Hollow core photonic crystal fiber: the anatomy of confinement loss and more

Federico Melli

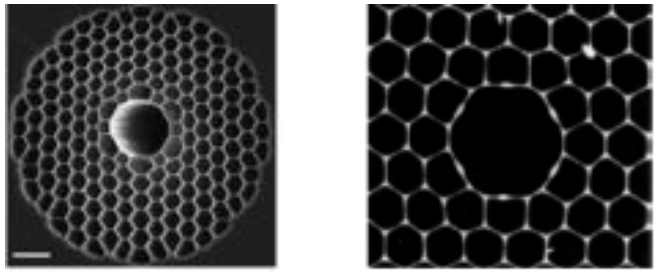
Dept. of Engineering and Architecture, University of Parma,Parma, Italy

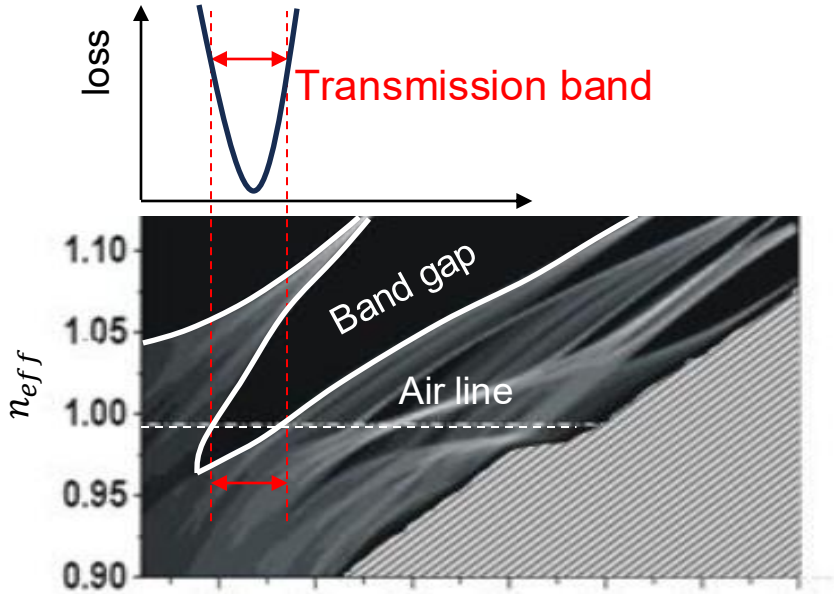
Outline

- **Hollow-Core Fibers (HCFs):** *two families, why Inhibited Coupling leads*
- **The anatomy of Confinement Loss (CL)**
  - ***two mechanisms*** *that connect the* ***IC and antiresonant*** *models*
- **From physics to design**
  - *tube shape effect, and higher-order-mode loss tuning*

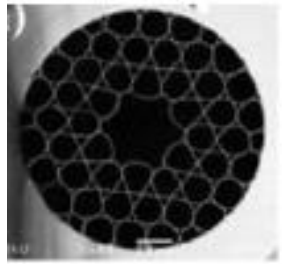
Inhibited Coupling took the lead

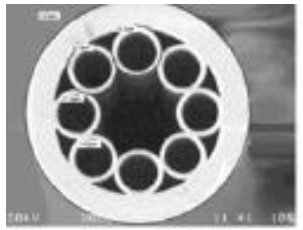
Photonic Bandgap

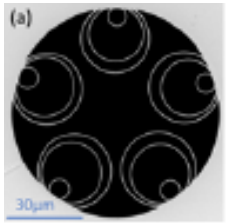


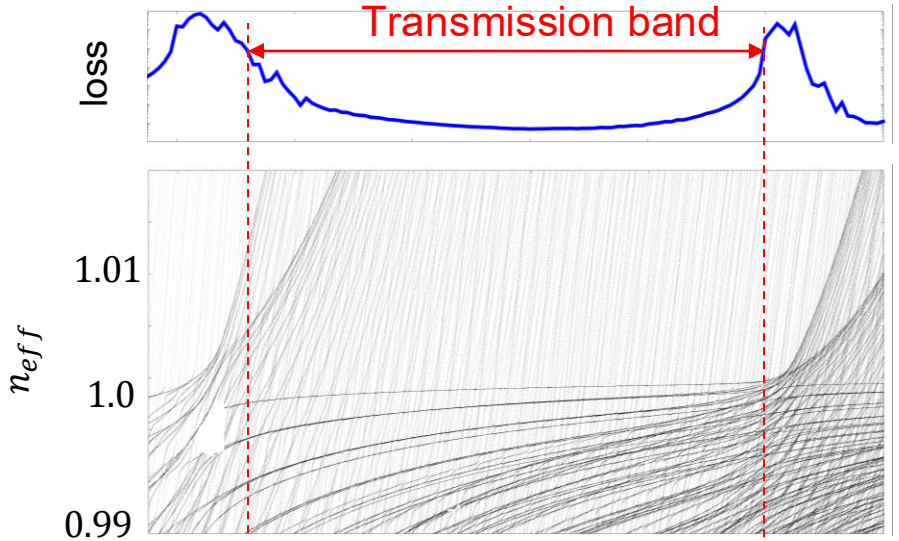


Inhibited Coupling







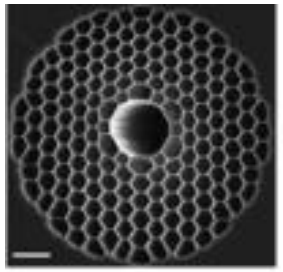


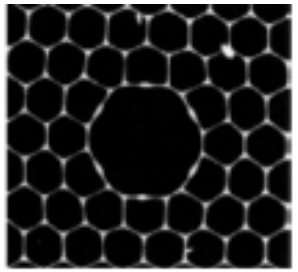
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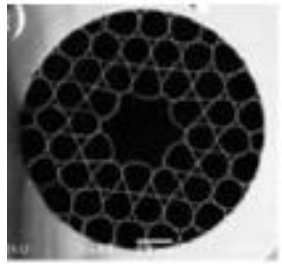
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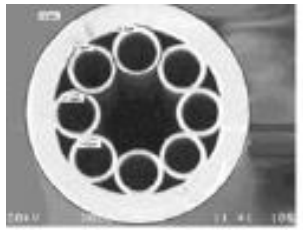
Photonic Bandgap

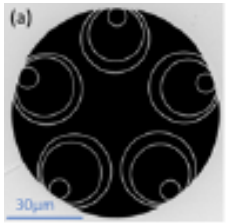


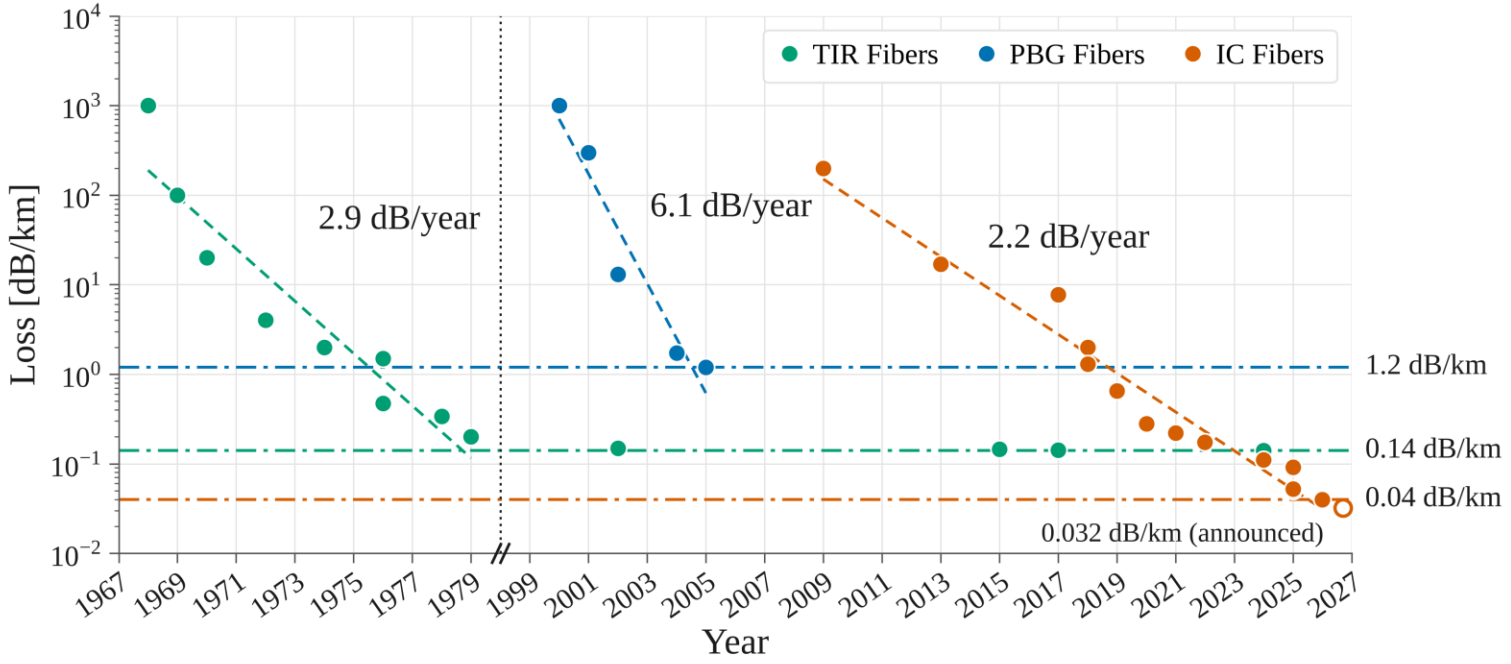


Inhibited Coupling

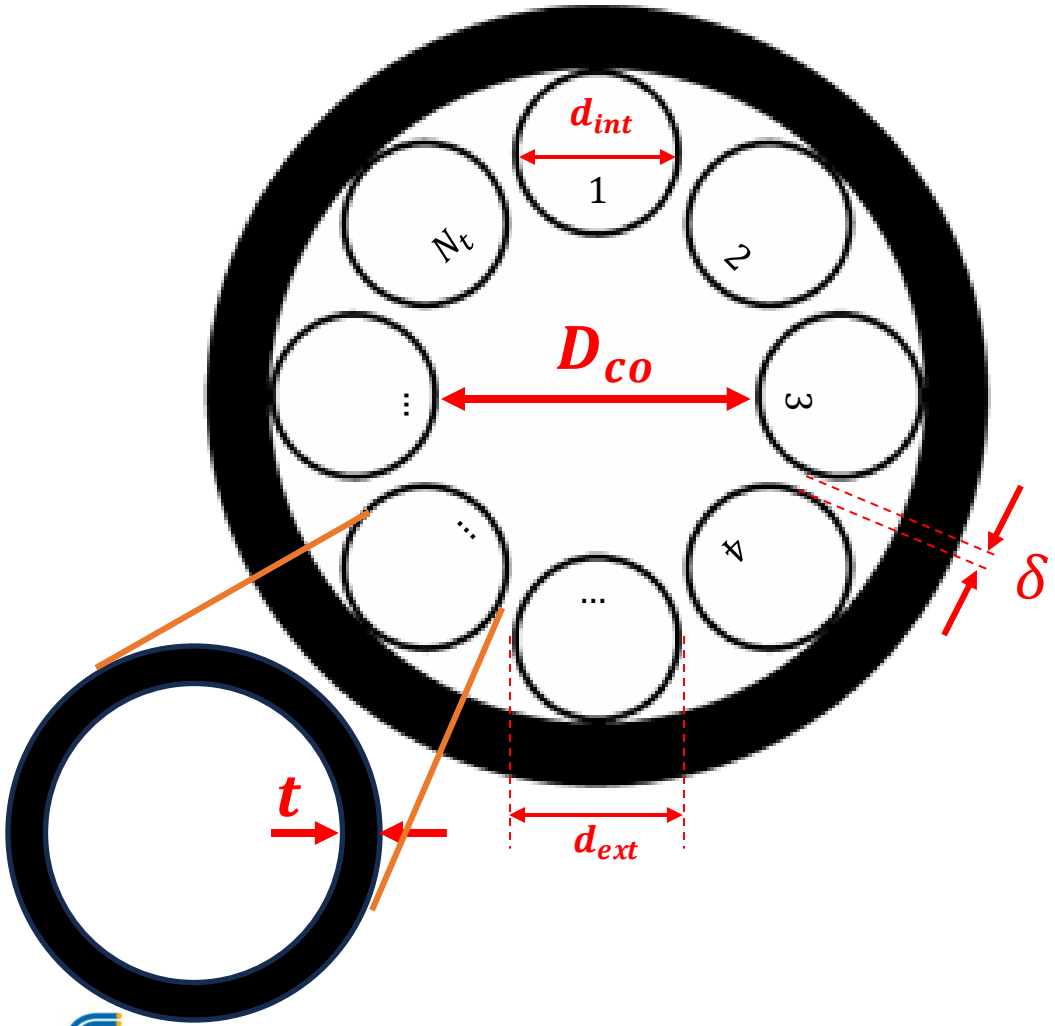








Inhibited Coupling - Tube Lattice Fiber

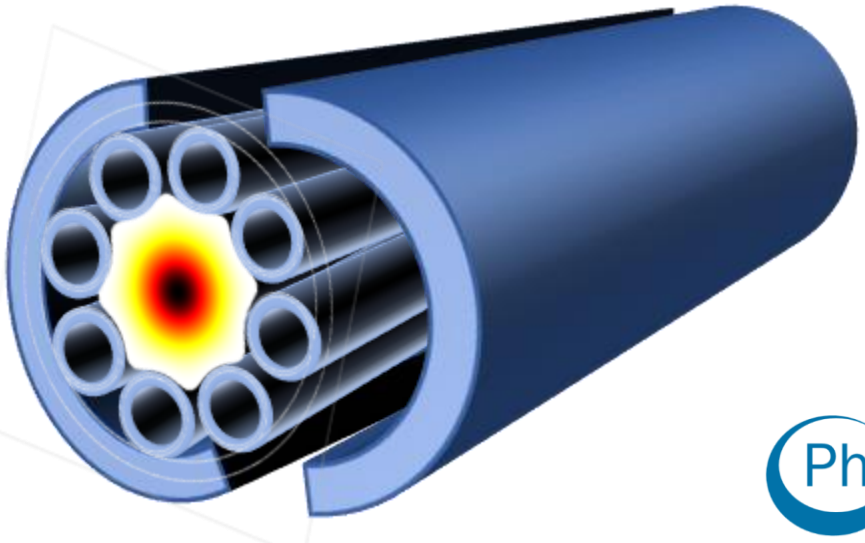


Geometry

- N_t Number of Tubes
- D_{co} Core Diameter
- d_{ext} Tube External Diameter
- d_{int} Tube Internal Diameter
- t Tube Thickness
- δ Tube-Tube gap

Materials

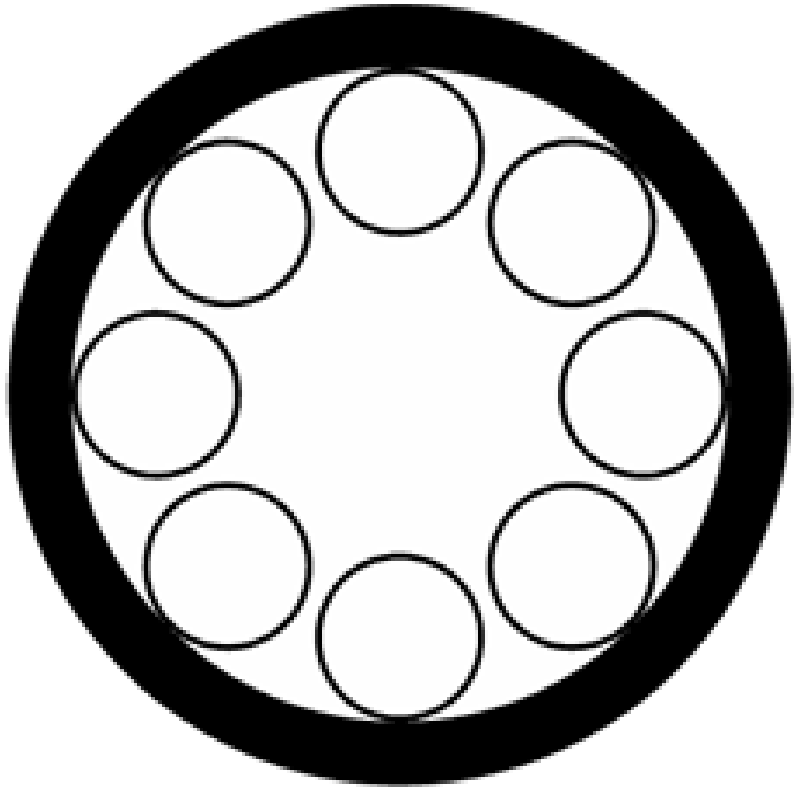
- n_d refractive index of the solid dielectric material
- n_g refractive index of the material filling the hollow core and tube holes



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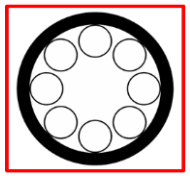
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TLFs Confinement Loss

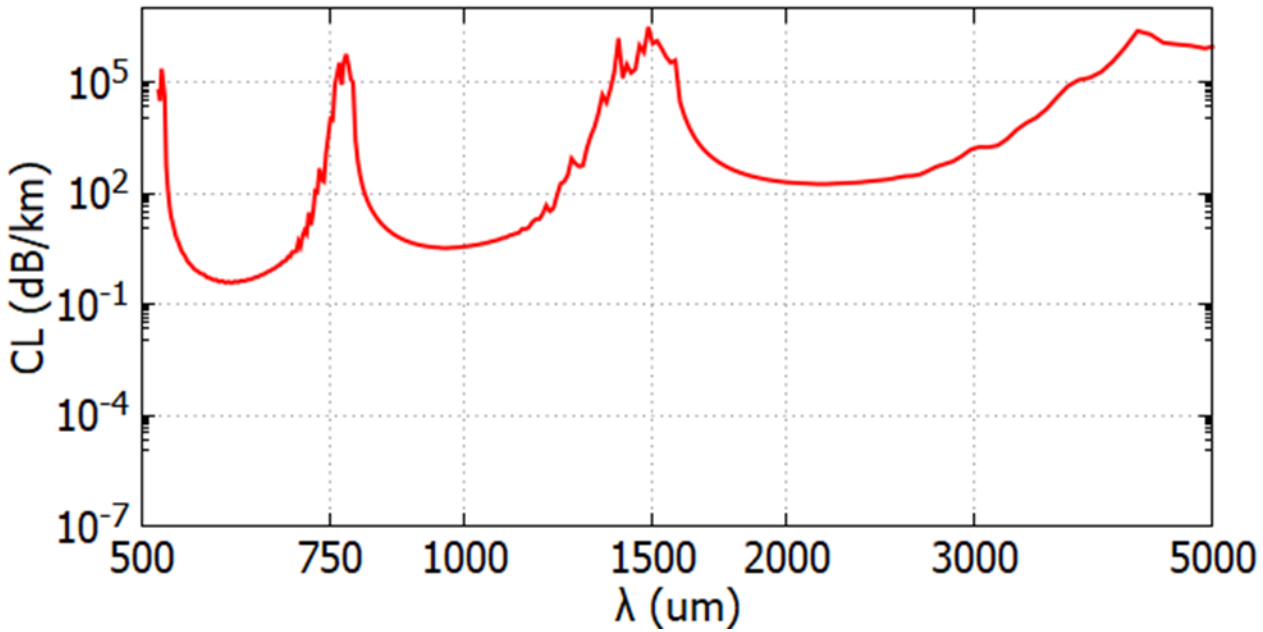


Confinement Loss (CL) of LP_{01} mode

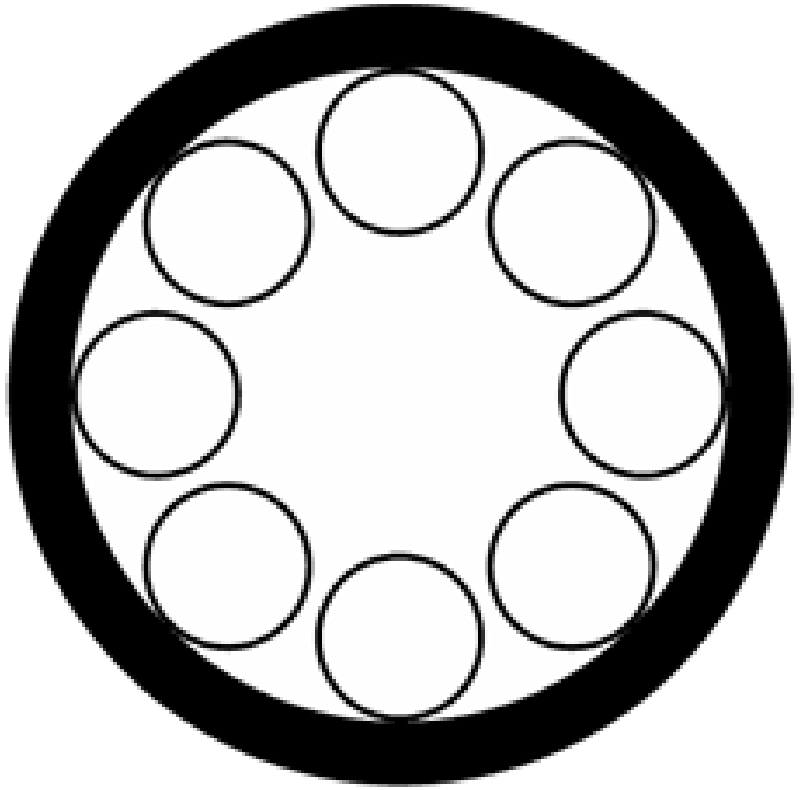
N_s: number of nested tubes



$N_s = 0$

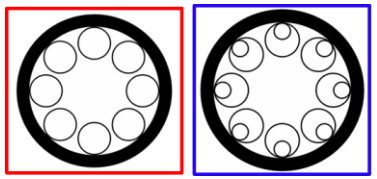


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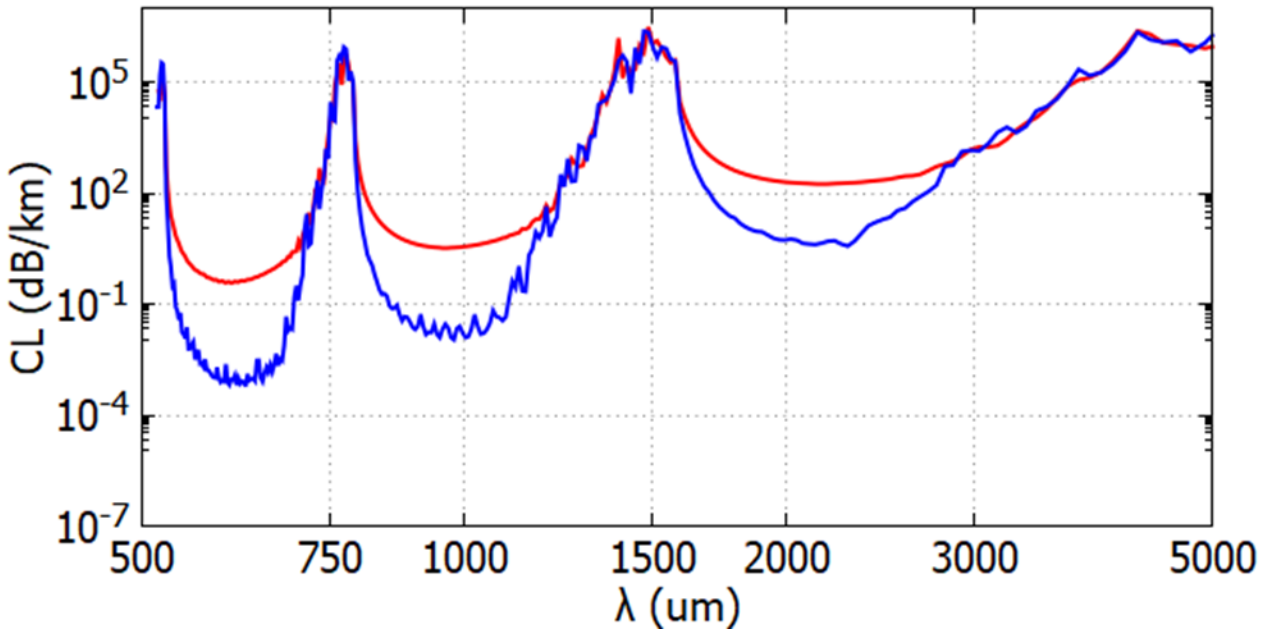


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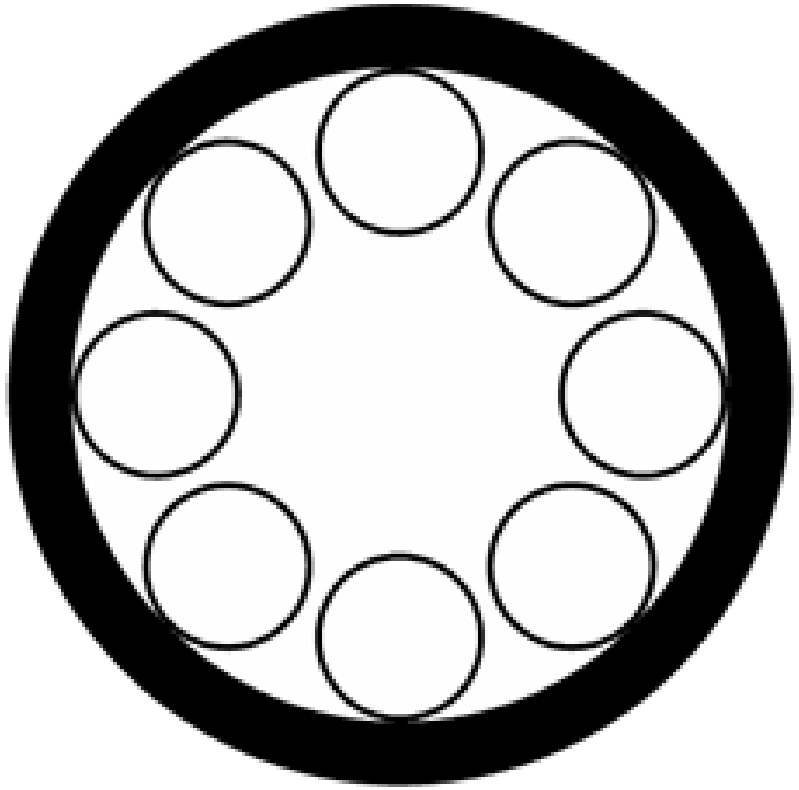
N_s: number of nested tubes



$N_s = 0$ $N_s = 1$

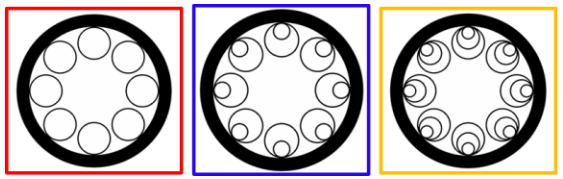


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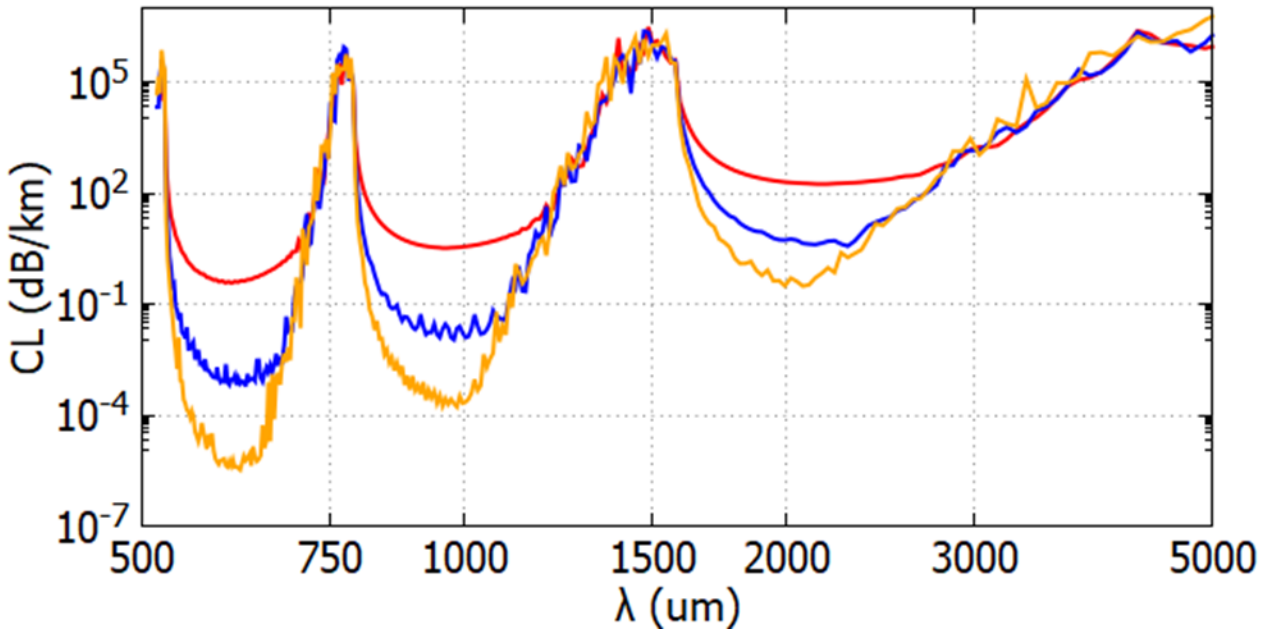


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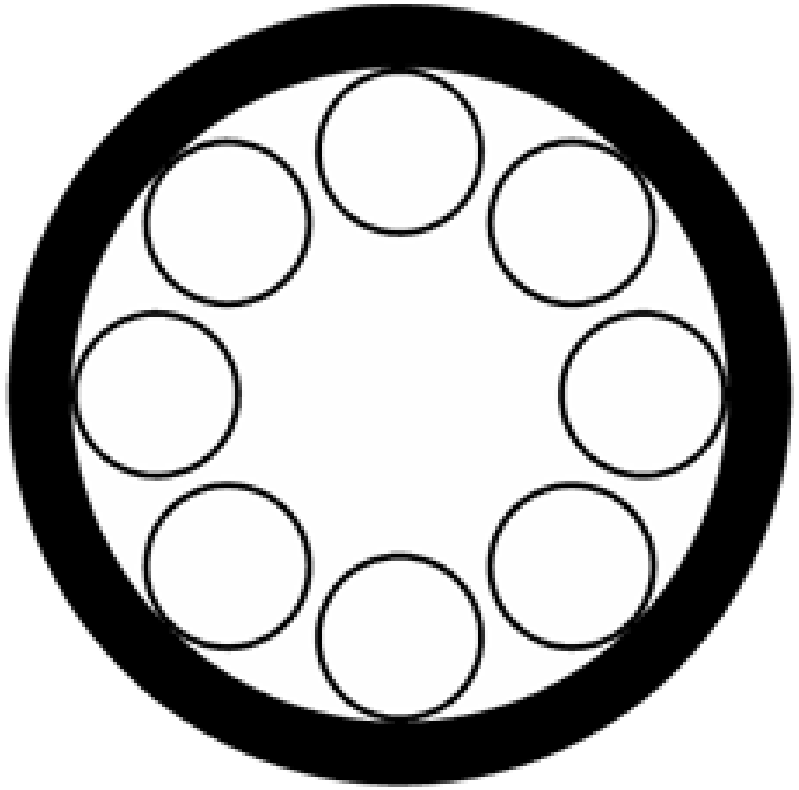
N_s: number of nested tubes



$N_s = 0$ $N_s = 1$ $N_s = 2$

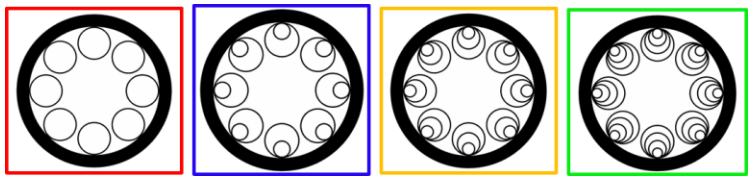


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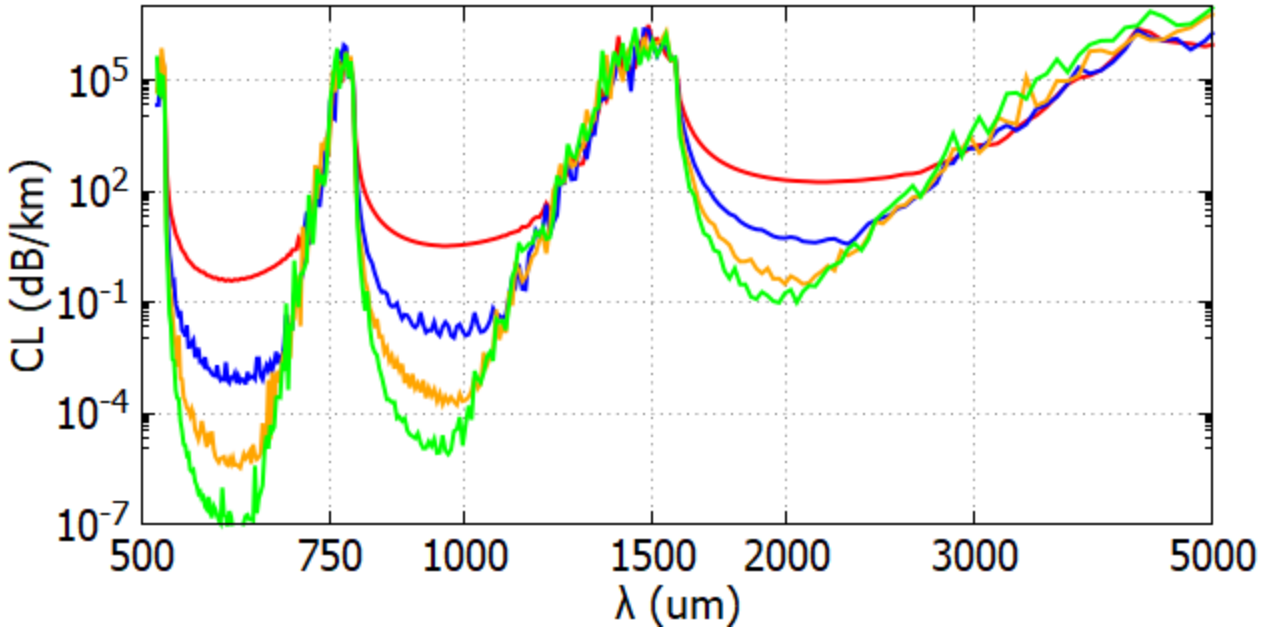


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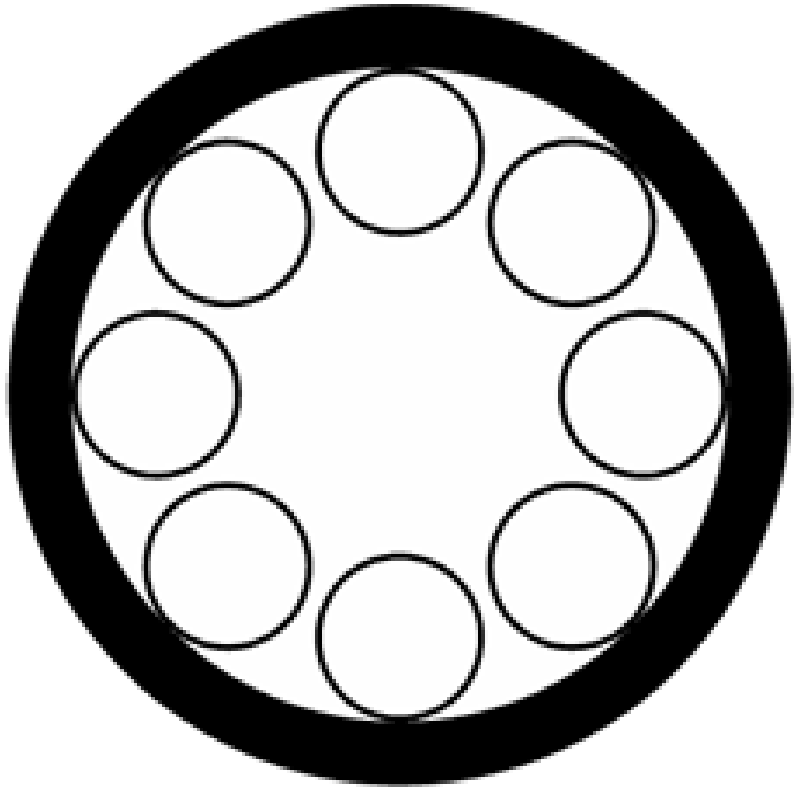
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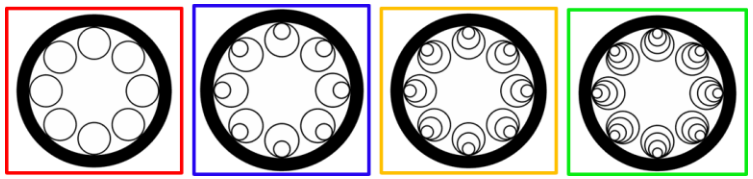
$N_s = 0$ $N_s = 1$ $N_s = 2$ $N_s = 3$



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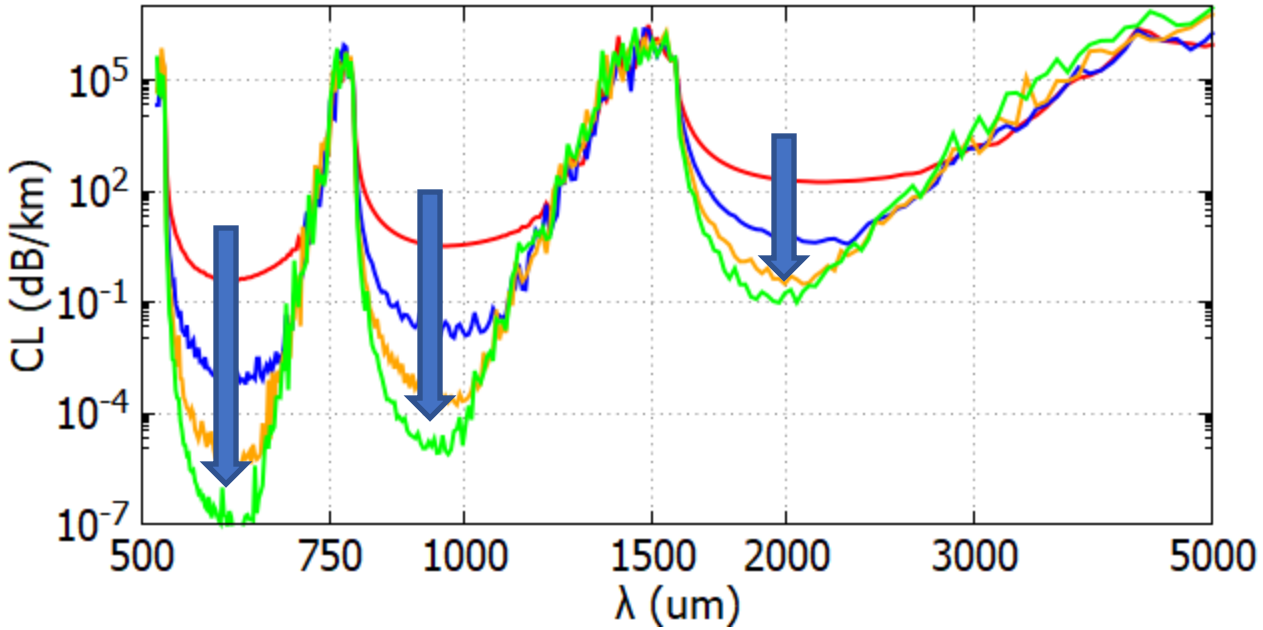
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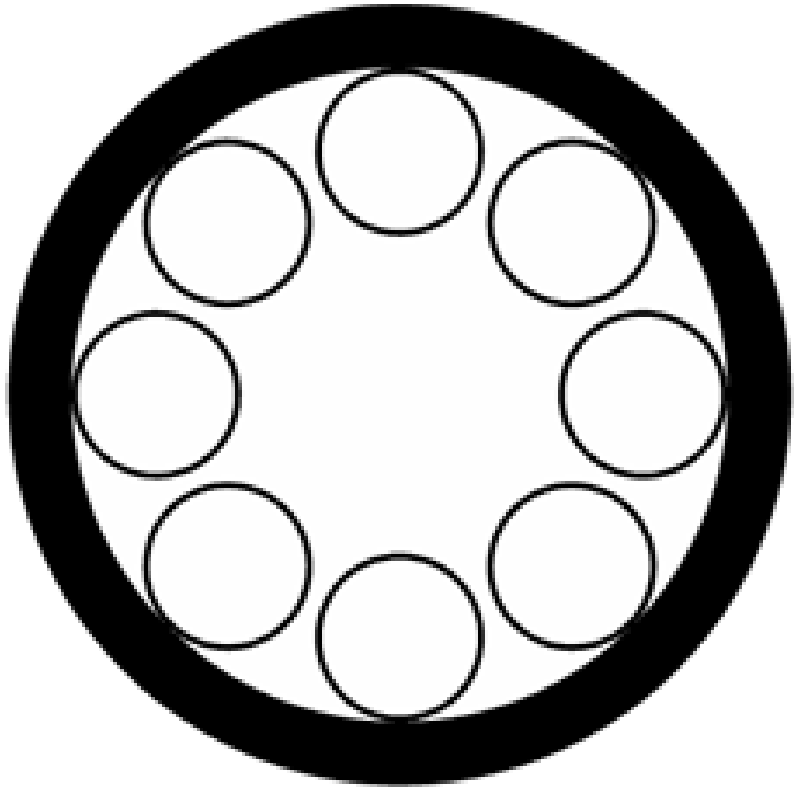
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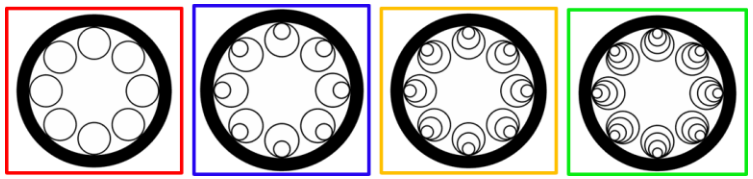
Minimum Losses strongly sensitive to nesting order



TLFs Confinement Loss



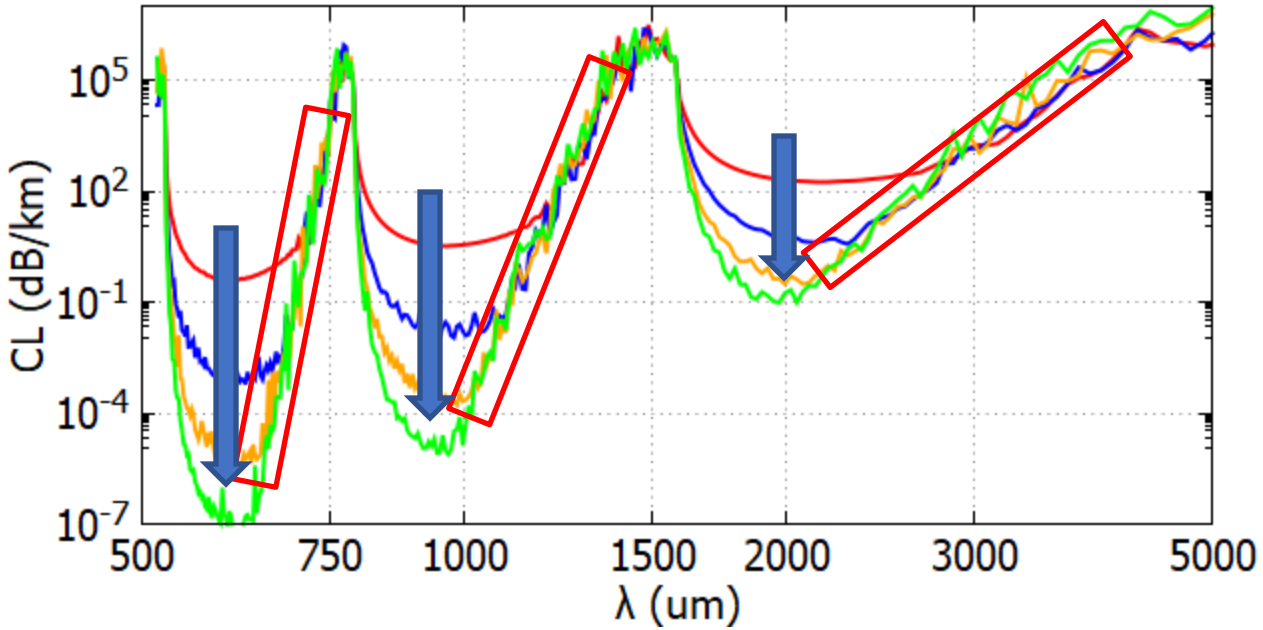
Confinement Loss (CL) of LP_{01} mode



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Minimum Losses strongly sensitive to nesting order

Bands Edges NOT sensitive to nesting order

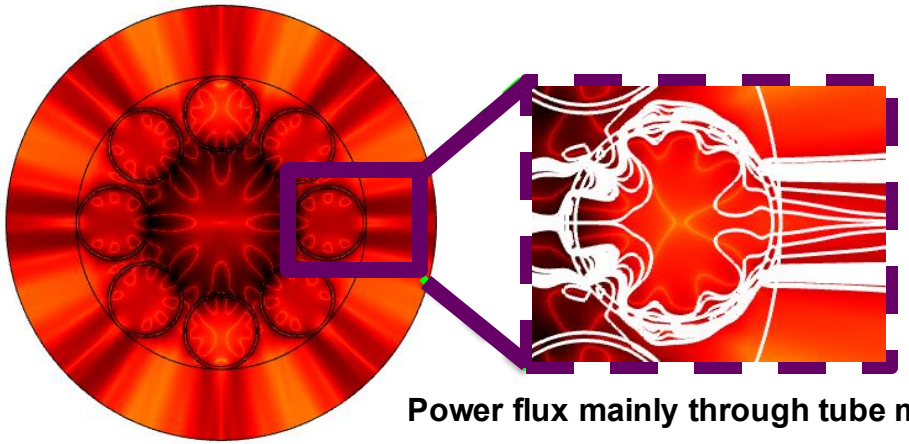


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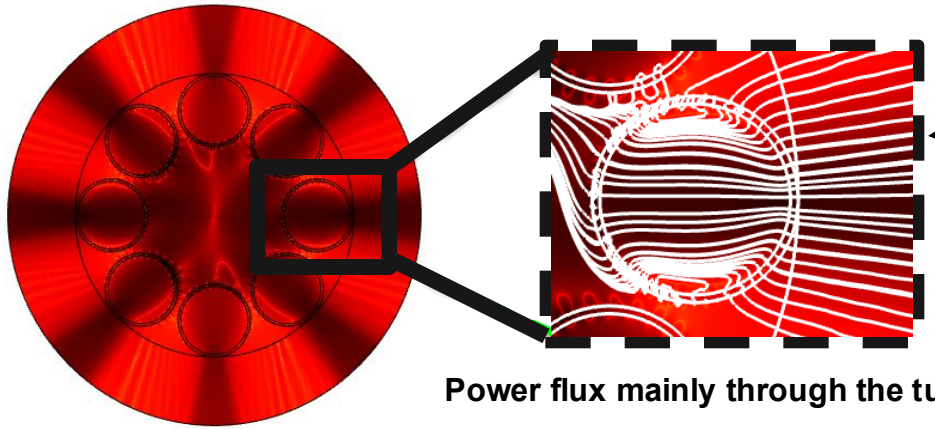
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TLFs Confinement Loss

Radial power flux

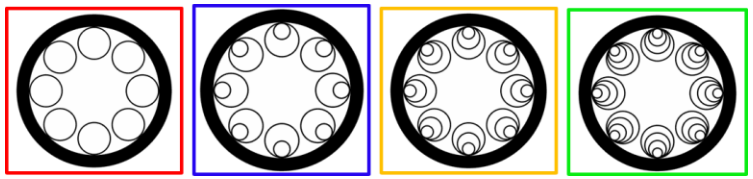


Power flux mainly through tube membranes



Power flux mainly through the tube holes

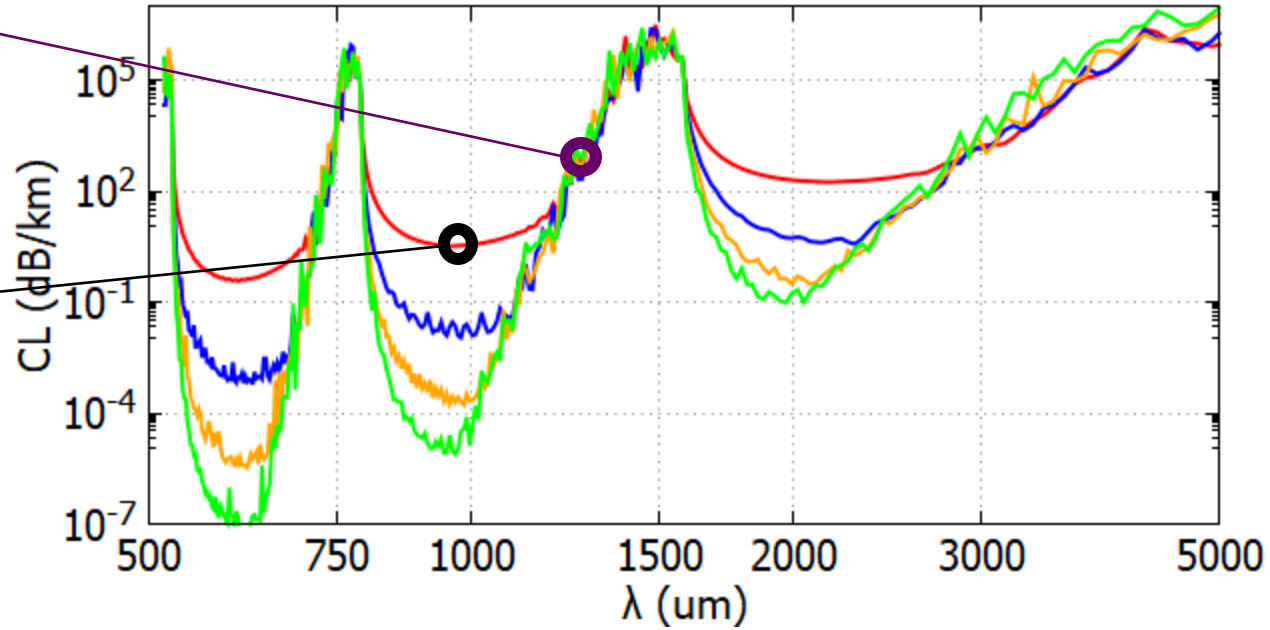
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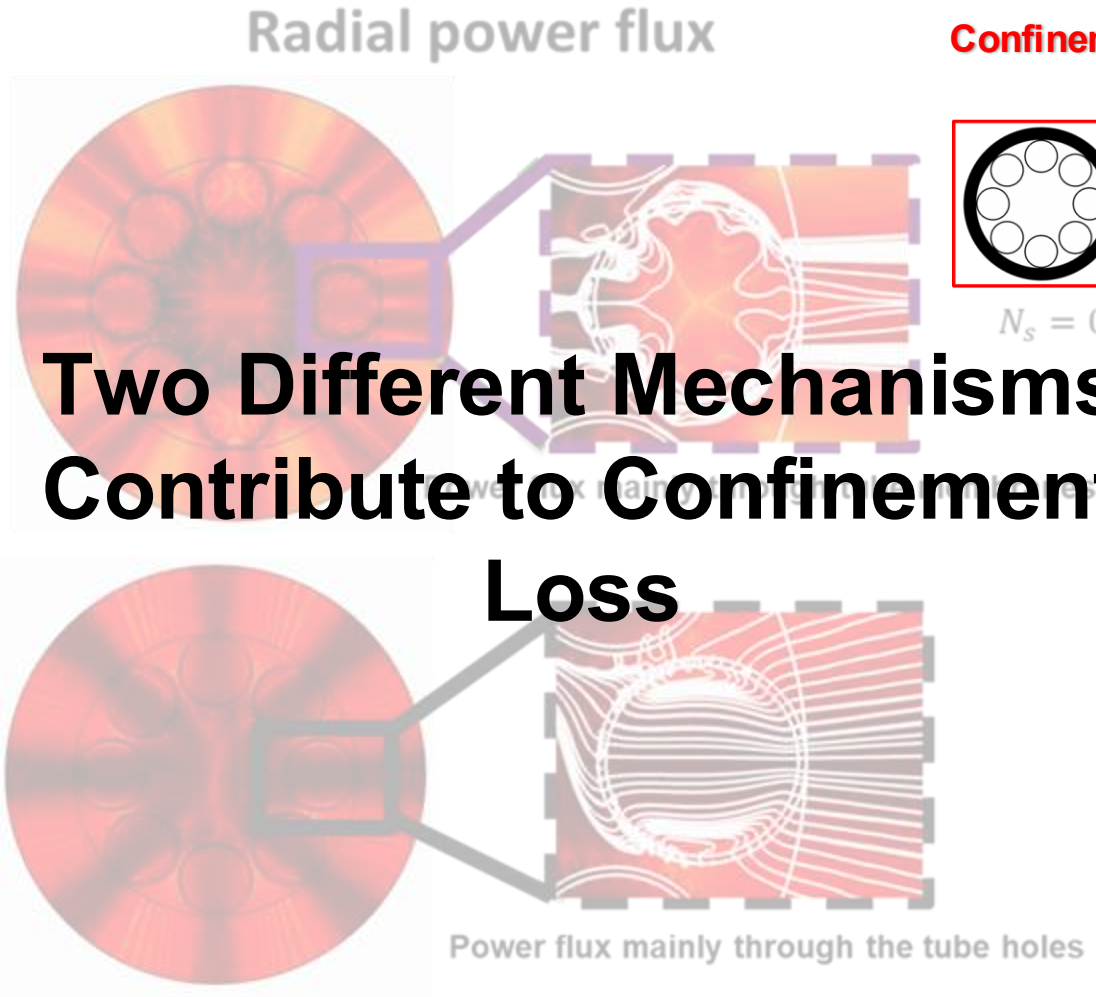
N_s: number of nested tubes

Minimum Losses strongly sensitive to nesting order

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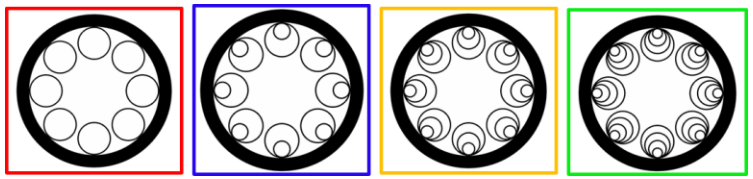


TLFs Confinement Loss



Two Different Mechanisms Contribute to Confinement Loss

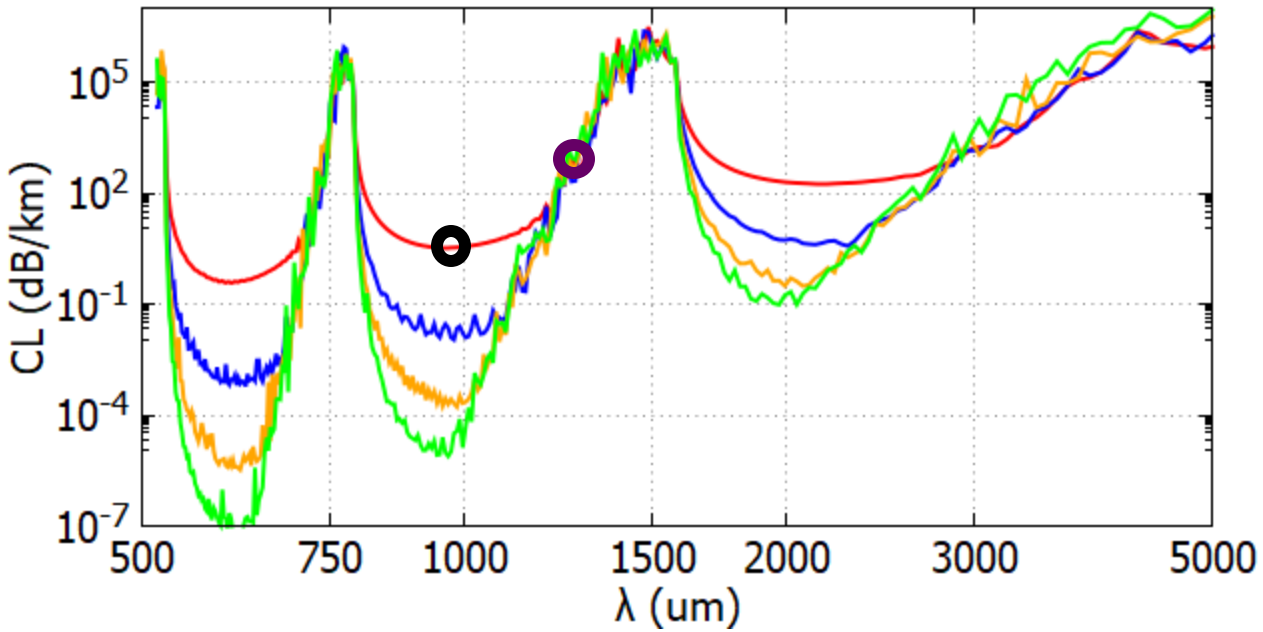
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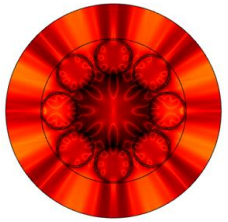


MCL & TTL

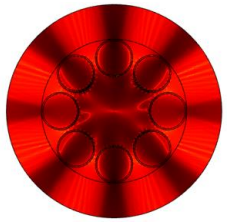
Confinement Loss is the result of two contributions:

- **Mode Coupling Loss (MCL)**
- **Tube Tunneling Loss (TTL)**

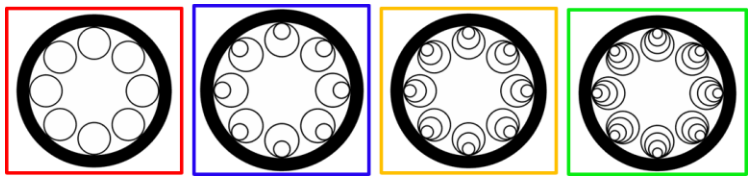
MCL is the loss due to the coupling with dielectric modes set by Azimuthal Fourier Decomposition (AFD) of Core Mode
[Melli et al Results In Optics (2024)]



TTL is the loss due to tunneling through the cladding tubes
[Melli et al JLT (2026)]



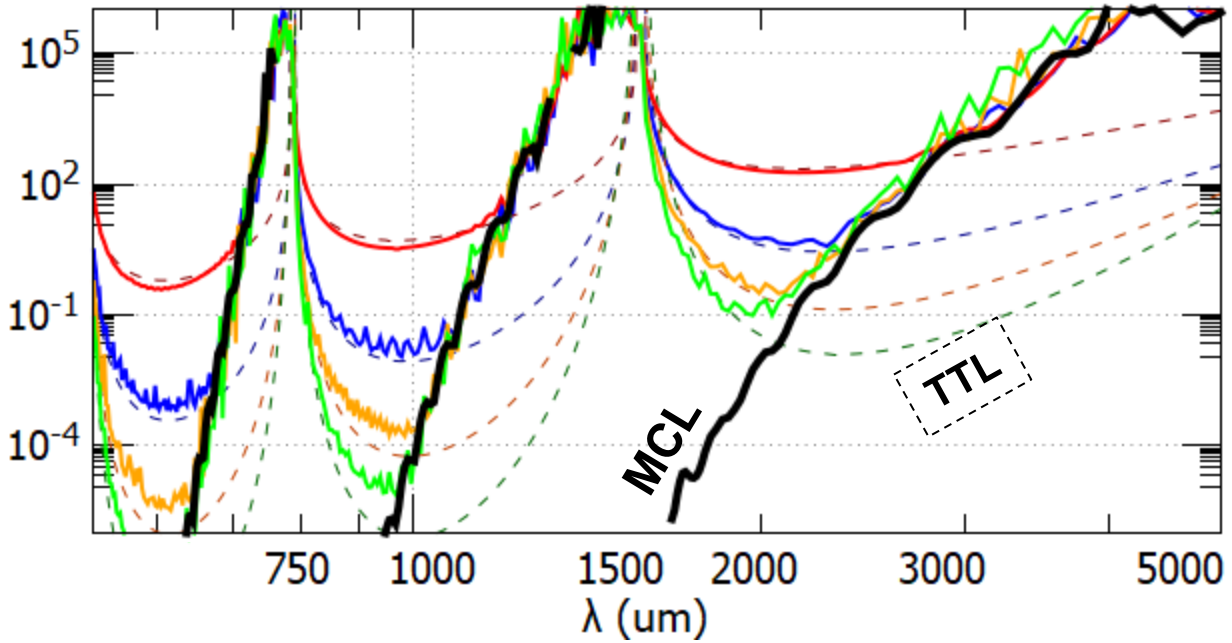
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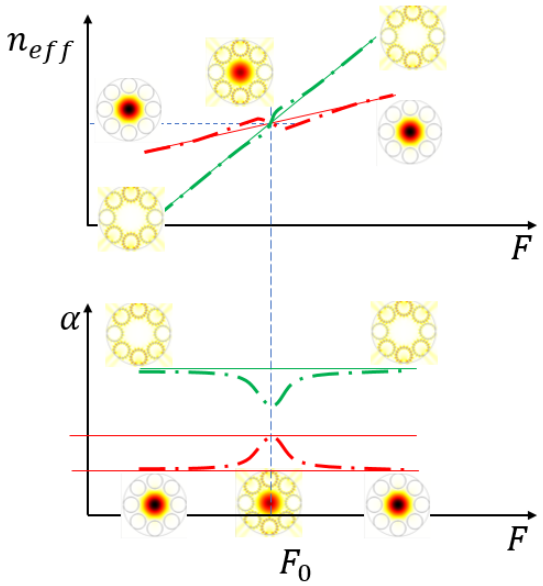
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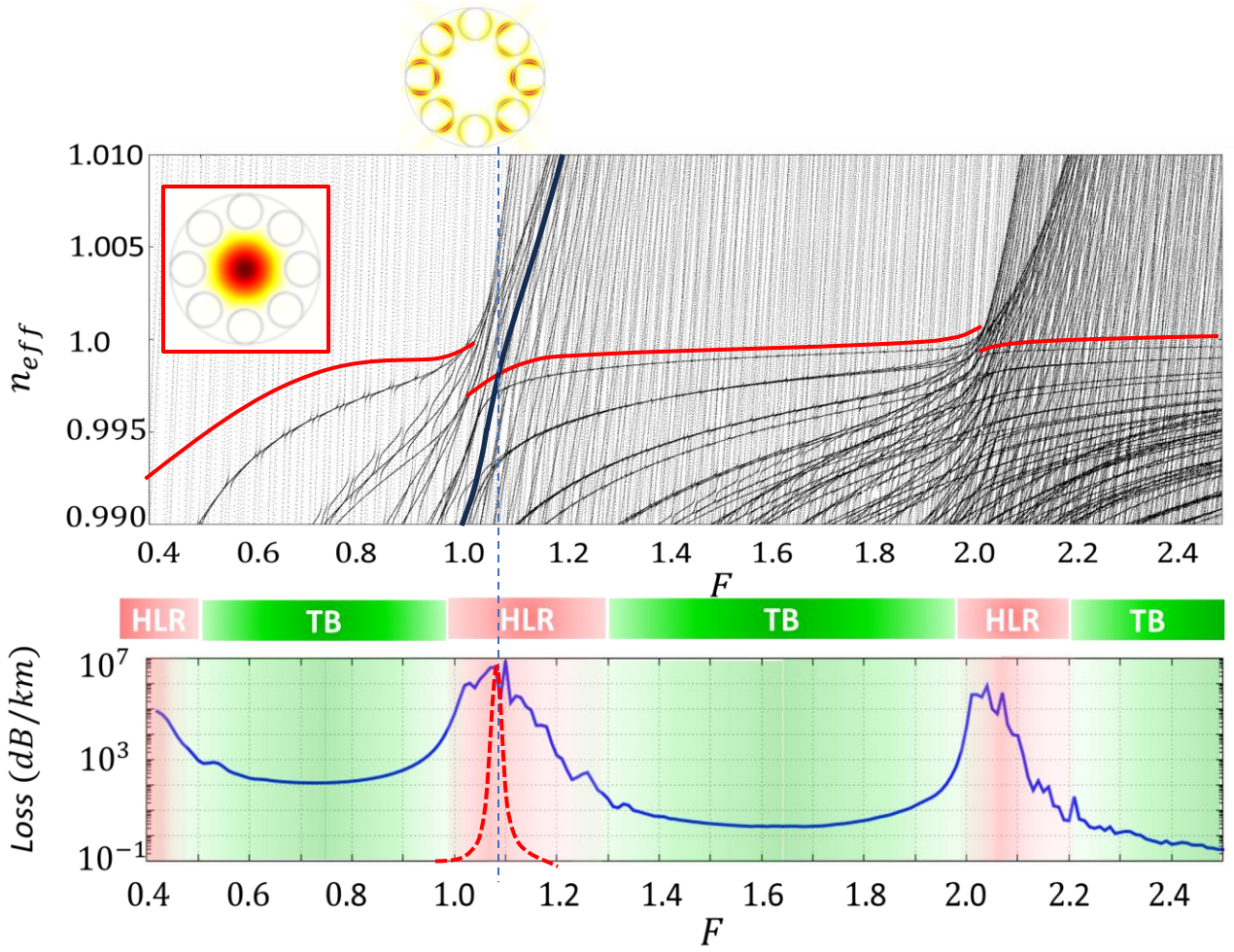
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MCL



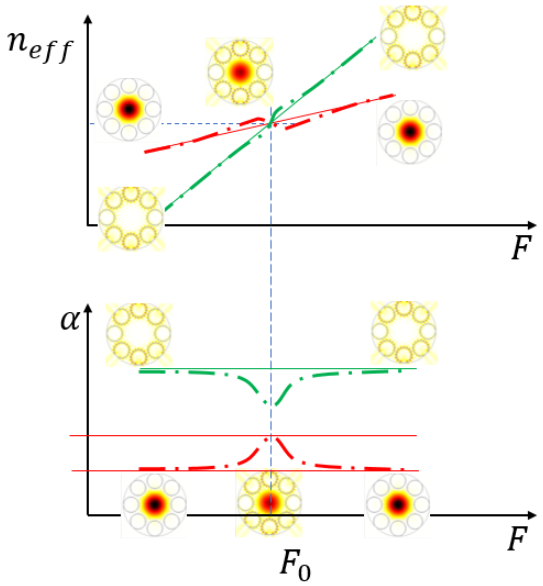
$$\delta\alpha \propto k^2 \propto \left(\iint_{S_\infty} \bar{E}_1 \cdot \bar{E}_2 dS \right)^2$$



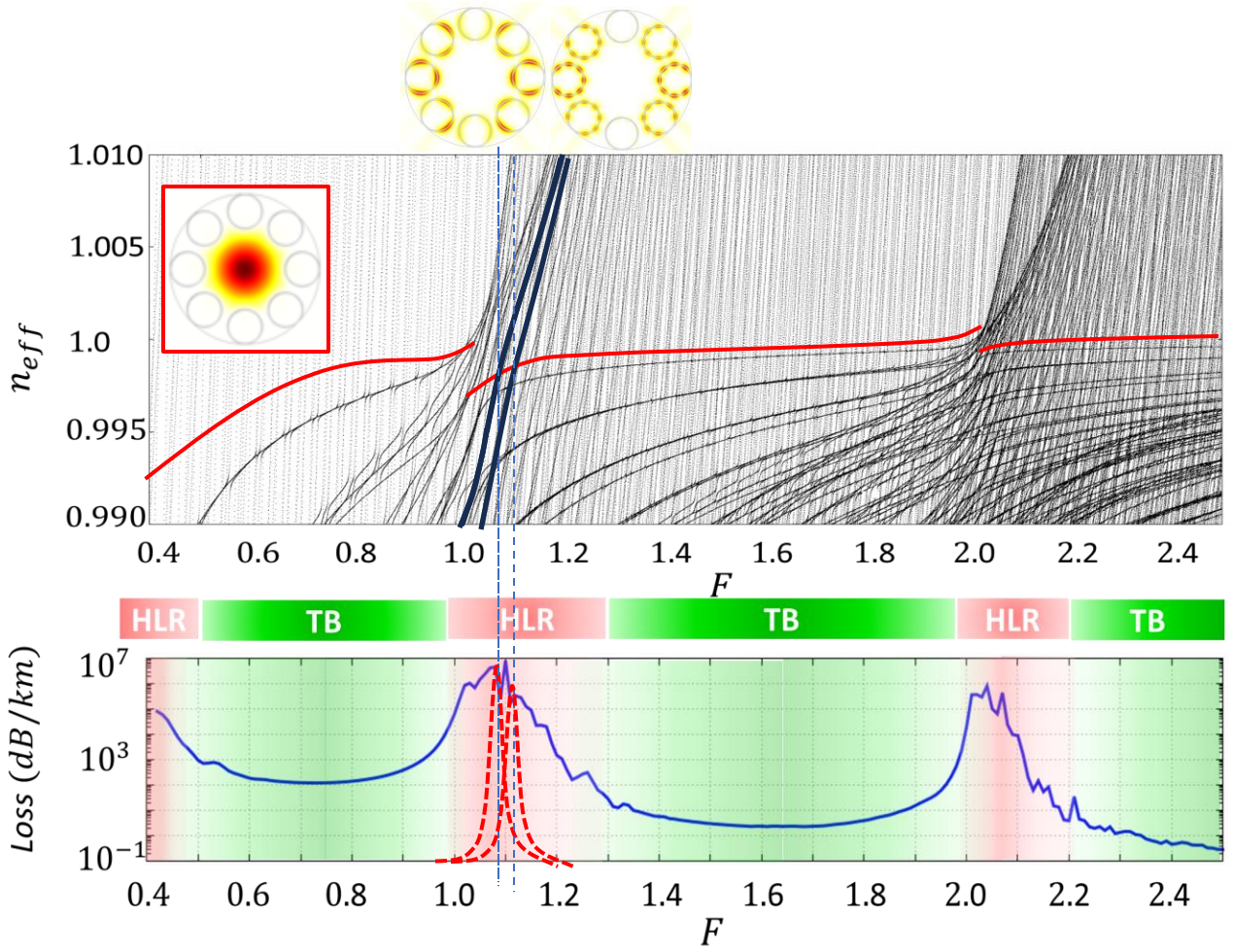
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MCL



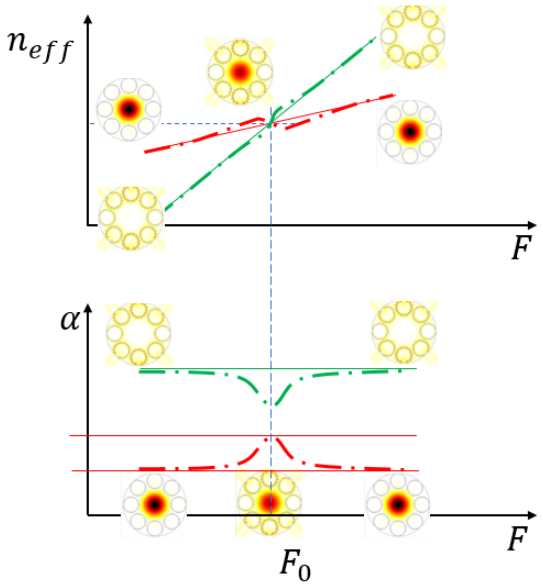
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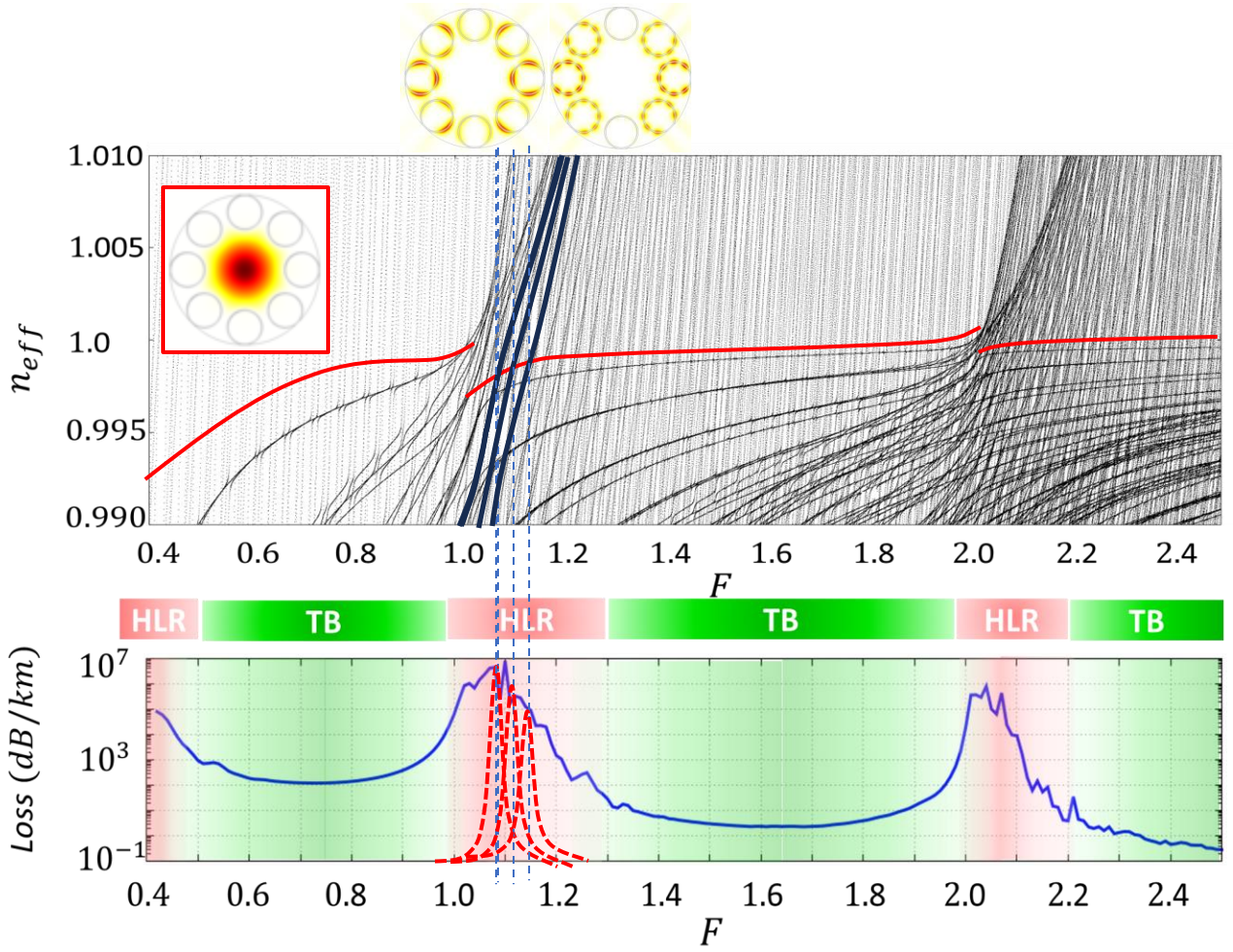
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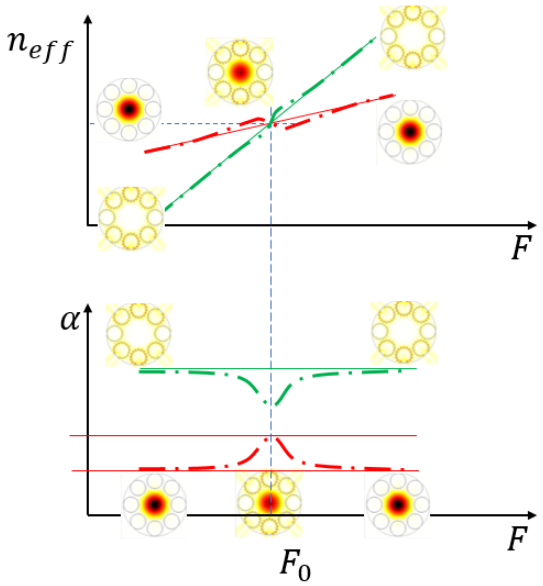
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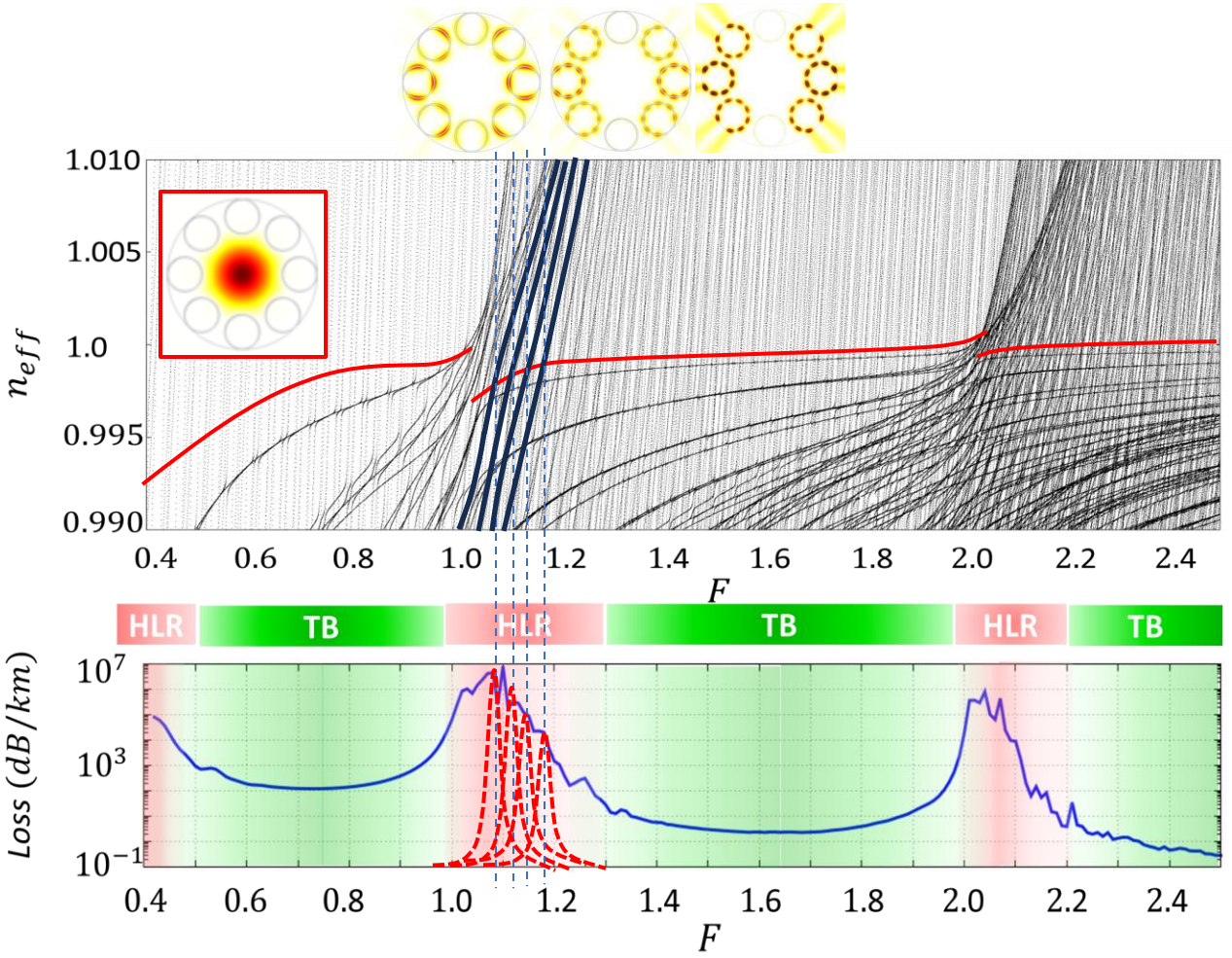
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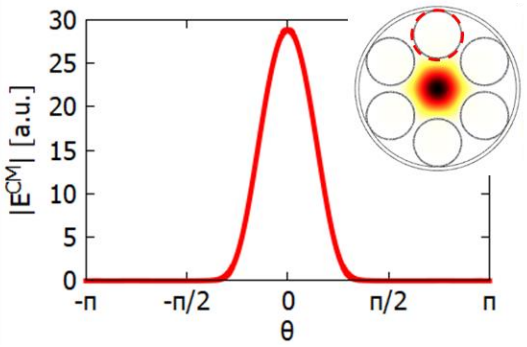
MCL

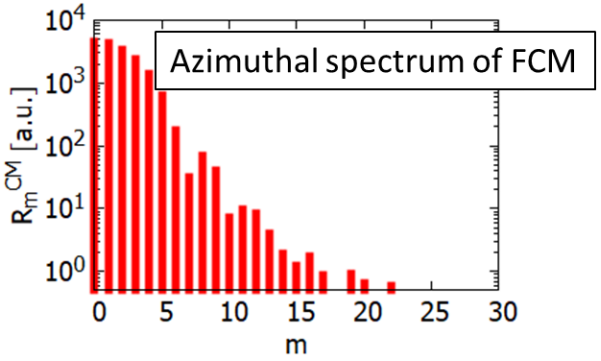
Azimuthal Fourier Decomposition

F. Melli, K. Vasko, L. Rosa, F. Benabid, and L. Vincetti, *Results in Optics*, vol. 15, p. 100657, 2024

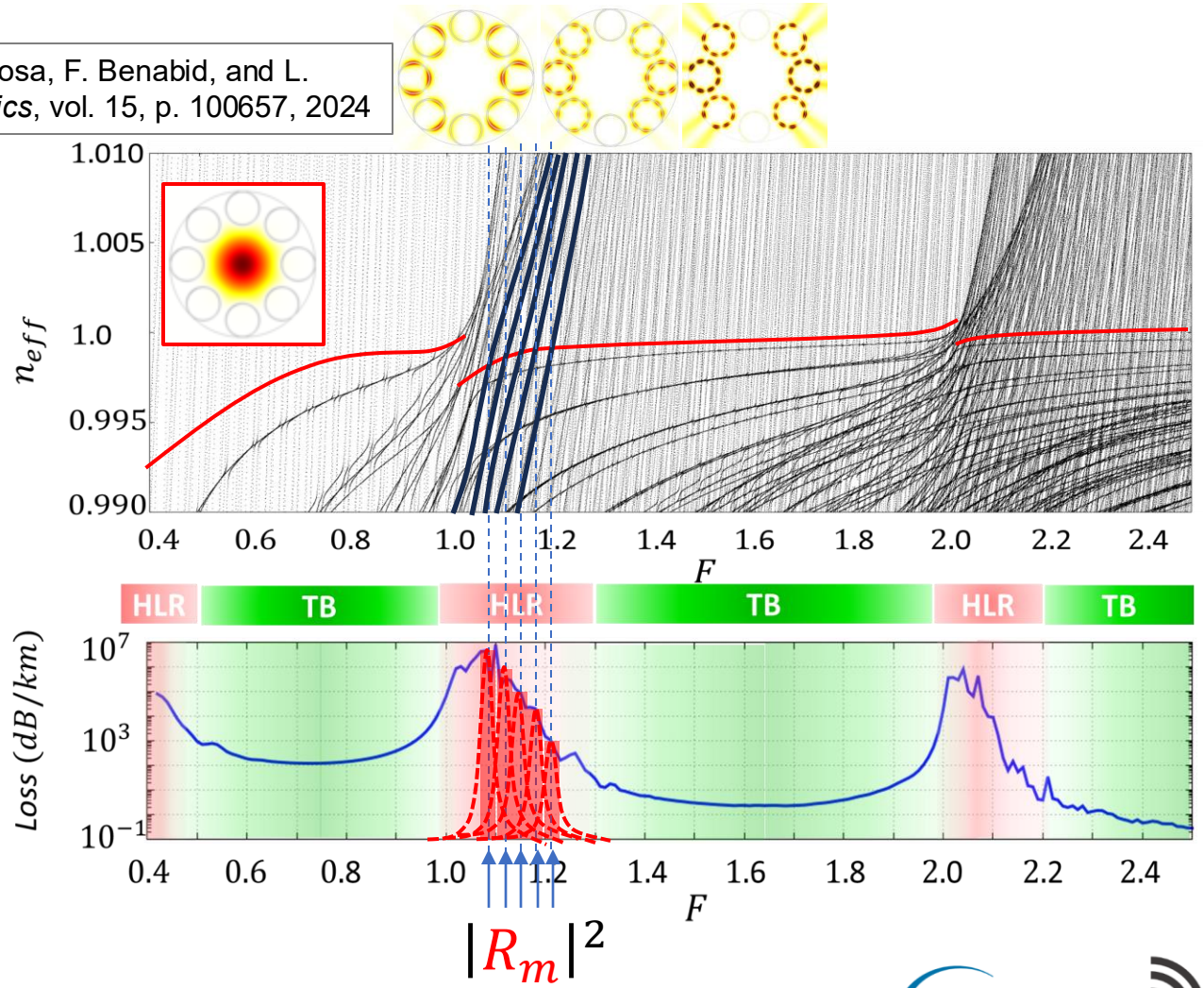
Azimuthal Fourier Series

$$R_m = \frac{1}{2\pi}\int_0^{2\pi} E_1(r_{int},\theta)e^{-jm\theta}\,d\theta$$





$$\delta\alpha \propto k^2 \propto \left(\iint_{S_\infty} \bar{E}_1 \cdot \bar{E}_2 dS\right)^2 \propto |R_m|^2$$



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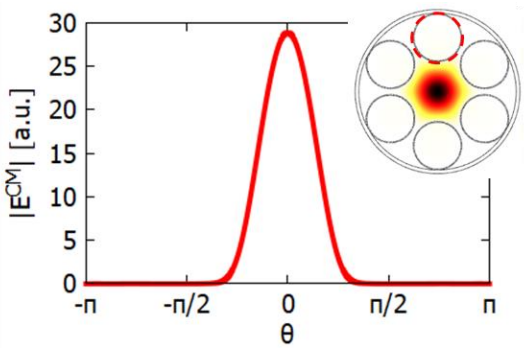
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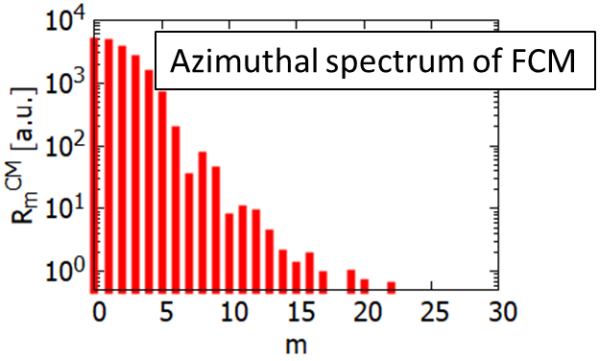
MCL

Azimuthal Fourier Decomposition

Azimuthal Fourier Series

$$R_m = \frac{1}{2\pi}\int_0^{2\pi} E_1(r_{int},\theta)e^{-jm\theta}\,d\theta$$

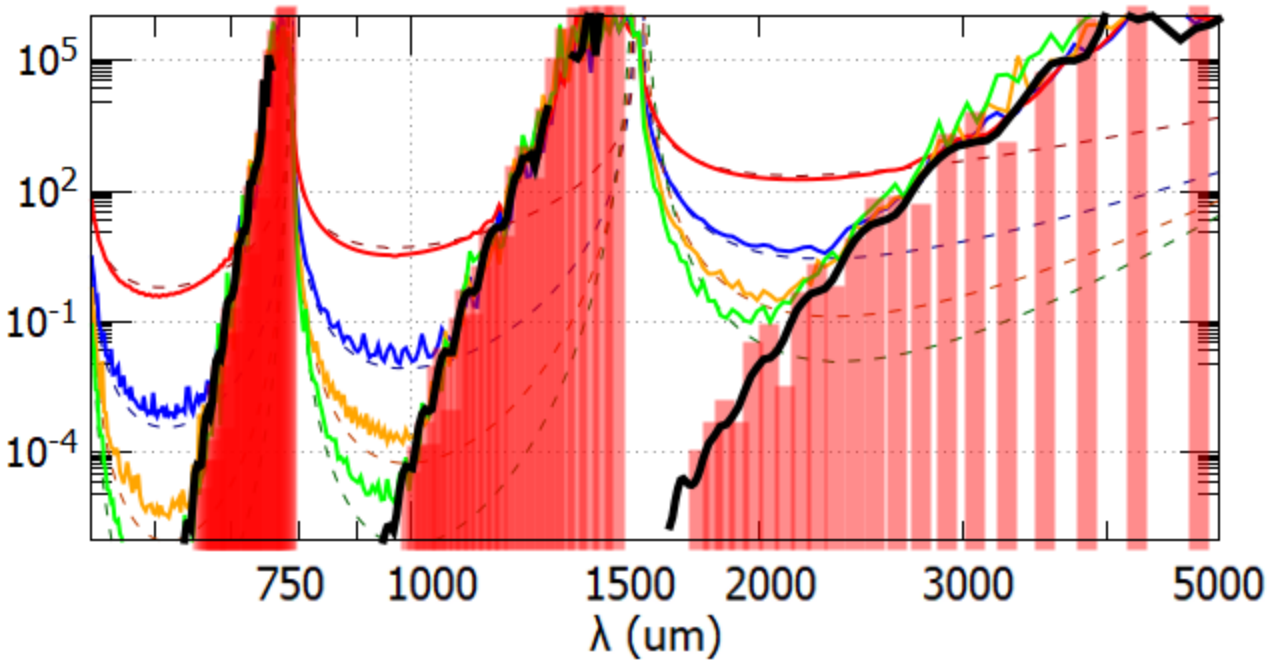




$$\delta\alpha \propto k^2 \propto \left(\iint_{S_\infty} \bar{E}_1 \cdot \bar{E}_2 dS\right)^2 \propto |R_m|^2$$

Field profile and azimuthal spectra do not depend on kind of elements



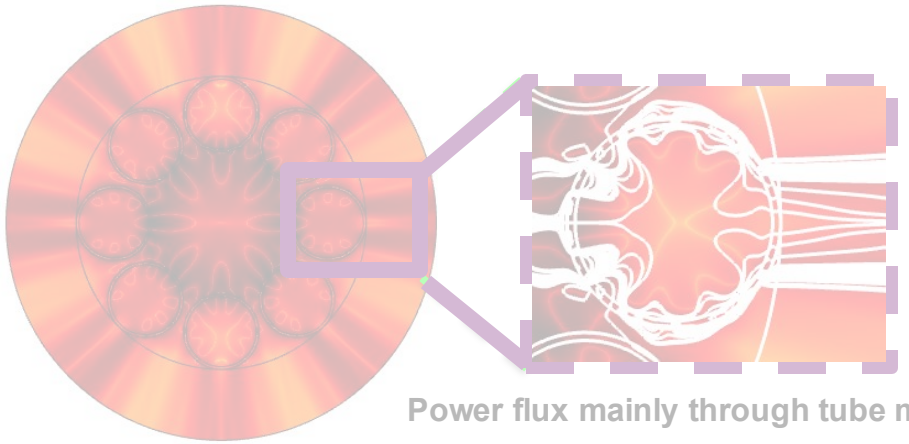


SOFIAPHOTONICS

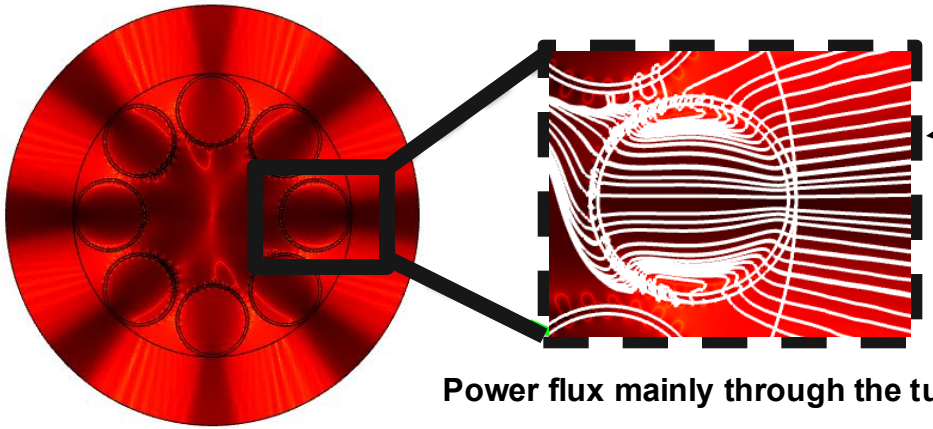
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TTL

Radial power flux

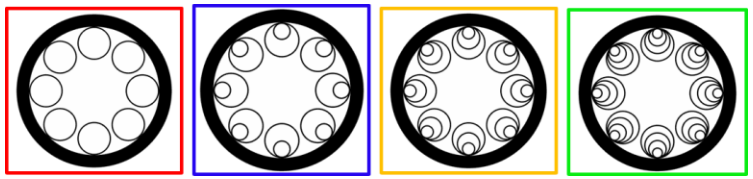


Power flux mainly through tube membranes



Power flux mainly through the tube holes

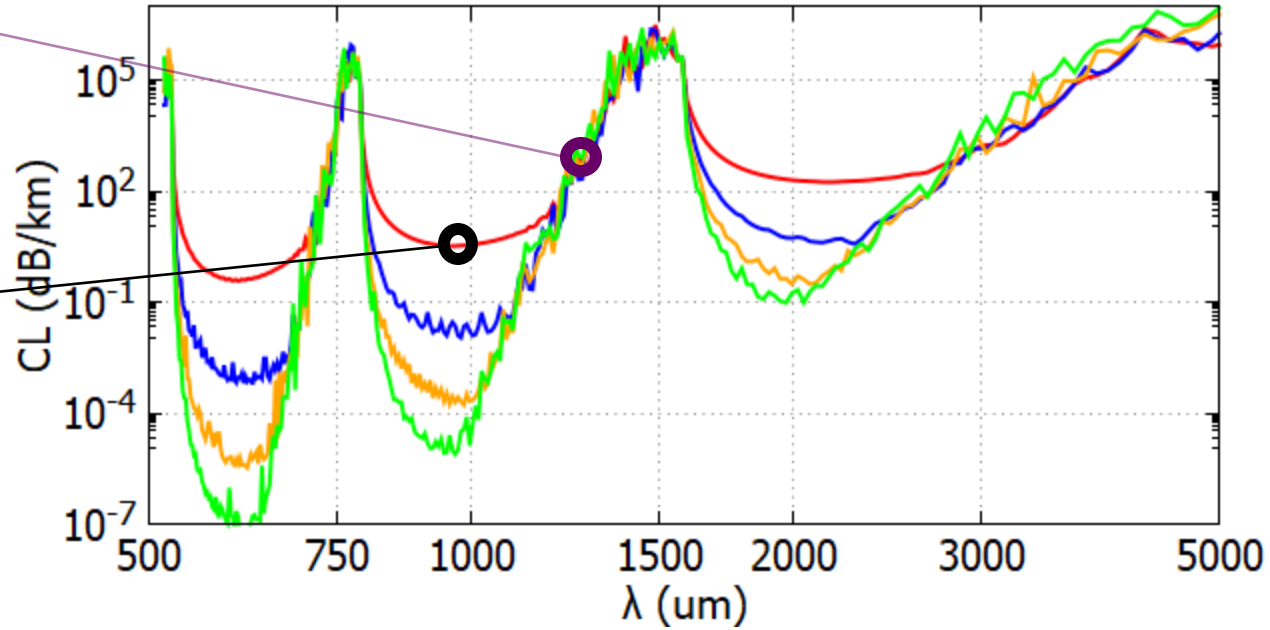
Confinement Loss (CL) of LP_{01} mode



N_s: number of nested tubes

Minimum Losses strongly sensitive to nesting order

Bands Edges NOT sensitive to nesting order

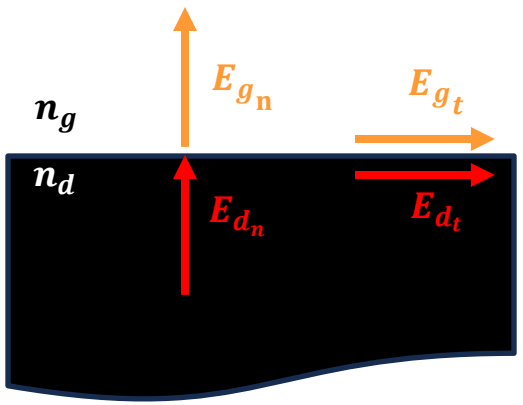


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At interface

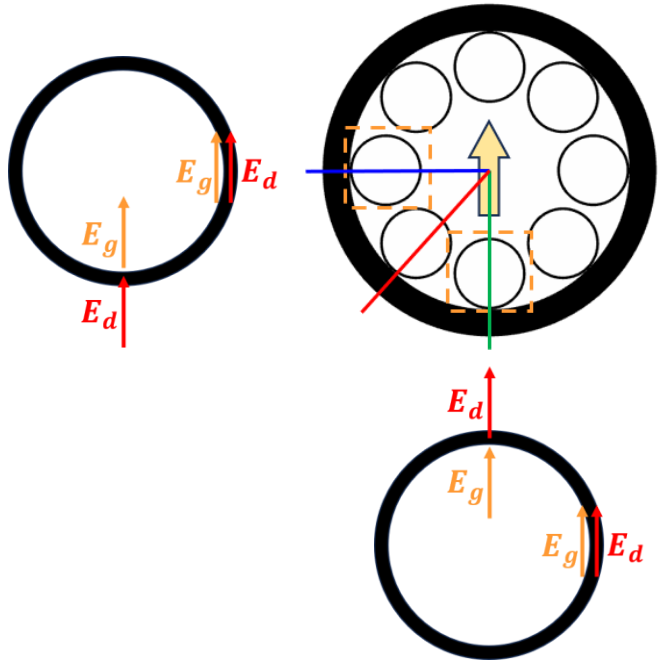


Boundary conditions (BCs)

$$E_{g_t} = E_{d_t}$$

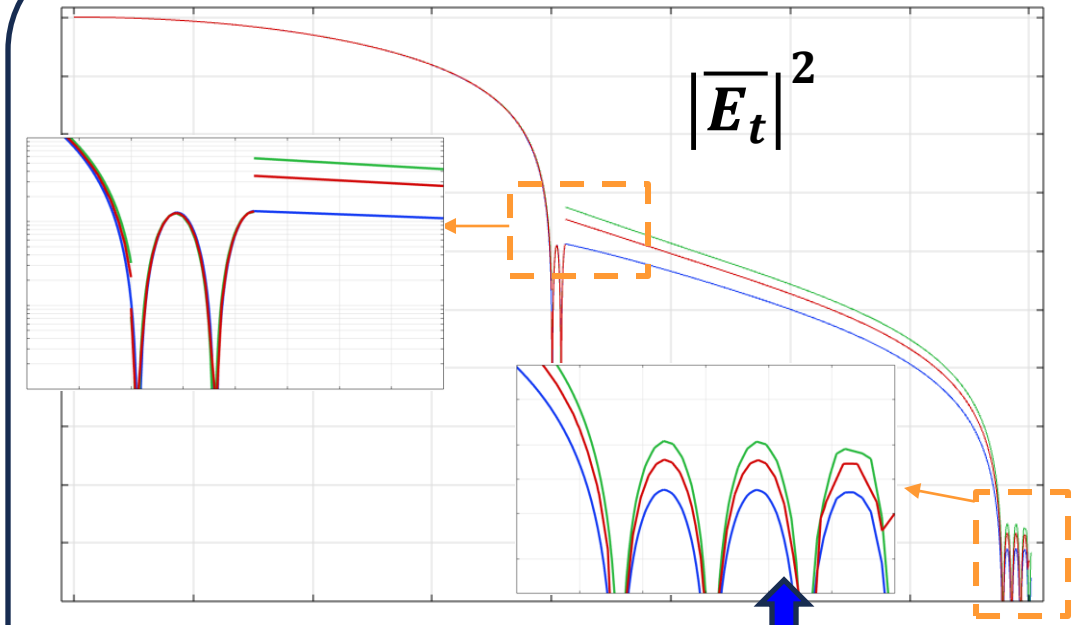
$$n_g^2 E_{g_t} = n_d^2 E_{d_t}$$

Different tube different BCs



depending on the **relative orientation** between $\overline{E}$ and tube the **boundary conditions** to be satisfied **change**

Radial profile



Different BCs result in different radial profile of $|\overline{E_t}|^2$ used to estimate power tunneling

Different orientation

↓

Different boundary conditions

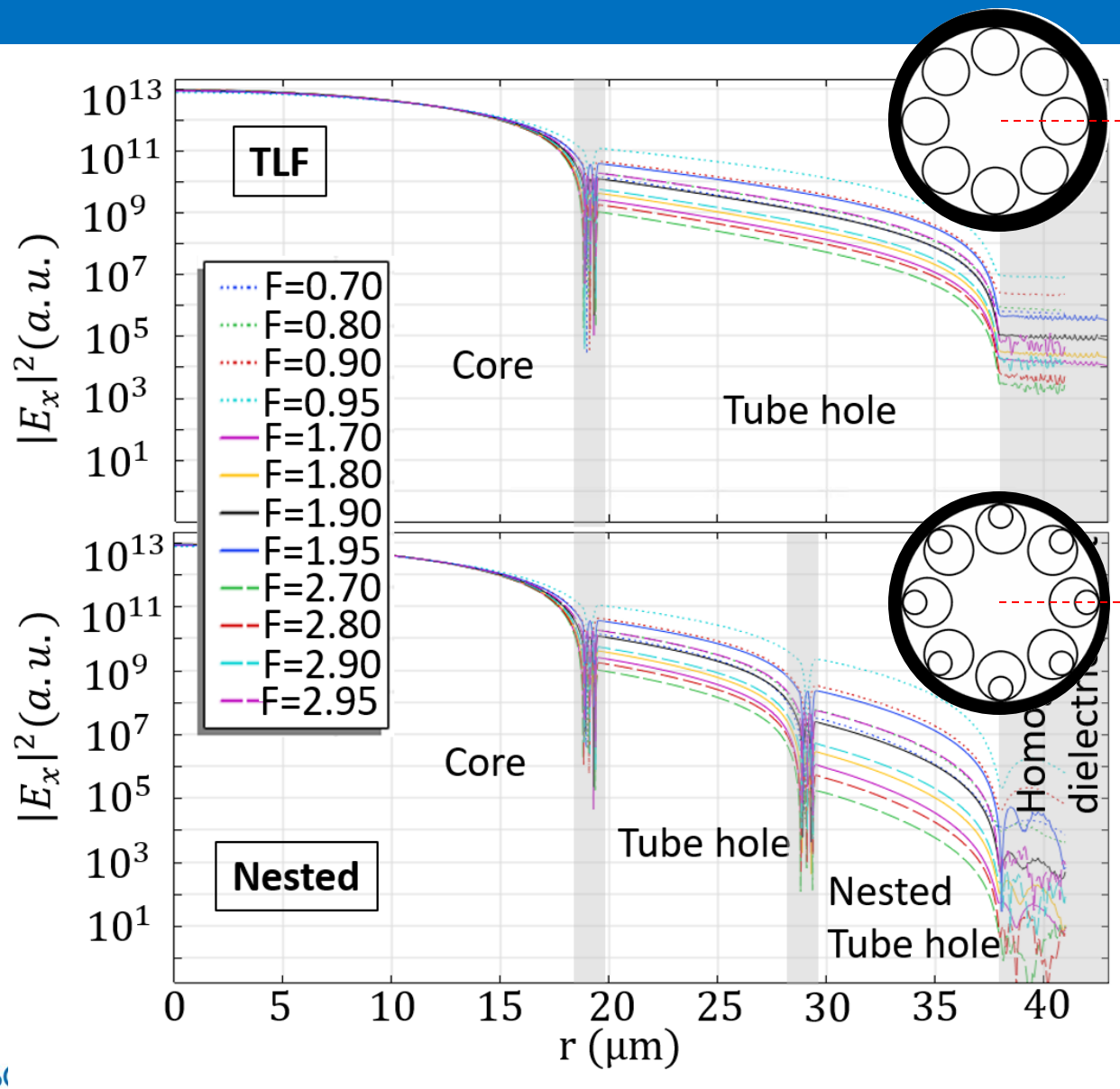
↓

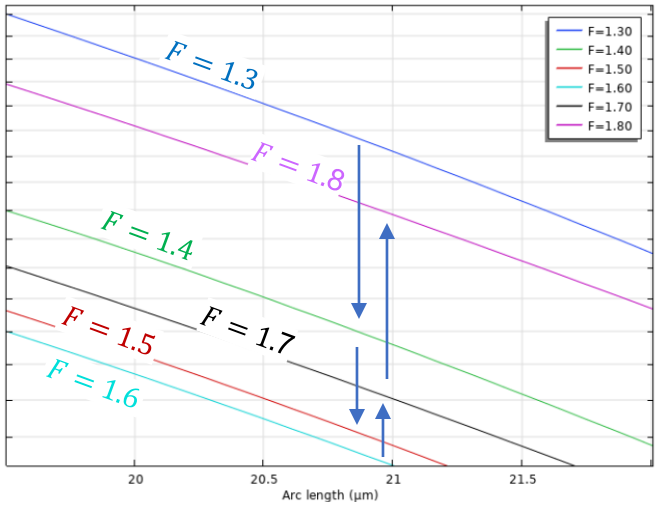
Different leakage into jacket

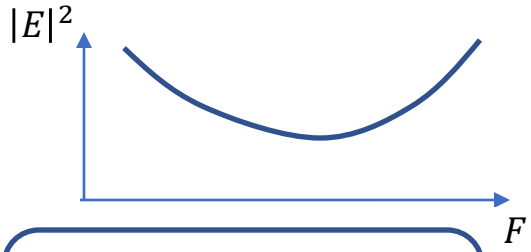
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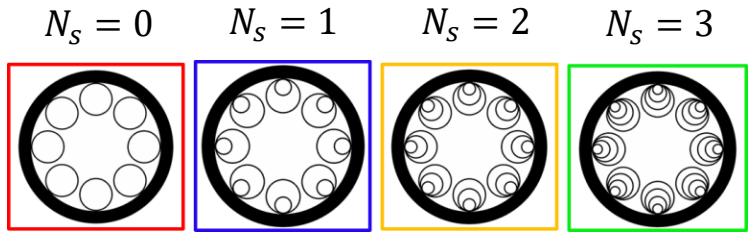




$$|E|^2 \propto \frac{1}{\sin^2(\pi F)}$$

Each tube membrane adds a $\frac{1}{\sin^2(\pi F)}$ factor

$$|E|^2 \propto \frac{1}{[\sin^2(\pi F)]^{1+N_s}}$$

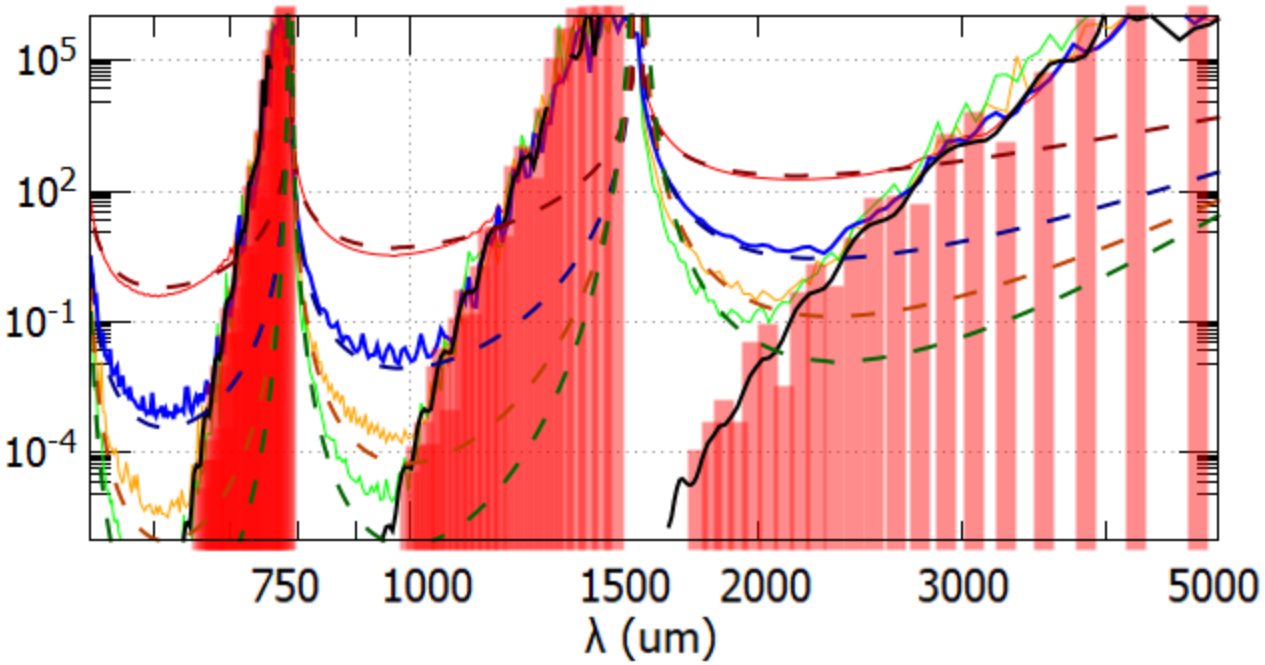


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TTL

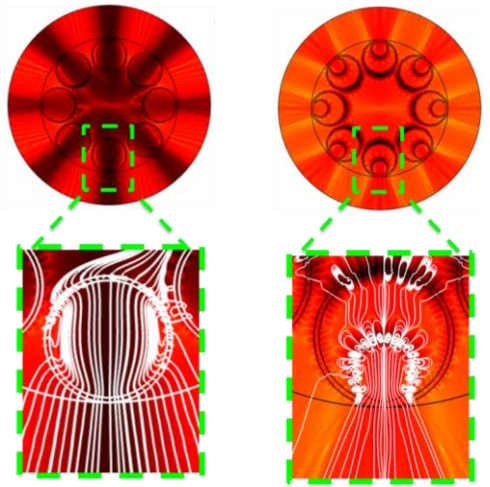
For silica N_s number of nested tubes

$$TTL(\lambda) = H \cdot \frac{\lambda^{4.5+2N_s}}{R_{co}^{4+3N_s}} \left(1 - \frac{t}{r_{ext}}\right)^{-12} \frac{1}{t\sqrt{r_{ext}}} e^{1.8\frac{\lambda}{r_{ext}}} \cdot \left[\frac{\sin(0.6\pi)}{\sin(\pi\lambda/2.1t)}\right]^{2(N_s+1)}$$



F. Melli et al "Disentangling Loss Mechanisms to Bridge Inhibited-Coupling and Anti-Resonant Models in Hollow-Core Fibers," in *J. Lightwave Technol.*, 2026

L. Vincetti «Empirical Formulas for calculating loss in hollow core tube lattice fibers» *Opt. Expr.* 2016



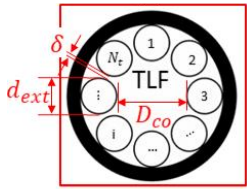
Power leakage mainly through the tubes

It strongly depends on the number of nested tubes

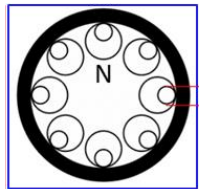
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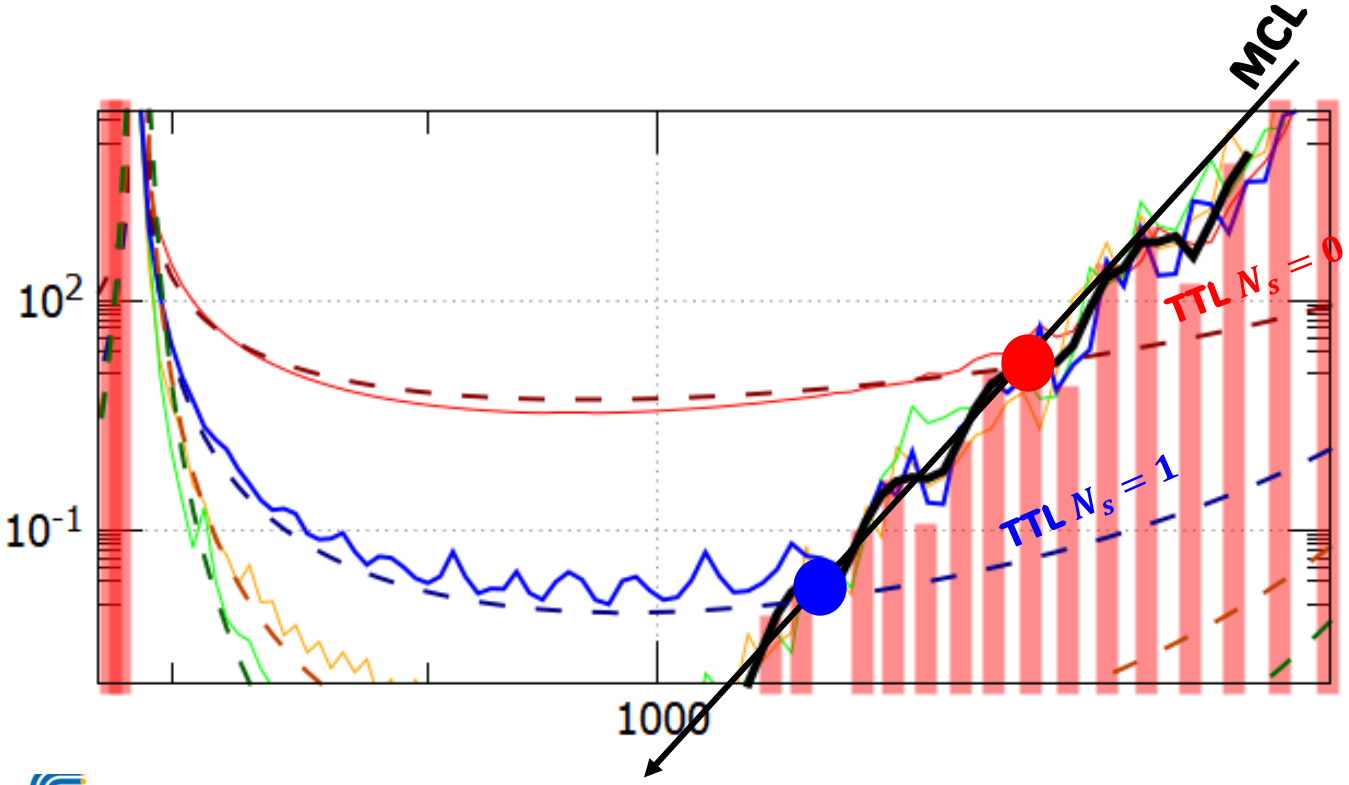
MCL & TTL



$N_s = 0$



$N_s = 1$



1. At long wavelengths MCL dominates
2. MCL does not depend on nested tube number
3. Loss due to MCL quickly reduces with wavelength (Inhibited Coupling)
4. Then the secondary mechanism TTL become no more negligible, and it dominates
5. TTL can greatly reduces increasing the nested tubes
6. MCL is the ultimate limit of loss in inhibited-coupling fibers

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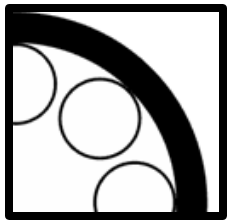
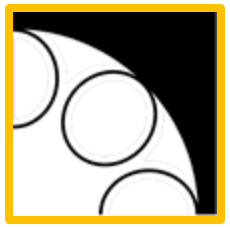
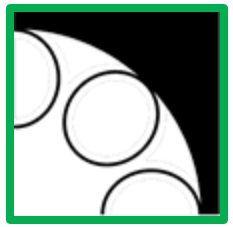
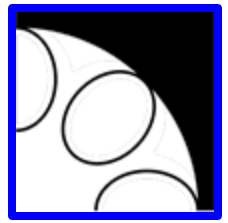
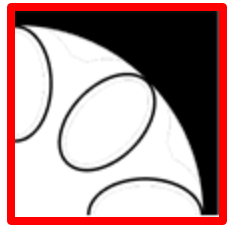
Outline

- **Hollow-Core Fibers (HCFs):** *two families, why Inhibited Coupling leads*
- **The anatomy of Confinement Loss (CL)**
  - ***two mechanisms*** *that connect the* ***IC and antiresonant*** *models*
- **From physics to design**
  - *tube shape effect, and higher-order-mode loss tuning*

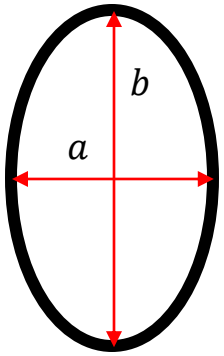
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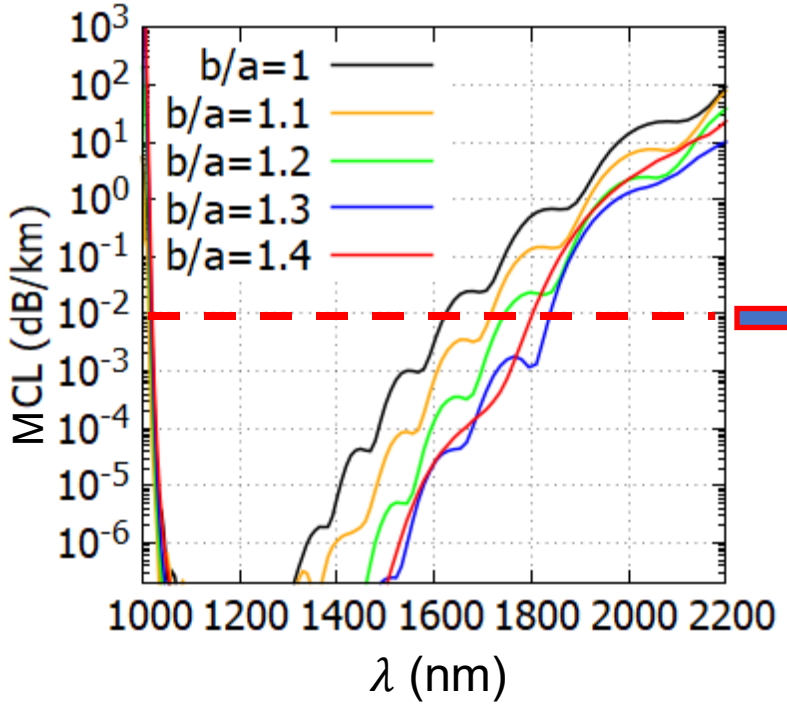
Elliptical tubes for bandwidth enlargement

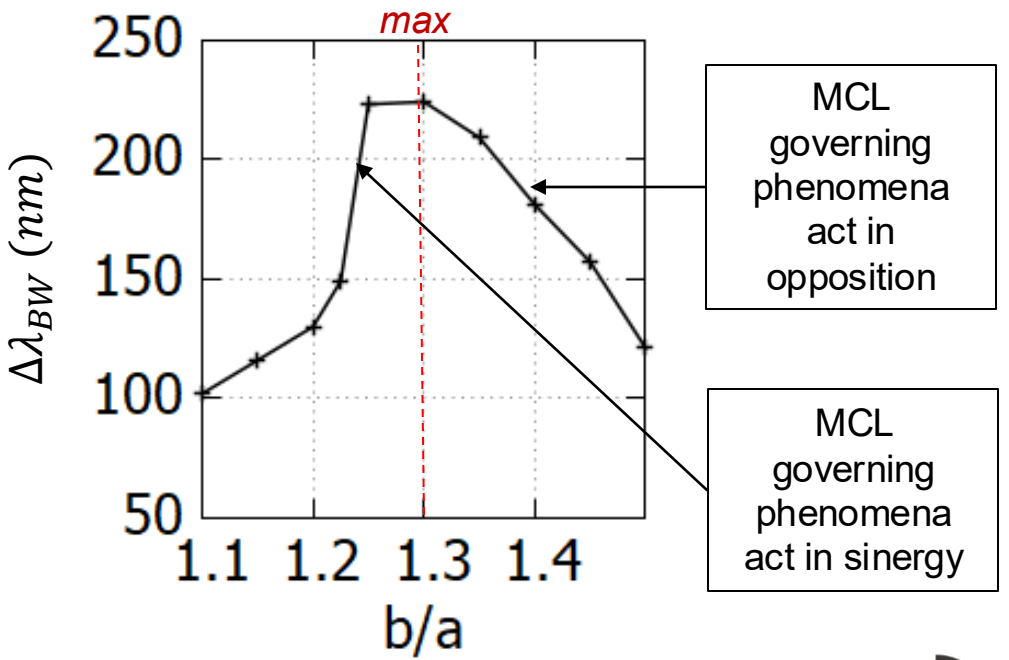
$\frac{b}{a} = 1$  $\frac{b}{a} = 1.1$  $\frac{b}{a} = 1.2$  $\frac{b}{a} = 1.3$  $\frac{b}{a} = 1.4$ 

Elliptical tube



$a = d_{tube}$



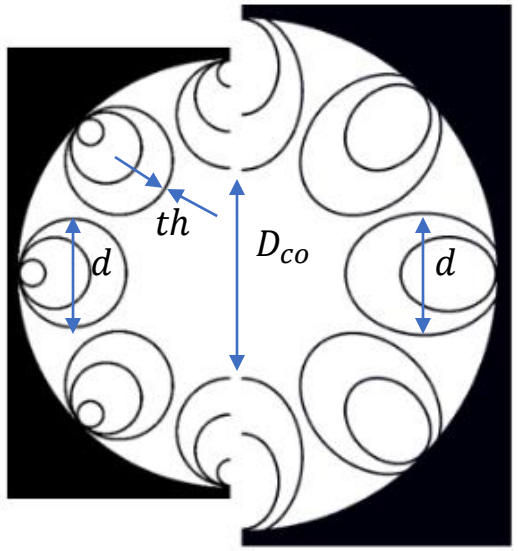


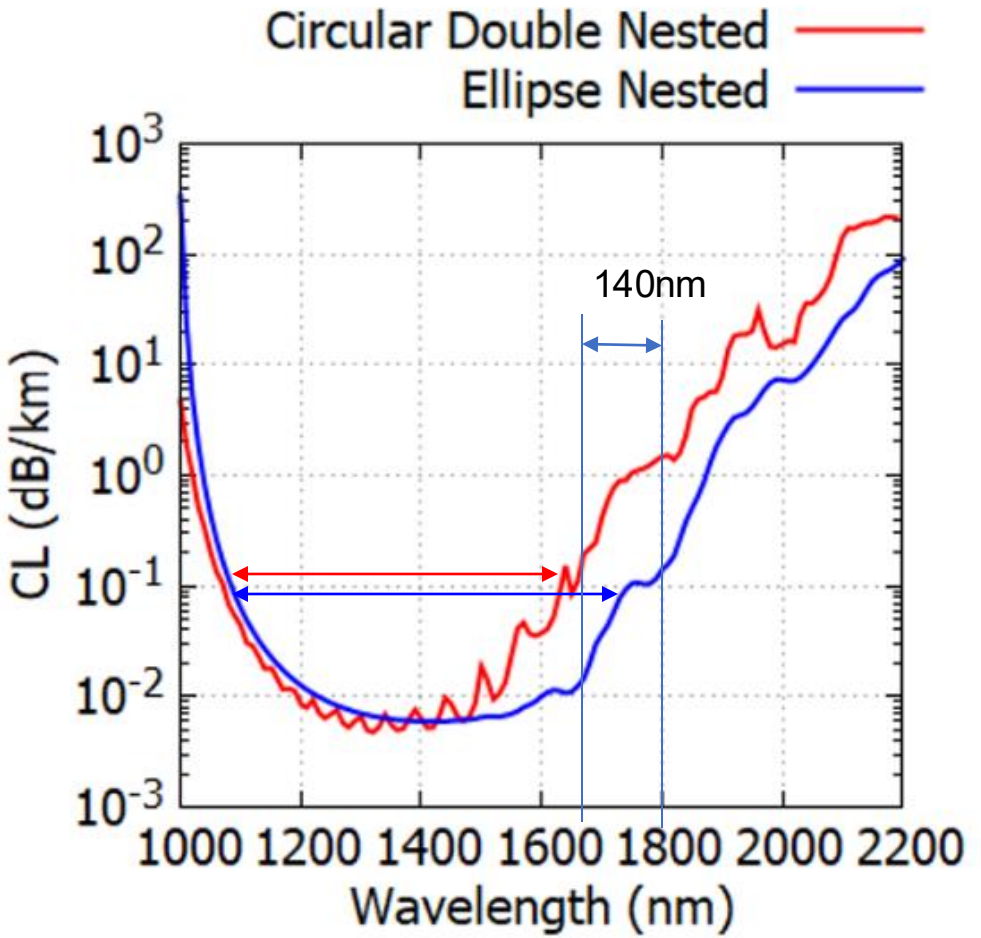
Elliptical Tubes for Bandwidth Enlargement

D_{co} = 36 μm
d = 20 μm
th = 0.455 μm

Different number of nested tubes to obtain the same minimum loss

(b)

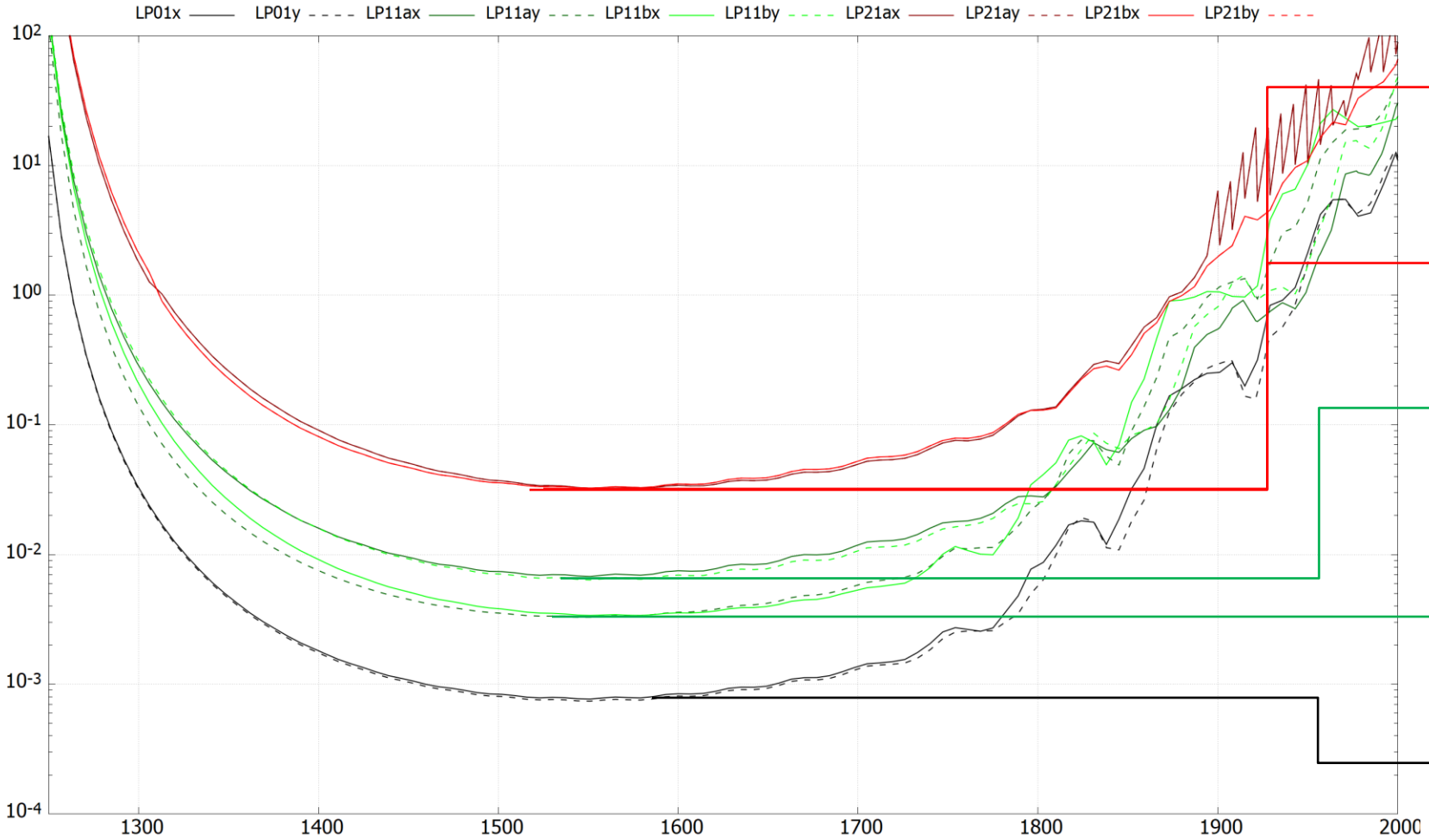


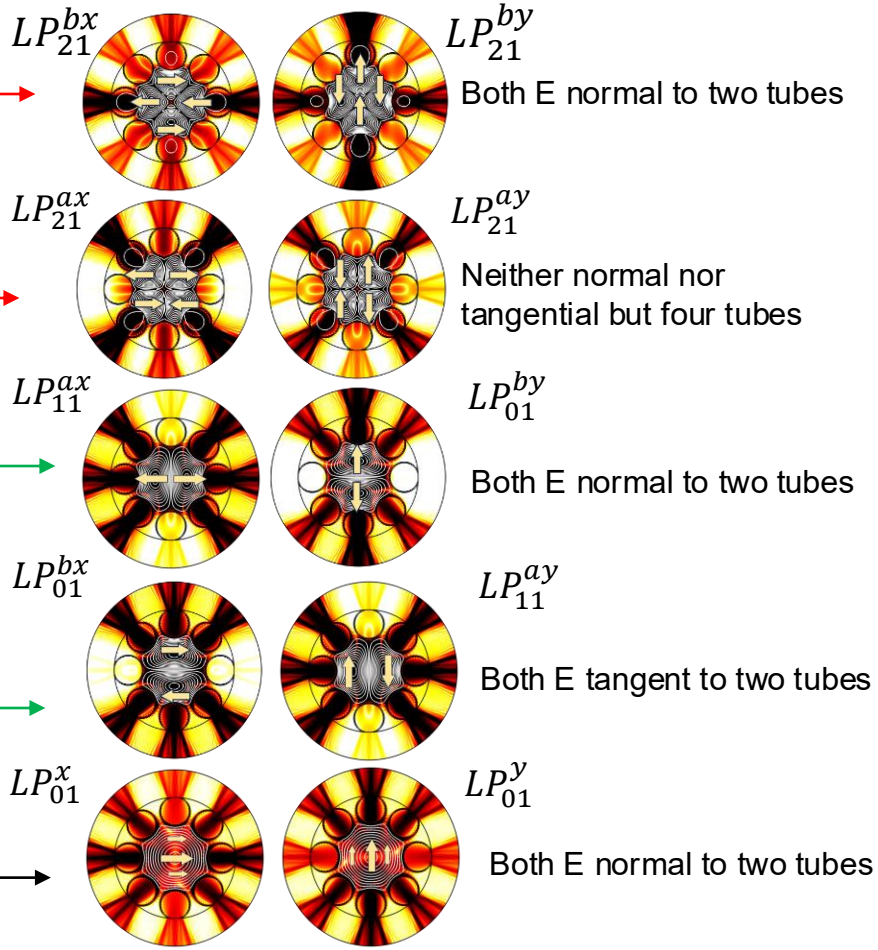


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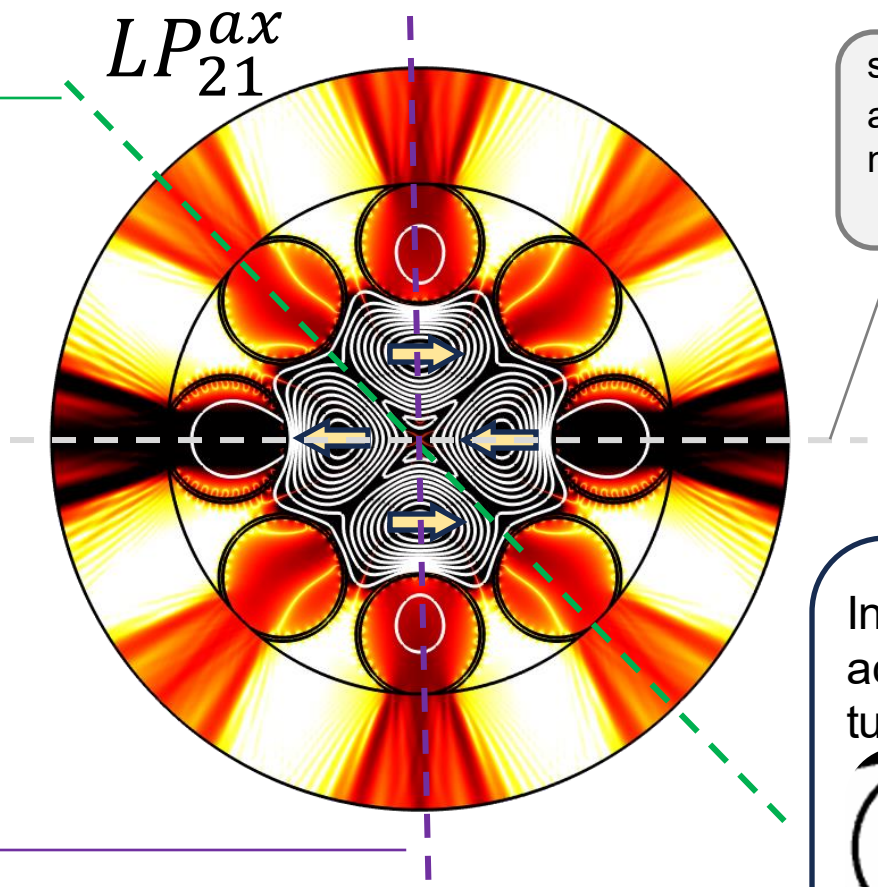
Mode loss hierarchy





From limitation to lever

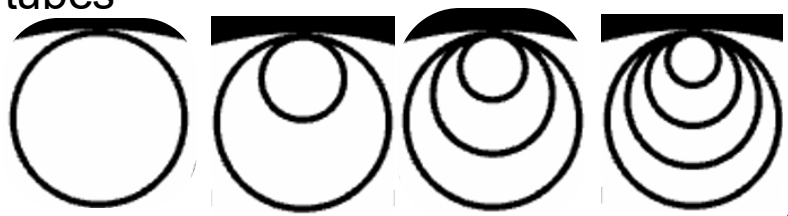
Extremely weak dependence on tube features along zero directions



strong dependence on tube features along maxima directions with $\overline{E}_t$ normal

moderate dependence on tube features along maxima directions with $\overline{E}_t$ tangent

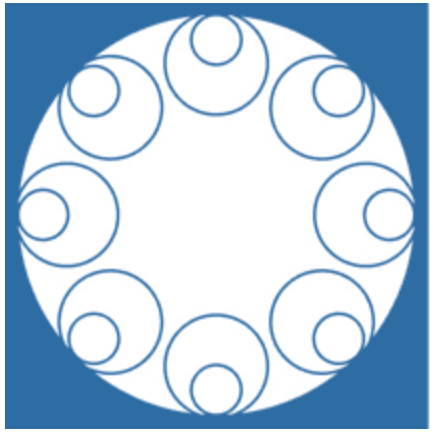
In each tube TTL_i can be tuned by acting on number and size of nested tubes

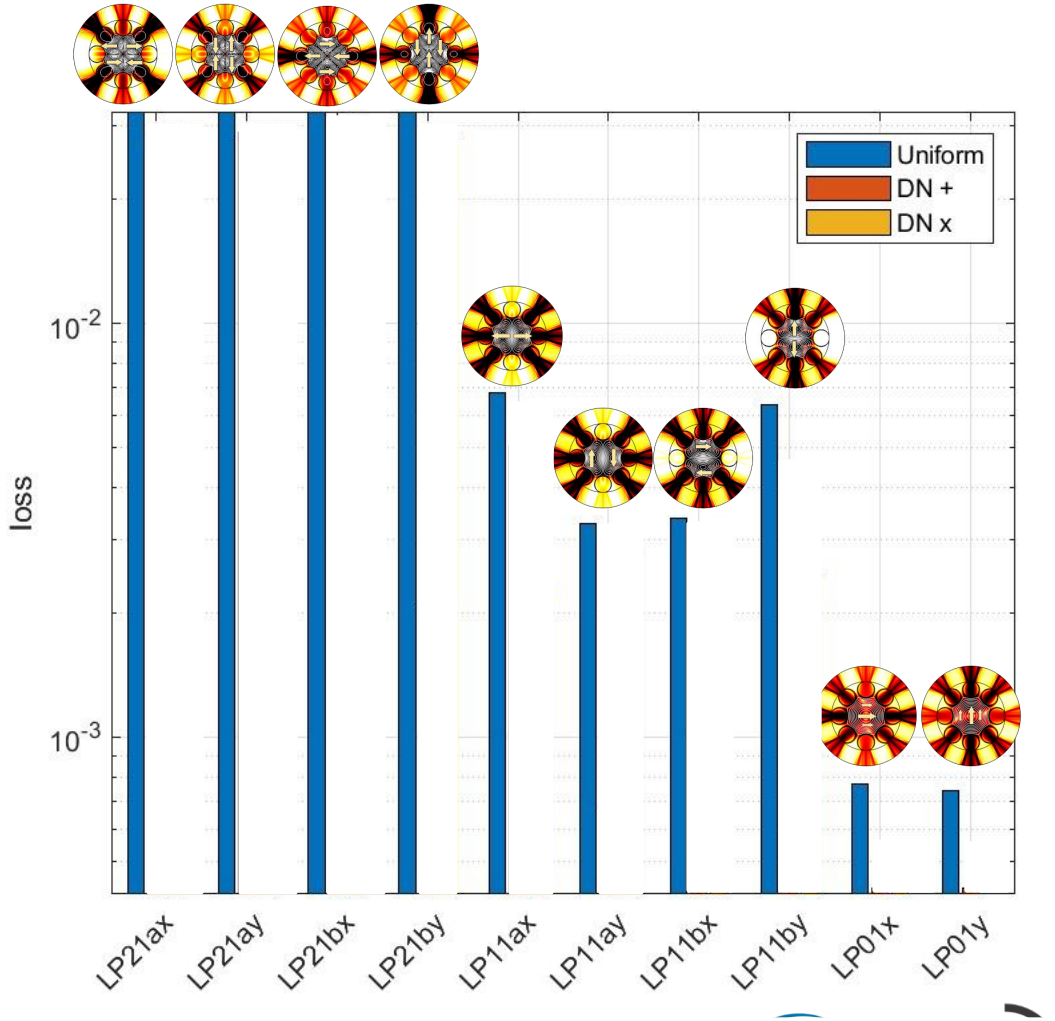


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From limitation to lever: example

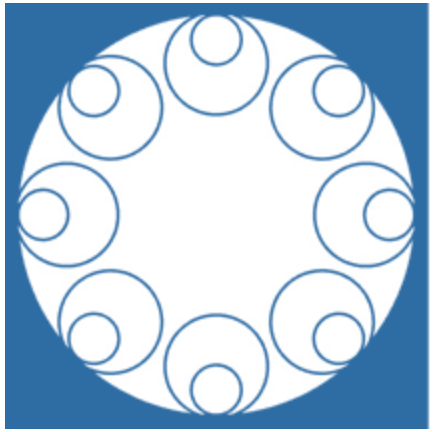
SN Uniform



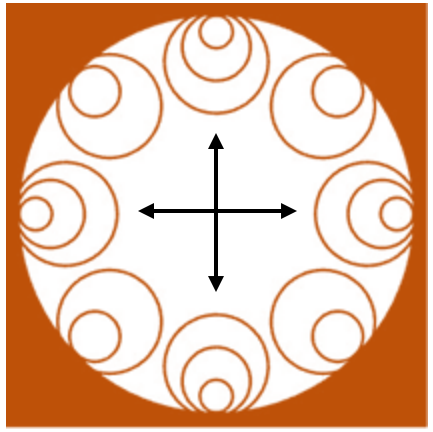


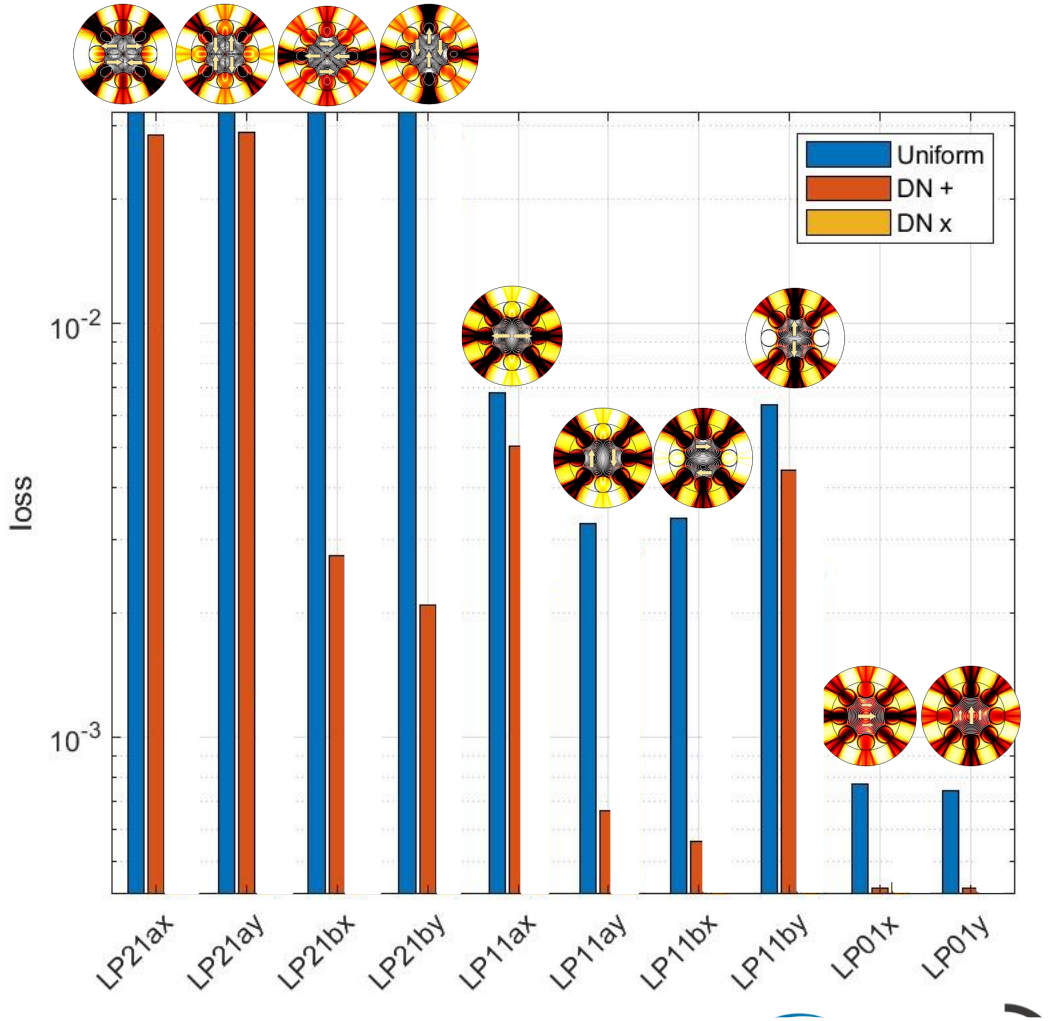
From limitation to lever: example

SN Uniform



SN – DN +



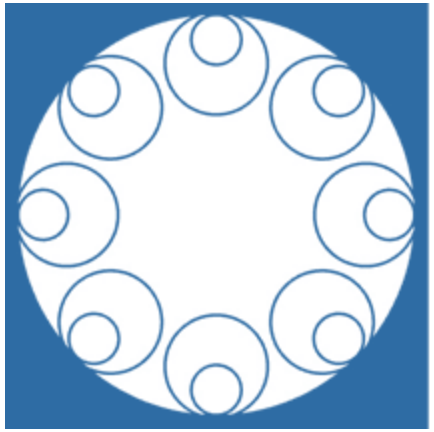


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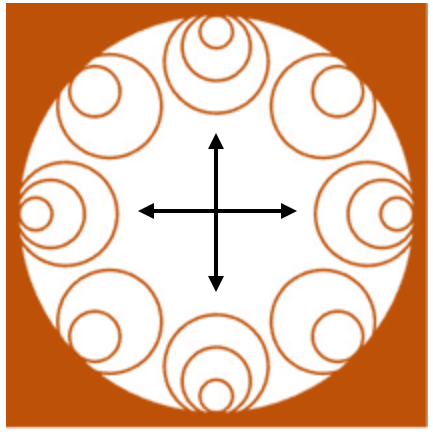
Lab

From limitation to lever: example

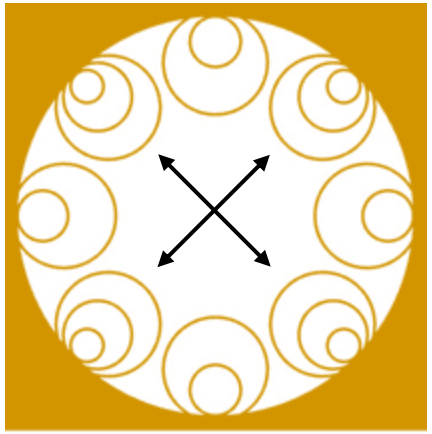
SN Uniform

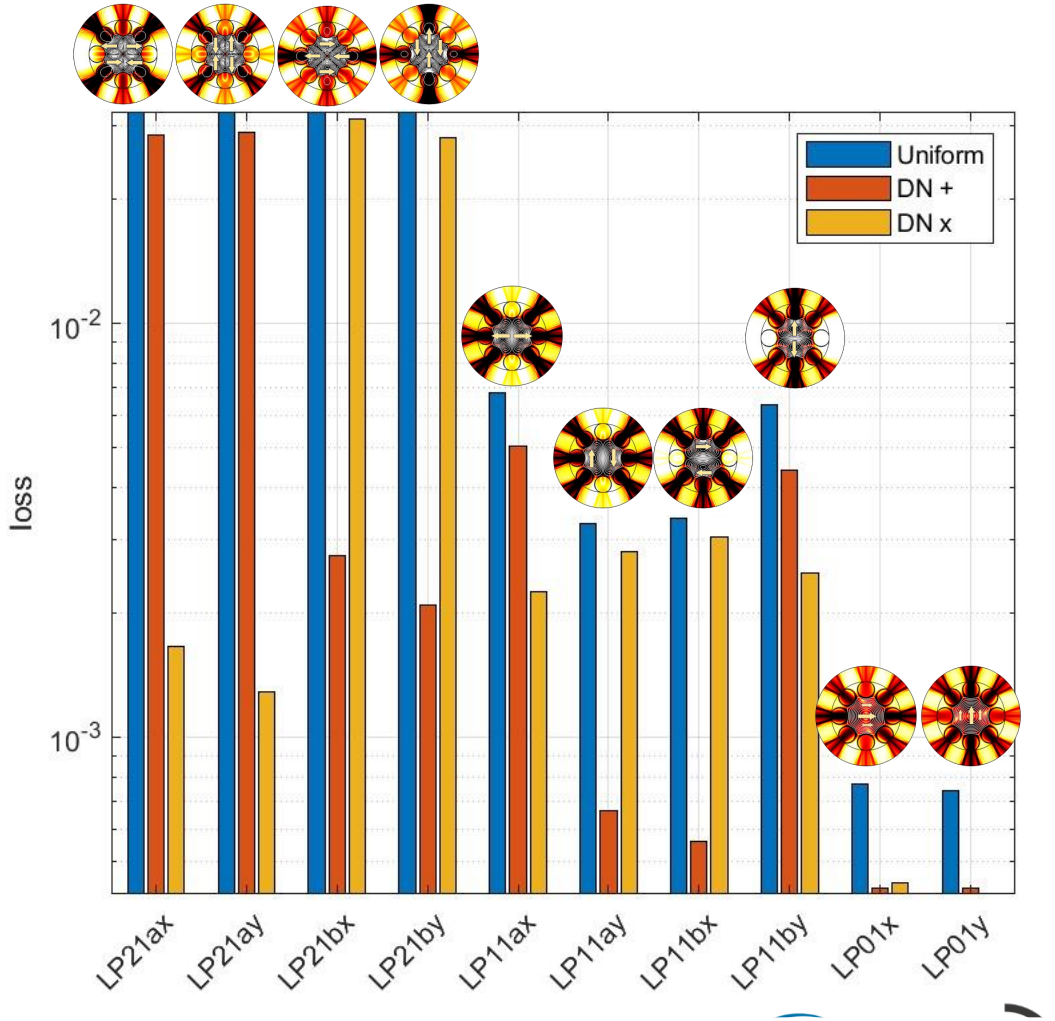


SN – DN +



SN – DN X

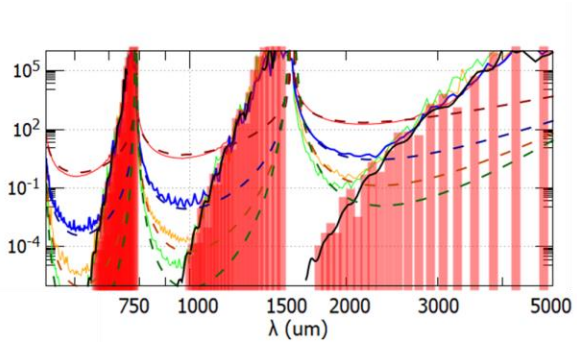




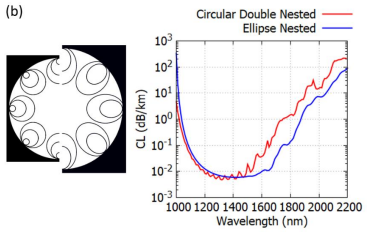
Conclusions

- CL decomposed into elementary contributions:
  - Mode Coupling Loss
  - Tube Tunneling Loss

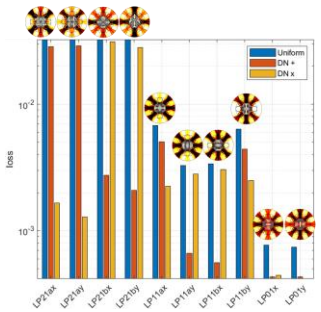




- Tube shape affects MCL allowing bandwidth enlargement



- The dependence of TTL on polarization and mode type can be exploited to control the mode-loss hierarchy in multimode hollow-core fibers



Ongoing work

- Study tube shapes different from ellipse
- Optimize cladding design for Mode Loss Equalization

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Thanks for the attention!





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