Ústav fotoniky
a elektroniky

OPTICAL FIBERS FOR FUTURE TELECOMMUNICATIONS AND ENERGY TRANSFER

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OUTLINE

- Limits of standard optical fibers
- Photonic band-gap fibers – structure, principle
- Microstructure fibers – structure, principle
- Preparation of photonic band-gap fibers, microstructure fibers, examples of real structures, their use for sensing
- Bragg fibers for energy transfer

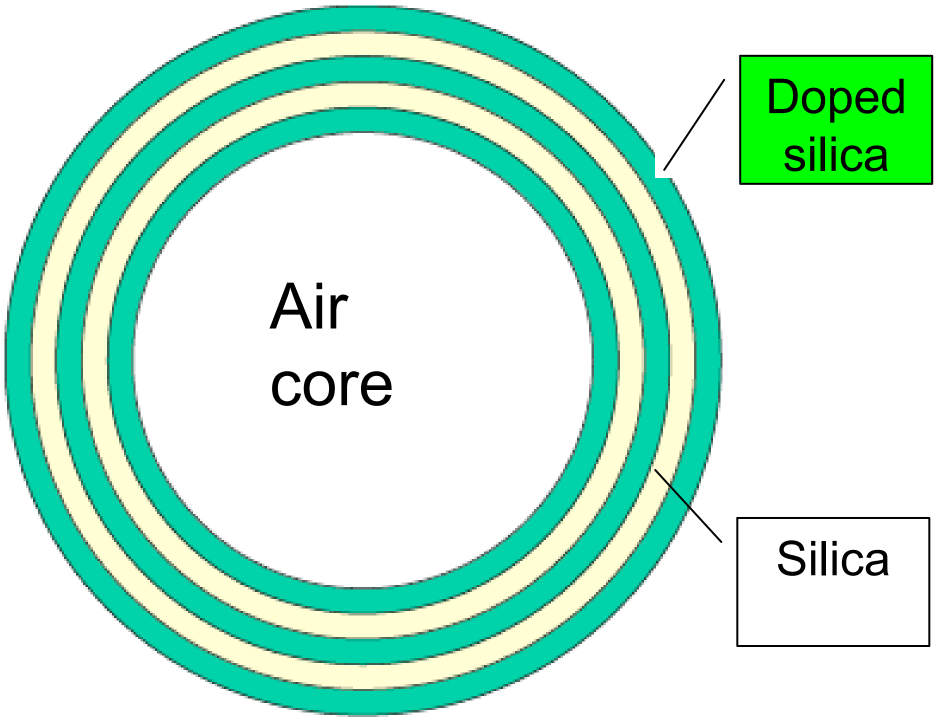
LIMITS OF SILICA

- Losses: 0.2 dB/km→ amplifiers every 50-100 km further decrease limited by Rayleigh scattering, can' t be used in MIR
- Nonlinearities: effect after ~ 100 km, cause dispersion, power limits; they can' t be made very large for nonlinear devices
- Radical modification to dispersion and polarization effects

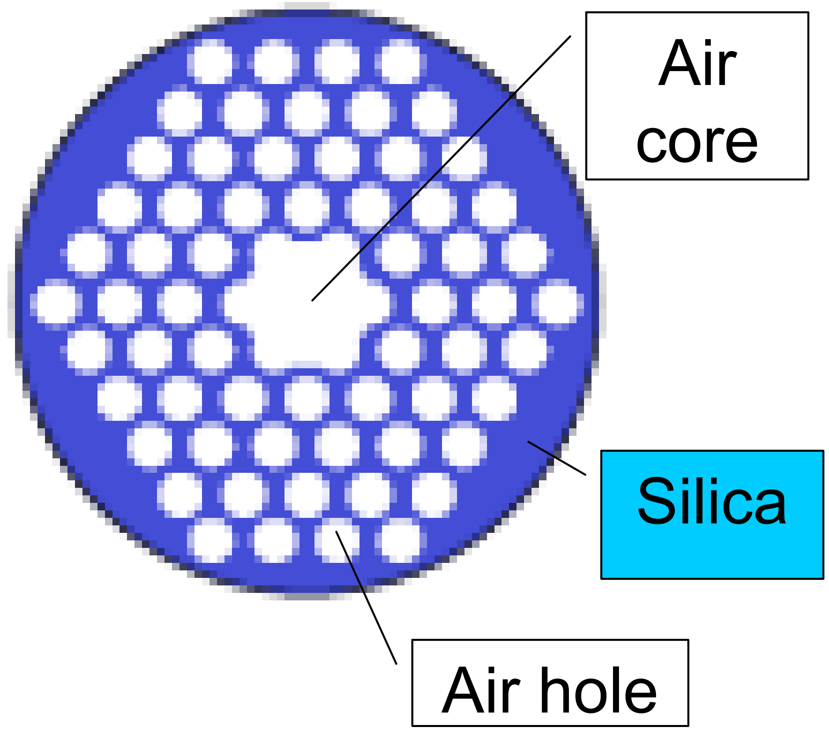
Solution - photonic crystal fibers where **light is confined in an air core**

HOLLOW-CORE BAND GAP FIBER (HCBGF)

1D Photonic crystal – Bragg fiber

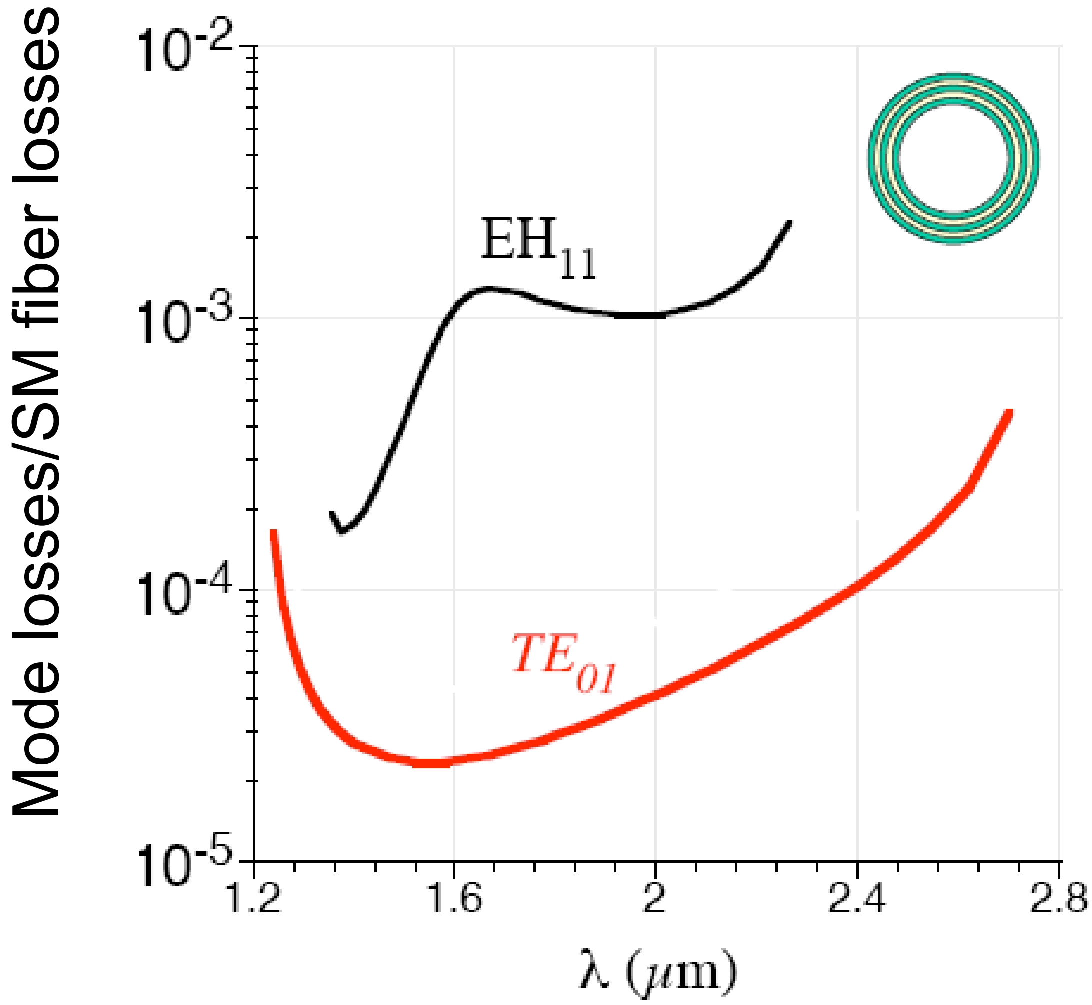


2D Photonic crystal – Photonic Crystal Fiber

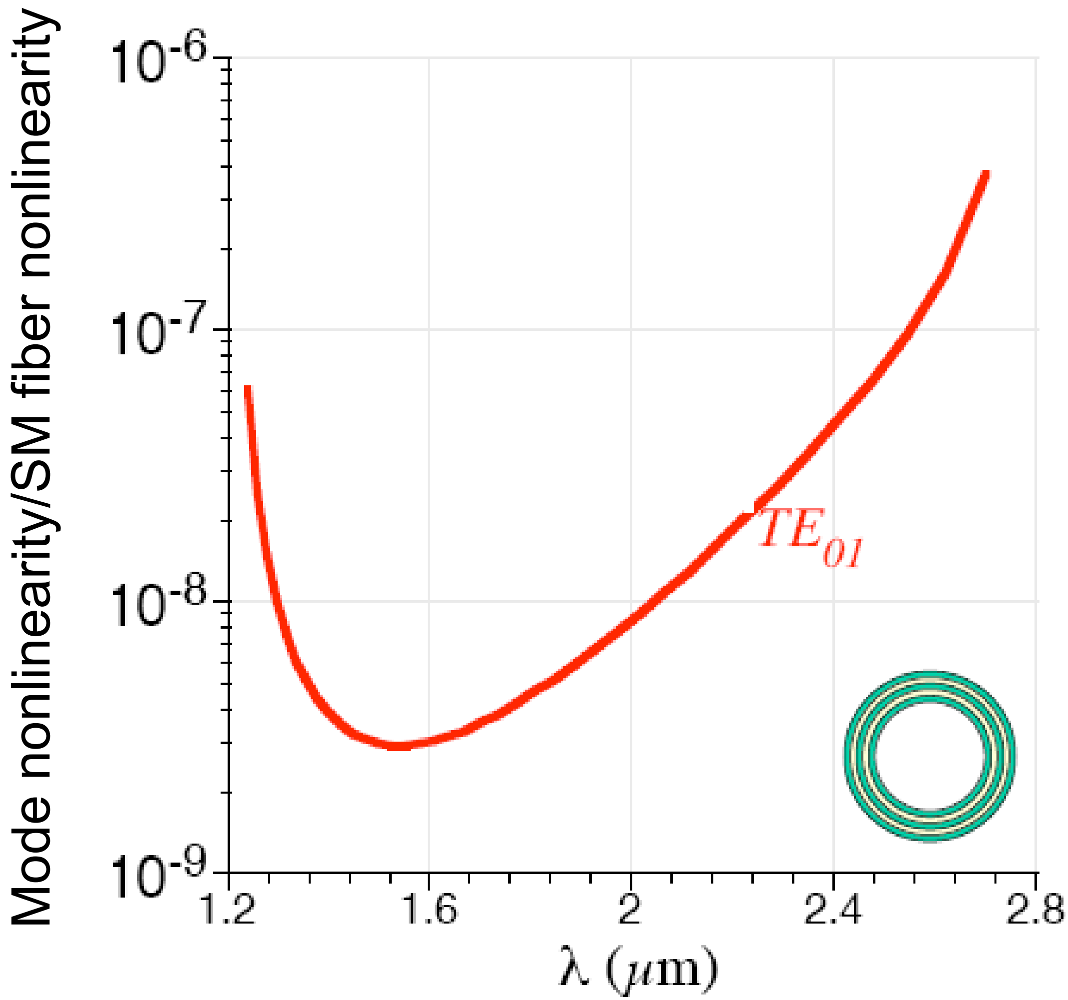


1000 times lower losses and nonlinearities than silica fibers

DECREASE OF FIBER LOSSES



DECREASE OF FIBER NONLINEARITY

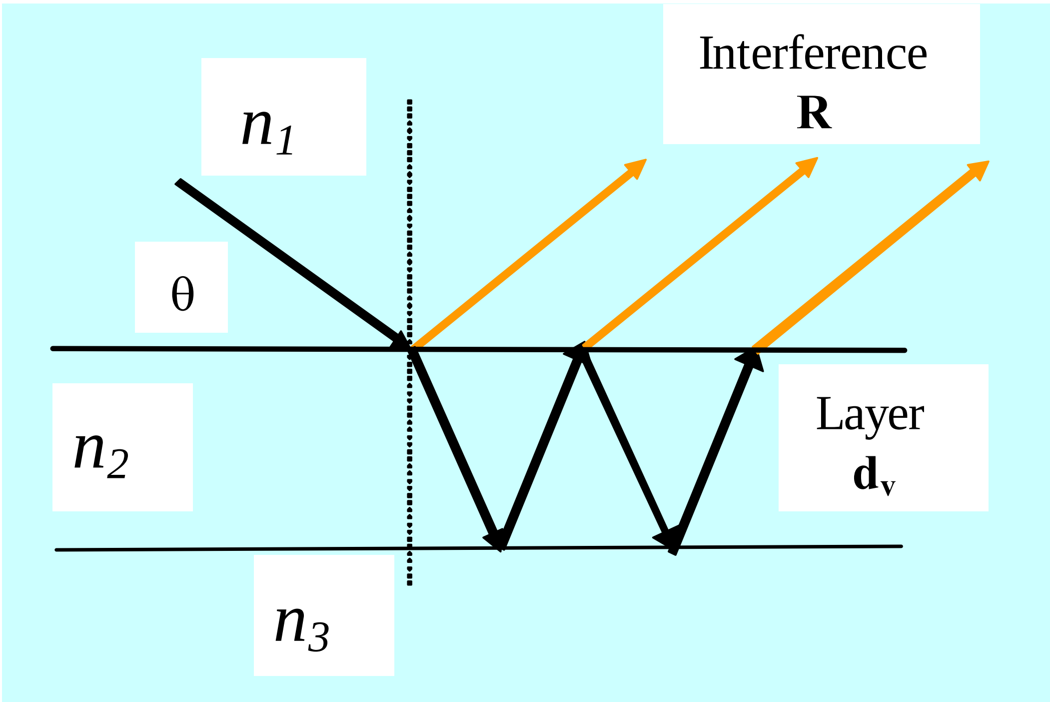


WHY LIGHT IS GUIDED IN AIR CORES OF HCBGF?

No total reflection of light on the core/grid boundary $n_{co} < n_{grid}$

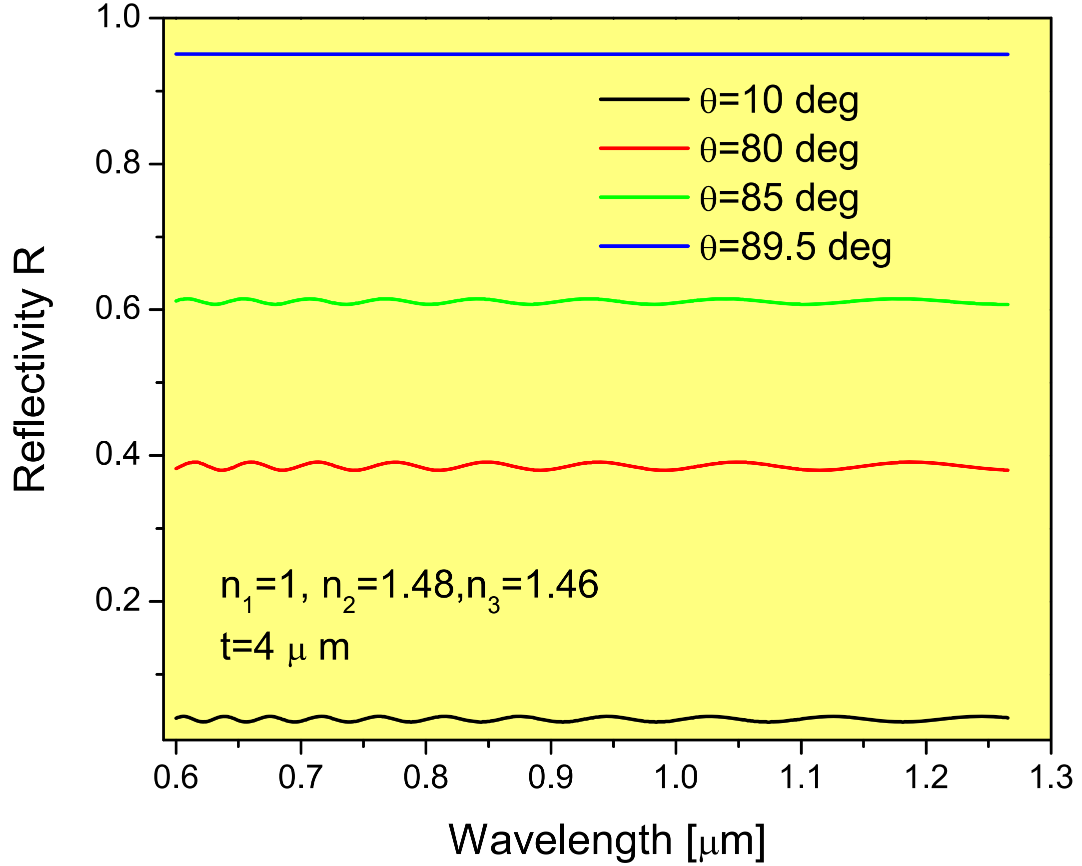
Bragg reflection from regular grid in the fiber cladding

Reflection on a layer (1D grid)



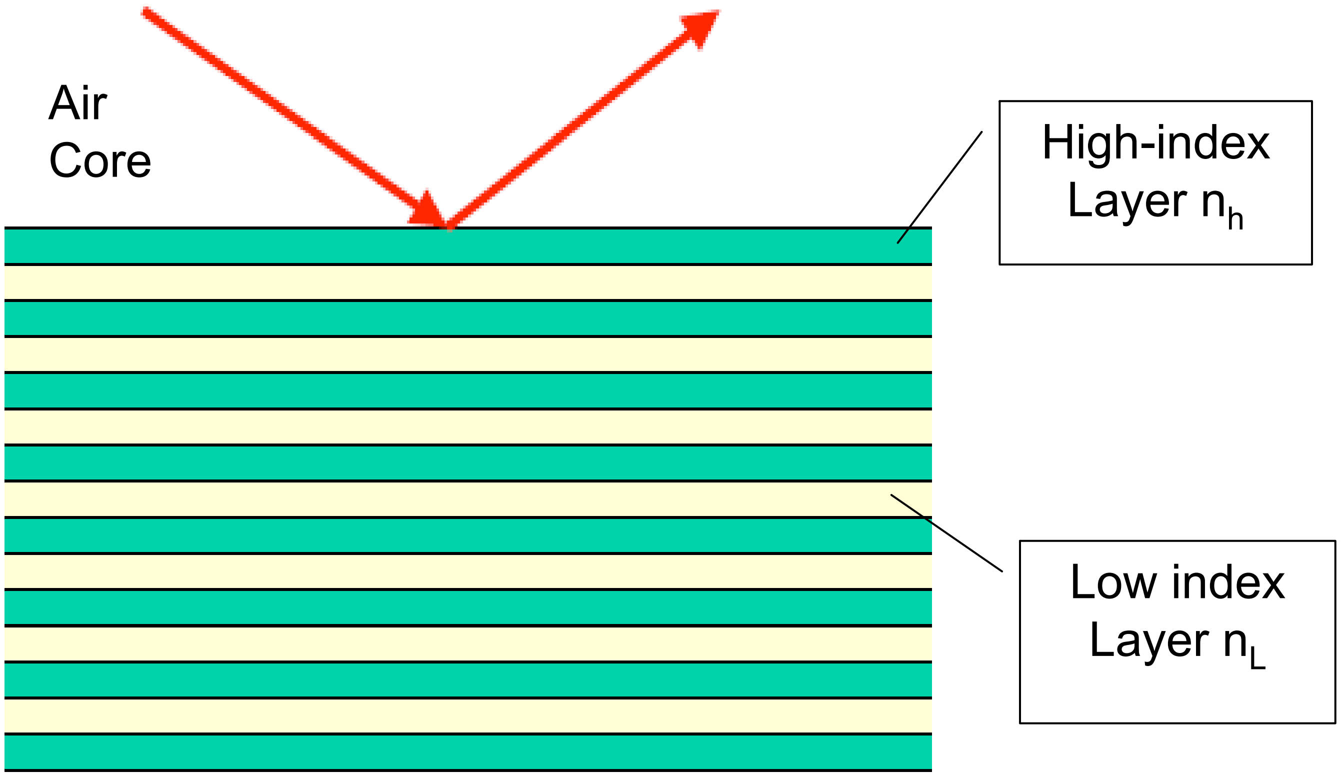
WHY FIBER PIPES CAN GUIDE LIGHT?

Modulations of R due to light interference



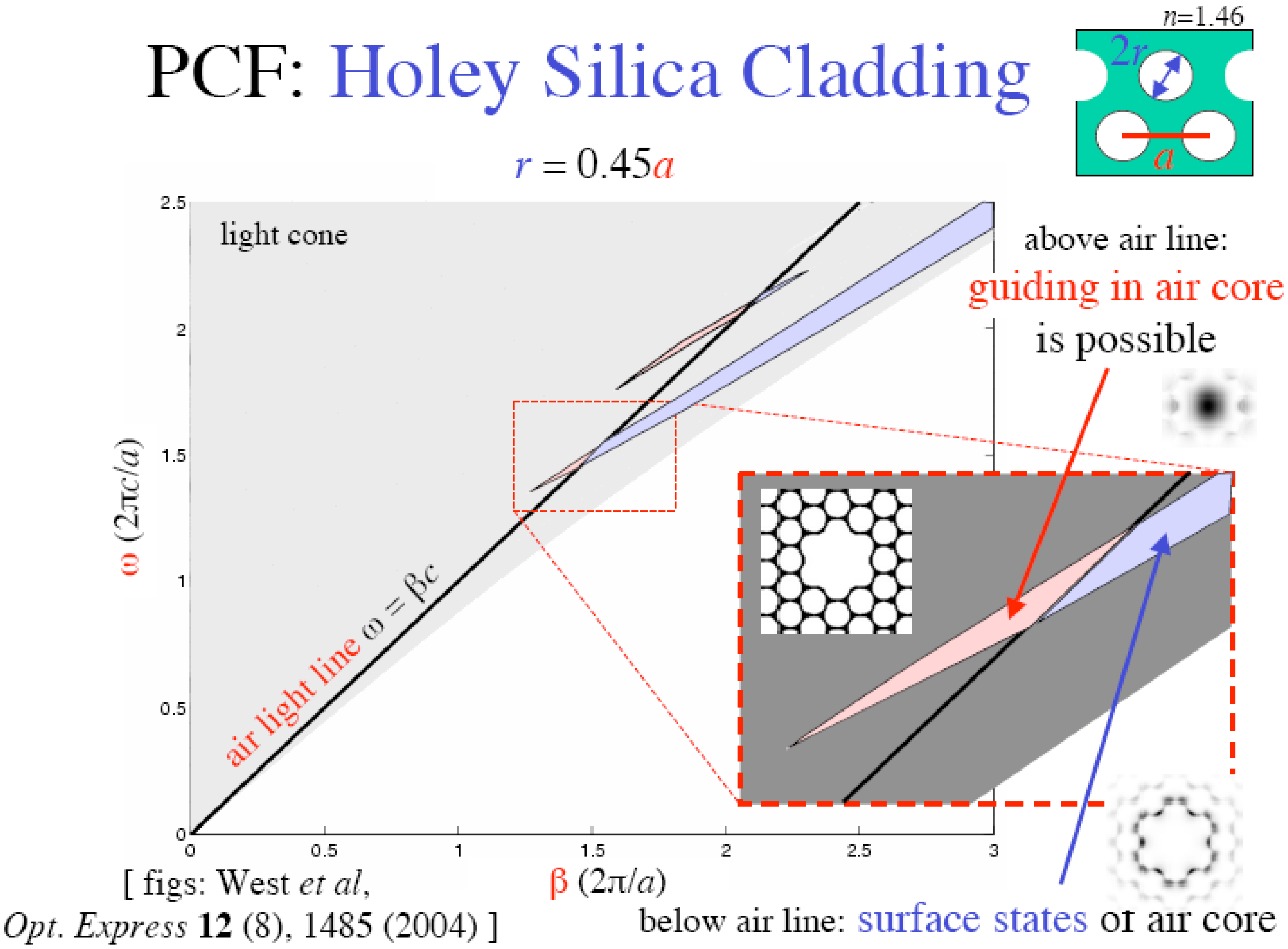
R =1 photonic bandgap, at some values of θ,λ - light guiding

MULTILAYER STACK



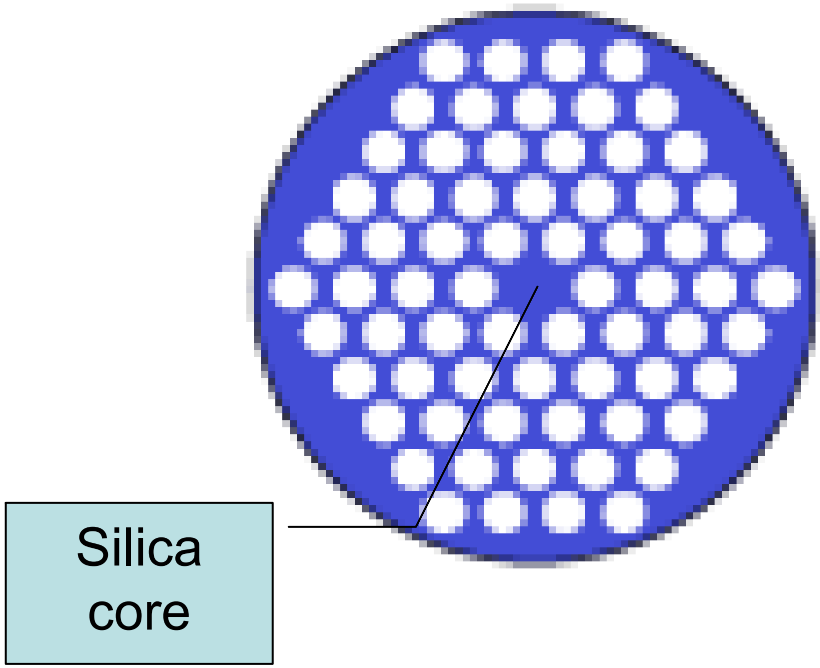
Increased number of layers and $n_H - n_L \rightarrow$ light is more confined in the air core $\beta \leq < \omega c$

PHOTONIC CRYSTAL FIBERS



BAND GAP FIBERS WITH SOLID CORES

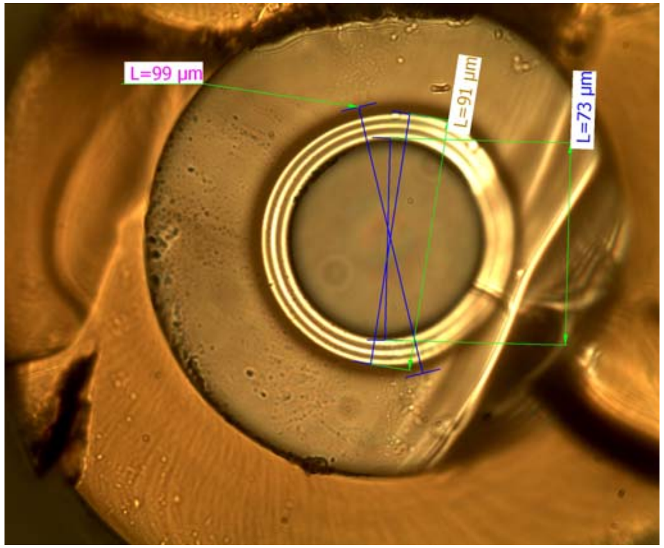
- **Bragg fibers** with silica cores – light is guided due to photonic band gap
- **PCF = Microstructure fibers (MSFs)** – light is guided due to total reflection, because air holes in silica cladding decrease its refractive index below that of silica

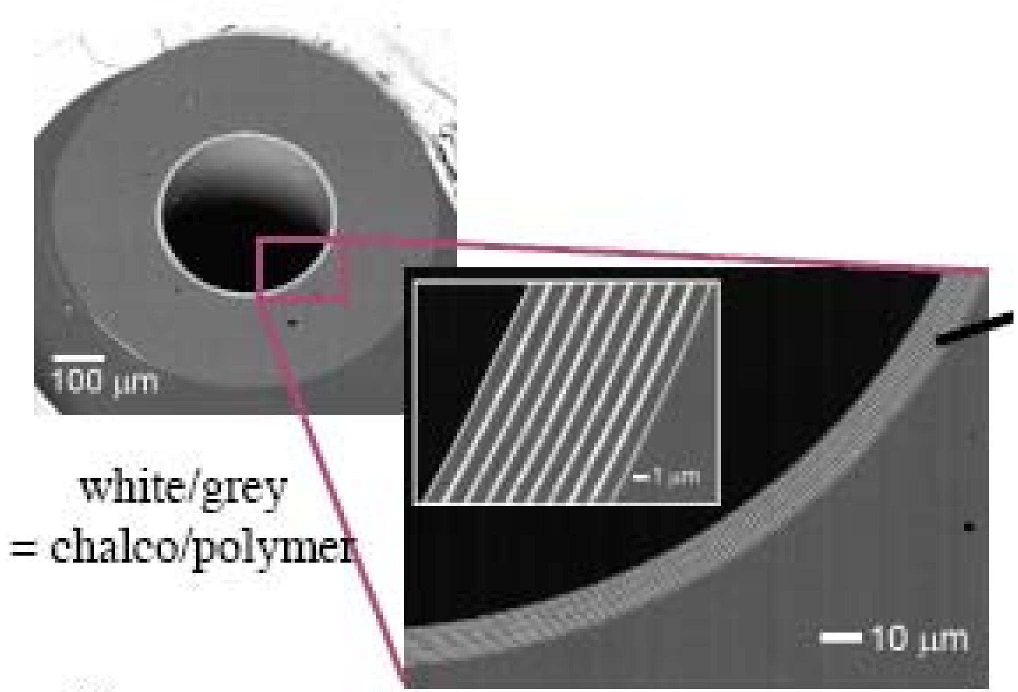


$$n_{clad}^2 = n_{silica}^2 (1 - P) + P$$

P – porosity, ↑ with a number and dimensions of air holes

BRAGG FIBERS WITH AIR CORES

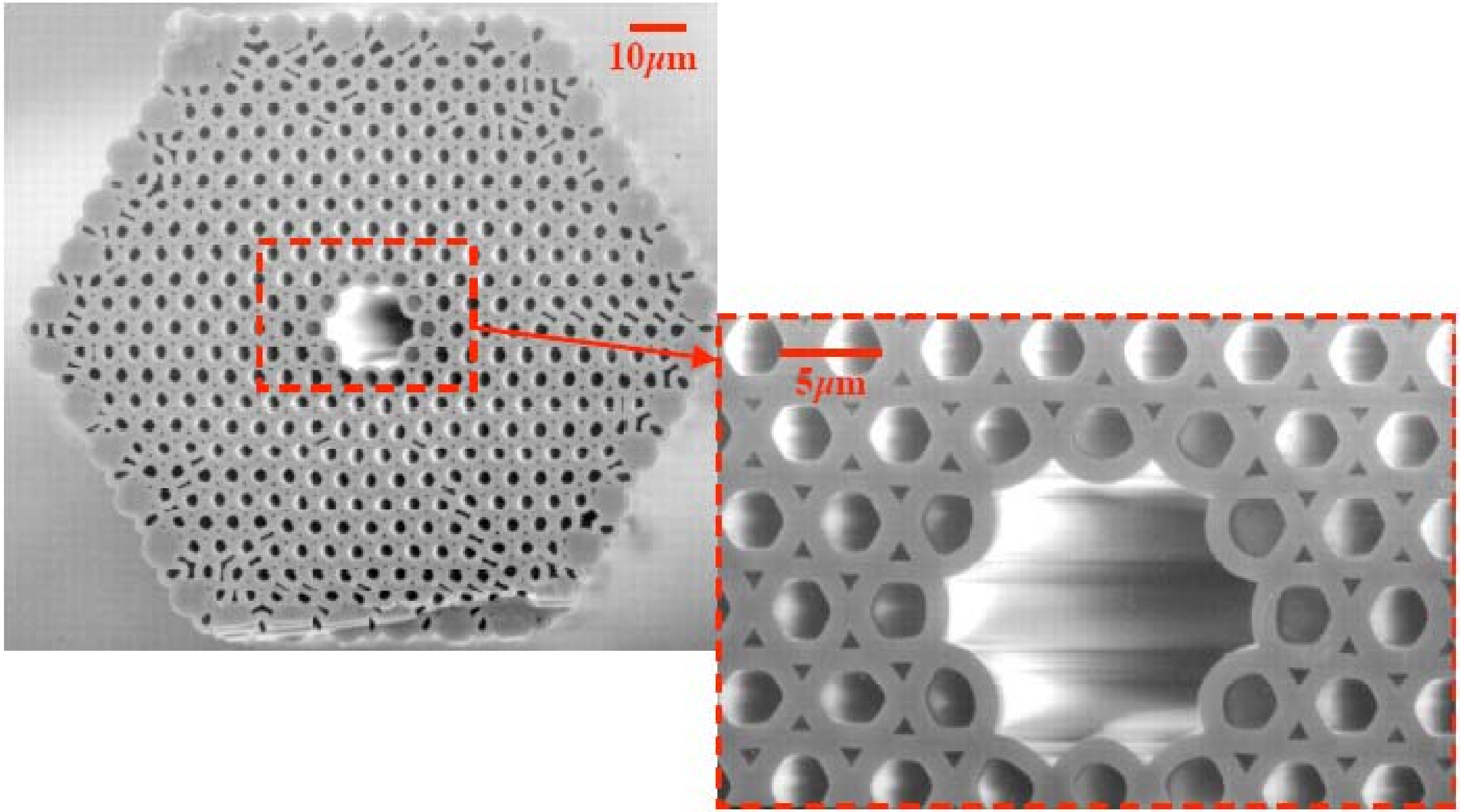




Silica fiber (IPE)

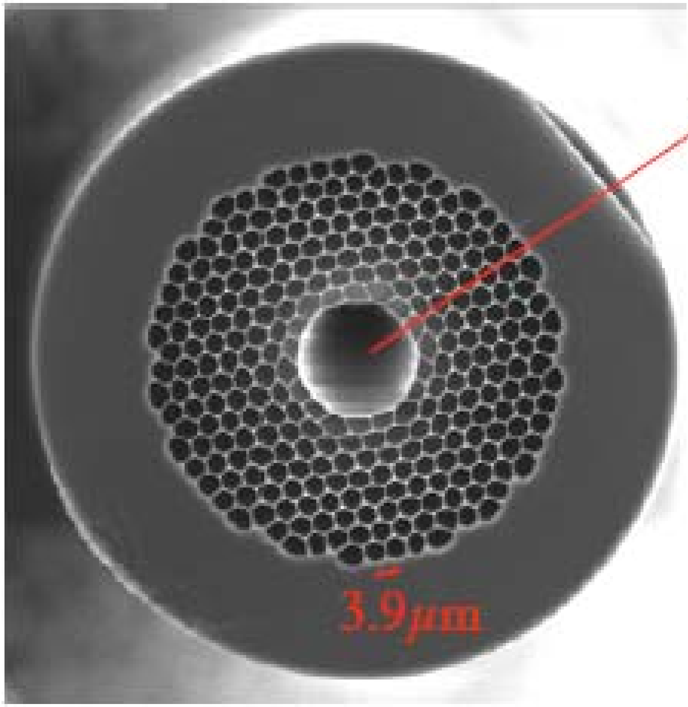
Chalcogenide/polymer fiber (MIT USA)

REAL AIR-CORE BGF



R. F. Cregan *et al.*, *Science* 285, 1537 (1999)

REAL AIR CORE BGF



Air core

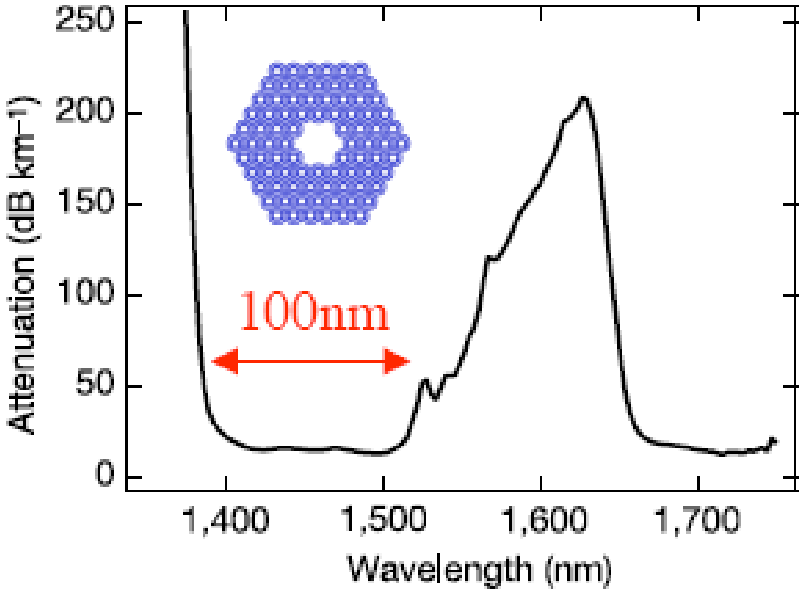
Losses 1, 7 dB/km at 1570 nm

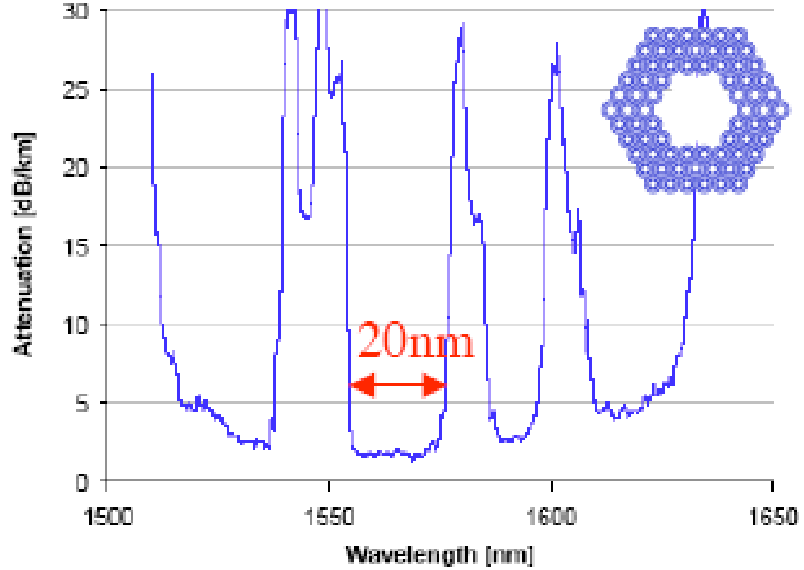
Mangan *et al., Conference* OFC 2004, paper PDP24

Losses 0.28 dB/km at 1550 nm

Tajima, ECOC 2003

LOSSES OF AIR CORE BGF





Small air core

13 dB/km -1500 nm

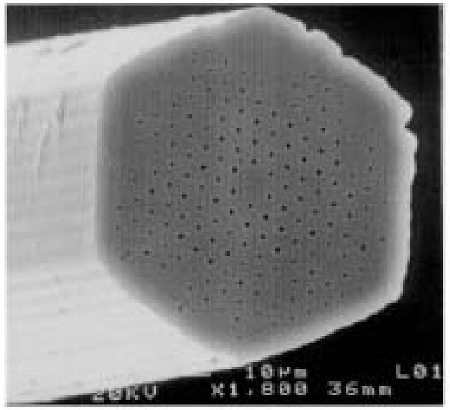
Smith, *et al.*, *Nature* 424, 657 (2003)

Large air core

1.7 dB/km – 1570 nm

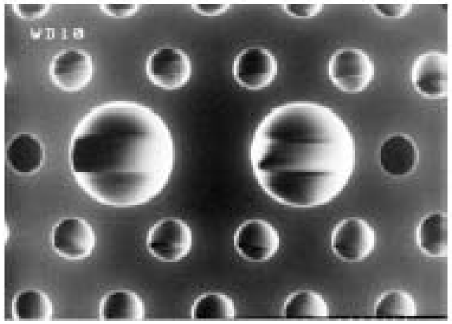
Mangan, *et al.*, *OFC 2004*, PDP24

REAL MSFs



endlessly
single-mode

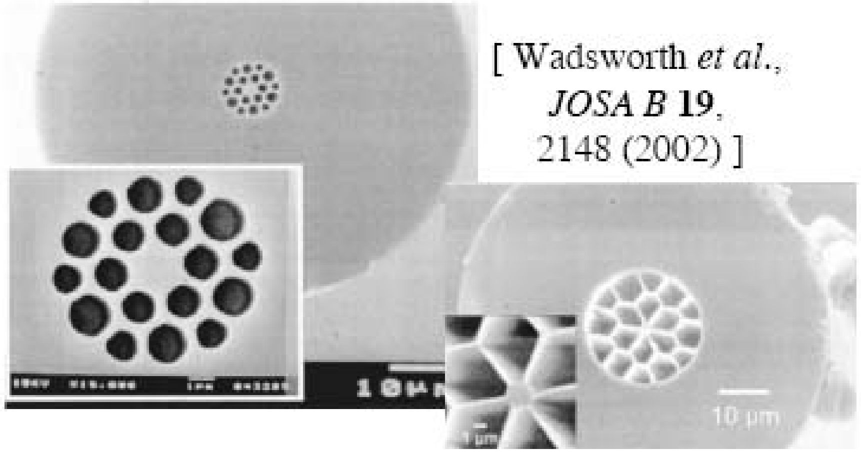
[T. A. Birks *et al.*,
Opt. Lett. **22**,
961 (1997)]



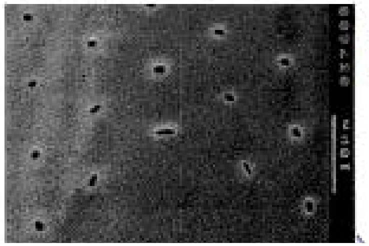
polarization
-maintaining

[K. Suzuki,
Opt. Express **9**,
676 (2001)]

nonlinear fibers



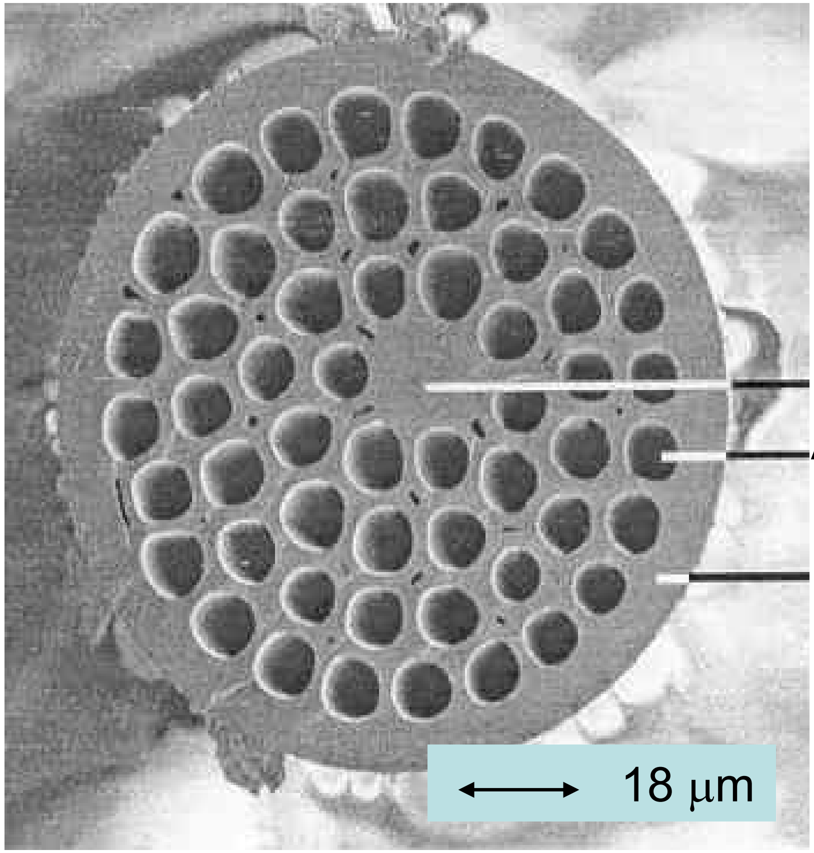
[Wadsworth *et al.*,
JOSA B **19**,
2148 (2002)]



low-contrast
linear fiber
(large area)

MSFs WITH DOPED CORES

d_{hole} ~ 9 μm
Λ ~ 12 μm



Nd-doped core,
Al oxide in silica

Treshold ~ 220 mW, Slope efficiency ~ 6%, L ~ 0.38 m, Direct pump 805 nm, Emission 1060 nm

P. Glas et al. , Opt. Expr. 10(6), 286-290 (2002)

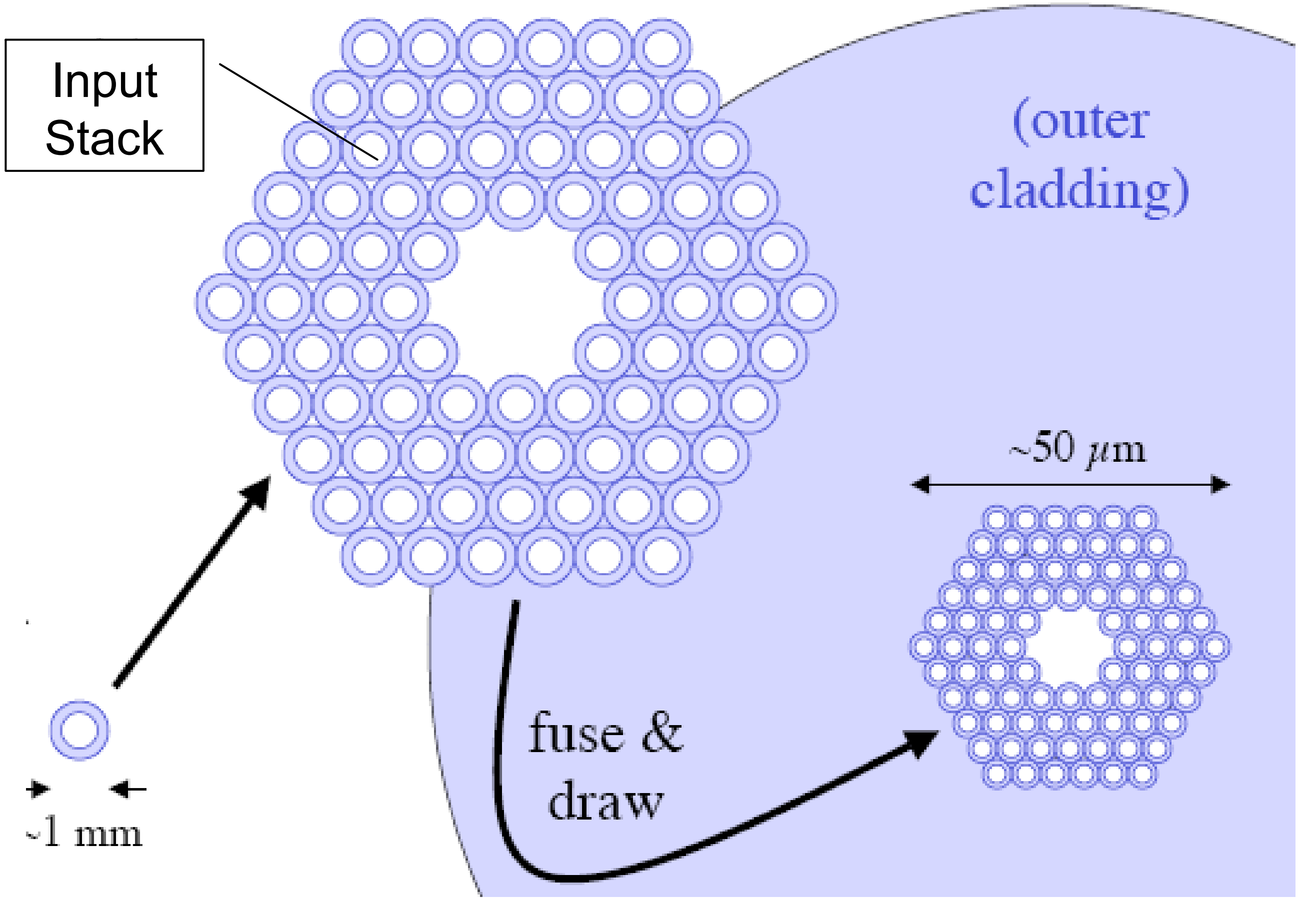
FABRICATION OF MSFs AND HCBGFs

- Usually "Stack and Draw" technique

  An **input stack** is set from a central silica rod (tube) and surrounded by silica tubes

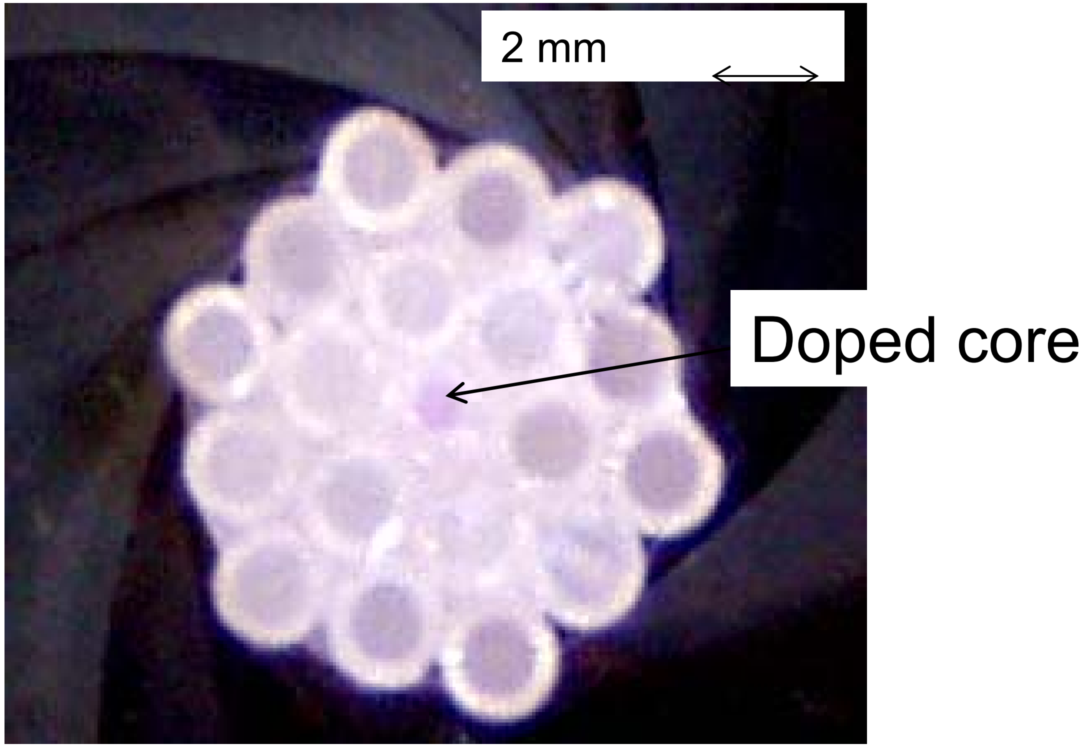
  The **stack is inserted into a silica tube** and fiber is drawn
- Sol-Gel technique (USA)

PRINCIPLE OF STACK AND DRAW METHOD



The input stack inserted into a silica tube and fiber drawn

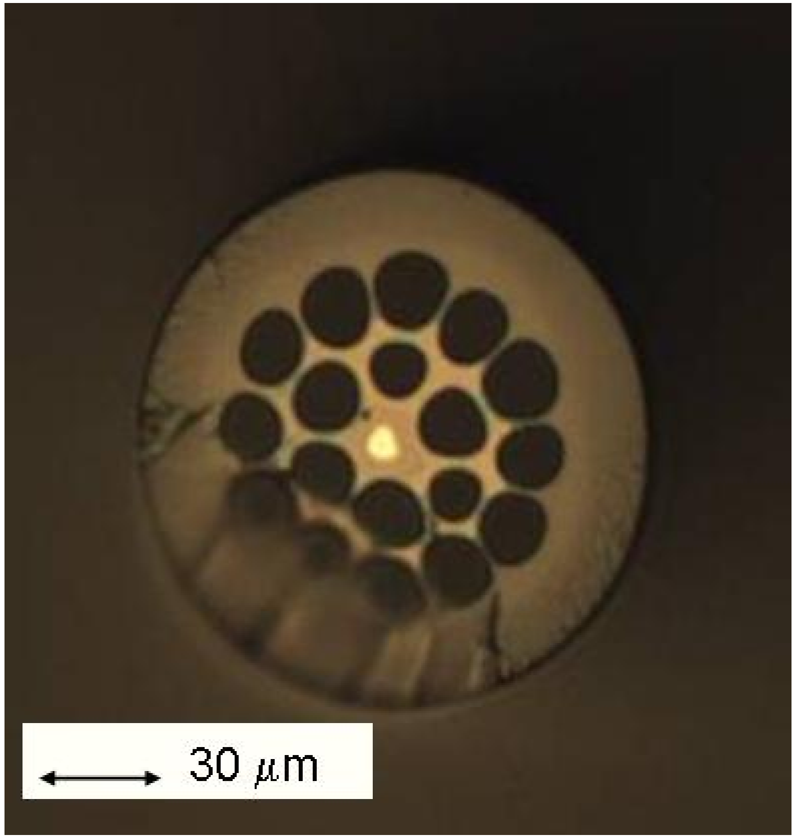
MSF FOR LASERS - INPUT STACK IPE



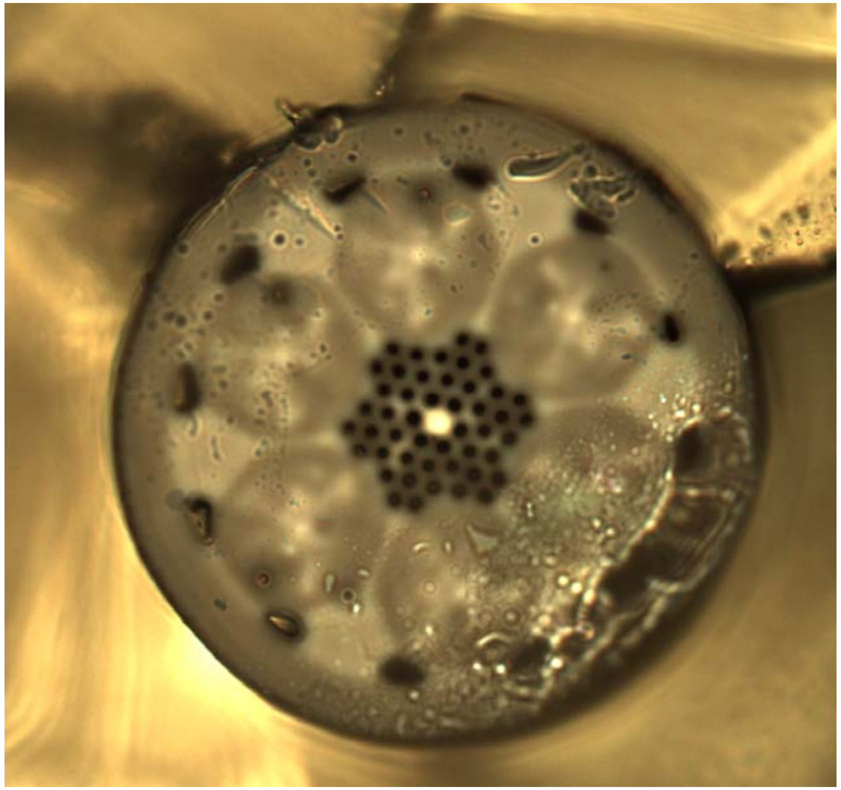
Rod of silica doped with Er and phosphorous pentoxide used in the stack center instead of capillary

MSFs IPE

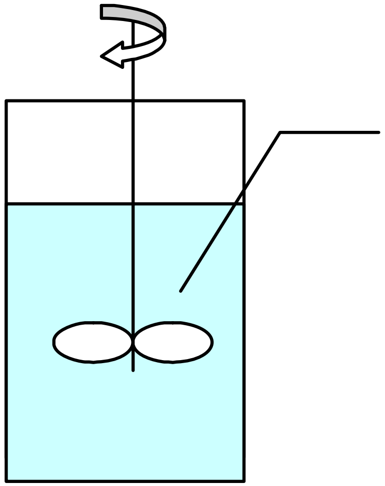
MSFs for fiber lasers



Flower MSFs



SOL-GEL PROCESS (USA - BELL LAB)



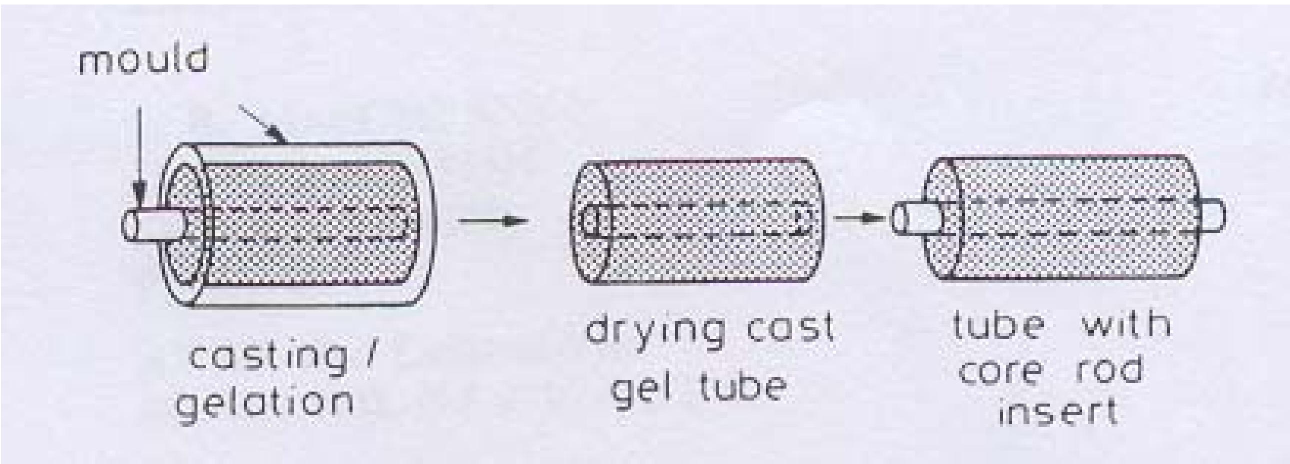
pH~11

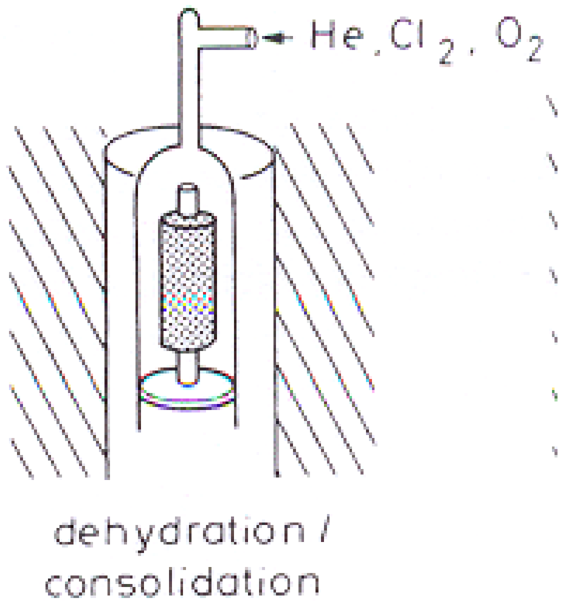
Fumed silica
50 m^2/g; 46%
Water
TMAH
Lubricant
Polymer

Centrifugation

Vacuum deaeration

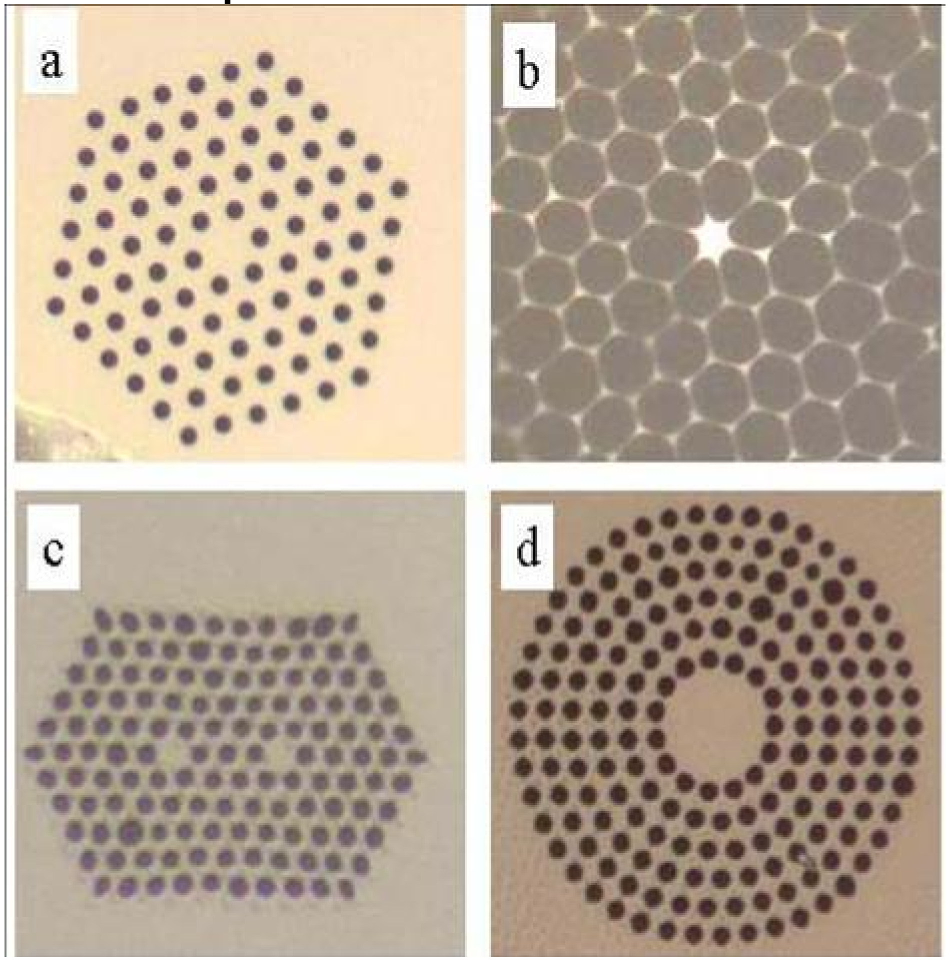
Addition of ester





MSF VIA SOL-GEL METHOD

multiple mandrel elements



a) Endlessly SM design

b) Highly non-linear fibers

c) Dual-core fibers

d) Circular-core fibers

R.T. Bise, et al., http://www.specialtyphotonics.com/pdf/knowledge_base/white_papers/microstructure/bise_ofc_2005.pdf

WHY TO EMPLOY PCFs AND MSFs

- Optical communications (HCBGFs)

  Broad single-mode range (400-1700 nm)

  (T.A. Birks *et al.*, *Opt. Lett.* **22** 961-963 1997)

  Unique dispersion characteristics (λ_{0D}<1000 nm)

  (J.K. Ranka *et al.*, *Opt. Lett.* **25** 796-798 2000)

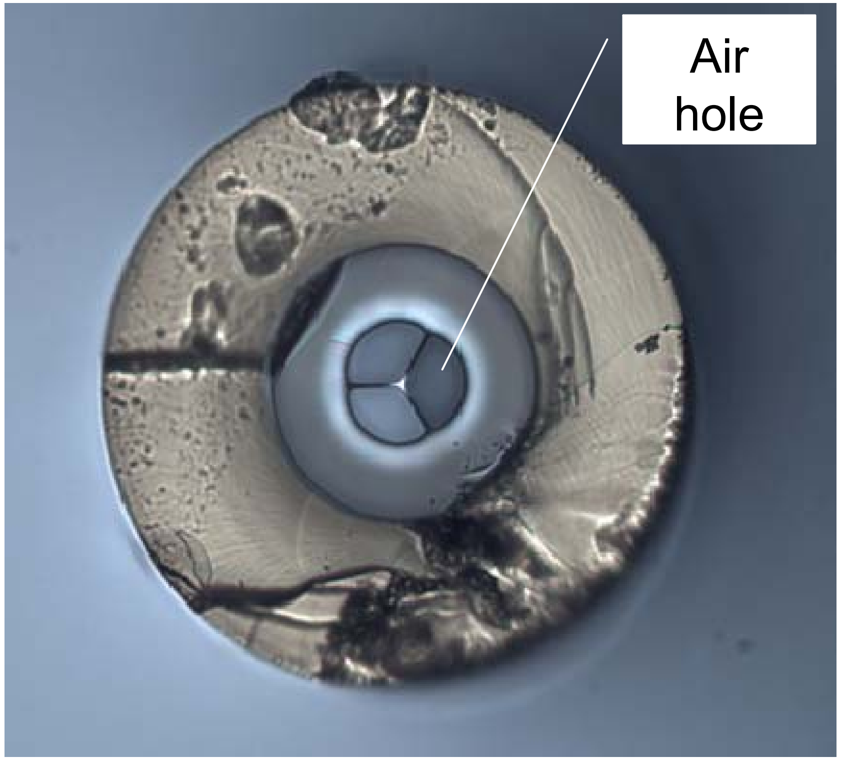
  Unique nonlinear optical properties (a broadband continuum)

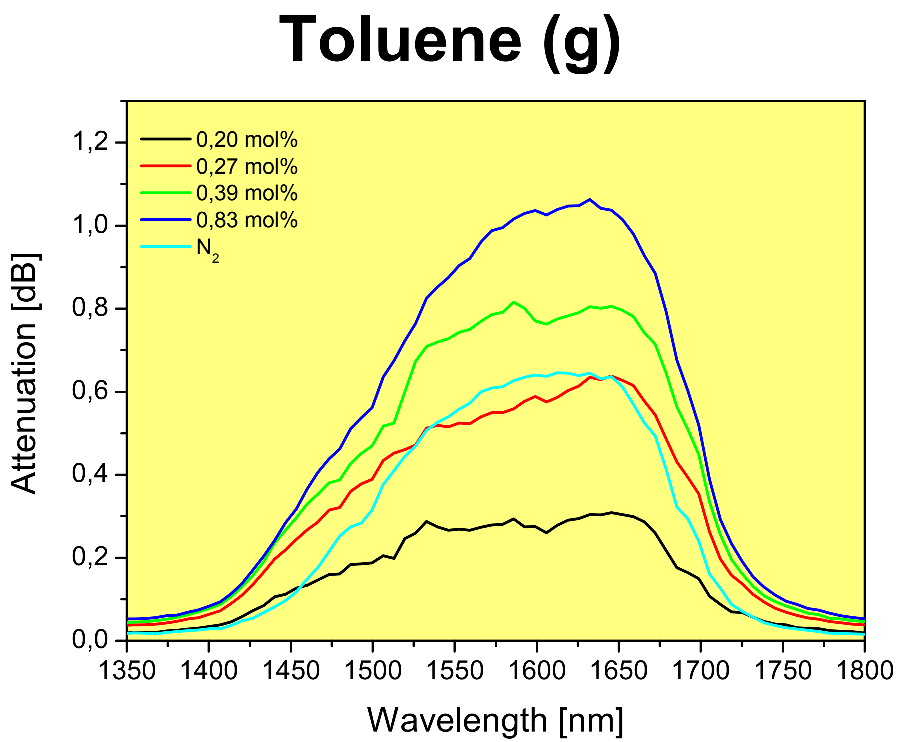
  (J.K. Ranka *et al.* , *Opt. Lett.* **25** 25-27 2000)

  MSFs with doped cores can be used for fiber lasers, gratings

  (W.J. Wadsworth *et al.*, *Electr. Lett.* **36** 1452-1454 2000)
- Evanescent-wave sensors (MSFs) – analytes filled into air holes

IPE MSFs FOR TOLUENE DETECTION





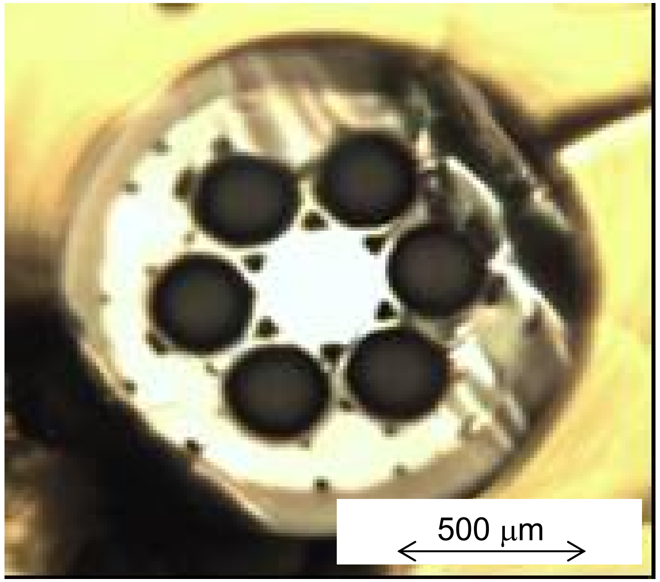
Toluene vapor in large cladding air holes, Core diameter 1 μm, toluene spectrum measured

Review on MSF-based sensors

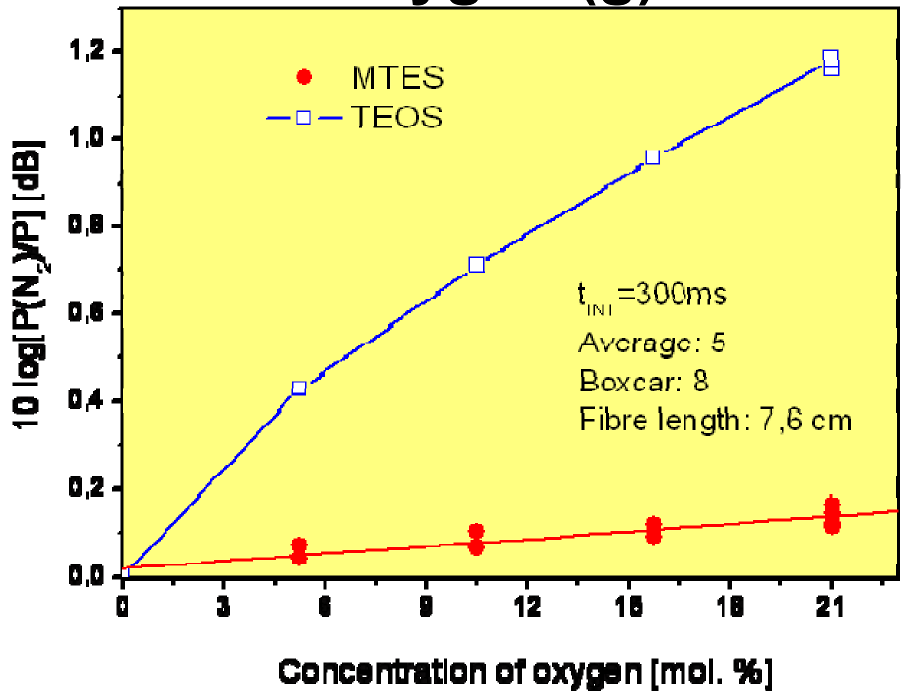
R.V. Nair, Progress in Quantum Electronics 34, 89–134, 2010

M. Skorobogatiy, J. Sensors Vol. 2009, Article ID 524237, 20 pages

MSFs FOR OXYGEN DETECTION



Oxygen (g)



Two types of detection membranes applied onto walls of air holes, hydrophobic – MTES, hydrophilic-TEOS, RU complex in membranes, **fluorescence intensity quenching by oxygen**

V. Matějec et al., Mater Sci Eng, C28 (2008) 876-881

PREPARATION OF BRAGG FIBERS - IPE

MCVD method - application of glass layers

- high-index layers - silica doped with germanium dioxide (>10mol.%)
- low-index layers (core) - silica slightly doped with phosphorous pentoxide

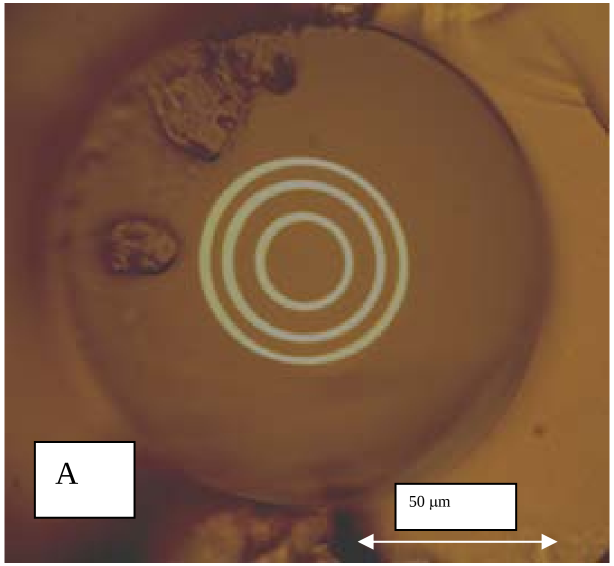
Preform: Tube with the applied layers

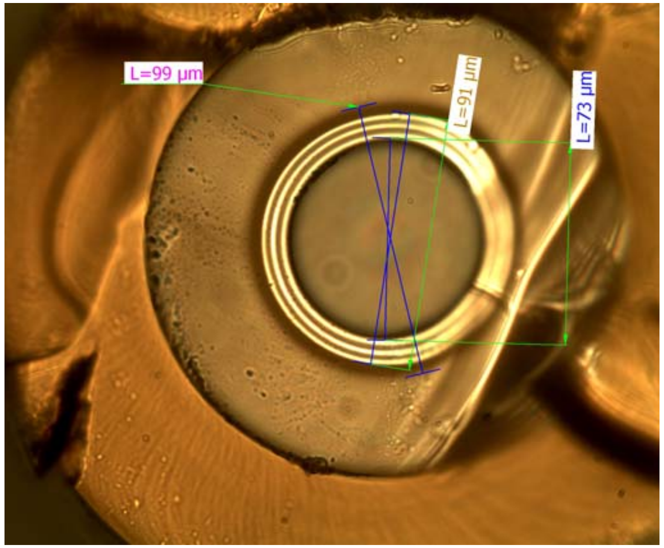
Collapsed to rod – **Bragg fiber with solid core**

Un-collapsed – **Bragg fiber with air core**

The rod or the tube drawn into Bragg fiber

BRAGG FIBER CROSS SECTIONS



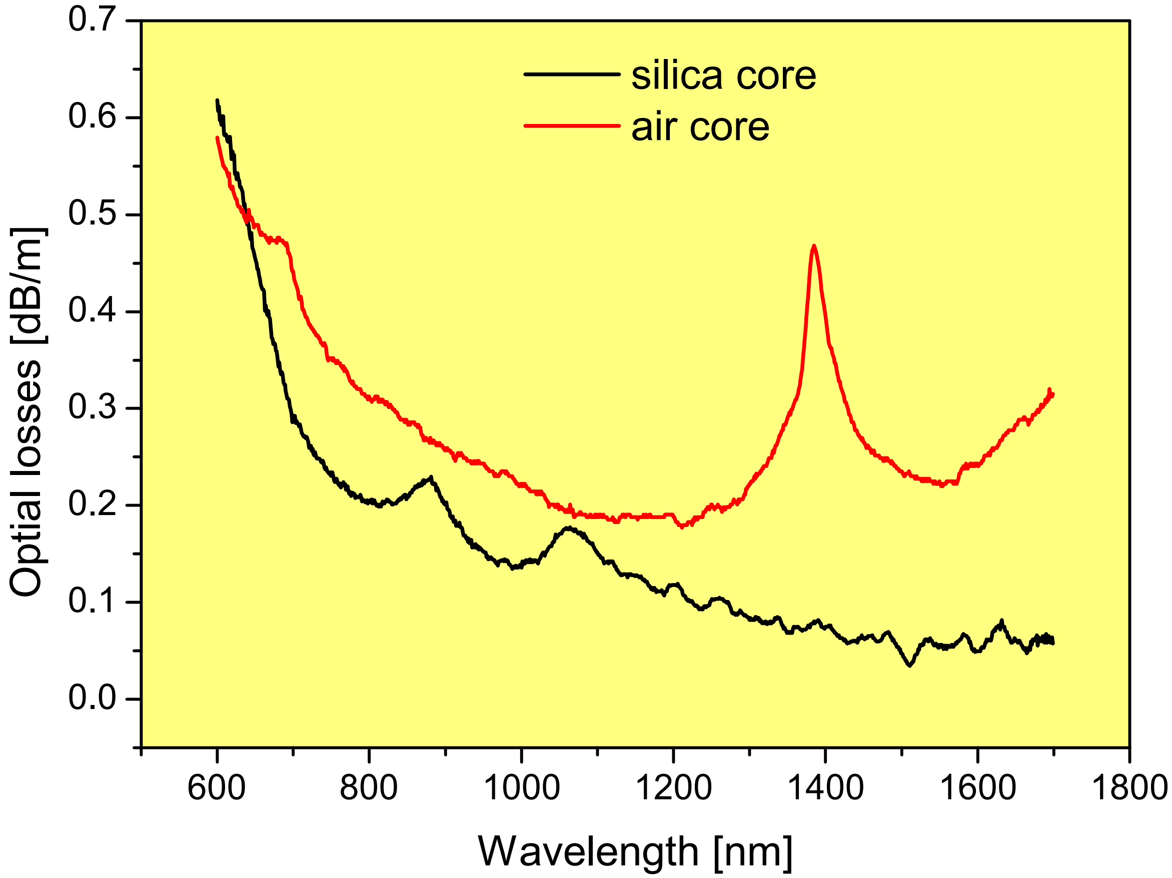


Silica core, Φ_c ~26 µm

Air core Φ_c ~70 µm

Outer fiber diameter of 170 µm, protective jacket of UV curable acrylate

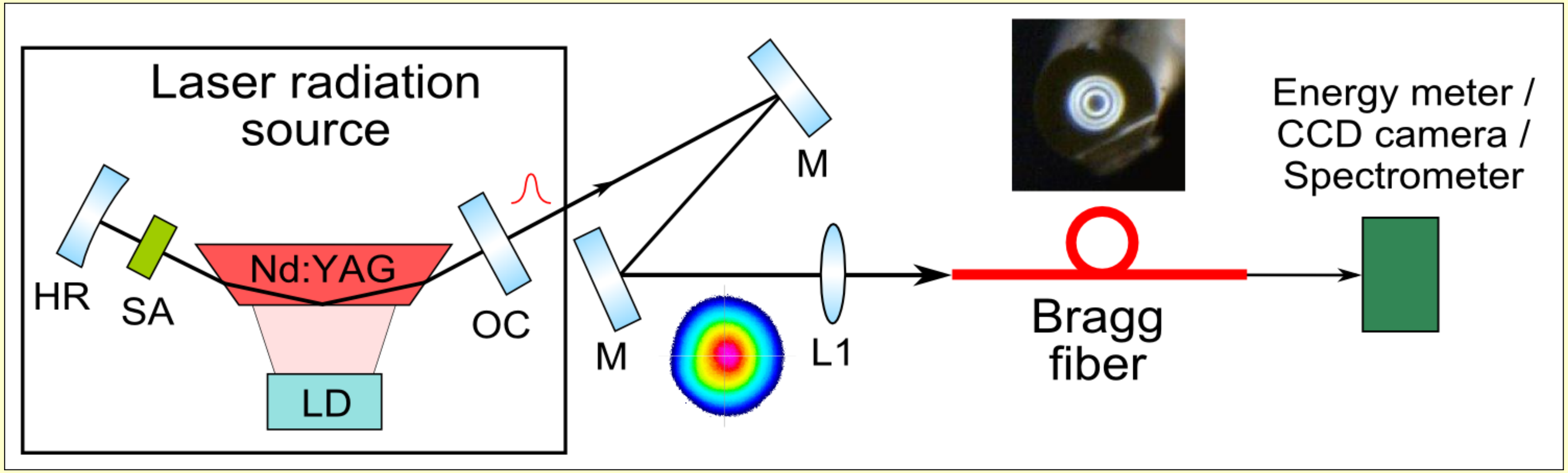
SPECTRAL LOSSES – CUT BACK METHOD



Fiber length 10 m, reference fiber 2 m, focal spot ~50 μm

DELIVERY OF HIGH LASER ENERGIES

Nd:YAG laser 1064 nm, Pulse duration 9 ns, E_{max} 1mJ, repetition rate 10 Hz



Nd:YAG: active laser crystal, LD: Pumping laser diode, HR: High reflective mirror (R = 100 % at 1.06 mm, r = - 1 m), OC: Output coupler (R = 60 % at 1.06 mm), SA: Cr:YAG saturable absorber, M: High reflective mirror,

L1: Focusing lens (f = 5 cm). – focal spot Φ~34 μm

M. Jelínek, V. Kubeček, Laser Phys. Lett. 8 (2011) 657-660

CHARACTERIZATION by Nd:YAG laser

Parameters

Lower energies 1-180 μJ

Transmission: **fiber segment l =1 m (energy from fiber/laser energy)**

Attenuation: **cut back method fiber length 10 or 50 m, reference length 1 m**

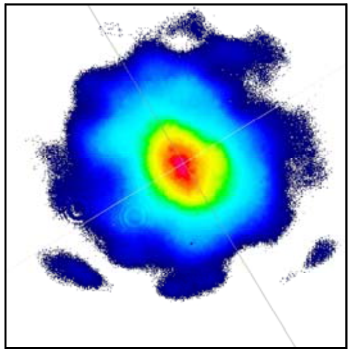
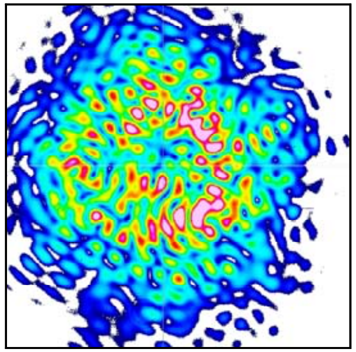
Spatial profiles of output beams: **CCD camera placed 0.5-1 cm from the fiber face**

Bending loss: **fiber segment l=1 m, coiled on mandrels Φ 5-50mm**

High energies >200 μJ

Damage threshold: plasma formation, fiber melting

RESULTS OF DELIVERY OF LASER ENERGY

	Silica core	Large air core
Core diameter [μm]	26	72
Transmittance, fiber 1 m long	**83%**	**52%**
Attenuation [dB/m]	**0.171 ± 0.005** (50m)	**0.070 ± 0.006** (10m)
Bending loss, 1 turn, mandrel D=50 mm [dB]	**0.305 ± 0.026**	**0**
Bending loss, 1 turn, mandrel D=13 mm [dB]	2.851 ± 0.585	0.151 ± 0.007
Damage threshold energy, 9 ns pulse [μJ]	685	800
Damage threshold intensity [GW/cm^2]	**25**	**29**
Output beam profile	Multimode with central maximum 	Highly multimode 

POTENTIAL APPLICATION

Solar systems

lighting, heating, electricity, medicine similar to that below

A bundle of PMMA fibers – length 3 m

C. Kandilli et al., Energy and Buildings 40 (2008) 1505-1512

CONCLUSIONS

- HC BGF offer novel means with lower losses and nonlinearities for future telecommunications
- MSFs create new performance for advanced fiber lasers and amplifiers, fiber-optic sensors
- Bragg fibers and HCBGFs can be used for delivery of high energies of lasers or solar radiation on long distances. They can be employed in medicine, in systems for lighting, heating, electricity production.

GENERAL CONCLUSIONS

• Currently, optical fibers represent rapidly developing subject in research, development, and applications. Advanced telecommunications can be hardly imagined without optical fibers.

•Optical fibers can be employed for development of advanced laser sources and sensors applicable for environment protection, in medicine, in safety systems.

• One can expect that new nanomaterials and metamaterials will stimulate research and development of novel types of optical fibers for transmitting high energies by solitary waves and thus they contribute to improve energy management over the world

IPE - OPTICAL FIBER TECHNOLOGY TEAM

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Fiber lasers, telecommunications

Jiri Ctyroky
Modeling of fiber sensors

Pavel Peterka
Fiber lasers and amplifiers

Filip Todorov
LPG gratings

FINANCIAL SUPPORT

• Czech Science Foundation – Research projects (last one 102/12/2361 deals with optical fibers for delivery of high energies)

•Academy of Sciences of the Czech Republic – Institutional financing

•European Community - research projects on fiber-optic sensors

THANK YOU FOR ATTENTION