Photonic crystal fibres

(PhD course: Optical at the nanoscale)

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Outline:

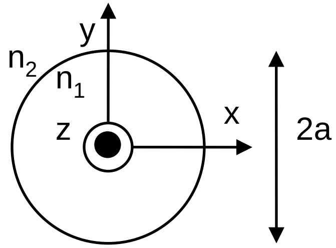
Brief review of the standard step index fiber

Index guiding PCF's
- Endlessly single-mode fibers / large core fibers

Bandgap guiding PCF's
- Guiding light in air-holes

Example of data sheet

The standard step-index fiber



$$n = \begin{cases} n_1 & \text{for} \quad \rho \le a, \\ n_2 & \text{for} \quad \rho > a. \end{cases}$$

Bølgeligningen for det elektriske (eller magnetiske) felts z-komposant:

$$\left(\nabla^2 + k_0^2 n^2\right) E_z = \frac{\partial^2 E_z}{\partial \rho^2} + \frac{1}{\rho}\frac{\partial E_z}{\partial \rho} + \frac{1}{\rho^2}\frac{\partial^2 E_z}{\partial \phi^2} + \frac{\partial^2 E_z}{\partial z^2} + k_0^2 n^2 E_z = 0$$

$$E_z(\rho, \phi, z) = F(\rho)\Phi(\phi)Z(z)$$

$$\frac{d^2 Z}{dz^2} + \beta^2 Z = 0 \quad , \quad \frac{d^2 \Phi}{d\phi^2} + m^2 \Phi = 0 \quad , \quad \frac{d^2 F}{d\rho^2} + \frac{1}{\rho}\frac{dF}{d\rho} + \left(k_0^2 n^2 - \beta^2 - \frac{m^2}{\rho^2}\right) F = 0$$

$$E_z = \begin{cases} A J_m(\kappa\rho) e^{im\phi} e^{-i\beta z} & \text{for} \quad \rho \le a \\ C K_m(\gamma\rho) e^{im\phi} e^{-i\beta z} & \text{for} \quad \rho > a \end{cases}$$

$$\kappa^2 = k_0^2 n_1^2 - \beta^2 \quad , \quad \gamma^2 = \beta^2 - k_0^2 n_2^2 \quad ,$$

$$H_z = \begin{cases} B J_m(\kappa\rho) e^{im\phi} e^{-i\beta z} & \text{for} \quad \rho \le a \\ D K_m(\gamma\rho) e^{im\phi} e^{-i\beta z} & \text{for} \quad \rho > a \end{cases}$$

$$n_2 < \frac{\beta}{k_0} < n_1 \quad \left(n_2 < -\frac{\beta}{k_0} < n_1 \quad \text{for den tilbageløbende} \right)$$

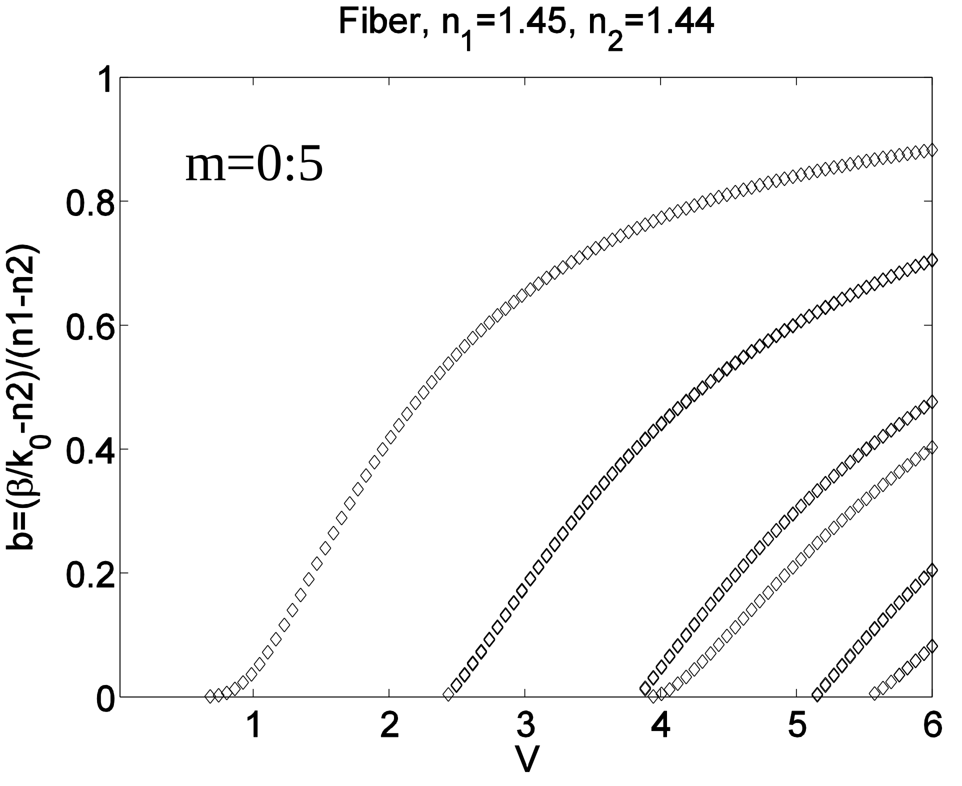
$$E_\rho = \frac{i}{\kappa^2}\left(\beta \frac{\partial E_z}{\partial \rho} + \mu_0 \frac{\omega}{\rho}\frac{\partial H_z}{\partial \phi}\right) \quad , \quad E_\phi = \frac{i}{\kappa^2}\left(\frac{\beta}{\rho}\frac{\partial E_z}{\partial \phi} - \mu_0 \omega \frac{\partial H_z}{\partial \rho}\right) \quad \text{for} \quad \rho \le a$$

$$H_\rho = \frac{i}{\kappa^2}\left(\beta \frac{\partial H_z}{\partial \rho} - \varepsilon_0 n_1^2 \frac{\omega}{\rho}\frac{\partial E_z}{\partial \phi}\right) \quad , \quad H_\phi = \frac{i}{\kappa^2}\left(\frac{\beta}{\rho}\frac{\partial H_z}{\partial \phi} + \varepsilon_0 n_1^2 \omega \frac{\partial E_z}{\partial \rho}\right) \quad \text{for} \quad \rho \le a$$

$$\left(\frac{J_m'(\kappa a)}{\kappa J_m(\kappa a)} + \frac{K_m'(\gamma a)}{\gamma K_m(\gamma a)}\right)\left(\frac{J_m'(\kappa a)}{\kappa J_m(\kappa a)} + \frac{n_2^2}{n_1^2}\frac{K_m'(\gamma a)}{\gamma K_m(\gamma a)}\right) = \left(\frac{m\beta}{n_1 a k_0}\right)^2 \left(\frac{1}{\kappa^2} + \frac{1}{\gamma^2}\right)^2$$

The standard step-index fiber

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



A standard step-index fiber becomes multi-mode when the V-parameter exceeds 2.405.

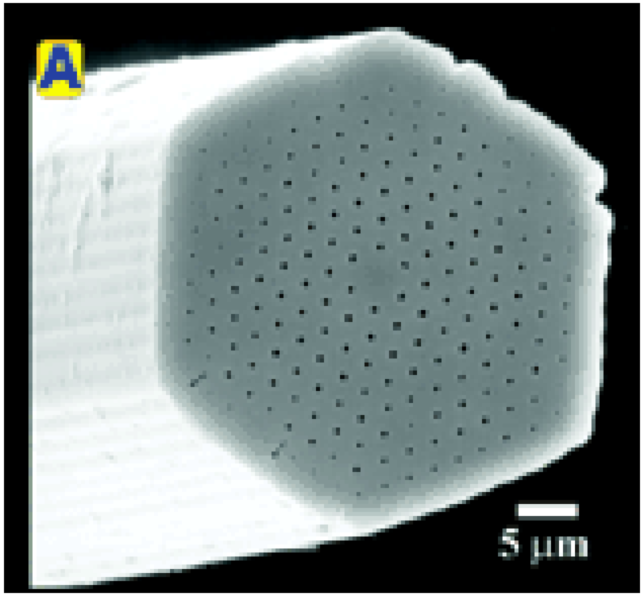
The number of modes that a fiber supports depends on
1) how strong the contrast is between core and cladding
2) the size of the core region (relative to the wavelength)

The theory of the standard step-index fiber can e.g. be found in:
G.P. Agrawal, "Fiber-optic communication systems", Wiley & Sons, New York, 1992

The ”index” of the cladding increases with increasing frequency for a PCF

$$V_{eff} = \frac{2\pi}{\lambda}\Lambda\sqrt{n_{core}^2 - n_{eff,cladding}^2},$$

$$n_{eff,cladding} = \beta_{FSM} / k_0$$



Ref.: P. Russell, Science **299**, 358-62 (2003).

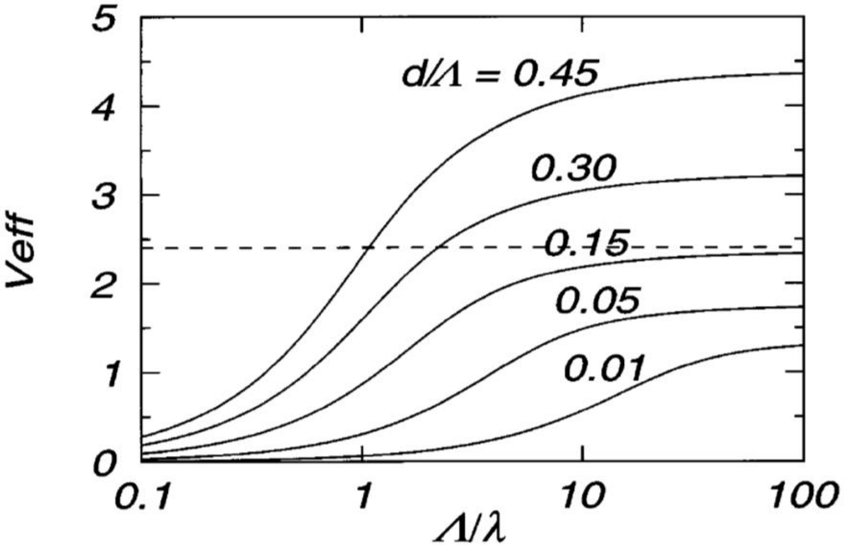
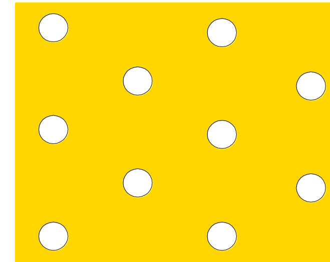


Fig. 3. Variation of V_{eff} with Λ/λ for various relative hole diameters d/Λ. The dashed line marks $V_{\text{eff}} = 2.405$, the cutoff V value for a step-index fiber.

Ref.: T. Birks, J.C. Knight, and P. St. J. Russell, Opt. Lett. **22**, 961 (1997).

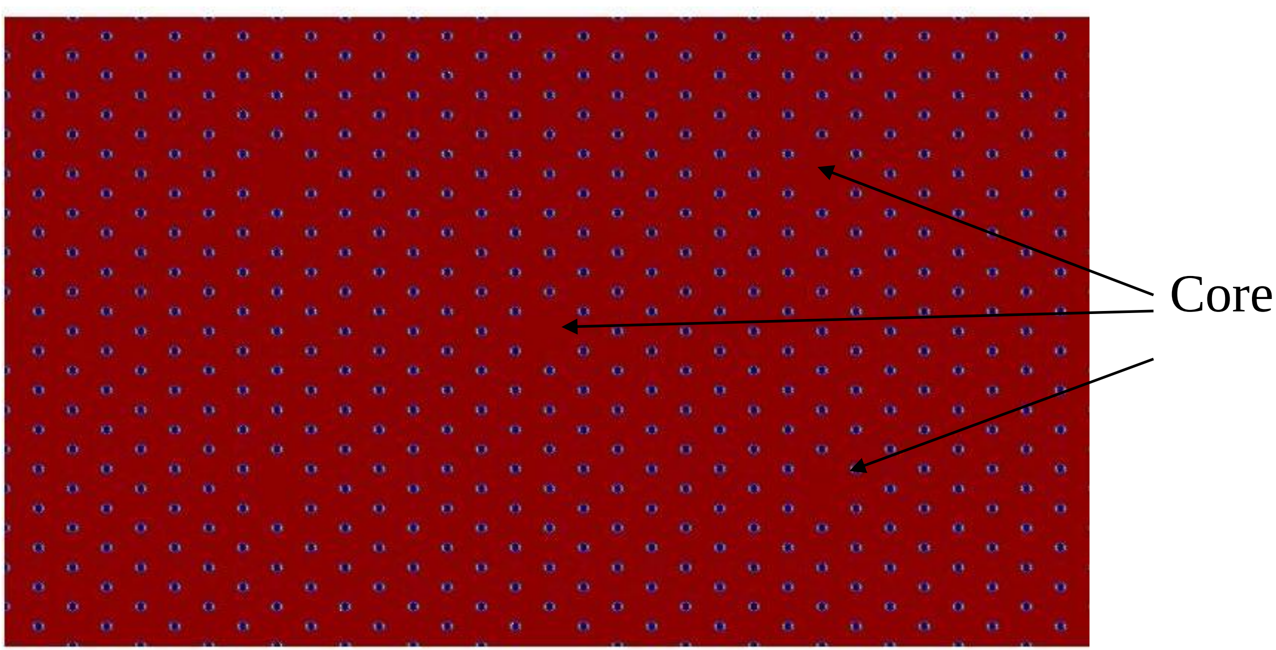
Super cell approximation method



The plane wave method requires a periodic structures.

The cladding material of a photonic crystal fibre is periodic.

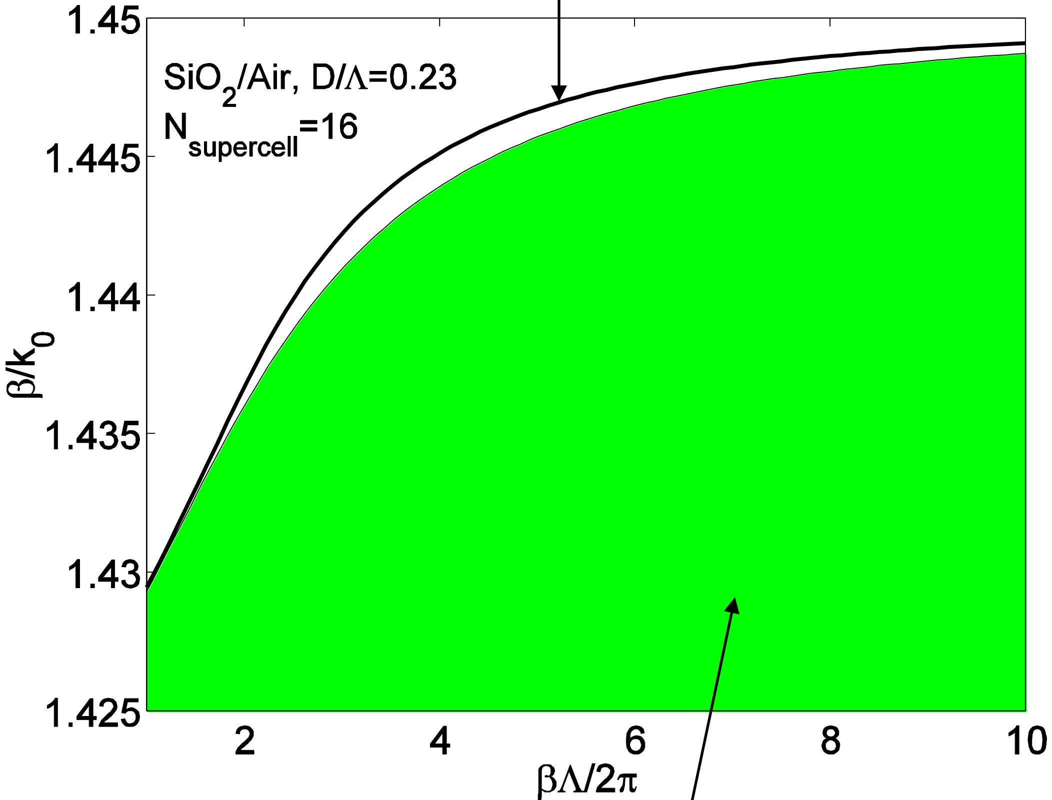
However, a photonic crystal fibre is not a periodic structure due to the core region. This problem is overcome by approximating the structure with a periodic structure in which the periodically repeated core regions are separated sufficiently far from each other that guided modes do not ”see the other core regions”.

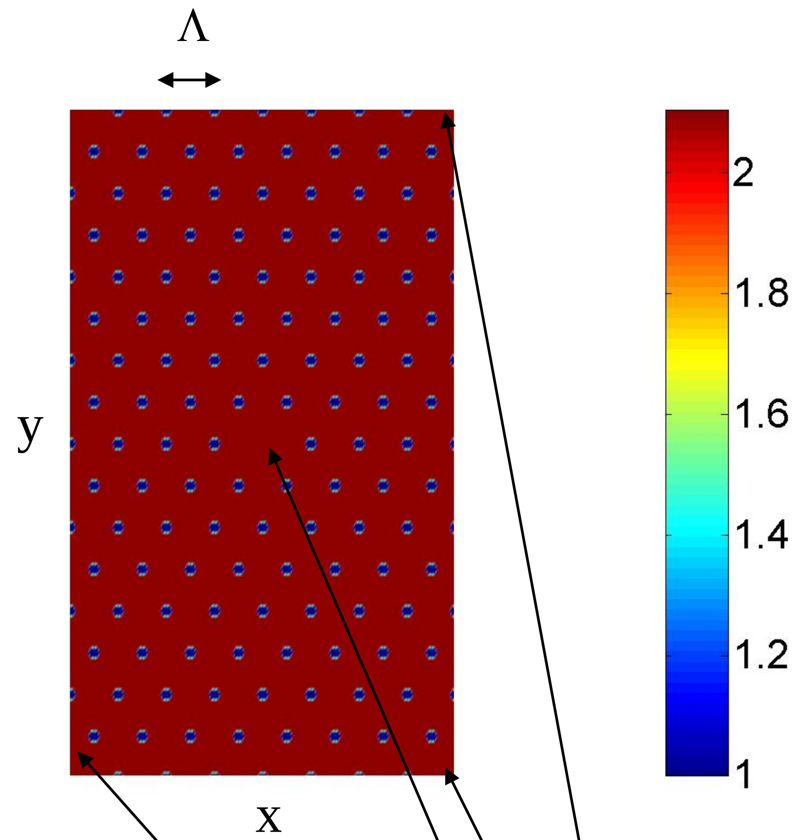


Localized waveguide mode of the form

$$\mathbf{E}(\mathbf{r}) = \mathbf{F}(x, y)e^{i\beta z}$$

Dielectric constant distribution for a supercell of size 8

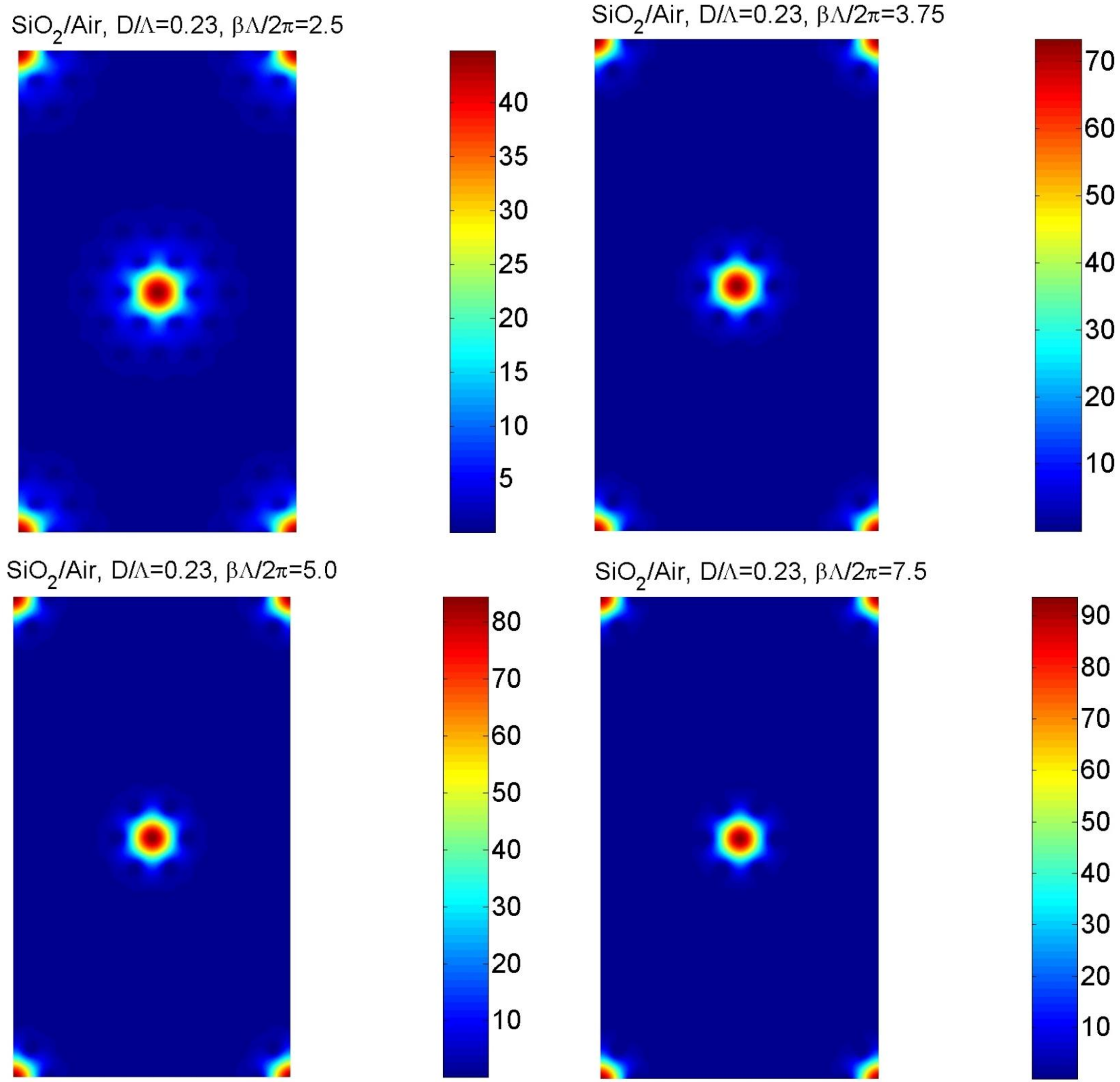




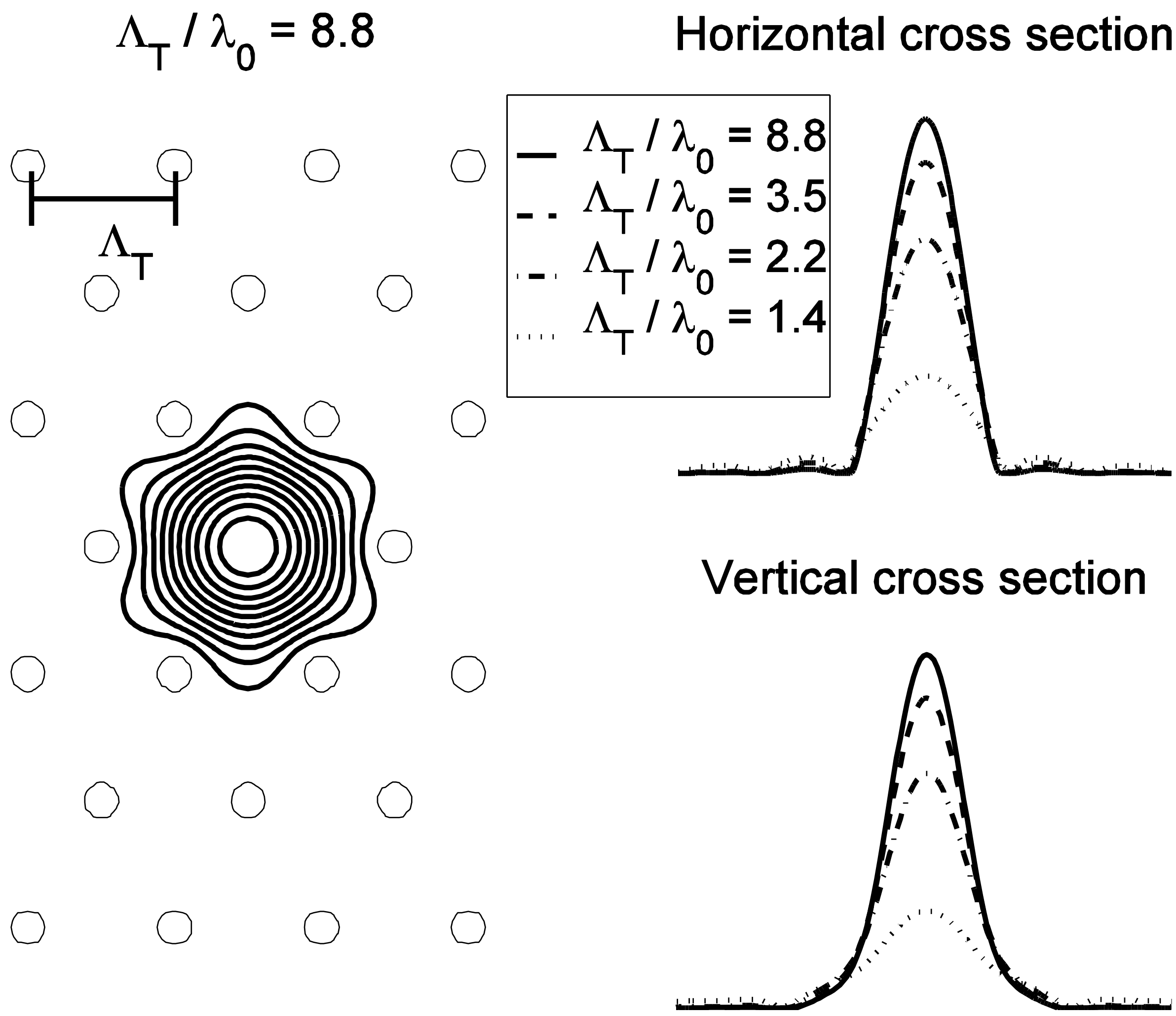
Waveguiding core region

Continuum of cladding modes

The distance between neighbouring cores must be sufficient to avoid field overlap for the guided modes being calculated



SiO2/Air, D/Λ=0.23, βΛ/2π=2.5
40
35
30
25
20
15
10
5
SiO2/Air, D/Λ=0.23, βΛ/2π=3.75
70
60
50
40
30
20
10
SiO2/Air, D/Λ=0.23, βΛ/2π=5.0
80
70
60
50
40
30
20
10
SiO2/Air, D/Λ=0.23, βΛ/2π=7.5
90
80
70
60
50
40
30
20
10

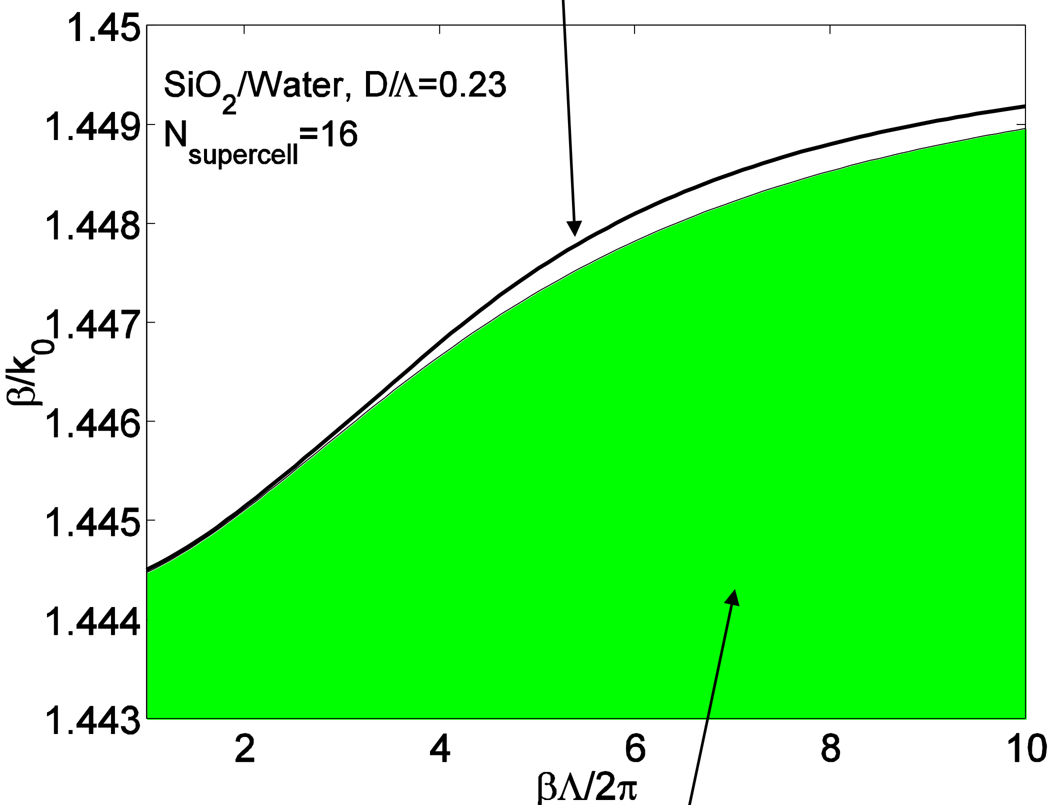


Notice how the field tends to avoid the air-holes

Taken from T. Søndergaard, Journal of Lightwave Technol. **18**, 589 (2000).

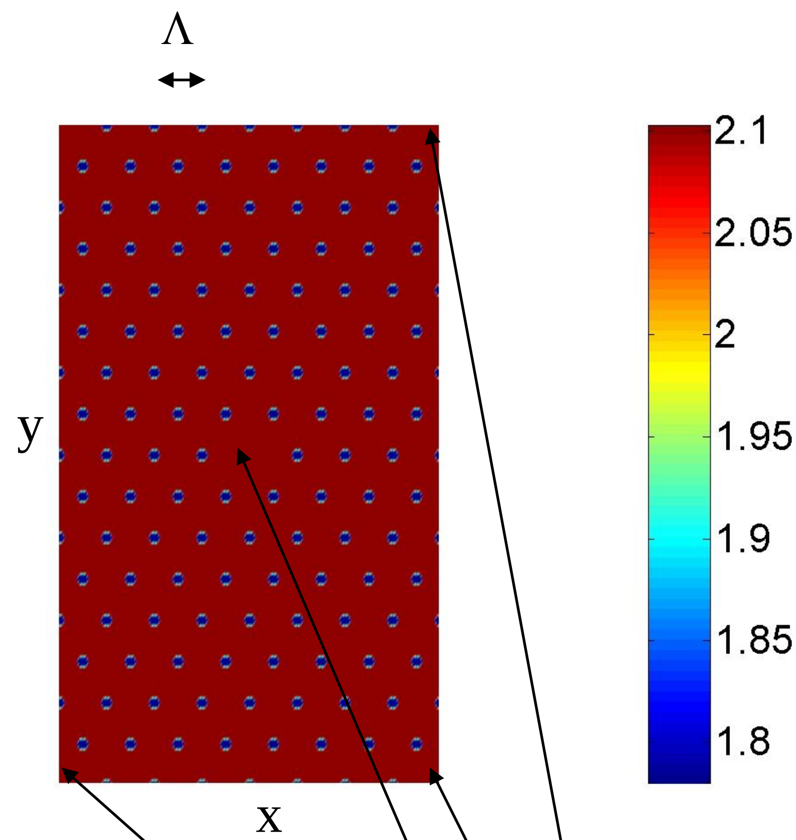
Localized waveguide mode of the form

$$\mathbf{E}(\mathbf{r}) = \mathbf{F}(x, y)e^{i\beta z}$$

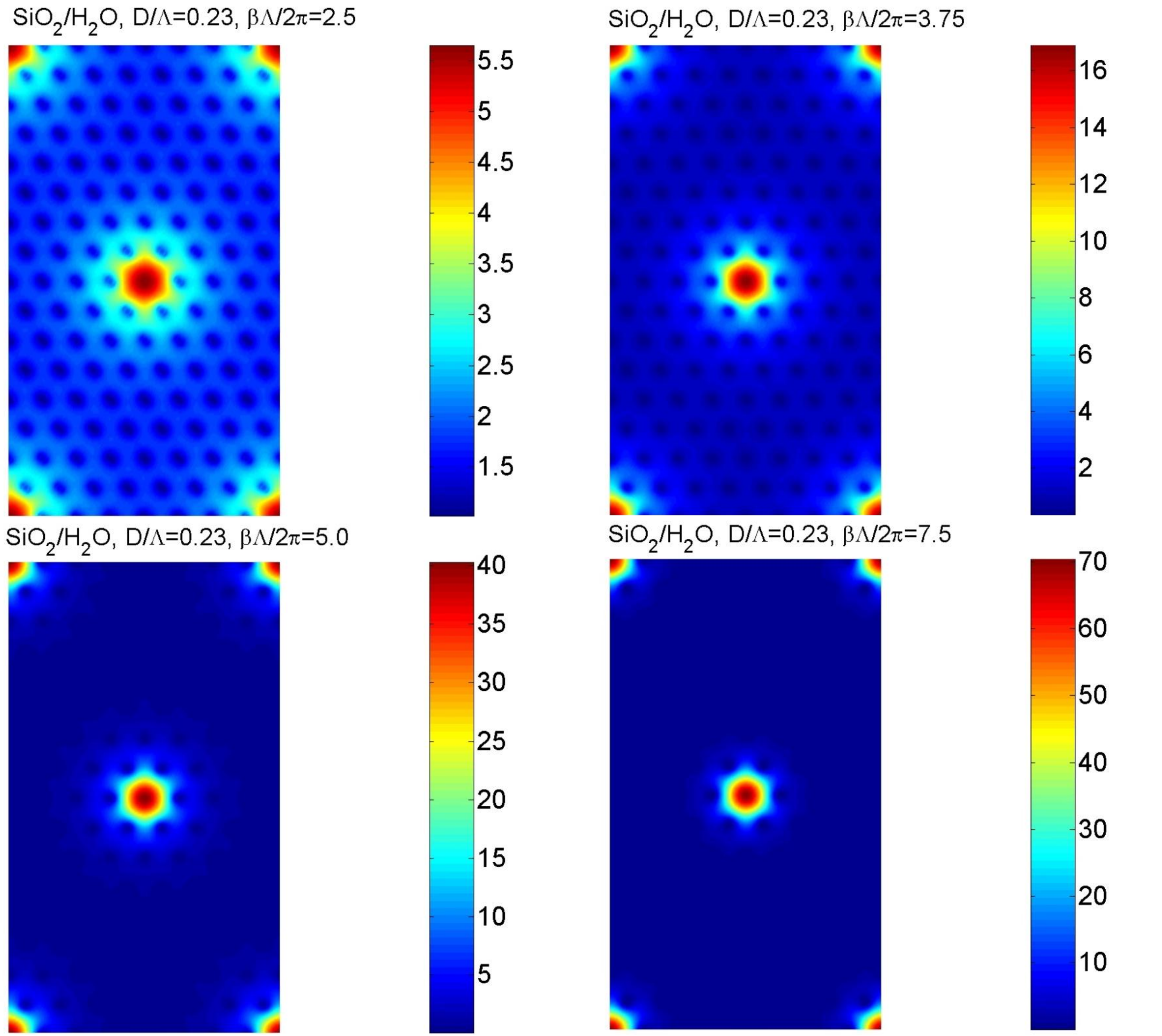


Continuum of cladding modes

Dielectric constant distribution for a supercell of size 8



Waveguiding core region

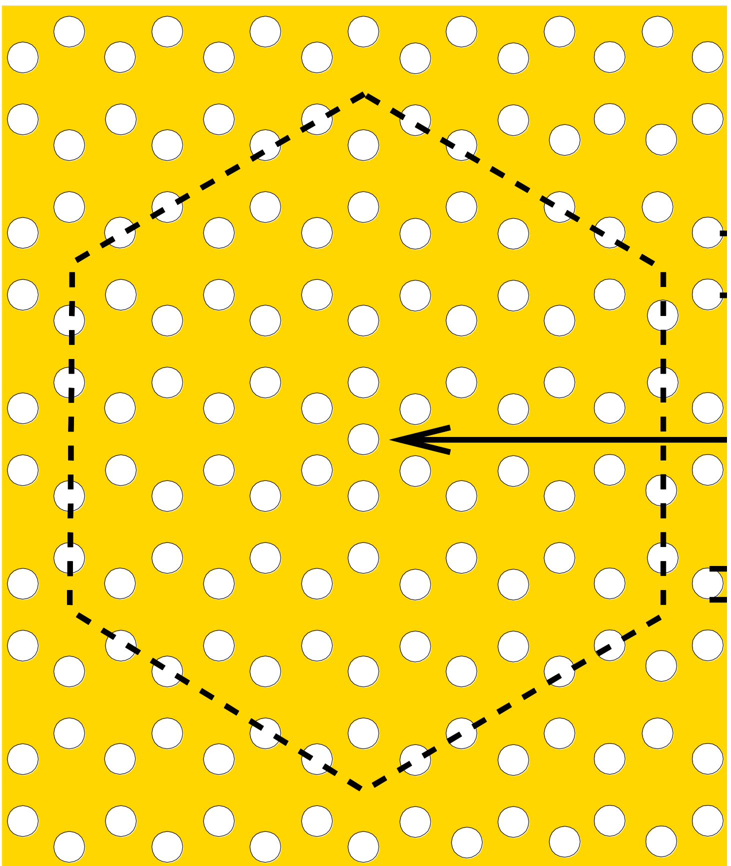


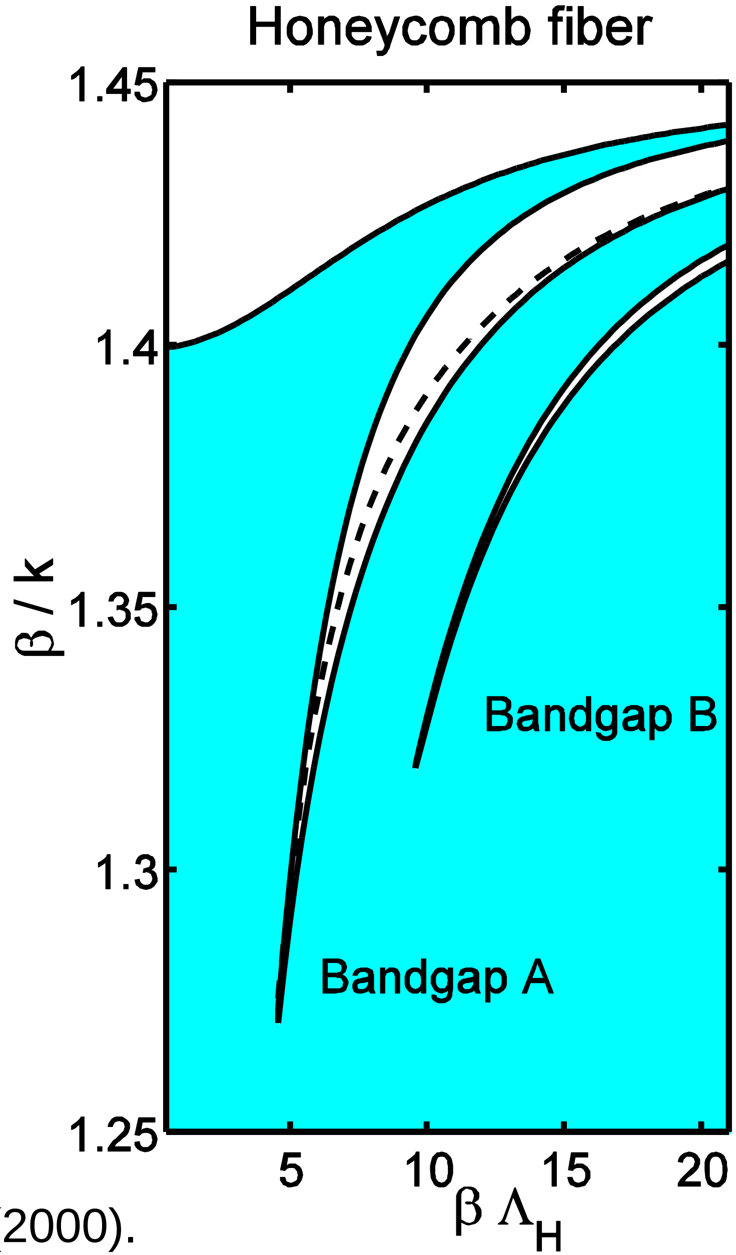
SiO2/H2O, D/Λ=0.23, βΛ/2π=2.5
5.5
5
4.5
4
3.5
3
2.5
2
1.5
SiO2/H2O, D/Λ=0.23, βΛ/2π=3.75
16
14
12
10
8
6
4
2
SiO2/H2O, D/Λ=0.23, βΛ/2π=5.0
40
35
30
25
20
15
10
5
SiO2/H2O, D/Λ=0.23, βΛ/2π=7.5
70
60
50
40
30
20
10

Bandgap-guiding fibres: The honeycomb fiber

Honeycomb fiber

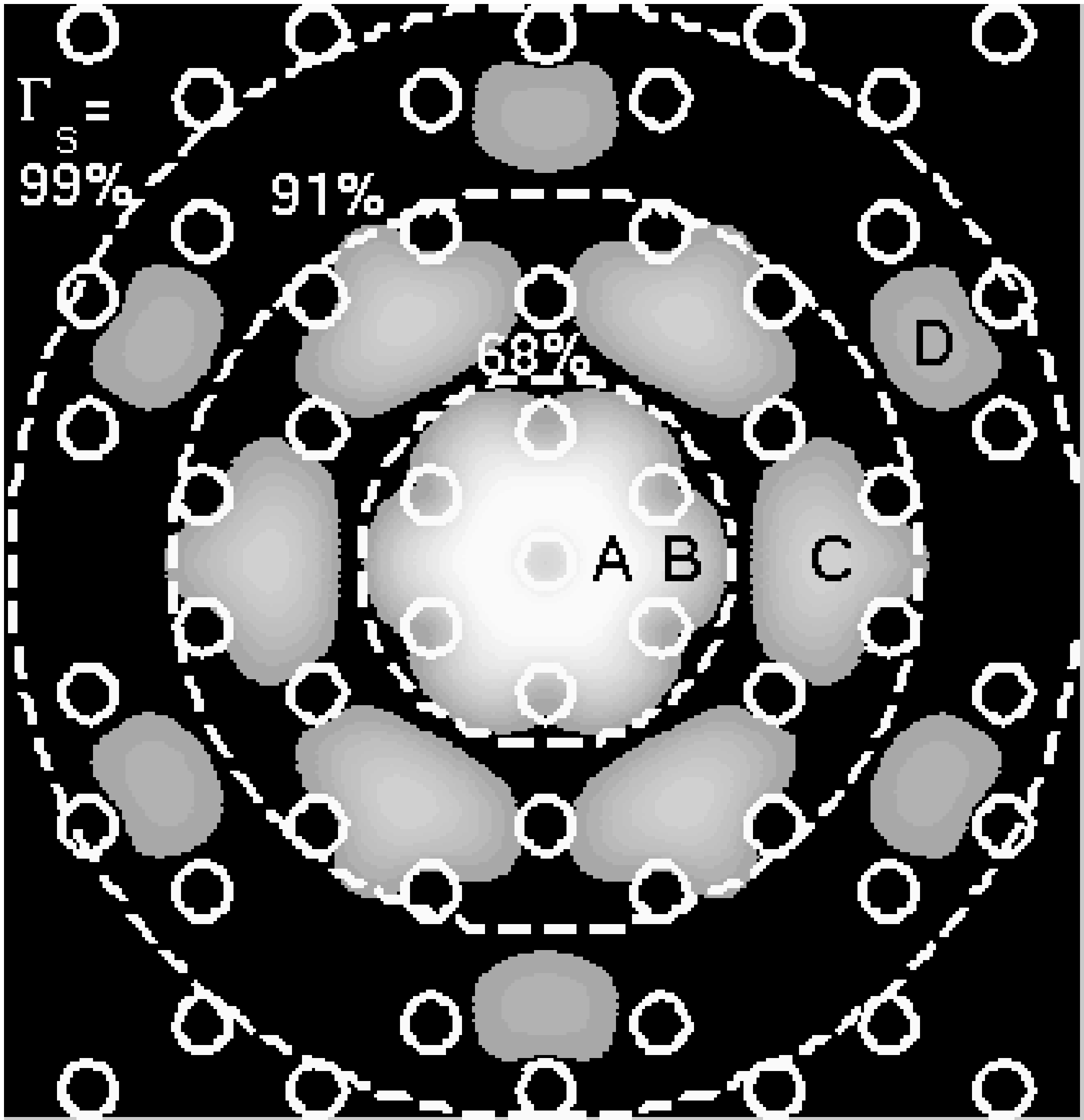
- - - - Supercell

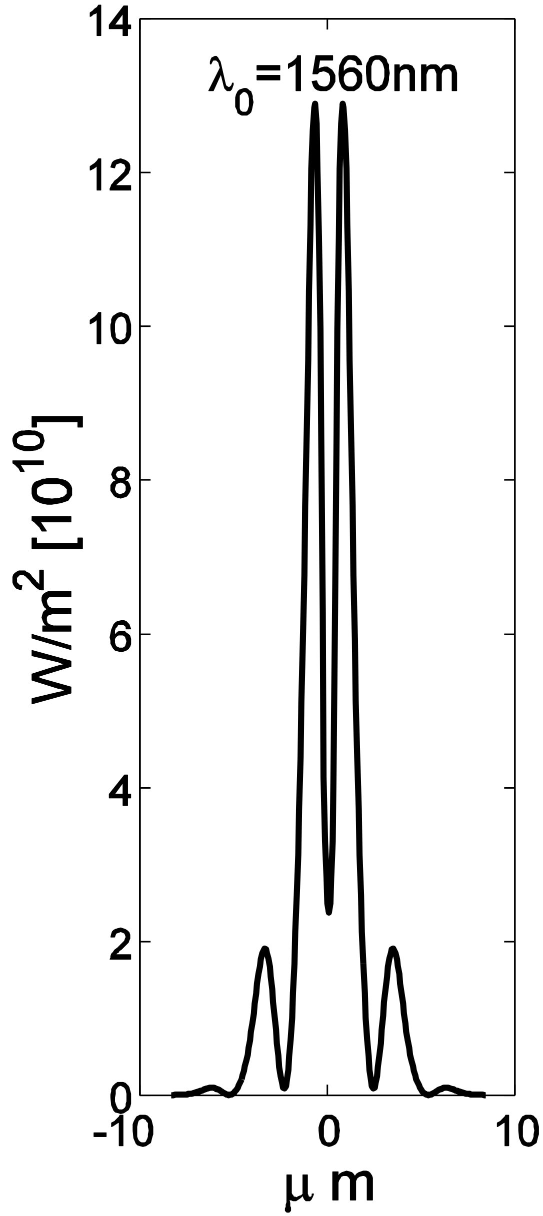




Taken from T. Søndergaard,
Journal of Lightwave Technol. **18**, 589 (2000).

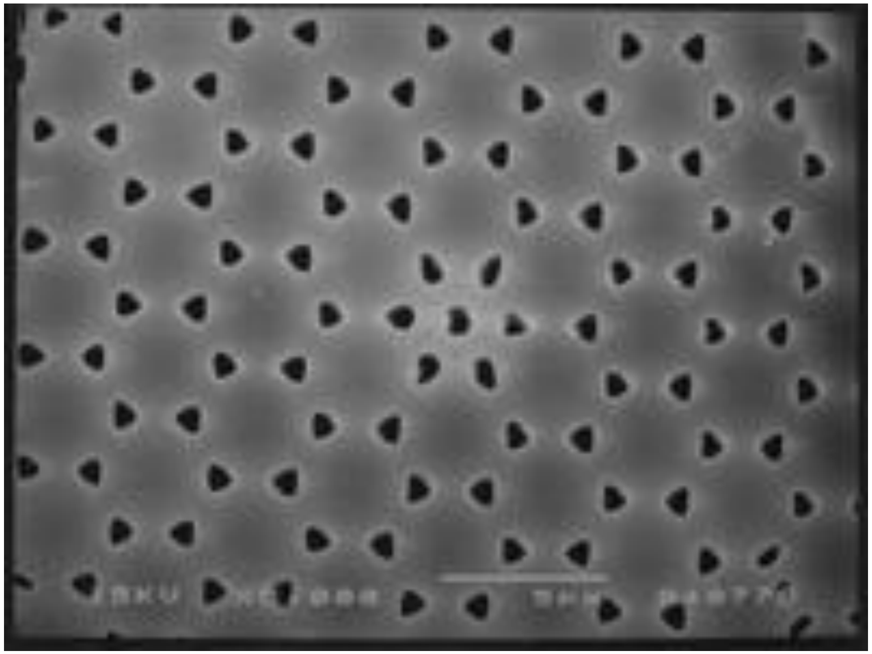
Bandgap-guiding fibres: The honeycomb fiber

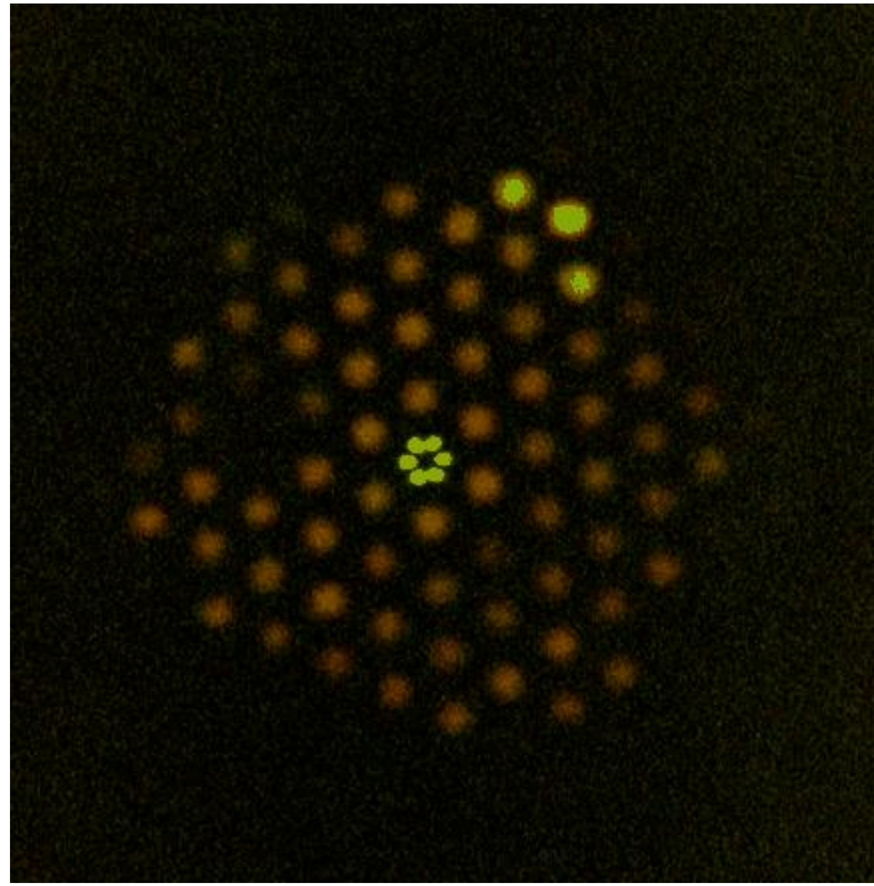




Taken from T. Søndergaard,
Journal of Lightwave Technol. **18**, 589 (2000).

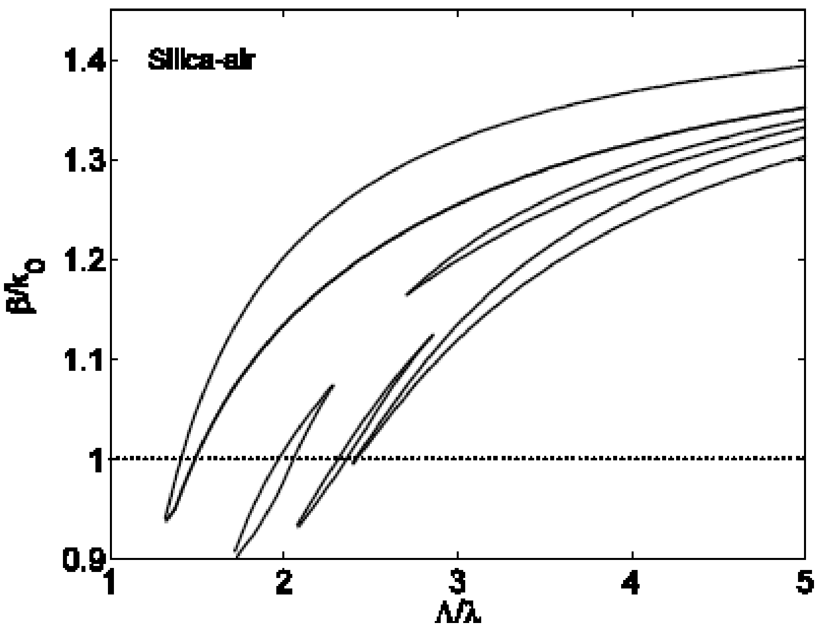
Bandgap-guiding fibres: The honeycomb fiber

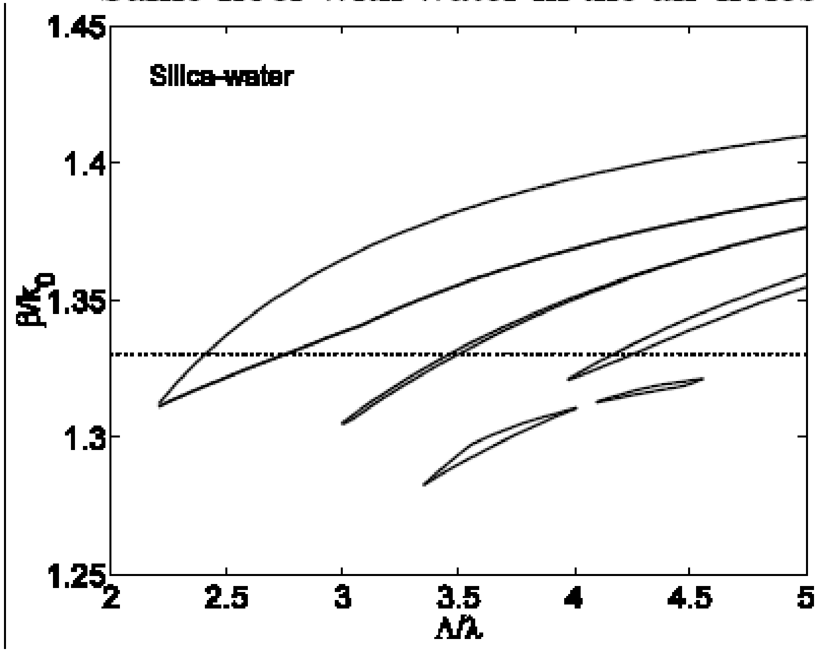


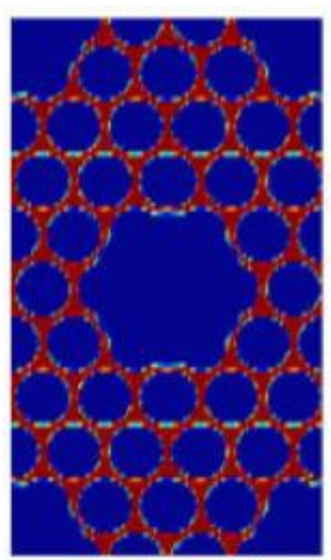


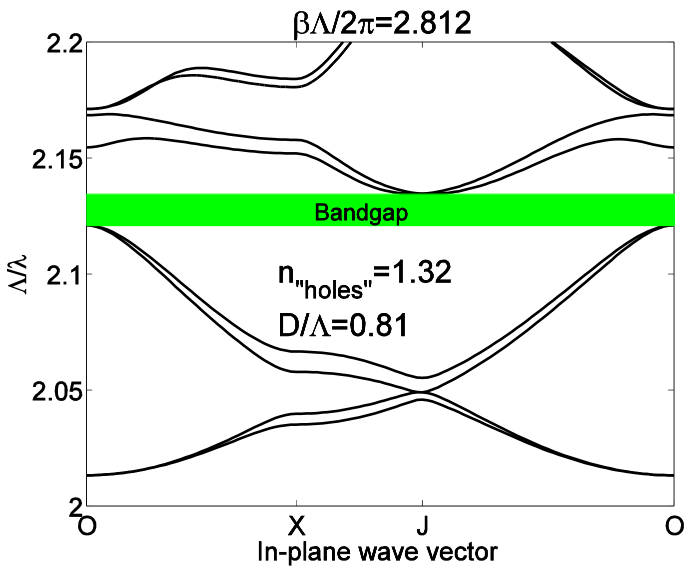
Experimental pictures taken from J.C. Knight et al., Science, **282**, 1476 (1998).

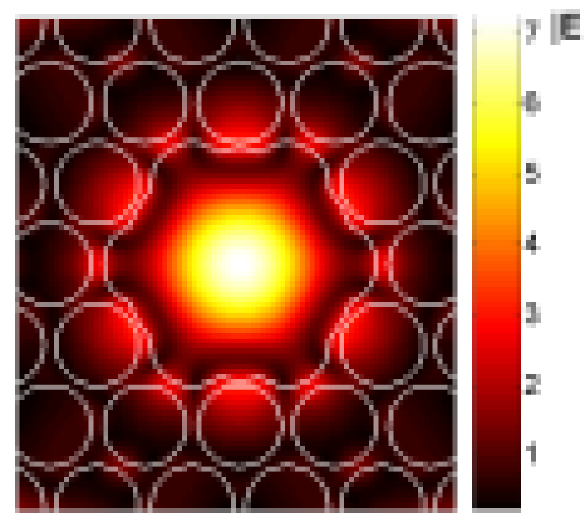
Same fiber with water in the air-holes



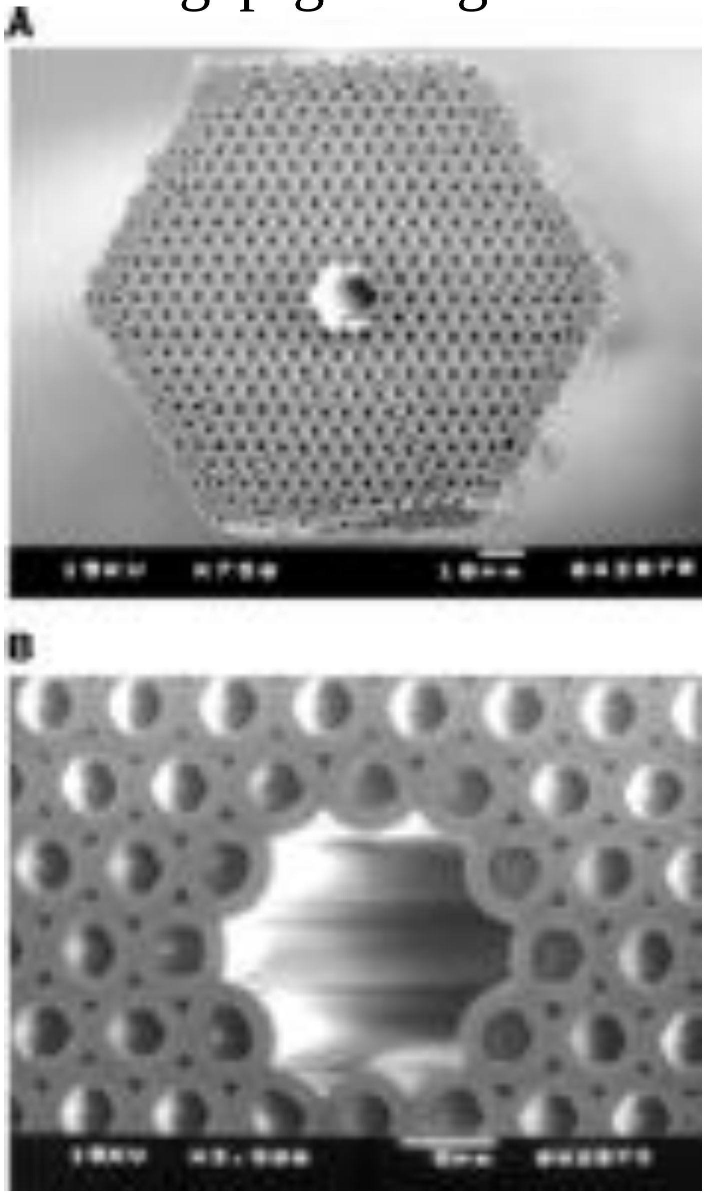


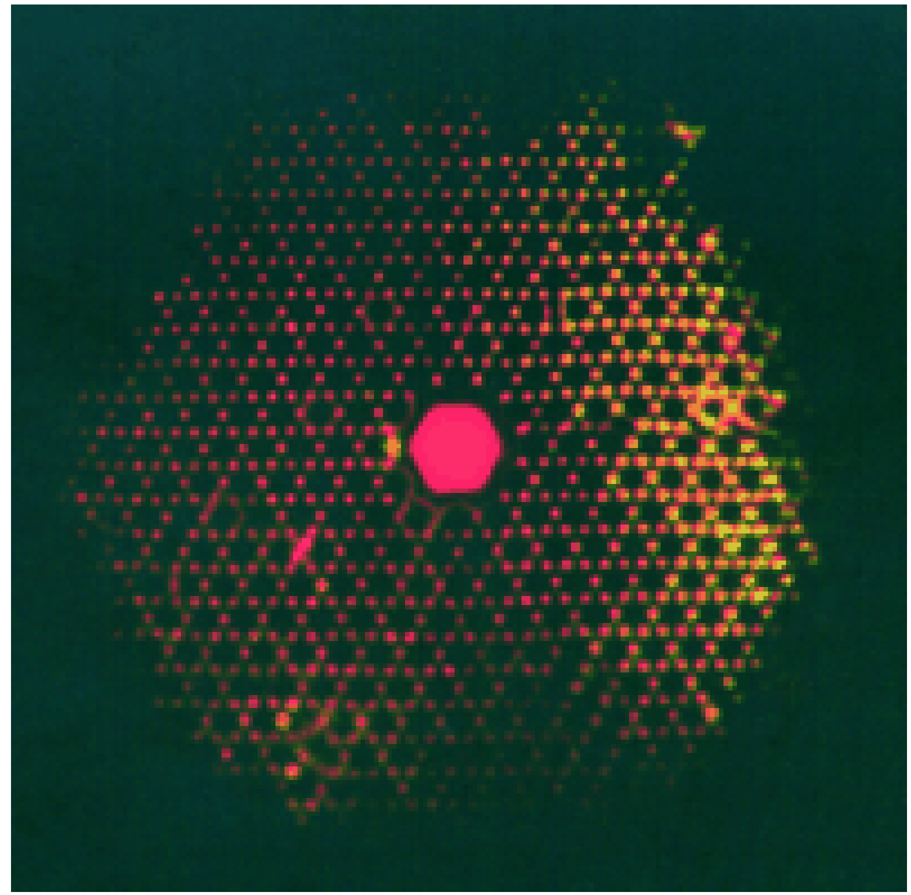






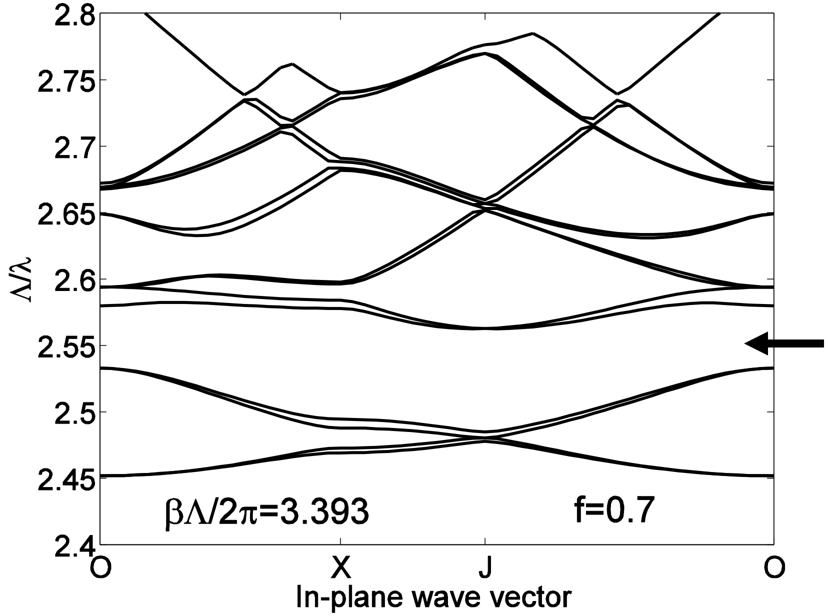
Bandgap-guiding fibres: The triangular fibre with large air-holes

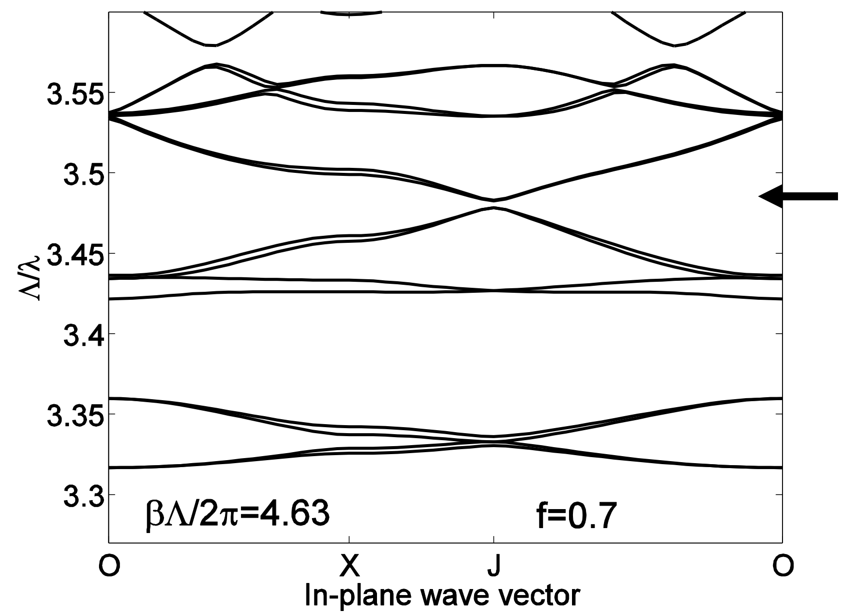




Experimental pictures taken from R.F. Cregan et al., Science, **285**, 1537 (1999).

Band diagrams of photonic crystal fiber-cladding material with water in the air-holes

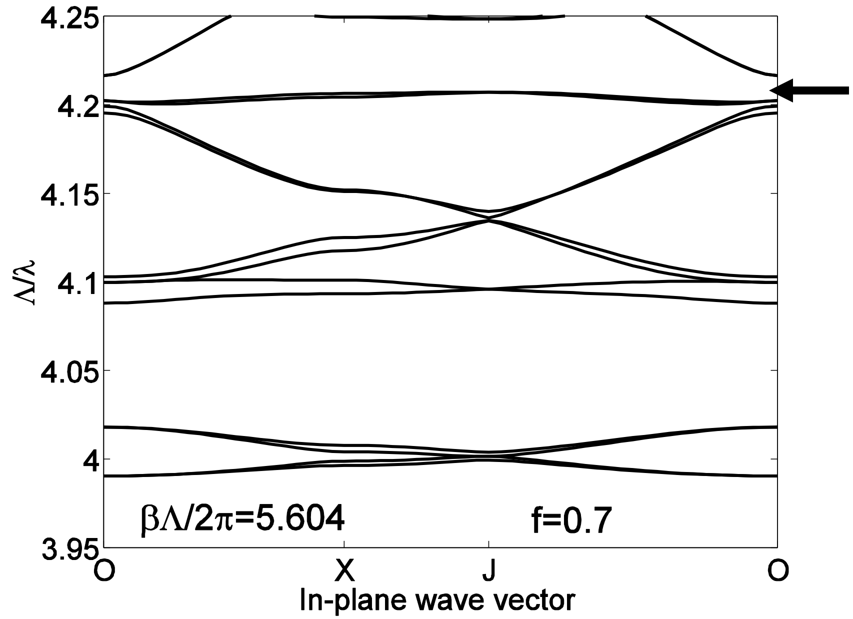




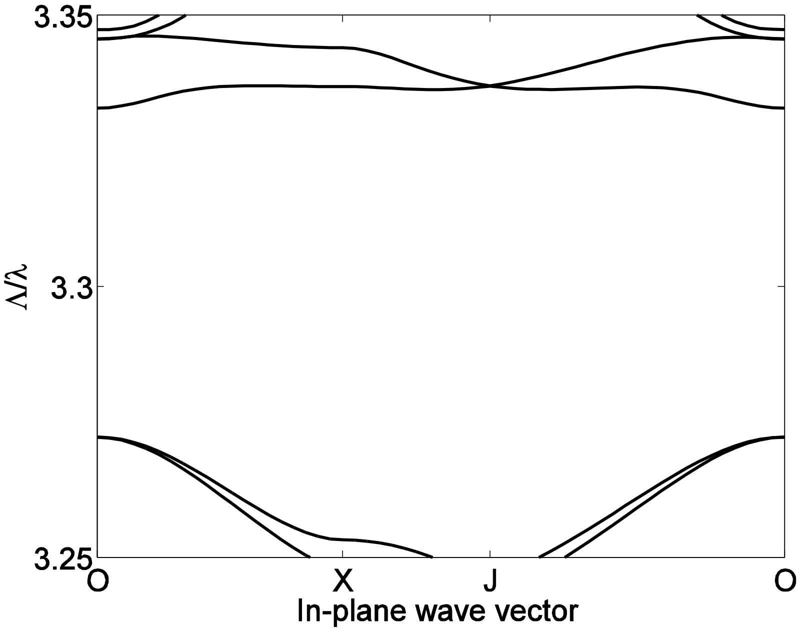
3.393/2.55=1.33

4.63/3.48 =1.33

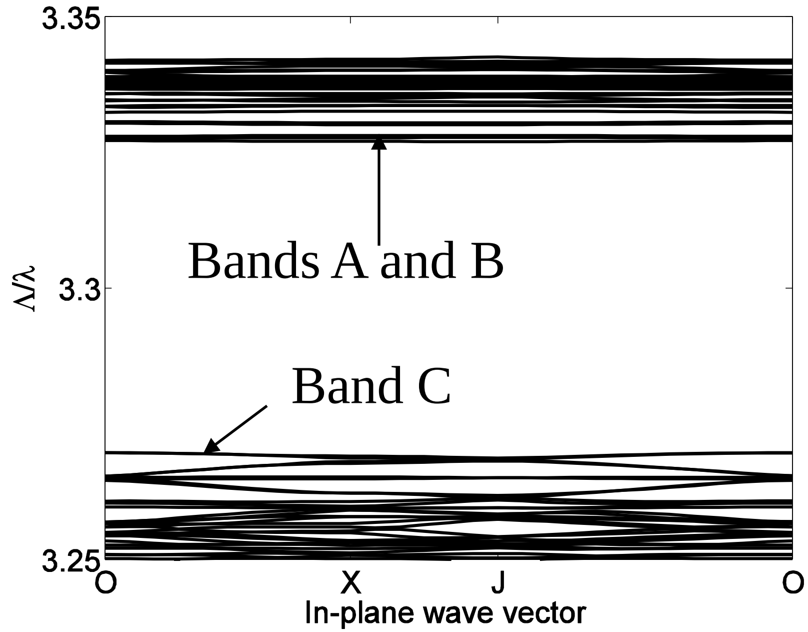
5.604/4.21=1.33



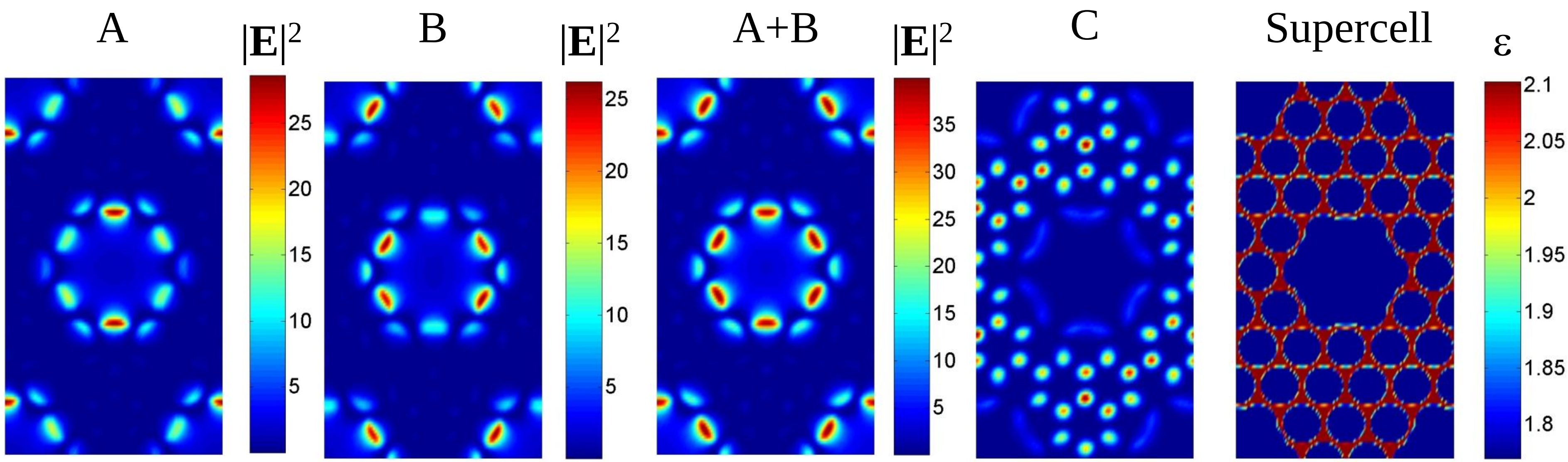
Simple cell (cladding)



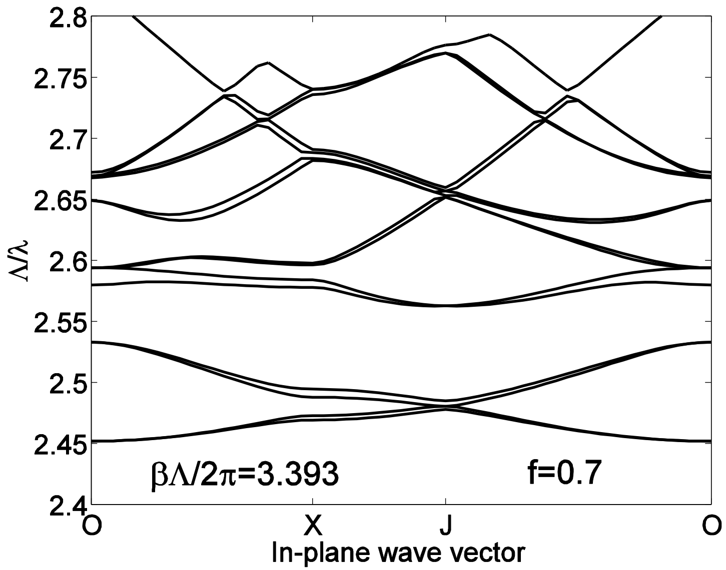
5x5 supercell with large water core region



βΛ/2π=4.5 => β/k0 (A/B)=1.353 > 1.33 => the mode is not primarily in the water



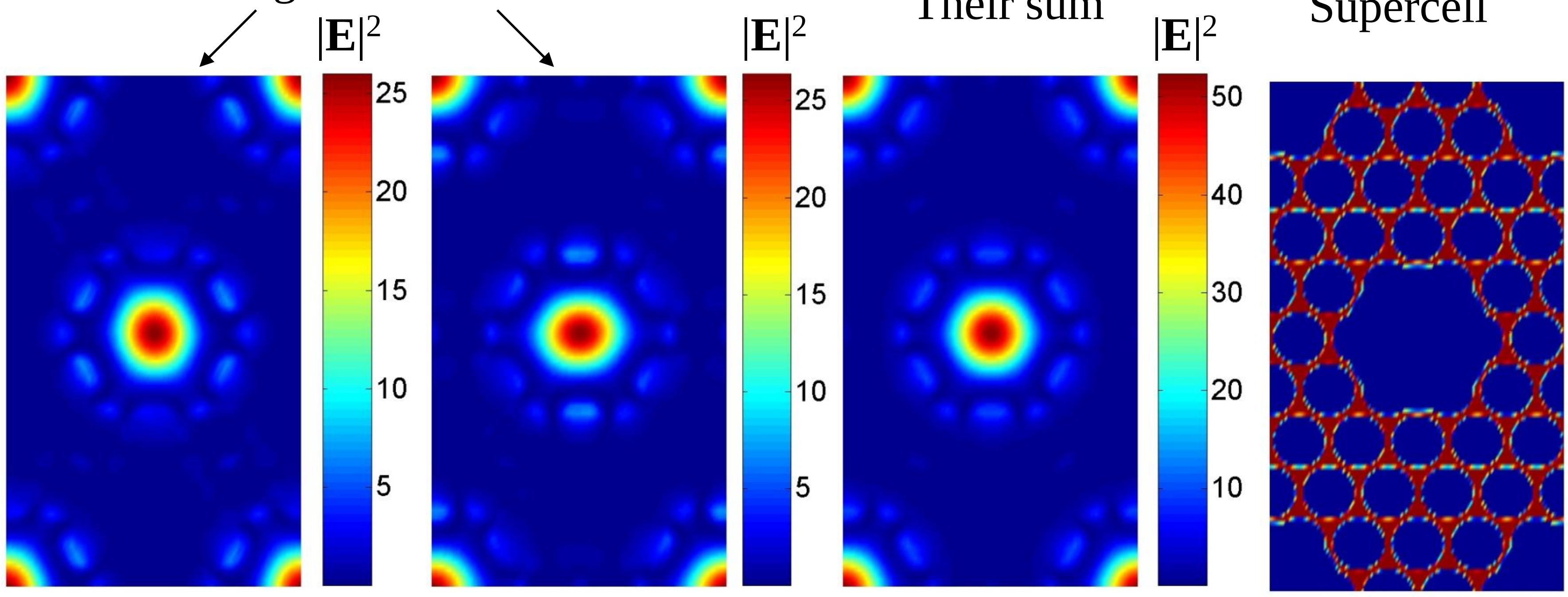
$\beta\Lambda/2\pi$=3.393 => there is a bandgap that can allow modes with a mode index equivalent to the refractive index of water, and such a mode is expected to be primarily confined in the water core region. Calculations show that there are also a large number of localized modes that are not primarily in the water core region similar to the previous slide (at least 10 even for this small core region).

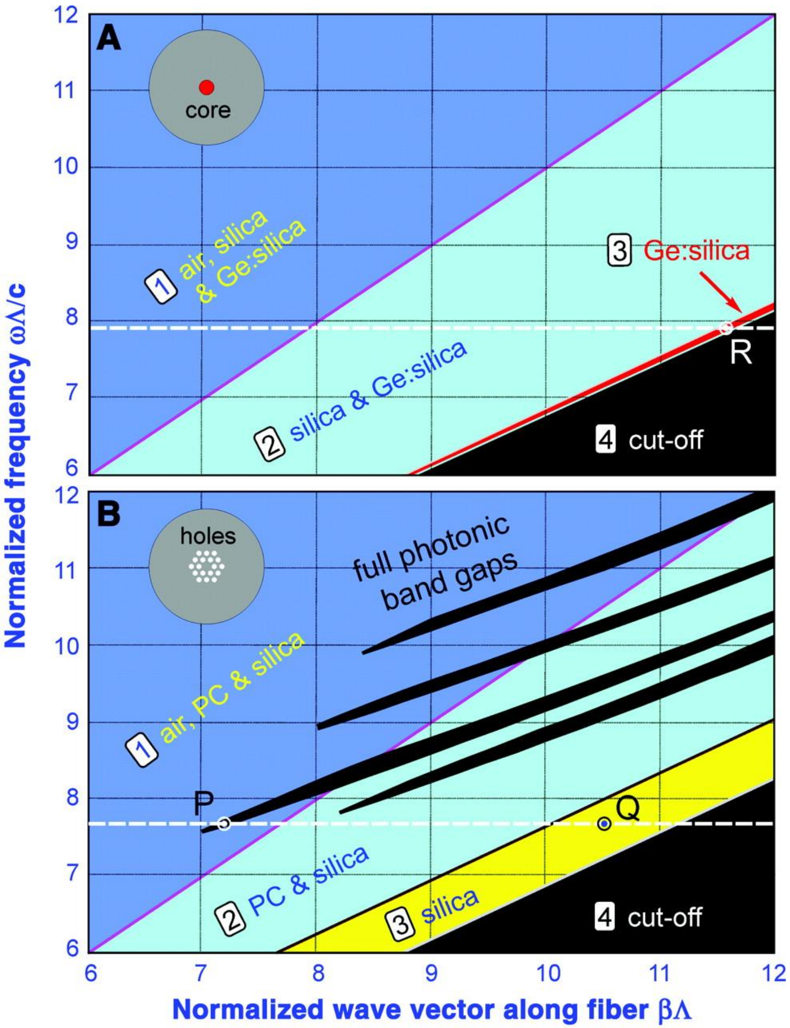


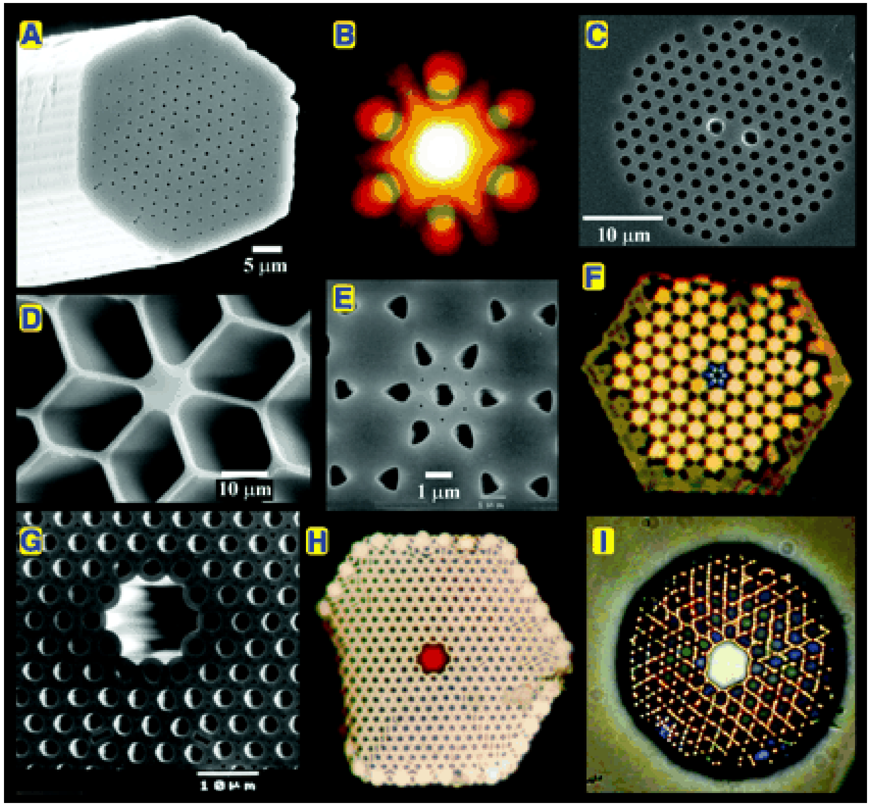
Two degenerate core modes

Their sum

Supercell

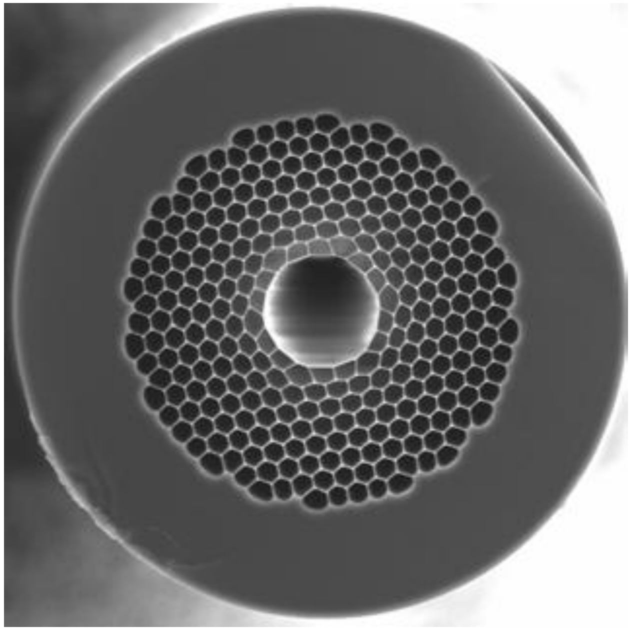


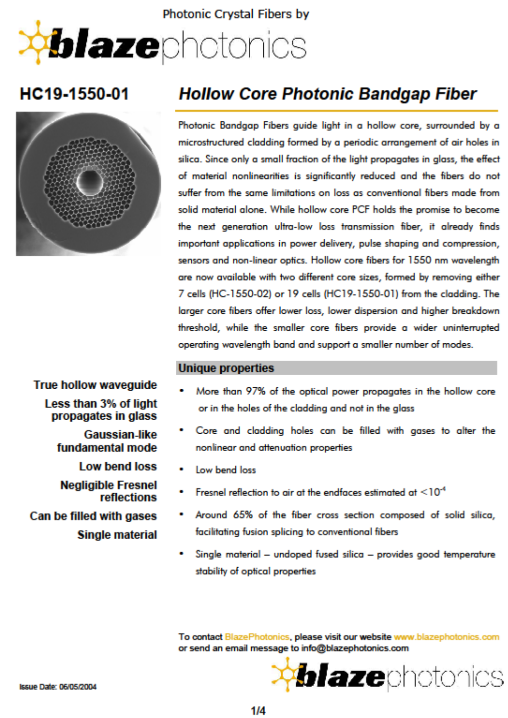




Ref.: P. Russell, Science **299**, 358-62 (2003).

Data sheets




Photonic Crystal Fibers by

blazephotonics

HC19-1550-01

Hollow Core Photonic Bandgap Fiber

Photonic Bandgap Fibers guide light in a hollow core, surrounded by a microstructured cladding formed by a periodic arrangement of air holes in silica. Since only a small fraction of the light propagates in glass, the effect of material nonlinearities is significantly reduced and the fibers do not suffer from the same limitations on loss as conventional fibers made from solid material alone. While hollow core PCF holds the promise to become the next generation ultra-low loss transmission fiber, it already finds important applications in power delivery, pulse shaping and compression, sensors and non-linear optics. Hollow core fibers for 1550 nm wavelength are now available with two different core sizes, formed by removing either 7 cells (HC-1550-02) or 19 cells (HC19-1550-01) from the cladding. The larger core fibers offer lower loss, lower dispersion and higher breakdown threshold, while the smaller core fibers provide a wider uninterrupted operating wavelength band and support a smaller number of modes.

Unique properties

True hollow waveguide
Less than 3% of light propagates in glass
Gaussian-like fundamental mode
Low bend loss
Negligible Fresnel reflections
Can be filled with gases
Single material

- More than 97% of the optical power propagates in the hollow core or in the holes of the cladding and not in the glass
- Core and cladding holes can be filled with gases to alter the nonlinear and attenuation properties
- Low bend loss
- Fresnel reflection to air at the endfaces estimated at $<10^{-4}$
- Around 65% of the fiber cross section composed of solid silica, facilitating fusion splicing to conventional fibers
- Single material – undoped fused silica – provides good temperature stability of optical properties

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Issue Date: 06/05/2004

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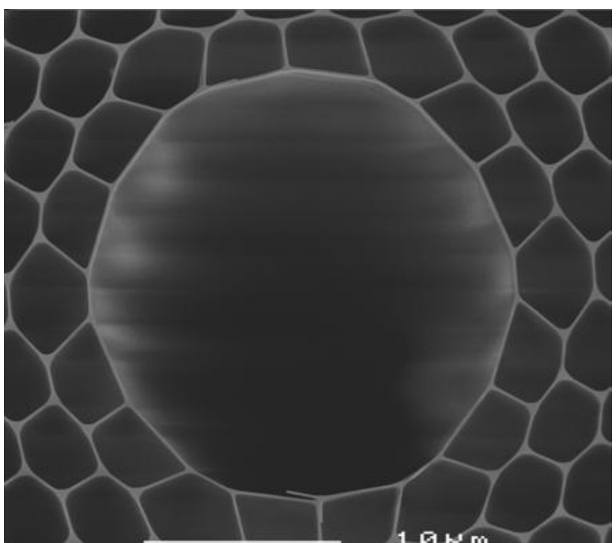

Physical properties

- Core diameter 20 μm ± 2 μm
- Pitch (distance between cladding hole centers) 3.9 μm
- Air Filling Fraction in the holey region > 90%
- Diameter of holey region 73 μm
- Diameter of silica cladding 115 μm
- Coating diameter (single layer acrylate) 220 μm
- Available length up to 1 km