OPTICAL FIBERS FOR FUTURE TELECOMMUNICATIONS AND ENERGY TRANSFER

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• 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
• 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

Mode losses/SM fiber losses

\( \lambda (\mu m) \)

\( 1.2 \)
\( 1.6 \)
\( 2 \)
\( 2.4 \)
\( 2.8 \)

\( \times 10^{-5} \)
\( \times 10^{-4} \)
\( \times 10^{-3} \)
\( \times 10^{-2} \)

\( EH_{11} \)
\( TE_{01} \)
DECREASE OF FIBER NONLINEARITY

Mode nonlinearity/SM fiber nonlinearity

$\lambda$ (\(\mu\text{m}\))
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 $\theta, \lambda$ - light guiding

$n_1 = 1, n_2 = 1.48, n_3 = 1.46$
$t = 4 \mu m$
Increased number of layers and $n_H - n_L \rightarrow$ light is more confined in the air core $\beta < \omega c$
PHOTONIC CRYSTAL FIBERS

PCF: Holey Silica Cladding

\[ r = 0.45a \]

above air line: guiding in air core is possible

below air line: surface states of air core


V. Matějec, ITC Zacatepec, Mexico, April 2013
• **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

\[ n_{clad}^2 = n_{silica}^2 \left(1 - P\right) + P \]

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

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

**Large air core**
- 1.7 dB/km – 1570 nm


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

endlessly single-mode

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

polarization-maintaining

low-contrast linear fiber (large area)
MSFs WITH DOPED CORES

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


\[ d_{\text{hole}} \sim 9 \, \mu m \]
\[ \Lambda \sim 12 \, \mu m \]
• 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)
The input stack inserted into a silica tube and fiber drawn
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

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SOL-GEL PROCESS (USA - BELL LAB)

Centrifugation
Vacuum deaeration
Addition of ester

Fumed silica
50 m²/g; 46%
Water
TMAH
Lubricant
Polymer

pH~11

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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

**WHY TO EMPLOY PCFs AND MSFs**

- **Optical communications (HCBGFs)**
  Broad single-mode range (400-1700 nm)
  **Unique dispersion characteristics** ($\lambda_{OD}<1000$ nm)
  **Unique nonlinear optical properties** (a broadband continuum)

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

V. Matějec, ITC Zacatepec April 2013,
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

V. Matějec, ITC Zacatepec April 2013,
Two types of detection membranes applied onto walls of air holes, hydrophobic – MTES, hydrophilic-TEOS, RU complex in membranes, **fluorescence intensity quenching by oxygen**

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, $\Phi_c \sim 26 \mu m$

Air core $\Phi_c \sim 70 \mu m$

Outer fiber diameter of 170 $\mu m$, 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, \( E_{\text{max}} \) 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 \( \Phi \sim 34 \) \( \mu \)m

CHARACTERIZATION by Nd:YAG laser

Parameters

Lower energies 1-180 \( \mu \text{J} \)

Transmission: fiber segment \( l = 1 \text{ m} \) (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 \( l = 1 \text{ m} \), coiled on mandrels \( \Phi 5-50\text{mm} \)

High energies >200 \( \mu \text{J} \)

Damage threshold: plasma formation, fiber melting
# RESULTS OF DELIVERY OF LASER ENERGY

<table>
<thead>
<tr>
<th></th>
<th>Silica core</th>
<th>Large air core</th>
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<tbody>
<tr>
<td>Core diameter [μm]</td>
<td>26</td>
<td>72</td>
</tr>
<tr>
<td>Transmittance, fiber 1 m long</td>
<td>83%</td>
<td>52%</td>
</tr>
<tr>
<td>Attenuation [dB/m]</td>
<td>0.171 ± 0.005 (50m)</td>
<td>0.070 ± 0.006 (10m)</td>
</tr>
<tr>
<td>Bending loss, 1 turn, mandrel D=50 mm [dB]</td>
<td>0.305 ± 0.026</td>
<td>0</td>
</tr>
<tr>
<td>Bending loss, 1 turn, mandrel D=13 mm [dB]</td>
<td>2.851 ± 0.585</td>
<td>0.151 ± 0.007</td>
</tr>
<tr>
<td>Damage threshold energy, 9 ns pulse [μJ]</td>
<td>685</td>
<td>800</td>
</tr>
<tr>
<td>Damage threshold intensity [GW/cm²]</td>
<td>25</td>
<td>29</td>
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<tr>
<td>Output beam profile</td>
<td>Multimode with central maximum</td>
<td>Highly multimode</td>
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POTENTIAL APPLICATION

Solar systems
lighting, heating, electricity, medicine similar to that below

A bundle of PMMA fibers – length 3 m

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 a 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 – FIBER-OPTIC PHYSICS

Pavel Honzatko
Fiber lasers, telecommunications

Jiri Ctyroky
Modeling of fiber sensors

Pavel Peterka
Fiber lasers and amplifiers

Filip Todorov
LPG gratings

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THANK YOU FOR ATTENTION