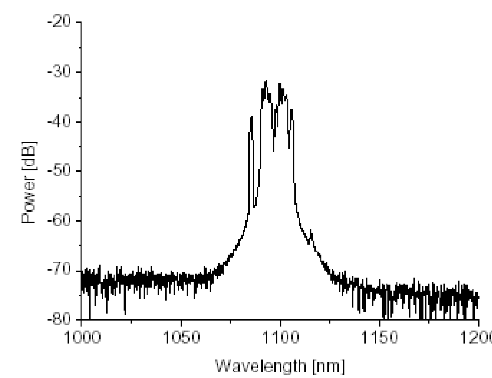
Part III: Example fiber laser and amplifier platforms

- The first 1kW near single mode (M2 ~3.4) fiber laser was demonstrated in 2004 (ORC, University of Southampton) using free space laser cavity
- HR mirror and 4% Fresnel reflection from the fiber endface formed the cavity



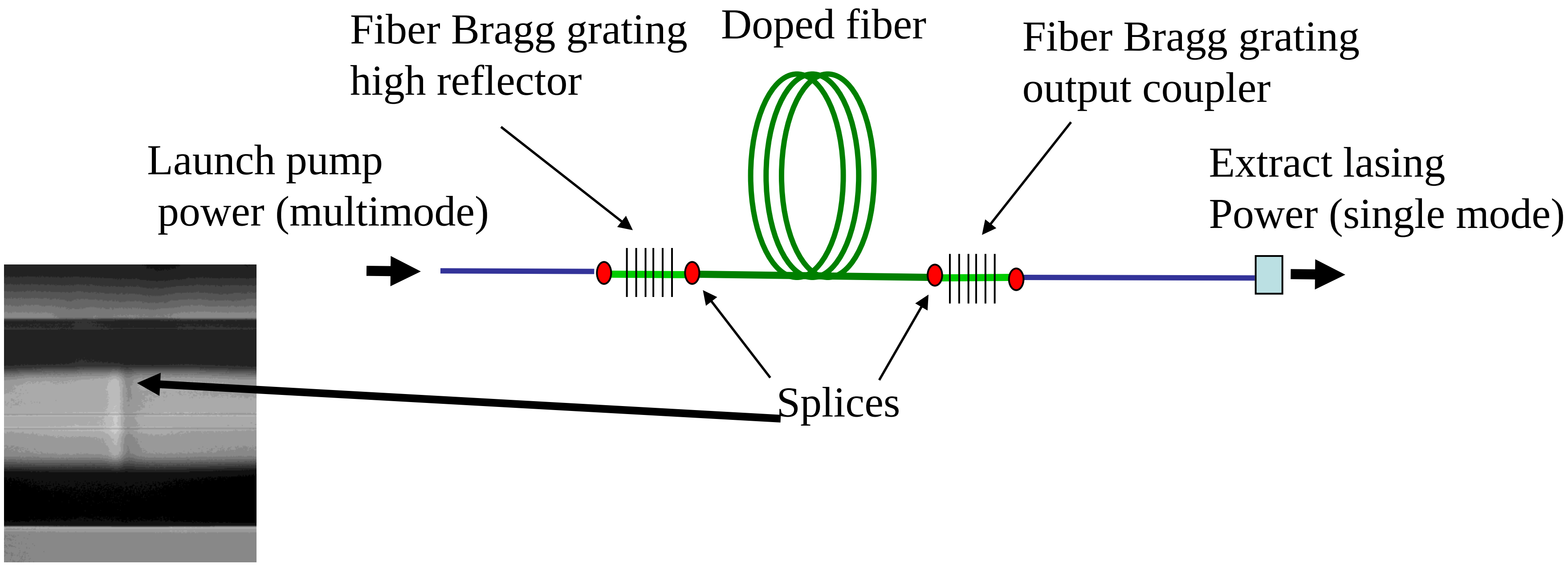
Y. Jeong et al,
Electron. Lett, 2004





Part III: Example fiber laser and amplifier platforms

- However the use of free space optics within the laser cavity has proved unreliable at the high power levels fiber lasers now operate
- Monolithic designs are now preferred using fiber Bragg gratings to form the laser cavity
- Writing the gratings in the core of a double clad fiber allows the pump to pass down the fiber unaffected by the grating

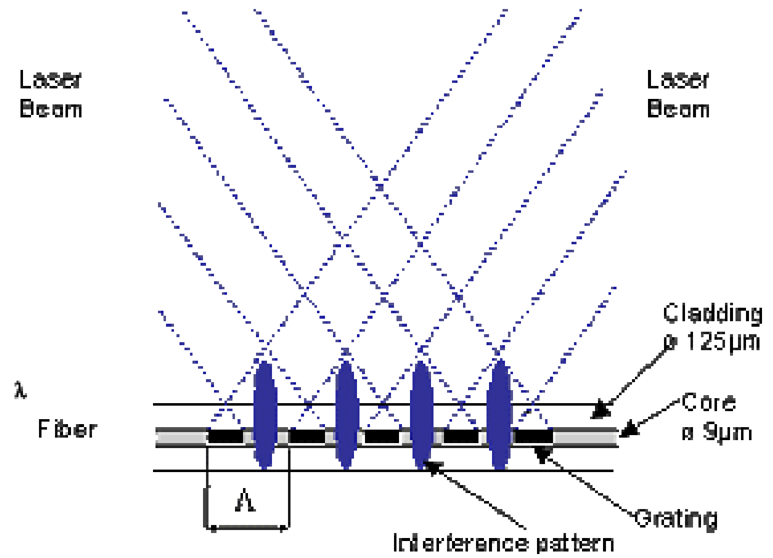


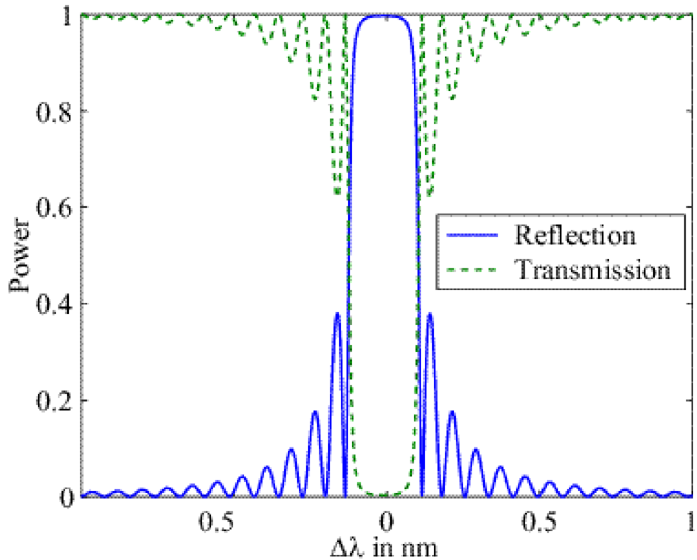
Part III: Example fiber laser and amplifier platforms

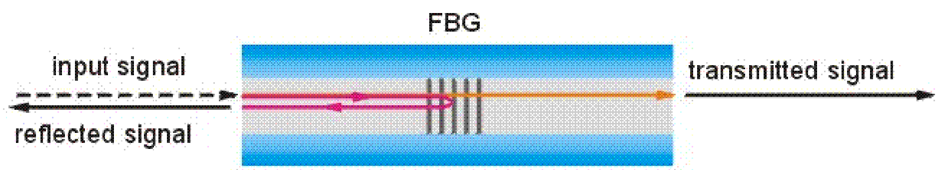
- Photosensitive (PS) fibers were developed and optimized for the telecom industry during the 1990's (key component in WDM systems)
- Modification of these "telecom" fibers has enabled high power FBG's for the fiber laser industry
- LMA versions of these PS fibers such as 20/400 are now standard in the industry and used to fabricate high reflector (HR) and output coupler (OC)
- Tight control of the key fiber parameters are critical to keep intra-cavity splice losses low and improve reliability of the laser

Part III: Example fiber laser and amplifier platforms

- Typically this fiber is a different composition from the RE doped fiber (Ge doped fiber) for enhanced photosensitivity
- Most common method for writing FBG is UV exposure through the side of the fiber using a phase mask
- Requires stripping of the polymer coating







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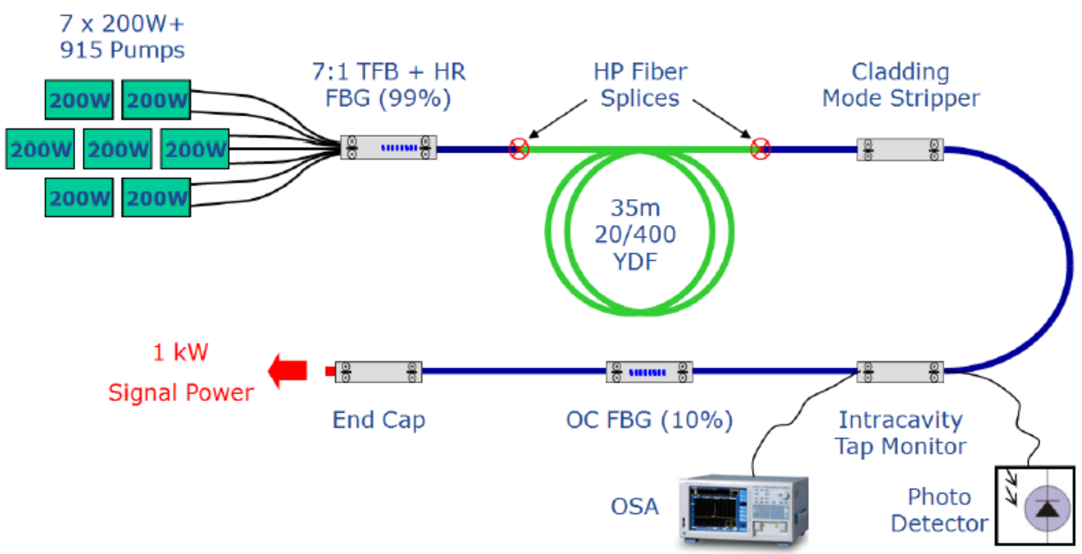
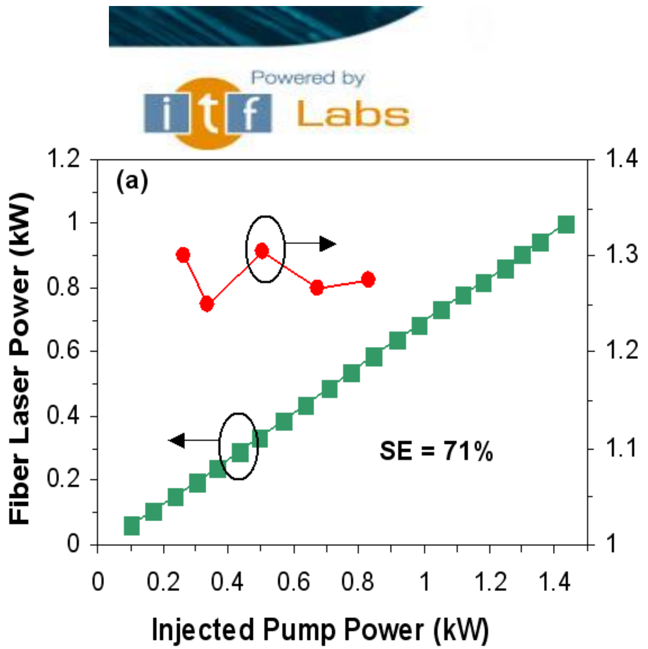
Part III: Example fiber laser and amplifier platforms

- Complete monolithic fiber lasers now routinely operate at >1kW output power based on LMA Yb-doped fiber and LMA FBGs spliced together
- High slope efficiency and good beam quality at high power level

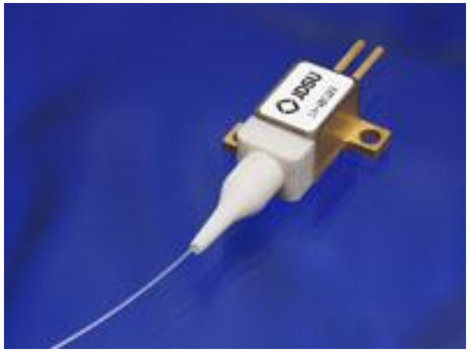




Y. Xiao et al, Optics Express, Jan 2012

Part III: Example fiber laser and amplifier platforms

- Diode options for pumping Yb-fibers depend on the application and may be split into different categories by technology and wavelength
- Single emitter based pump diodes
- Typically coupled into 105/125 fiber (10-12W)



- Multi-emitter packages
- Combine several of these single emitters (60-100W)

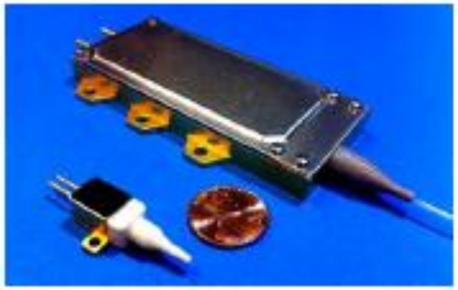


Figure 1. Photograph of the high-brightness pump source that provides 100 W of power from a standard 105/125 µm fiber. The package dimensions are 87 x 39 x 10 mm^3. An L4i pump diode and penny are shown is in the foreground for comparison.

- Diode bar based pumps delivering 100-200W
- Typically coupled into 200µm core fiber

Part III: Example fiber laser and amplifier platforms

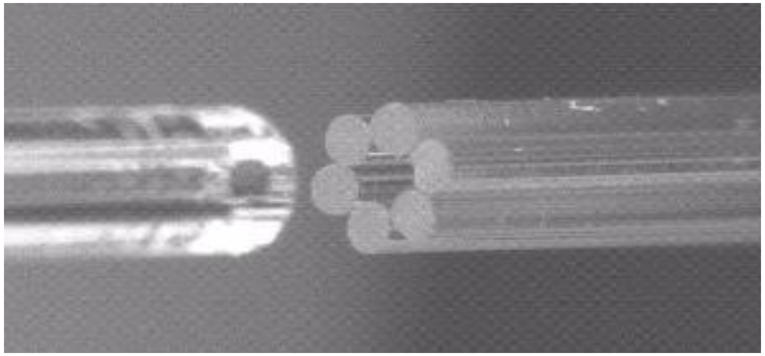
- Pump combiner is a component that combines multiple fibers from the pump laser diodes into one output fiber (7x1 combiner for example)
- The number of input fibers depends on the diameter and NA of the output fiber

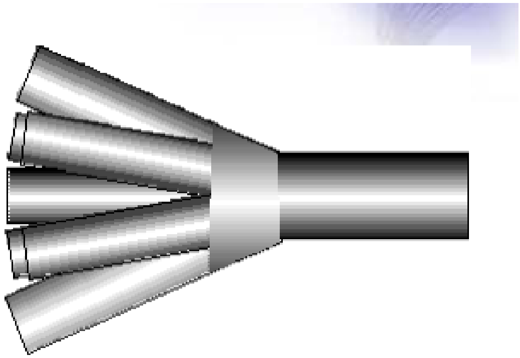
Typical delivery fibers for single emitter pumps (rows 1–2)

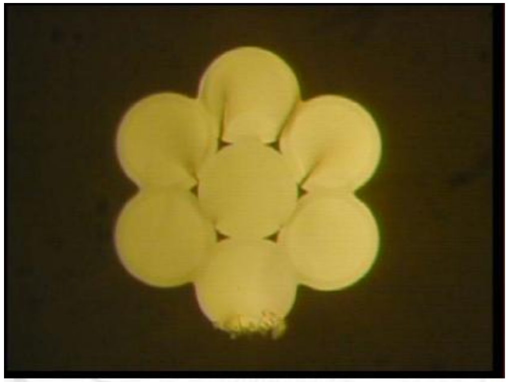
Typical delivery fibers for diode bar pumps (rows 3–4)

Input fibers\ Output fiber	125 μm PCF, NA =0.46	250 μm PCF, NA = 0.46	400 μm PCF, NA =0.46
105 / 125 μm, NA = 0.15	7 x 1	19 x 1	61 x 1
105 / 125 μm, NA = 0.22	4 x 1	7 x 1	37 x 1
200 / 220 μm, NA = 0.22	1 x 1	4 x 1	7 x 1
400 / 440 μm, NA = 0.46	N/A	1 x 1	3 x 1

Table 1: Multimode fused fiber bundle combiner arrangement as a function of input fibers (indicated with core/cladding diameters and numerical aperture). A 1 x 1 configuration indicates that a single input fiber can be tapered down and spliced to the output fiber without loss.







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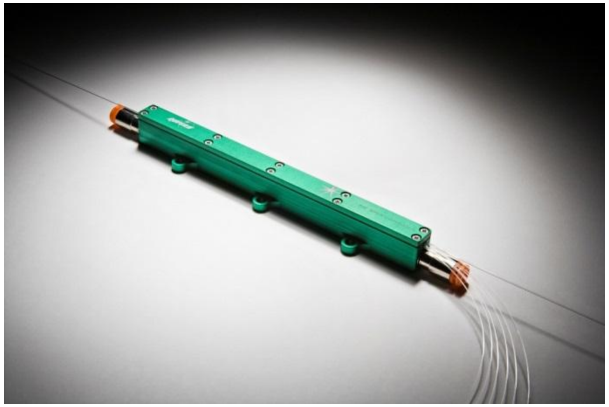
Part III: Example fiber laser and amplifier platforms

- In order to handle kW of pump light these combiners need to be low loss
- Versions carrying signal fiber are also needed for amplifiers (6+1 to 1)

	Co-Pump	Counter- P
Total	2.81 kW	2.2 kW
Pump	2.8 kW	1.1 kW
Signal	10W	1.1 kW
Loss (Pump)	< 0.1dB	< 0.1dB
Loss (Signal)	< 0.1dB	< 0.1dB
M^2	N/A	< 1.1



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H. Yu et al, Photonics West 2012

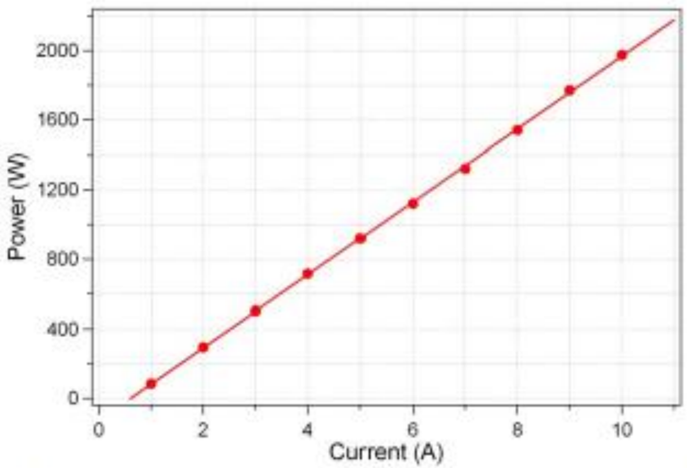

Figure 4. Pump power from the 19:1 combiner vs. diode current. The maximum pump power at 10 A was 2.0 kW. The output fiber of the pump combiner was spliced to an anti-reflection (AR) coated pigtail.

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Part III: Example fiber laser and amplifier platforms

- These combiners are commercially available from multiple suppliers in various standard configurations
- Cladding light strippers & end cap terminations are also commercially available to match the various standard LMA fibers

ITF Labs

Part No.	Fiber Type	Operating Wavelength	Max Absorbed Power	Absorbtion	Signal Loss
CPS10011	20/400 µm NA=0.06/0.46	800-1000	100 W	>20 dB	<0.1 dB
CPS10033	25/250 µm NA=0.11/0.46	800-1000	100 W	>20 dB	<0.2 dB
CPS10044	15/130 µm NA=0.08/0.46	800-1000	100 W	>20 dB	<0.3 dB
CPS10055	PM 20/400 µm NA=0.06/0.46	800-1000	100 W	>20 dB	<0.1 dB
CPS10077	PM 25/250 µm NA=0.11/0.46	800-1000	100 W	>20 dB	<0.2 dB
CPS10088	PM 15/130 µm NA=0.08/0.46	800-1000	100 W	>20 dB	<0.3 dB

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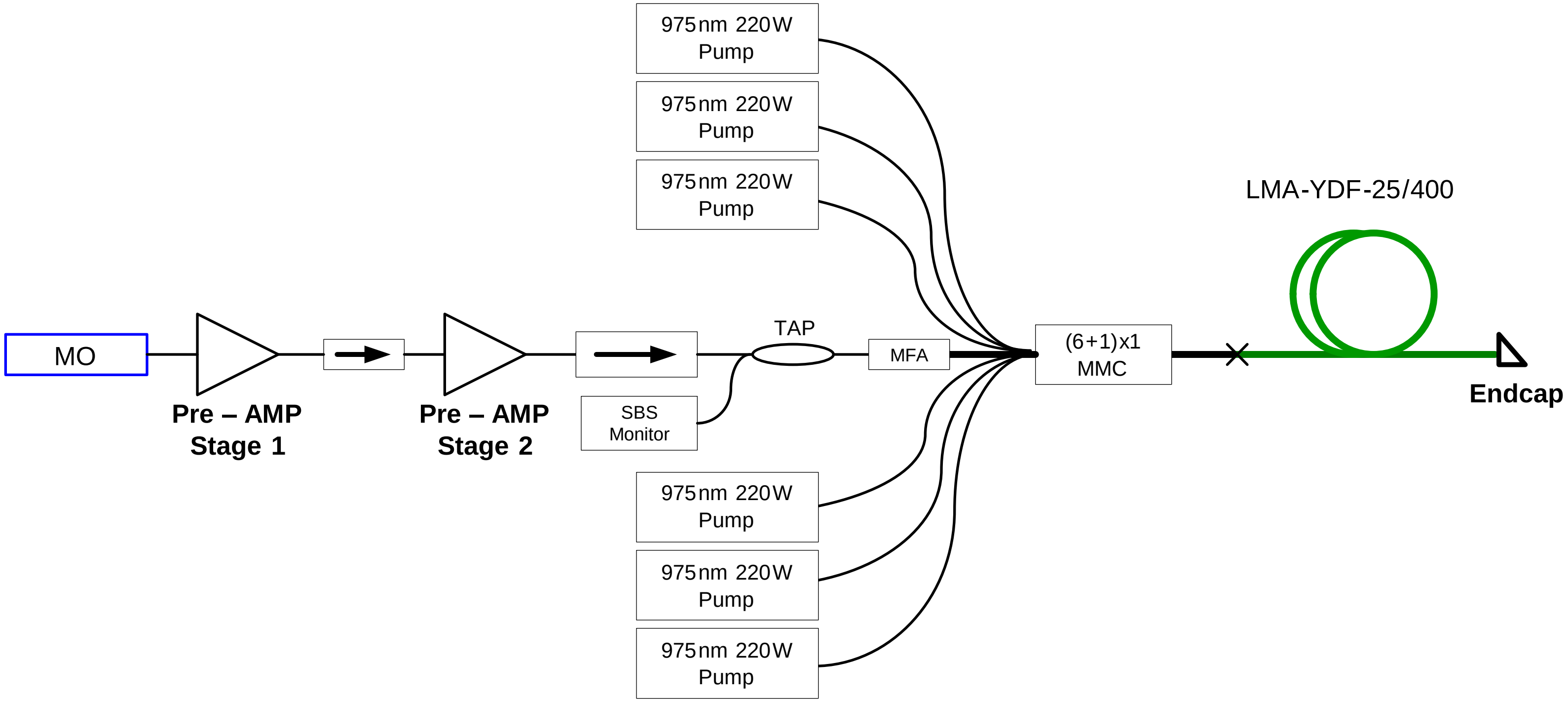
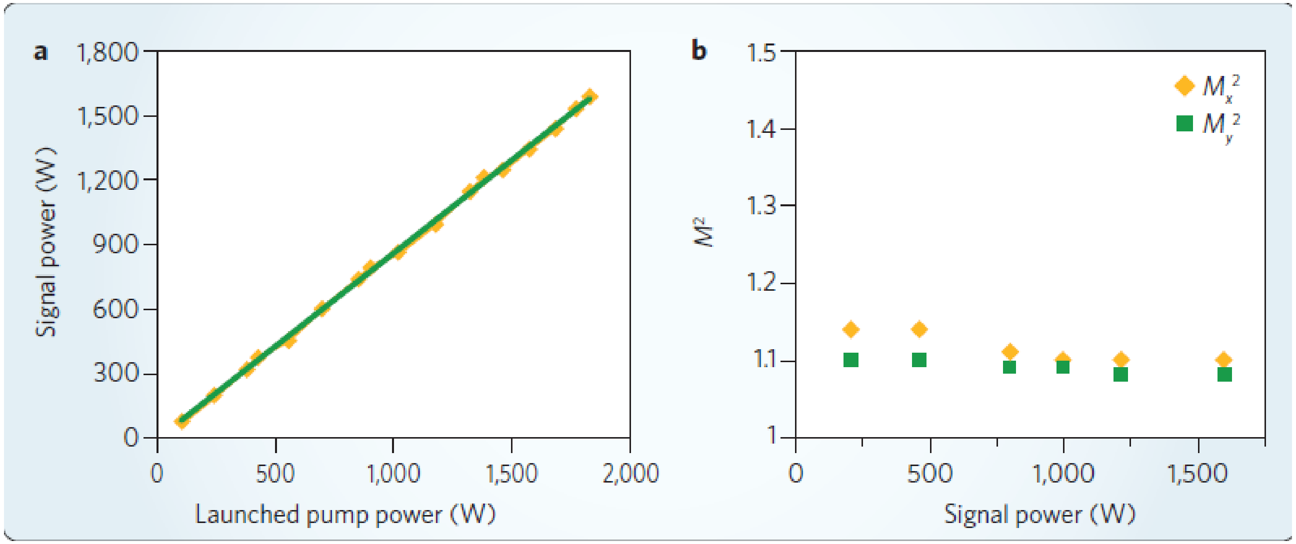
Part III: Example fiber laser and amplifier platforms

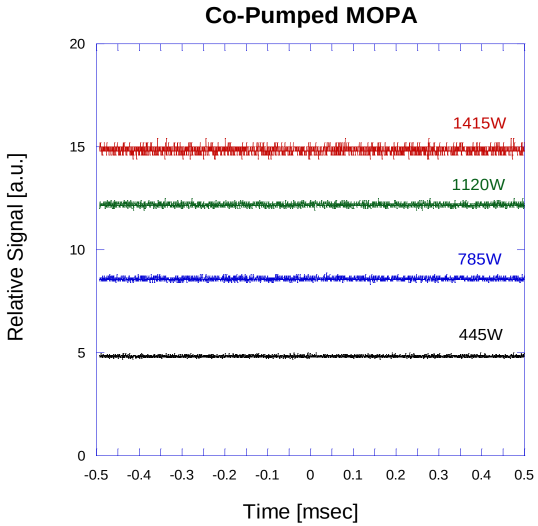
- For some applications a MOPA system (master oscillator, power amplifier) is preferred and can contain multiple amplifier stages with inter-stage isolation
- Can use PM fiber for a linear polarized output and deliver narrow linewidth output better than a high power FBG laser cavity



Part III: Example fiber laser and amplifier platforms

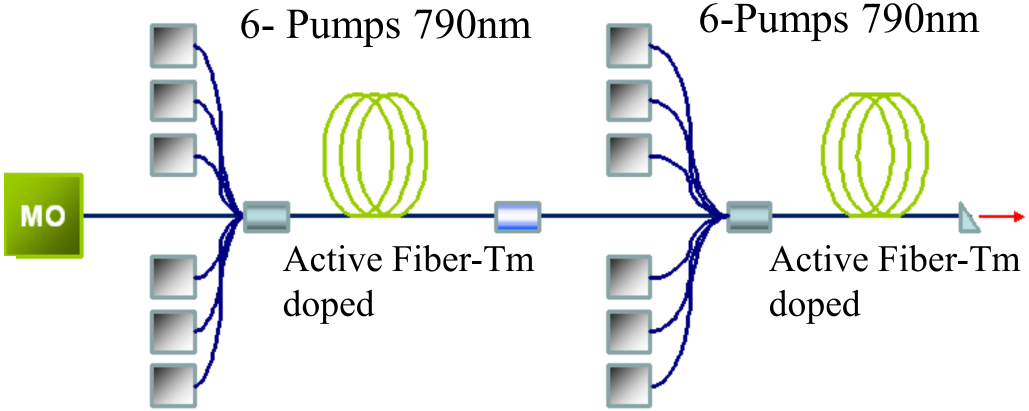
- Co-pumped MOPA operating at ~1.5kW using LMA-YDF fiber and delivering single mode output with no sign of multimode instability (MMI)

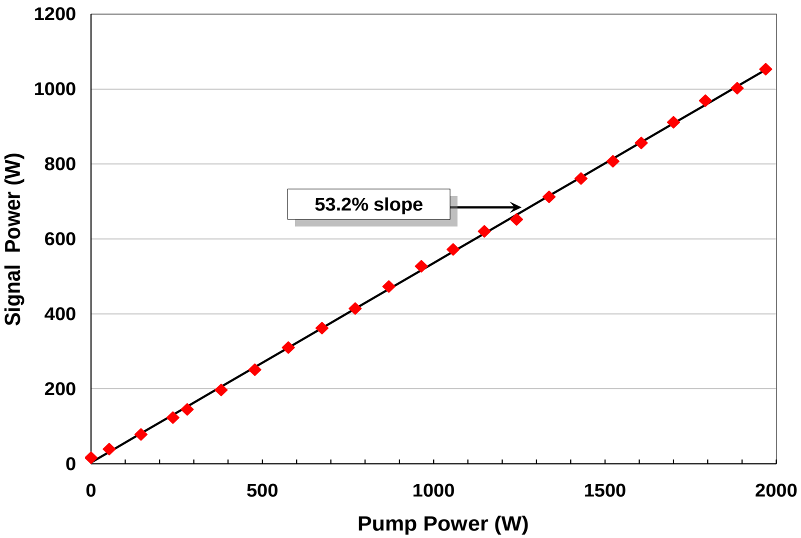




Part III: Example fiber laser and amplifier platforms

- Tm-doped fibers have operated at 1kW output power, pumped at 790nm
- Delivering good beam quality from standard LMA Tm- doped fiber in 2-stage MOPA system





T. Ehrenreich et al, Photonics West 2012

Part IV: Future Trends and Conclusion

- Further improvements in Yb-doped LMA fibers for higher output power without multimode instability (MMI) & maintaining beam quality
- New fiber technologies continue to be developed with advances in fibers aimed at higher performance lasers
- In general the goal of all of these new fiber technologies is to scale the core diameter to >30μm (current limit of LMA fibers) without deteriorating the beam quality
- This is now the major focus of most of the emerging silica based fiber designs
- Much of the focus is towards ultra-fast fiber lasers where the fiber can limit the performance of the device
- Examples include, tapered fibers, large flattened mode (LFM) fibers, chirally coupled core (CCC) fibers, photonics crystal fibers (PCF), rod-type fibers, leakage channel fibers (LCF), photonics bandgap fibers (PBG), higher order mode (HOM) fibers

Part IV: Future Trends and Conclusion

- Fiber laser industry has benefited from standardization of Yb-doped fibers and associated components over the last 10 years
  - This has helped drive down the costs of the technology
  - Made it easier for new entrants into the fiber laser market without the need to make their own fiber
- Maturity of the 2μm fiber laser technology is occurring and new applications emerging
  - This will increase demand and drive down costs for fibers, components and pumps
- Growing interest in improving the performance of fibers for ultra-fast fiber lasers
  - Currently pushing the limit of LMA fiber performance and now driving the research into new fiber technologies

Part IV: Conclusion and Q&A

- Thank you for your attention

- Any questions?