Modeling of Modes Competition and Thermal Effects in Large Mode Area Photonic Crystal Fibers

C. Molardi, F. Poli, A. Cucinotta, S. Selleri

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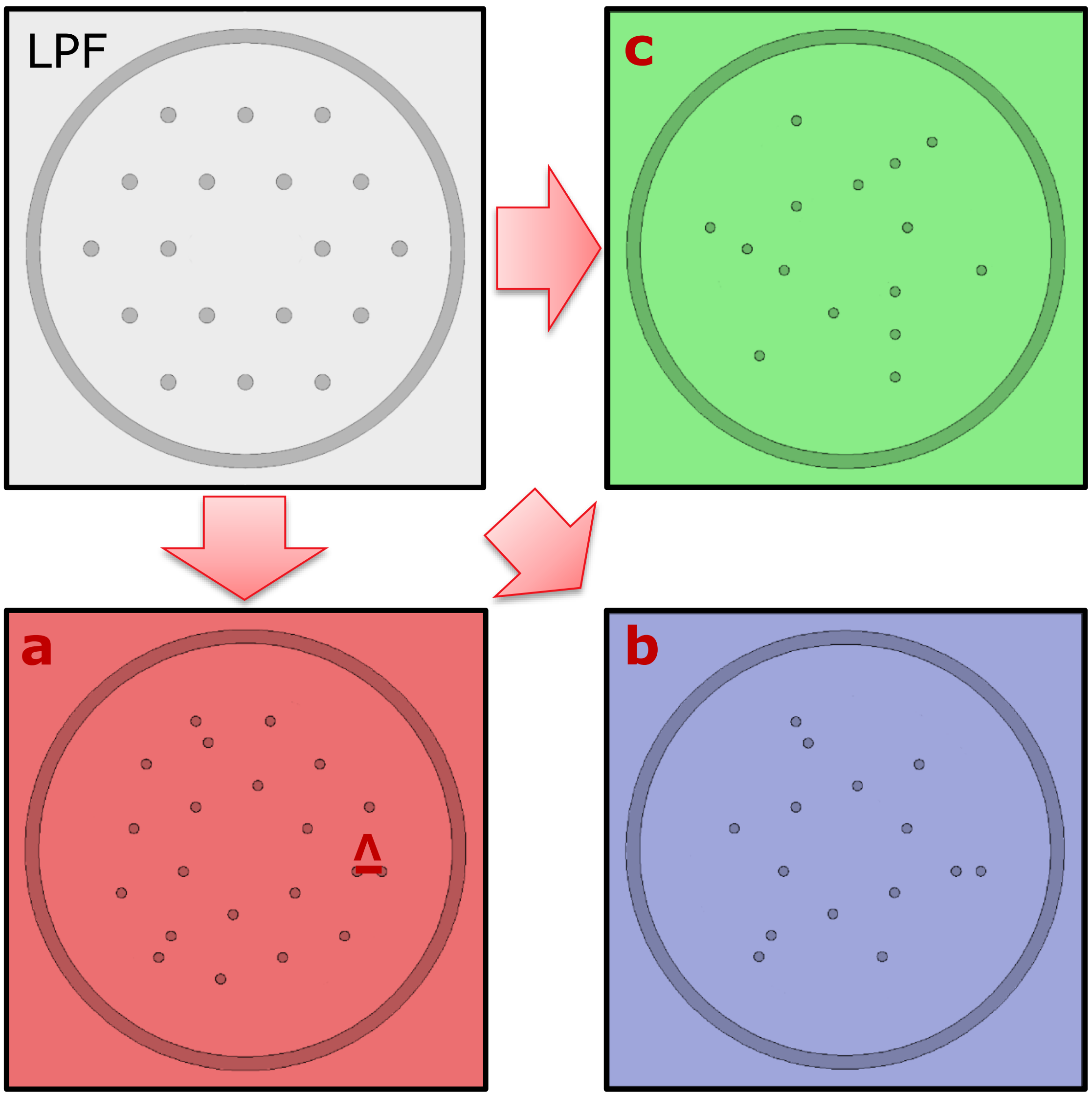
Outline

- New designs of large mode area Yb-doped fibers without symmetry in the inner cladding
- Numerical simulations:
  - Modal analysis
  - Thermal effect model
- Study of the thermal effect influence on:
  - Single mode behavior
  - Effective area
- New model to describe z-variation
- Conclusion

Reduced symmetry PCFs



Idea: remove mirror symmetry of the cladding to enhance delocalization of LP_{11} mode

- 19-cell hexagonal core (edge of 36 μm)
- Air-hole diameter: d = 5.76 μm = 0.4Λ
- Pitch: Λ = 14.4 μm
- Inner cladding radius: 120 μm
- Air-cladding width: 8 μm

FEM simulations

Fundamental Mode (FM) and first LP_{11}-like Higher-Order Modes (HOM = $HOM_{1x,\ x=1\ldots4}$) at 1032 nm

Overlap integral Γ on the hexagonal doped core calculated to evaluate the mode confinement:

$$\Gamma = \iint_S i(x,y)\,dx\,dy$$

S: hexagonal core
i(x,y): normalized intensity

- Differential overlap ΔΓ (overlap difference between FM and HOM) considered to define the Single Mode (SM) region:

$$\Delta\Gamma > 0.3$$

- FM tight confinement ($\Gamma > 0.8$) required in the SM region

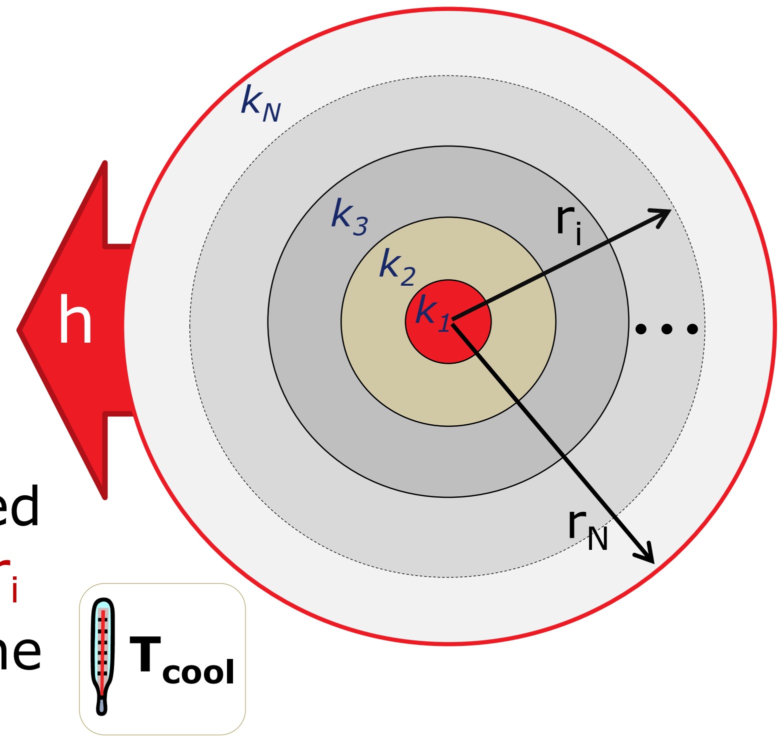
Effective area A_{eff} evaluated to study the influence of thermal lensing on the FM confinement

Thermal effect model

- Heat generation
- Temperature gradient ΔT
- Refractive index change $\Delta n = \beta \cdot \Delta T$, $\beta = 1.16 \cdot 10^{-5}$ 1/K for silica

New guiding properties

- PCF section: different rings, described by thermal conductivity k_i and radius r_i
- Heat density Q_0 generated into the doped core
- Convection cooling, described by convection coefficient h, at the outer surface

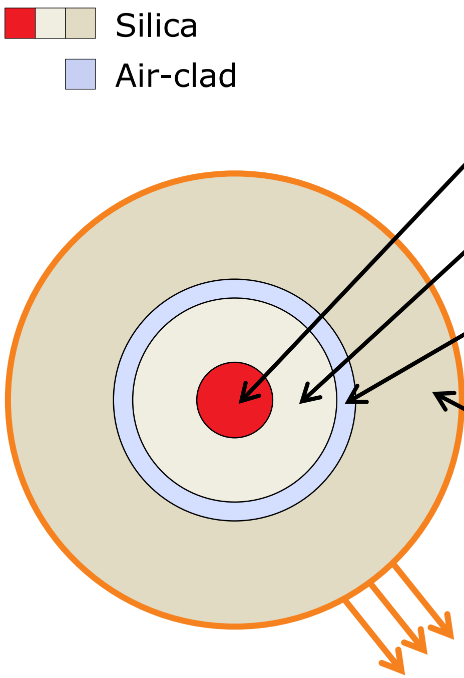


- $k_1,\ldots,k_N$: thermal conductivity (silica: 1.38 W/(m·K))
- $r_1,\ldots,r_N$: external radius
- T_{cool}: outer temperature

E. Coscelli et al, Journal of Lightwave Technology, Vol. 30, pp. 3494-3499 (2012)

Fiber parameters

Fiber cross-section characteristics



Core: r_1 = 32.74 μm, k_1 = 1.38 W/(m K)

Inner cladding: r_2 = 120 μm, k_2 = 1.38 W/(m·K)

Air cladding*: r_3 = 128 μm
n = 111, b = 0.35 μm
k_{air} = 0.023 W/(m·K)
k_{silica} = 1.38 W/(m·K)
} k_{eq} = 0.0918 W/(m·K)

Outer cladding: r_4 = 850 μm, k_4 = 1.38 W/(m·K)

Convection cooling: h = 80 W/(K·m^2) (air flow)

T_{cool} = 298.15 K

***air-cladding equivalent thermal conductivity:**

$$k_{eq,AC} = k_{air} + \frac{n \cdot b \cdot k_{silica}}{2\pi(r_3 - r_2)} \ln\left(\frac{r_3}{r_2}\right)$$

Heat generation

- Quantum defect-generated heat density Q_0
- $Q_0 = q/A_{core}$

q: heat load per unit length (W/m)

A_{core}: core doped area

Generated heat due to pump conversion

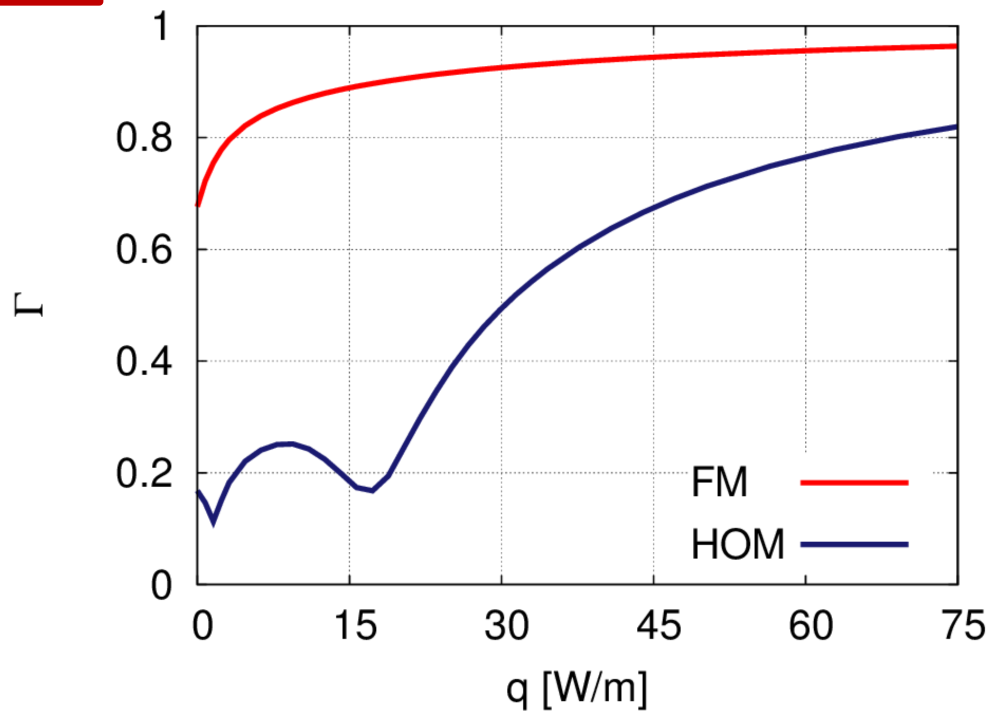
$$q = \frac{1 - 10^{-\alpha \frac{dL}{10}}}{dL} \left(1 - \frac{\lambda_p}{\lambda_s}\right) P$$

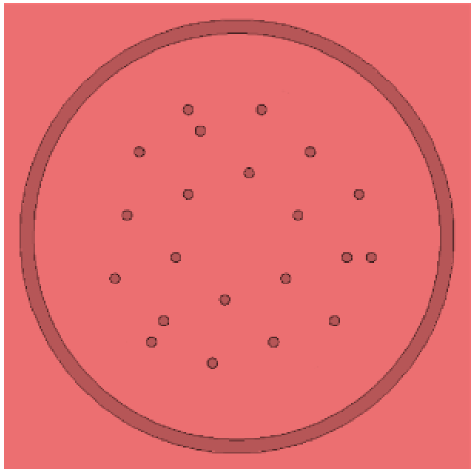
α	Pump absorption	27 dB/m
dL	Fiber length over which average heat load is calculated	0.1 m (close to pumping end)
λ_p	Pump wavelength	976 nm
λ_s	Signal wavelength	1032 nm
P	Pump power	0 – 300 W

Mode confinement Fiber a

DII

λ = 1032 nm

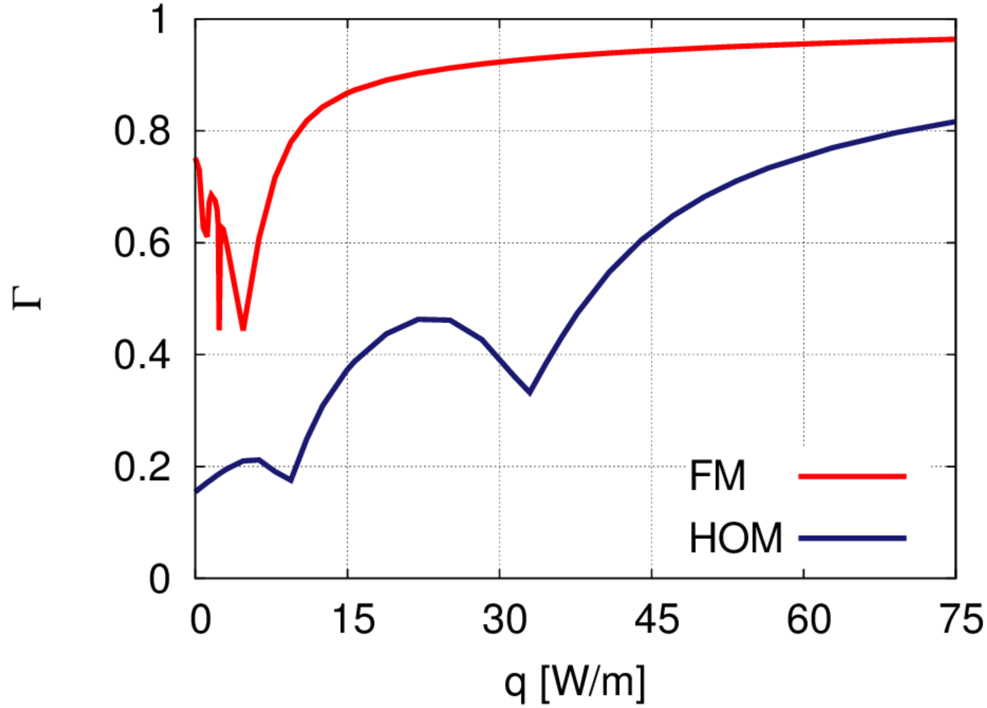


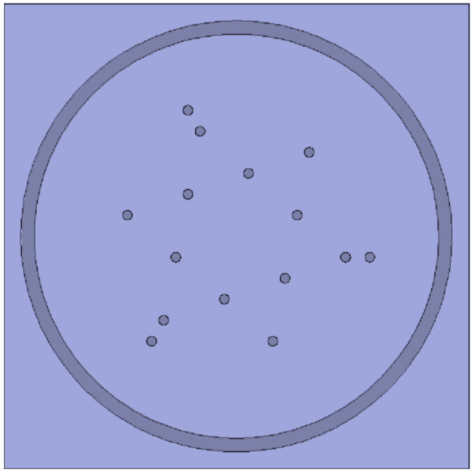


- FM well confined (Γ≥0.8) for q≥3.9 W/m, and guided even without pumping (Γ≈0.68 in the "cold" fiber)
- HOM poorly guided for low q values, with significant field in the inner cladding, and better confinement as q increases
- Different HOM solutions due to coupling with cladding modes

Mode confinement Fiber b

λ = 1032 nm

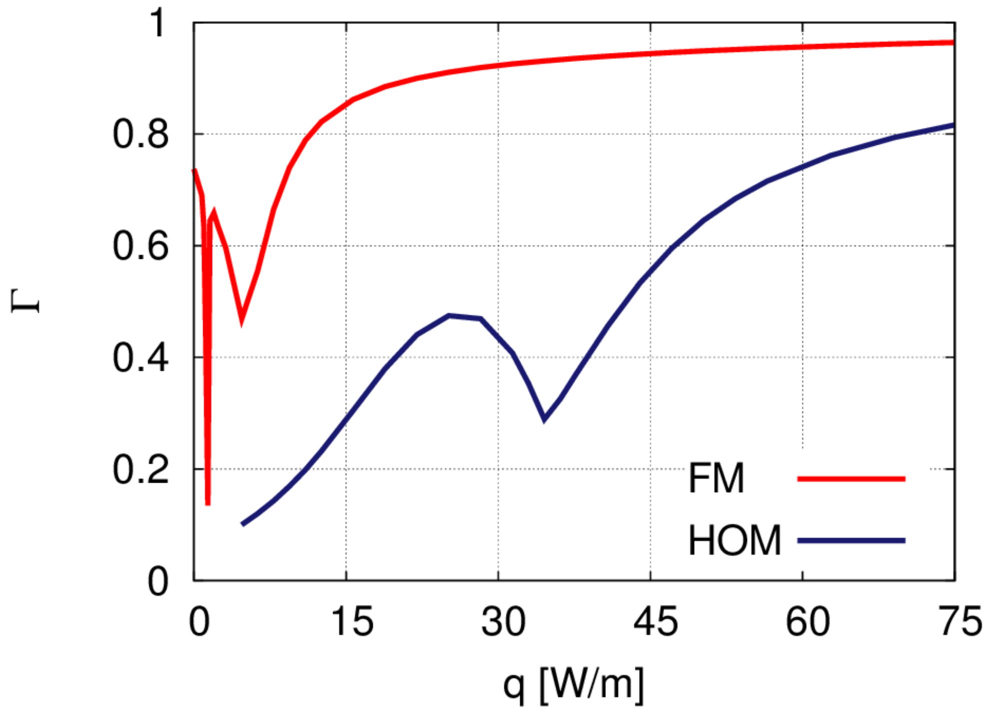


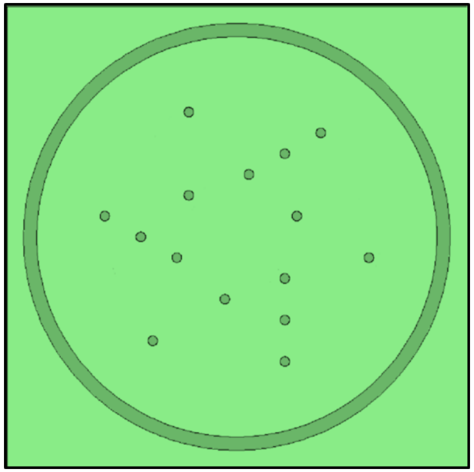


- FM not truly guided in the "cold" fiber and for low pump power values (effective refractive index difference not enough), and well confined (Γ≥0.8) for q≥8.6 W/m
- Different HOMs, coupled to cladding modes, for q≤32 W/m
- Tighter FM and HOM confinement as q increases

Mode confinement Fiber c

λ = 1032 nm

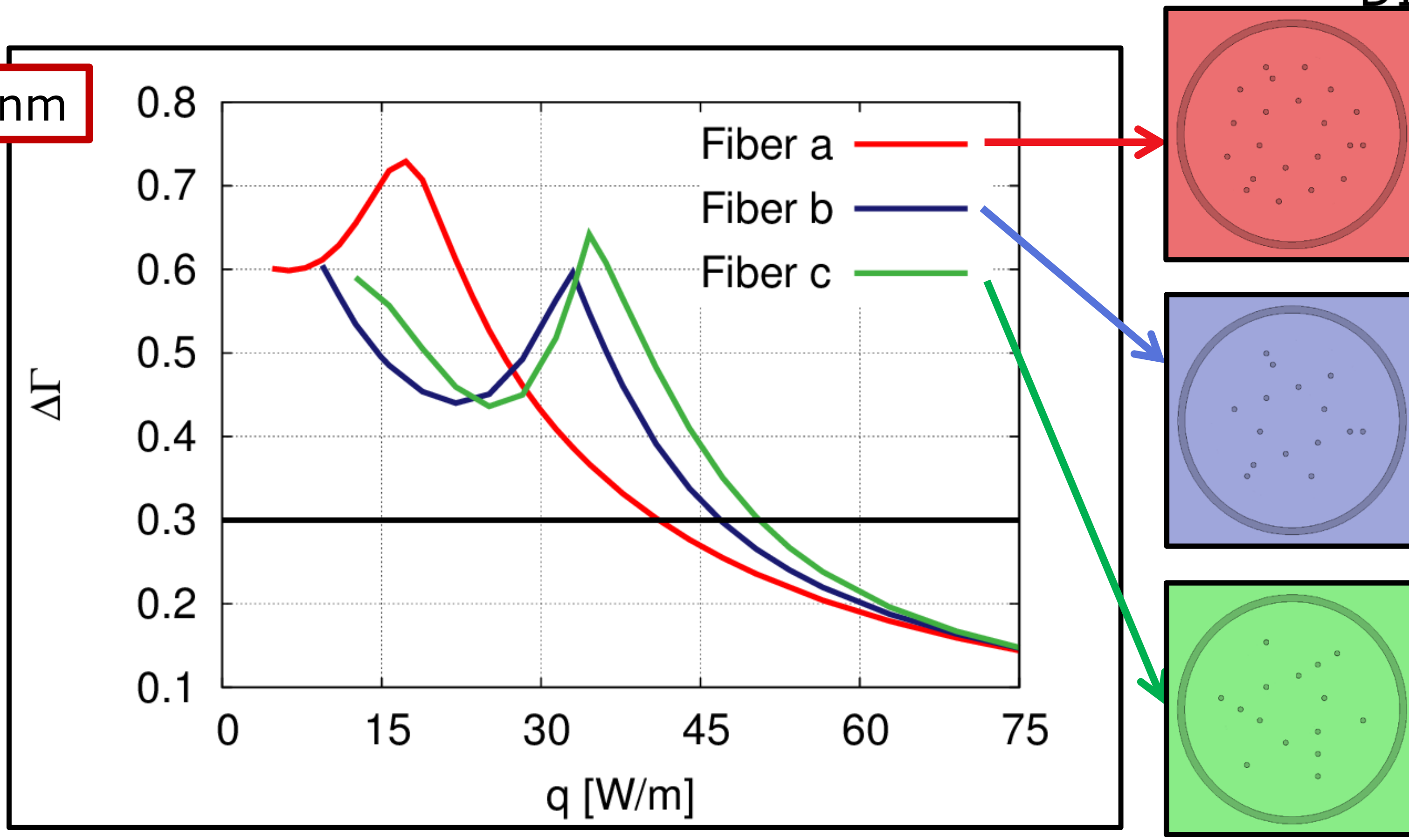




- FM and HOM poorly guided for low pump power values, with significant field distribution in the inner cladding (unwanted coupling with cladding modes)
- Better confinement of both modes as q increases
- FM well confined (Γ≥0.8) for q≥11 W/m

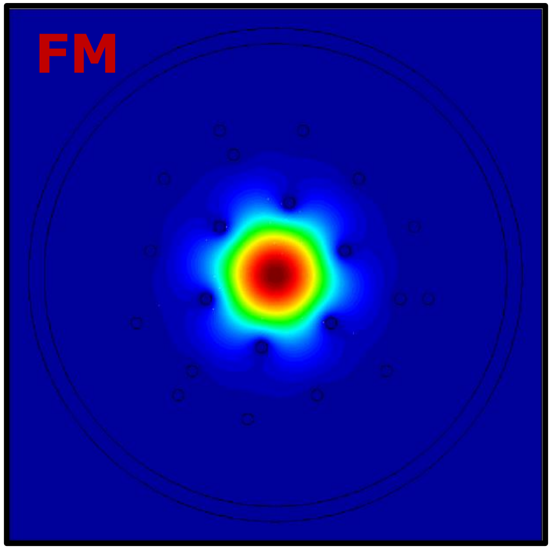
SM regime

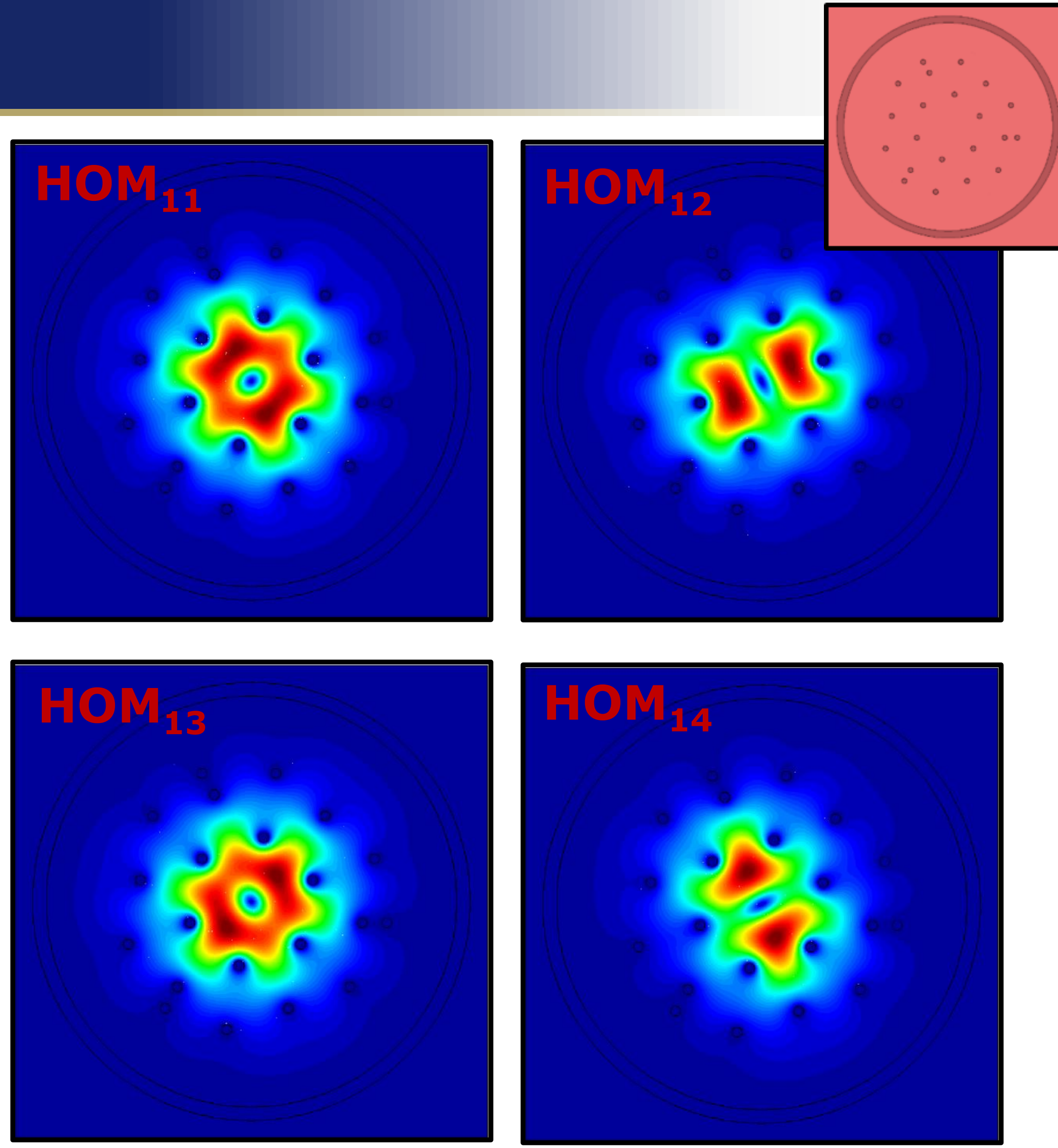
λ = 1032 nm



- Fiber *c* SM range similar to the Fiber *b* one, only slightly shifted towards higher q values (q between 11 W/m and 50 W/m)
- Only Fiber *a* is SM for low heat load values
- Higher q values (≈50 W/m) reached by Fiber *b* and *c* with SM behavior

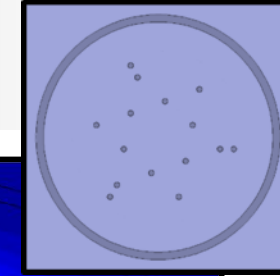
Fiber a

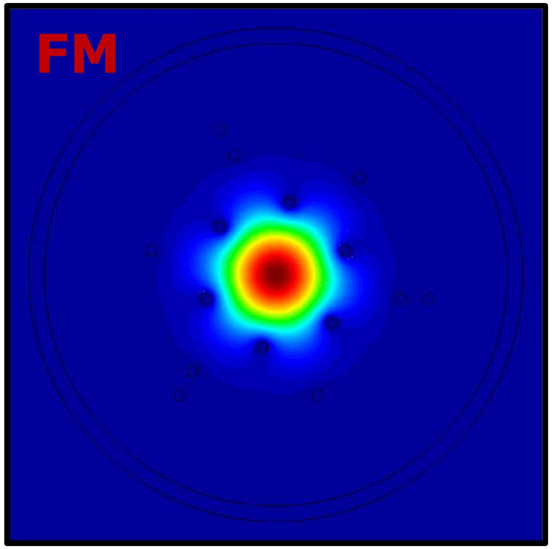


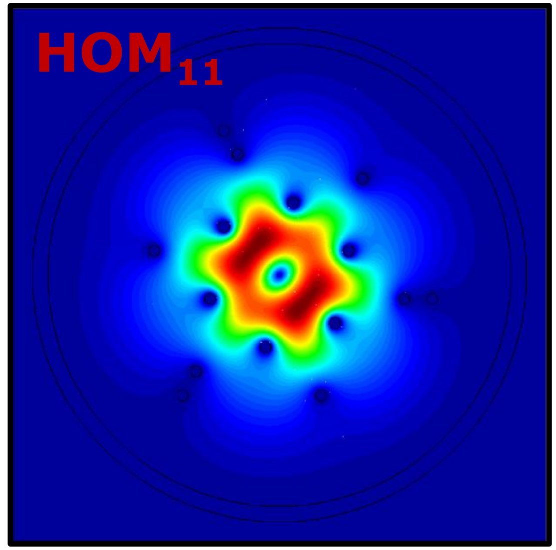


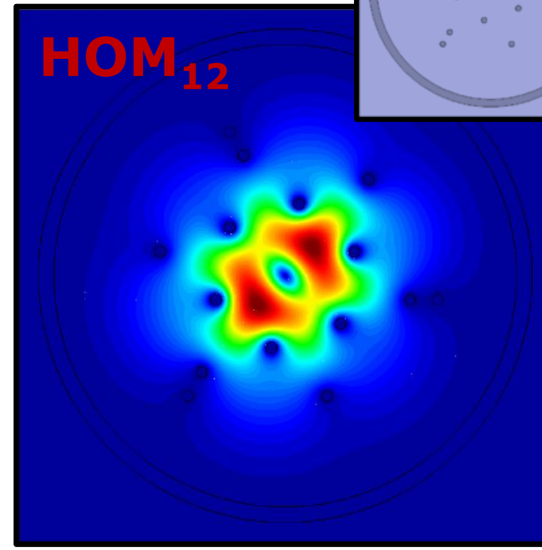
FM and HOM magnetic field modulus distributions at the SM range edge, for $q \approx 41$ W/m

Fiber b

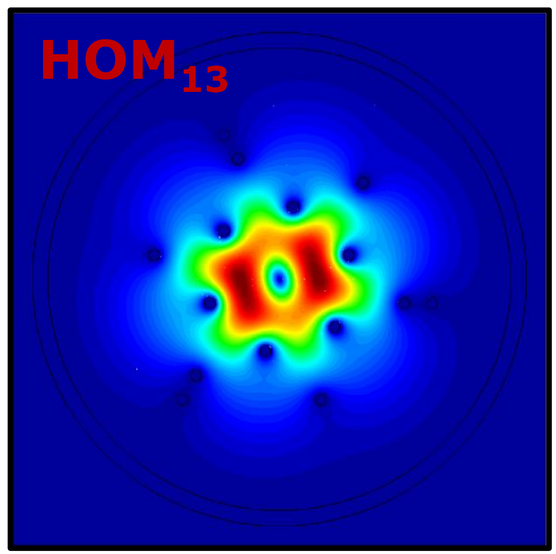


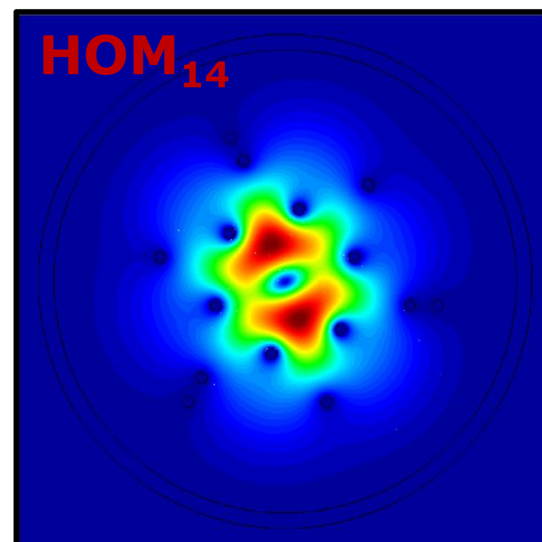




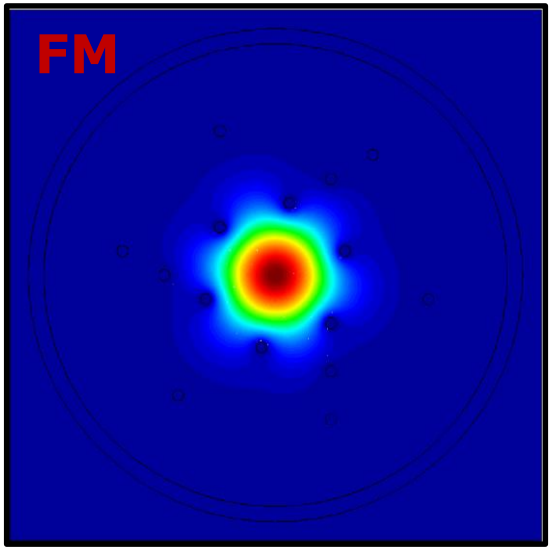


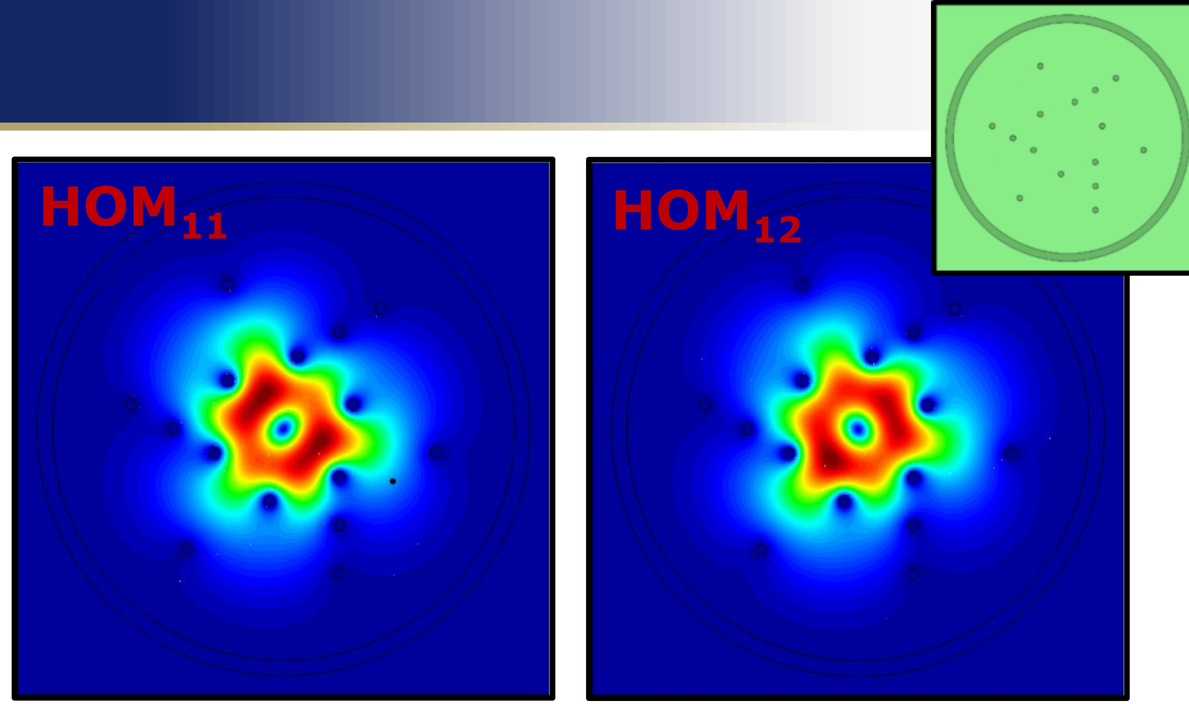
FM and HOM magnetic field modulus distributions at the SM range edge, for q ≈ 47 W/m



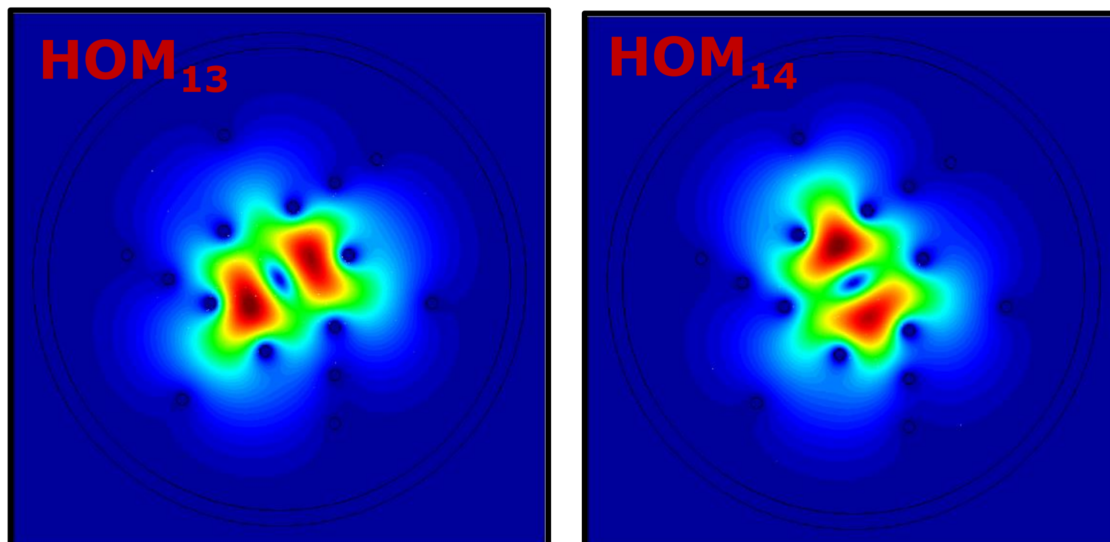


Fiber c

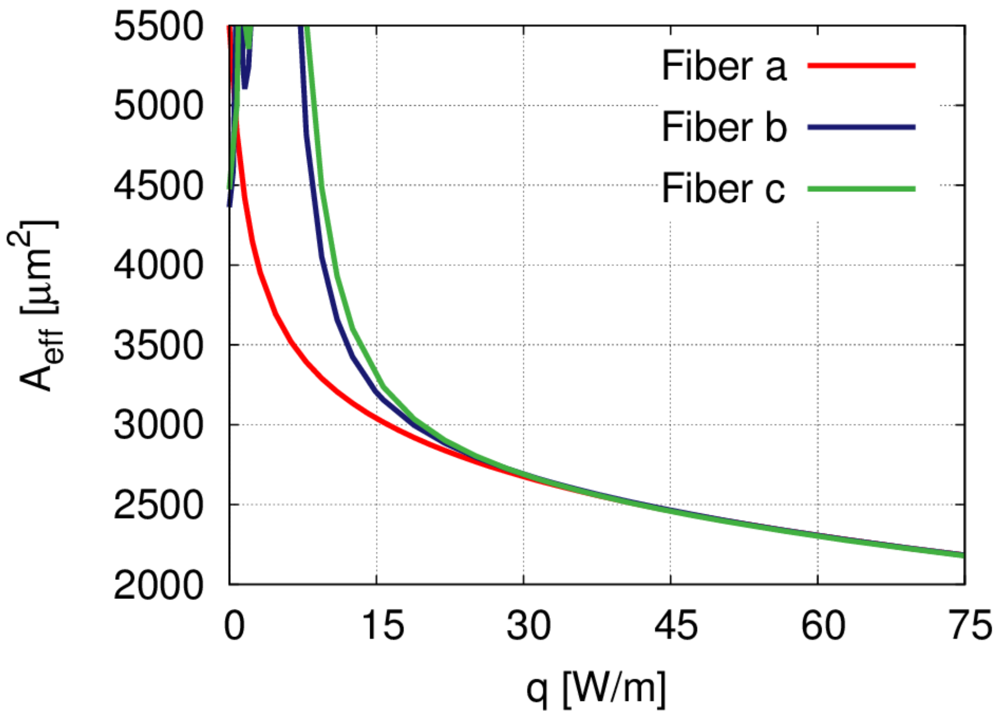


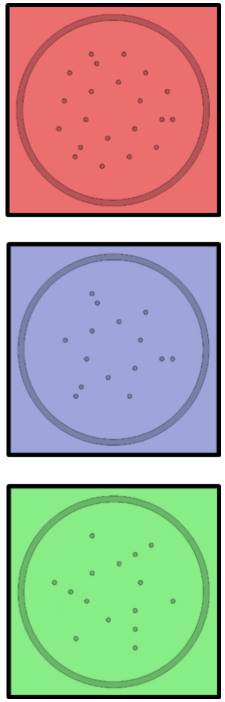


FM and HOM magnetic field modulus distributions at the SM range edge, for $q \approx 50$ W/m



Effective area



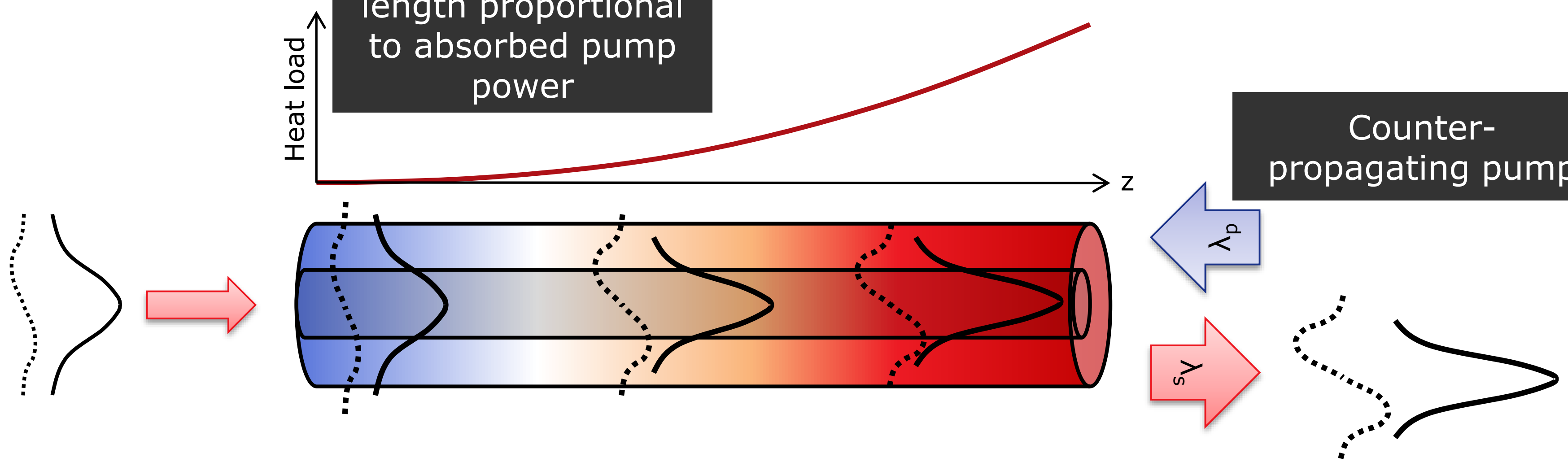


- A_{eff} values of Fiber *c* very similar to the ones of Fiber *b* in all the q range where the FM is well confined (q≥7 W/m) due to the cross-section geometry similarity
- The three PCFs have the same effective area for q≥25 W/m = FM guiding no longer influenced by inner cladding geometry, being provided mainly by the index gradient caused by thermal effects

Thermal effects along z

Heat load/unit length proportional to absorbed pump power

Counter-propagating pump

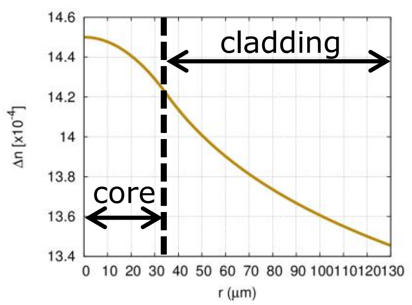


Higher temperature in the core

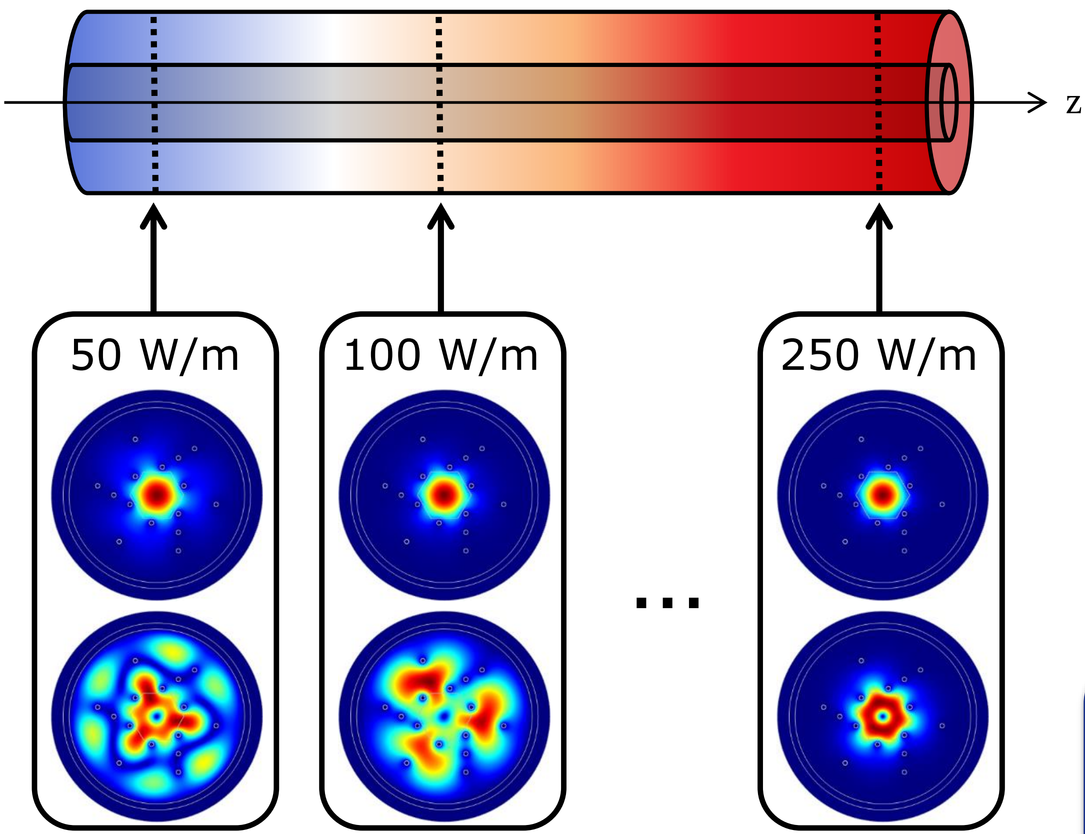
Thermally-induced graded-index profile

Increase confinement of high-order modes

Loss of transverse single mode output



Amplifier model with thermal effects



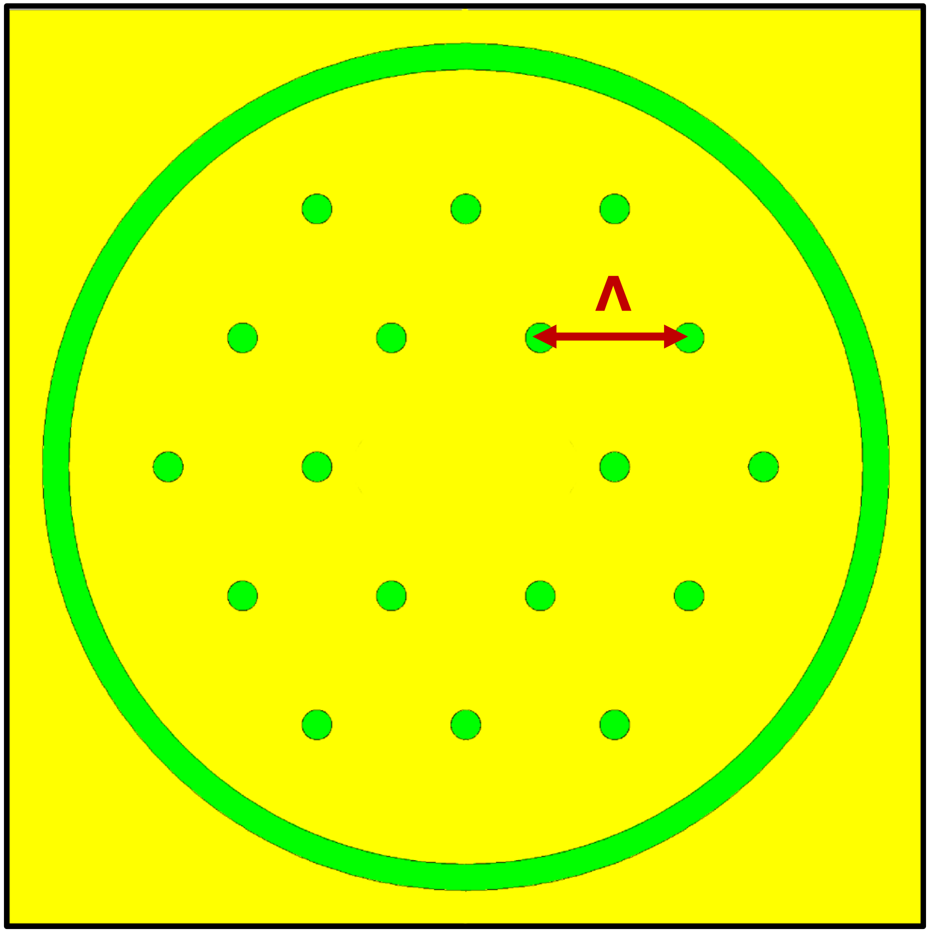
- At any step along z, use FEM solver to calculate field distribution of each guided mode
- Calculate amplifier gain, population inversion, generated heat, according to thermally-influenced field distribution
- Obtain heat load at z+Δz and calculate new field distribution
- Iterate back and forth

No approximations on fiber cross-section

Possible to consider resonant effects

Fast computation

Gain competition



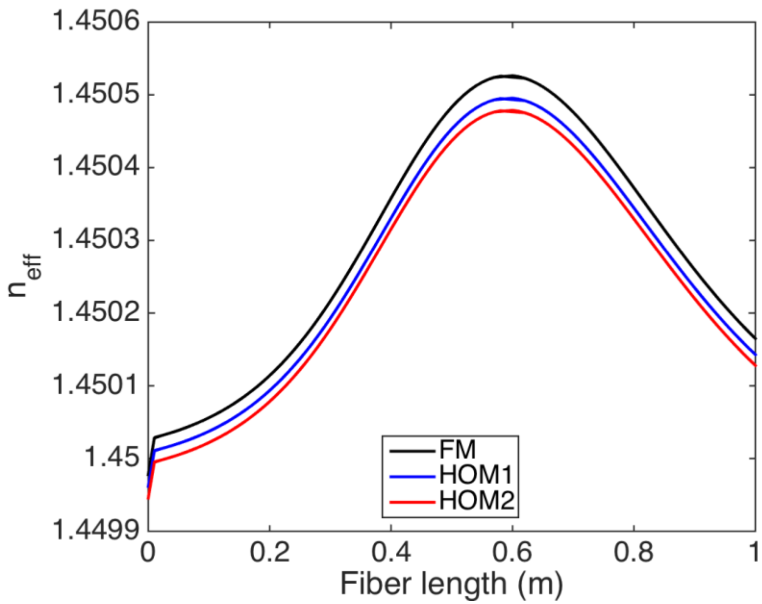
LPF45

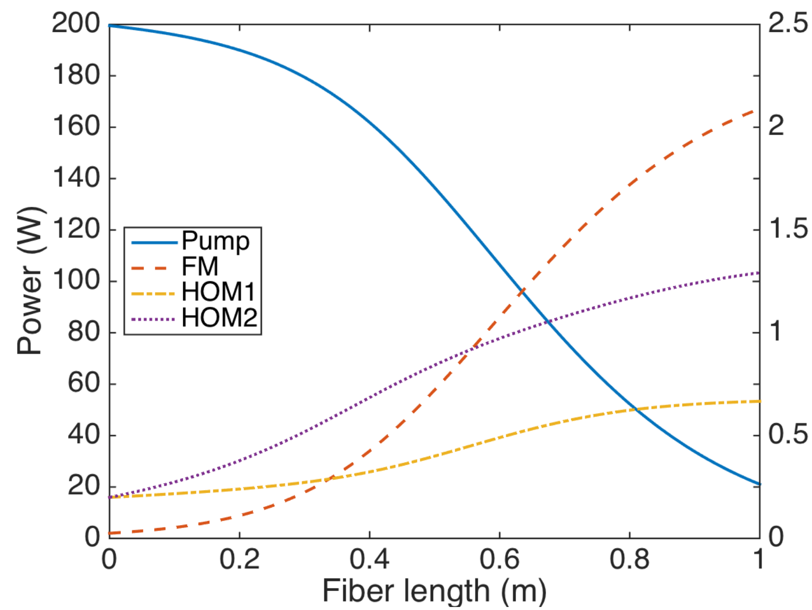
Hexagonal core area

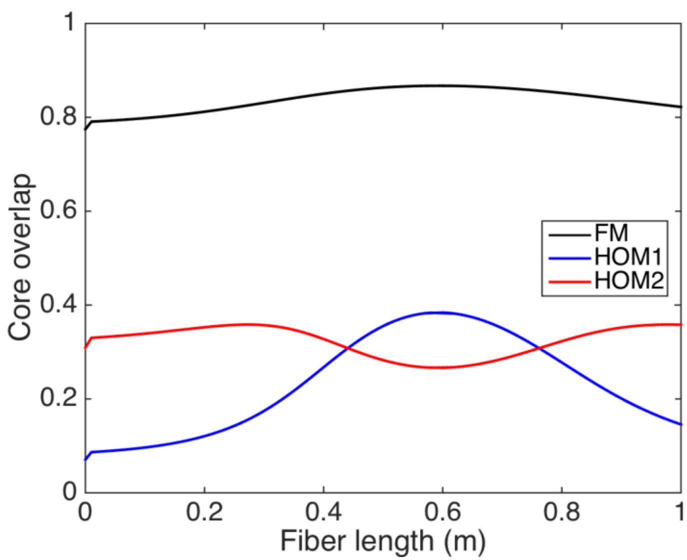
Air-hole diameter: d = 9 μm = 0.2Λ

Pitch: Λ = 45 μm

Gain competition in LPF45







LPF45, forward pump

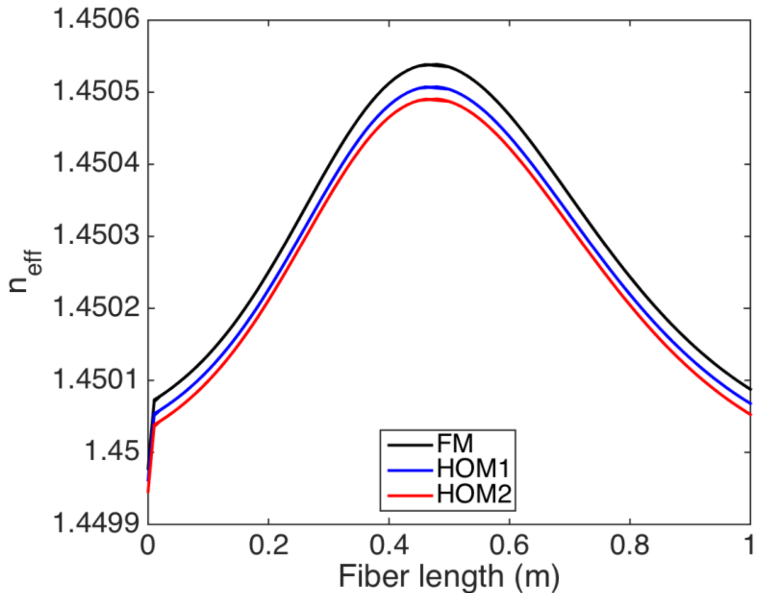
P_p^+ = 200 W

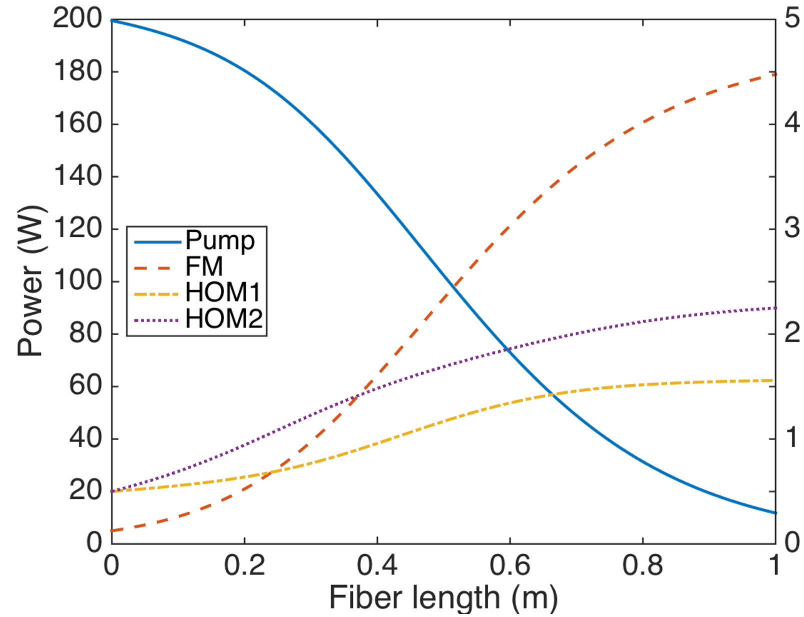
P_{FM} = 2 W (G = 19.2 dB)

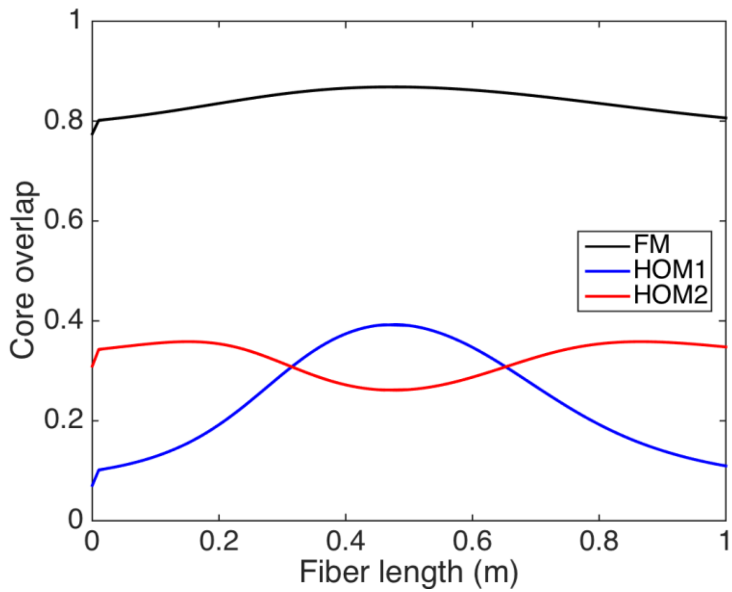
P_{HOM1} = 200 mW (G = 5.2 dB)

P_{HOM2} = 200 mW (G = 8.1 dB)

Gain competition in LPF45







LPF45, forward pump

P_p^+ = 200 W

P_{FM} = 5 W (G = 15.5 dB)

P_{HOM1} = 500 mW (G = 4.9 dB)

P_{HOM2} = 500 mW (G = 6.5 dB)

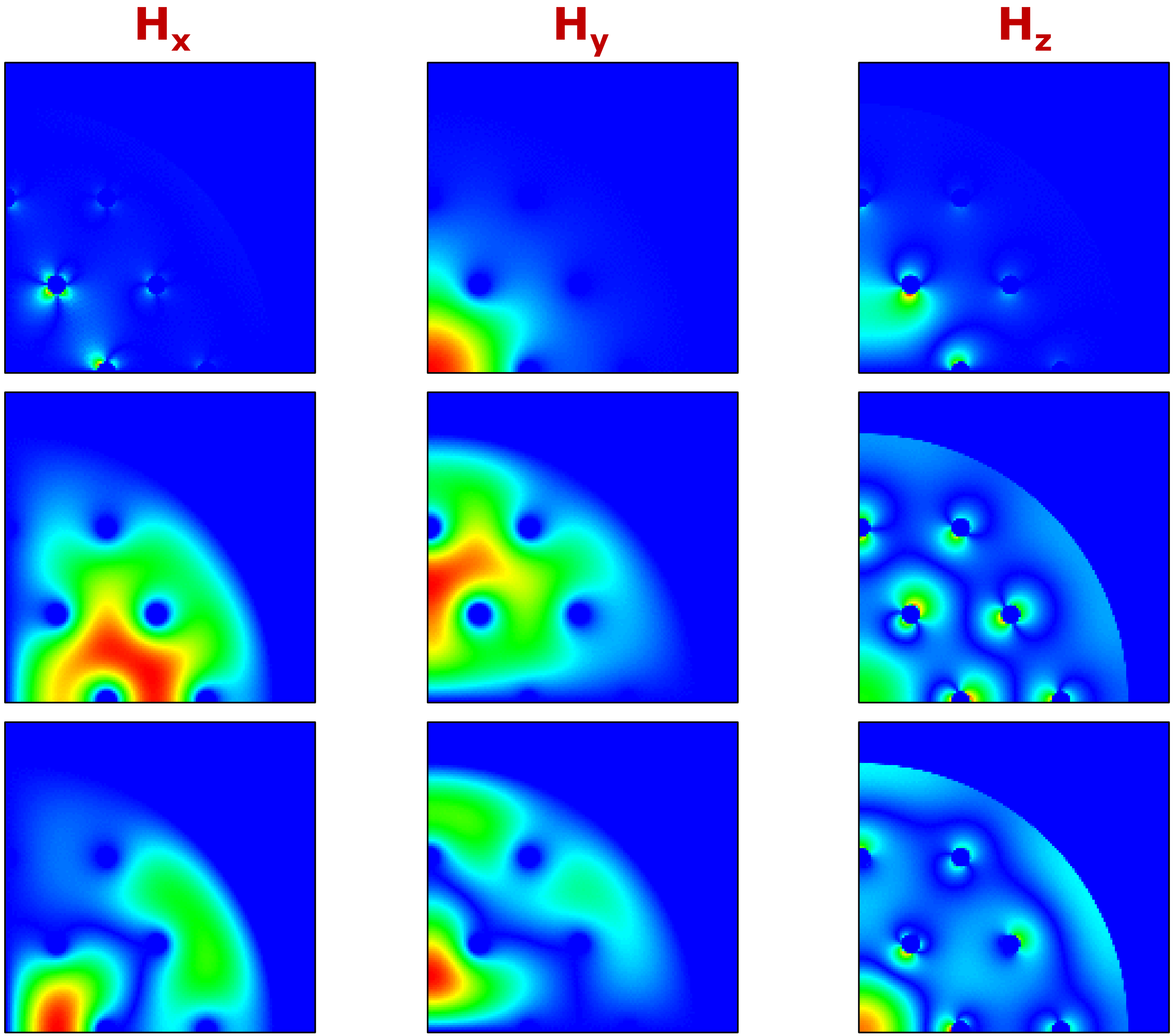
Gain competition in LPF45

P_{FM} = 5 W

Fundamental Mode

1st Higher-Order Mode

2nd Higher-Order Mode



Conclusion

- New LMA PCFs with reduced symmetry inner cladding design proposed
- Thermal effect influence on the SM properties and the effective area of the new fibers analyzed
- Good SM properties demonstrated for the reduced symmetry fibers at quite high pump power values
- NO FM guidance for low pump power values and in the absence of the pump in the asymmetric fibers with lower effective refractive index difference
- Significant effective area decrease in the SM range obtained for all the fibers with reduced symmetry inner cladding
- Similar SM properties obtained for asymmetric fibers with analogous effective refractive index distribution
- New model for pump and thermal load evolution along the fiber length, able to describe gain competition.

Acknowledgments

http://gaem.tlc.unipr.it/

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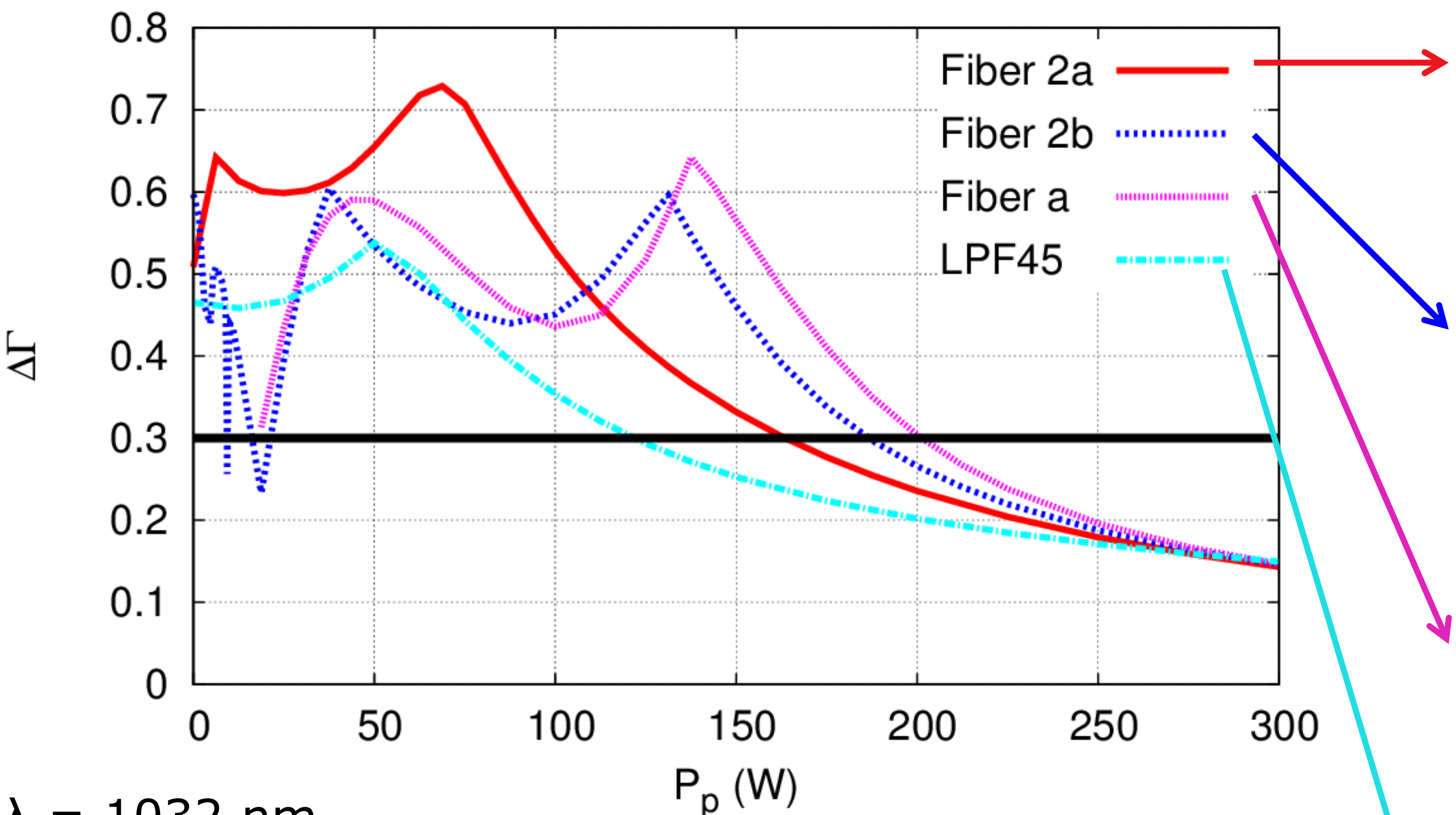
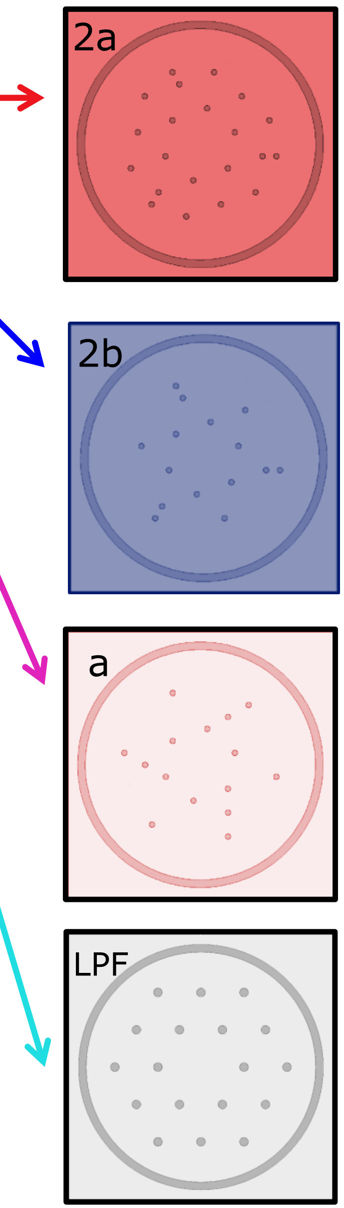
Thank you!

Mode discrimination ΔΓ





λ = 1032 nm

Differential overlap ΔΓ (difference between FM and HOM) considered to define the Single Mode region: >0.3

Non-symmetric design allows better HOM discrimination under higher heat load