Thermal effects on supermodes in Yb-doped multicore fibers for high-power lasers

Federica Poli[1], Jesper Lægsgaard[2], Annamaria Cucinotta[1], Stefano Selleri[1]

[1]Department of Engineering and Architecture, University of Parma, Italy
federica.poli@unipr.it

[2]DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, Denmark

2020 Italian URSI Annual Meeting – November 27th, 2020

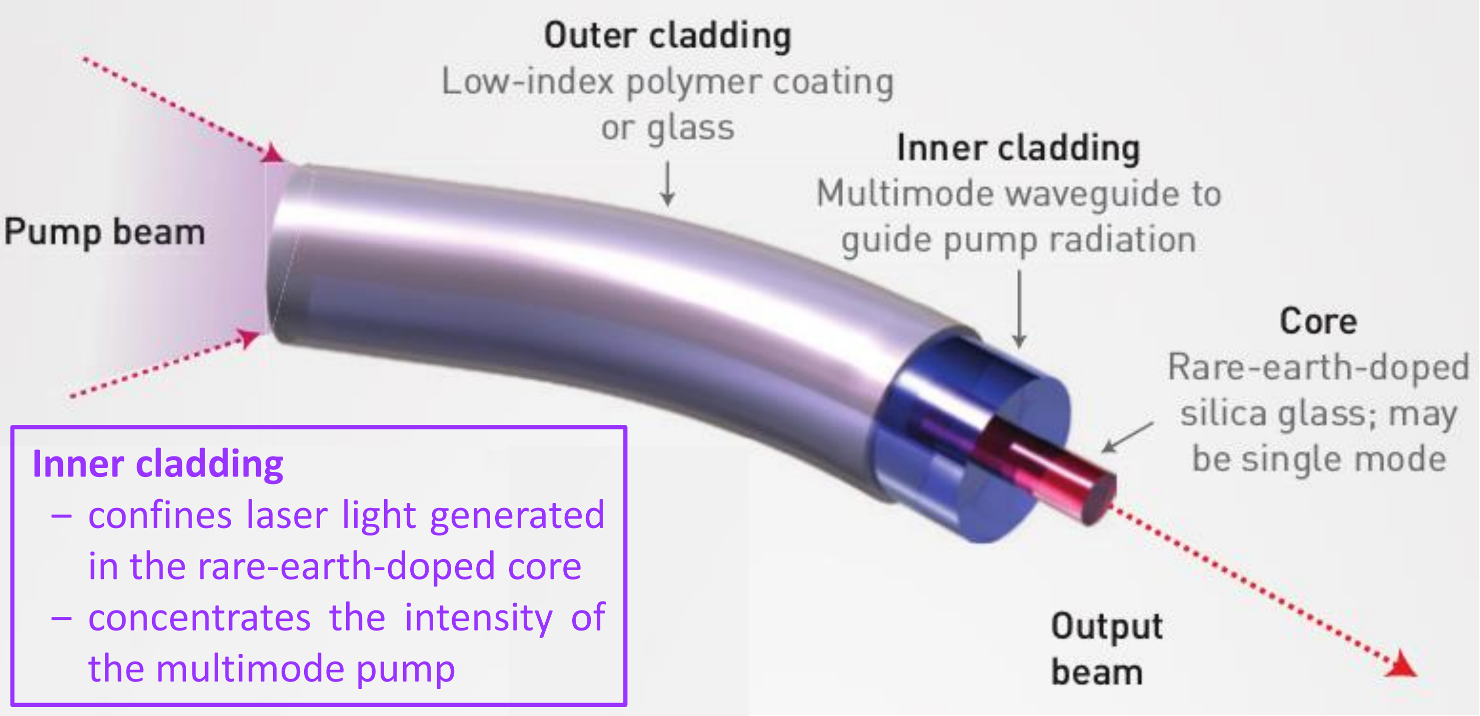
Outline

- High-power fiber lasers
- Yb-doped multicore fibers for high-power lasers
  - power scaling
  - thermal cross-talk
- Influence of thermal effects on supermodes in Yb-doped multi-core fibers
  - numerical model based on finite element method
  - influence on effective area and single-mode regime
- Numerical analysis results on 2- and 4-core fibers
  - different core separation
  - different heat load in each core
- Conclusions
- Future work

Fiber lasers

In the **1980s** fiber lasers at IR wavelengths launched in the metalworking market, disrupting the status quo

New fiber structure developed by Elias Snitzer in 1988 to better couple pump light into the fiber



Inner cladding
- confines laser light generated in the rare-earth-doped core
- concentrates the intensity of the multimode pump

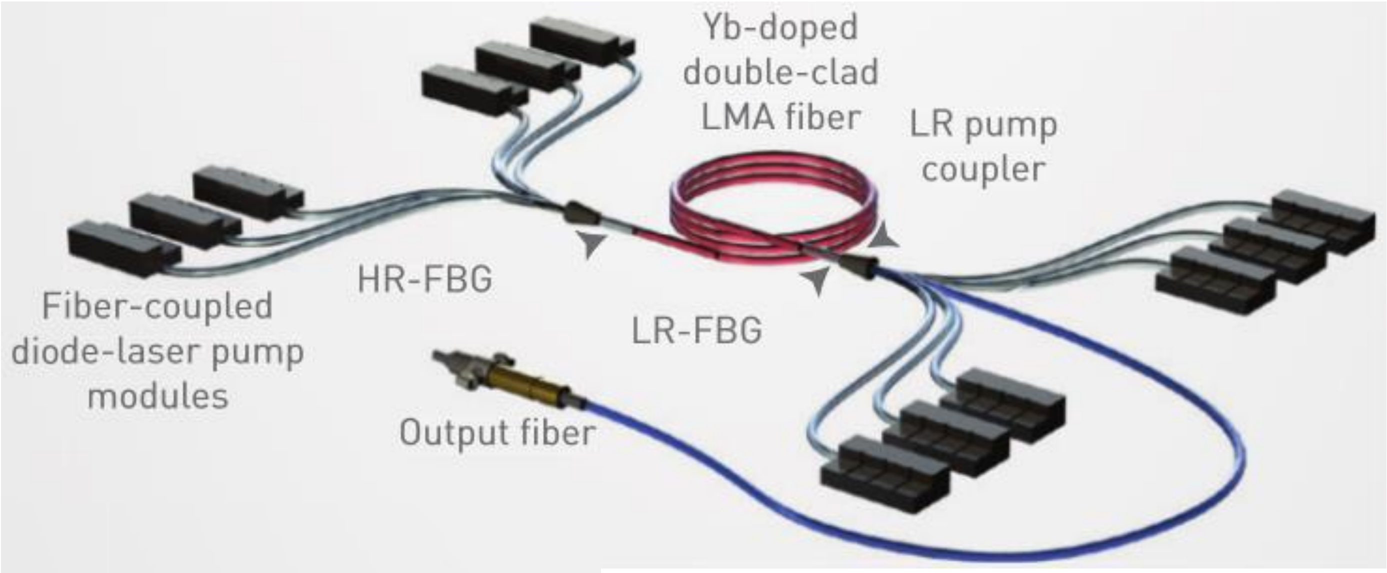
J. Hecht, "High-Power Fiber Lasers", OPN, pp. 30.37, October 2018

High-power fiber lasers

Ytterbium-doped fibers pumped with high-power diodes at 945- and 976-nm absorption bands to emit at 1030 to 1080 nm ⇒ high energy efficiency

A number of **pump diodes** directed into separate fibers that join together in a **tapered fiber bundle** or **combiner** that could be used with single-diode emitters, bars or stacks ⇒ high pump power

⇒ **Significant rise** of fiber laser **power**

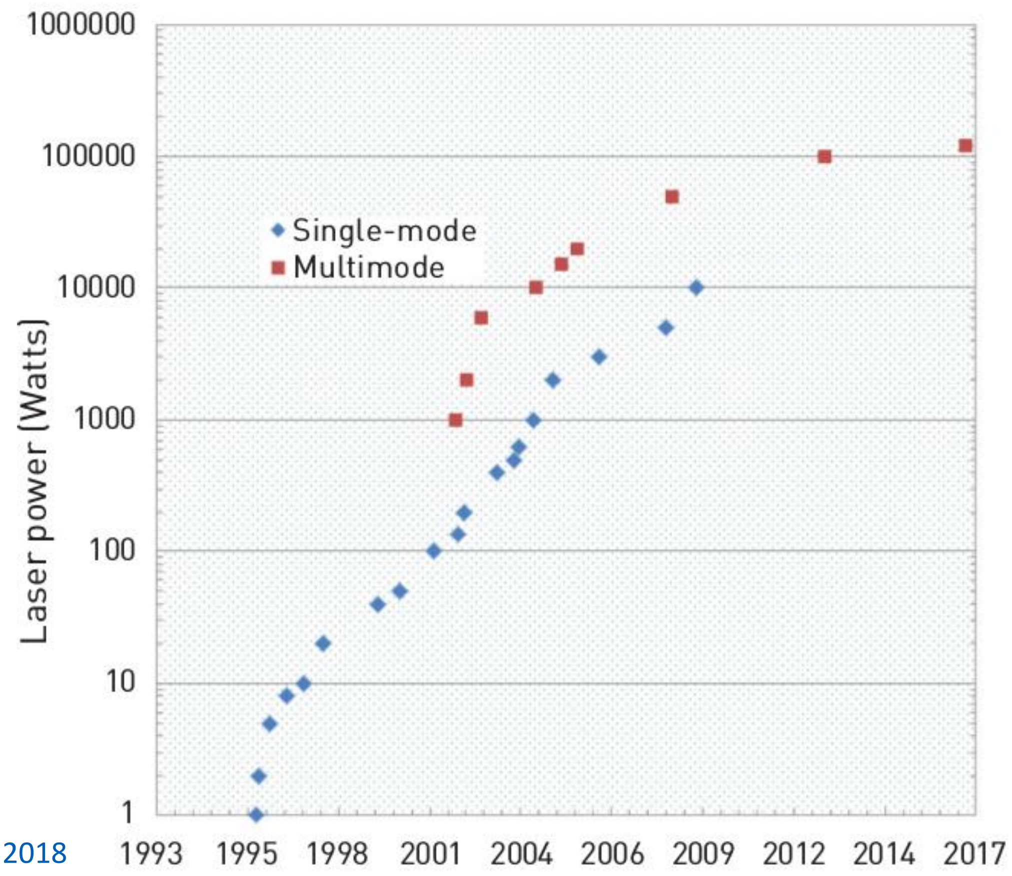


J. Hecht, "High-Power Fiber Lasers", OPN, pp. 30.37, October 2018

Fiber laser power evolution

Major progress in ytterbium-doped fiber lasers made by IPG Photonics, founded in Moscow in 1990 by Valentin Gapontsev

- **Single-mode fiber laser** power from **1 watt** (1995) to **1 kilowatt** in CW (2004)
- **Record 10 kW** from a single-mode fiber laser (2009) ⇒ impressive engineering achievement
- Single-mode fiber lasers extended to **15-20 kW** by IPG in recent years



J. Hecht, "High-Power Fiber Lasers", OPN, pp. 30.37, October 2018

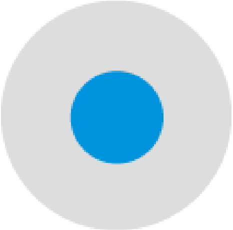
Limits to further power scaling

Fiber lasers have laid down a strong track record for **high-power**, **high-quality beams** for **industry**: they

- **improved conversion efficiencies**
- **reduced maintenance costs**

over CO_2 lasers $\Rightarrow$ a much more **economical choice**

Today: fiber lasers have largely replaced CO_2 lasers in **cutting** and **welding**



large mode area fiber

Users $\Rightarrow$ **higher powers** + **good beam quality**

Problem to overcome: **nonlinear** effects

Solution: **increase** the **effective mode area** in **single-mode fibers**

$\Rightarrow$ The **smaller** the refractive-index difference between core and cladding, the **larger** the core diameter that could support single-mode transmission

$\Rightarrow$ Reducing the core-cladding refractive-index difference comes with **higher impact** of **thermal effects** on **waveguiding** as the output power increases

Thermal effects in fiber lasers

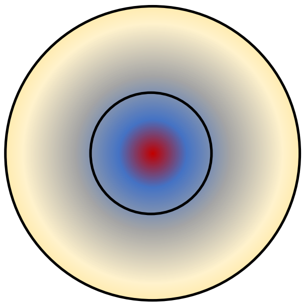
Italian National Committee

Power scaling for Single-Mode (SM) lasers severely limited by **thermal effects**

In ytterbium (Yb) doped fibers

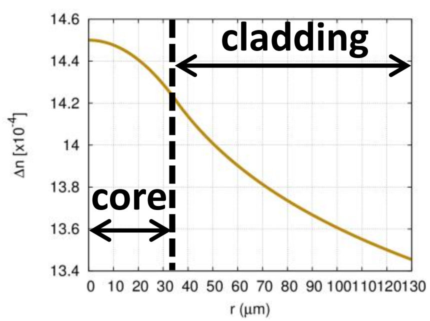
$\boxed{q = h\nu_p - h\nu_s \rightarrow \text{HEAT}}$

- significant amount of heat generated in the core, due to **quantum defect**
  $\Rightarrow$ **thermally–induced Refractive Index (RI) change**
- **Higher-Order Mode** (HOM) **propagation** in originally SM fibers



Higher temperature in the core

Thermally-induced graded-index profile



Increase confinement of high-order modes

Loss of transverse single-mode output

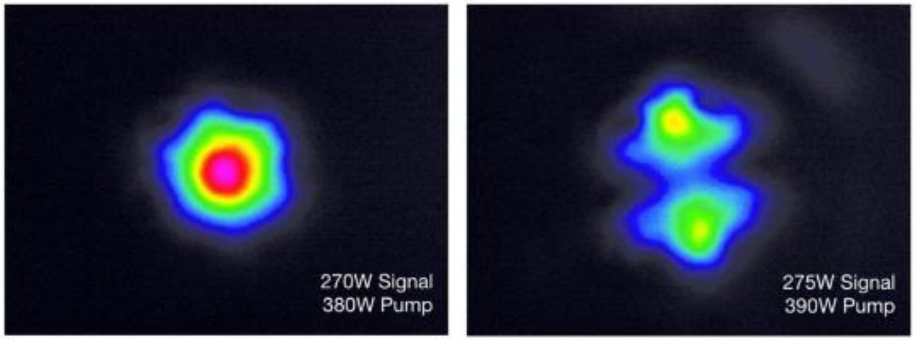
UNIVERSITÀ DI PARMA

Transverse mode instability

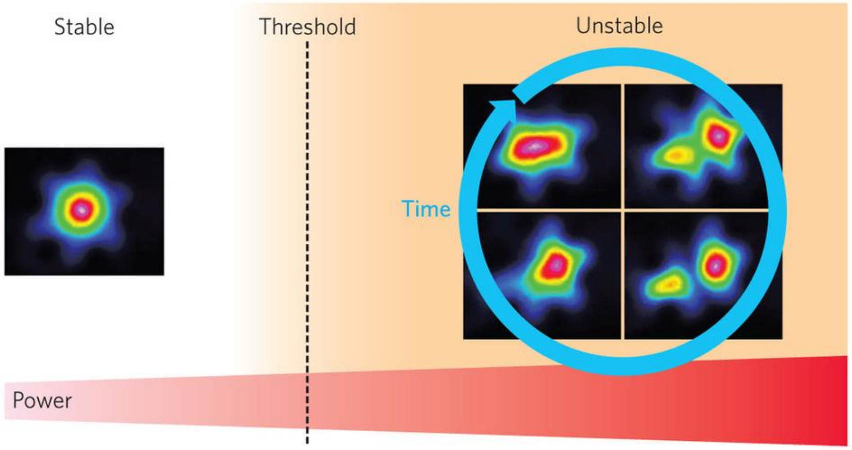
Transverse Mode Instability (TMI): when the amplified signal power exceeds a certain **threshold**

- beam profile (stable, nearly Gaussian-shaped) ⇒ **temporally unstable**
- apparently random **temporal change** in **mode content** + sudden **decrease** in **beam quality** ⇒ increased HOM content

⇒ **Multicore fibers** to overcome thermal effect problems



Optics Express **19**, 13218 (2011)

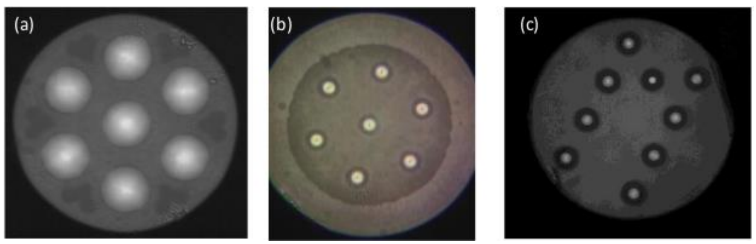


Nature Photonics **7**, 861 (2013)

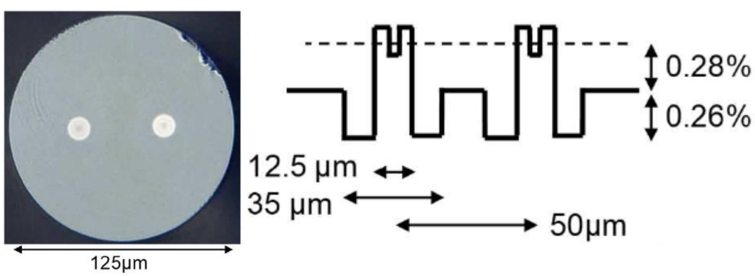
Italian National Committee

Multicore fibers

Multicore fibers for **Spatial Division Multiplexing (SDM)** transmission: weakly-/strongly-coupled single-/few-mode cores, erbium-doped cores

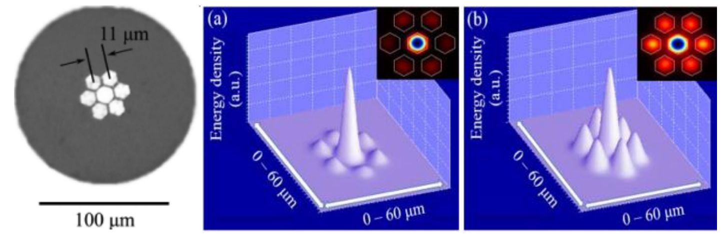


OFC 2019, paper M1F.4

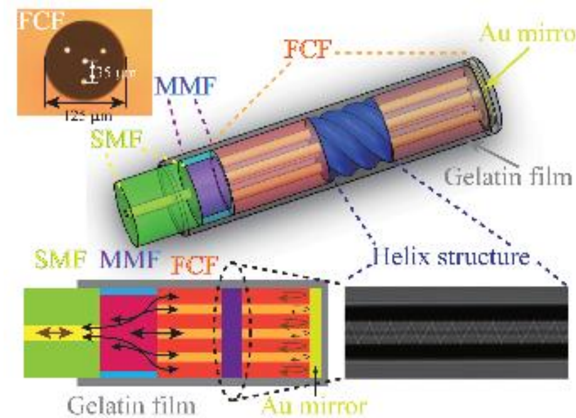


OFC 2019, paper M1E.5

Multicore fibers for **sensing**



Temperature sensor, JLT **37**, 2328 (2019)



Humidity sensor, JLT **37**, 2452 (2019)

Multicore fibers for **high power lasers** and **amplifiers**

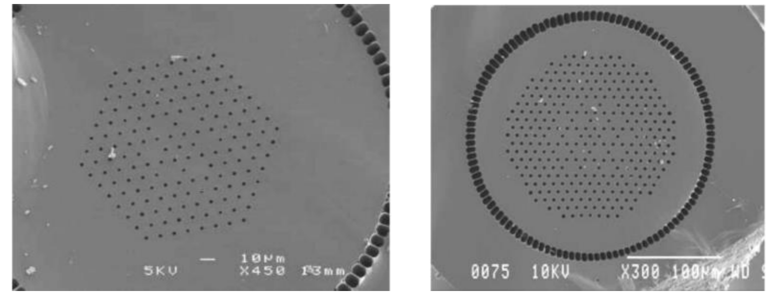
High-power applications

Multicore **Photonic Crystal Fibers (PCFs)**

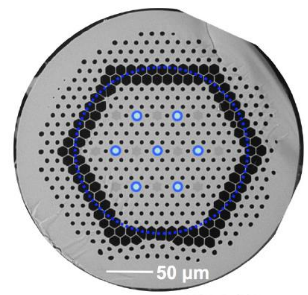
Rod-type PCF (single-mode core with large mode field diameter) + **multicore technology** (further scaling up the mode field area)

Multicore fibers for **coherent beam combination** = **performance scaling concept** for laser parameters

Complexity and footprint grow linearly with channel count (= scaling factor) ⇒ integration of **multiple amplification channels** into a **multicore fiber** to drastically **reduce component count**

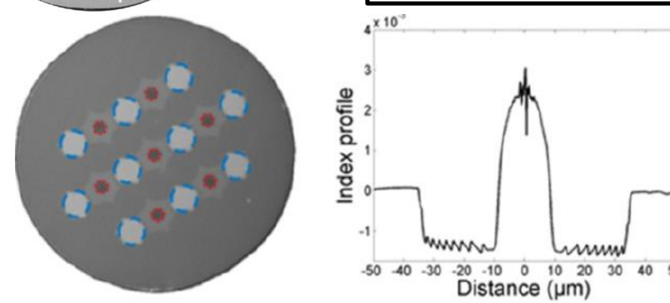


OL **30**, 1668 (2005); IEEE JSTQE **15**, 328 (2009)



OE **23**, 5406 (2015)

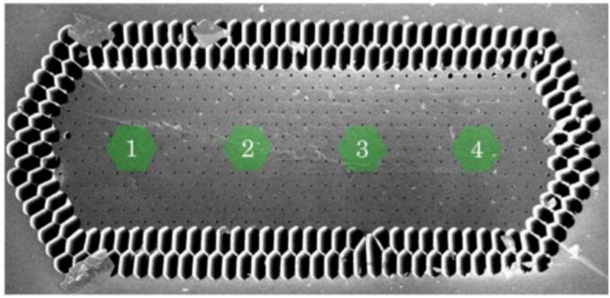
OE **25**, 9528 (2017)



TMI in multicore fibers

Italian National Committee

OL **39**, 2680 (2014)



Core diameter = 50 µm
Core-to-core distance = 56 µm

Coherent beam combination in **4 Yb-doped core design**

- core-to-core spacing: **large**
- light confinement in the core: **tight**

NO optical coupling

TMI threshold ↑ with core number, if thermal coupling is neglected

In Yb-doped **multicore** fibers

- **thermally-induced RI change** caused in **one core** due to **heat load** of a **neighboring one** ⇒ **thermal cross-talk**
- **HOM propagation** in originally SM cores

OL **43**, 1519 (2018)

16 step-index Yb-doped cores in a **4x4 pattern**: core diameter = 19 µm, pitch between core centers = 55 µm, NA = 0.06

Recently: coherent combination of **ps** and **fs pulses** with **efficiency** of **80%** experimentally demonstrated in **16 Yb-doped core fiber**

Non-perfect efficiency

Dominant cause: **HOM content** emitted from different fiber cores

ASSL 2018, AM2A.7

Thermal effects in multicore fibers

Italian National Committee

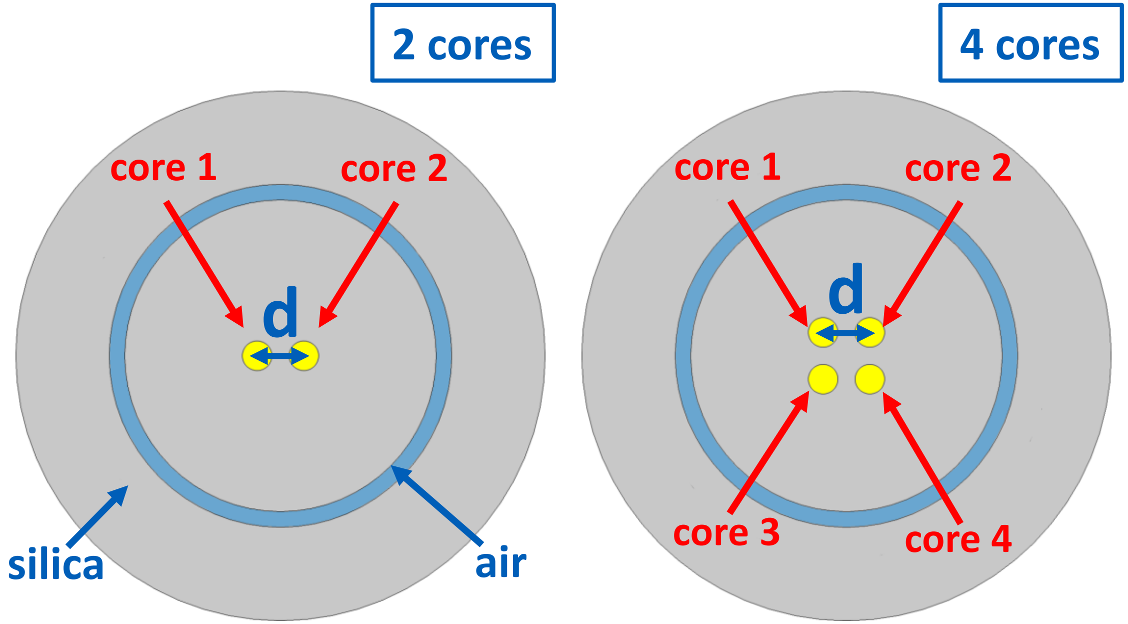
This work: impact of **thermo-optic RI change**, due to applied heat load, on **supermodes** in Yb-doped multicore fibers. **Influence** of

- **core number** ⇒ 2, 4
- **core-to-core distance d**

on supermode **effective area** and **core overlap integral** ⇒ **SM regime**

*Core overlap integral **difference** between **fundamental supermode** and **most detrimental HOM > 0.3***

Fiber parameters	Value
Core diameter	19 µm
Core spacing	20 ÷ 65 µm
V parameter	2.2
Pump cladding diameter	200 µm
Air layer width	10 µm
Outer diameter	340 µm



UNIVERSITÀ DI PARMA

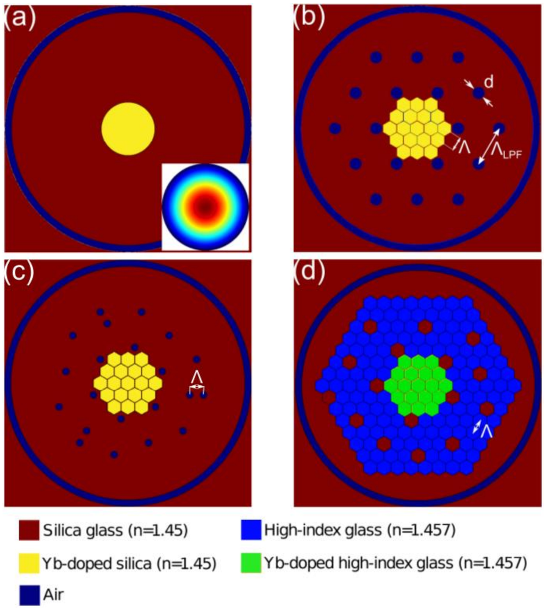
Numerical model

Full-vector modal solver based on **Finite Element Method (FEM)** + embedded **thermal model**

Method successfully applied to different kinds of **large mode area PCFs** with **single Yb-doped core** ⇒ extended to multicore fibers with **uniform heat load q** in each core

- *Steady-state heat equation solved*
- *Temperature gradient ΔT on multicore fiber cross-section calculated*
- *Thermally-induced refractive index change* $\Delta n = \beta \cdot \Delta T$
- *Fundamental and higher-order supermodes evaluated at 1032 nm*

JSTQE **22**, 4900808 (2016)



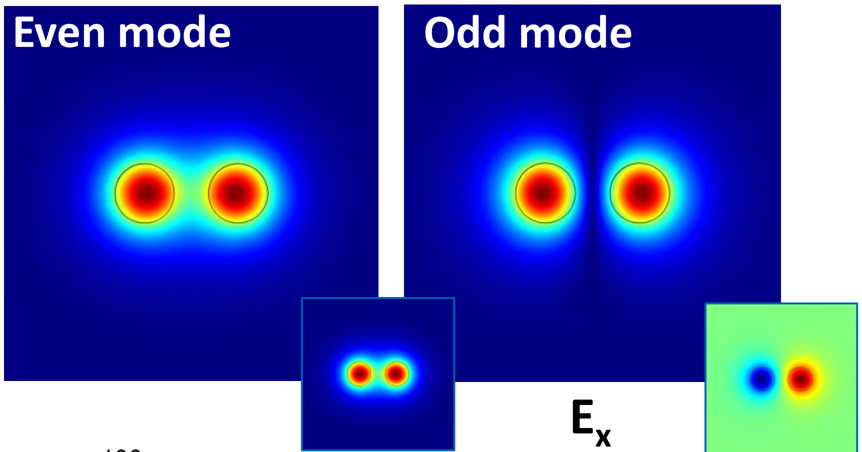
Model parameters	Value
Silica thermal conductivity	1.38 W/(m·K)
Convective heat transfer coefficient	80 W/(m^2·K)
Temperature (outside)	23°C
β (silica)	1.16·10^{-5} 1/K

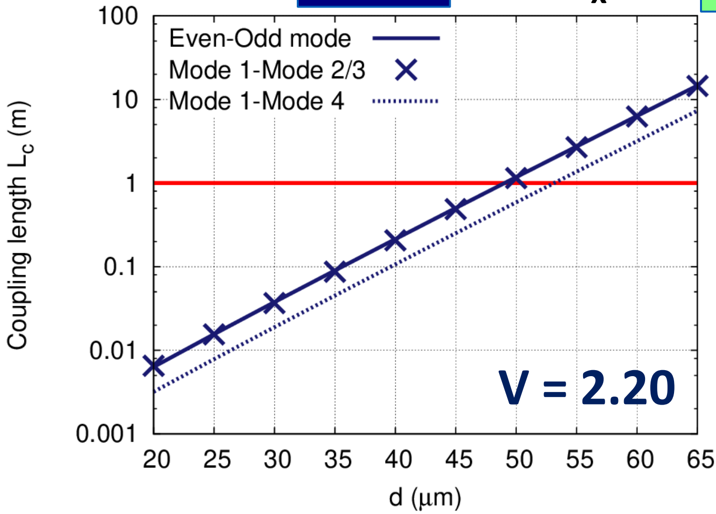
V = 1.73, d = 30 µm

Supermodes in “cold” multicore fibers

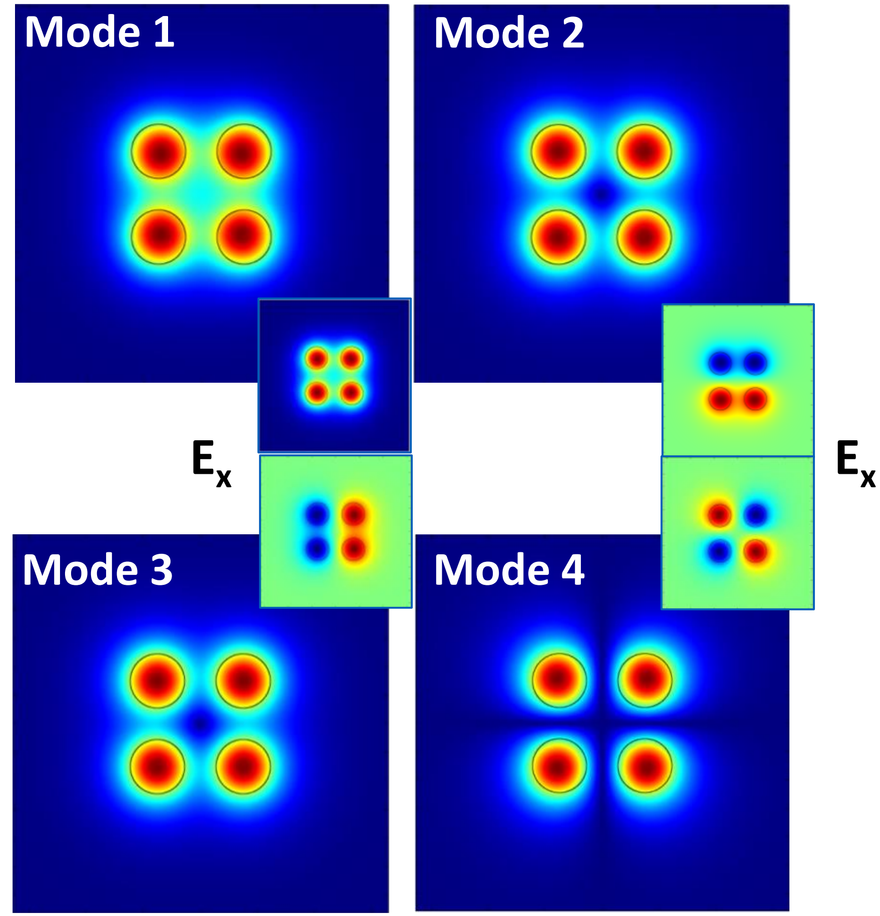
All cores are identical ⇒ supermodes are linear combinations of guided modes in different cores

2 cores





4 cores



V = 1.73

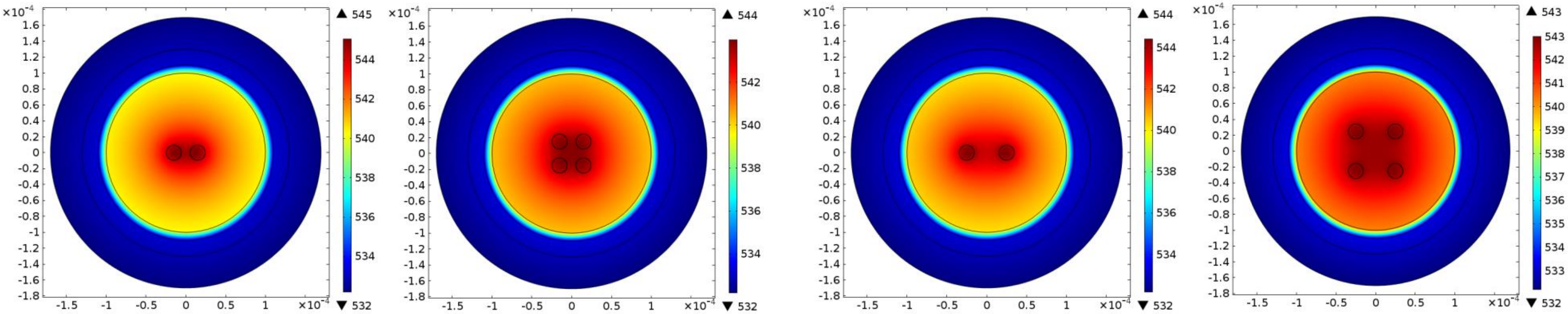
T distribution in 2- and 4-core fibers

Italian National Committee

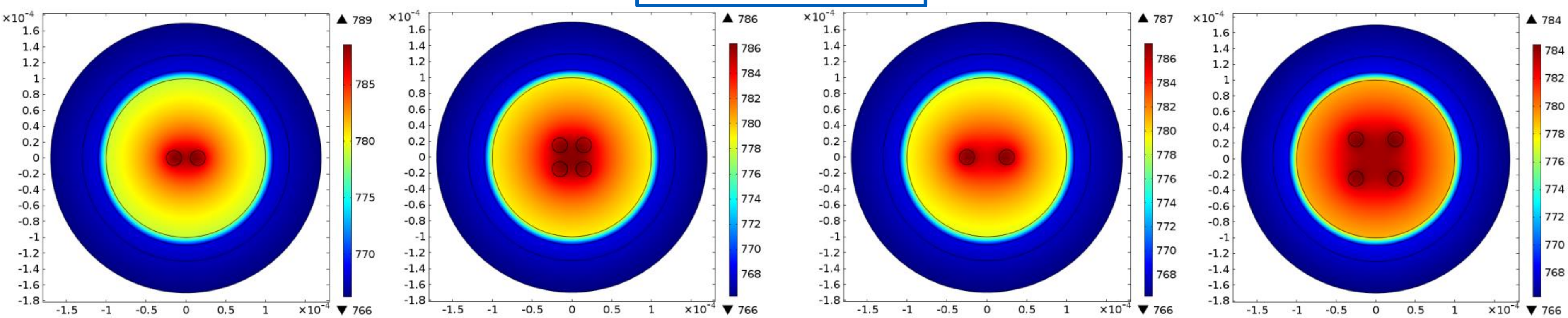
d = 30 µm

q_{tot} = 20 W/m

d = 50 µm



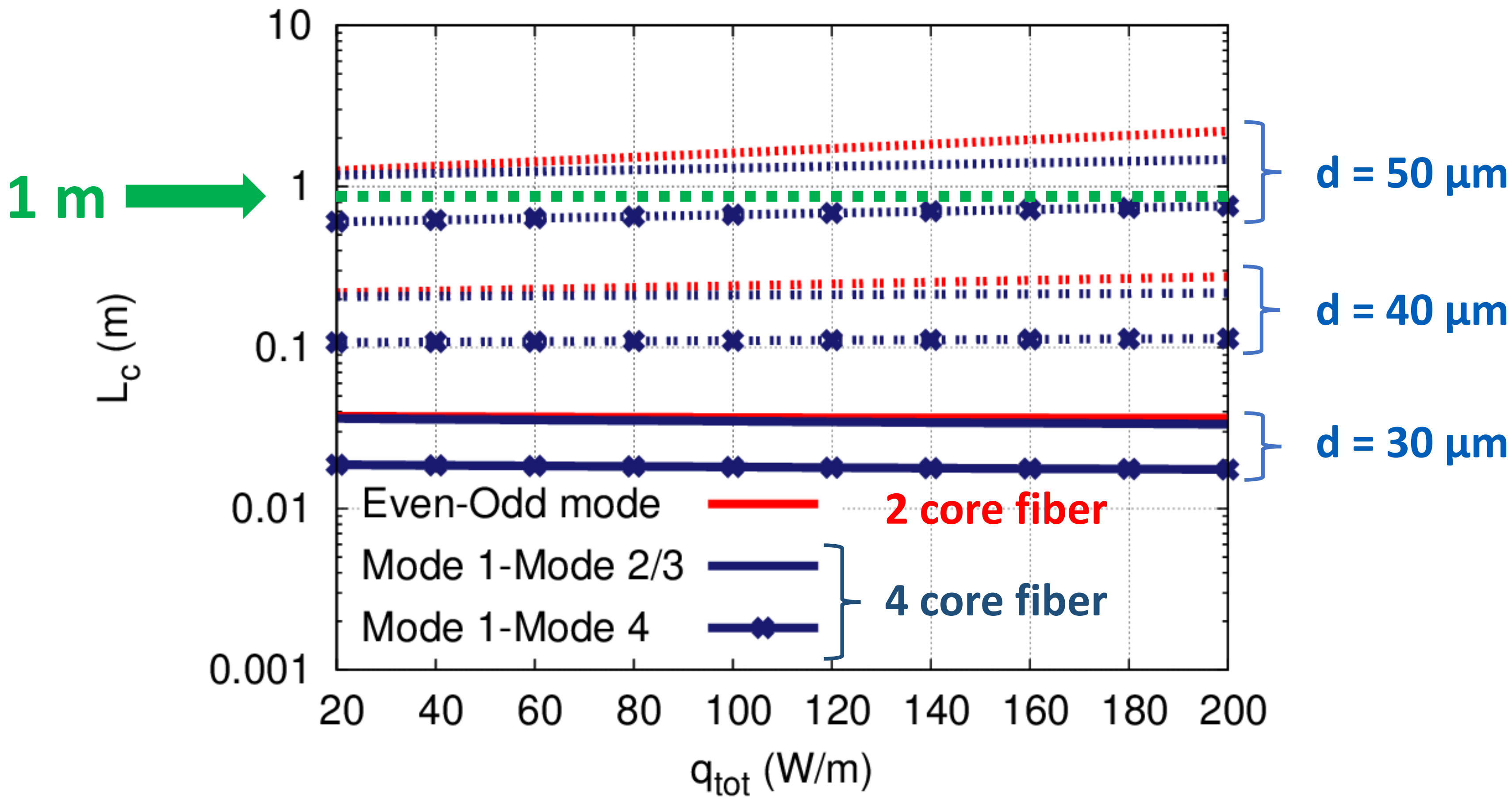
q_{tot} = 40 W/m



q_{tot} = q x core number

UNIVERSITÀ DI PARMA

Coupling length L_c vs q_{tot}

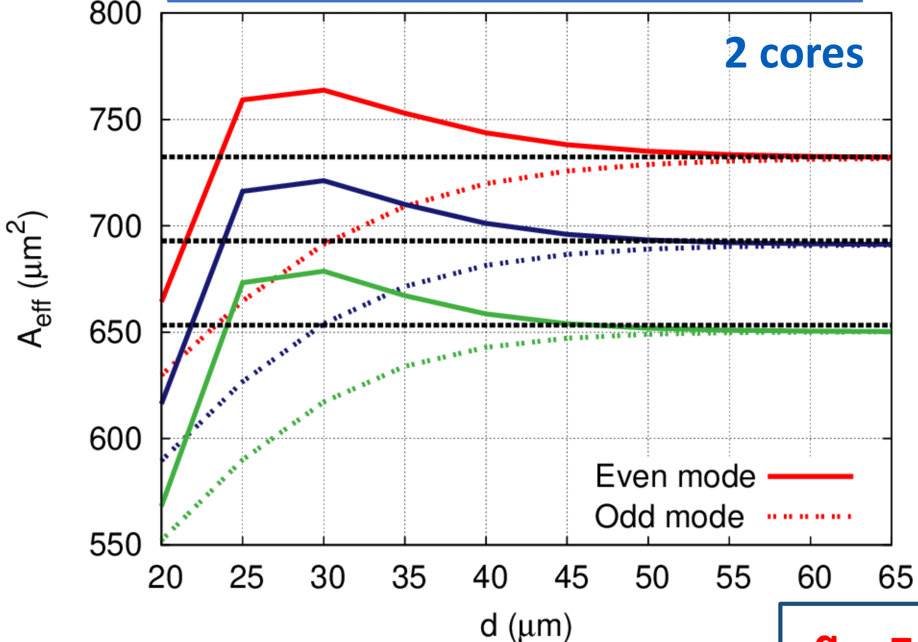


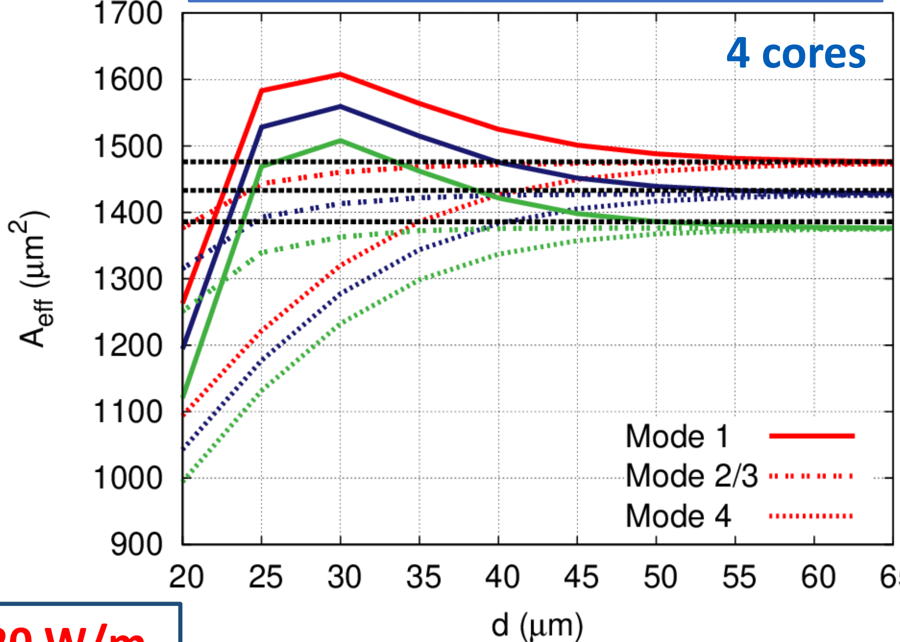
Effective area A_{eff} vs d, q_{tot}

Italian National Committee

max A_{eff} = 764, 721, 679 μm² for **d = 30 μm** as q_{tot} increases

max A_{eff} = 1608, 1559, 1508 μm² for **d = 30 μm** as q_{tot} increases





q_{tot} = 20 W/m
q_{tot} = 100 W/m
q_{tot} = 200 W/m

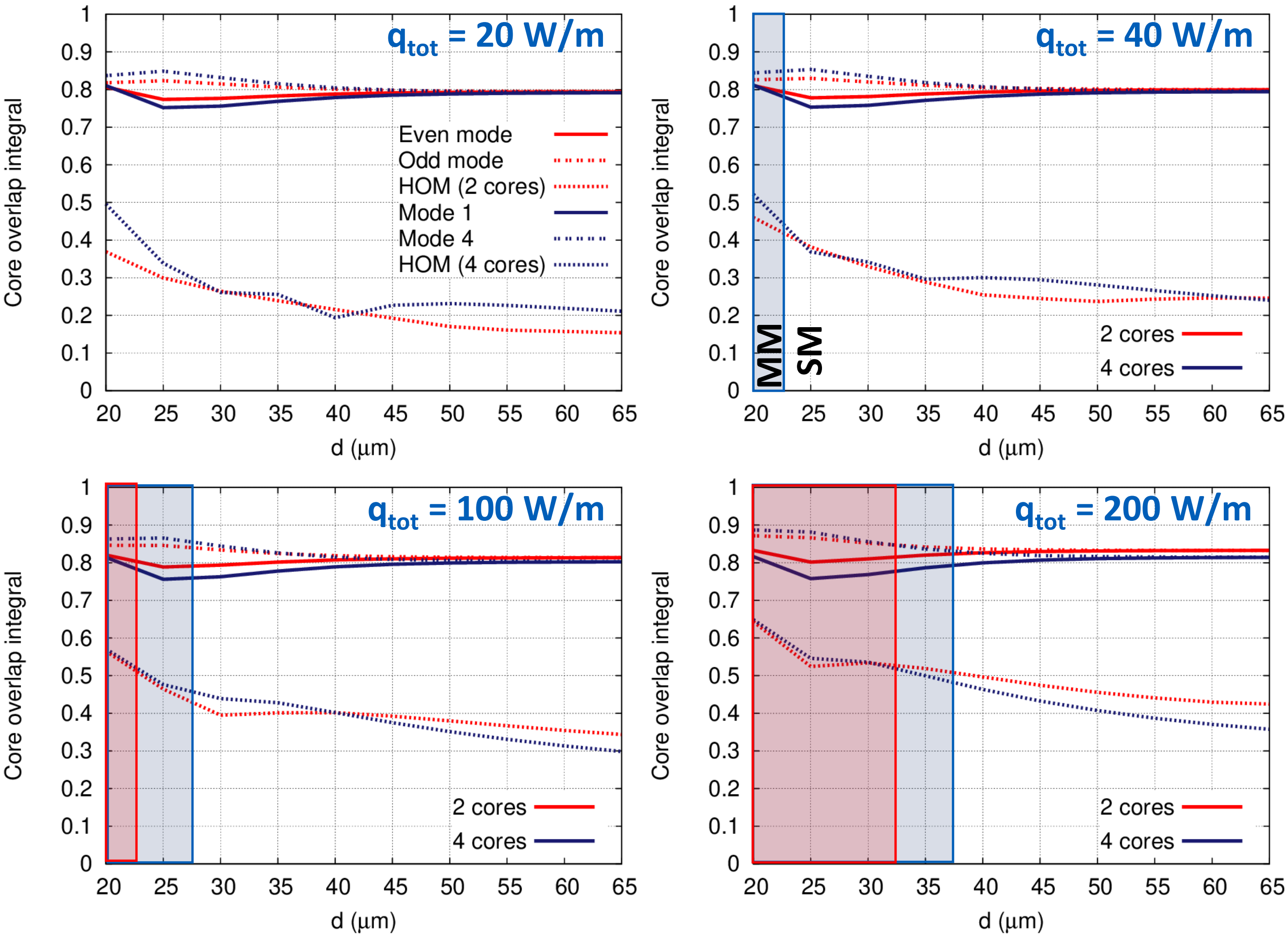
Even mode A_{eff} **> odd** mode A_{eff} for all d and all q_{tot}
d range where even mode A_{eff}>2 x single-core fiber A_{eff}

Low A_{eff} differences at large d
A_{eff} decrease at higher q_{tot}

Mode 1: highest A_{eff} and **d range** where > 4 x single-core fiber A_{eff}
Mode 4: lowest A_{eff}

UNIVERSITÀ DI PARMA

All core overlap integral vs d: q_{tot} fixed



Short d: lower influence of core number on HOM overlap integral ($\Rightarrow$ SM regime)

Large d: core overlap integral influenced by **q** (**not** by $\mathbf{q_{tot}}$) for high heat load

Conclusions

- Thermally-induced RI change influence on A_{eff} and SM regime of Yb-doped 2- and 4-core fibers with different core separation thoroughly studied
- Analysis carried on with FEM-based numerical simulations for different heat load configurations
- Results demonstrated
  - highest A_{eff} for even SM in 2-core fibers and Mode 1 in 4-core fibers when d = 30 μm
  - lower A_{eff} at higher applied heat load values (as expected)
  - fixed q_{tot}: lower impact of core number on SM regime at high heat load for small core separation
- **Thermal effects** have a **significant role** in **Yb-doped multicore fiber design**

What is the influence of a refractive index asymmetry in Yb-doped multicore fibers under heat load?

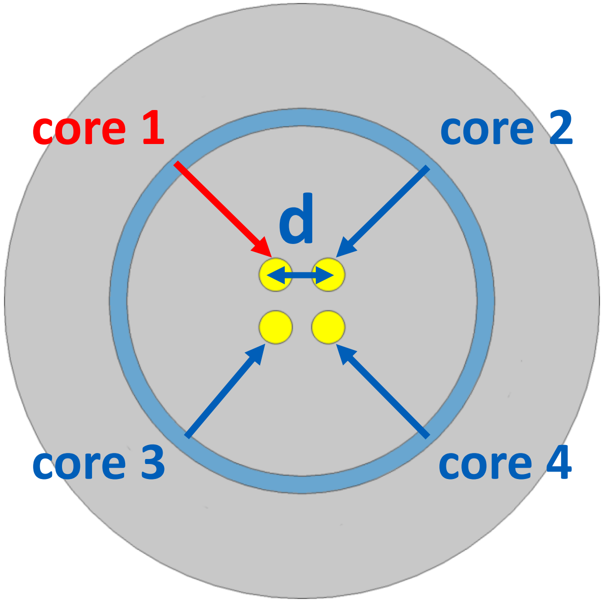
Refractive index asymmetry

Italian National Committee

Refractive index asymmetry in Yb-doped **4-core fibers** under heat load

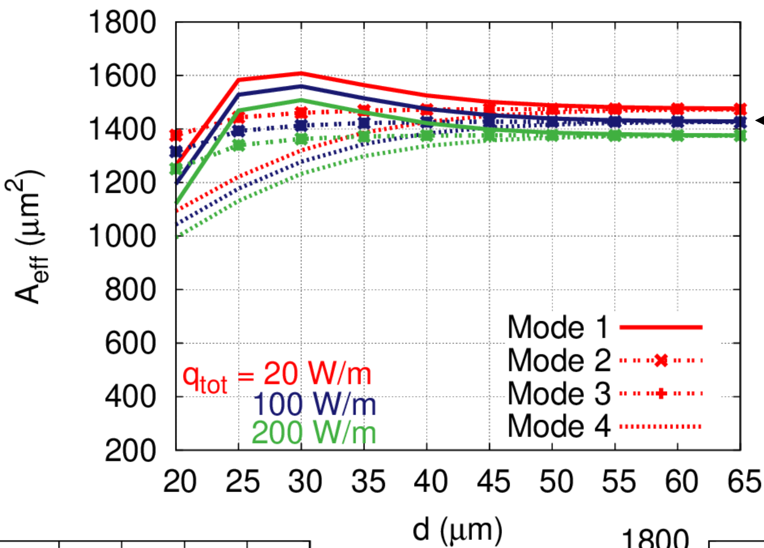
Effect on **supermode** properties: effective area, core overlap integral $\Rightarrow$ SM regime

$$\boxed{\begin{array}{c} n_{core1} = n_{core} - \Delta n \\ \Delta n = 10^{-6}, 10^{-5} \end{array}}$$



Effective area A_{eff} vs n_{core1}

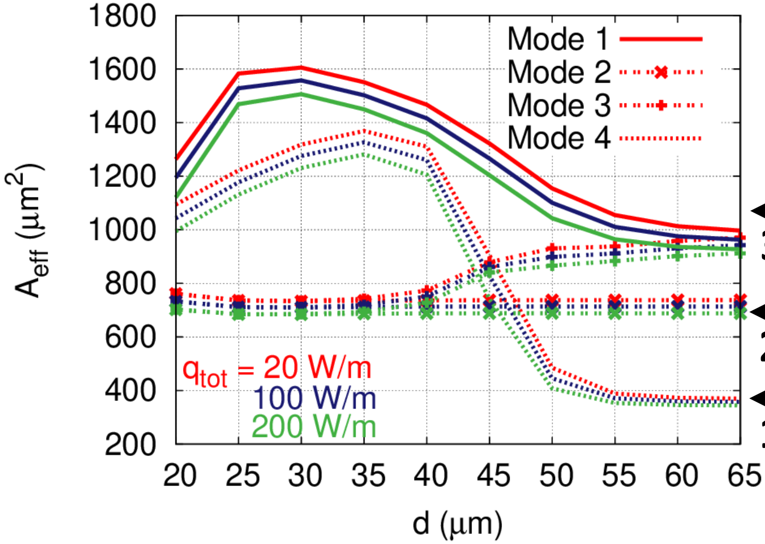
Different supermode confinement in the 4 cores $\Rightarrow$ A_{eff} behaviour significantly modified



4 x A_{eff} 1 core

Δn = 0

Δn = 10^{-6}

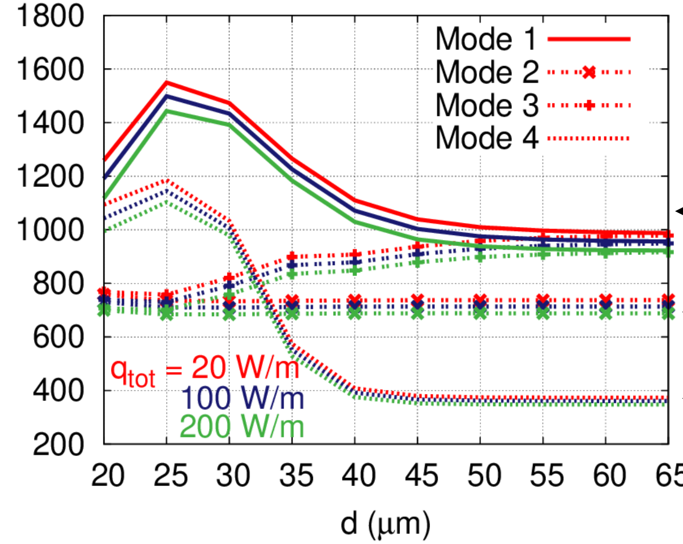


3 x A_{eff} 1 core

2 x A_{eff} 1 core

1 x A_{eff} 1 core

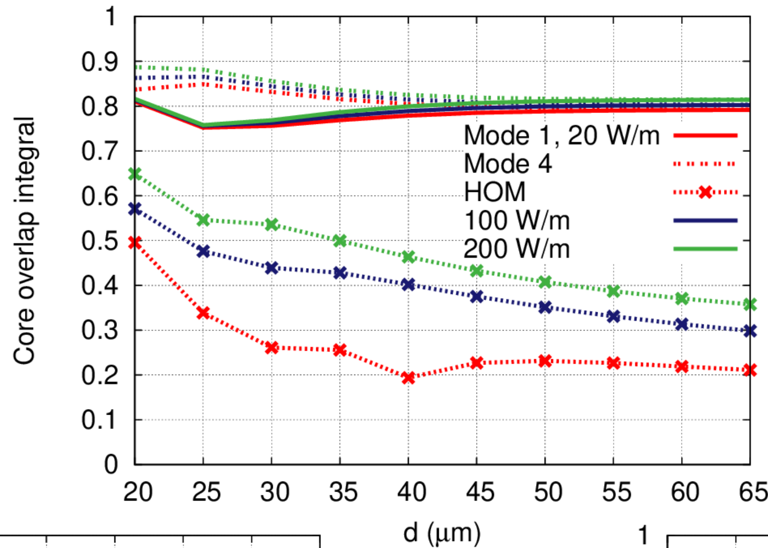
Δn = 10^{-5}



Italian National
Committee

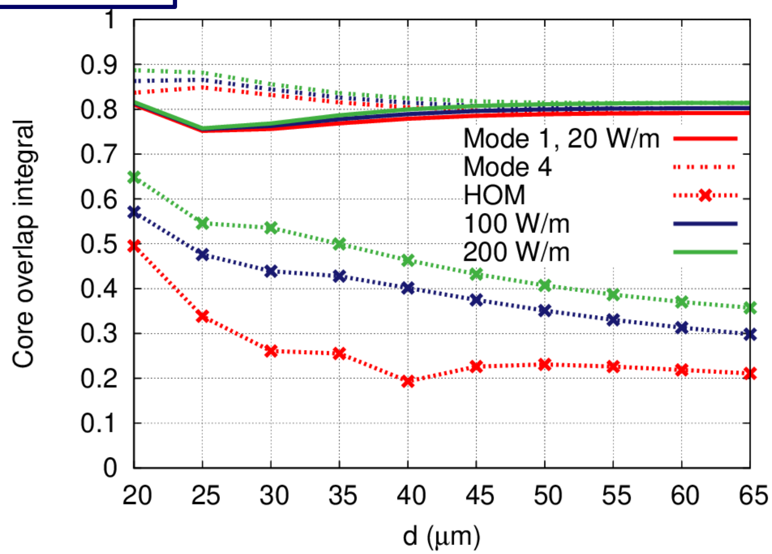
All core overlap integral vs n_{core1}

Strong impact of core asymmetry only on supermode overlap integral on different cores ⇒ SM regime?

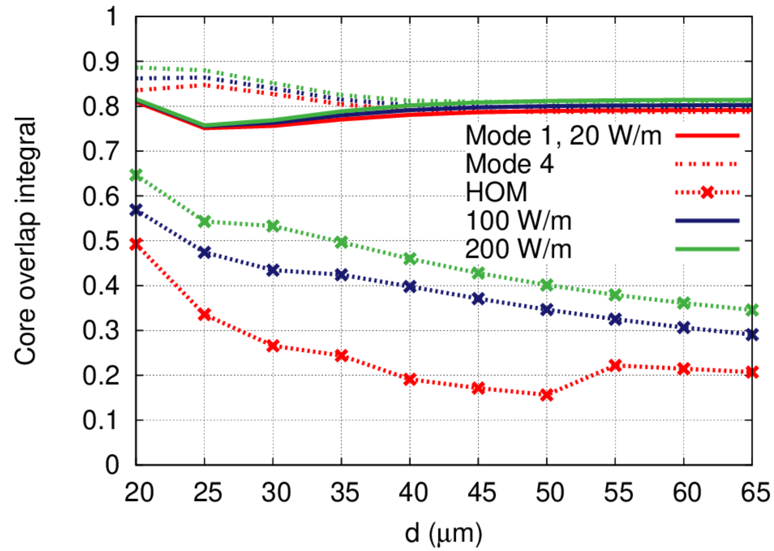


Δn = 0

Δn = 10^{-6}



Δn = 10^{-5}

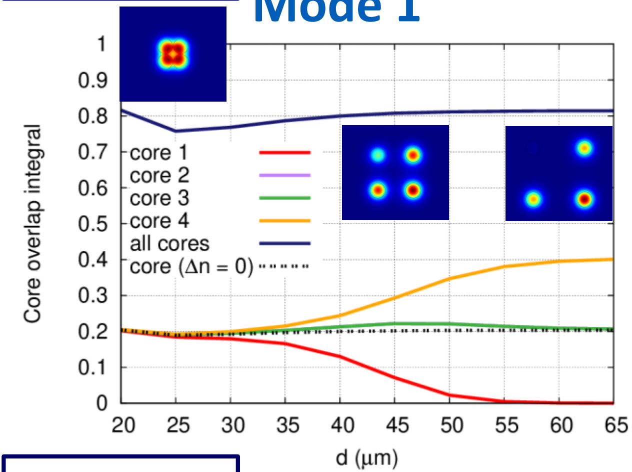


Core overlap integral @ 200 W/m

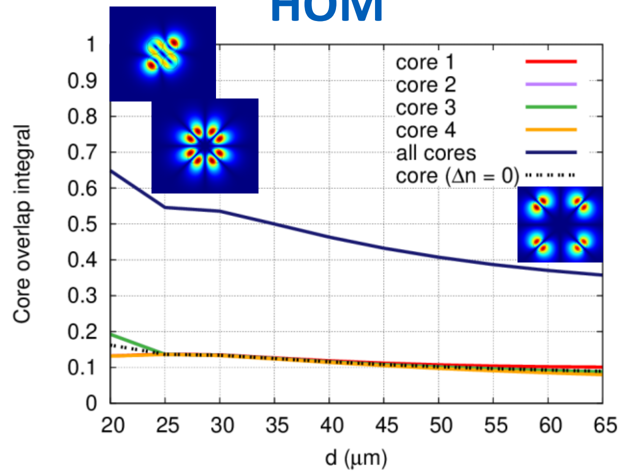
Italian National Committee

Δn = 10^{-6}

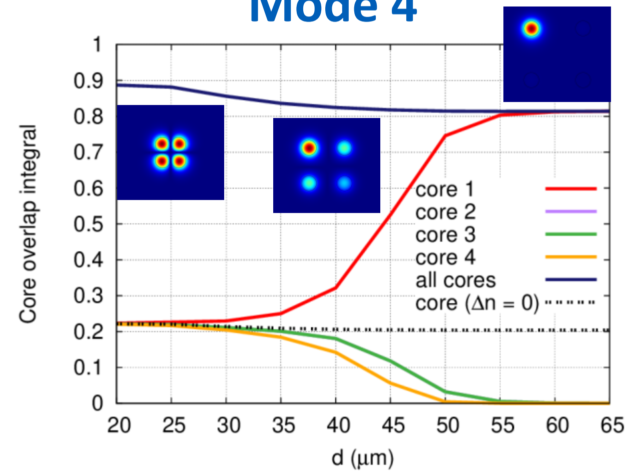
Mode 1



HOM

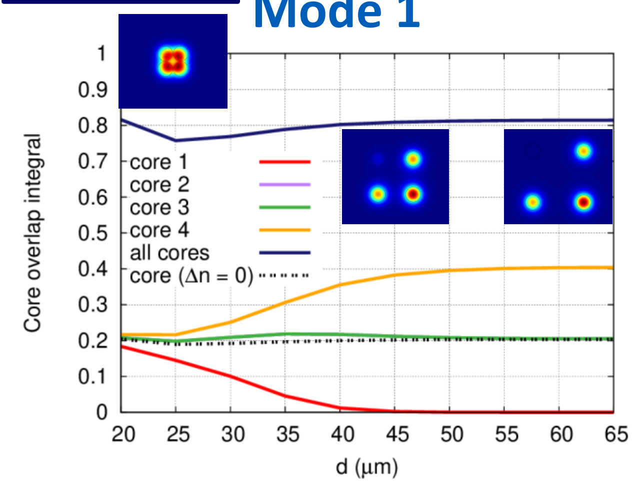


Mode 4

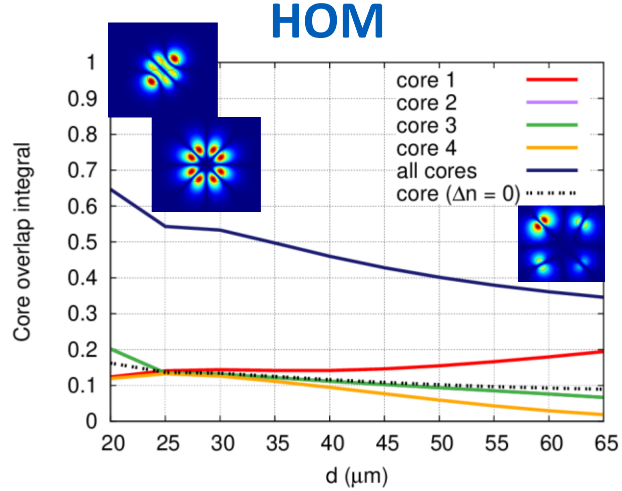


Δn = 10^{-5}

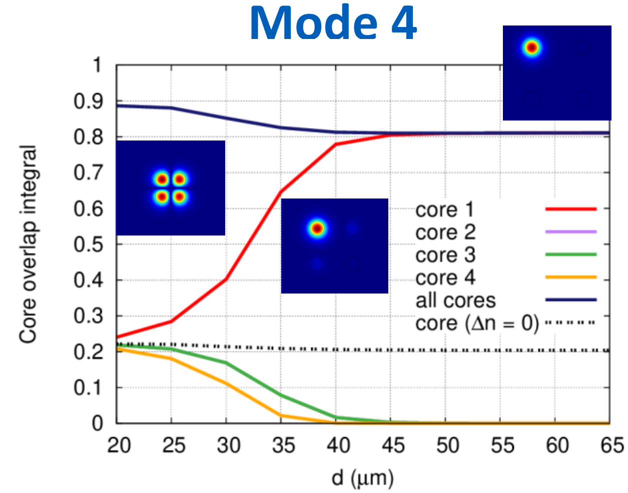
Mode 1



HOM



Mode 4



UNIVERSITÀ DI PARMA

THANK YOU

FOR YOU ATTENTION

UNIVERSITÀ
DI PARMA