A glimpse of optical fiber modes with COMSOL Multiphysics

Course of Photonics Devices
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DIPARTIMENTO DI INGEGNERIA DELL' INFORMAZIONE

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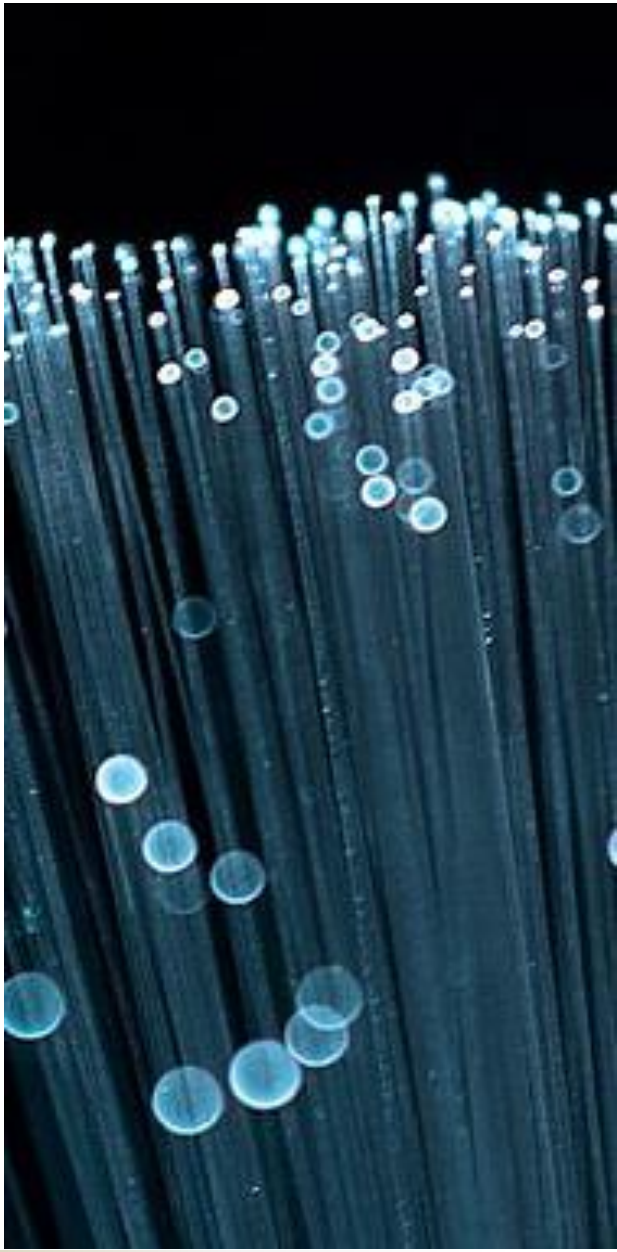
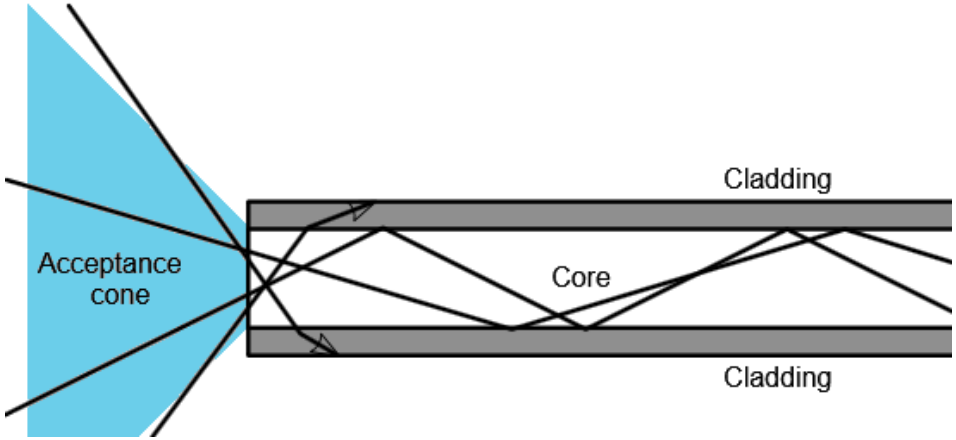


Propagation in a step-index fiber

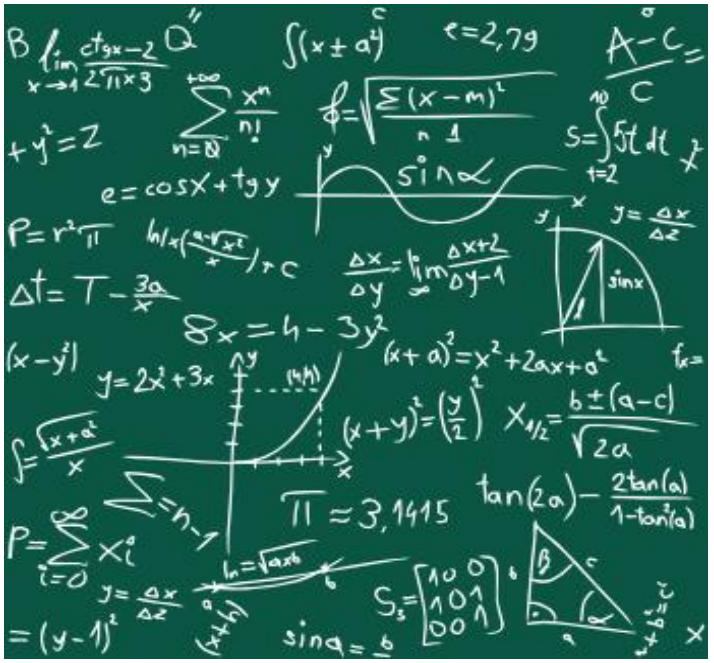
[A little warm-up…]



- Total internal reflection
- Acceptance angle θ_a
- Allowed rays: **modes**
- Attenuation, dispersion…

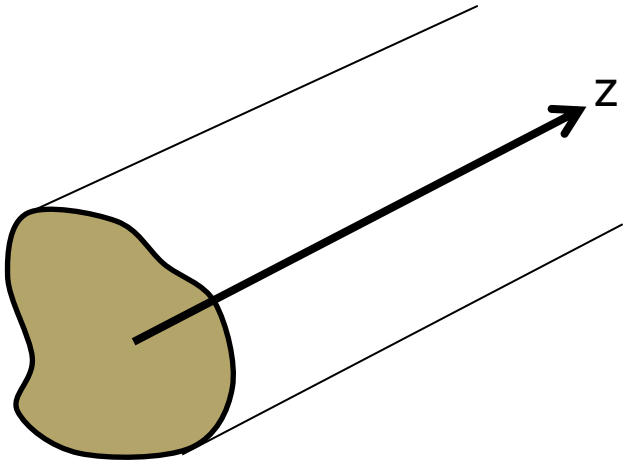
Simplified model!

- Formal description: **Maxwell's equations**, boundary conditions…
- **Guided modes**: solution of Maxwell's equations with certain properties (like being *guided*…)



Modal analysis

- **Straight waveguides** (metallic or dielectric) are solved with Hp of **cylindrical structure**



Cylindrical structure:

invariant along one axis (*z*)

Solutions:

$$\bar{e}(x,y,z) = \bar{E}(x,y)\cdot e^{-\beta(\omega)z}$$

$$\bar{h}(x,y,z) = \bar{H}(x,y)\cdot e^{-\beta(\omega)z}$$

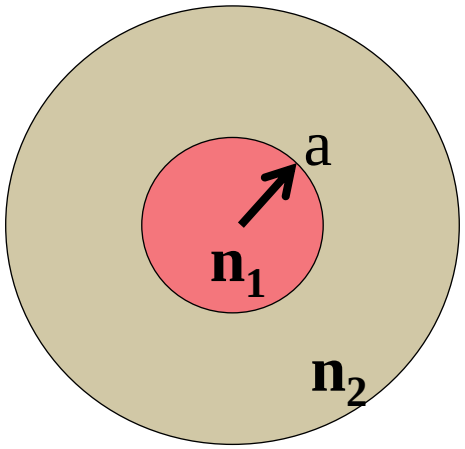
Propagation

Electric and magnetic field vectors

Distribution on transverse plane

Modes of a step-index fiber

- Optical fibers supports a **discrete set** of guided modes
- The number of guided modes at a given wavelength is determined by the core radius and by the index contrast between core and cladding



- Norm. frequency (V-number):

$$V = \frac{2\pi}{\lambda} a \sqrt{n_1^2 - n_2^2}$$

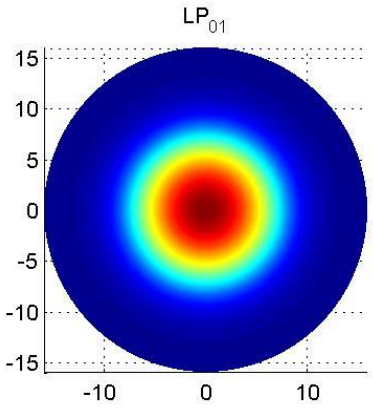
- Modes are guided at $V > V_c$, i.e. $\lambda < \lambda_c$
- λ_c is the **cut-off wavelength** of the mode

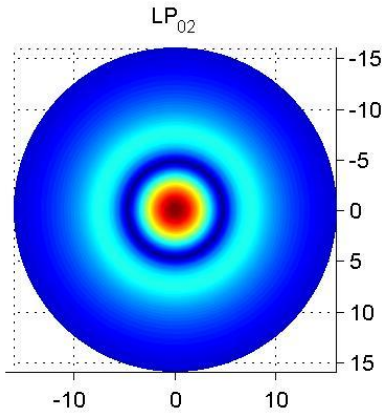
- V_c e λ_c can be calculated analytically in **step-index fibers**

Field distribution

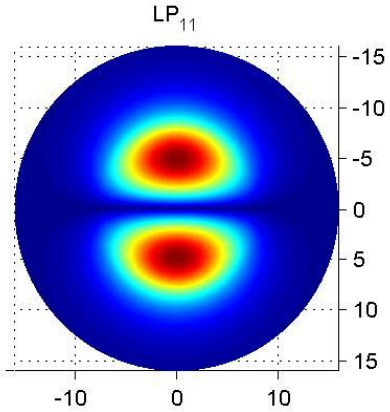
Intensity

Fundamental mode
$V_c = 0$

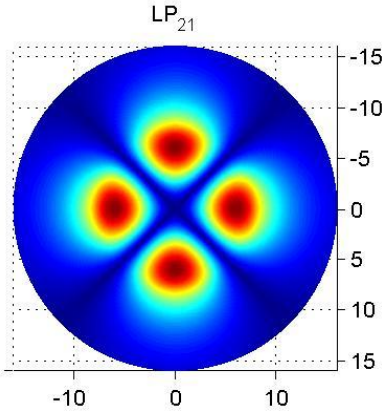




$V_c = 3.832$



$V_c = 2.405$



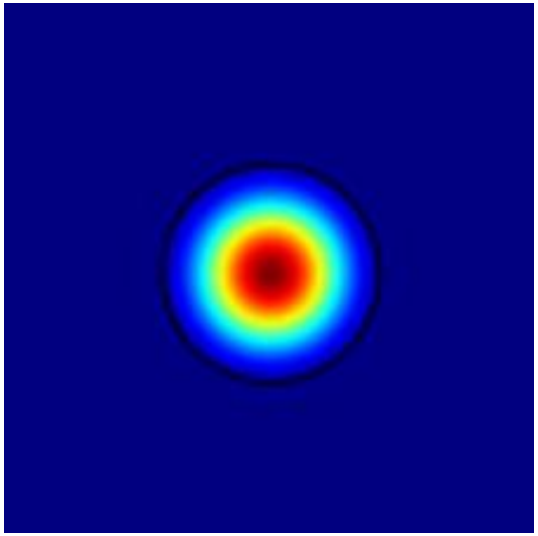
$V_c = 3.832$

$$n_{eff} = \frac{\beta}{k_0}$$

$$k_0 = \frac{2\pi}{\lambda}$$

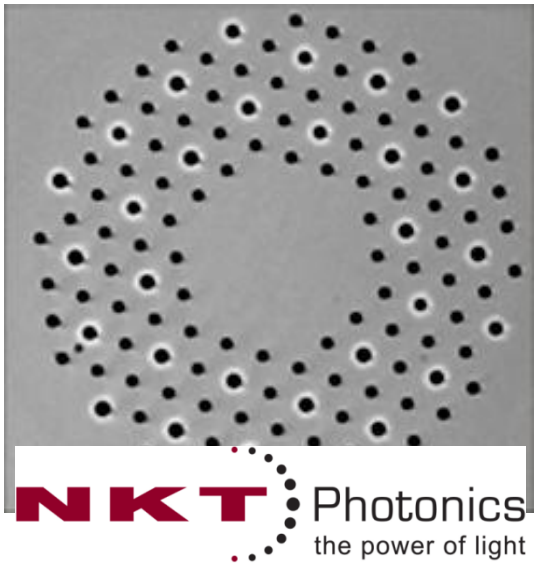
How to find the modes?

- **Solution of Maxwell's eqns. in the waveguide**
  - **PDE: Partial Differential Equation** problem
  - Analytic solution exists only for "simple" structures (i.e.: azimuthally-invariant…)

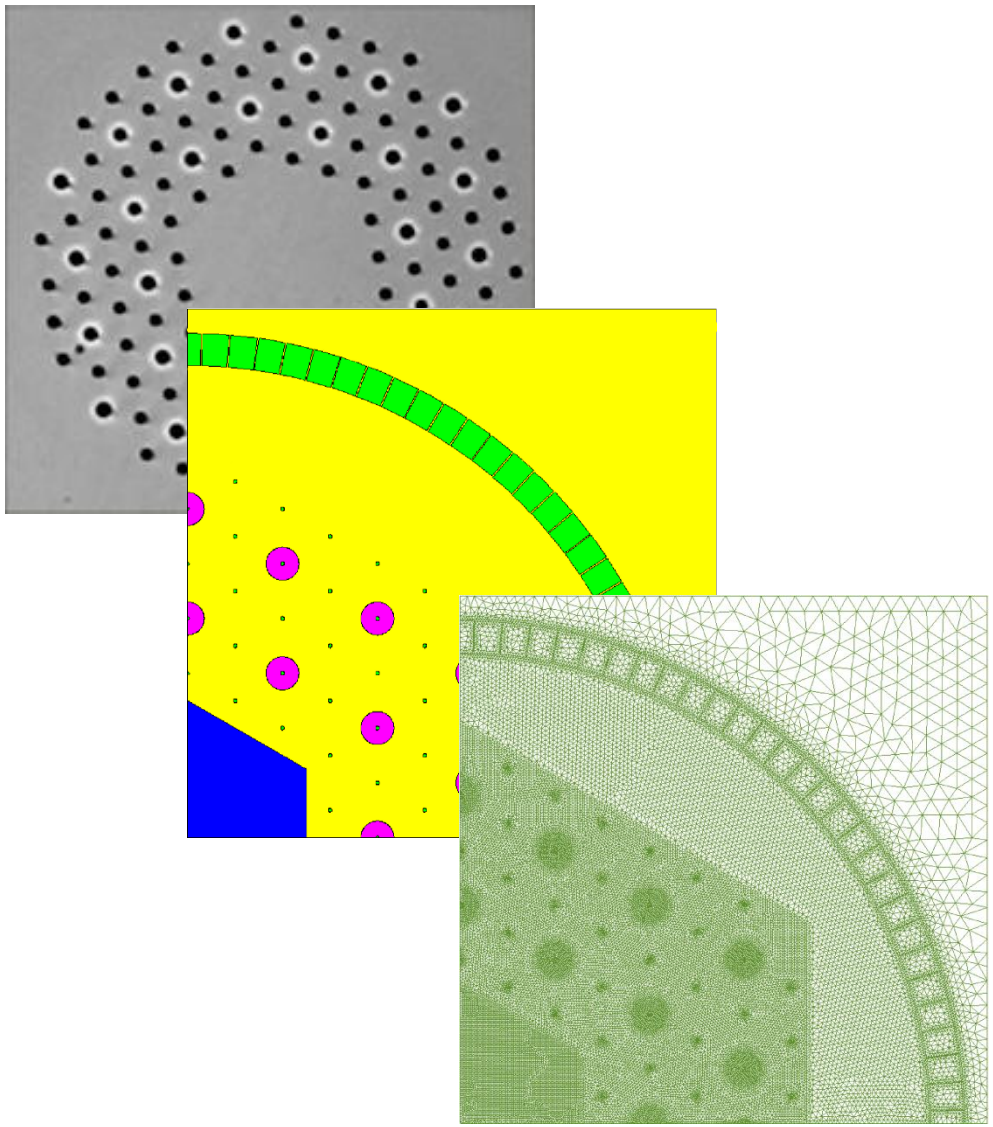


- **And otherwise??**
  - Approximate solutions
  - Numerical methods

Finite-Element Method (FEM)



Finite-element method



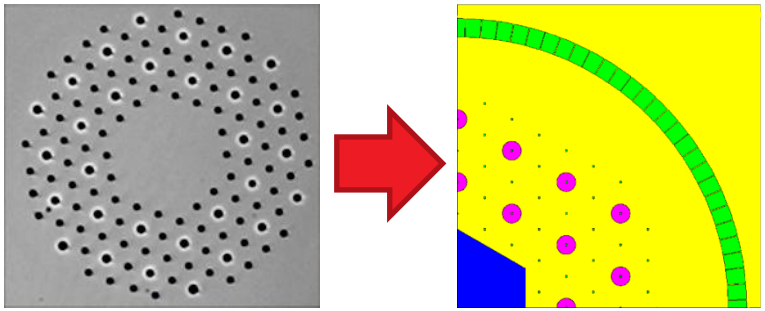
Based on discretization of the domain into a set of small elements (mesh)

PDE is simplified into a system of linear equations

General and stable mehod

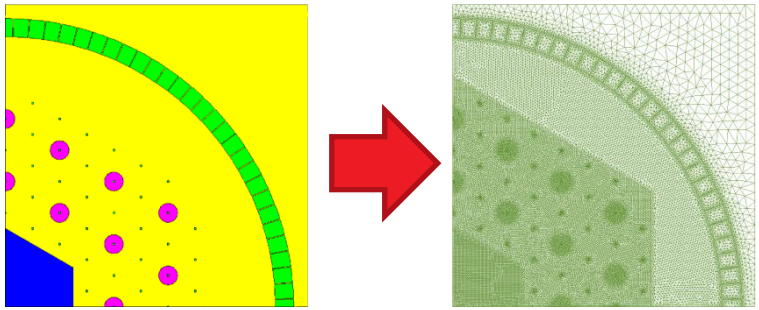
Precision of the solution determined by the quality of the mesh

Modal analysis with FEM solver



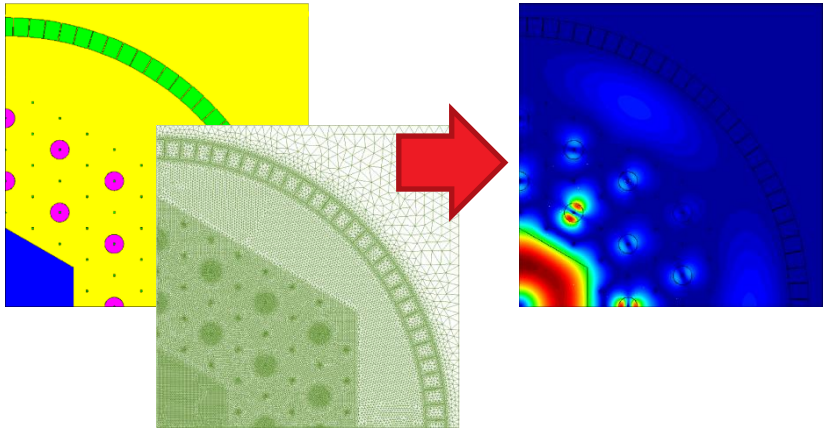
MODELING

definition of physical and geometric properties



DISCRETIZATION

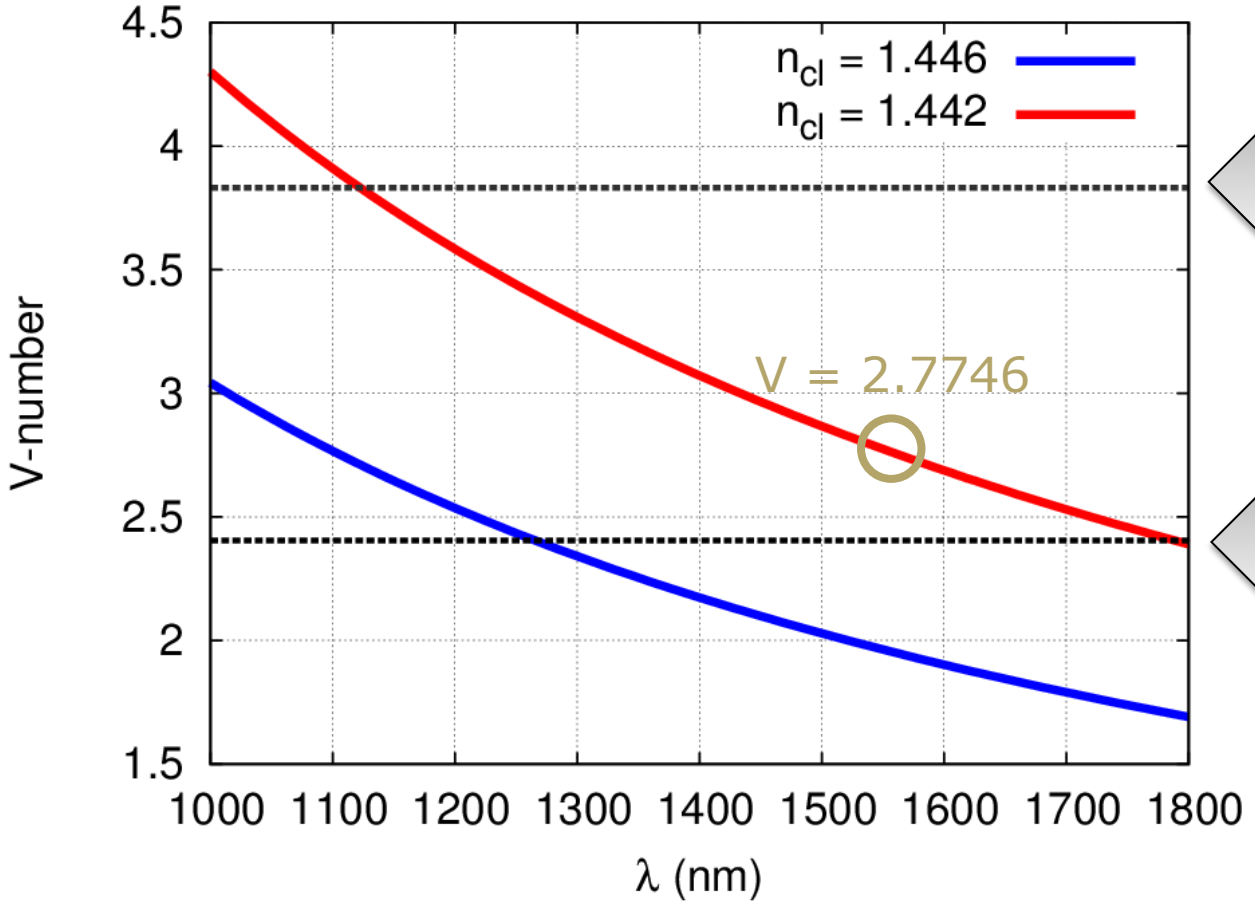
mesh creation



SOLUTION AND POST-PROCESSING


HANDS ON!

V-number

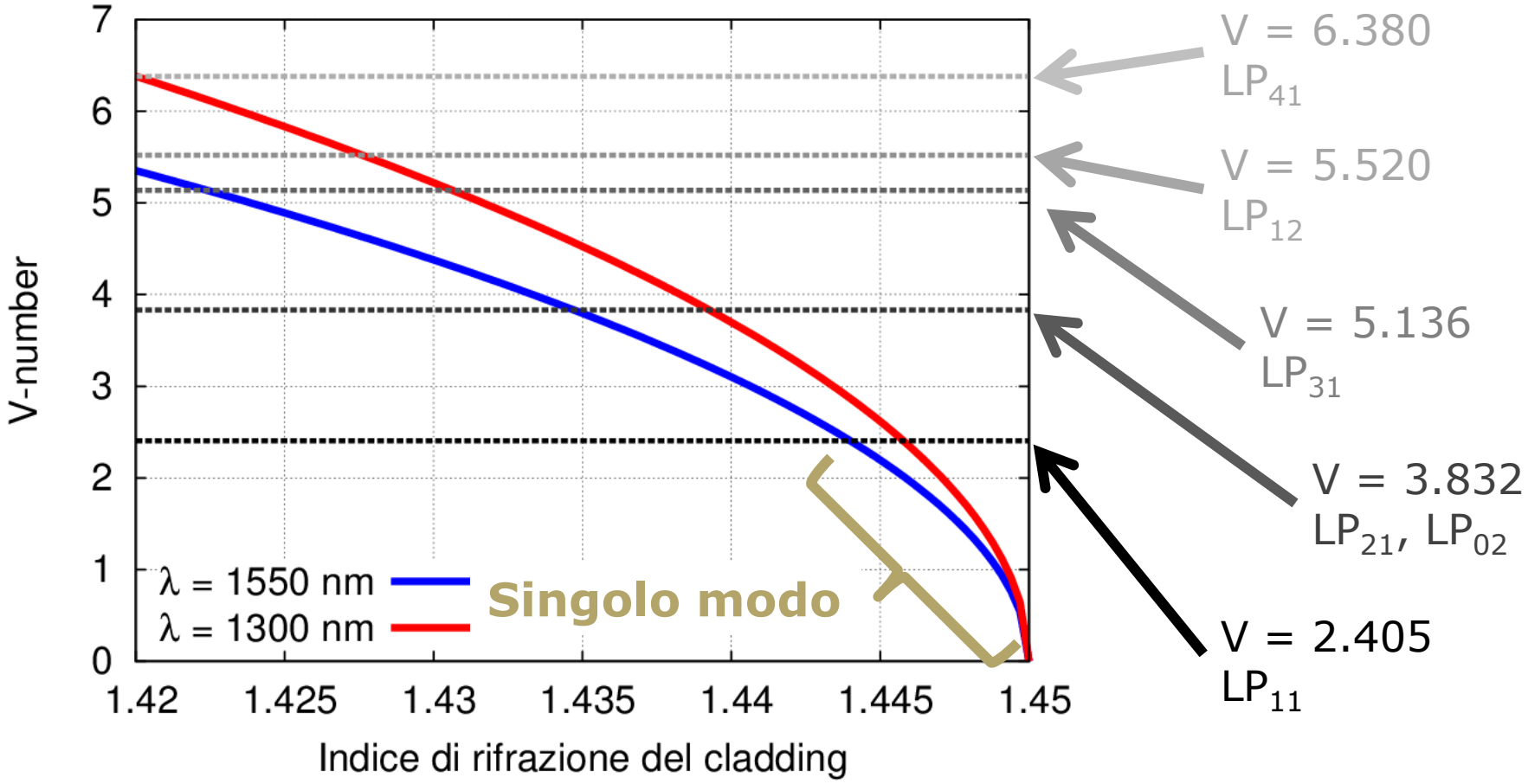


V = 3.832
HE_{12}, EH_{11}, HE_{31}

V = 2.405
TE_{01}, TM_{01}, HE_{21} (2x)

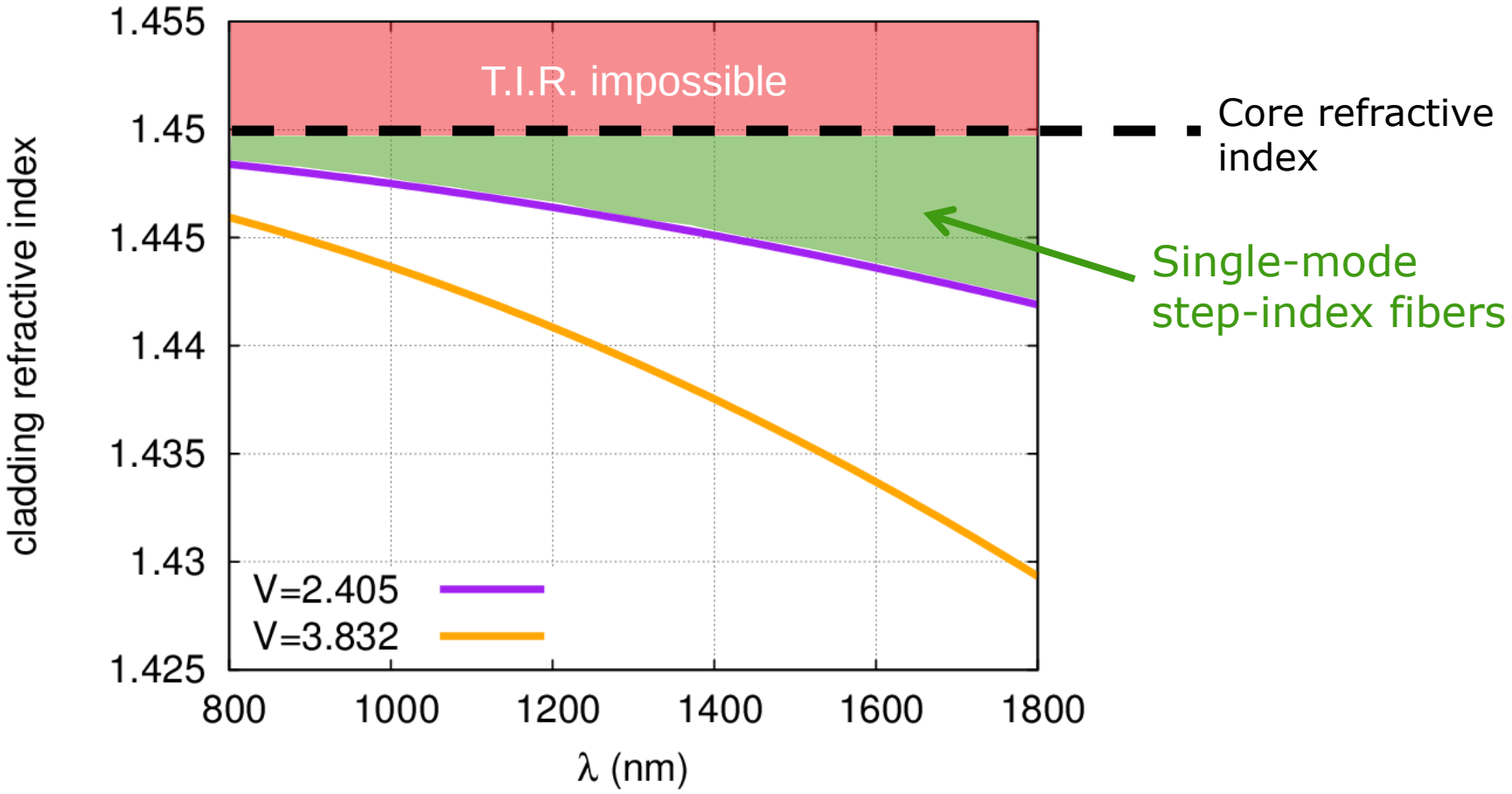
$n_{co} = 1.45$

V-number vs n_{cl}



$n_{co} = 1.45$

Guided-mode cut-off



n_{co} = 1.45
a = 4.5 μm