Ytterbium Doped Phosphate Fiber Laser with Nanoctructured Core

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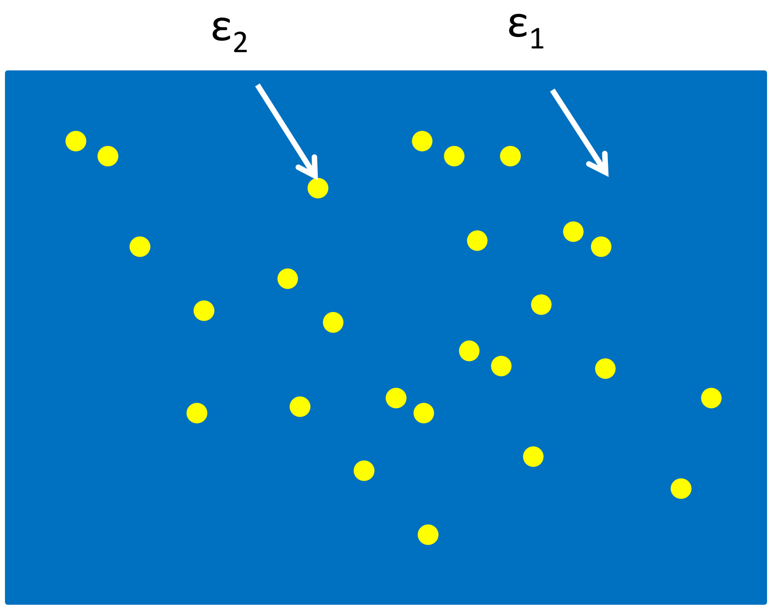
Outline

- Concept of nanostructurization in dielectric medium
- Motivation
- Phosphate glass
- Nanostructured core fiber fabrication
- Fiber laser structure
- Laser Performance
- Conclusions

Effective medium theory – original approach

- Description a random nanostructured dielectric material in terms of effective permittivity ε_{eff}
- Assumption:

  - density $\varepsilon_2 \ll \varepsilon_1$
  - size of ε_2 inclusions $\ll \lambda$



Maxwell-Garnett mixing formula:

$$\varepsilon_{eff} = \langle \varepsilon \rangle - f(\varepsilon_1 - \varepsilon_2)\frac{\varepsilon_1 - \langle \varepsilon \rangle}{3\langle \varepsilon \rangle}$$

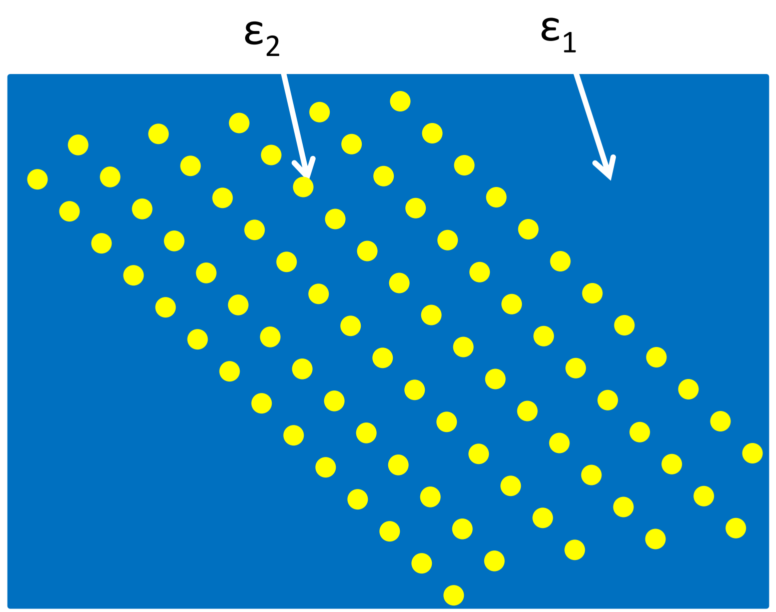
$$\varepsilon_{eff} \approx \langle \varepsilon \rangle = \varepsilon_2 + f(\varepsilon_1 - \varepsilon_2)$$

Effective medium theory – our modification

- Description arbitrary nanostructured dielectric material in terms of effective permittivity ε_{eff}
- Assumption:

  - ~~density ε_2~~ << ε_1

  - size of ε_2 inclusions << λ



Maxwell-Garnett mixing formula:

$$\varepsilon_{eff} \approx < \varepsilon > = \varepsilon_2 + f(\varepsilon_1 - \varepsilon_2)$$

$n = \sqrt{\varepsilon\mu}$ $\mu \approx 1$ for glass

$$n_{eff} = \sqrt{f{n^2}_1 + (1-f){n^2}_2}$$

How nanostructured medium „works” ?

Metamaterial consist of many thin dielectric rods.

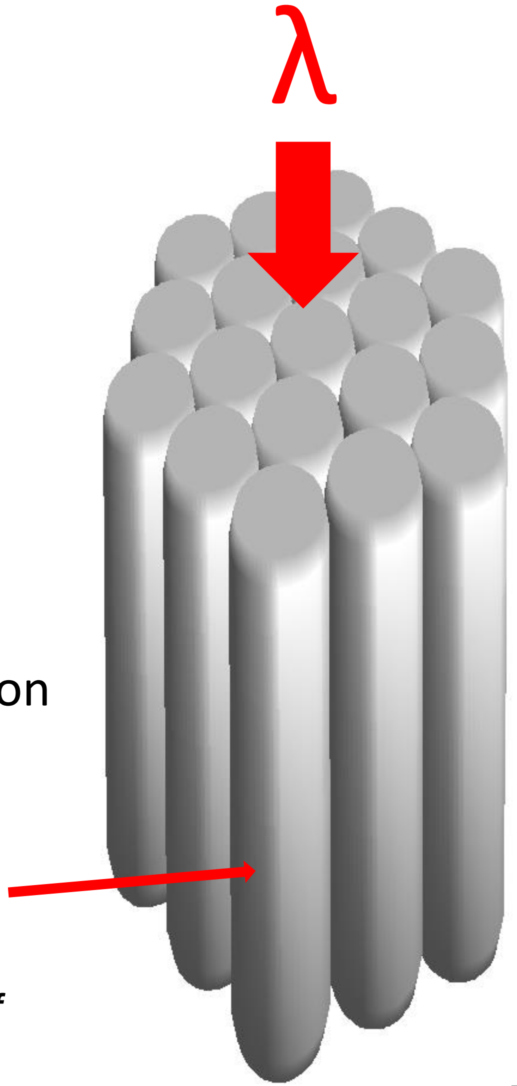
Discrete structure. Feature size (i.e. rod diameter) << λ

↓

Light ‘sees’ averaged (effective) refractive index distribution

↓

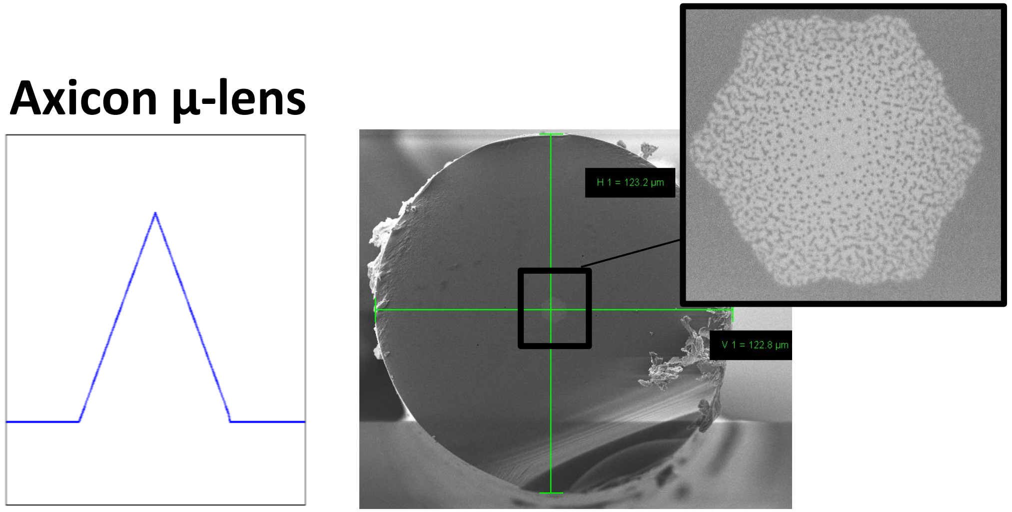
Created metamaterial with arbitrary refractive index distribution in cross-section (gradient-index, step-index or any profile)



F. Hudelist, R. Buczynski, A. J. Waddie, and M. R. Taghizadeh, "Design and fabrication of nano-structured gradient index microlenses," Opt. Express 17, 3255-3263 (2009).

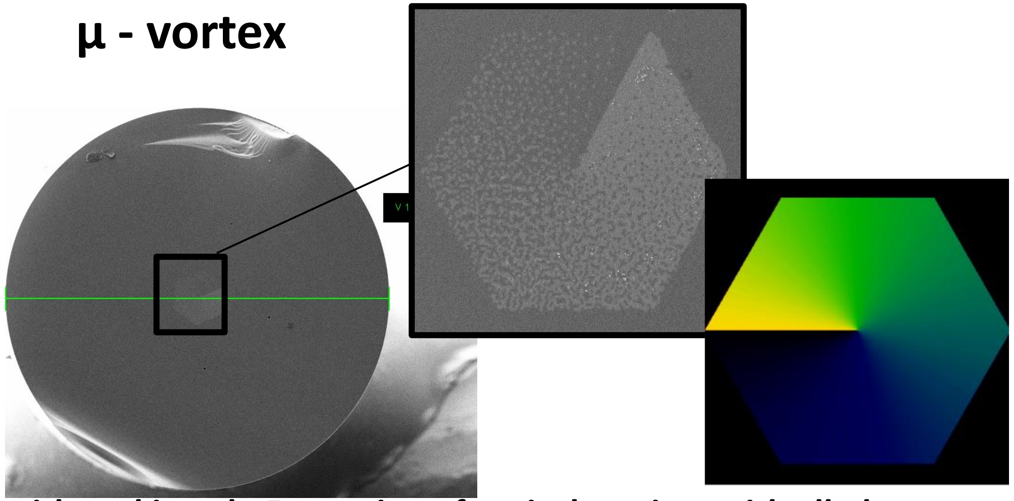
Motivation – new realizations in soft and silica glass

Axicon μ-lens



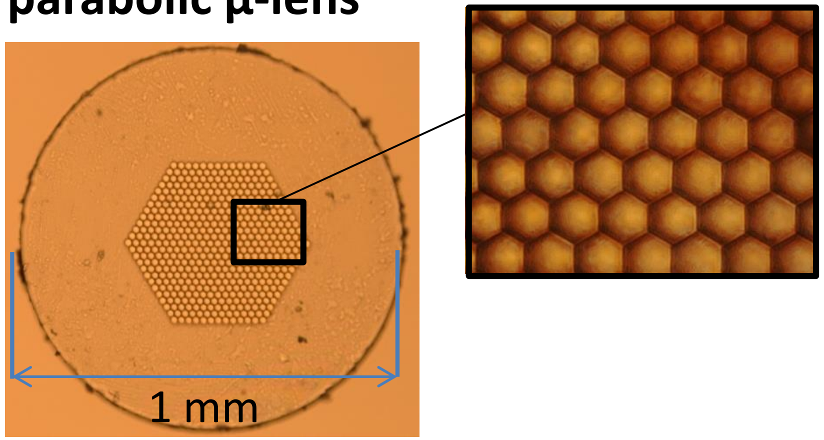
A. Filipkowski et al., Nanostructured gradient index microaxicons made by a modified stack and draw method, Opt. Lett., 40, 5200 (2015)

μ - vortex



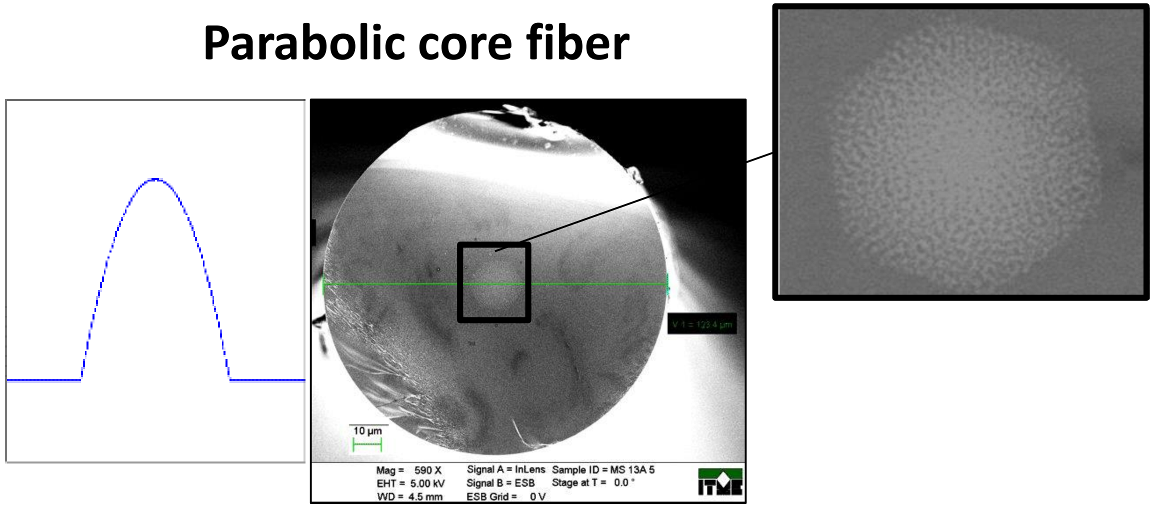
Switkowski et al., Formation of optical vortices with all-glass nanostructured gradient index masks, *Opt. Express, 25* 31443 (2017)

Array 469 parabolic μ-lens



R. Kasztelanic et al., High resolution Shack-Hartmann sensor based on array of nanostructured GRIN lenses, Opt. Express, 25, 1680 (2017)

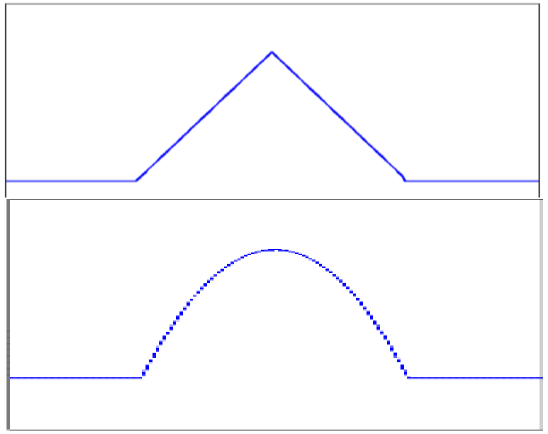
Parabolic core fiber



R. Buczynski et al., Optical fibers with gradient index nanostructured core, Opt. Express, 23, 25588 (2015)

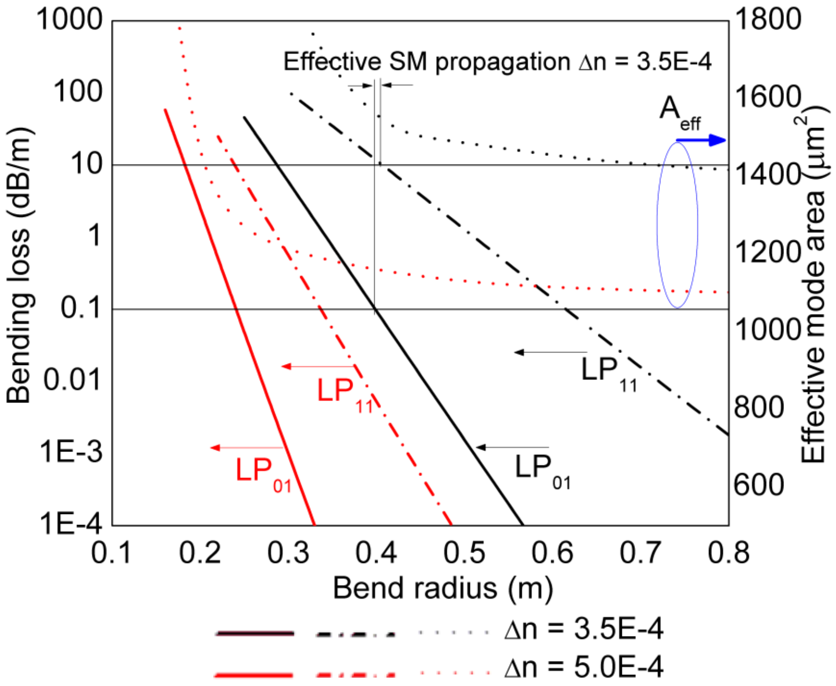
Motivation – nanostructurization in LMA fibers

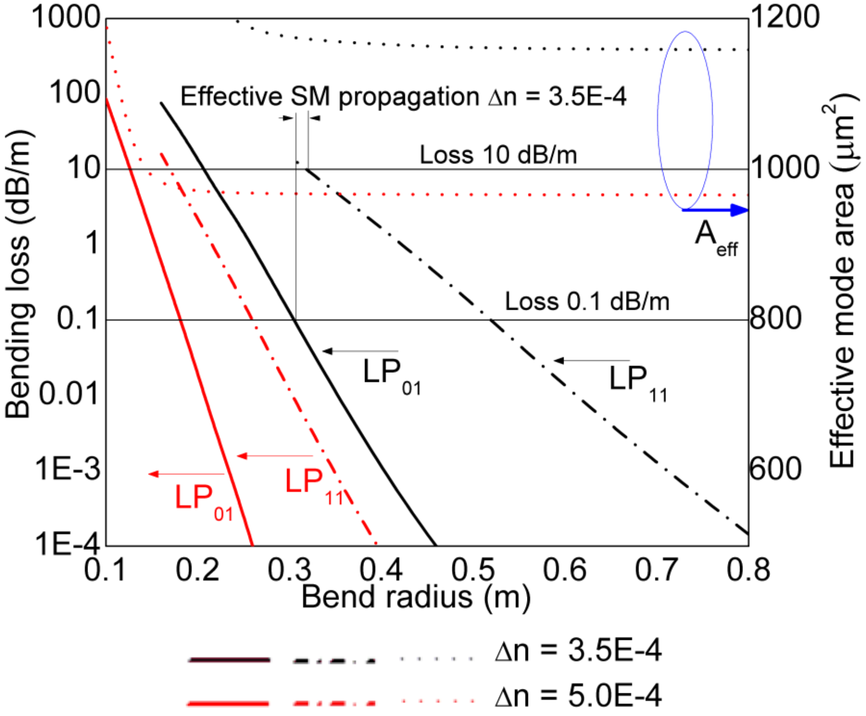
- nanostructurization enables to attain precisely defined refractive index distribution, not achievable with standard fiber fabrication methods
- the largest effective single-mode (SM) area (A_{eff}) achieved with bending, λ =1050nm:

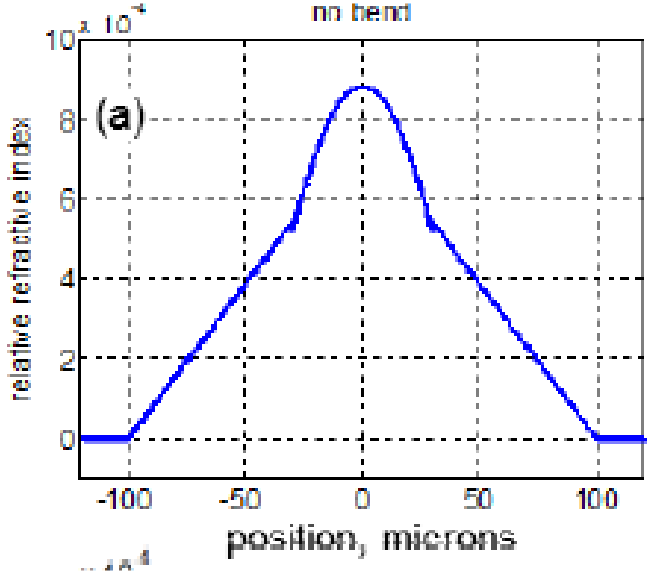


Axicon ø 110 µm
1530 µm^2 , Δn=3.5*10^{-4}

Parabolic ø 70 µm
1170 µm^2 , Δn=3.5*10^{-4}

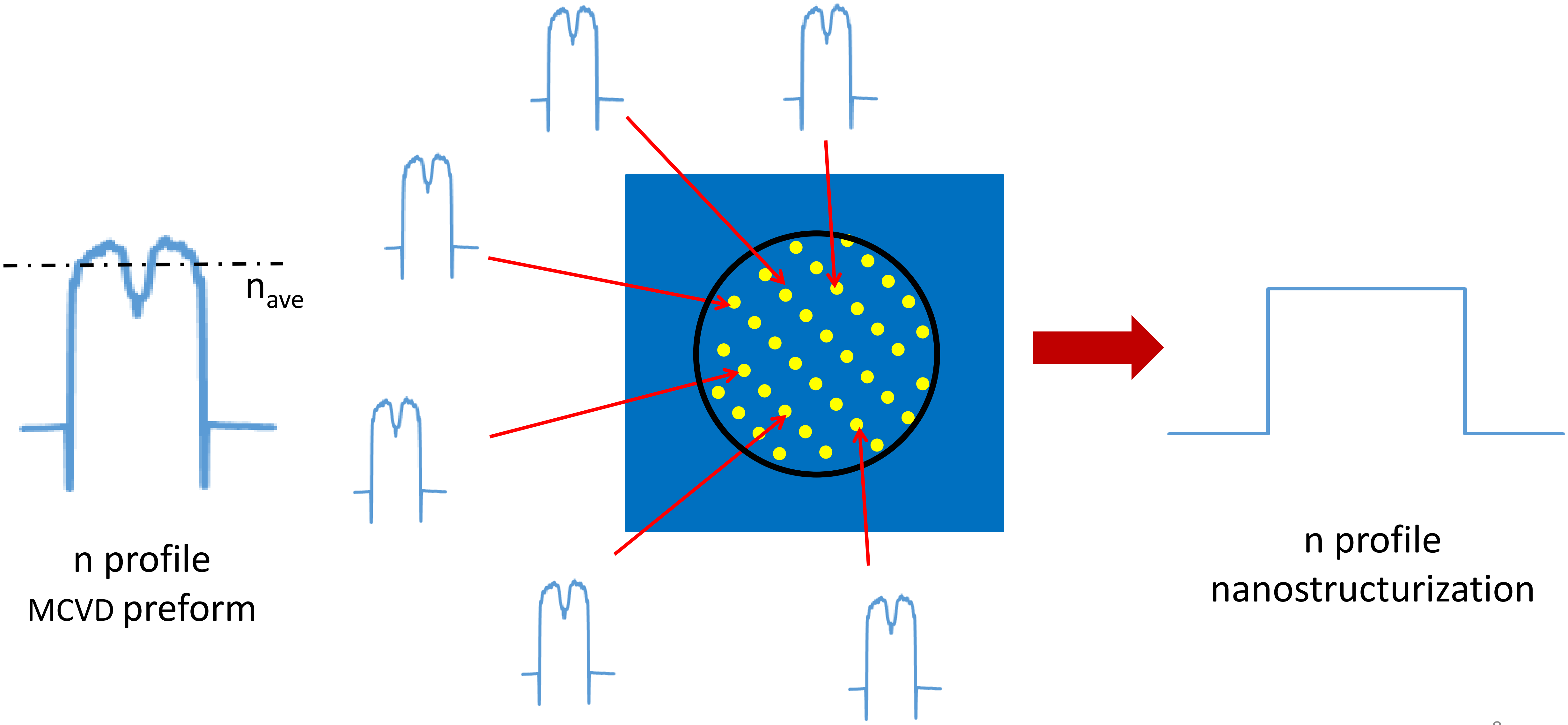






J. Fini, J. Nicholson, **Bend compensated large-mode-area fibers,** ***Opt. Express, 21(2013)***

Motivation – improving refractive index homogeneity



Yb doped phosphate fiber laser with nanostructured core

The proof of ACTIVE nanostructured core fiber

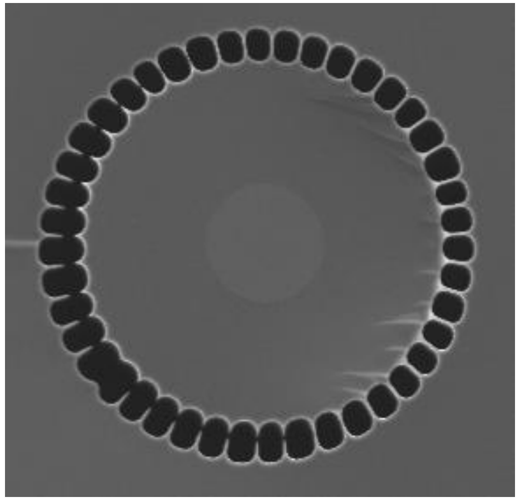
⇒ design – ”step index” profile fiber

⇒ compare with previously developed laser fiber - standard step-index core and double-clad structure

- similar geometrical parameters:
  - core: Ø 19 μm
  - inner cladding: Ø 59 um
  - high NA of pump waveguide (air-cladding)
- similar material: Yb highly doped phosphate glass

⇒ laser parameters

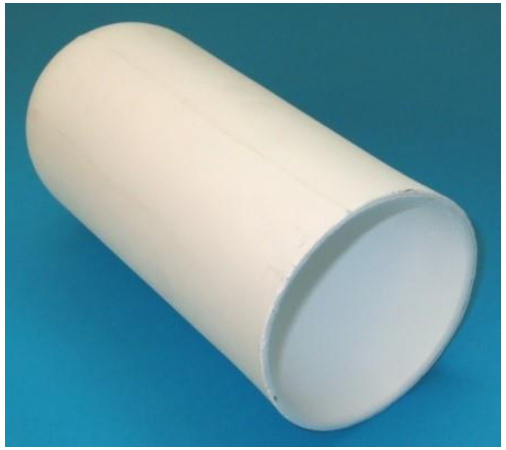
- L = 4cm, η_{slope}= 67%
- pump absorption up to 718 dB/m
- SM operation, $\Delta n = 4*10^{-4}$



M. Franczyk et al., High efficiency Yb3+-doped phosphate single mode fibre laser, Laser Phys. Lett., 14 (2017)

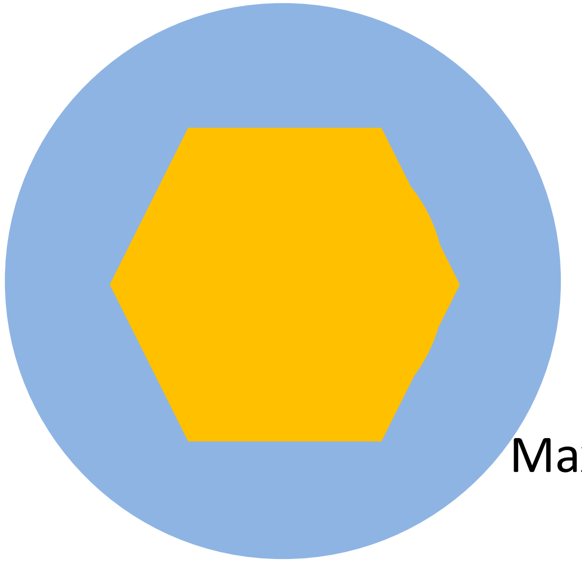
Phosphate Glass Material

- Phosphate glass P_2O_5-Al_2O_3-BaO-ZnO-MgO-Na_2O
- Doped with Yb_2O_3 of intensity of 6mol% (18%wt)
- Dopants liftime $\tau \approx 600$ µs
- Doped and undoped glass
  - rheological properties
  - thermal expansion coefficient
  - Δn=0.0010



Design of nanostructured core with LMA step index profile

target refractive index distribution



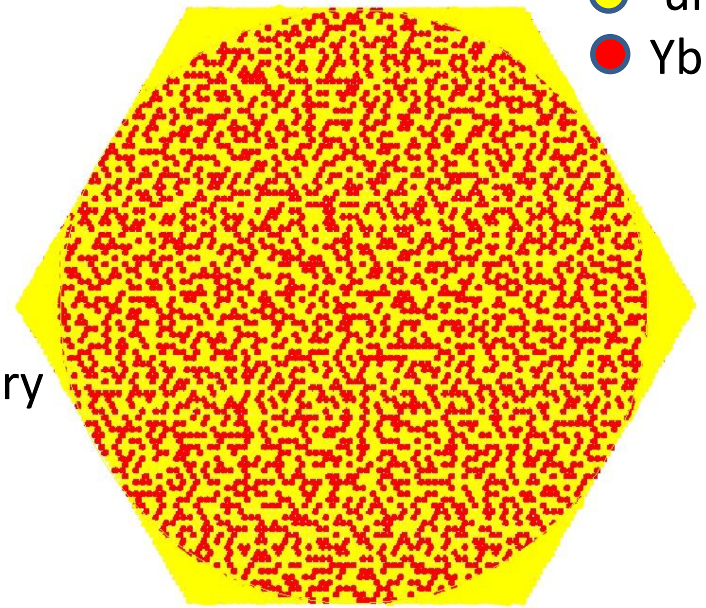
Effective medium

Maxwell–Garnet theory

two glass equivalent structure

undoped rod

Yb doped rod

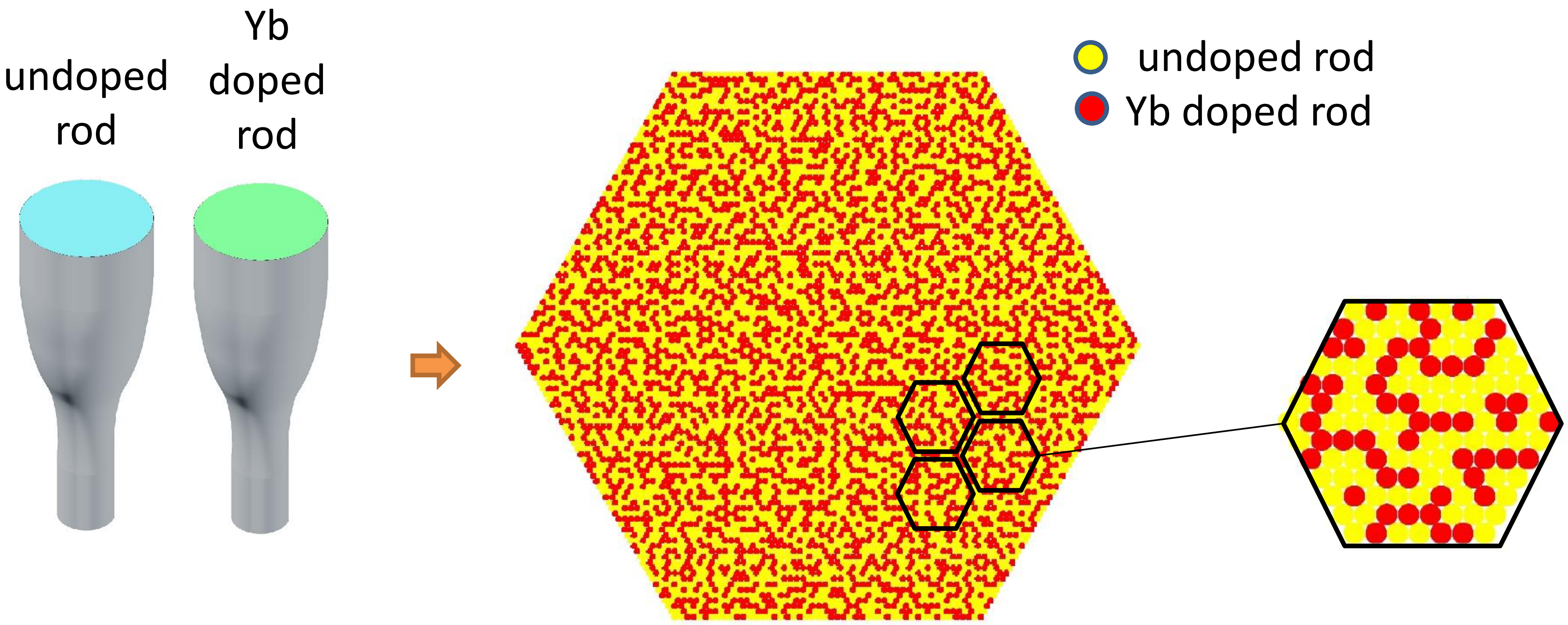


7651 rods

- single area diameter < λ/5
- fiber core size ⌀ 20 µm => 100 rods at diagonal
- 43% doped rods => $\Delta n_{ave} = 4.3*10^{-4}$
- multimode fiber for 20 µm if $\Delta n = 10*10^{-4}$
- rods are composed according to designed pattern

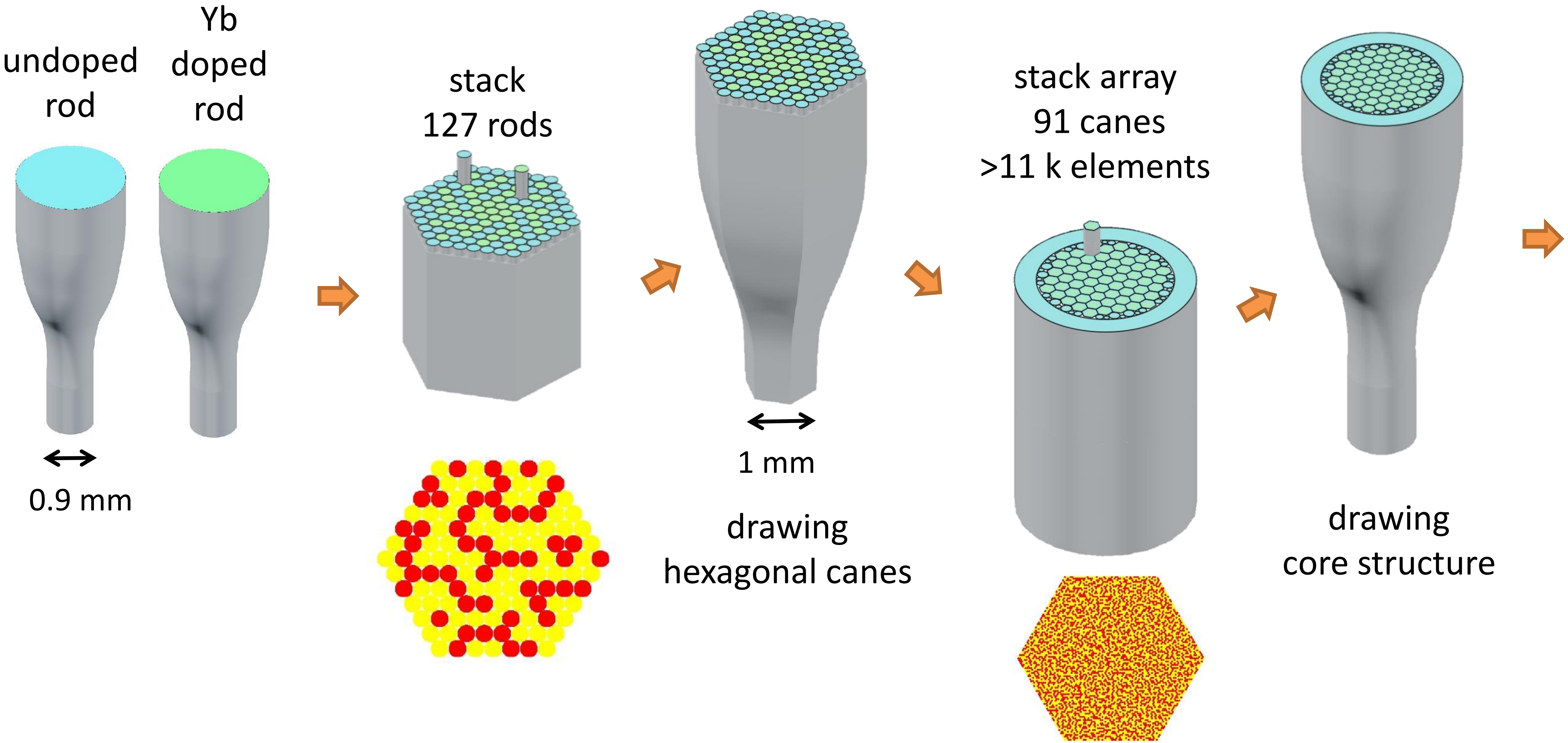
- Simulated annealing algorithm – minimalization difference between target and current refractive index distribution

Fabrication process - nanostructured core - step index refractive index distribution - modification



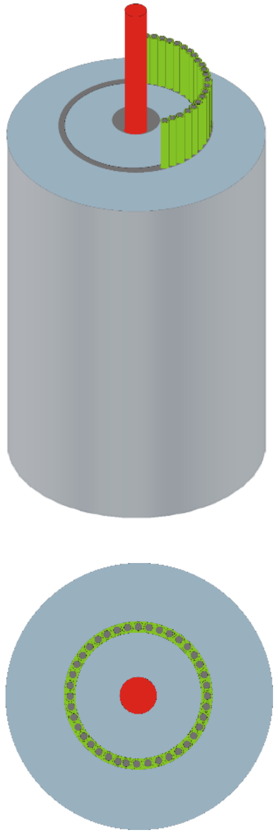
- modified method: only 127 rods instead of 7651 rods

Fabrication process - nanostructured core - step index refractive index distribution



Fabrication process - fiber

preform stacked with
- nanostructured core in tube
- capillaries for air-cladding
- outer tube

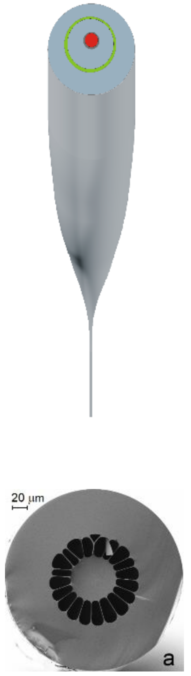


30 ÷ 40 mm

drawing
supreforms

2 ÷ 3 mm

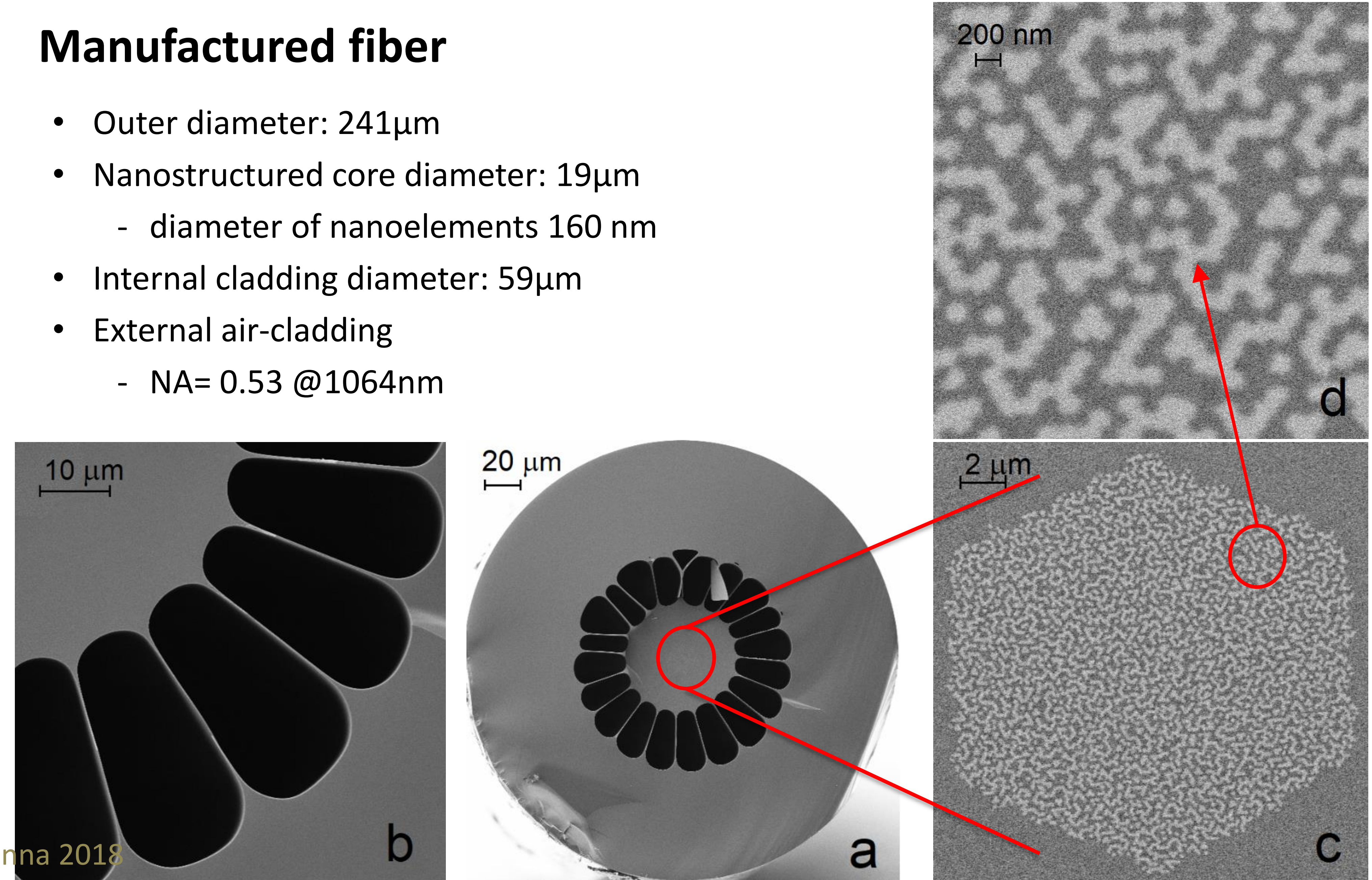
drawing
final fiber



200 µm

Manufactured fiber

- Outer diameter: 241µm
- Nanostructured core diameter: 19µm
  - diameter of nanoelements 160 nm
- Internal cladding diameter: 59µm
- External air-cladding
  - NA= 0.53 @1064nm



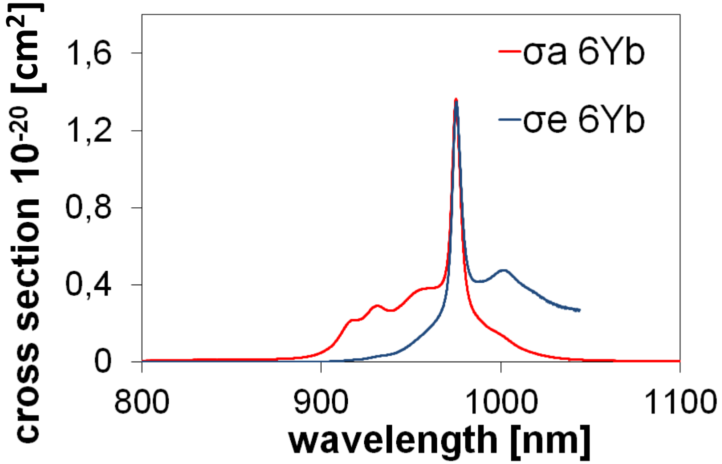
Unsaturated pump absorption in final fiber

Bulk glass

- peak absorption @975.2nm abs_{glass}= 9248dB/m
- average absorption abs_{glass}= 6923 dB/m
  (pump diode 973.5nm, FWHM= 3nm)
- absorption and emmision cross section [McCumber 1964]

σ_a (975.2nm) = 1.40*10^{-20}cm^2

σ_e (1030nm) = 0.35*10^{-20}cm^2



$$\sigma_{emi}(\lambda) = \sigma_{abs}(\lambda)\frac{Z_l}{Z_u}exp(\frac{E_{ZL} - hc\lambda^{-1}}{kT})$$

Fiber

$$abs_{fiber} = \eta_S \frac{A_{doped}}{A_{clad}} abs_{glass}$$

[Zenteno 1993] [Zervas JSTQE 2014]

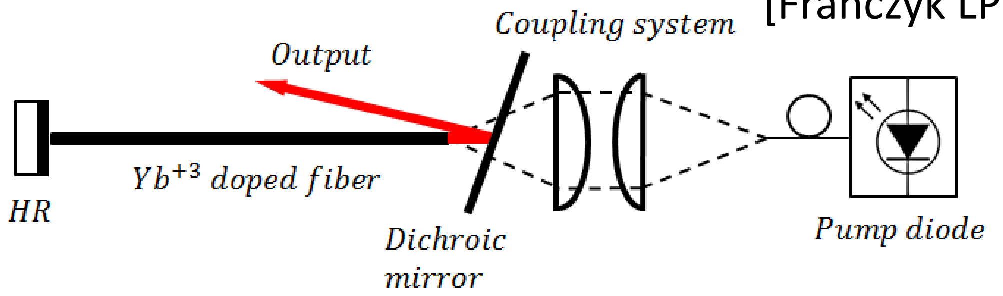
A_{doped}(19µm - hexagon) = f · 234 µm^2 , A_{clad}(59µm) = 2 734µm^2 f=0.43

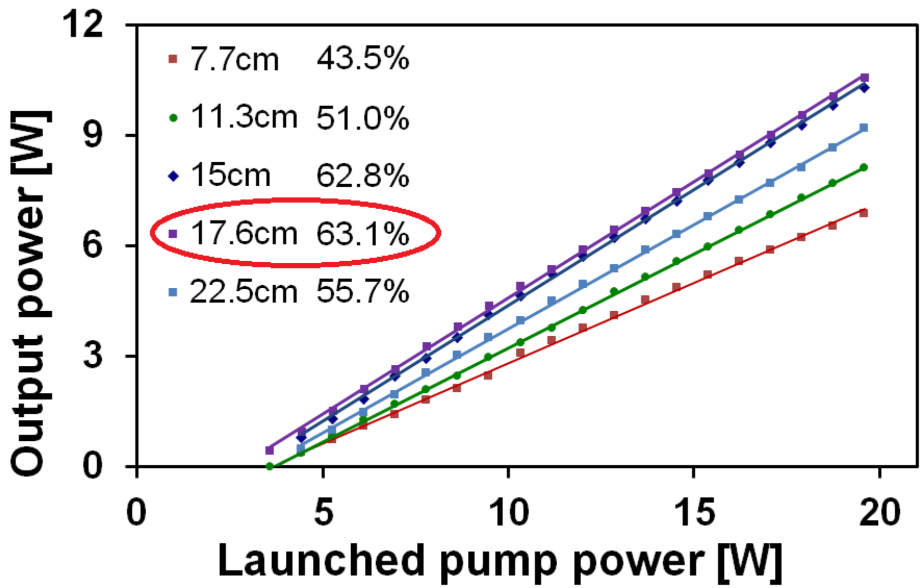
abs_{fibre}= **130 ÷ 255 dB/m** (η_S = 0.51 ÷ 1) => short fiber laser

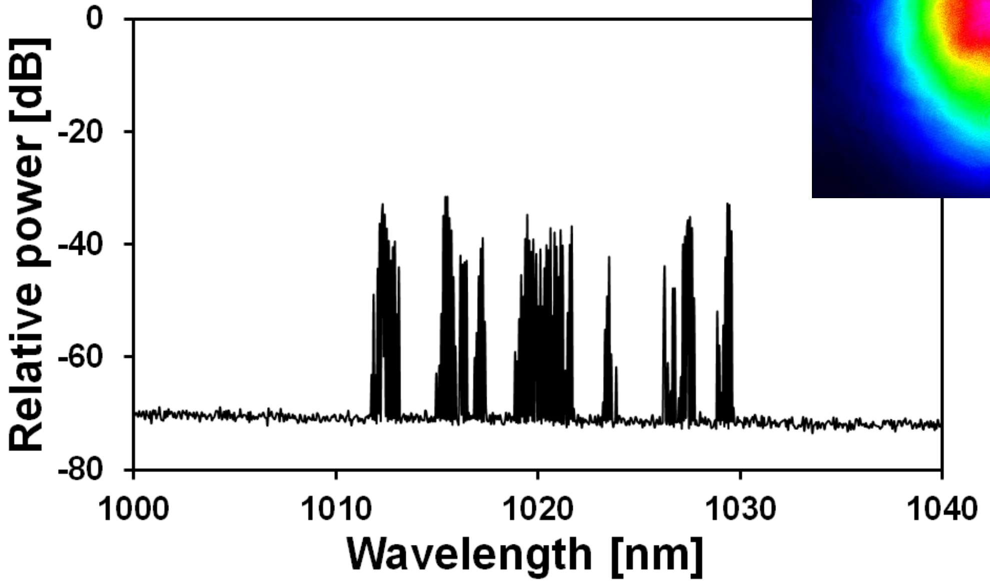
Laser performance

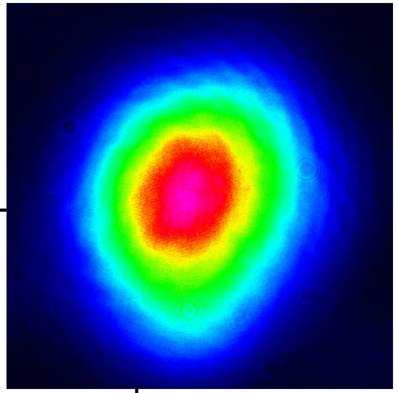
- fiber lengths (L): 7.7 - 22.5 cm
- L_{opt} = 17.6 cm , P_{tresh} = 2.7 W, η_{slope} = 63.1%
- P_{max}= 10.6 W
- SM performance, M_x^2 = 1.1, M_y^2 = 1.3, NA = 0.04
- Spectrum 1012 ÷ 1030 nm

[Franczyk LPL 2017]

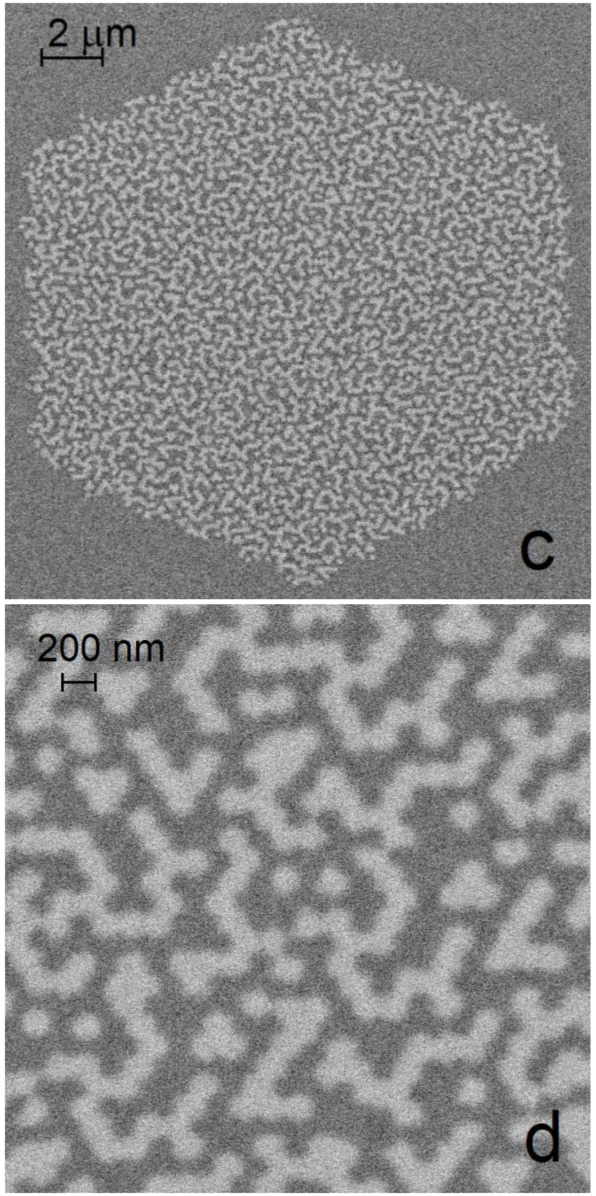








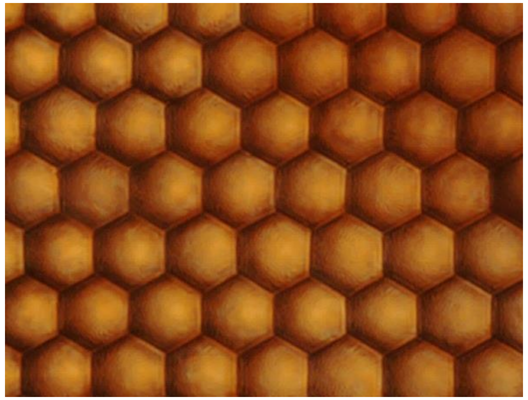
Conclusions

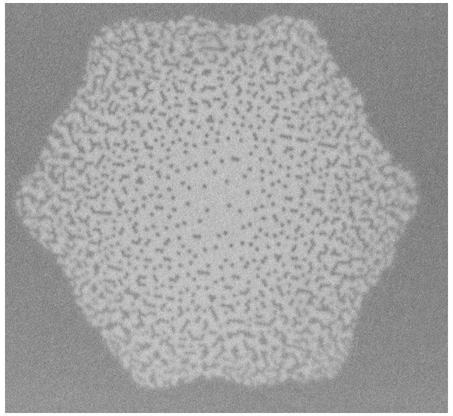


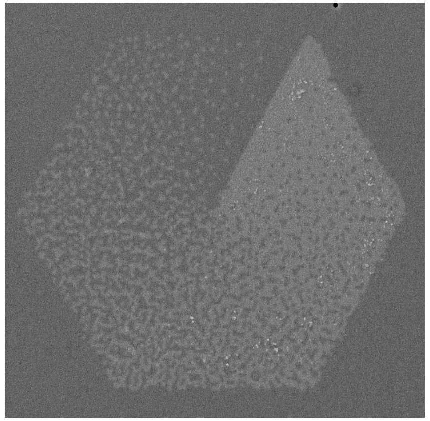
- First proof of nanostructurization concept in ACTIVE fiber
- One of the highest slope efficiency η_{slope}= 63.1% in phosphate d-c fiber laser 67% [Franczyk LPL 2017], 50.6% [Lee JSTQE 2009]
- Nanostructurization does not bring substantial loss if proceeded in clean room facility

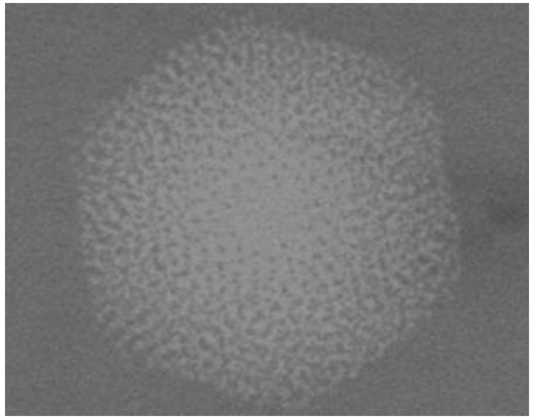
Conclusions

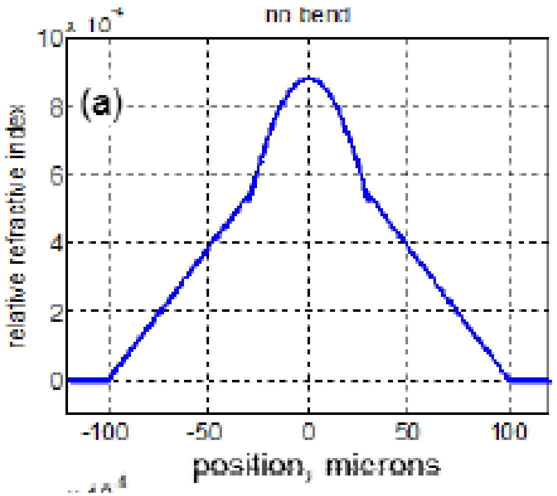
- Nanostructurization
  - develope any refractive index profile defined with high precison
    => e.g. bent-resistance, shaping dispersion, birefringent specialty fibers
  - available in any glass material
  - develope LMA fibers for high power performance in silica
  - design for decreasing TMI effect











We invite you to cooperation

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Laser Setup

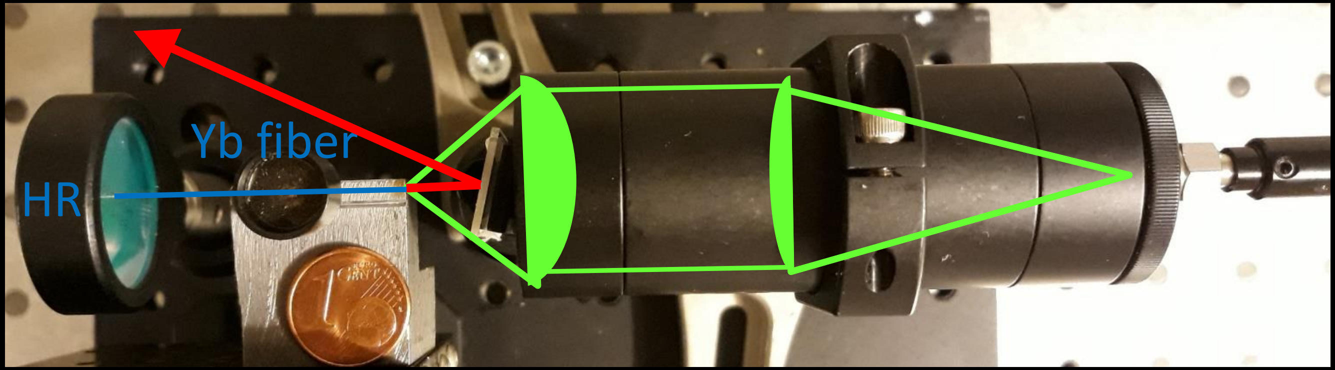
Laser cavity
- 4.3% Fresnel reflection
- HR broadband mirror 99% @975nm and @1030nm

Pumping setup
- pump diode: D=100 µm, NA=0.22
- achromatic lens: f1=50mm, f2=20mm

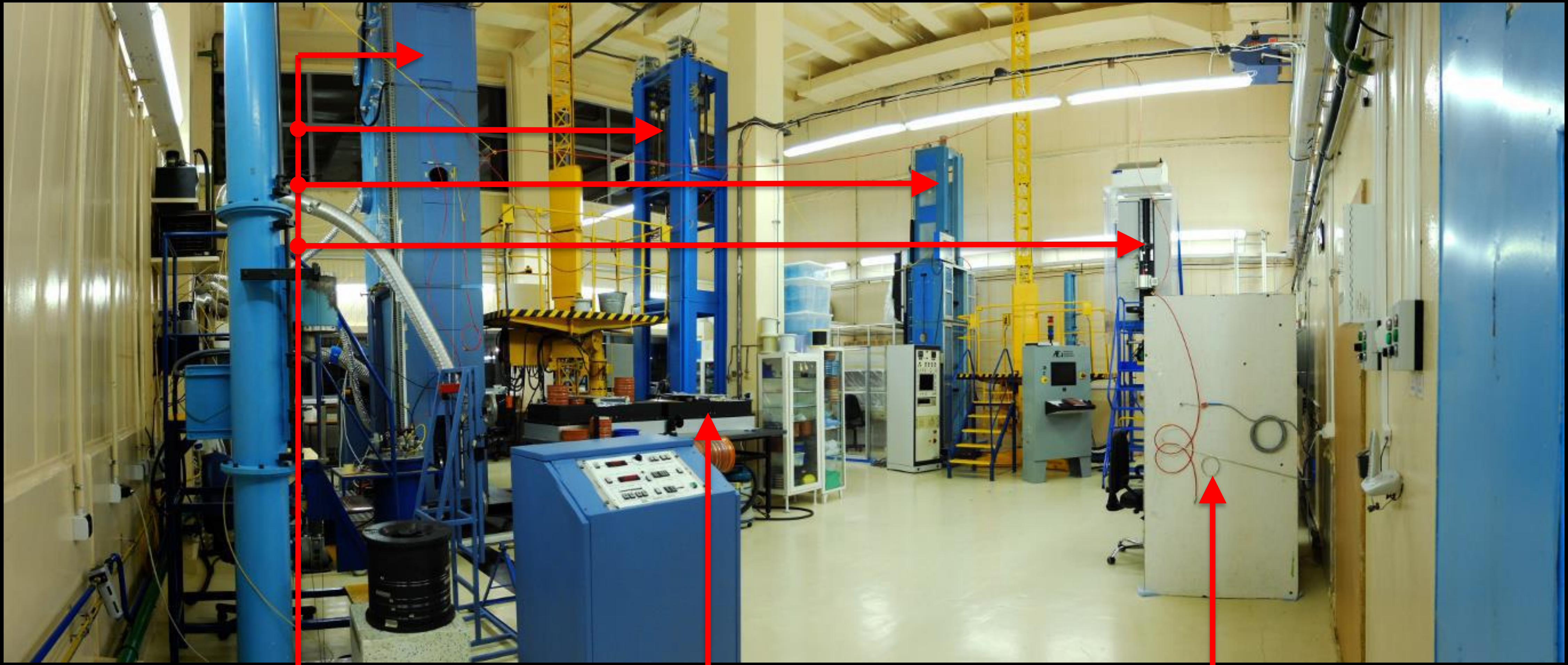
Laser output

Dichroic mirror HR >1010nm HT<990nm

Pump beam
- model: waist 45 µm, NA = 0.52
- measured: waist 57 µm, NA = 0.45



Fabrication facility



4 fiber drawing towers

3SAE fiber plasma splicer

2 laminar flow cabinets for preform assembly

How nanostructured medium „works" ?

Sihvola, *Electromagnetic Mixing Formulas and Applications*, London: The Institution of Electrical Engineers (1999)

$$\varepsilon_{eff} \approx \varepsilon_e + f(\varepsilon_i - \varepsilon_e)$$

n = $\sqrt{\varepsilon \cdot \mu}$ μ ≈ n^2 μ≈1 for glass

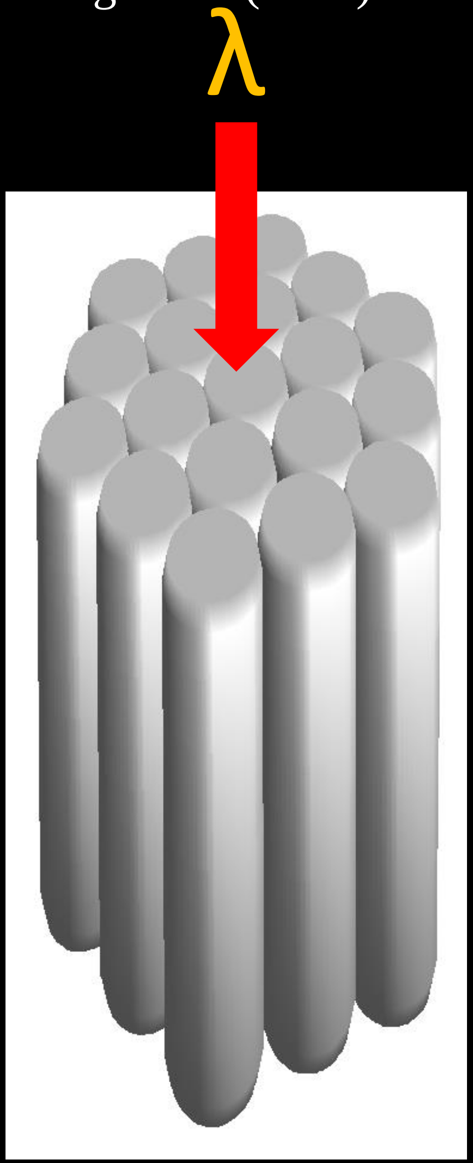
area of 1.5 λ, μ≈1 for glass

Metamaterial consist of many thin dielectric rods.

Discrete structure. Feature size (i.e. rod diameter) << λ λ/5

Light 'sees' averaged (effective) refractive index distribution

Created metamaterial with arbitrary refractive index distribution in cross-section (gradient-index or step-index)



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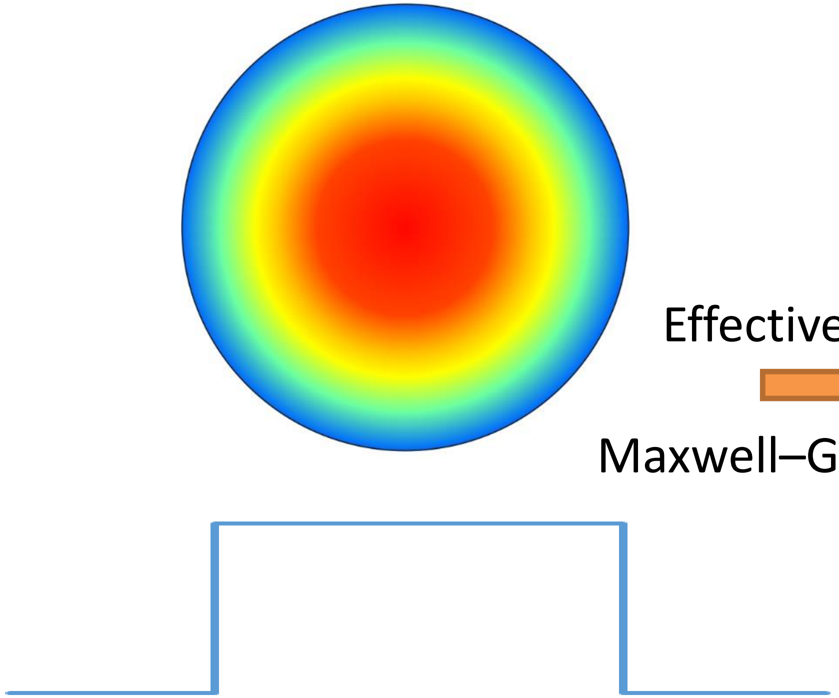
Design of nanostructured core with uniform profile

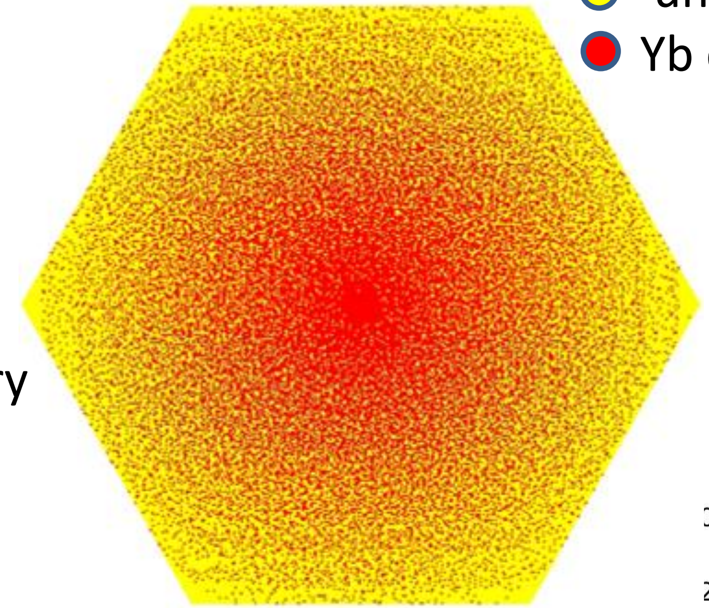
target refractive index distribution



Effective medium

Maxwell–Garnet theory

two glass equivalent structure

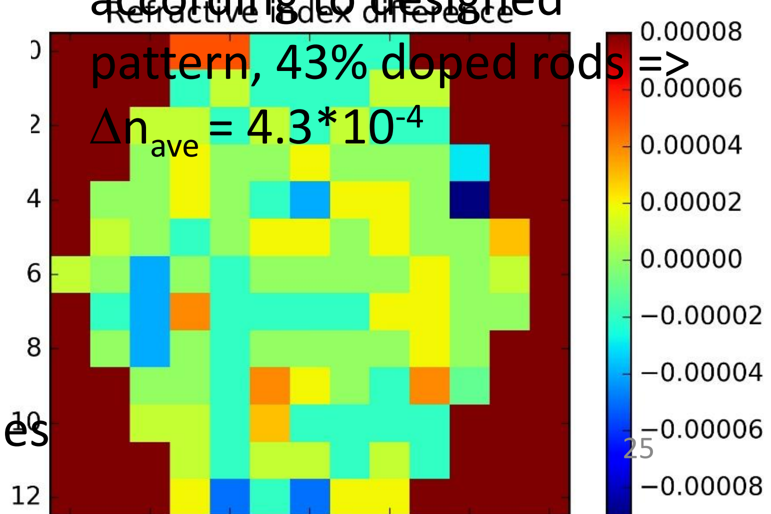


undoped rod

Yb doped rod

7651 rods

- single area diameter < λ/5
- lens /fiber core size 20 μm => 100 rods at diagonal
- rods are composed according to designed pattern, 43% doped rods => $\Delta n_{ave} = 4.3 \cdot 10^{-4}$

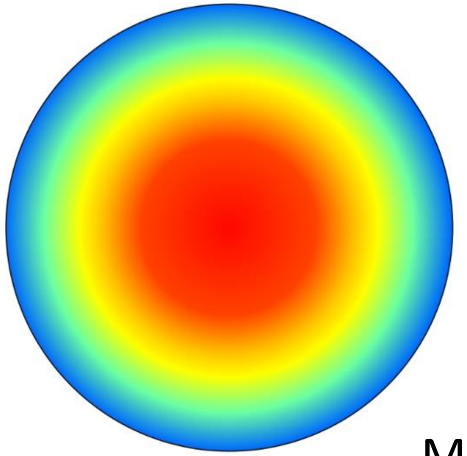


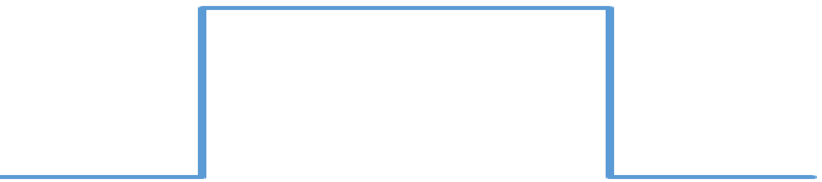
- Simulated annealing algorithm – minimalization of cost function = difference between target and current refractive index distribution
- Beam propagation method – verification of designed component functionalities

Design of nanostructured core with uniform profile

- rods are composed according to designed pattern, 43% doped rods => $\Delta n_{ave} = 4.3 \times 10^{-4}$

target refractive index distribution

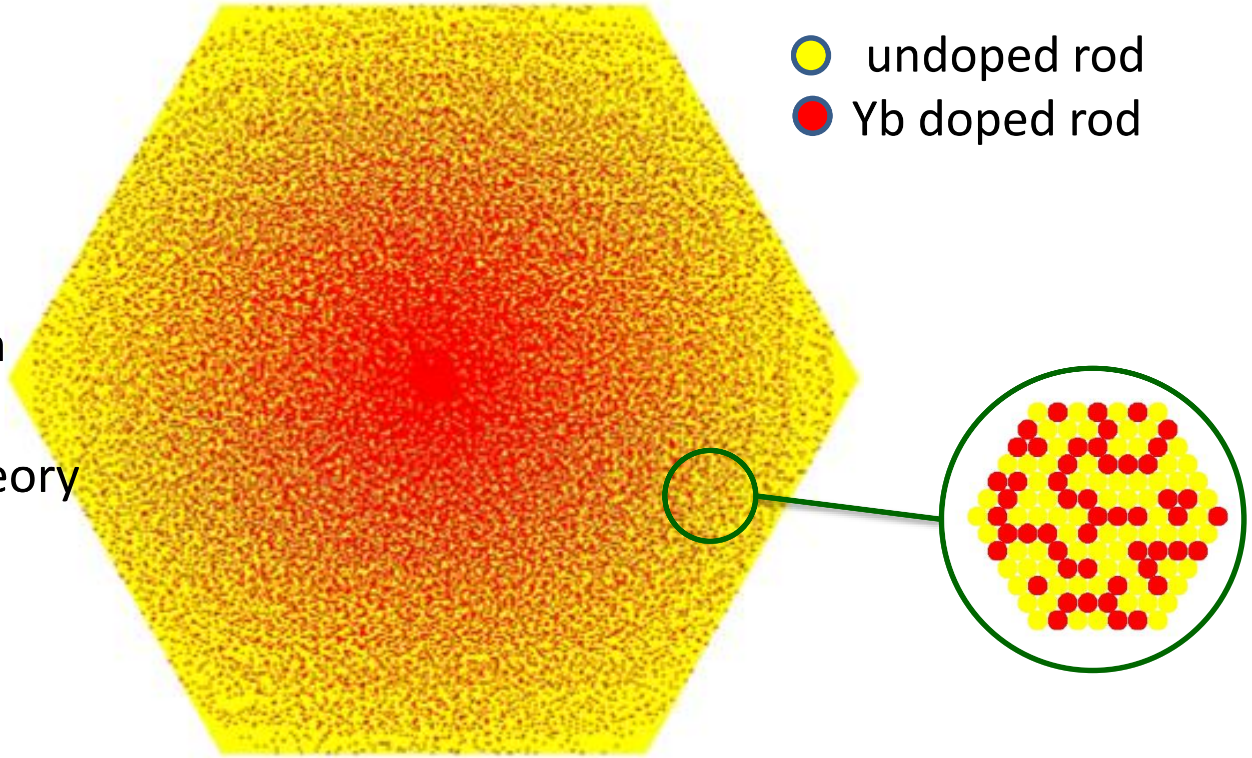




Effective medium

Maxwell–Garnet theory

two glass equivalent structure



7651 rods

- Simulated annealing algorithm – minimalization of cost function = difference between target and current refractive index distribution
- Beam propagation method – verification of designed component functionalities

- lens /fiber core size 20 µm =>
- single area diameter < λ/5 =>
- modified method: only 127 ro