DND Technology - a Core platform for Specialty Mode Guiding Structures

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The Nanoparticle Fiber Company

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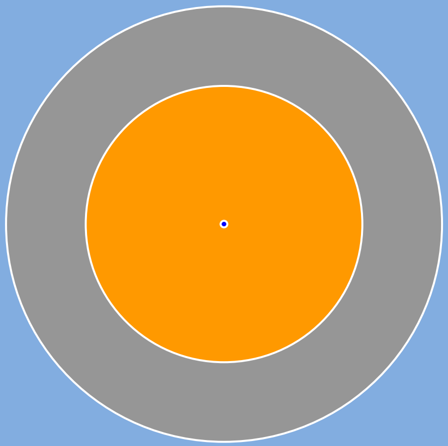
www.liekki.com

Synopsis

- What’s DND and why is it good for you
- Comparisons with other processes
- DND made DC fibers - performance
- New developments and new potential
- Photodarkening measurements
- Conclusions

Active fibers very different from Telecom fiber - much more required from manufacturing Process

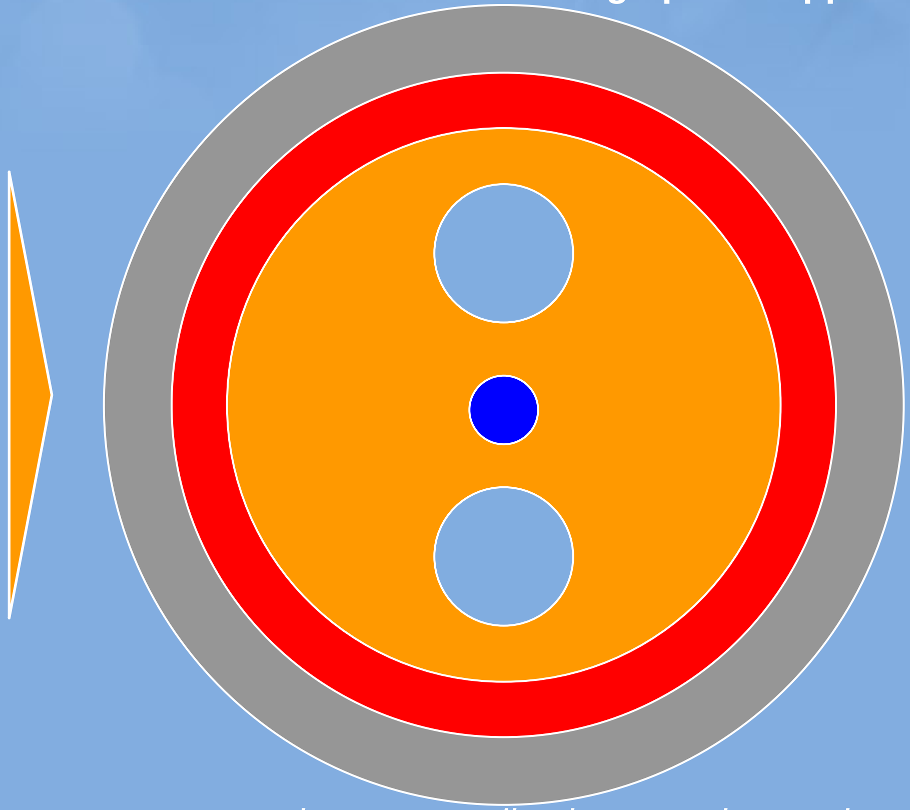
Doped fiber used in traditional telecom



Existing fiber production technologies were developed for traditional telecom fibers...

- Small core/cladding ratio
- Very small core volume
- Thick plain glass cladding with acrylate coating
- Simple geometry

Double clad LMA fiber for high power applications



New requirements

- *Much larger cores*
- *High doping levels*
- *Controlled doping and homogenity across core*
- *No photodarkening*

... but new applications require much more from the production process

- Large core/cladding ratio
- Double clad, dual coated
- Novel geometries, stress rods for PM

Processes used for specialty fiber fabrication

PROCESS	METHOD	RE?	RE DELIVERY (to soot)	DOPING METHOD
OVD*	Hydrolysis	(X)	Aerosol/Vapor/Solution	Diffusion
VAD*	Hydrolysis	(X)	Aerosol/Vapor/Solution	Diffusion
PCVD	Oxidation	?		
MCVD*	Oxidation	X	Solution/Vapor(/Chelate)	Diffusion
DND	Hydrolysis	X	Liquid droplets (Aerosol)	Direct doping

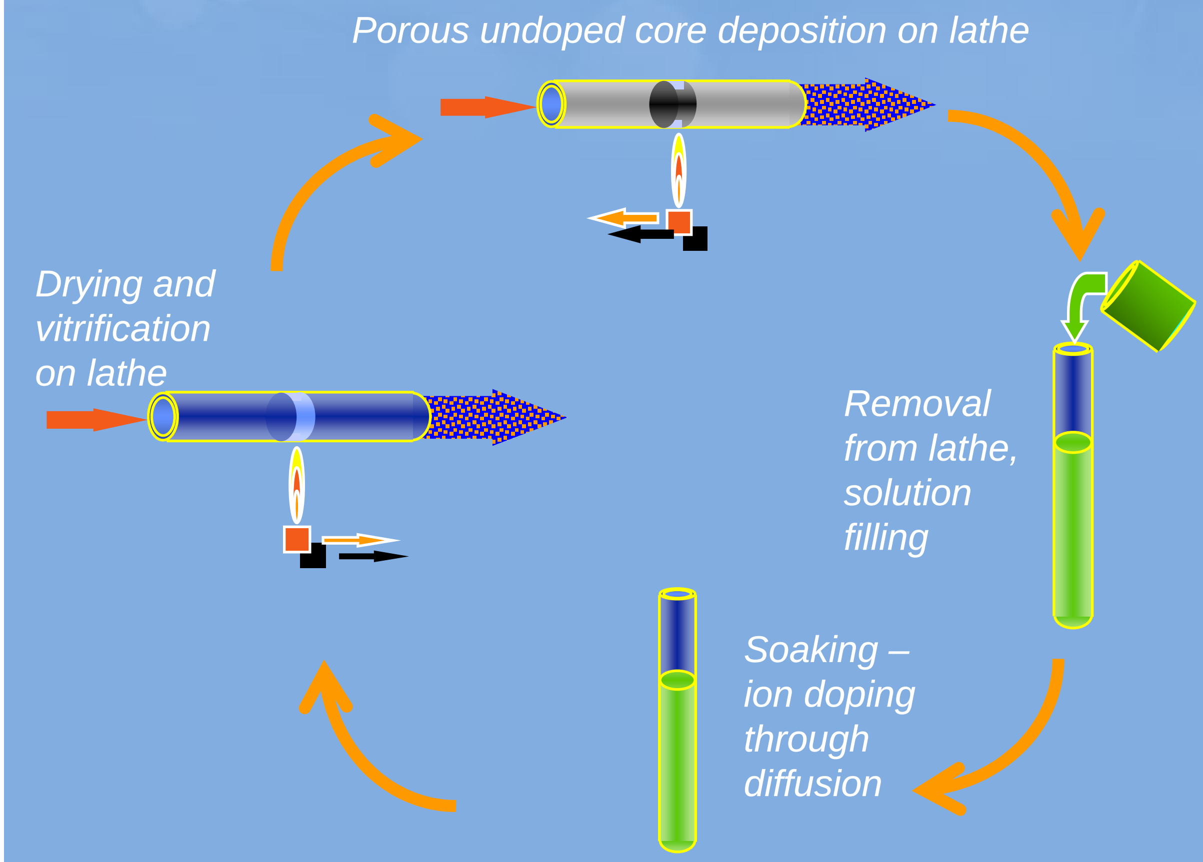
*Fundamental problems in delivering RE ions to reaction zone – delivery temperatures of ~200 degC required.

Optical fiber fabrication methods

Process	Users
Modified Chemical Vapor Deposition – MCVD	OFS, Fibercore
Vapor Axial Deposition – VAD	Shin-Etsu
Plasma Chemical Vapor Deposition – PCVD	Draka
Modified Chemical Vapor Deposition – MCVD	IPG, Nufern, SPI
Direct Nanoparticle Deposition – DND	Liekki
Outside Vapor Deposition – OVD	Corning

→ Specialty Fibers

MCVD with solution doping is cumbersome



Porous undoped core deposition on lathe

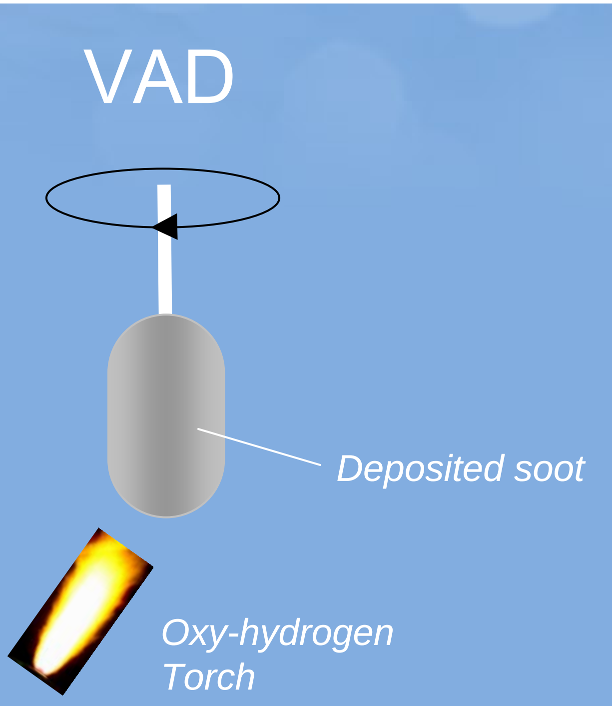
Removal from lathe, solution filling

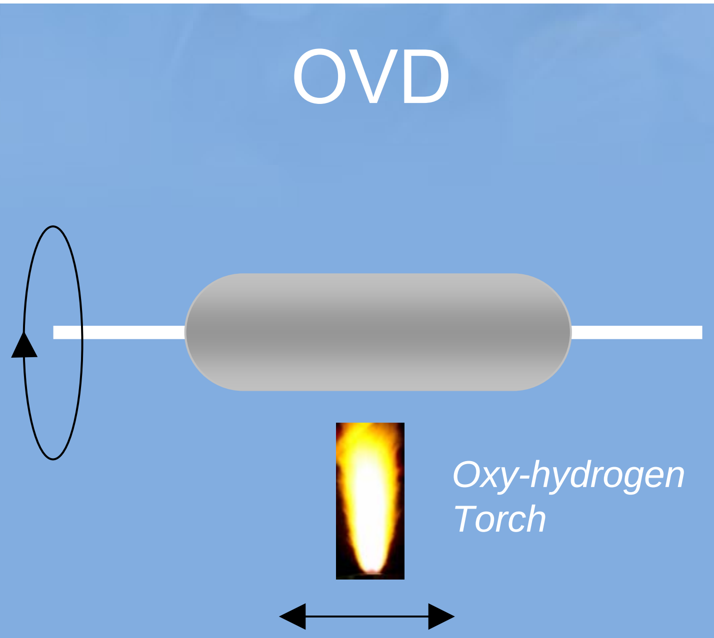
Soaking – ion doping through diffusion

Drying and vitrification on lathe

- No stable high vapor pressure precursors for RE doping - solution doping is the modification of choice to existing MCVD equipment
- Iterative 4-phase process with long throughput times
- Non-uniform (directional) doping --> sensitiver to production parameters
- Diffusion process --> clustering limits concentration
- Typically 2-4 deposition layers

Flame Hydrolysys Techniques - VAD and OVD



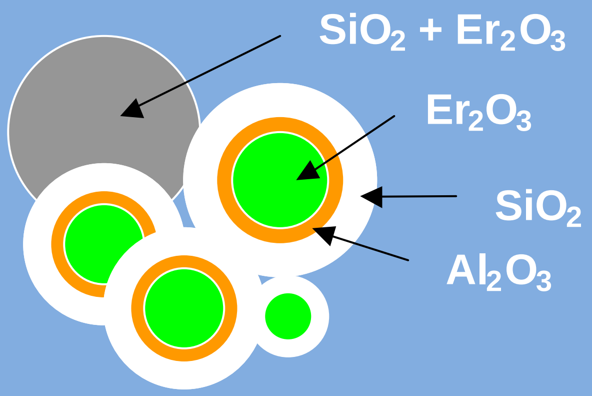


- Si and waveguiding dopants typically delivered as Chlorides
- Rare Earths (RE) can (in principle) be delivered as vapors, aerosols or solution
- RE's tend to cluster – limited doping concentration (equipment modifications may help - but at cost of increased complexity)
- Economics for modified version used for specialty fibers (Corning) still TBD
- Flame hydrolysis techniques suitable for large volume telcom grade fibers but lack flexibility

OVD/VAD vs MCVD Process

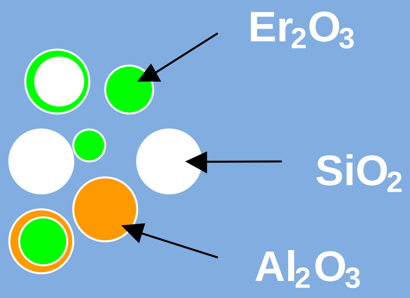
OVD / VAD

- Doping during soot deposition
- flame hydrolysis => large particles



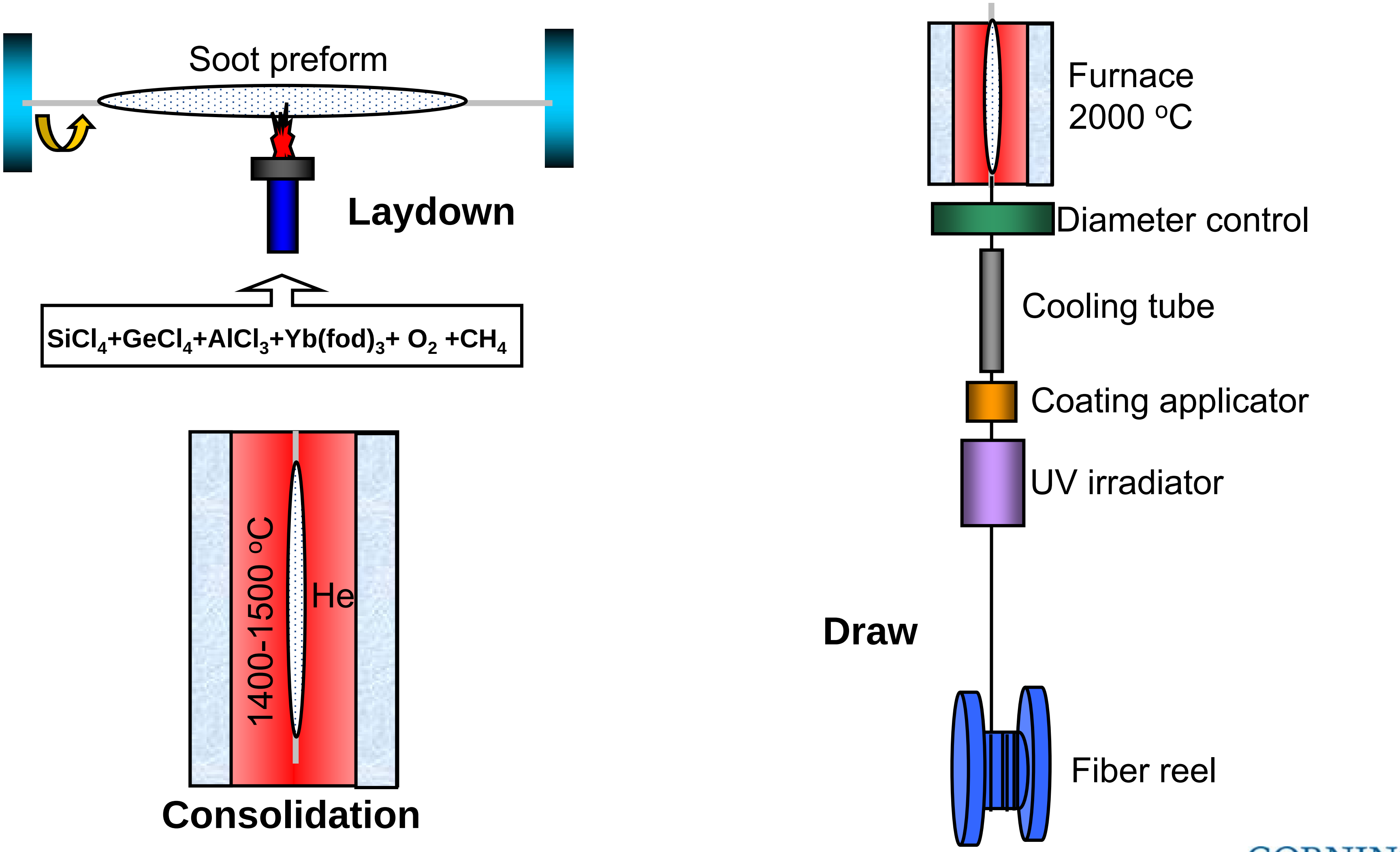
MCVD

- doping after soot deposition
- oxidation => small particles



Reference: ”Optical Amplifiers: materials, devices, and applications” , Shoichi Sudo editor, Artech House 1997

Outside vapor deposition (OVD) is telecom-proven technique of producing reliable optical fiber



Soot preform

Laydown

$SiCl_4+GeCl_4+AlCl_3+Yb(fod)_3+O_2+CH_4$

1400-1500 °C

He

Consolidation

Furnace
2000 °C

Diameter control

Cooling tube

Coating applicator

UV irradiator

Draw

Fiber reel

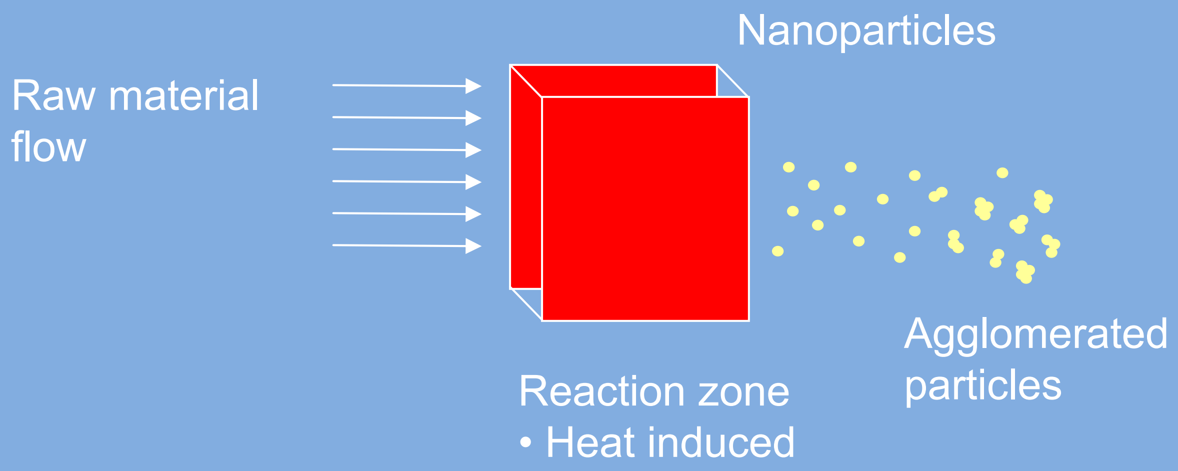
What nanoparticle technology provides

Key Process Advantages

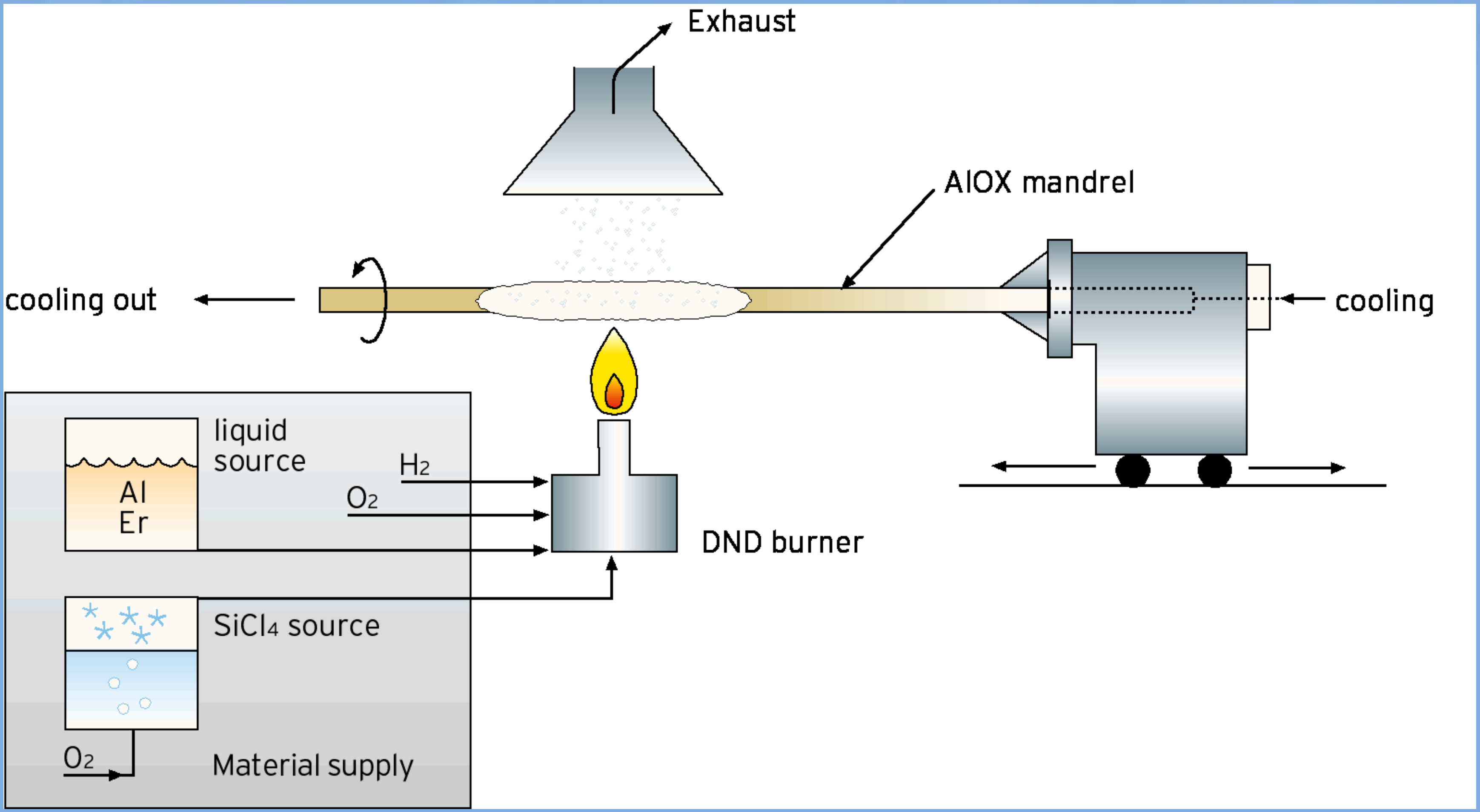
- Possible to use both high and low vapor pressure raw materials
- Good homogeneity of the sintered glass
- Homogeneous sites for the rare-earth ions
- A nanoparticle generation and deposition process offers great flexibility

Process Challenges

- Agglomeration can limit the nanoparticle generation speed
- Small particle size moderates growth rate --> trade-off against accuracy, yield

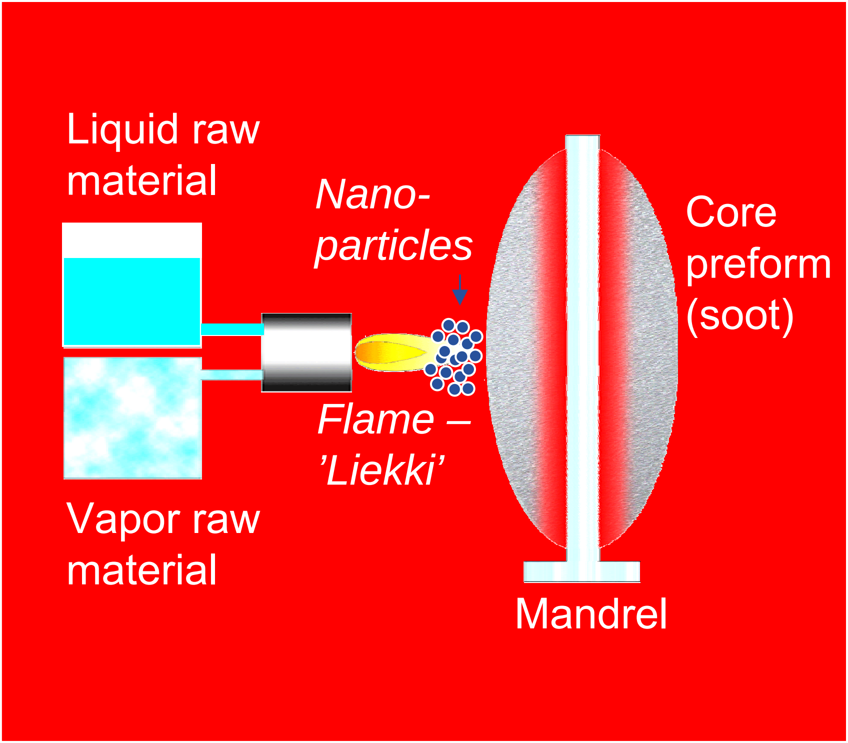


DND Fiber Preform Manufacturing Principles



Liekki DND process: a breakthrough approach to manufacturing Guided Wave Structures

Liekki Direct Nanoparticle Deposition (DND) process overview



Unique patented process

- Combustion of gaseous and atomized liquid raw materials

  --> All-liquid sources possible

  --> Greater flexibility for RE doping

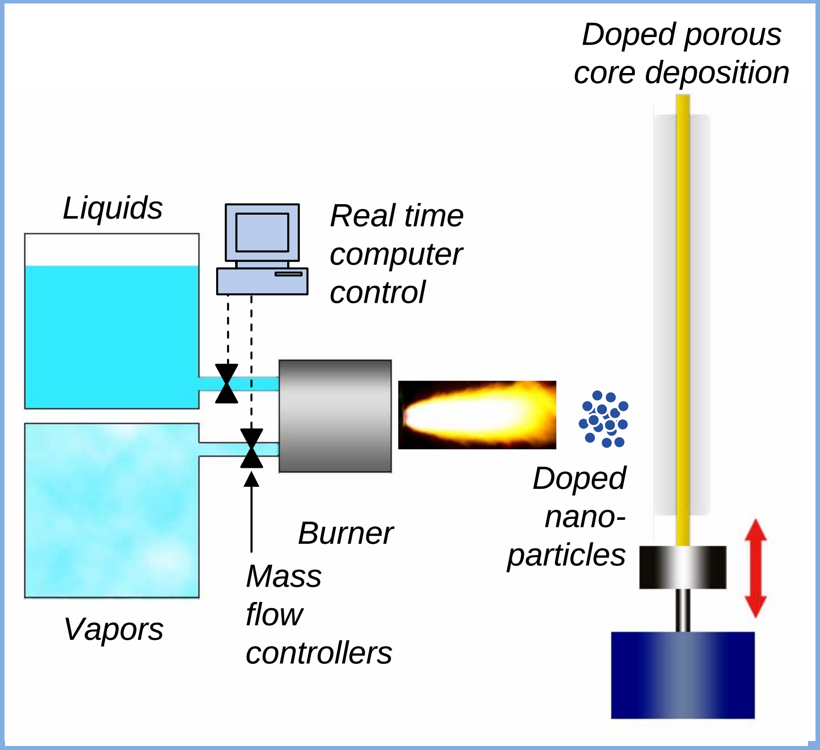
- Accurate control of the doping profile – ***flat refractive index profile (RIP) -->***

  Ideal for Large Mode Area (LMA)

- High dopant concentrations **–->** ***shorter application lengths***

Liekki's DND process uses nanoparticle deposition for highly controllable doping

Liekki DND process overview



Process features

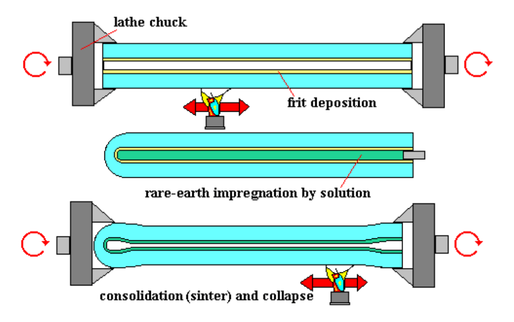
- Direct, single-step doping process
- Creates 100s of doped nanoparticle layers in core - superior consistency, minimizes clustering --> high doping
- Simultaneous and independent radial control of guiding (index-effecting) and active dopants
- Rapid process, LMA core in matter of hours
- Can be readily adapted to non-circular structures (rectangular)

S. Tammela et al., " Potential of nanoparticle technologies for next generation erbium-doped fibers" OFC'04, OFC2004 Technical digest, FB5 (2004)

DND technology is a breakthrough in fiber manufacturing process capability

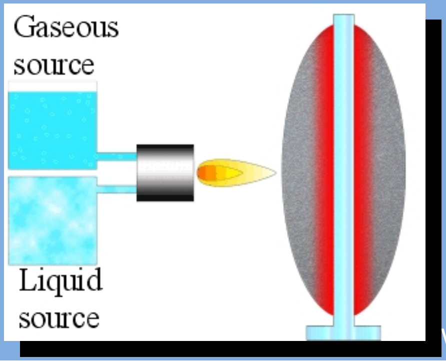
Incumbent MCVD process

- 35 years in industrialization – at end of S-curve
- Designed for traditional small core telecom fiber production
- Large particle size = microns
- Typically an in-tube deposition process
- Solution diffusion of dopants into glass – few layers of doped material, clustering
- Moderate doping of active elements
- Slow, multi-step process for large cores
- Moderate threshold to photodarkening
- Control of radial doping profile difficult
- Complex process required for flat RIP and elimination of core burn out
- Limited to round fiber core geometries

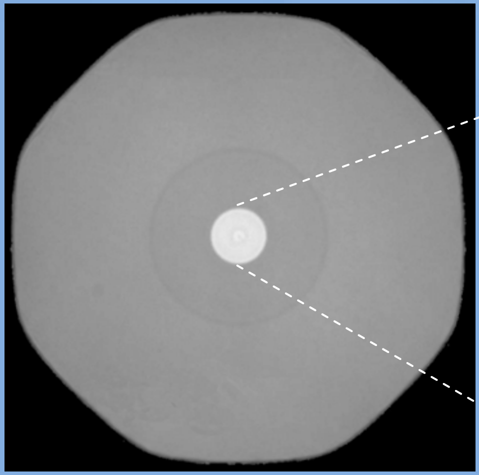


DND fiber process

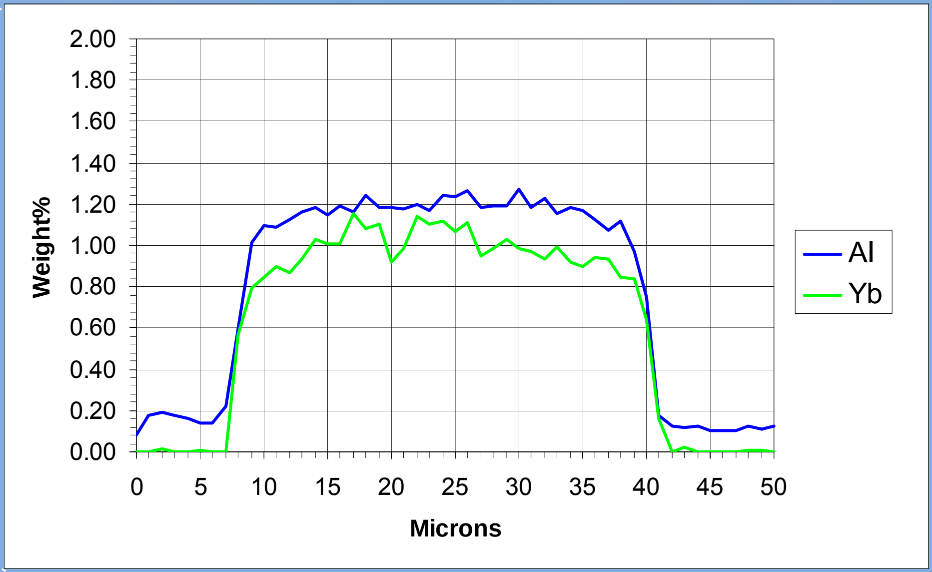
- 6 years into industrialization – at beginning of S-curve
- Designed for advanced highly doped large mode area fiber production
- Small particle size = nanometers
- Outside-tube deposition process
- Direct deposition of dopants within glass – 100s of layers doped material, no clustering
- Highest possible doping of active elements
- Fast direct deposition of large cores
- High threshold to photodarkening
- Accurate radial control of doping profile
- Inherent flat RIP and no core burn out
- Square fiber core geometries and planar designs possible



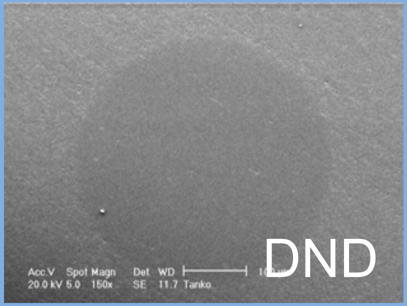
Homogeneous fiber core – crucial for fiber application performance

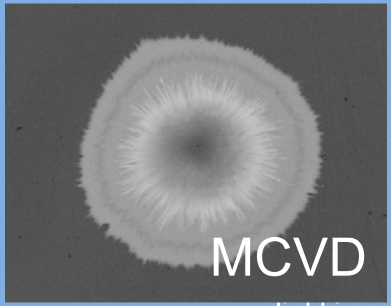


Doping distribution

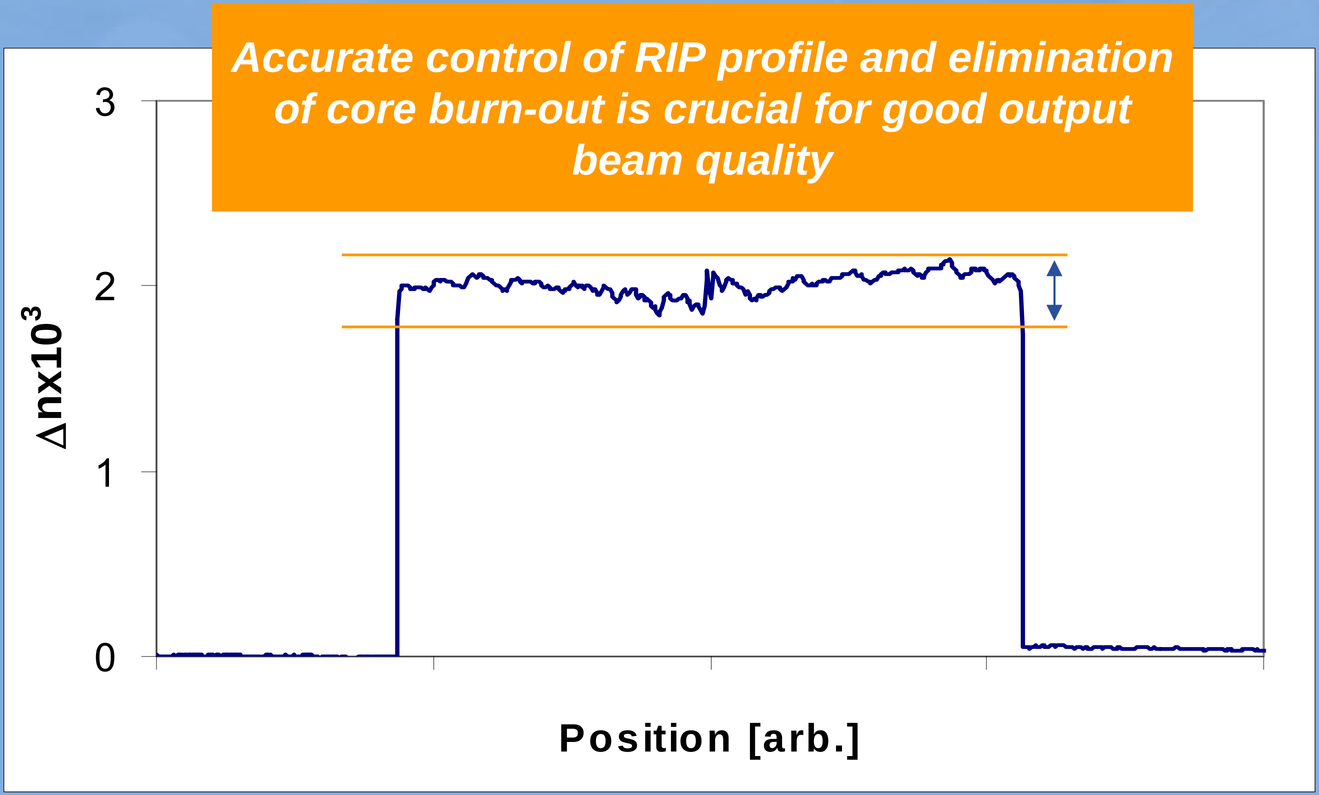


Fiber made with Liekki DND technology
- Homogeneous doping, 100s of layers
- High doping, low clustering
- No core burn-out
- Sharp geometry, large core/clad possible





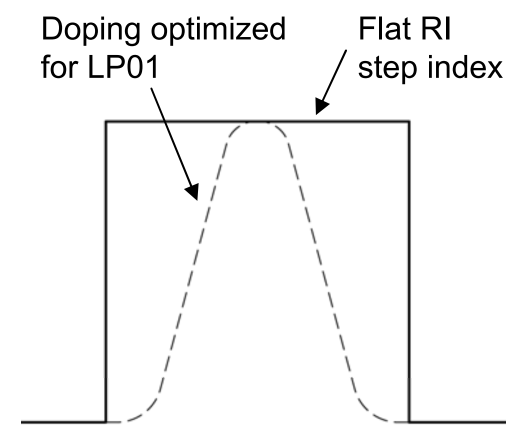
High Doping Control Required for Flat RIP -->
Key Goal for LMA Fibers: Eliminate Core Burn-Out



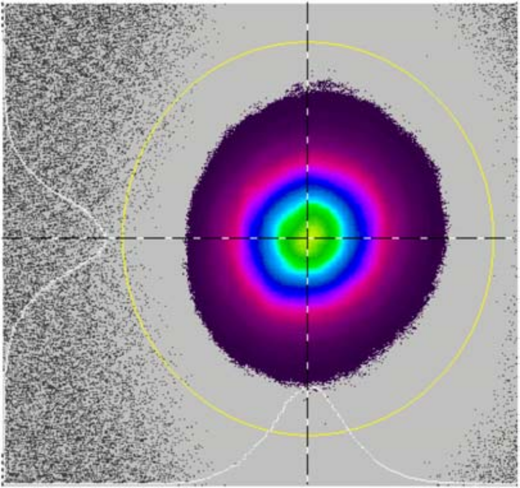
Accurate control of RIP profile and elimination of core burn-out is crucial for good output beam quality

- With DND - Typical radial refractive index variation: < ± 15%
  Profile variation along preform < ± 5%

Radial profile control for improved LP01 tranmission/amplification



M^2 ~1.6 for 25μm, 0.065 NA



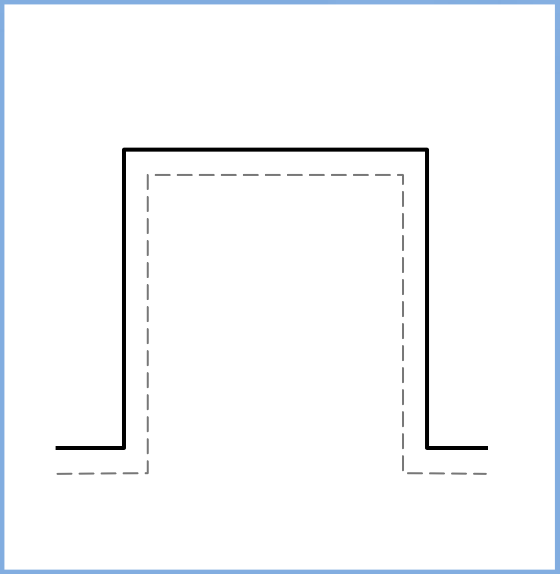
- Preferential gain for LP01 by matching doping with fundamental mode
- LAD used to optimize the doping profile for a straight fiber
- Up to 7dB higher gain for LP01 vrs next mode in 25μm core expected
- Constrained by mode distortion/offset when fiber is bent
- M^2 ~1.6 measured with loosely coiled (20cm diameter) 25μm core fiber

ILLUSTRATIVE

Exploit DND’s <u>independent</u> and <u>accurate</u> control of both doping profile and RIP

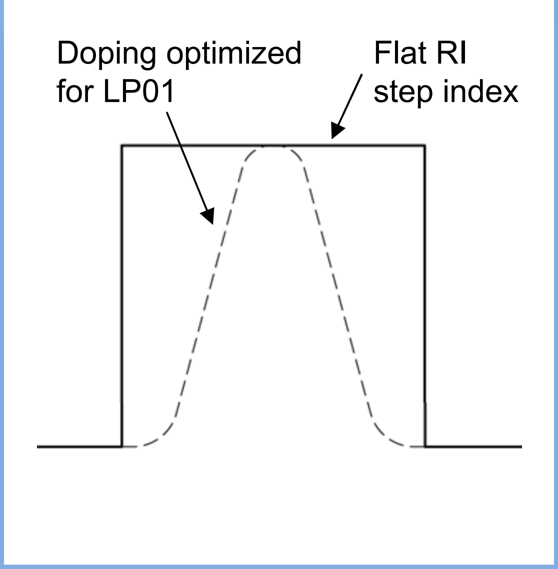
——— *Refractive index (RI)*
– – – – – *Doping*

✓

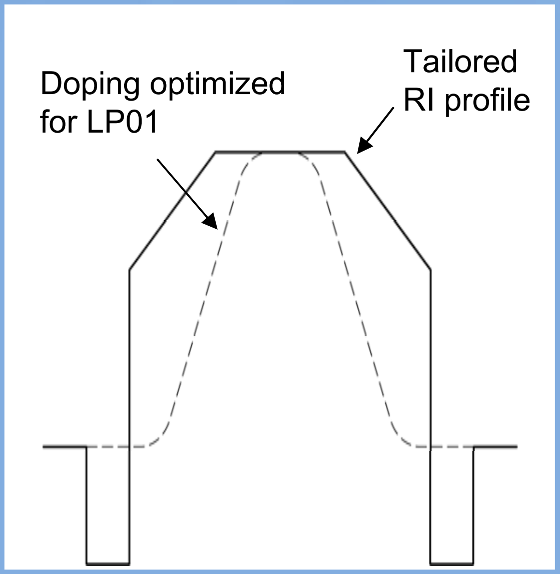


Conventional
- Step index RI
- Normal or confined doping
- No radial control
- Beam quality may suffer from core burnout

✓



Current with DND
- Very flat RI, no core burnout
- Doping optimized for LP01 – preferential gain
- Good beam quality, no core burnout



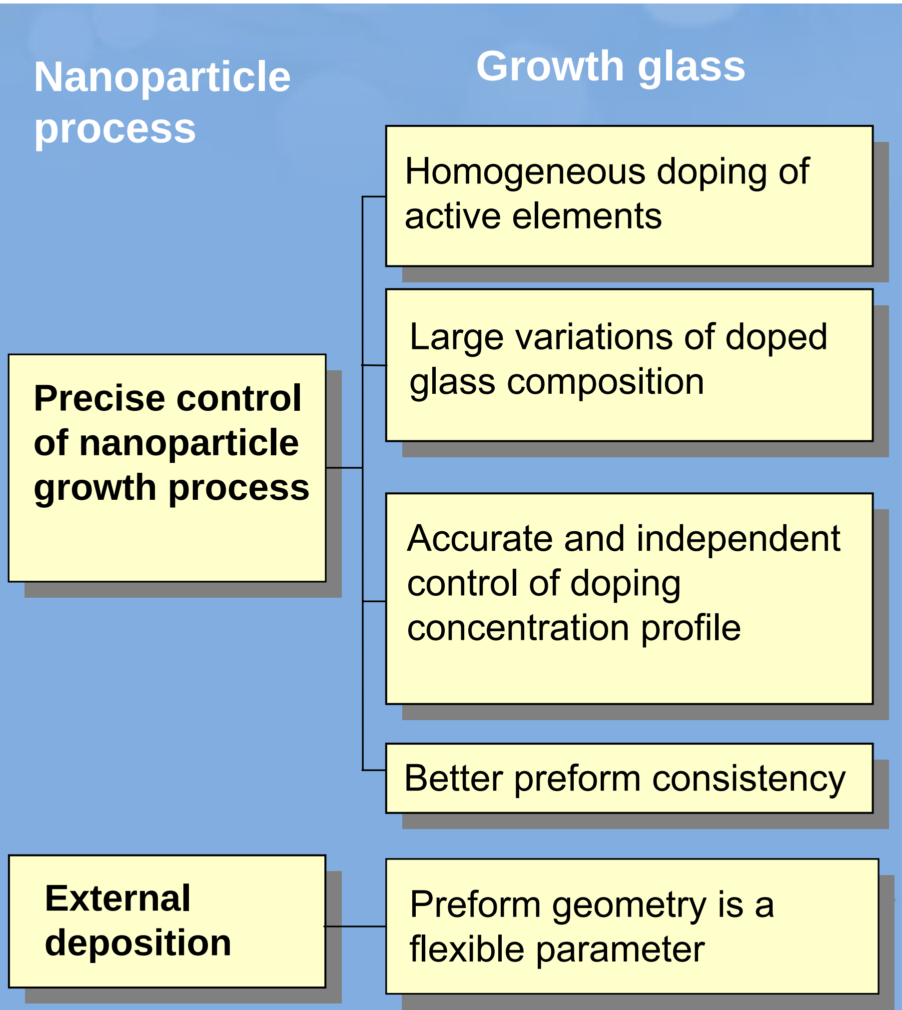
Future with DND (illustrative)
- Radial control of both RI and doping
- Large core single mode

DND capabilities match up well with advanced high-power fiber laser requiremements

Requirement	DND technology	Conventional technologies (MCVD, solution doping)
Increasing peak and average power levels (power scaling)	•High-doping •Short fibers	•Medium/low doping •Medium/long fibers
Improved power and thermal efficiency	•High efficiency •Good power tolerance	•High efficiency
Improved beam quality	•Accurate and independent RIP control, rapid single-step process	•Poor/laboursome RIP control, iterative process
Improved product quality and lifetime	•Much improved photodarkening resistance •Large core-to-clad ratio LMA preforms/fibers	•Poor photodarkening performance (except phosphosilicate?) •Limited core-to-clad ratios

DND process capabilities offer even more potential for advanced fiber manufacturing - e.g., core platform!

What Nanoparticle Technology can Provide



Nanoparticle process

Growth glass

Precise control of nanoparticle growth process

- Homogeneous doping of active elements
- Large variations of doped glass composition
- Accurate and independent control of doping concentration profile
- Better preform consistency

External deposition

- Preform geometry is a flexible parameter

Benefits in fiber

Higher doping possible
- Shorter fiber required for laser application
- Lower cost
- Better performance on
  - Bending loss, PMD and nonlinear effects

Simpler glass structure
- Uniform local environment for the RE ions
  - Repeatable spectral properties

Homogeneity and control on refractive index
  - Less mode coupling in LMA fibers

Short and large diameter core preforms
  - LMA fibers with small core/cladding ratio
  - Simpler glass work

Outside-the-tube Deposition
  - **Potential for Core Platform - A new paradigm in active fiber manufacture**

NANOPARTICLE TECHNOLOGY ADVANTAGES SUMMARY

- **Nanoparticle technology provides**
  - –Possibility of using high and low vapor pressure materials simultaneously
  - –Potential to produce uniform material both in nano- and macroscopic scale
  - –Independent selection of deposition process and preform geometry
    - New types of doped/undoped waveguide structures
  - –Scalability - process speed, yield, geometries, performance

To rare-earth doped fibers this means

- –Higher concentrations, shorter fibers, less non-linearity and dispersion
- –Potential for lowering susceptibility to photodarkening and other degradation mechanisms by more precise engineering of compositions
- –Better uniformity in doping and in spectral properties
  - Within fiber, both in lateral and longitudinal
  - From fiber to fiber
- –Simpler preform glass work
- –Wide range of core/cladding ratios (small to large)

The Road toward Mass Customization - Streamlining of Fiber manufacturing Process

- Market for LMA Fibers is highly fragmented - Broad requirements trade space, high demand for custom fibers
  - So many different fibers, so few standards
  - Little commonality between vendors' definitions of fiber attributes (doping level, fiber efficiency, polarization, etc.)
  - In-fiber components need to be developed for each class of fiber

- Mass Customization model needed for manufacturing a broad :variety of fibers optimized for different applications
  - Core sizes that range from SMF to very large mode areas (100µm)
  - Different core-to-clad ratios for different applications using different pumping methods
  - The challenge: optimize core and clad separately would streamline process
    - Examples: One core - different claddings - All glass, PM, raised, coatings
    - Requires process with fast preform production and advanced draw technology (sleeving)
  - Advantages: Customization of product moved down the fabrication steps (final draw)
    - Provide custom fibers without sacrificing overall yields --> Better process economy
    - A uniform production environment for both standard and custom waveguides
    - Improve availability of in-fiber components(e.g., FBG's) and matched passive structure

DND COMPATIBLE WITH CORE PLATFORM

- **External deposition allows stocking separate core preforms designed to different specifications**
  - – Variations may include; alternate compositions, doping concentrations/ profiles, range of NA’S, different dimensions. ranked quality ratings
  - – Offer high degree of selectivity, e.g., for CW vs.pulsed applications
  - – Rapid deposition process will allow highest resistance to photodarkening

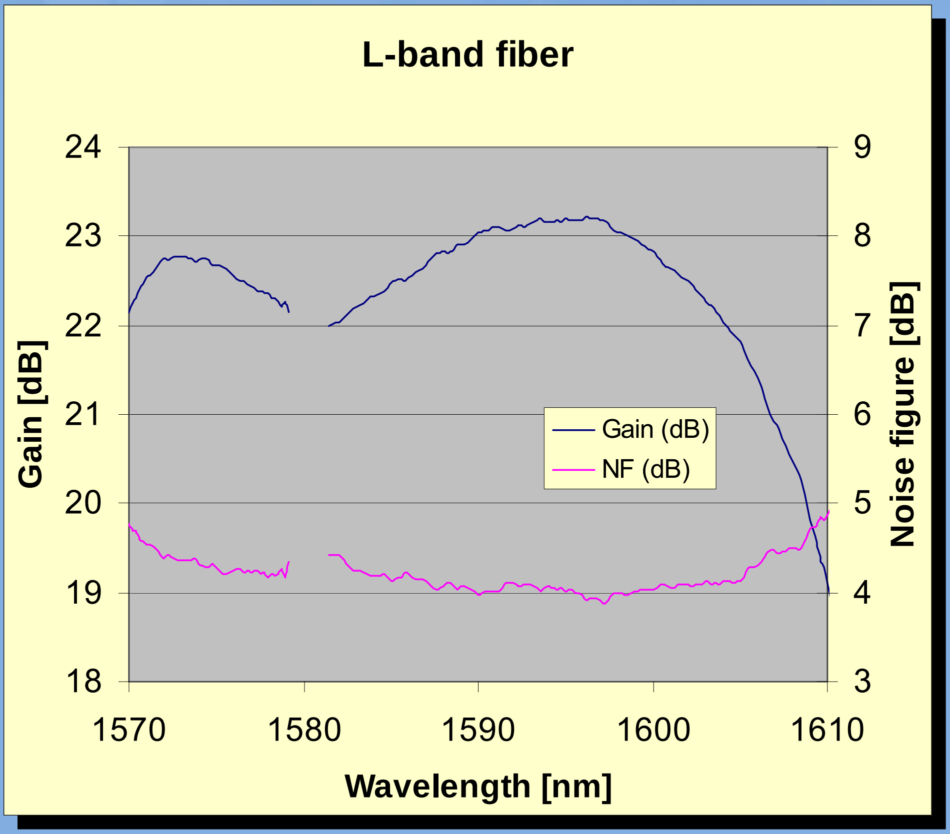
- **Single core preform can be used for several different clad structures**
  - – Greatly improved process economies
  - –Sleeving
  - – New fabrication paradigm for lasers: mass customization at affordable prices - the right thing for a highly fractured (but idea-rich) market?

- **Wide applicability to circular and non-circular structures**
  - – Can be used for all circular fiber types, including PCF’s
  - – Can be modified for planar wave guiding structures (fiber and/or wafer)
  - – a new approach to mass customization of wave-guiding structures

Brief history of Liekki

Early 1990s	DND research initiated
1999	Company founded
1999-2002	Focus on telecom, Er
2003-2005	Extension to laser market, Yb
Today	* Full-blown Yb-DCF(-PM) LMA product range * Erbium fibers * Mached passives & FBGs * Optical Engines * Liekki Application Designer software (LAD) * Photodarkening Measurements * Radial doping capability

Highly-doped DND Er fibers demonstrated <u>low clustering</u> and high-efficiency in 2001-2

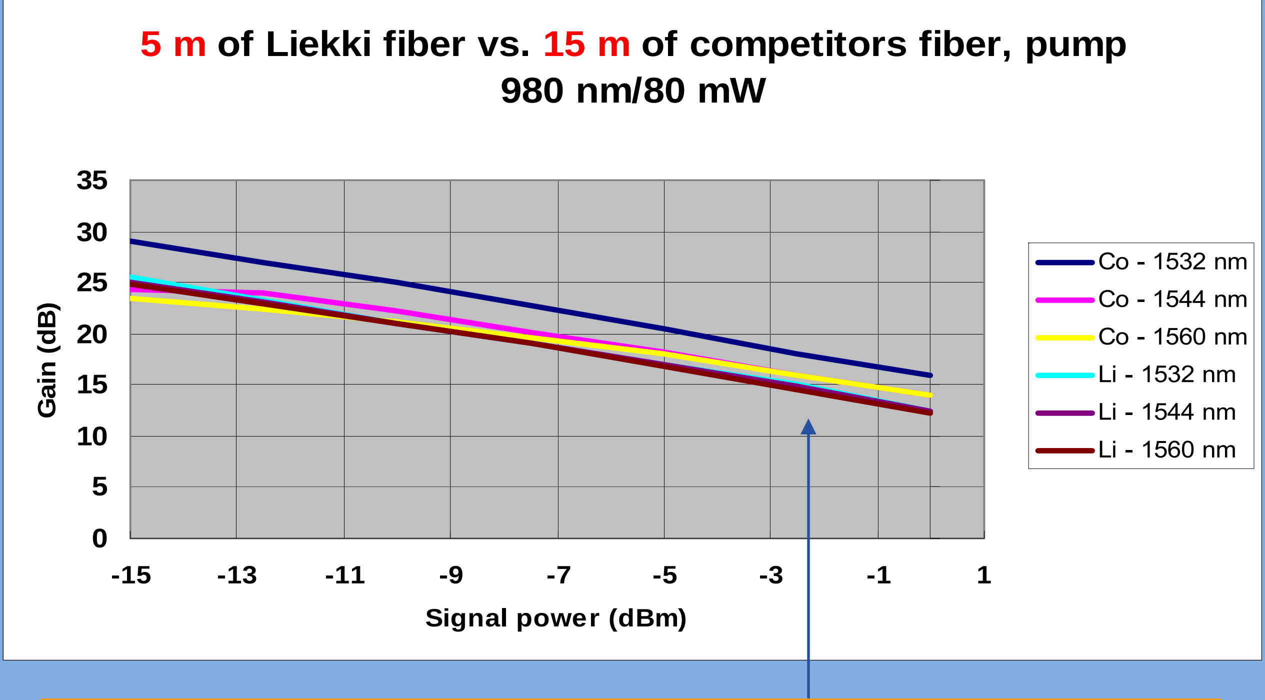


- Liekki among first to released highly-doped Er-fibers in 2002
- Much reduced length, 22m vrs ~70m (conventional Er-fiber)
- Low level of Er-ion clustering
- Very high L-band efficiency with QCE: 65%

S. Tammela et al., “Very short Er-doped silica glass fiber for L-band amplifiers,” OFC’03, OFC2003 Technical digest, 1, 376-377 (2003)

Higher doping means improved performance and shorter fiber

Comparison of Er fiber gain profiles for different wavelengths



5 m of Liekki fiber vs. 15 m of competitors fiber, pump 980 nm/80 mW

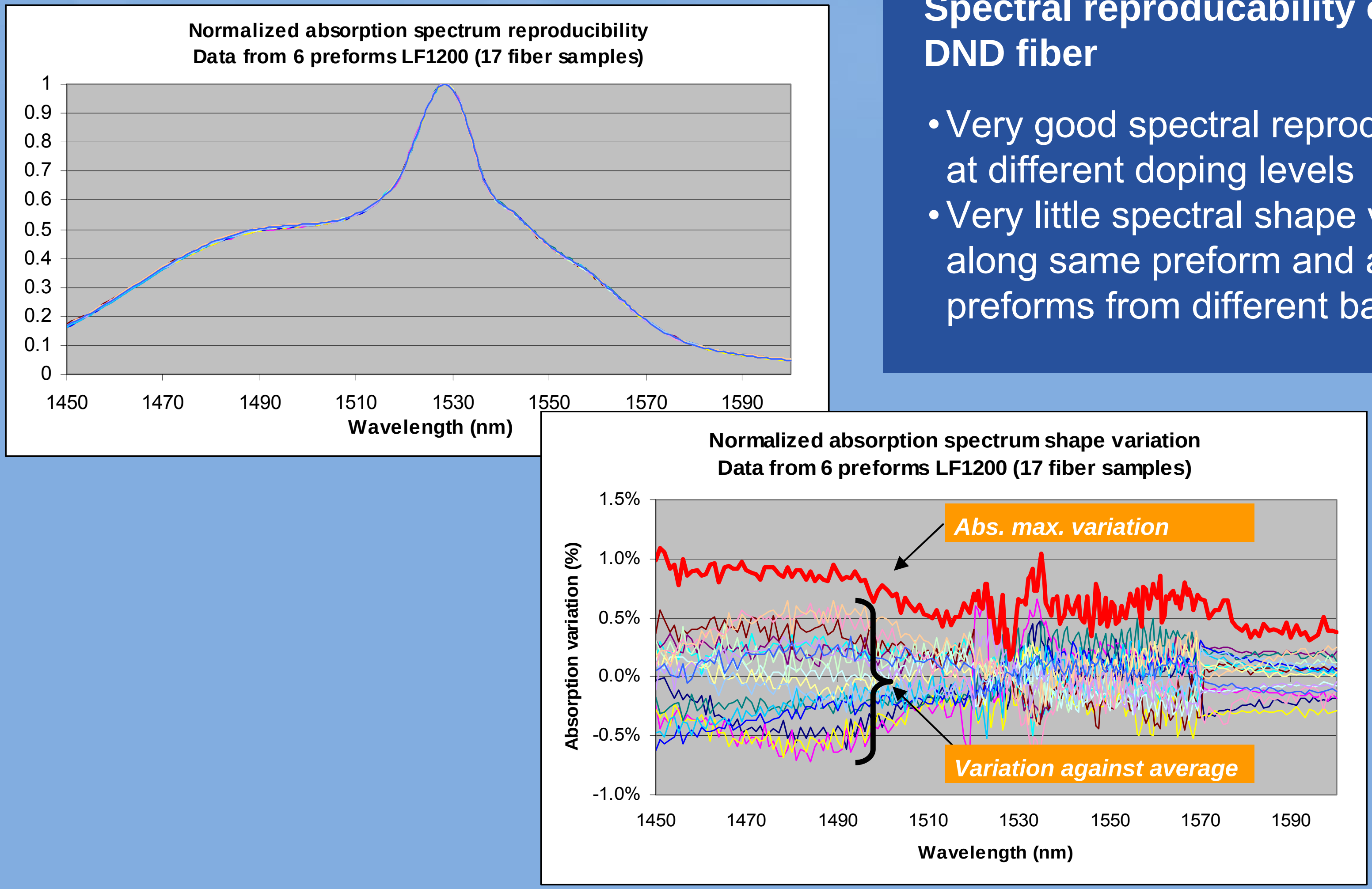
Same or better performance with 60% less fiber!

Beneficial Features

- Higher gain per unit length, up to 70% less fiber needed – lower materials and assembly cost
- Shorter fiber – less undesired nonlinearity and PMD effects
- Flat and wide gain spectrum makes wide band design easy – less cost for gain flattening filters (Telecom)
- Good splicing characteristics – easy to use in production

Note: Co – competitor fiber, Li – Liekki DND fiber

Reliable and repeatable process - excellent fiber consistency <u>along</u> and <u>across</u> preforms

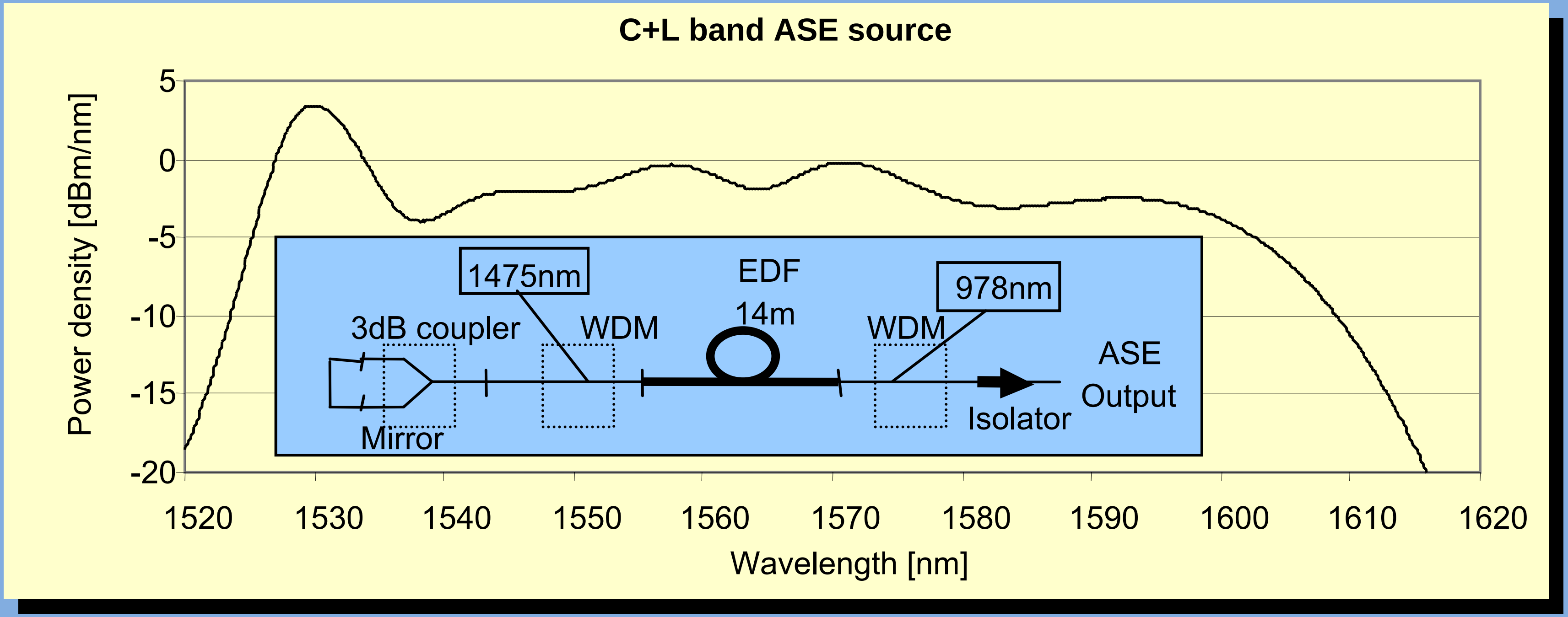


Spectral reproducability of Liekki DND fiber

- Very good spectral reproducability at different doping levels
- Very little spectral shape variation along same preform and across preforms from different batches

DND fibers: ASE source

- The broad band gain bandwidth results also broad ASE sources
- When the gain at C and L band are close enough it is possible to make C+L band ASE source using one active fiber



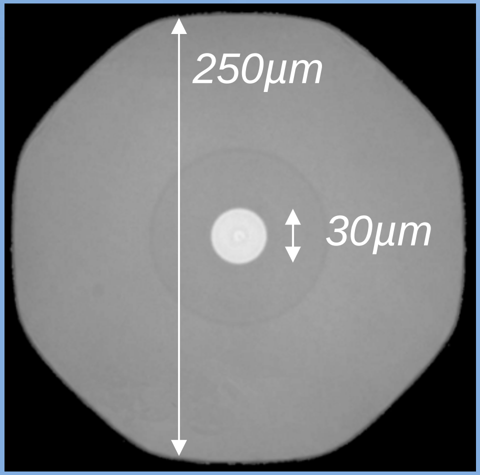
Current Liekki fiber capabilities

- Er, Yb, Er/Yb, Nd, Tm doped specialty fibers
- High-doping concentrations – short fibers
- SM to LMA cores (100+ µm)
- Cladding dimensions from 50µm to 1+mm
- Panda PM fibers (active/passive)
- Photosensitive fibers (SM/LMA)
- Radial/confined doping for LP01 preferential gain
- Phosphosilicate fibers (in progress)
- Rectangular fibers (diode delivery/active)
- Fluorosilicate all-glass + high T coatings
- Specialty components (stress rods, ASE filters, FBGs...)
- Doped nanoparticles, soot & preforms

Ongoing Research & Development activities

- Type-testing of double clad fibers (T, OH, bending)
- High-temperature coatings (polyimide, copper, ...)
- Optical/radiation damage limits of doped fibers
- In-fiber combiner solutions
- Flat waveguide Fiber designs for single-aperture power scaling
- Alternative soot deposition/collection methods
- Planar Integrated Waveguides

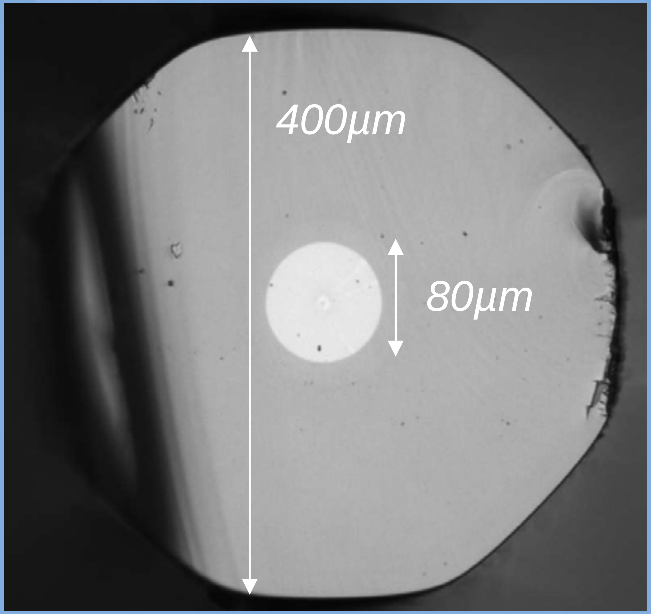
Yb-doped DND fibers feature high *pump absorption* and excellent *power tolerance*



- Highly-doped Liekki Yb1200-30/250DC
- Pump absorption ~15dB/m at 976nm
- Single-stage amplifier seeded with microchip lasers
- Near diffraction-limited beam profiles (M^2<1.2)
- Peak power >1.2MW achieved with 0.38ns pulses
- Pulse energy >1.1mJ achieved with 2.3ns pulses
- High peak fluence of 410J/cm^2 reached

Roger L. Farrow et al., ”*High-Peak-Power (>1.2MW) Pulsed Fiber Amplifier*”, Photonics West: Fiber laser III, Technology, Systems & Applications (6102), Session 7, paper 6102-22.

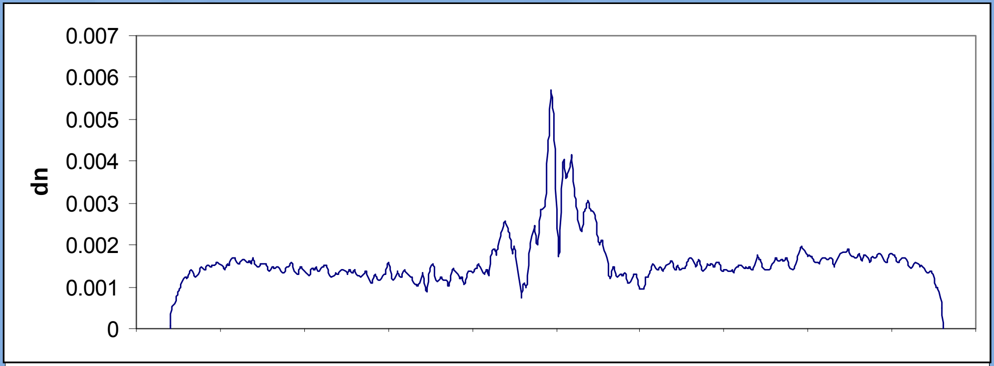
Extremely *flat refractive index profile* and uniform doping push the limits of LMA fibers

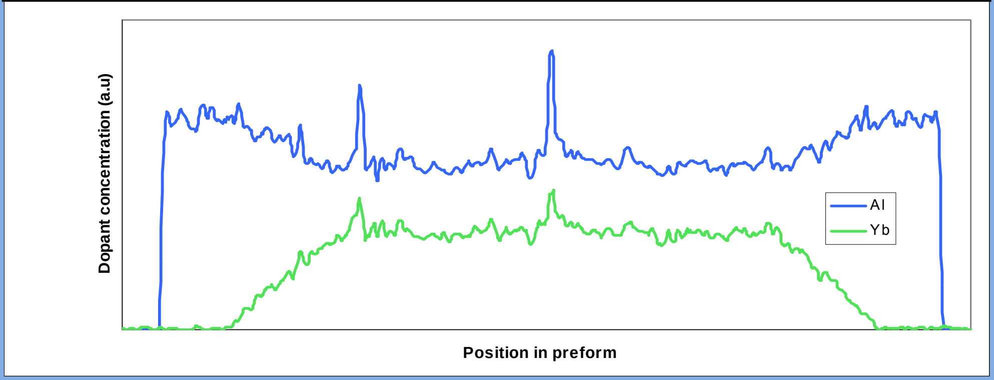


- Liekki Yb-DCF with 80µm core, 400µm clad
- Near diffraction-limited beam (M^2 <1.2) achieved
- Largest demonstrated mode area (2750-µm^2) with single-transverse-mode operation
- Highest (still?) reported peak powers (>6MW with sub-ns pulses)
- High average power scaling up to 85W with MW pulses
- Achieved peak powers beyond expected fiber optical (self-focusing) damage threshold

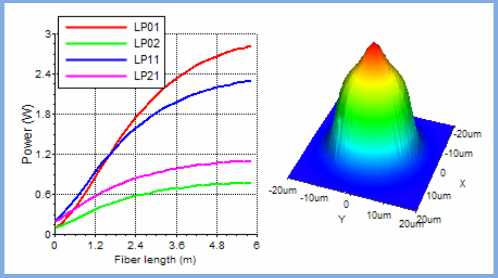
Kai-Chung Hou et al.,"*Multi-MW Peak-Power Single-Transverse Mode Pulse Generation with an Yb-doped LMA Fiber Amplifier*", Photonics West: Fiber laser III, Technology, Systems & Applications (6102), Late breaking development session, paper LBD2, Tuesday 24th, 4:40PM

Radial doping – further power scaling through preferential gain for the fundamental mode



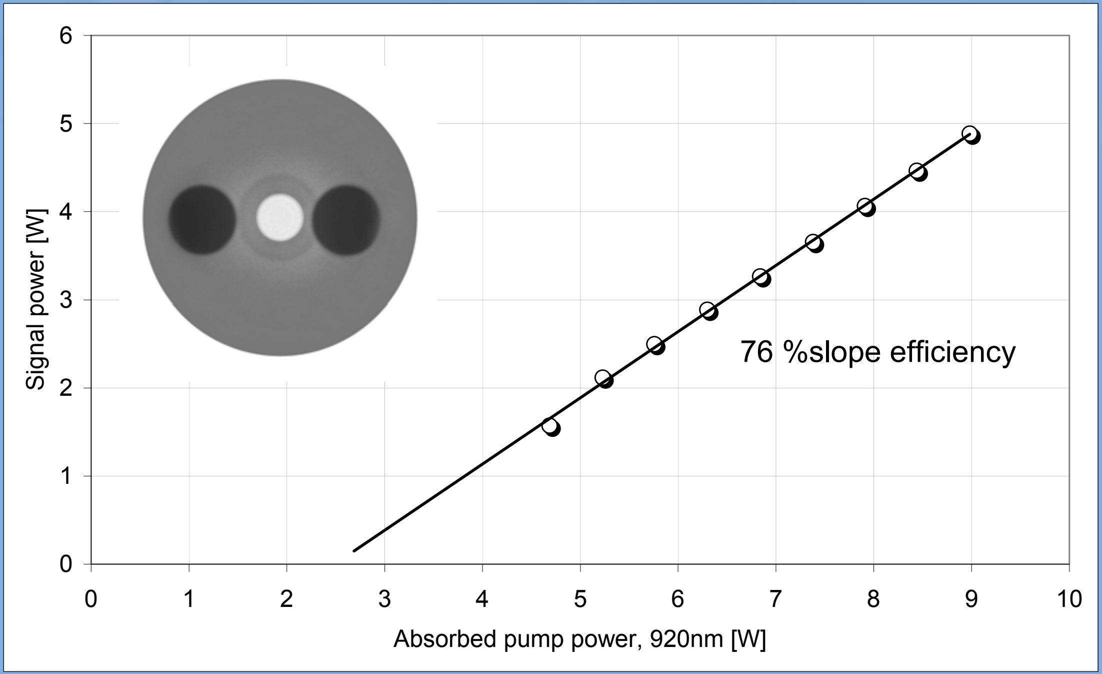


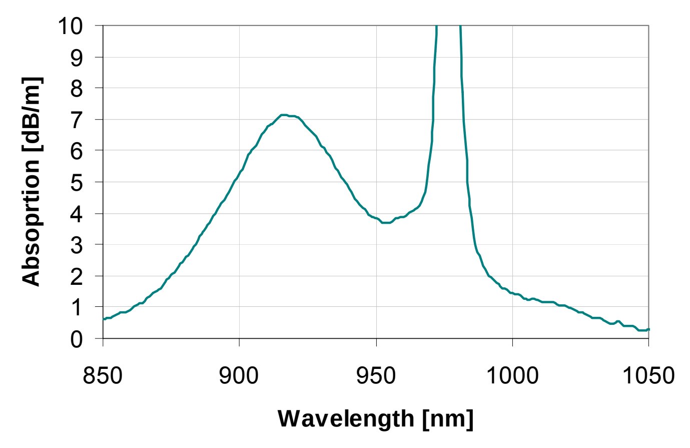
- Preferential gain for LP01 through optimized RE-ion doping
- Designed using Liekki Application Designer



Mircea Hotoleanu et al.,” *High Order Mode Suppression in Large Mode Area Active Fibers by Controlling the Radial Distribution of Rare Earth Dopant*”, Photonics West, Fiber laser III, Technology, Systems & Applications (6102), Paper 6102-64, Thursday 26th, 5:30pm.

Polarization maintaining DC fibers for high-energy amplification



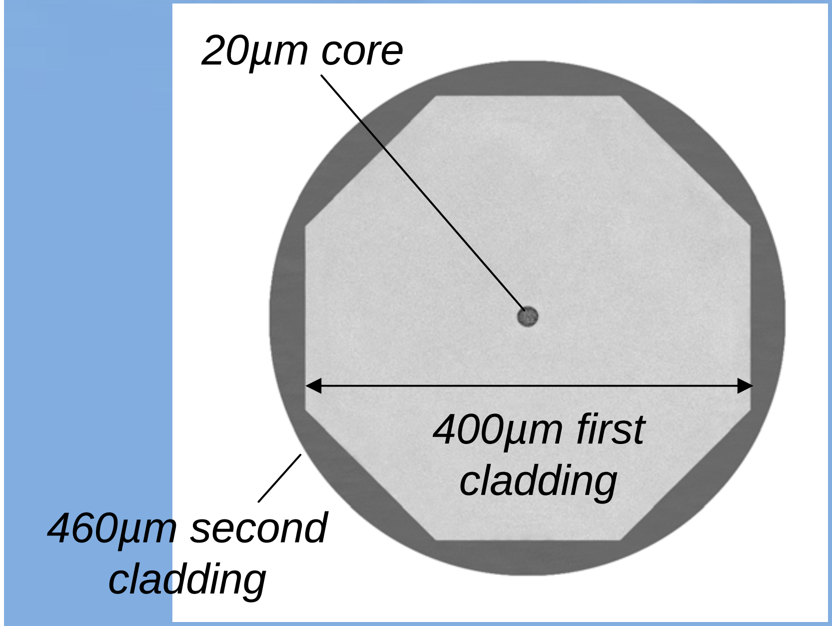


- Pump absorption 7.1dB/m (920nm)

- Yb1200-20/125DC-PM
- Birefringence: 1*10^-4, PER >16dB
- Less than 2m application lenght
- Combiner in development

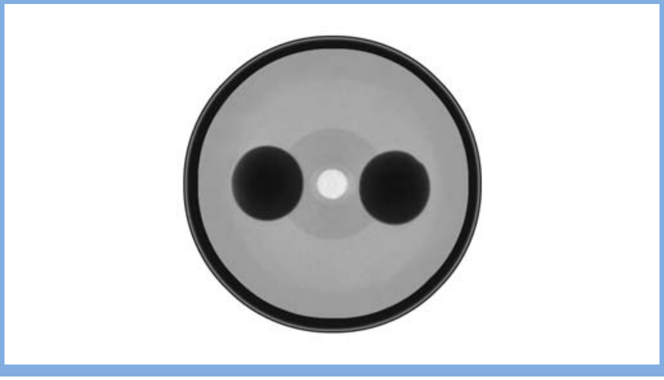
Fluorosilicate ”all-glass” coating for high-power applications

Polished fiber endface



Features

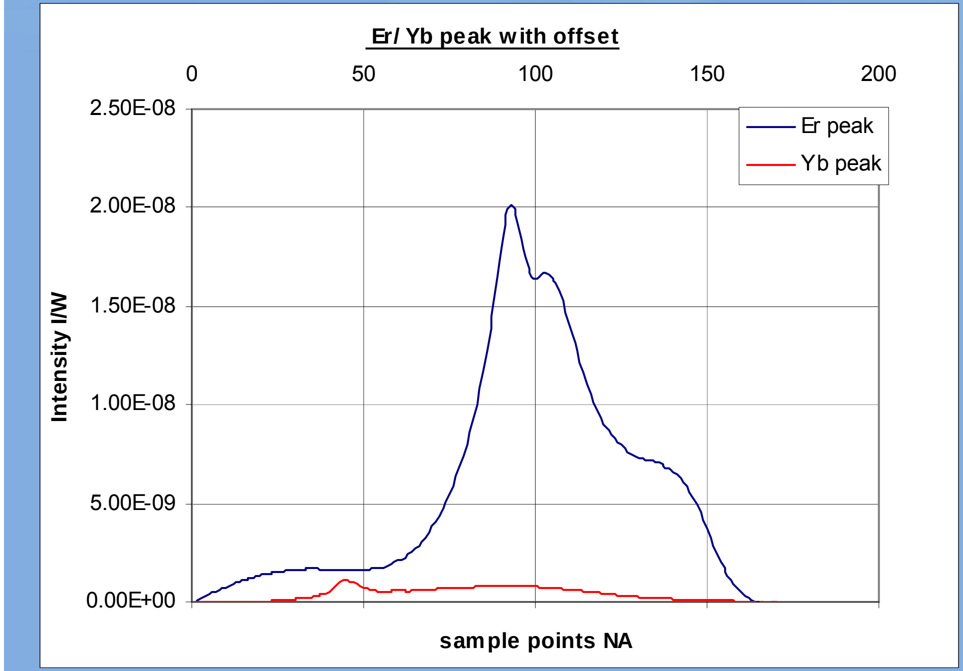
- ”Yb1200-20/400/460DC all-glass”
- Modular, builds on Yb1200-20/400DC
- Fluorosilicate glass cladding with NA 0.22
- ”True” octagonal inner cladding - good pump absorption maintained along fiber
- Tested (end pumped) up to 700W of lauched power
- Matched all-glass passive delivery fiber + FBGs in development



- ”Yb1200-30/300/360DC all-glass”
- Modular, builds on Yb1200-25/250DC-PM
- Experimental fiber

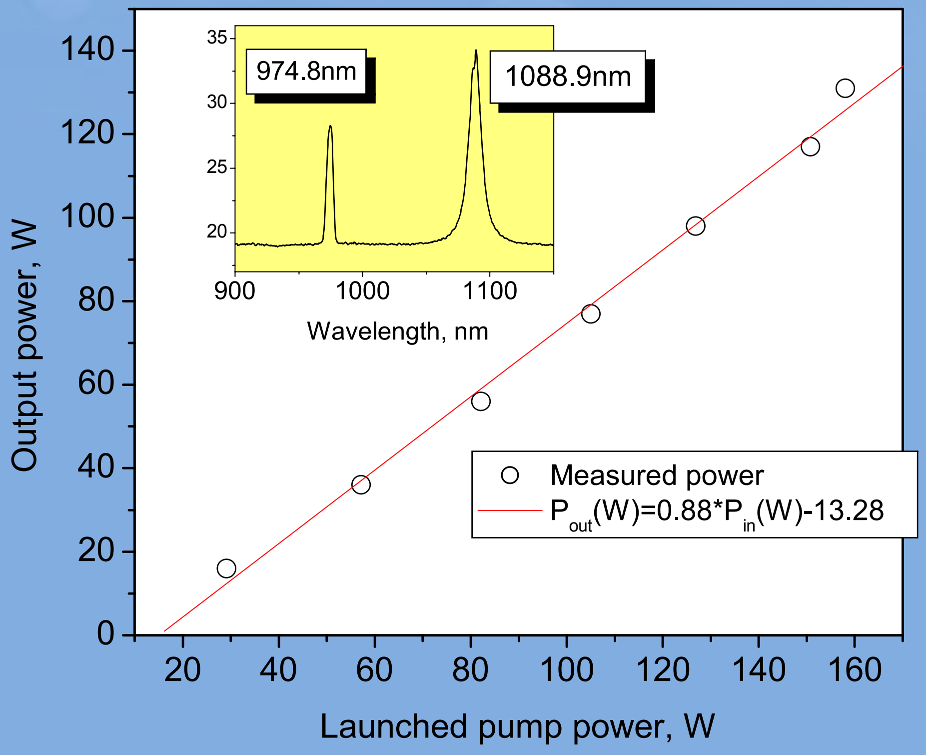
Phosphosilicate glass host for high concentration Yb and Er:Yb fibers

Emission from Er/Yb preform, 920nm pump

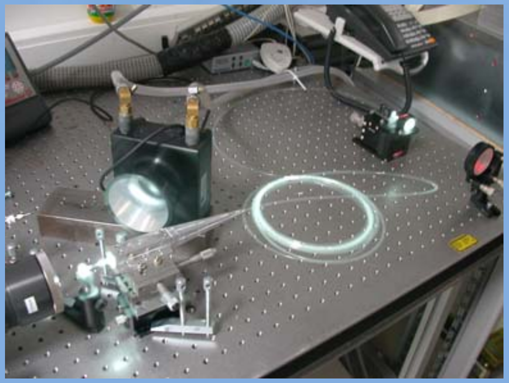


- P2O5 glass has higher RE-ion solubility than Al2O3 (~3x concentration)
  - – shorter fibers (...but also ½x cross-sections)
  - – higher extractable energy
  - – lower photodarkening
- High P2O5 doping (>10mol%) required
  - – increases index (core NA)
  - – volatile, results on core burnout
- Advantages of DND
  - – minimizes clustering (Er+Yb!)
  - – reduces/eliminates core burnout
  - – up-doped cladding for lower core NA
- Status (Er:Yb fiber)
  - – 94% transfer efficiency from Yb to Er
  - – In progress: first fibers drawn and tested

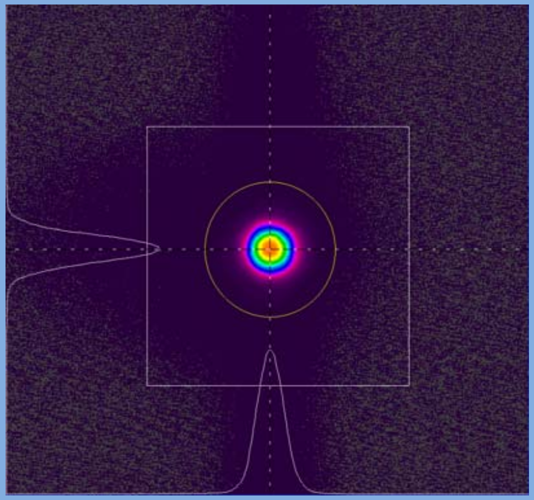
DND made Yb-DCF’s demonstrated high efficiency and beam quality -



- High-doped Yb-DCF, 20µm core with NA of 0.07
- High power conversion efficiency (>80%)
- Excellent beam quality ($M^2 < 1.1$)
- Improvements still needed

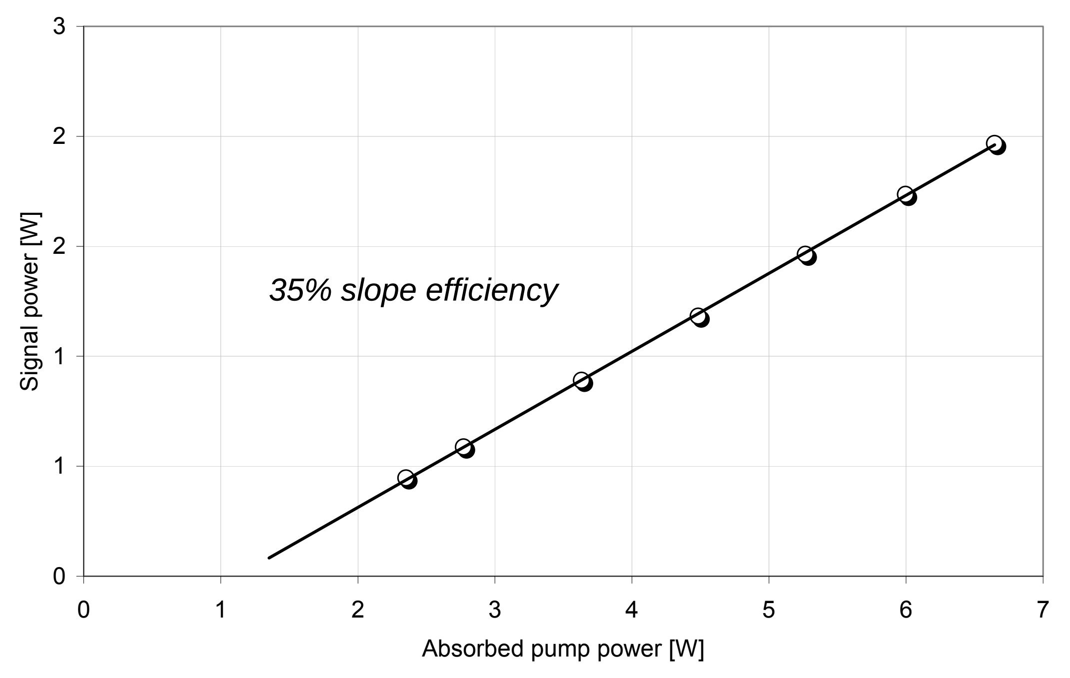


Beam profile measurement



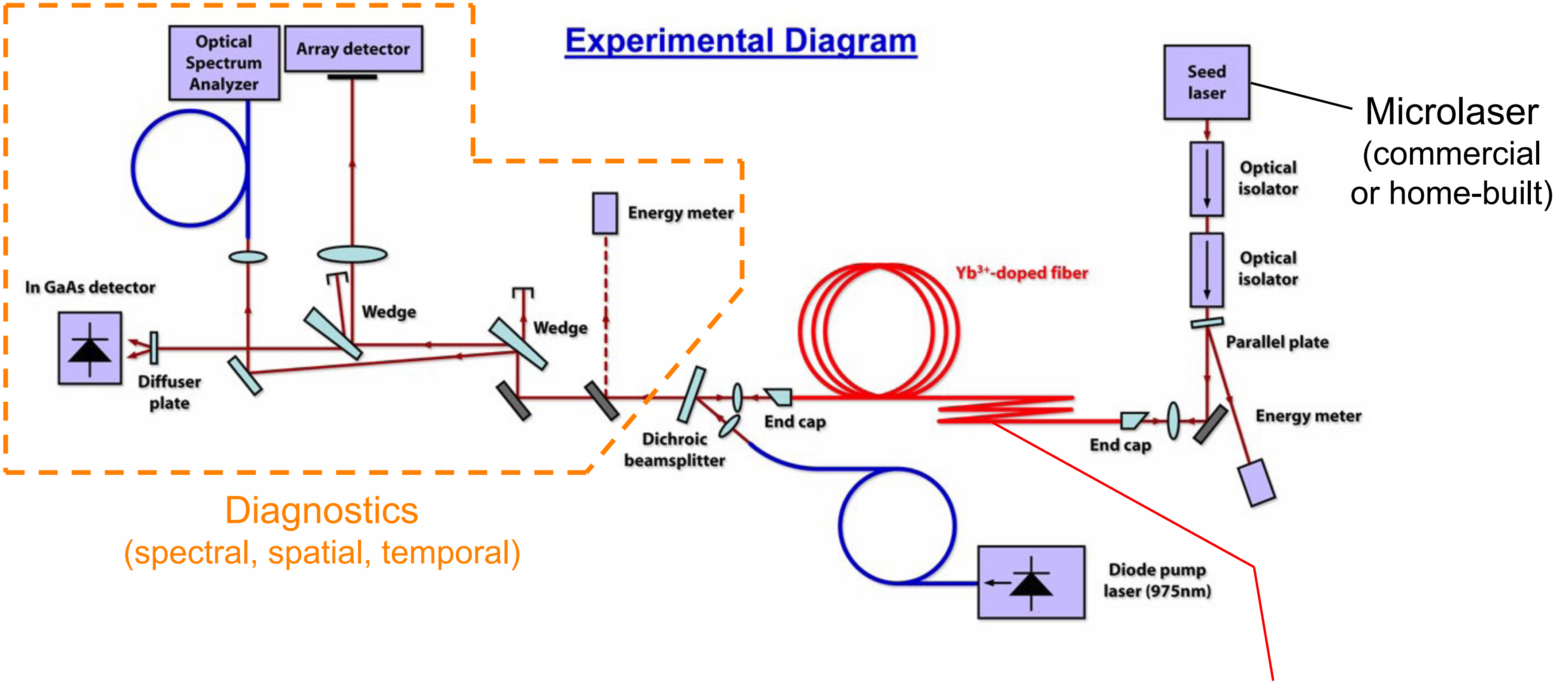
NEW PRODUCT RELEASE

A new high-efficiency, LMA Erbium double clad (Er-DC) fiber Er60-20/125DC for 980 nm pumping



- First high-efficiency, LMA Er-DC product
- Power scalable for Eye-safe military,medical and industrial applications
- Clearly better efficiency then with conventional Er:Yb codoped fibers

Sandia Experiments with Liekki 30 μm Fiber



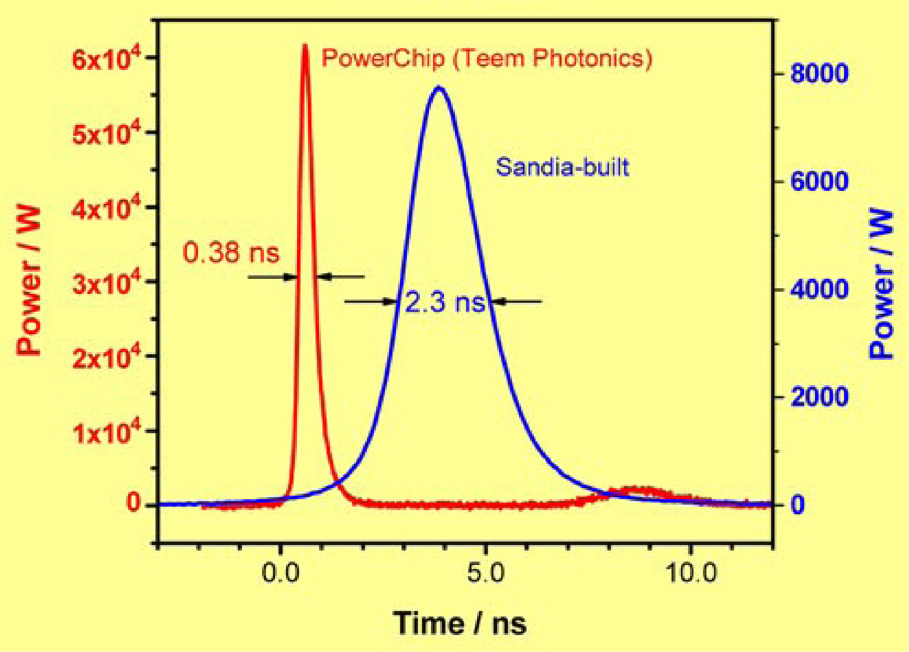
Microlaser (commercial or home-built)

Diagnostics (spectral, spatial, temporal)

Mode-filtered fiber amplifier [J.P. Koplow *et al.*, Opt. Lett. **25**, 442 (2000); U.S. Patent 6,496,301]

- Simple system architecture suitable for practical applications
  - single-stage, single-pass amplification
  - passive Q-switching
  - cw pumping

Nd:YAG Microlaser Seed Sources



Wavelength = 1064 nm

Repetition rate = 1.0 kHz

Pulse energy ≤ 35 μJ, 20 μJ

Linewidth ≈ 0.05 cm^{-1}, 0.02 cm^{-1}

Commercial

Sandia-built

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

- Nonlinear processes in fiber amplifier are sensitive to linewidth and pulse duration in the ~1 ns range

Experimental Results

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Highest reported peak irradiance: 440 GW/cm^2

Highest reported peak fluence: 410 J/cm^2

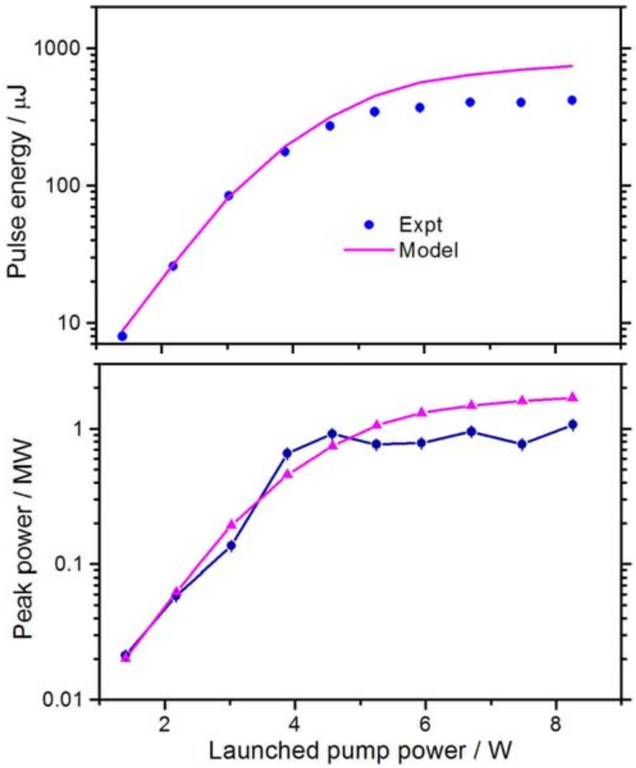
Consistent with recent preform damage-threshold measurements

R.L. Farrow *et al*., Photonics West 2006, Proc. of SPIE 6102, Paper 0L

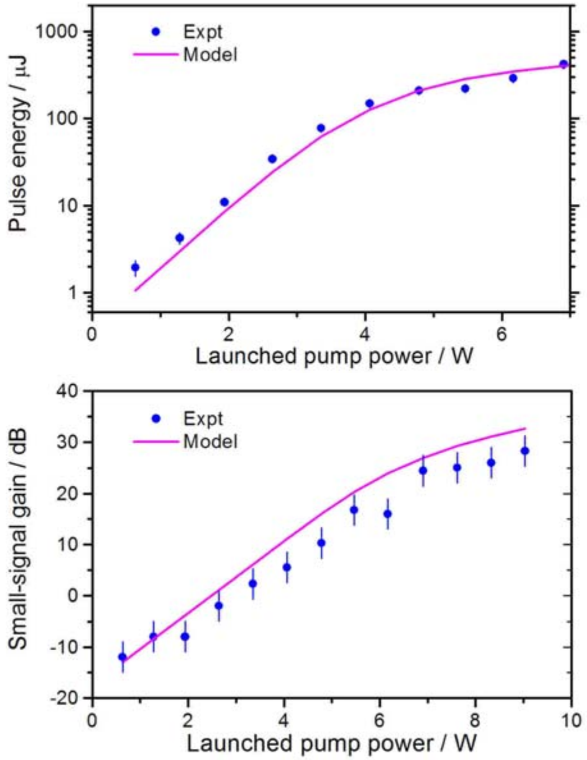
Sandia Pulsed Fiber Amplifier Model

- ZT model
  - no transverse dependence
- Initial inversion profile from Z model
  - simplified two-level rate equations
  - includes ASE
  - spectrally resolved
- Transient BPM model
  - includes GVD, SPM, and saturable gain
  - employs measured bend loss
  - no adjustable parameters

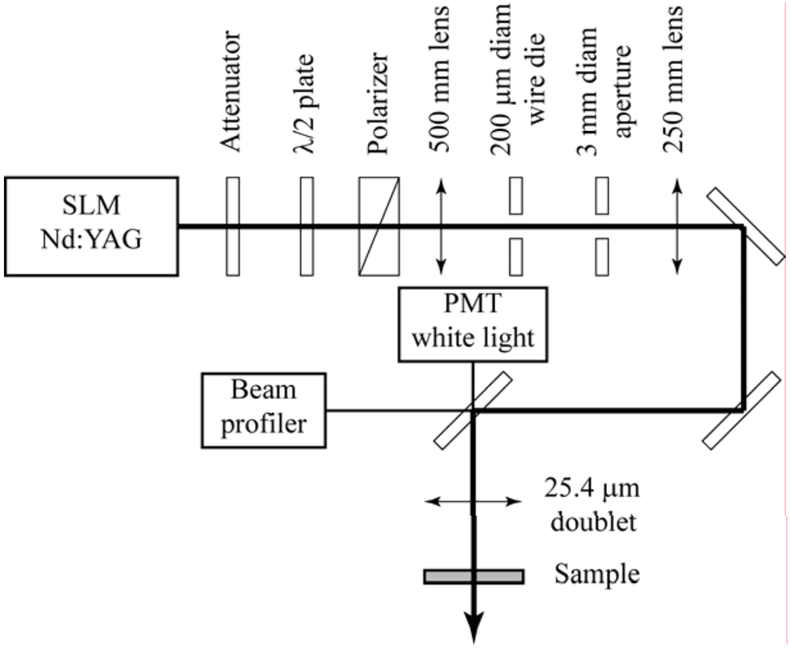
0.38 ns seed laser

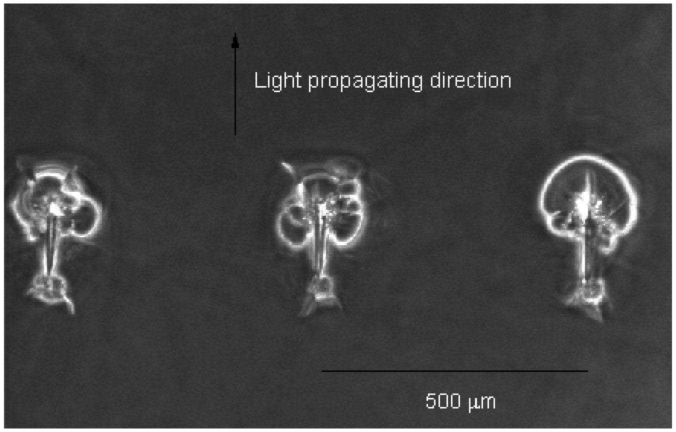


2.3 ns seed laser



Sandia Damage Threshold Measurements



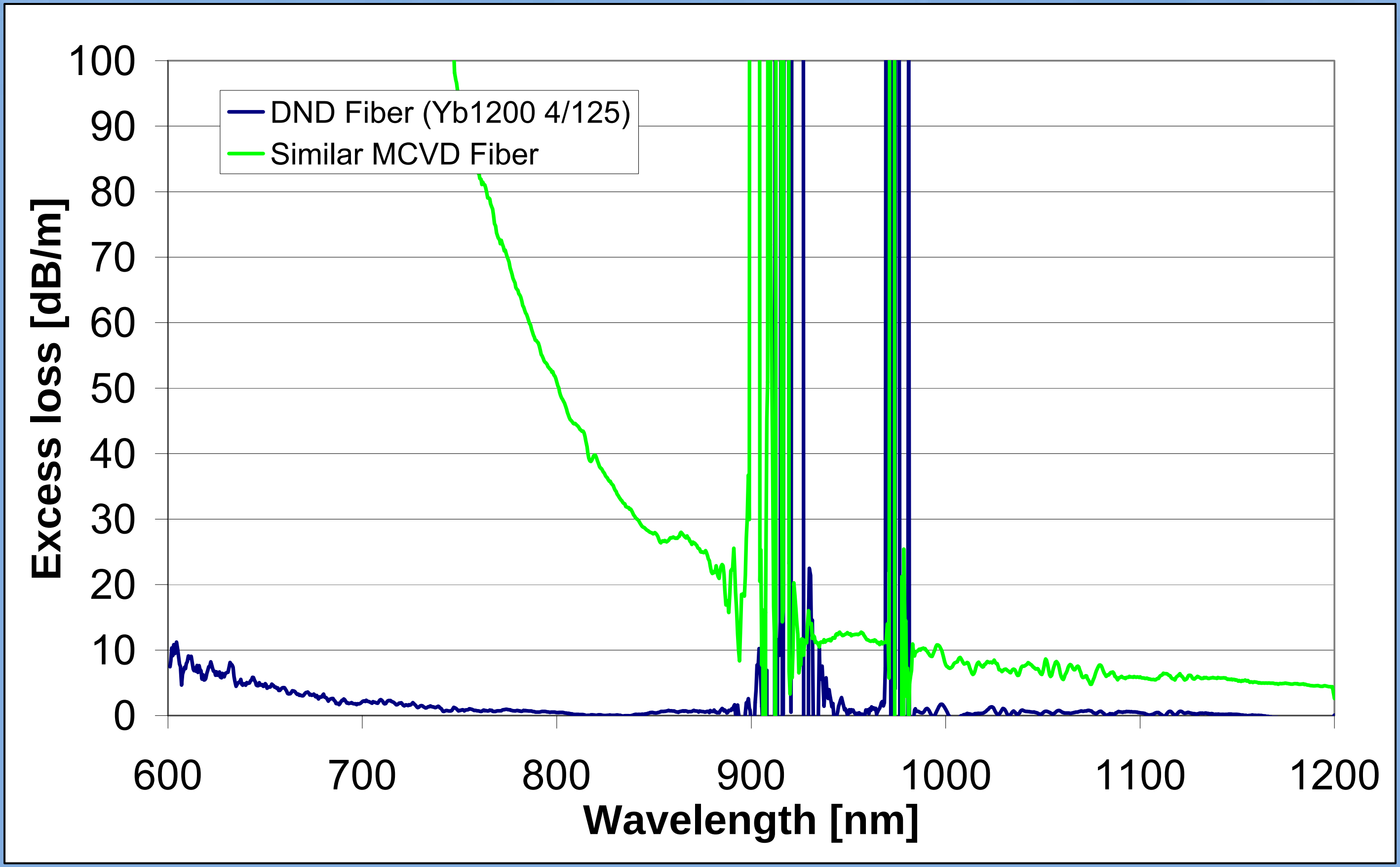


- Samples of high-purity fused silica and Liekki fiber preforms
- Surface and bulk damage measurements
- Fused-silica bulk damage threshold = 470 GW/cm^2
- Yb-doped core damage threshold = 640 GW/cm^2
  - reconciles pulsed fiber-amplifier results (440 GW/cm^2)

A.V. Smith and B.T. Do, to be presented at Boulder Damage Symposium 2006

PHOTODARKENING

Fibers made with DND show superior performance in head-on comparison



- Comparison made with Ytterbium concentration of roughly 1.1wt%

What drives photodarkening?

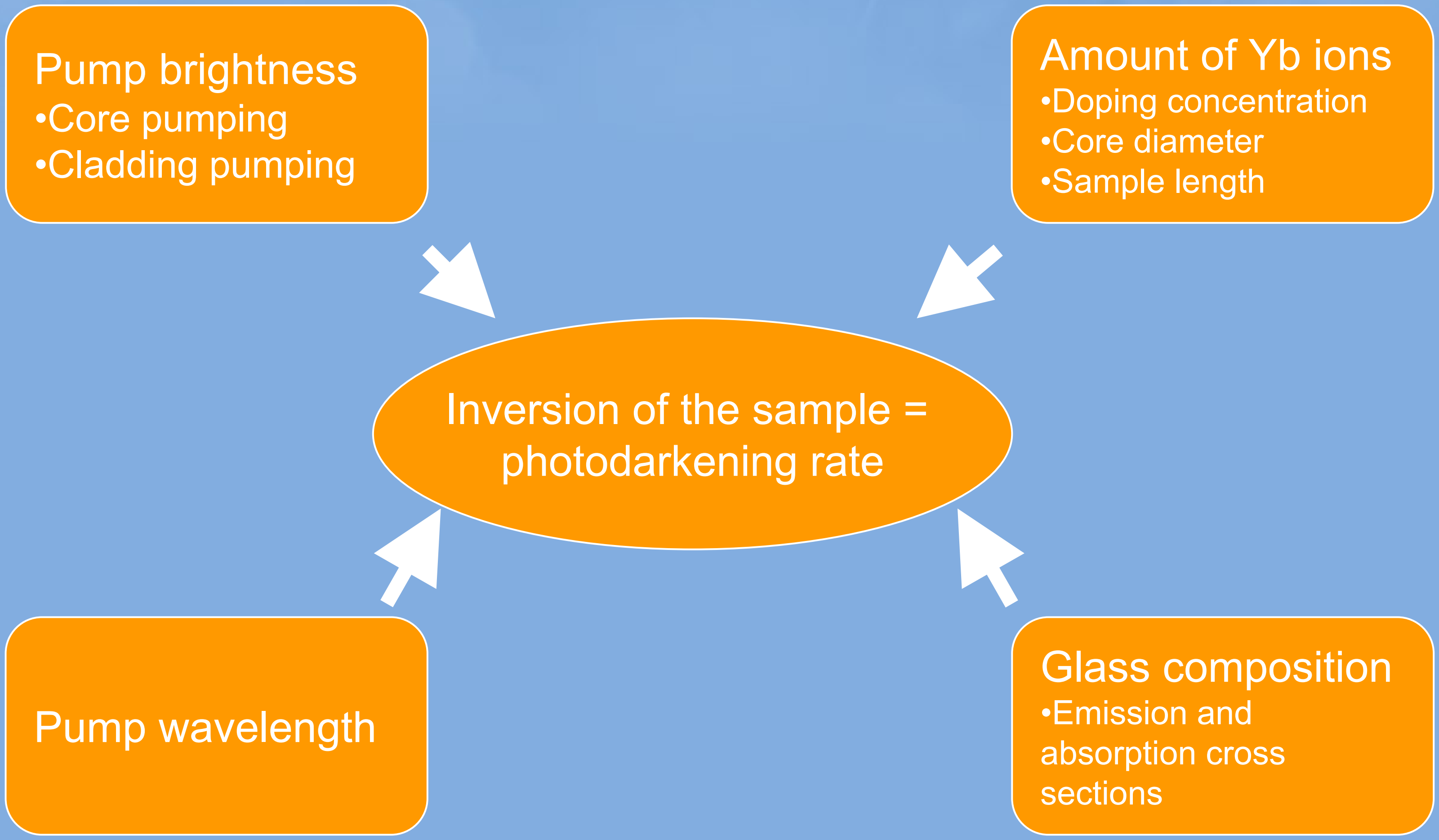
- **In many photodarkening studies, several parameters are changed simultaneously or are poorly constrained**

- **Background:** Core pumping results showed that when inversion saturates, photodarkening rate saturates

- **Hypothesis:** Inversion level is the dominant parameter determining the photodarkening rate

- **The procedure to test our hypothesis:**
  - *Provide flat and tunable inversion to fiber samples*
  - *Measure photodarkening rate as a function of inversion level for multiple fibers*

Photodarkening rate between measurements must be comparable



Pump brightness
- Core pumping
- Cladding pumping

Amount of Yb ions
- Doping concentration
- Core diameter
- Sample length

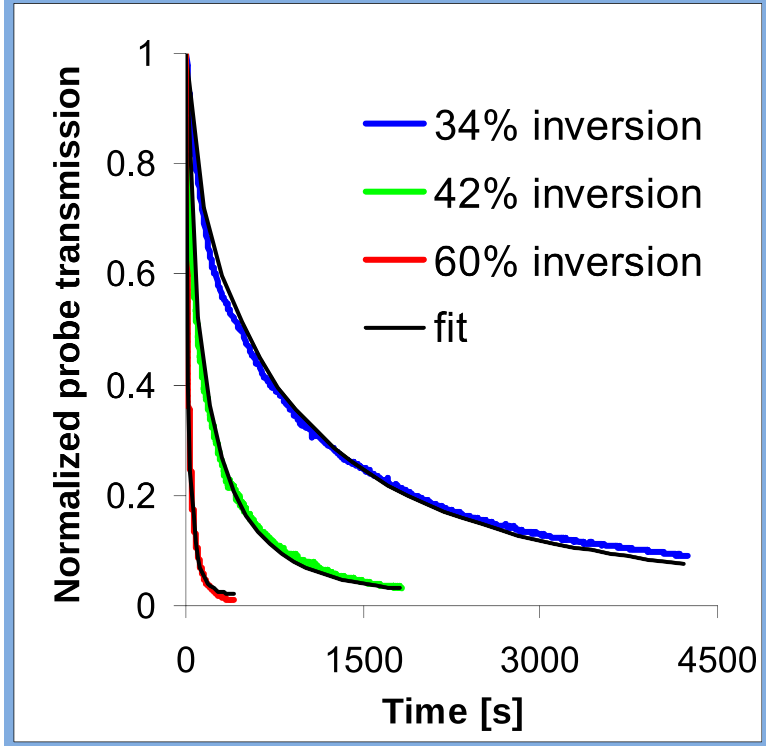
Inversion of the sample = photodarkening rate

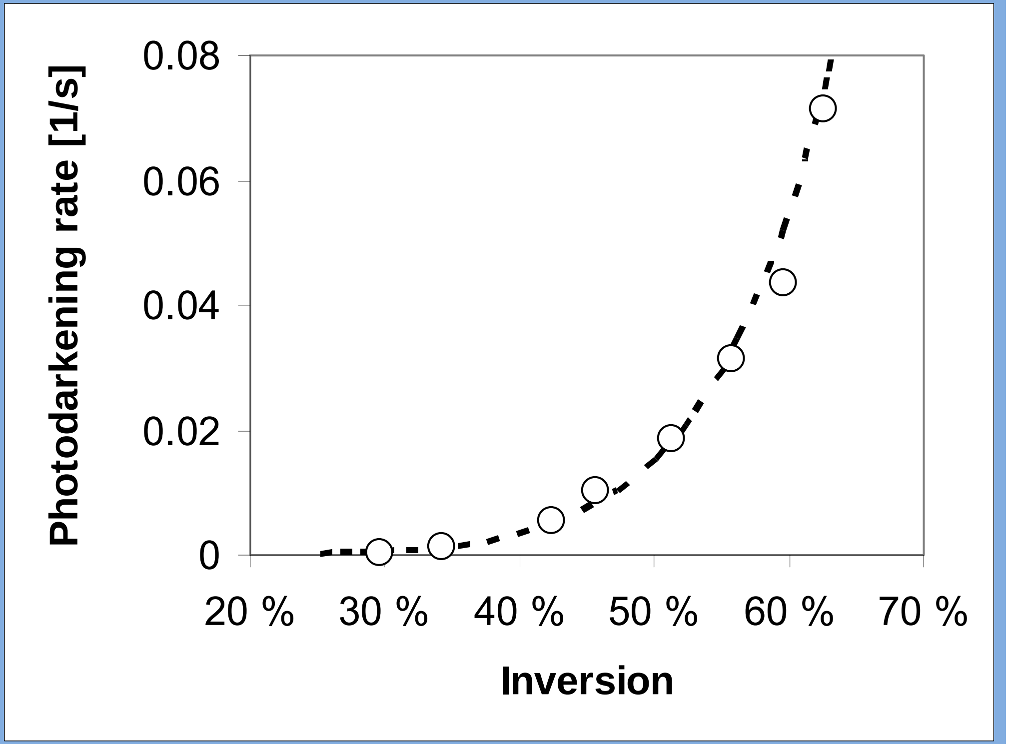
Pump wavelength

Glass composition
- Emission and absorption cross sections

Higher inversion leads to faster photodarkening

- Photodarkening rate was quantified by fitting the results with a stretched exponential function

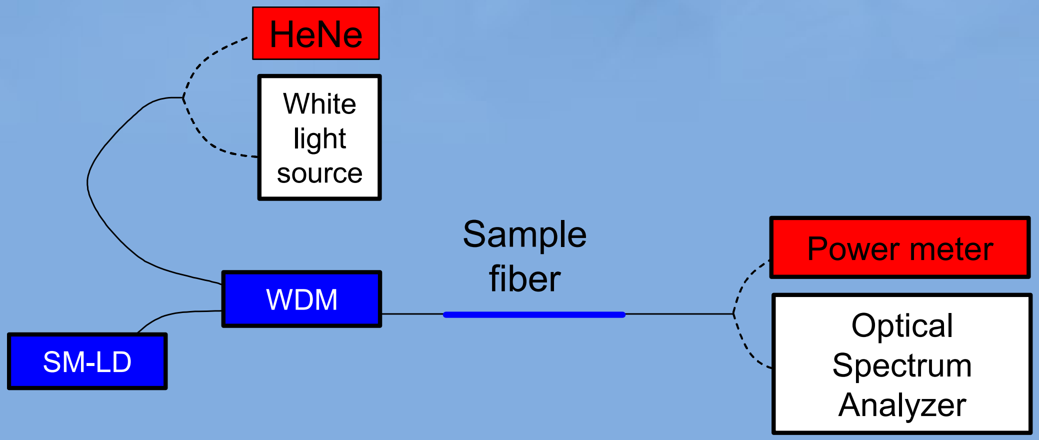




Methods for benchmarking are simple

Core pumping

- Single-mode pump diode
- ”Through pumping”
- Easy to implement to single-mode single clad fibers



HeNe

White light source

WDM

SM-LD

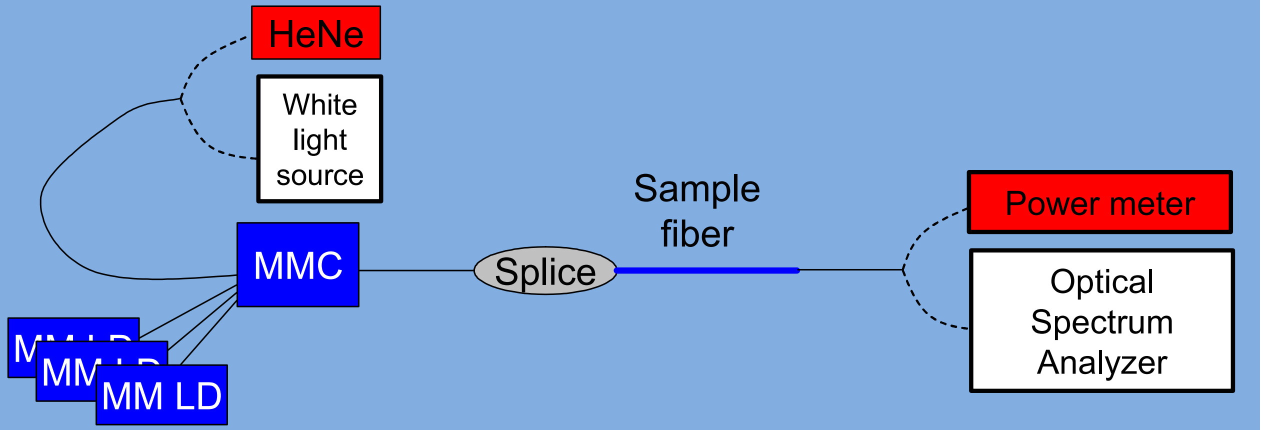
Sample fiber

Power meter

Optical Spectrum Analyzer

Cladding pumping

- Multimode pump diodes
- ”Side pumping”
- Easy to implement to DC fibers



HeNe

White light source

MMC

MM LD

MM LD

MM LD

Splice

Sample fiber

Power meter

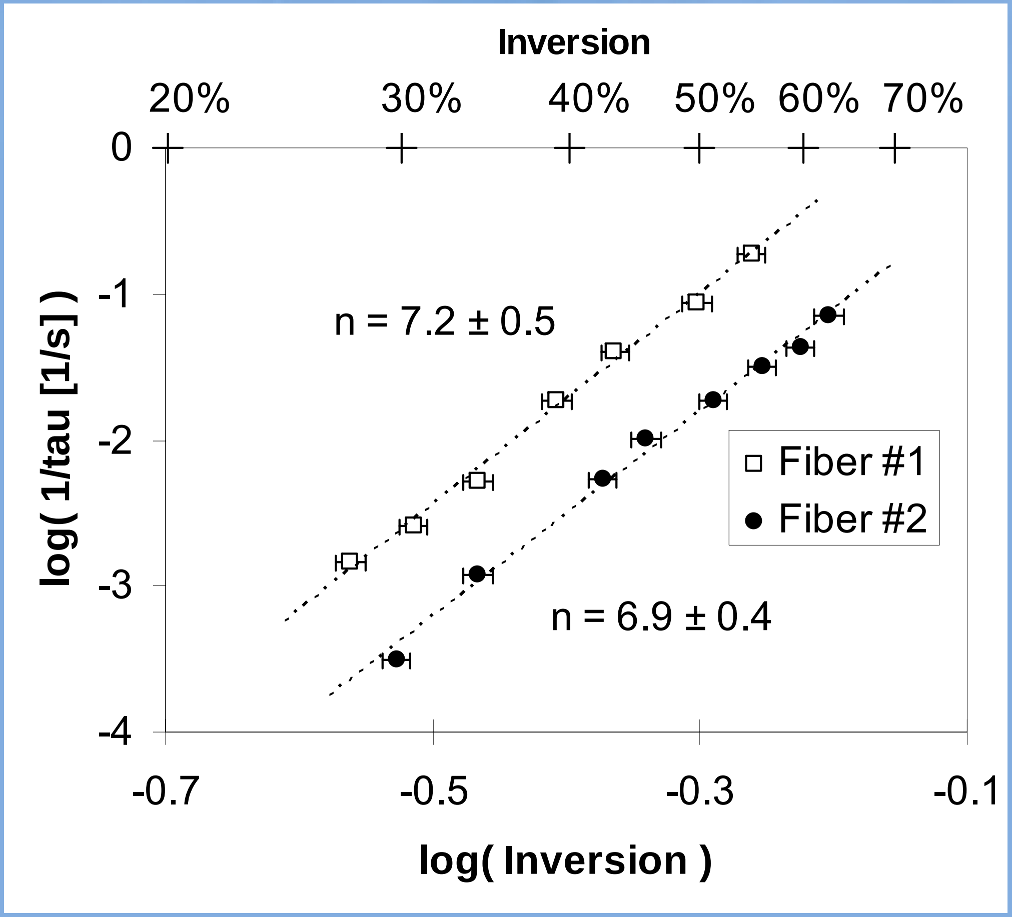
Optical Spectrum Analyzer

Photodarkening rate has a 7th-order dependence on inversion

- Two fibers with different Yb concentrations

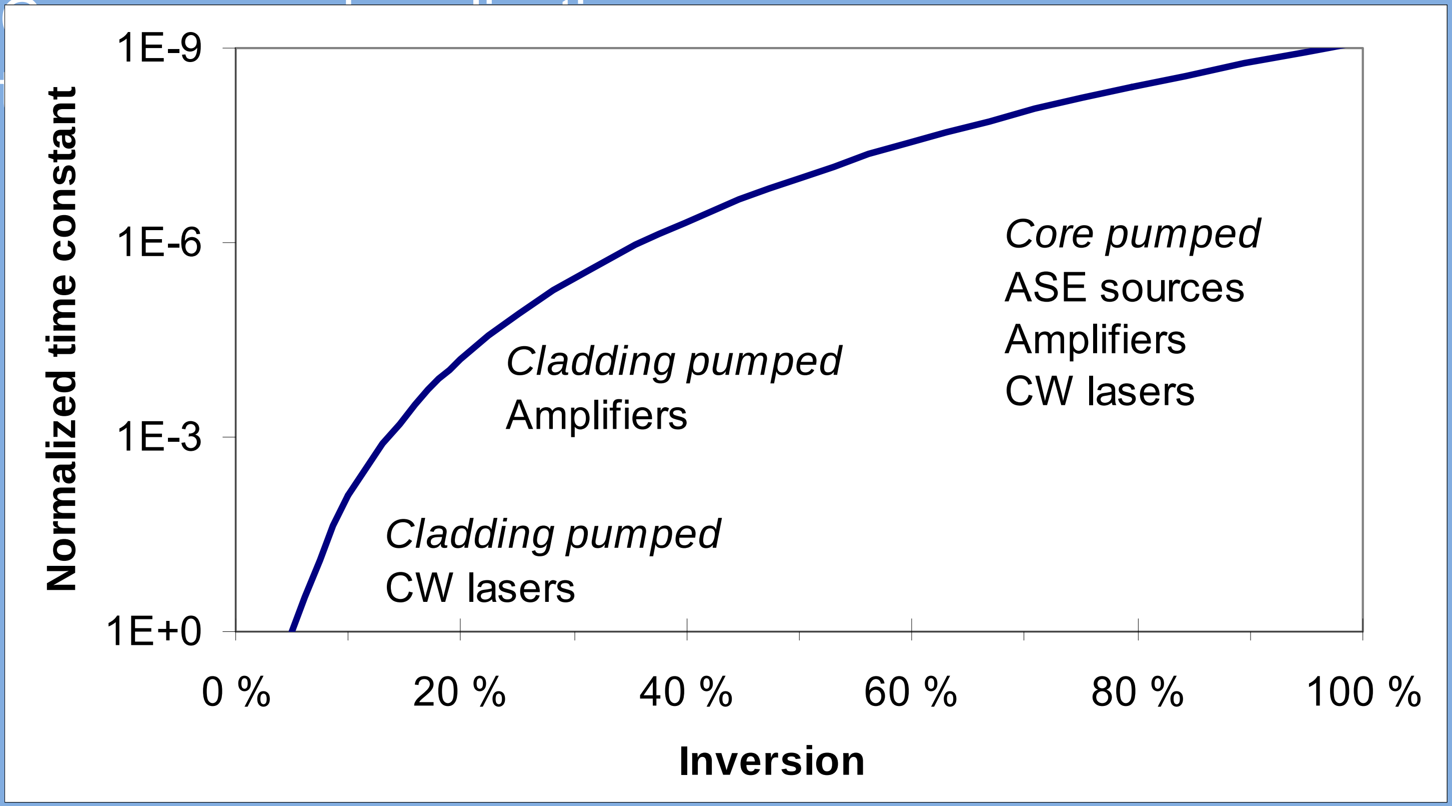
- The rate constant can be parameterized with a single variable, inversion

PD rate ∝ inversion^7



A given fiber will have very different photodarkening rates under different operating conditions

- Amplifiers photodarken up to 10^5-10^7 faster than cw lasers



Summary of benchmarking measurement conditions

	Core pumping method	**Cladding pumping method**
Preferred fiber type	Single-mode, single clad	LMA, double clad
Pump brightness	Higher	Lower
Inversion of the fiber	Saturated •Not pump power dependent •Defined by the ratio of absorption/emission cross sections	Non-saturated •Inversion tunable with pump power •Defined mainly by the absorption cross section
Inversion at 920nm	Higher (up to >90%)	Lower (pump power dependent)
Inversion at 976nm	Lower (up to >40%)	Higher (pump power dependent)

Photodarkening - Conclusions

1) Benchmarking of photodarkening is feasible for single-mode fibers and for LMA fibers

2) Photodarkening rate constant was found to depend strongly on a single variable: inversion

3) Rate constant follows a simple power law
   - ~7th order dependence on inversion
   - May indicate a single mechanism for color center formation

4) High inversion dependence of photodarkening has significant implications to fiber devices
   - Amplifiers may photodarken up to10^5-10^7 times faster than cw lasers

5) A uniform inversion is important in photodarkening measurements
   - Quantitative analysis difficult from a sample with spatially variable inversion

Photodarkening - the Oulook

- The conspiracy of silence is over
  - No reason to underestimate the impact of a steady, unpredictable degradation mechanism on commercial fiber laser acceptance
  - Better to perhaps solve the problem?
  - Increasing number of papers on the issue from different groups
  - Indications that the magnitude and rate of PD is highly glass composition and process dependent
- How to cure photodarkening?
  - The same way it's been done with other materials - consistent hard work, lots of patience and support from the laser community and research institutions
  - Some indications that photodarkening is substantially reduced in phosphosilicate fibers - but at what price?
    - **There is no free lunch even for fibers!!**
  - Temperature annealing may be feasible - but is it practical?

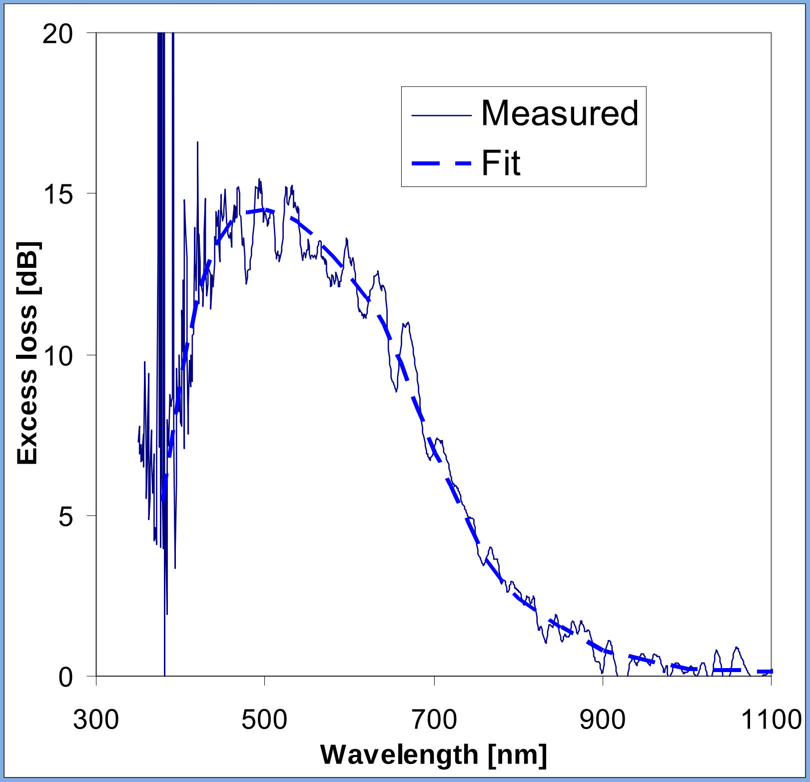
BACK-UPS

Photodarkening reduces system performance and reliability

What is photodarkening?

- Permanent* light-induced change in the absorption of glass
- A multi-photon process involving a rare-earth (RE) ion
- Seen (at least) in Tm^{3+}, Yb^{3+}, Ce^{3+}, Pr^{3+} and Eu^{2+}-doped RE-doped silica glasses

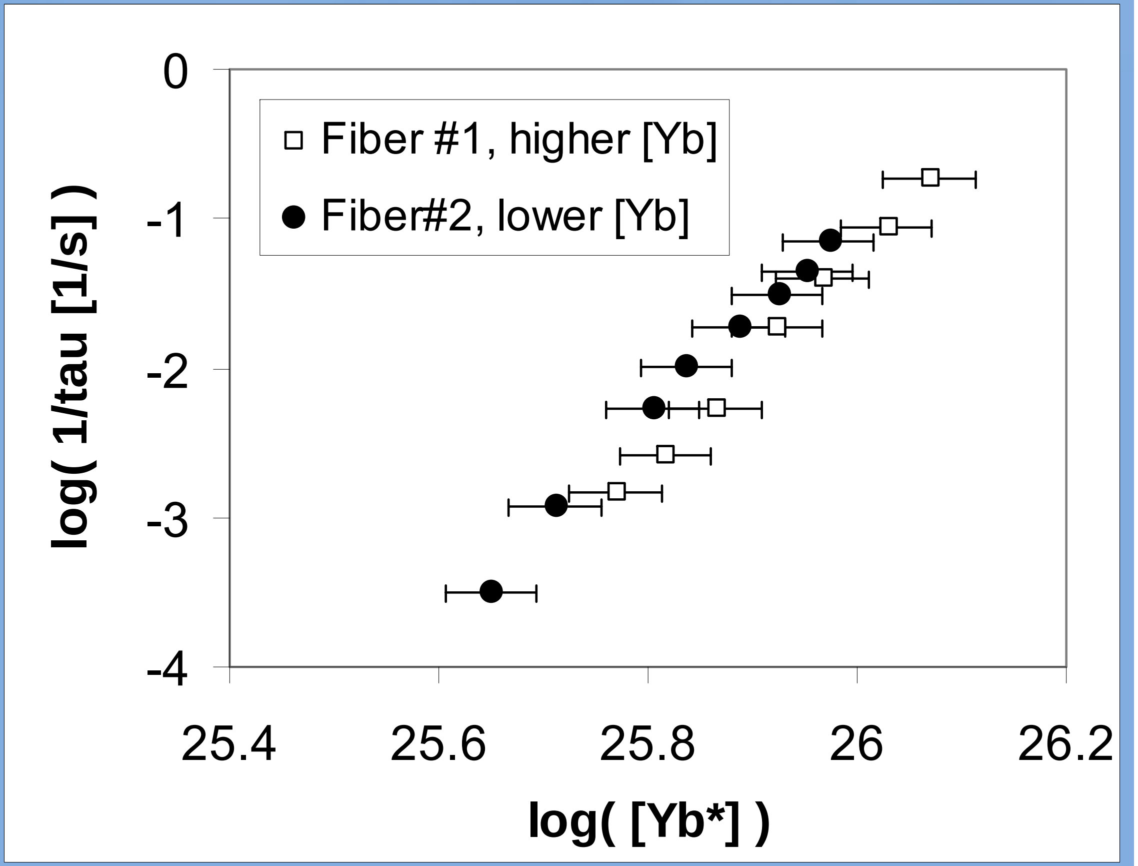
Photodarkening induced excess loss in Yb-doped silica glass



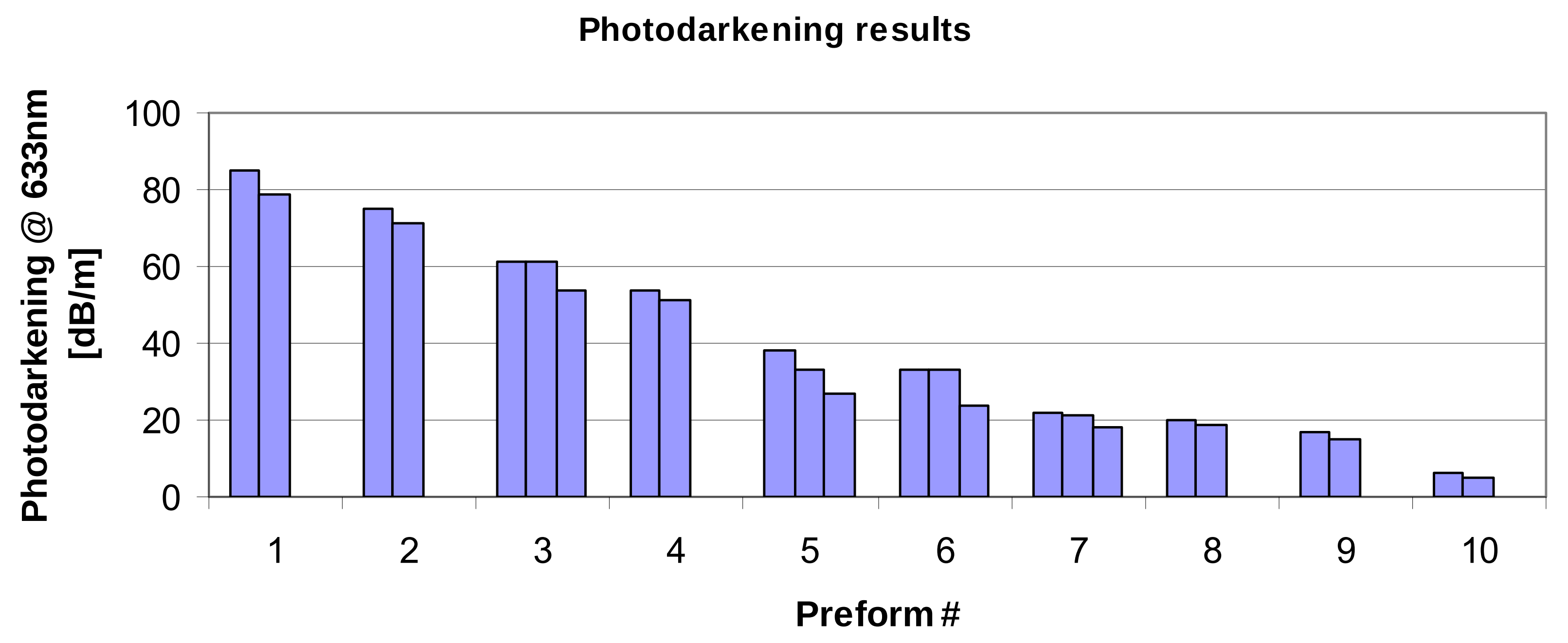
* High temperature annealing demonstrated: Jasapara et al., OFC ’06, CTuQ5

7th power dependency holds for [Yb*] as well

- [Yb] = Ytterbium ion density, ions/m^3
- [Yb*] = [Yb] * inversion, excited state number density, ions/m^3
- Intercomparison of glass compositions and manufacturing technologies possible for the first time
- Glass homogeneity of importance!



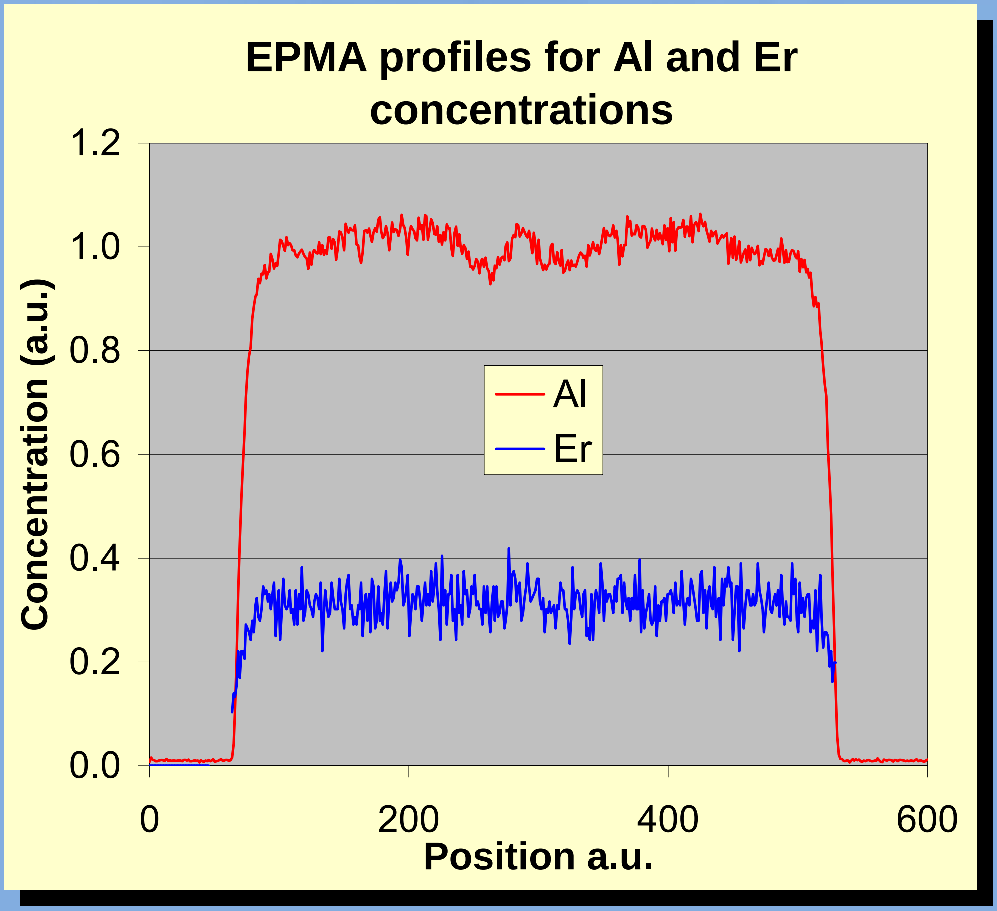
30 min photodarkening measurement is repeatable



Average repeatability +/- 6%

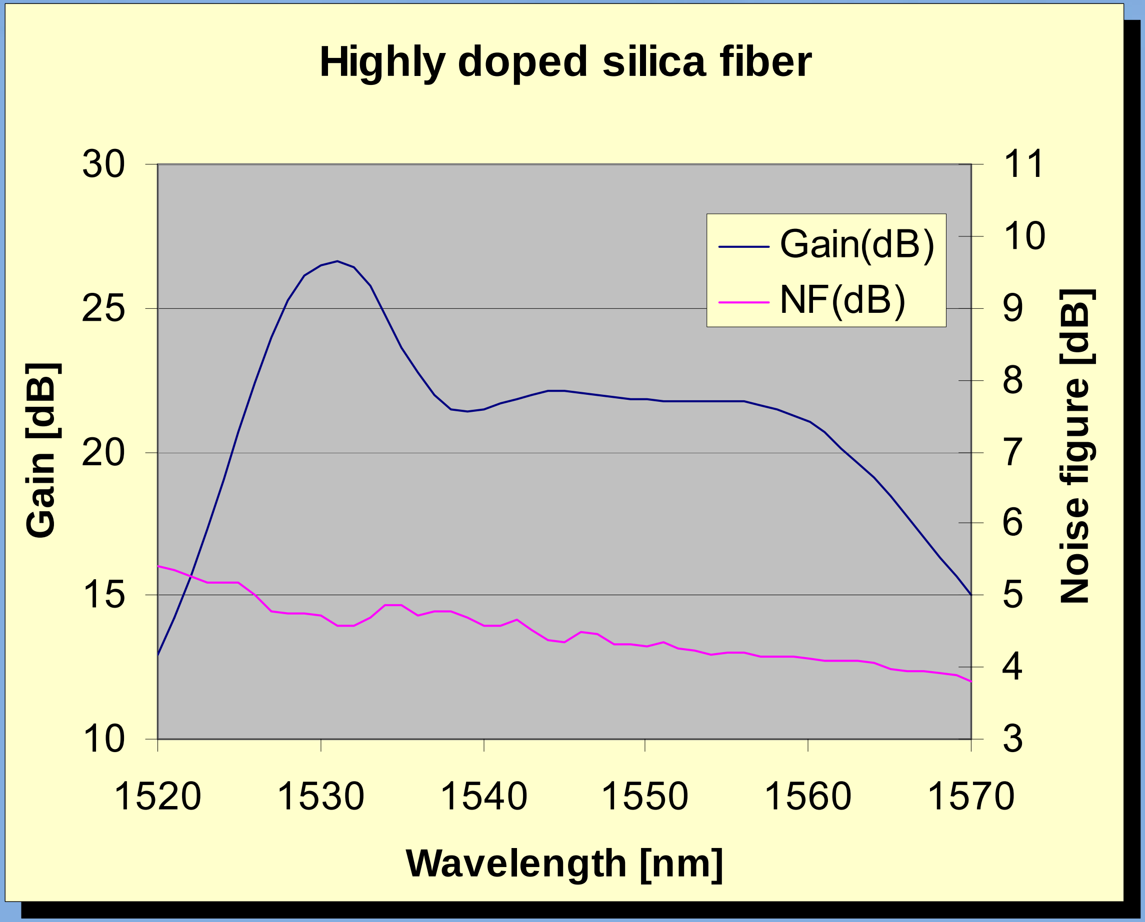
DND: doping uniformity in preform

- Core consists of about 100 layers
- The concentration variation within +- 5%
  - –Temperature non-uniformity in the reaction volume
  - –Process controlling at process start



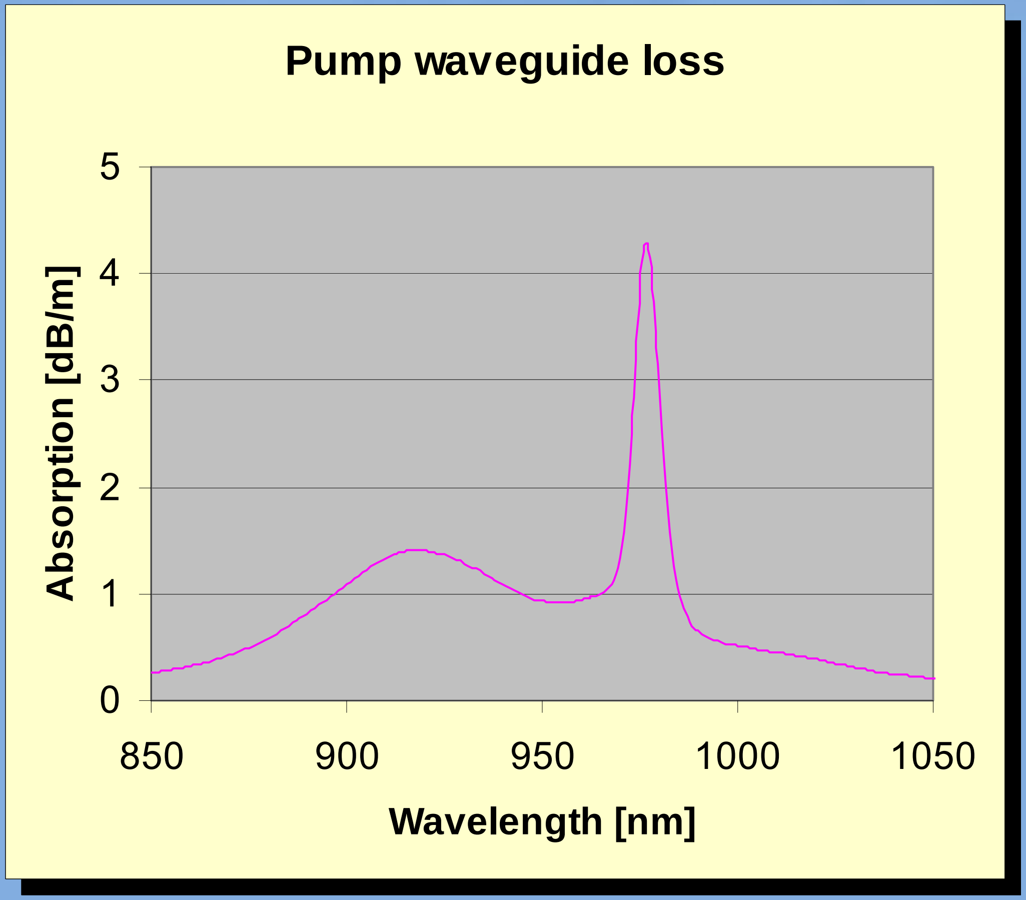
DND fibers: very short C-band fiber

- Uniform doping enables high doping with moderate up-conversion
- Absorption 100 dB/m @ 1530 nm
- Fiber length 0.58 m
- Pump 110 mW @ 980 nm
- QCE 21 % @ 0dBm input



DND fibers: Yb doped fibers

- Core / Cladding ratio is 6/125
- Core absorption about 2000 dB/m
- Pump absorption 1.4 dB/m @ 920 nm



DND for Active Fibers
More Conclusions

Completely new process, ideally suited for power scaling

- –Homogeneous, high doping
- –Excellent RIP control, 100s on nanoparticle layers
- –Rapid development cycle, large LMA preforms - good economics
- –Higher photodarkening threshold than other aluminosilicate based MCVD fibers
- –potential for core platform based manufacturing process - a new approach to mass customization of new wave guiding structures

DND fibers provides clear application benefits

- –Diffraction-limited beam quality up to 80µm cores
- –Peak fluences >410 J/cm^2
- –Peak power >6MW & mJ pulse energies with nanosecond pulses

Process still at the beginning of the ”learning curve”

- –Ideal for LMA fibers, unique radial doping feature
- –Manufacturing process no longer limits the designers imagination!