Light propagation in Photonic Crystal Fibers infiltrated with Nematic Liquid Crystals

Tomasz R. Wolinski, K. A. Brzdakiewicz, P. Lesiak, S. Ertman, A. Czapla, K. Nowecka, and A. W. Domanski

Faculty of Physics, Warsaw University of Technology, Warszawa, Poland

FoPOD FACULTY OF PHYSICS OPTICS DIVISION

Collaboration
(since ‘95):

Faculty of Physics, WUT

HDr. A. Domański, assoc. prof.

HDr. M. Karpierz, prof.

Dr. T. Nasiłowski (VUB)

Dr. A. Szymańska (EWUT)

Dr. P. Lesiak

Dr. M. Sierakowski

Dr. K. Brzdąkiewicz

K. Szaniawska, PhD student

S. Ertman, PhD student

A. Czapla, MSc

K. Nowecka, MSc

& Co-workers

Institute of Chemistry MTU

Prof. Roman Dąbrowski

& Co-workers

Institute of Physics MTU

Dr. E. Nowinowski-Kruszelnicki

& Co-workers

UMCS Lublin

Dr. Jan Wójcik

& Co-workers

Faculty of Mechatronis WUT:

Prof. M. Kujawińska

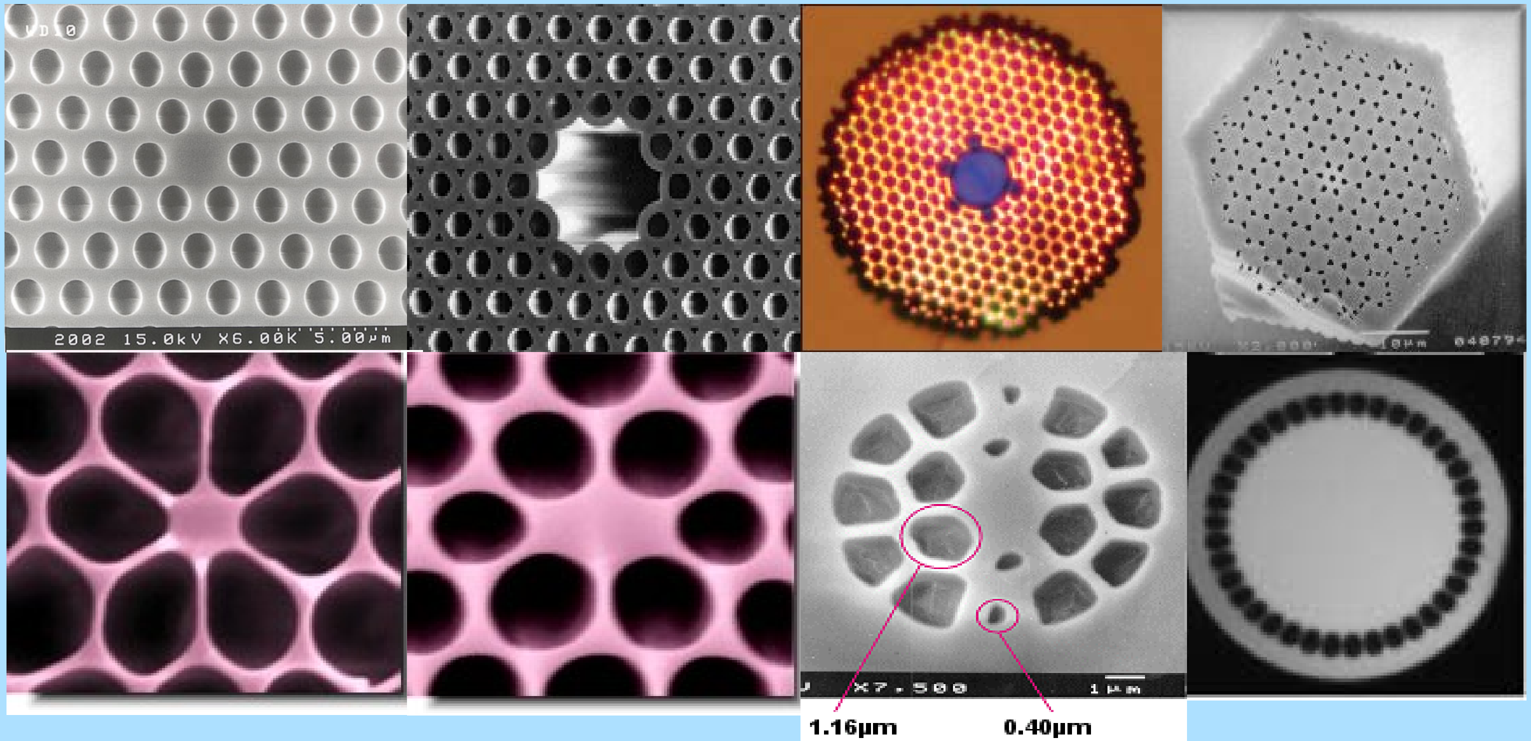
& Co-workers

Outline

- Motivation: PCF and LC
- Polarization phenomena in HB PMFs
- Highly birefringent PLCFs
- Theoretical analyses
- Experimental verification
- Research trends

Photonic Crystal Fibers

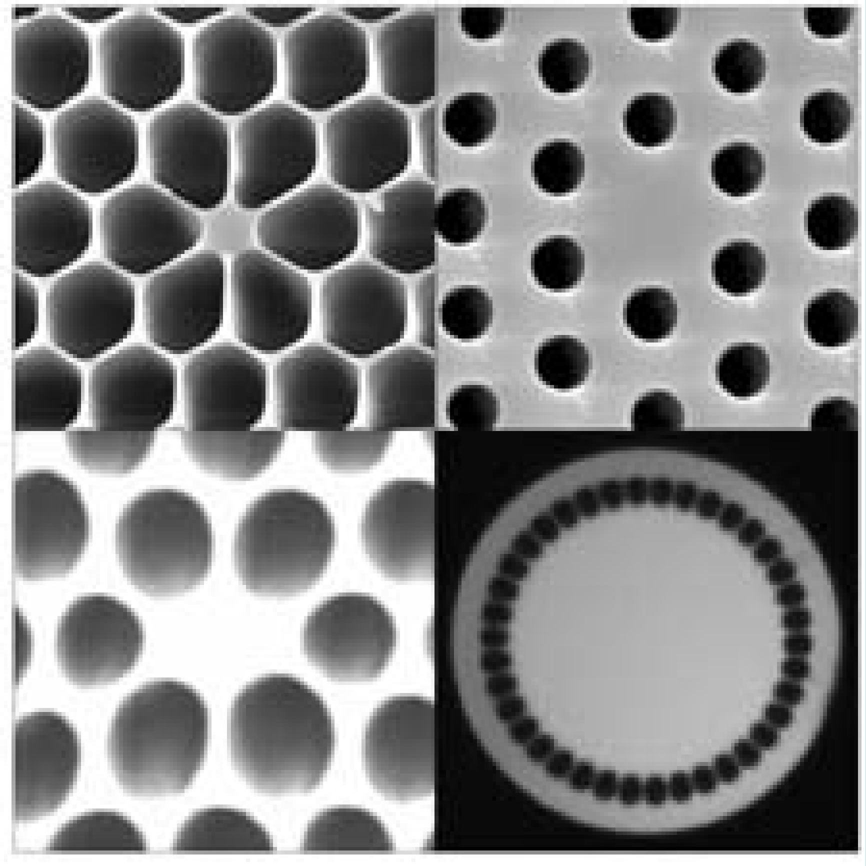
- a cladding made of a Photonic Crystal
- a core created by a defect in the PC structure



Solid-core Photonic Crystal Fibers

highly nonlinear

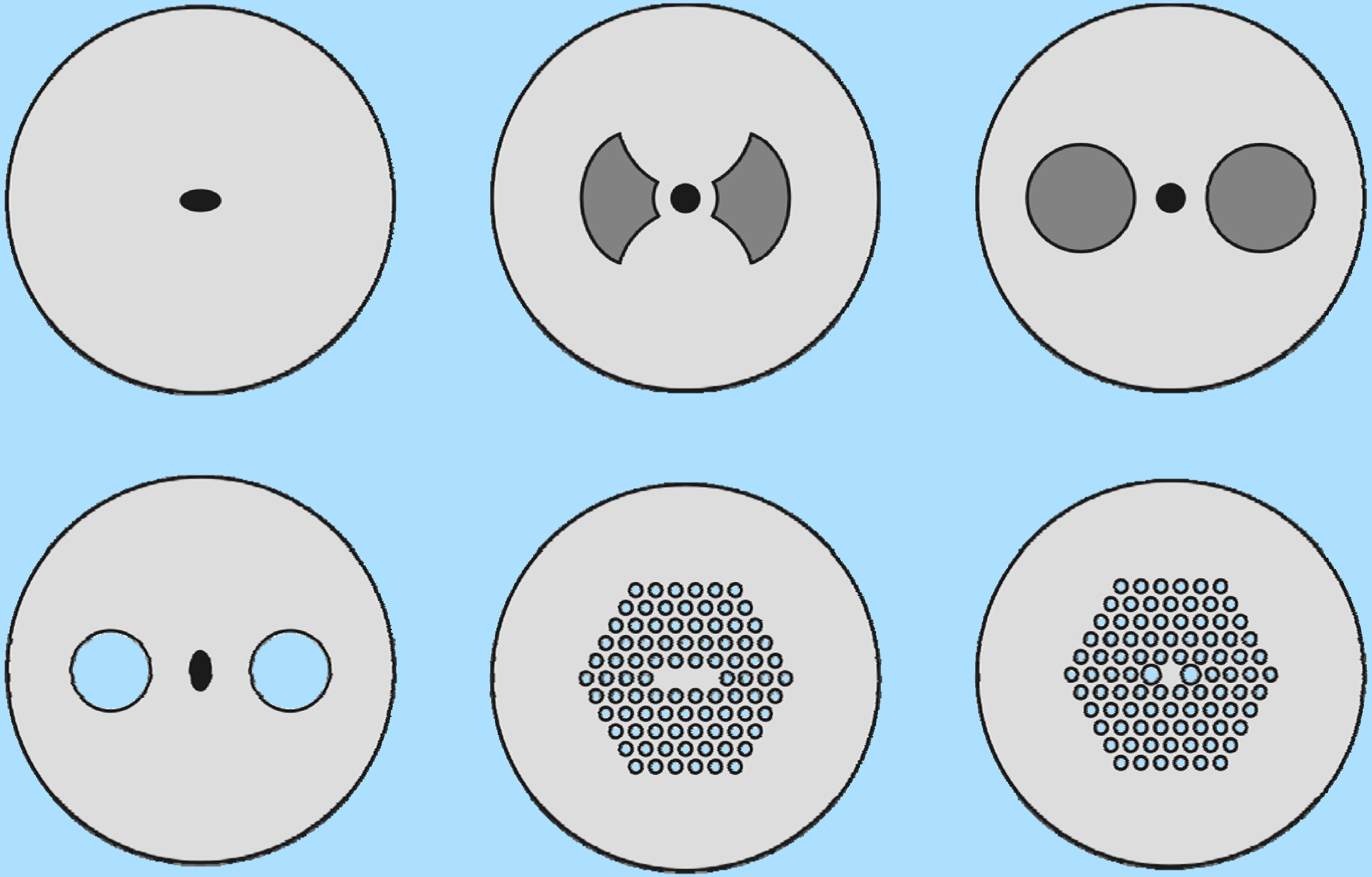
endlessly single-mode



polarization maintaining

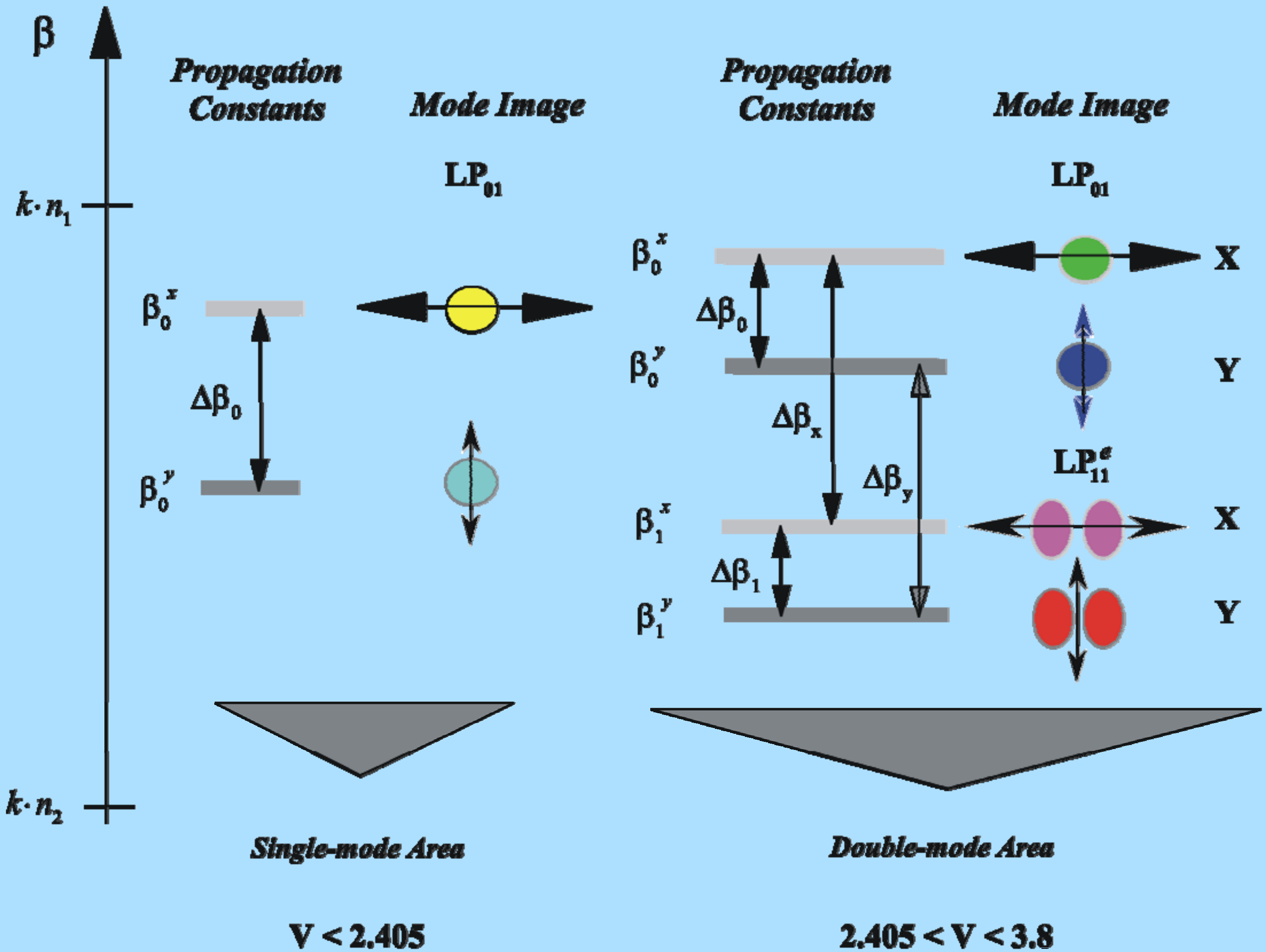
with high numerical aperture

Background: HB fibers



T. R. Woliński, *Progress in Optics* ed. E. Wolf, vol XL, pp. 1-75 (2000)

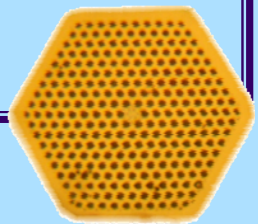
Lowest-order HB fibers



Photonic Liquid Crystal Fiber (PLCF)

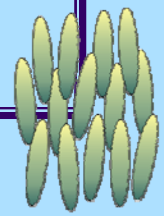
Photonic Crystal Fibers

- Advantages of both **mTIR** and **PBG** phenomena
- Variety of PCF structures (birefringence, SM, nonlinearity, etc.)



Liquid Crystals

- Thermal, external ac & dc fields, optical field sensitivity
- Variety of LC materials and LC structures; influence of molecular ordering



Tha highest level of tunability of propagation and polariation properties by external fields

Highly birefringent PCF + LC

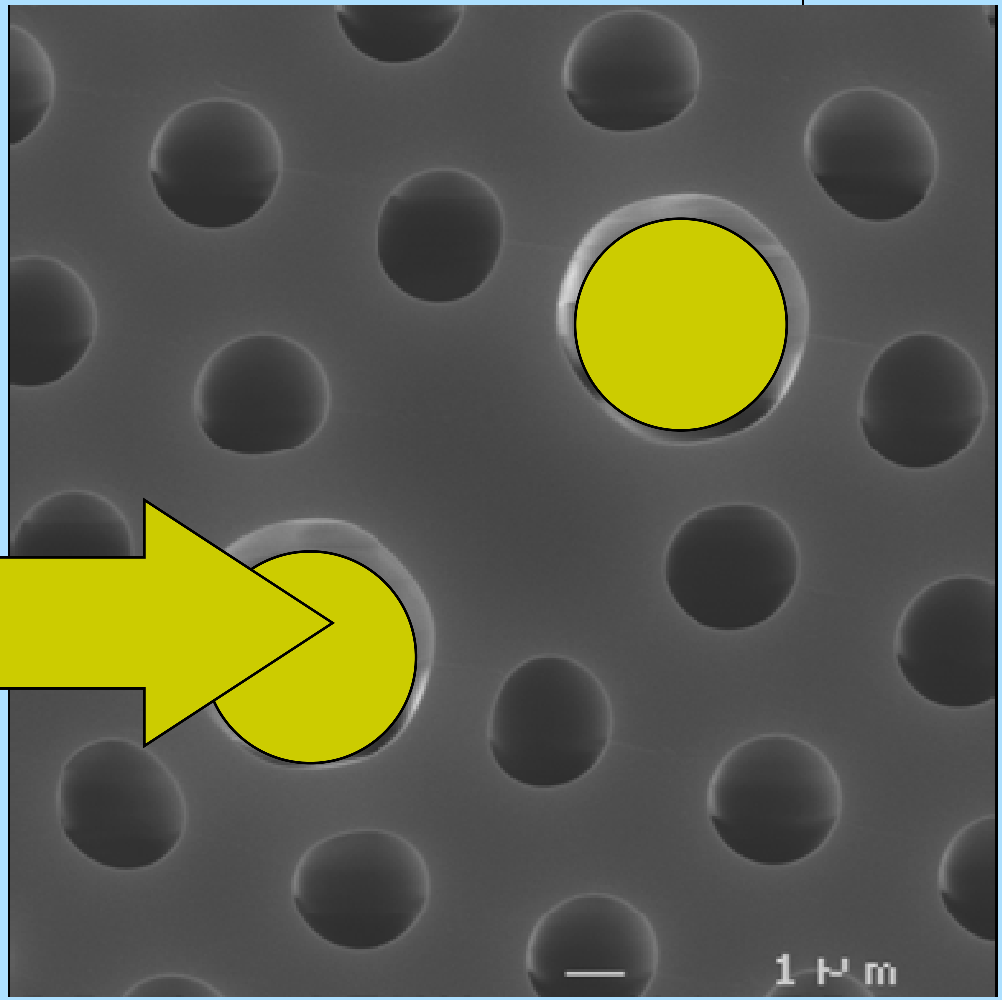
Photonic Crystal Fibers by blazephotonics

PM - 1550 - 01

Large holes filled

with LC

by capillary forces



Theoretical analyses

Starting from Maxwell's equations we obtain the vector wave equation

(for a linear, isotropic, and time-invariant medium)

$$\nabla \times \nabla \times \vec{E} = \nabla\left(\nabla \cdot \vec{E}\right) - \nabla^2 \vec{E} = n^2 k^2 \vec{E}$$

where: k=2π/λ

for **n=n(x, y)** we're looking for solutions in the form:

$$\vec{E} = \hat{E}\exp(-ikN_{eff} z)$$

where field envelope $\hat{E} = \hat{E}(x, y)$ is z-invariant

considering only E_x and E_y components

$$\hat{E} = (\hat{E}_x, \hat{E}_y) \equiv (E_x, E_y)$$

we obtain →

Vectorial mode solver

$$\begin{bmatrix} P_{xx} & P_{xy} \\ P_{yx} & P_{yy} \end{bmatrix} \begin{bmatrix} E_x \\ E_y \end{bmatrix} = k^2 N_{eff}^2 \begin{bmatrix} E_x \\ E_y \end{bmatrix}$$

where:

$$P_{xx}E_x = \frac{\partial}{\partial x}\left[\frac{1}{n^2}\frac{\partial\left(n^2 E_x\right)}{\partial x}\right] + \frac{\partial^2 E_x}{\partial y^2} + n^2 k^2 E_x \qquad P_{xy}E_y = \frac{\partial}{\partial x}\left[\frac{1}{n^2}\frac{\partial n^2 E_x}{\partial y}\right] - \frac{\partial^2 E_y}{\partial x \partial y}$$

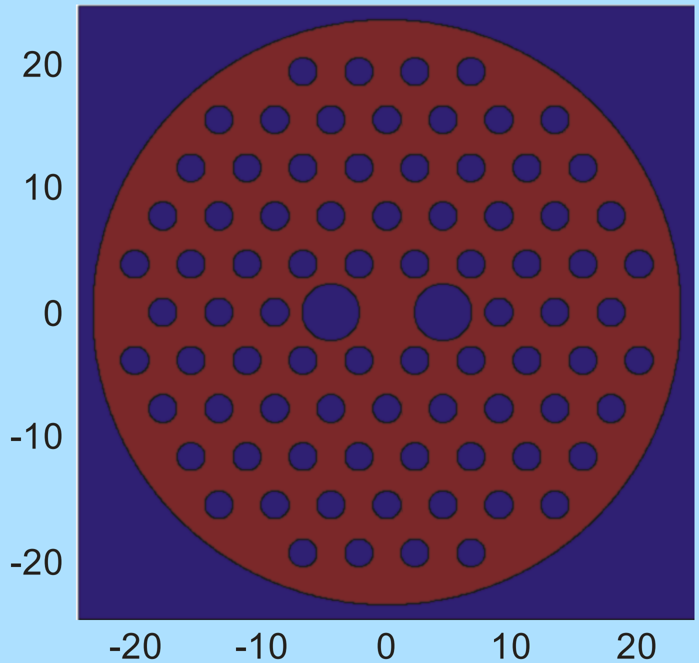
$$P_{yy}E_y = \frac{\partial}{\partial y}\left[\frac{1}{n^2}\frac{\partial\left(n^2 E_y\right)}{\partial y}\right] + \frac{\partial^2 E_y}{\partial x^2} + n^2 k^2 E_y \qquad P_{yx}E_x = \frac{\partial}{\partial y}\left[\frac{1}{n^2}\frac{\partial n^2 E_y}{\partial x}\right] - \frac{\partial^2 E_x}{\partial y \partial x}$$

Cross-coupling effects
between transverse fields

Theoretical calculations

$$\mathbf{M}E_{x,y} = k^2 N_{eff}^2 E_{x,y}$$

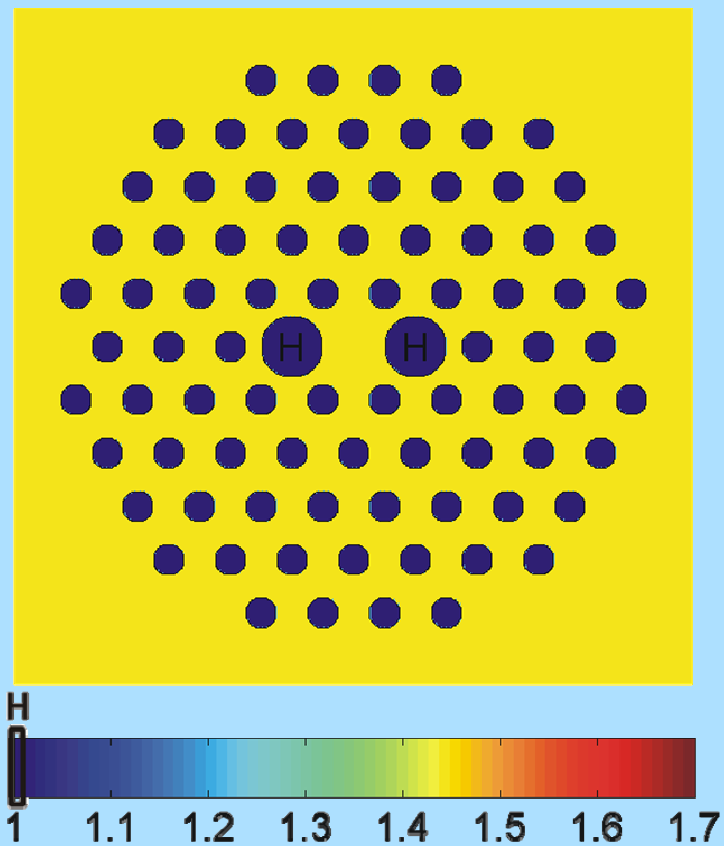
- eigenvalue problem for both E_x and E_y field
- problem discretization using finite-difference technique
- implementation of *Matlab* library for finding eigenvalues and eigenmodes
- matrix **M** contains absorbing boundary conditions



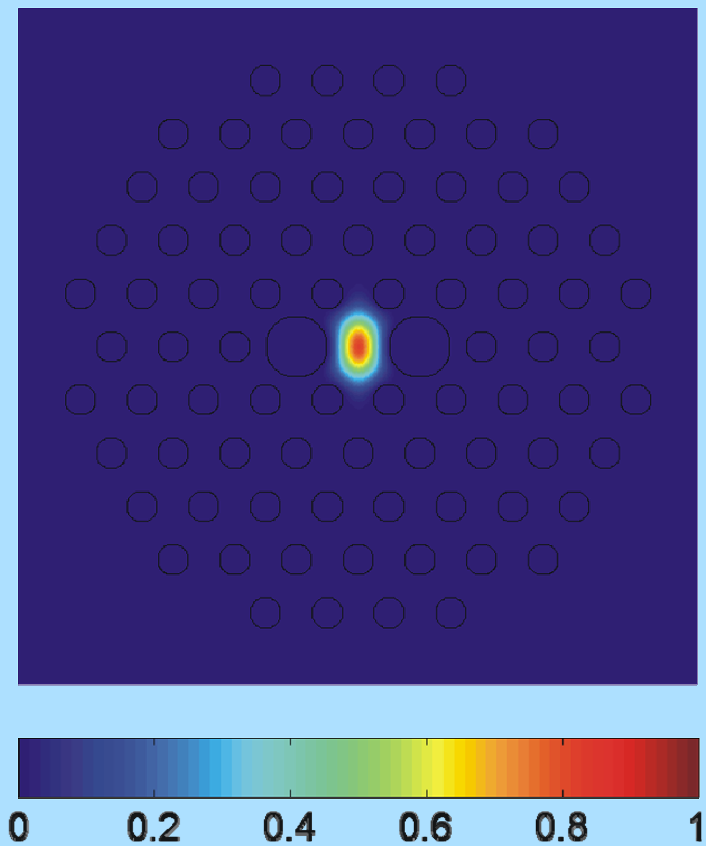
- grid period: 0.1µm (in both x and y direction)
- calculating window: 48.4µm x 48.4mm (all holey region)
- refractive index of the glass cladding: 1.444 @ λ=1550nm

Fundamental mode LP_{01} as a function of LC refractive index

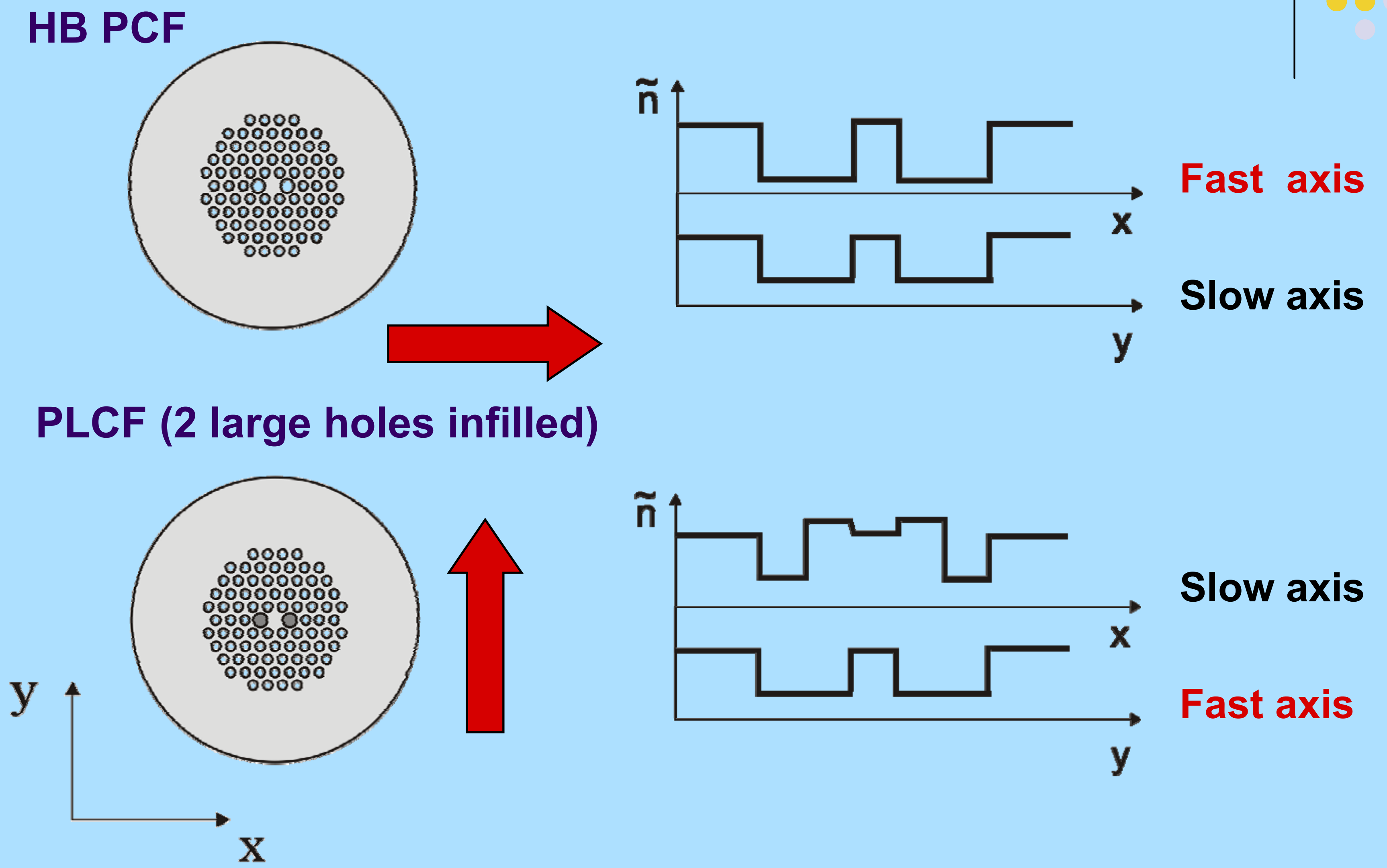
Refractive index distribution



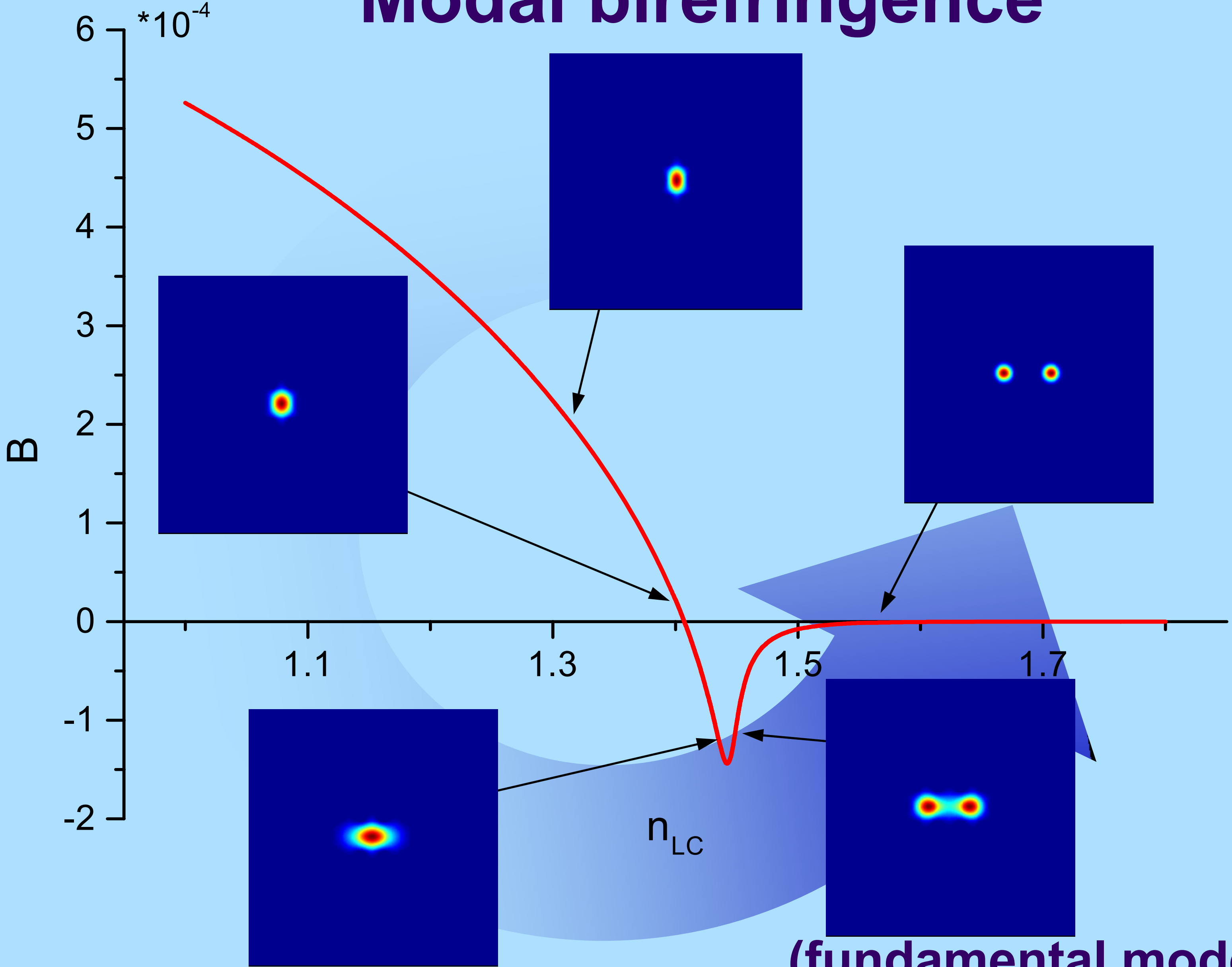
Normalized light intensity



Change of the birefringence axes

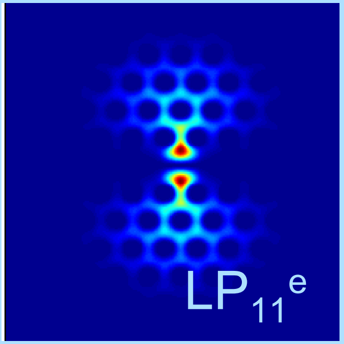


Modal birefringence

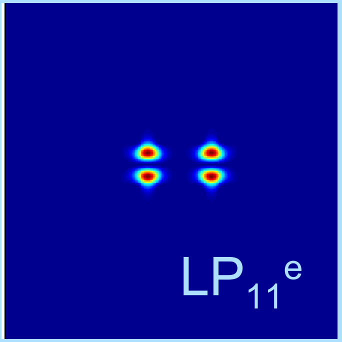


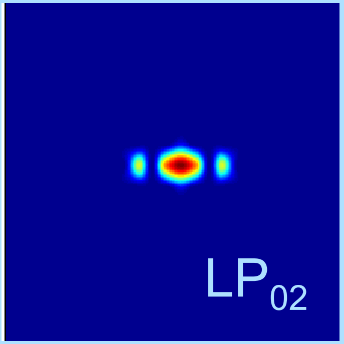
(fundamental mode LP_{01})

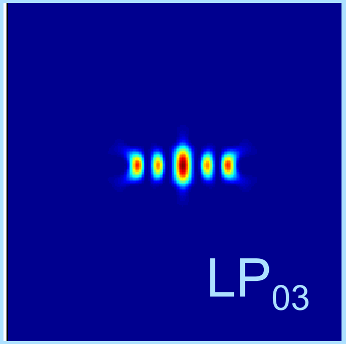
n_{LC}=1.42



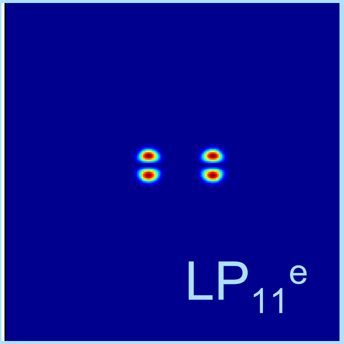
n_{LC}=1.46

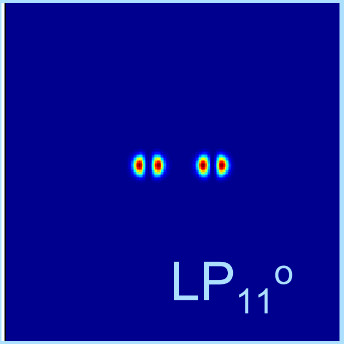


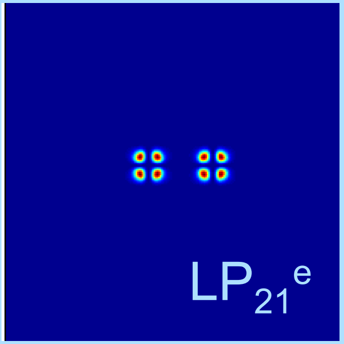




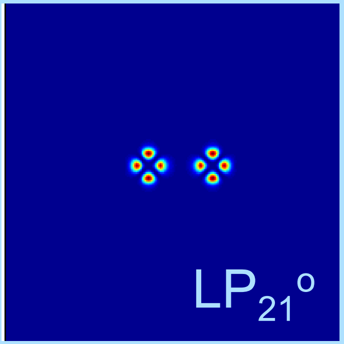
Higher order modes

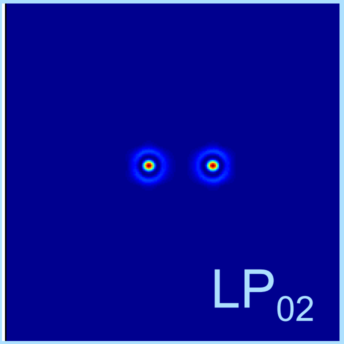


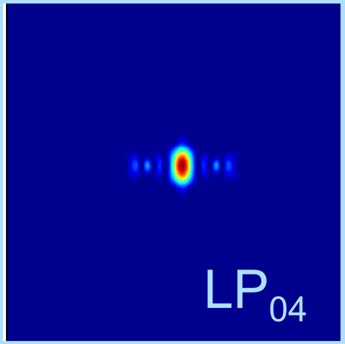




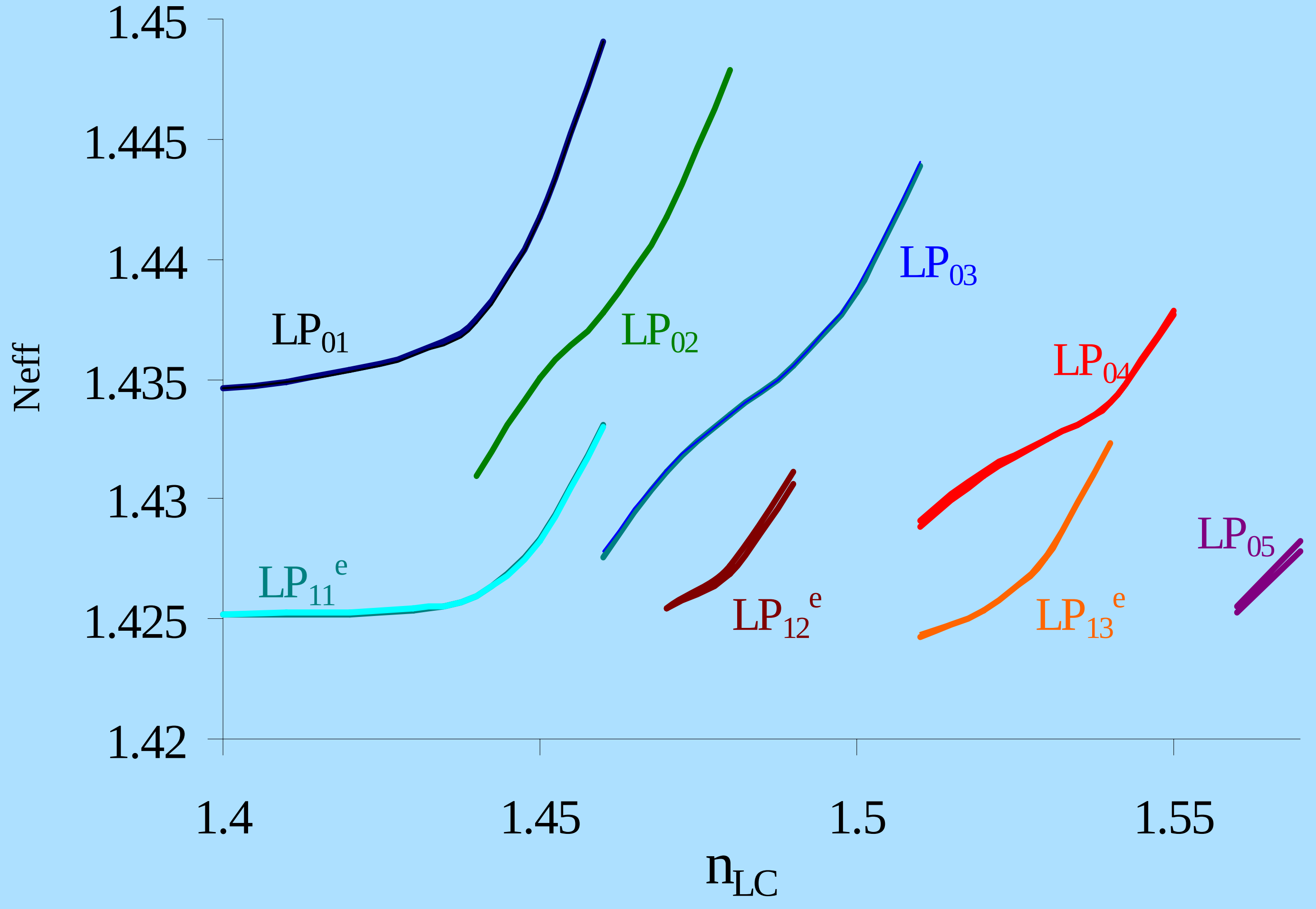
n_{LC}=1.52



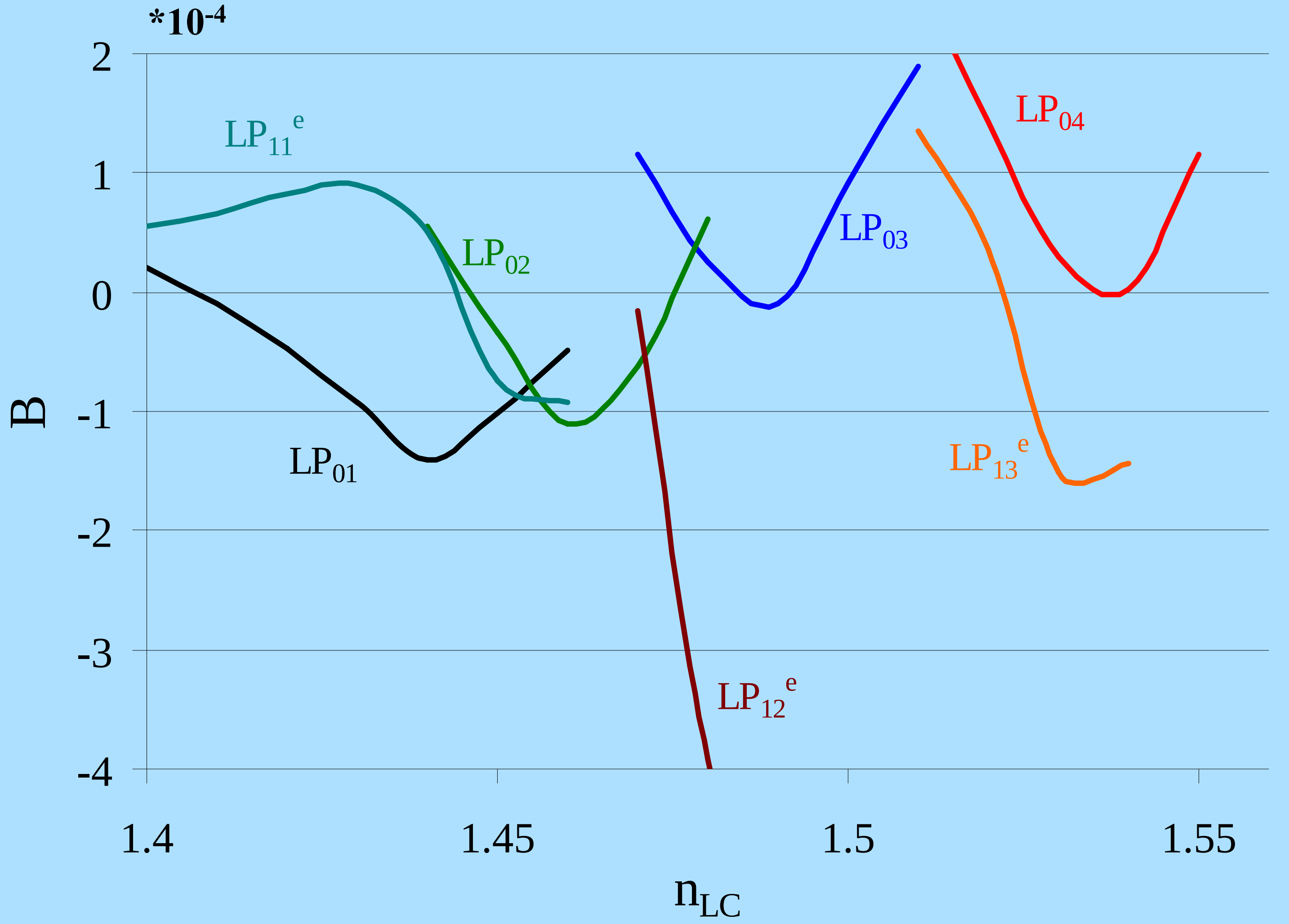




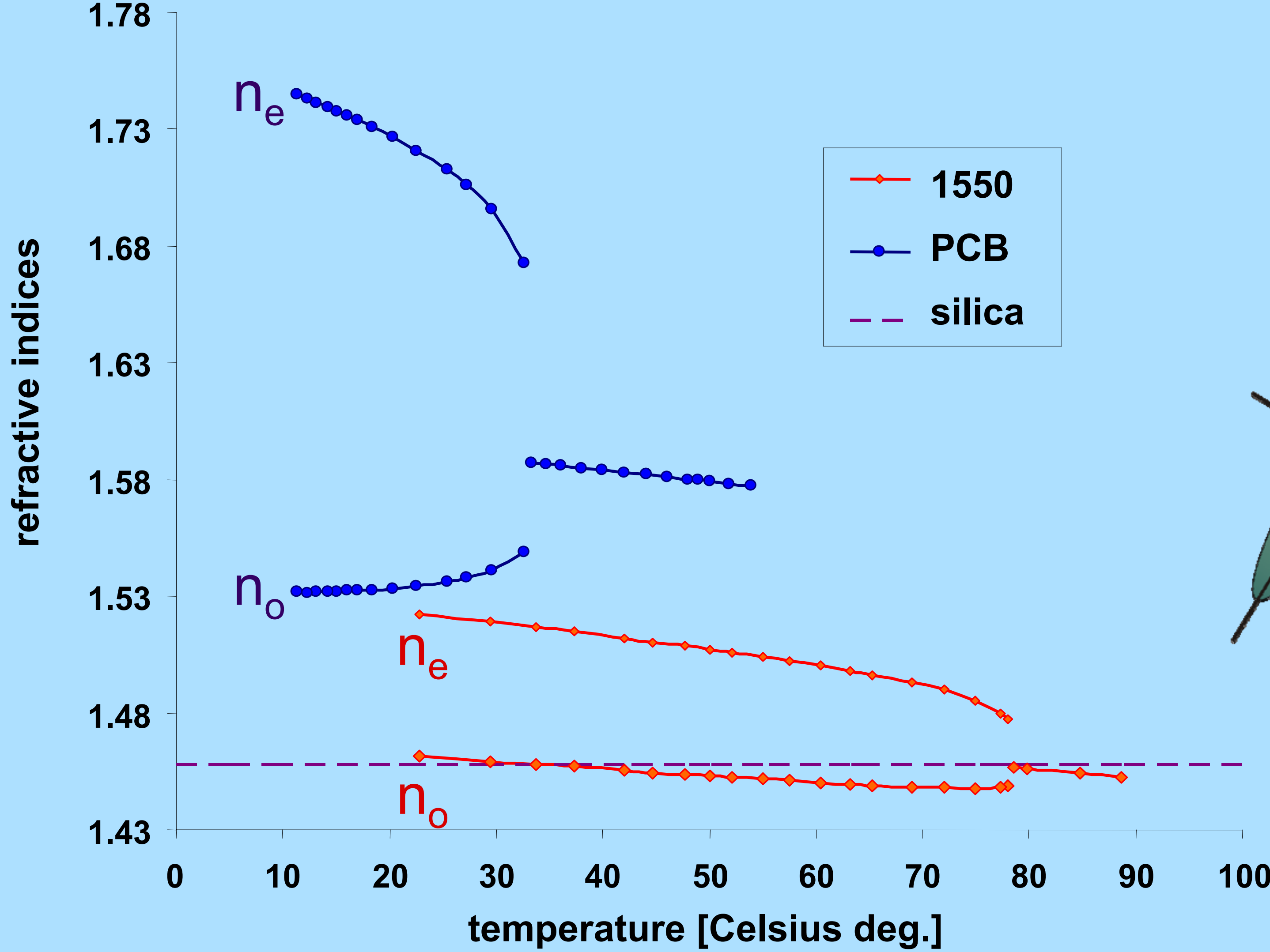
Propagation properties of LP modes

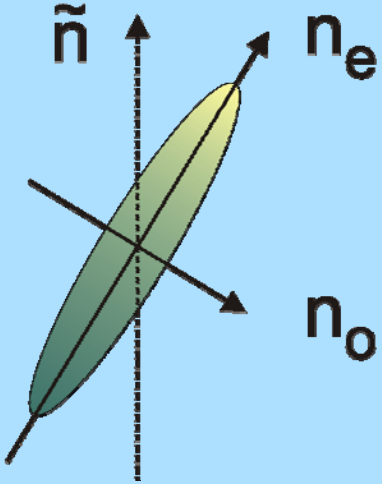


Modal birefringence

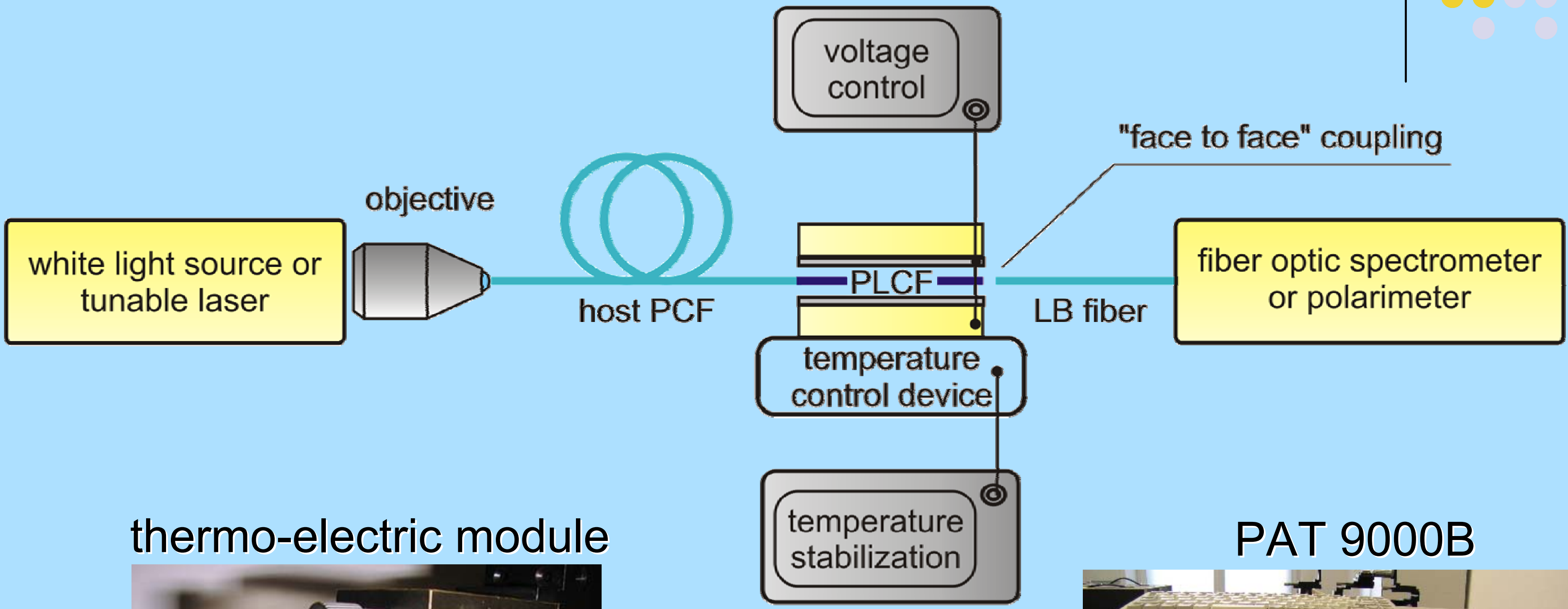


Temperature dependence of LC refractive indices (λ = 589 nm)

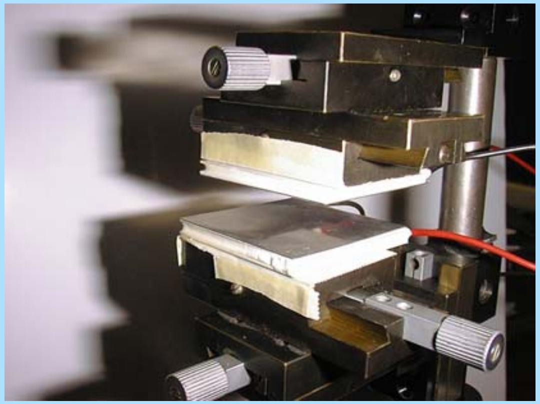




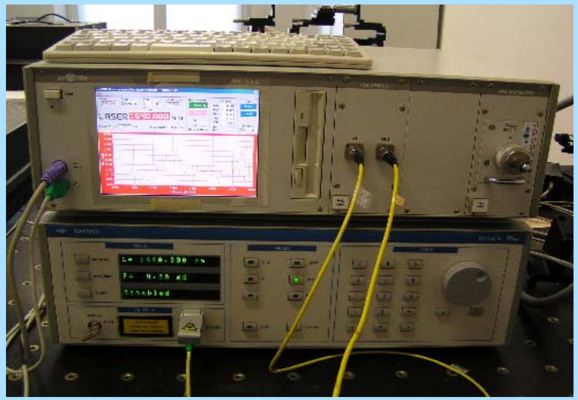
Experimental setup



thermo-electric module



PAT 9000B

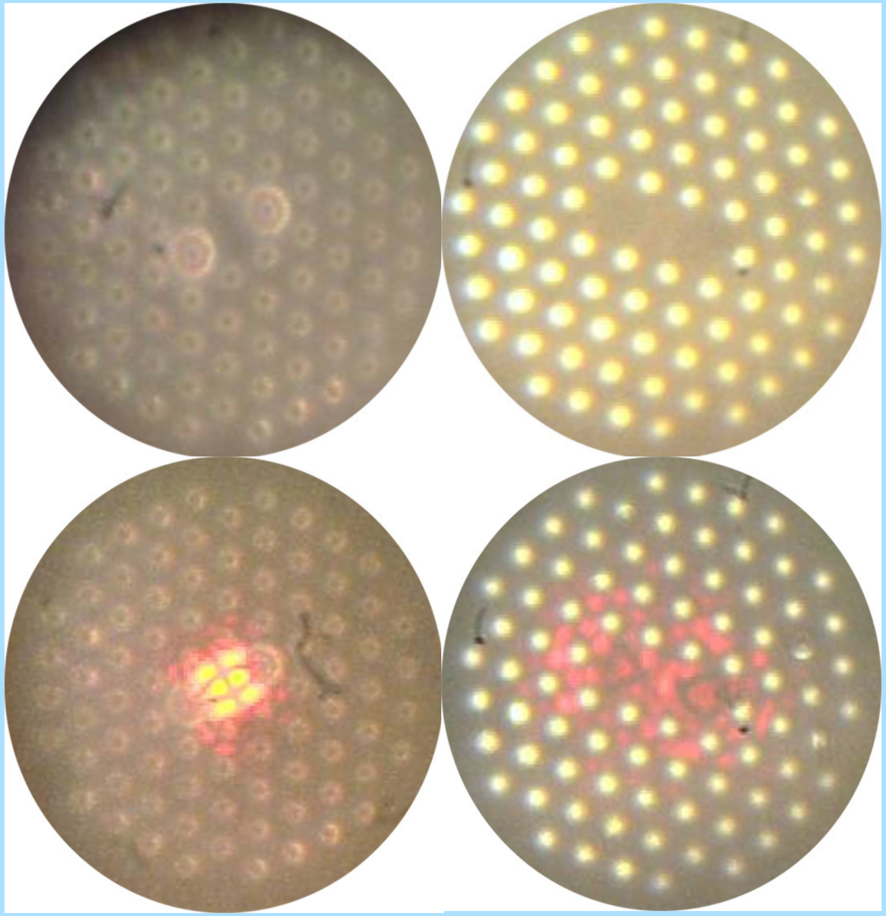


Endface of the PCF and PLCF

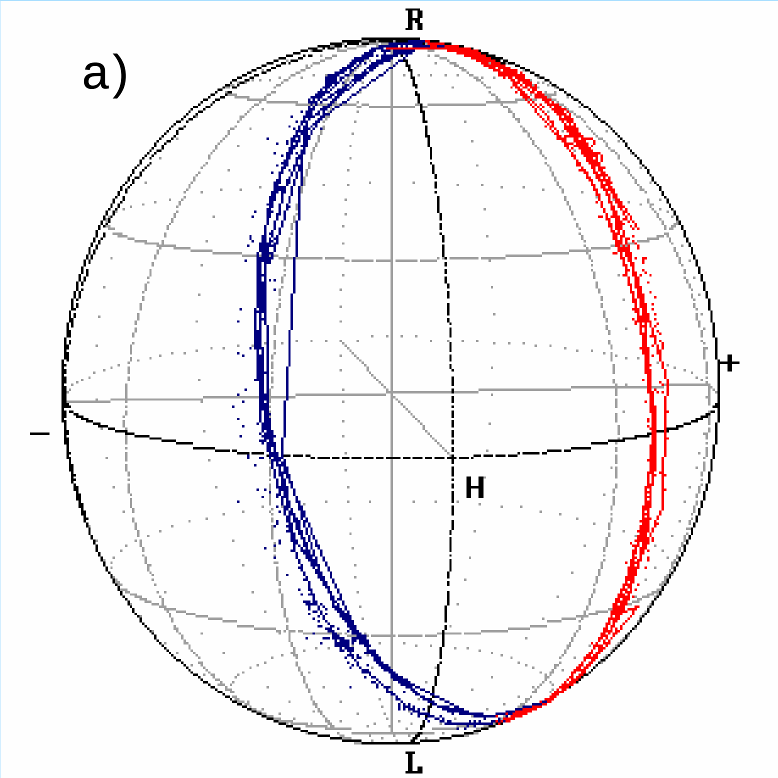
unfilled (PCF) filled (PLCF)

Laser off

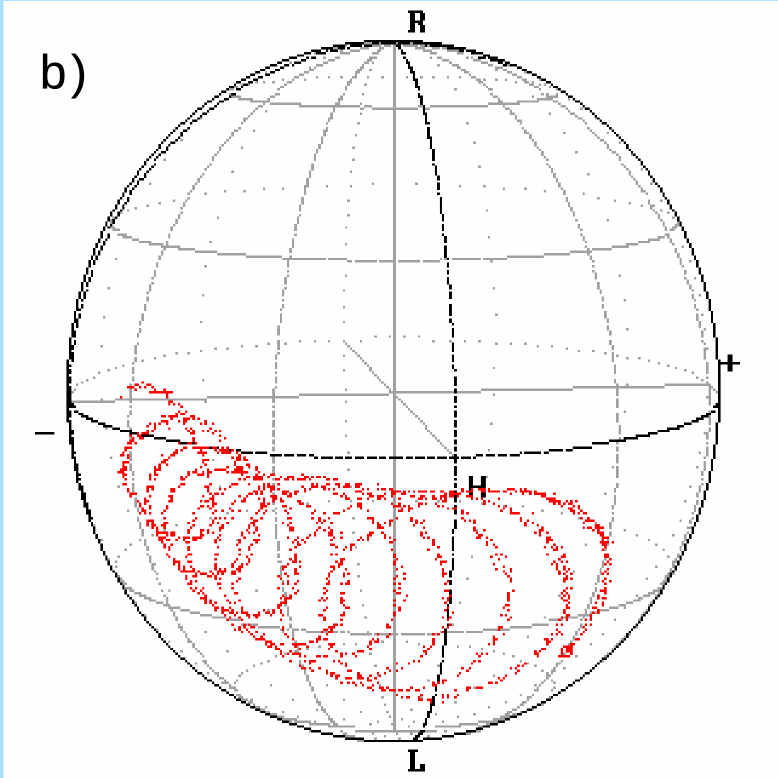
Laser on



Polarization modulation in HB Fibers

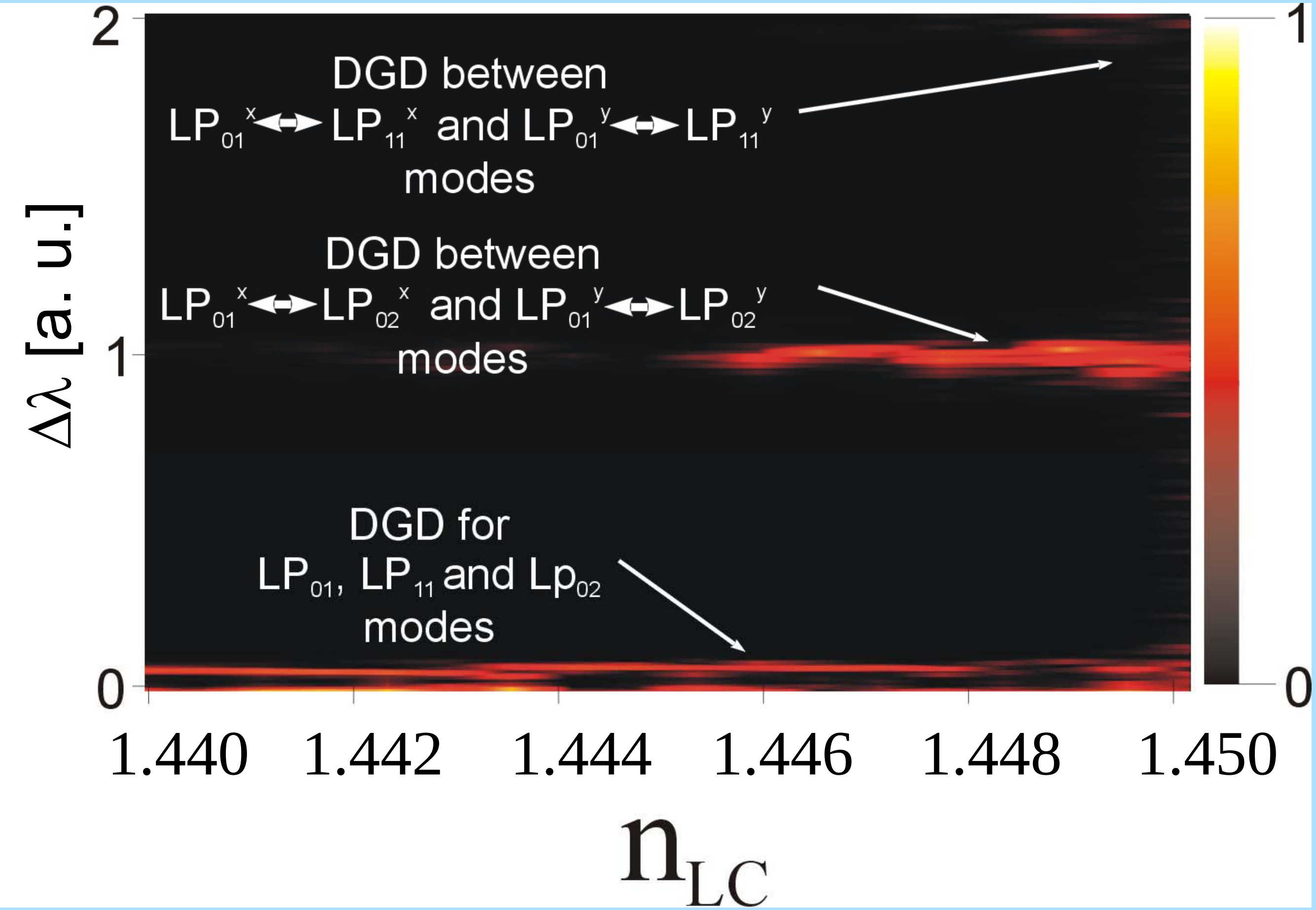


PANDA fiber

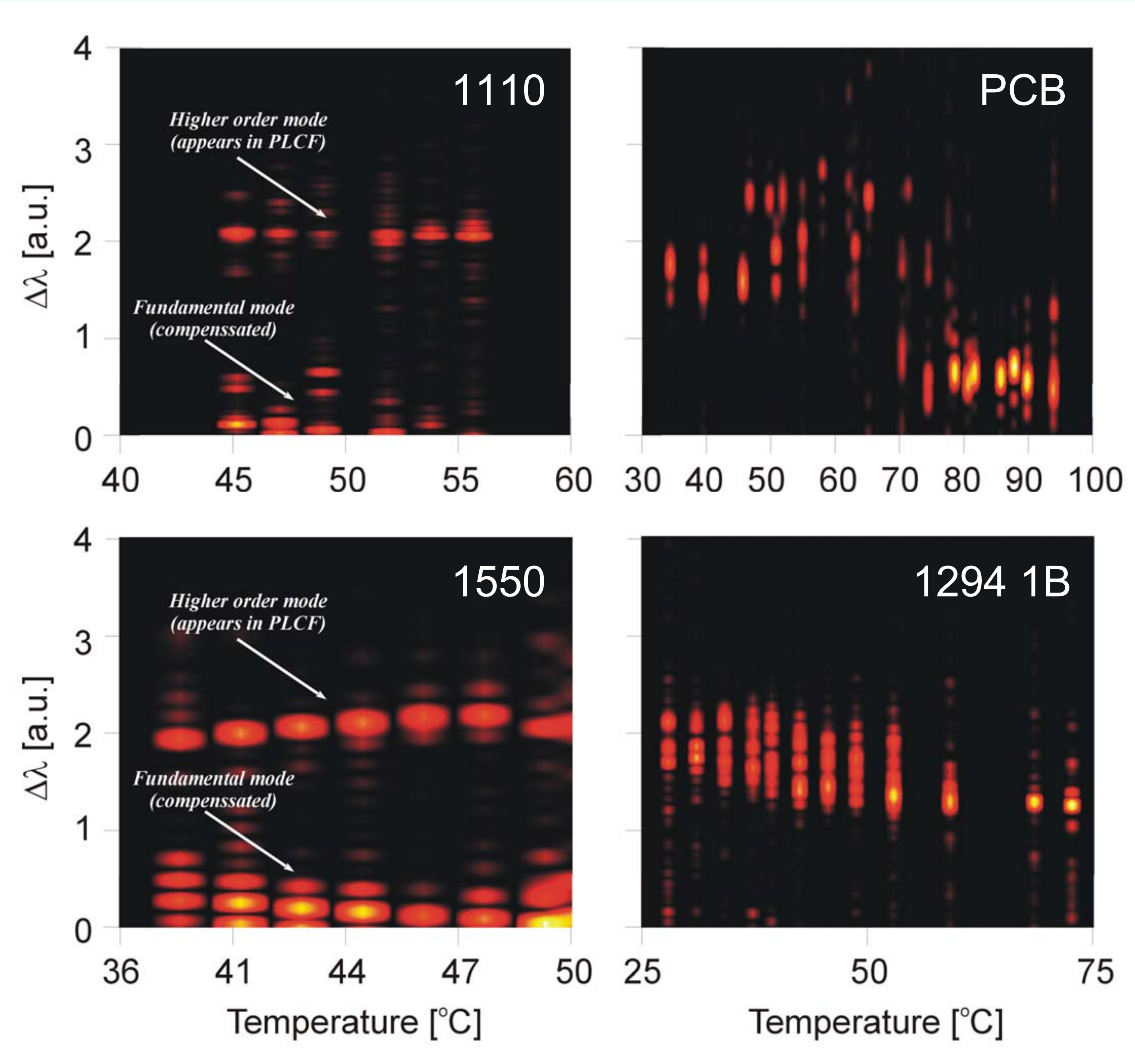


Blazephotonics + LC 1550 (thermal tuning)

Intermodal Δλ for PLCF filled with 1550 NLC

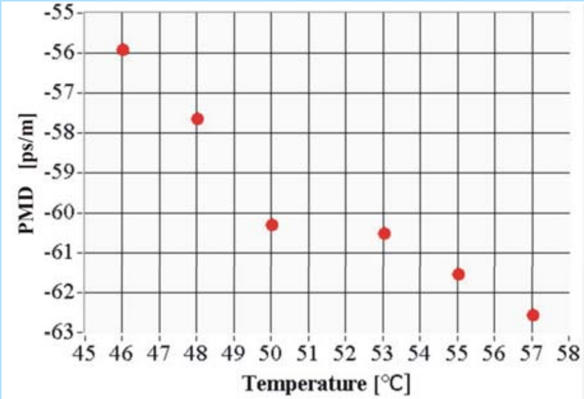


Modal $\Delta\lambda$ as a function of temp. for PLCF filled with NLC:

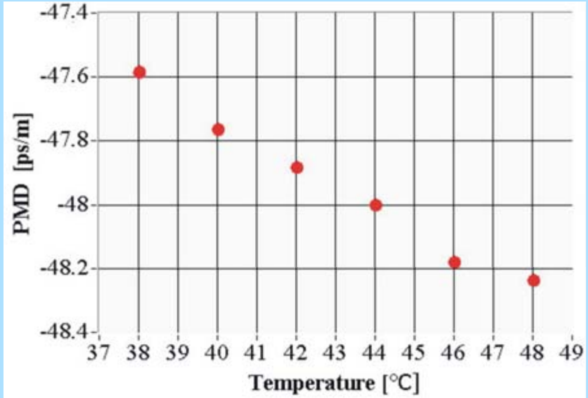


Calculated PMD as a function of temperature for PLCF filled with:

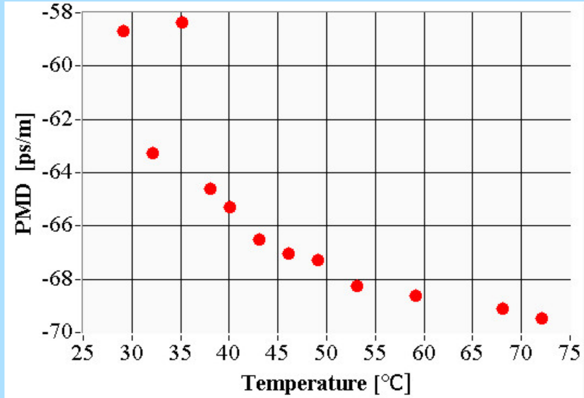
1110 - fundamental mode



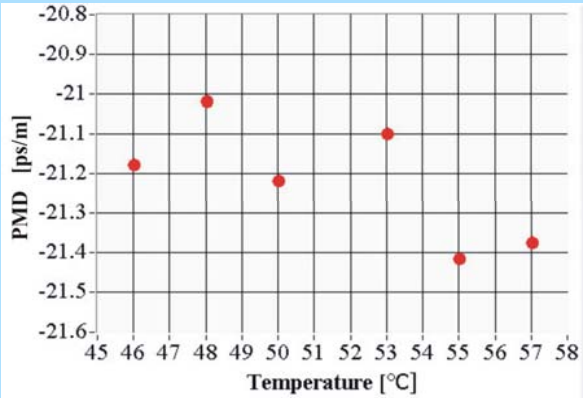
1550 - fundamental mode



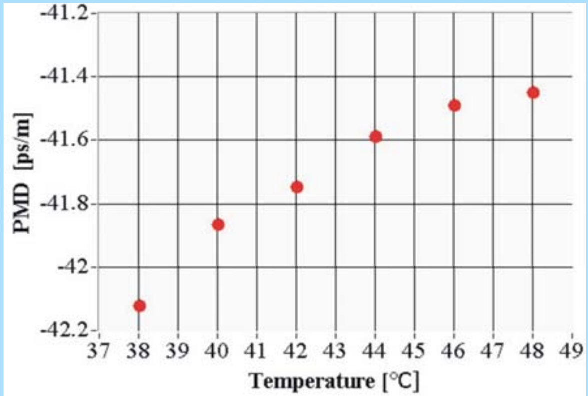
1294 1B



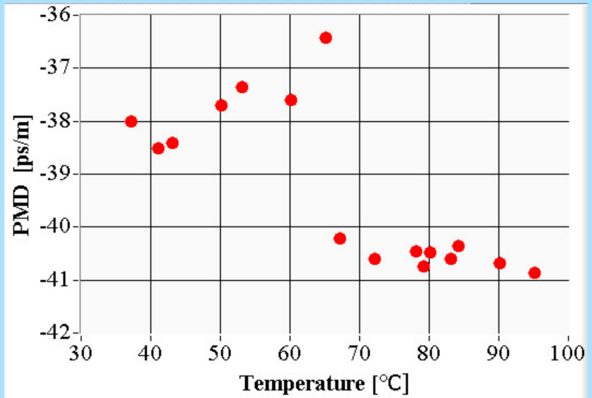
1110 – higher order mode



1550 - higher order mode



PCB

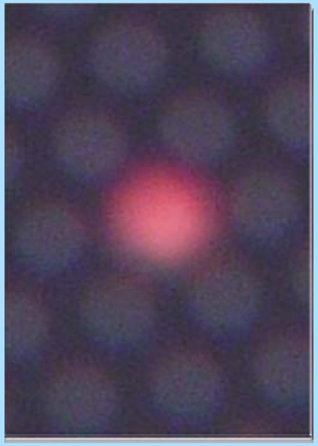


Research trends

- Tuning mechanisms: thermal, electrical, optical…
- In-line polarization and spatial modes switching
- Nonlinear effects: all-optical switching
- Tunable birefringence and wavelength filtering
- Photoalignment
- Multi-parameter fiber optic sensing
- Dynamic PMD compensators

Photonic Liquid Crystal Fibers

a new level
of tunability
in photonics



Thank you for your attention