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OSA Fiber Modeling and Fabrication Technical Group

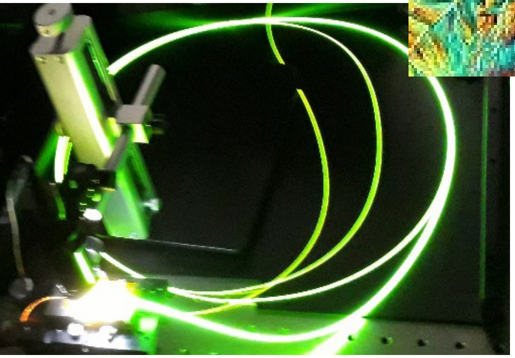

# Hybrid (M-type) Fibers for Dispersion Management

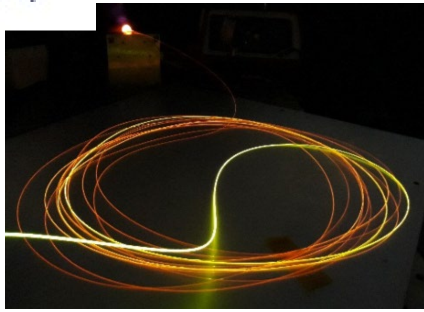
Svetlana S. Aleshkina, Prokhorov General Physics Institute of the Russian Academy of Sciences, Dianov Fiber Optics Research Center

Fiber Modeling and Fabrication Technical Group

# Fiber Modeling and Fabrication Technical Group

## Welcomes You for the webinar on



Fiber Modeling and Fabrication Technical Group

**About us:** A unique group of more than 900 researchers from 70+ countries from North America, South America, Europe, Asia, Africa, and Oceania.

**Goals:**

To benefit **OSA members** having interest in Fiber Design, Modeling, Fabrication, and Applications of fibers.

To Provide a platform to Fiber Community for connecting, Engaging and Exciting with others.

To Organize Webinars, Technical and Networking Events, and Special Journal Issues.

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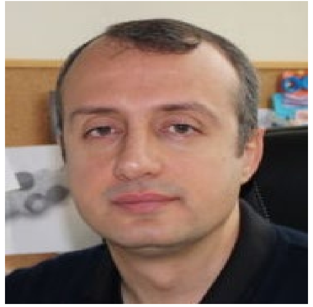

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# Past Events:

**1. Networking Event:** Date: Tuesday, 16 Jul 2019 17:00-18:00
Location: Naupaka III, Waikoloa Beach Marriott Resort & Spa, Waikoloa Beach, Hawaii

**2. Webinar 1: Everything you always wanted to know about supercontinuum modelling in optical fibers (but were afraid to ask)** Date: 26th August 2019, at Swiss time 2pm/ EDT 8am
A/Prof. Alexander Heidt, University of Bern, Switzerland.

**3. Webinar 2: The development of thulium and holmium fiber sources**
Date: 30th September, 2019 at 1pm (UK time)/ EDT 7am
Dr. Nikita Simakov, DSTO, Australia.

**4. Webinar 3: Recent development in hollow-core optical fiber**
Date: 14 November, 2019, 8 am Beijing Time
A/Prof. Y Wang, Beijing University of Technology, China.

Fiber Modeling and Fabrication Technical Group

**Events at CLEO San Jose, USA and FIO USA !!!!**

# Webinars this year:

**Webinar 1: Integration of 2-dimensional materials in fiber optics for ultra-short pulse lasers**
Date: 13th March 2020, 8 pm EDT.
Prof. Kyunghwan Oh, Yonsei University, South Korea.

**Webinar 2: Novel Optical Materials for optical Fibers**
Date: 24th April 2020, 11 am EDT.
Prof. John Ballato, Clemson University, USA.

**Webinar 3: Mid-Infrared Supercontinuum Generation in Optical Fibers**
Date: 20 May 2020, 10 am EDT.
Dr. Christian Petersen, Technical University of Denmark, Fotonik.

**Webinar 4: Hybrid (M-type) fibers for dispersion management**
Date: 18 September, 3 pm EDT.
Dr. Svetlana Aleshkina, Fiber Optics Research Center, Russian Academy of Sciences, Russia.

**How to join this Group:**

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If you are OSA member: Log-in to your OSA Account and chose FF group in Technical Groups Category.

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You can contact me if you are interested in giving a Webinar/Talk/Panel Discussion, on **deepakjain9060@gmail.com**

# Today's Webinar

OSA Fiber Modeling and Fabrication Technical Group

# Hybrid (M-type) fibers for dispersion management

**Dr. Svetlana Aleshkina,** Prokhorov General Physics Institute of the Russian Academy of Sciences, Dianov Fiber Optics Research Center, Russia

**Speaker's Short Bio:** Svetlana S. Aleshkina was born in Saransk, Russia, in 1985. She received the B.E. and M.E. degrees in physics from Mordovian State University, Saransk, Russia, in 2006 and 2008, respectively, and the Ph.D. degree in laser physics from Fiber Optics Research Center of the Russian Academy of Science (FORC RAS), Moscow, Russia, in 2012. She is currently Senior Researcher of FORC RAS. Her research activities are connected with development of special passive and active optical fibers for creation of all-fiber laser schemes (master oscillators, high power lasers and amplifiers). Area of expertise: Rare-earth-doped fiber lasers and amplifiers, Special optical fibers with anomalous dispersion in 1 um spectral range, Large-mode area fibers, High power Yb-doped lasers, Pulsed and Continuous wave lasers at 0.98 um.

# Hybrid (M-type) Fibers for Dispersion Management


- **Svetlana S. Aleshkina**
- *Prokhorov General Physics Institute of the Russian Academy of Sciences, Dianov Fiber Optics Research Center*
- *E-mail: sv_alesh@fo.gpi.ru

# Hybrid (M-type) Fibers for Dispersion Management

- Basics of hybrid fibers and guiding mechanism
- Modeling and fabrication of hybrid fibers
- Applications of hybrid fibers

## Audience:

- PhD Students
- Researchers both in academics and industry

## The field of interests:

- Specialty optical fibers
- All-fiber lasers and amplifiers
- Dispersion management in fiber laser schemes

# Content:

1. Motivation

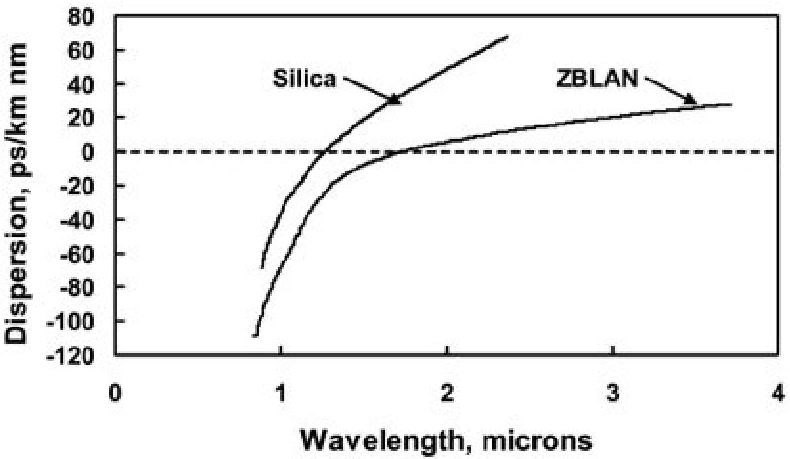
and

History of hybrid fiber development

# Motivation

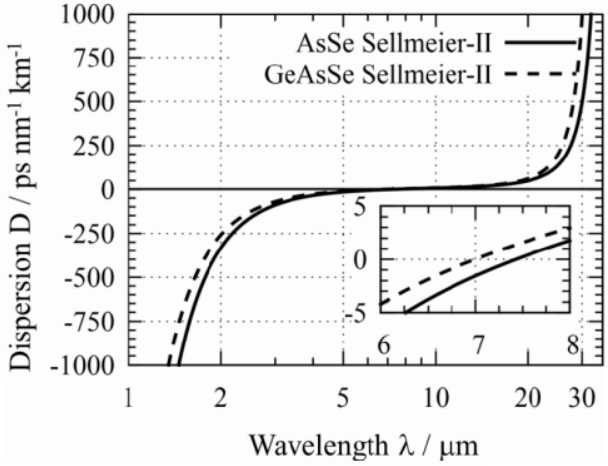
$$D = D_{material} + D_{waveguide}$$

Silica glass and ZBLAN




F. Gan, "Optical properties of fluoride glasses: a review," *J. Non-Cryst. Solids*, Vol. 184, pp. 9-20 (1995)

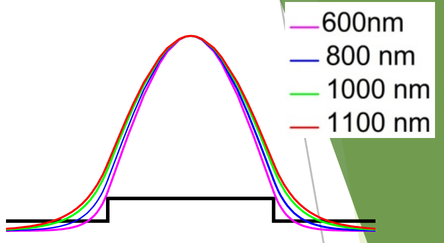
Chalcogenide glass




Harshana G. Dantanarayana, et.al, Opt. Mater. Express 4, 1444-1455 (2014)

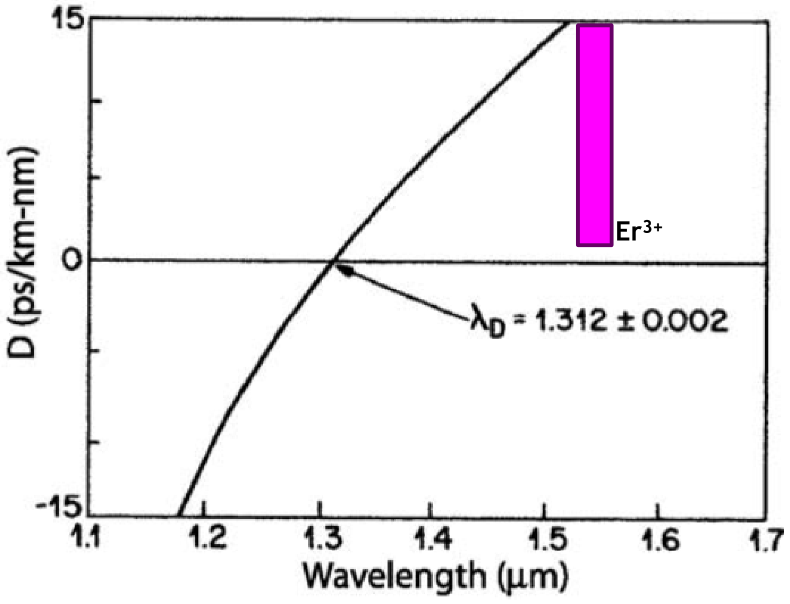
# Motivation

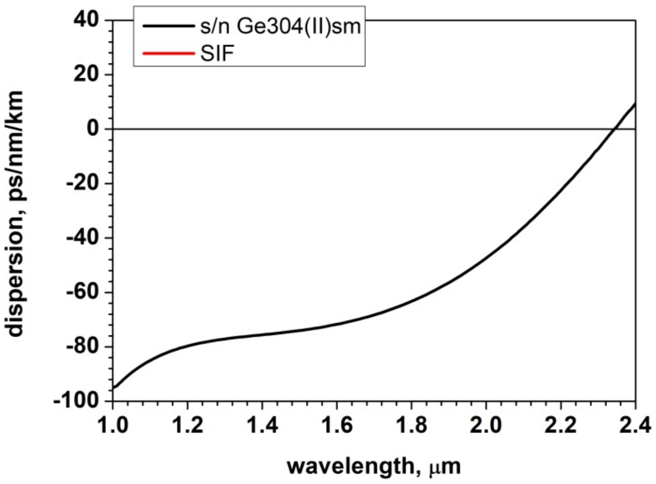
$$D = D_{material} + D_{waveguide}$$




| | SIF | |
|---|---|---|
| $D_{material}$ | $D_{waveguide}$ | D |
| anomalous | normal | normal |
| normal | normal | normal |

Silica glass



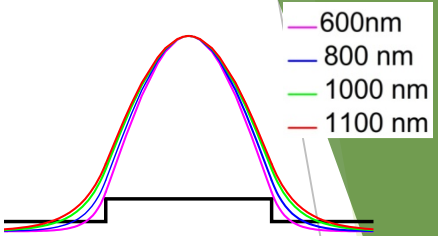




Ge304(II)sm
FORC-Photonics

http://www.forc-photonics.ru/en/fibers_and_cables/HNLF_Ge_doped_fibers/1/161/

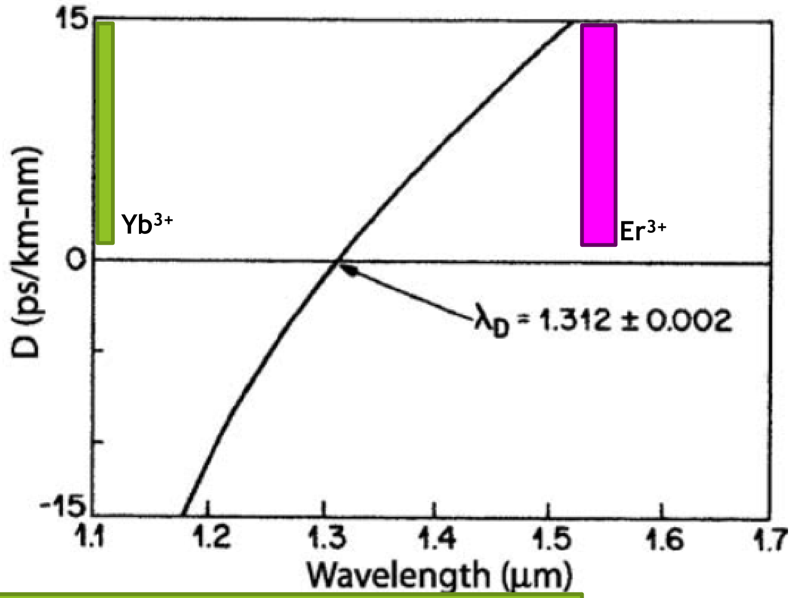
# Motivation

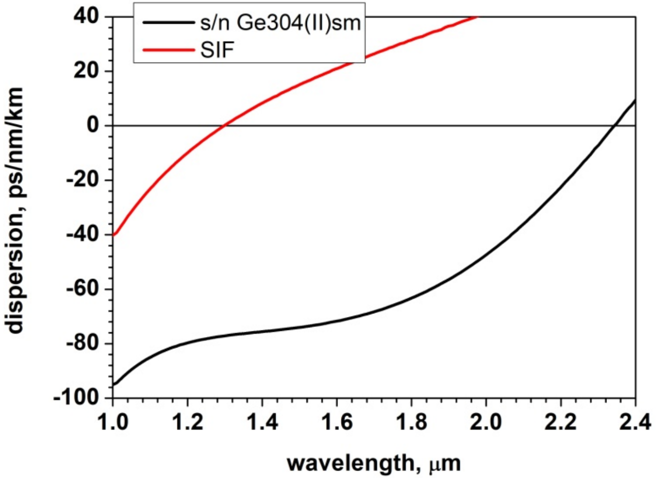
$$D = D_{material} + D_{waveguide}$$




| | SIF | |
|---|---|---|
| $D_{material}$ | $D_{waveguide}$ | D |
| anomalous | normal | normal |
| normal | normal | normal |

Silica glass




Ge304(II)sm
FORC-Photonics

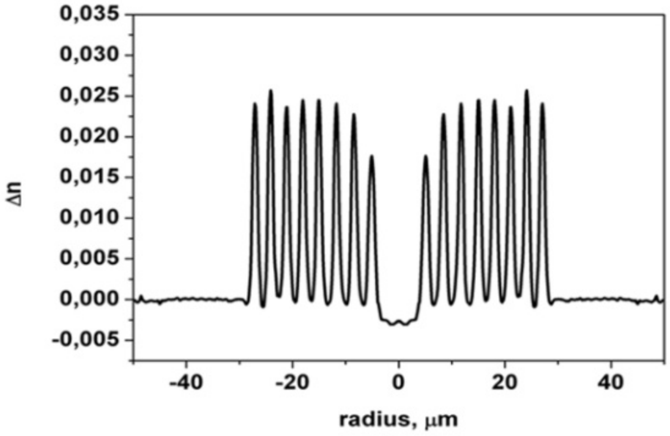
❖ Specialty optical fibers are required

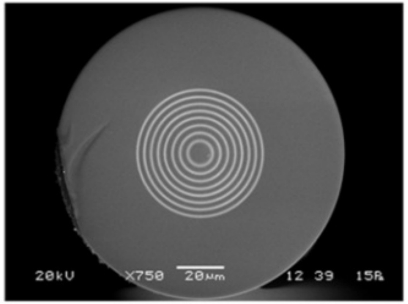
http://www.forc-photonics.ru/en/fibers_and_cables/HNLF_Ge_doped_fibers/1/161/

# The problem:

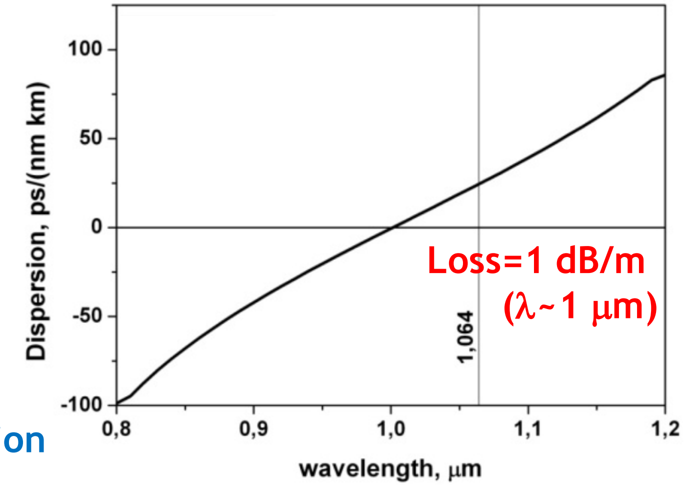
- **In SIF $D_{waveguide}$<0** → dispersion management is possible only for the spectral range **where $D_{material}$>0**
- For $D_{material}$<0 **specialty optical fibers** are required

# Bragg fiber is hybrid fiber prototype




Guiding mechanism is
Coherent Fresnel Reflection





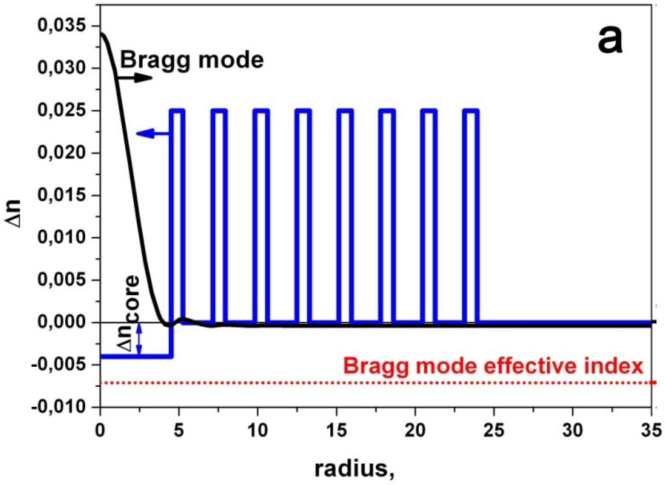
F. Brechet, P. Roy, J. Marcou and D. Pagnoux, in *Electronics Letters*, vol. 36, no. 6, pp. 514-515, 16 March 2000
M.E.Likhachev, and et. al, in ECOC2007, Berlin, Germany, We7.1.2

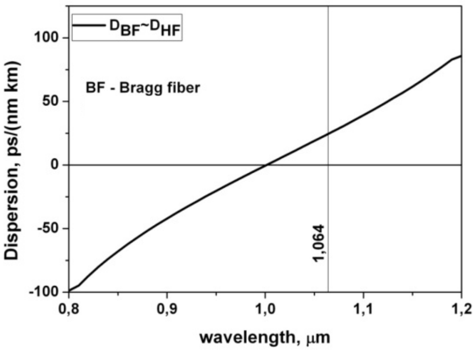

❖Appropriate design of the Bragg fiber allows dispersion management

❖Disadvantage: Leakage losses

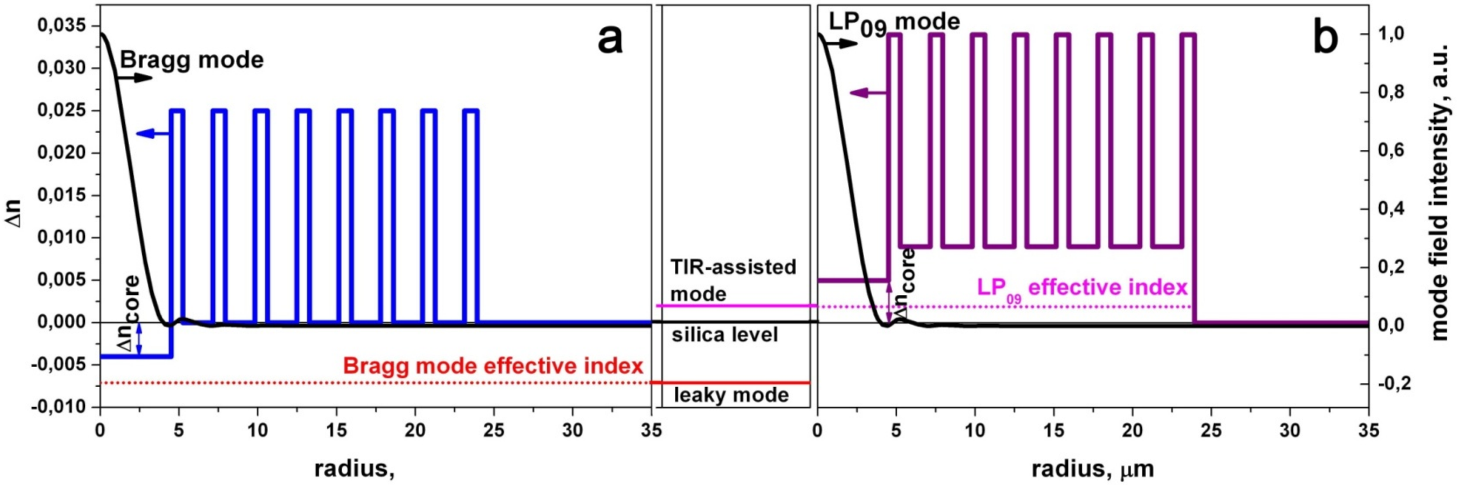
# Guiding mechanism

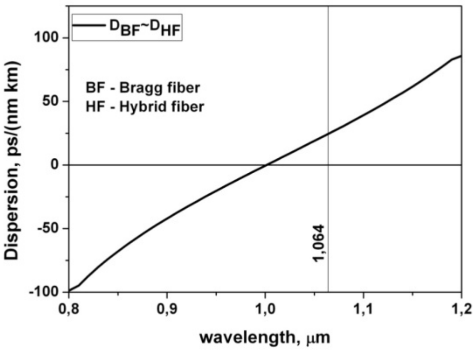
## 1. Increase the refractive index of the whole structure



# Guiding mechanism




1. $I_{LP09}(r) \sim I_{BF}(r)$
2. $D_{LP09}(\lambda) \sim D_{BF}(\lambda)$

**$LP_{09}$ mode**

❖Formation mechanism
(anomalous dispersion at 1 μm)

**CFR**

❖Waveguide mechanism
(low optical loss)

**TIR**

⇩

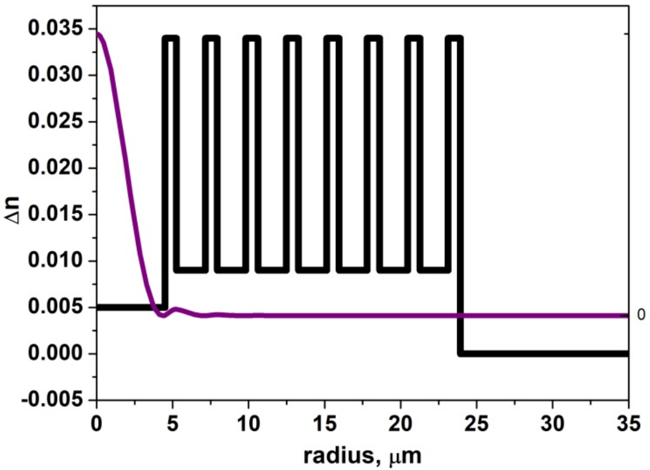
**The core mode propagates due to Hybrid mechanism**

2. Constantly decrease layers' number

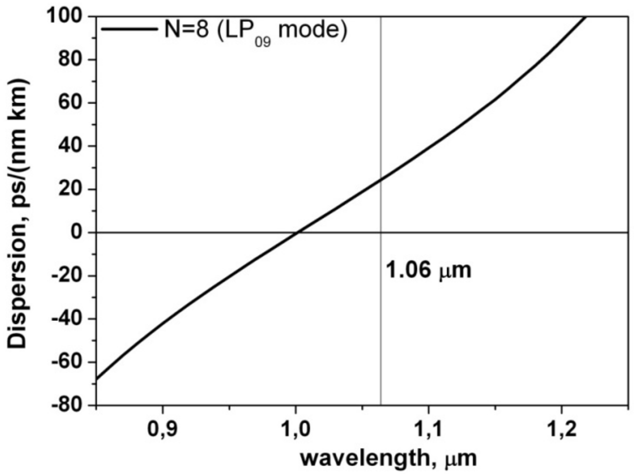
# Guiding mechanism

- 8 layers of BF **FOR OPTICAL LOSS MINIMIZATION**
- In HF there are not leakage losses

## N=8



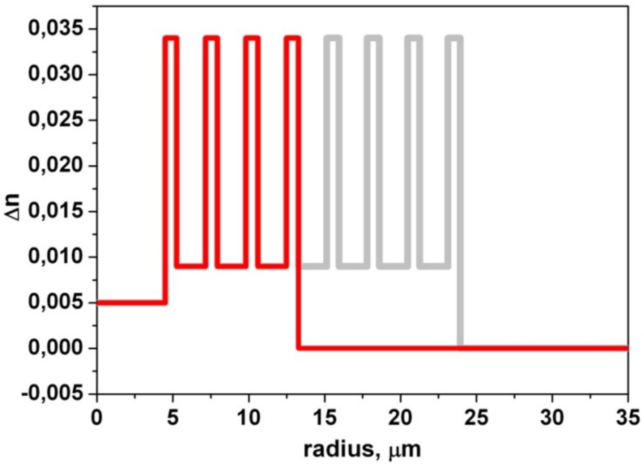

Operating mode is $LP_{09}$



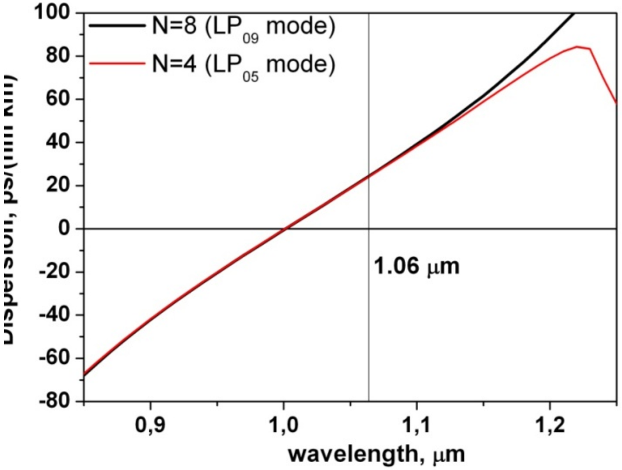
# Guiding mechanism

## 2. Constantly decrease layers' number

## N=4



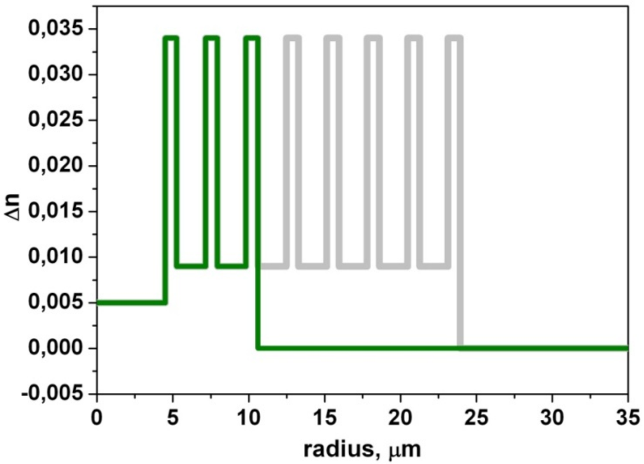

### Operating mode is $LP_{05}$



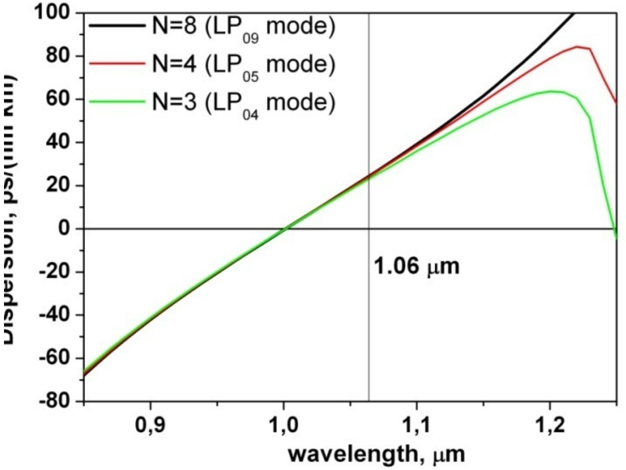
# Guiding mechanism

2. Constantly decrease layers' number

## N=3



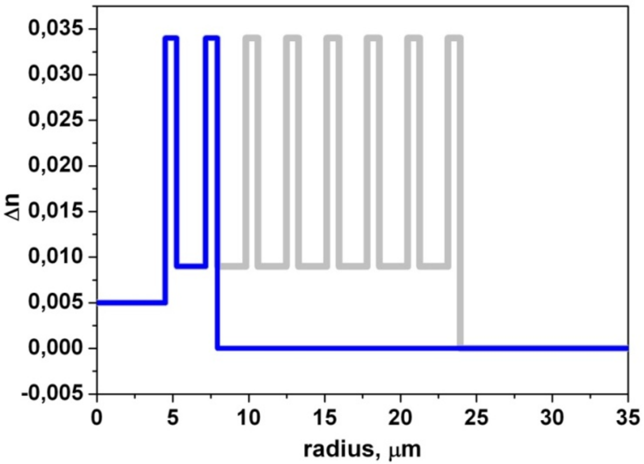

Operating mode is $LP_{04}$



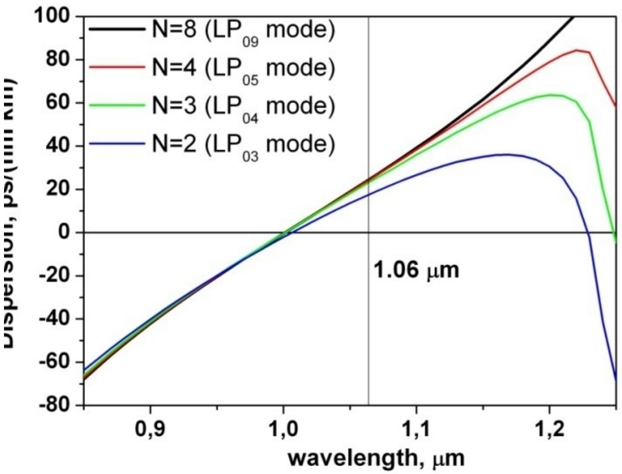
# Guiding mechanism

**2. Constantly decrease layers' number**

**N=2**



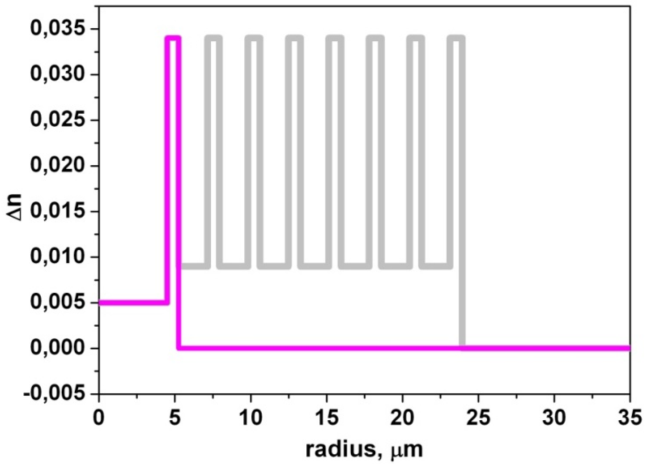

Operating mode is $LP_{03}$



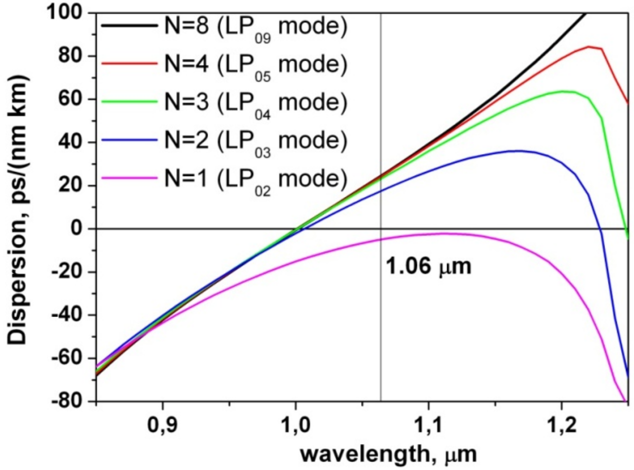
## 2. Constantly decrease layers' number

# Guiding mechanism

## N=1*




**Operating mode is $LP_{02}$**



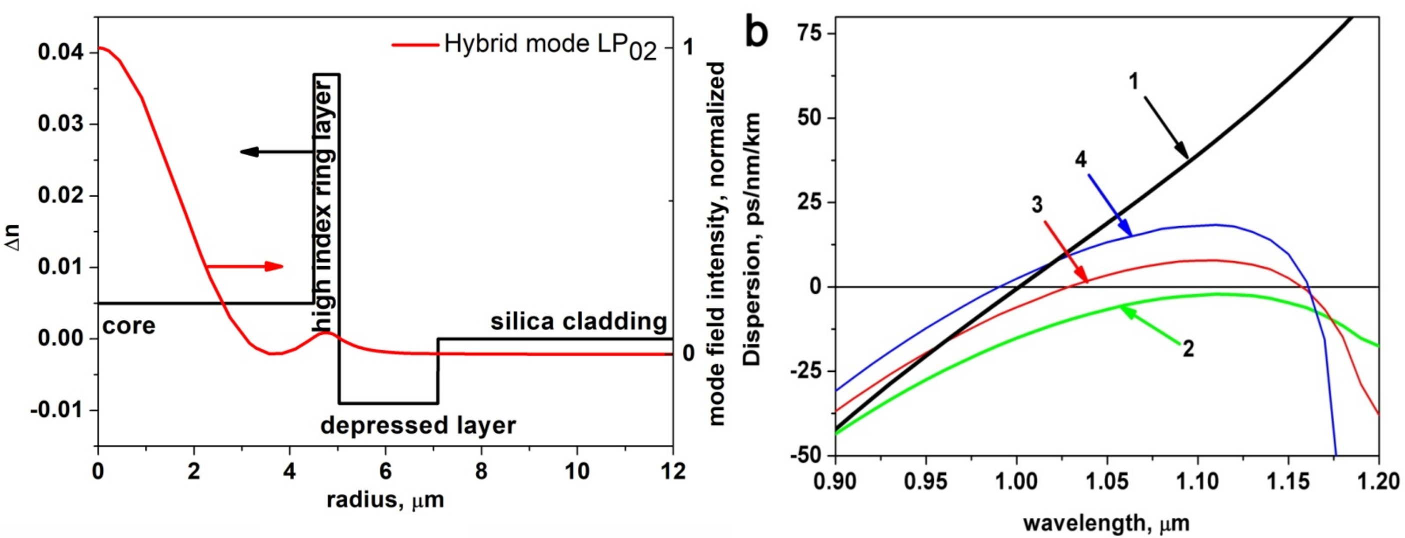


*A S Belanov, S V Tsvetkov, Quant. Electron., 2010, **40** (2), 160–162.

Svetlana S. Aleshkina, et.al, Opt. Express 21, 23838-23843 (2013)

# 3. Add depressed layer

## Guiding mechanism




1 – Dispersion of the Bragg fiber

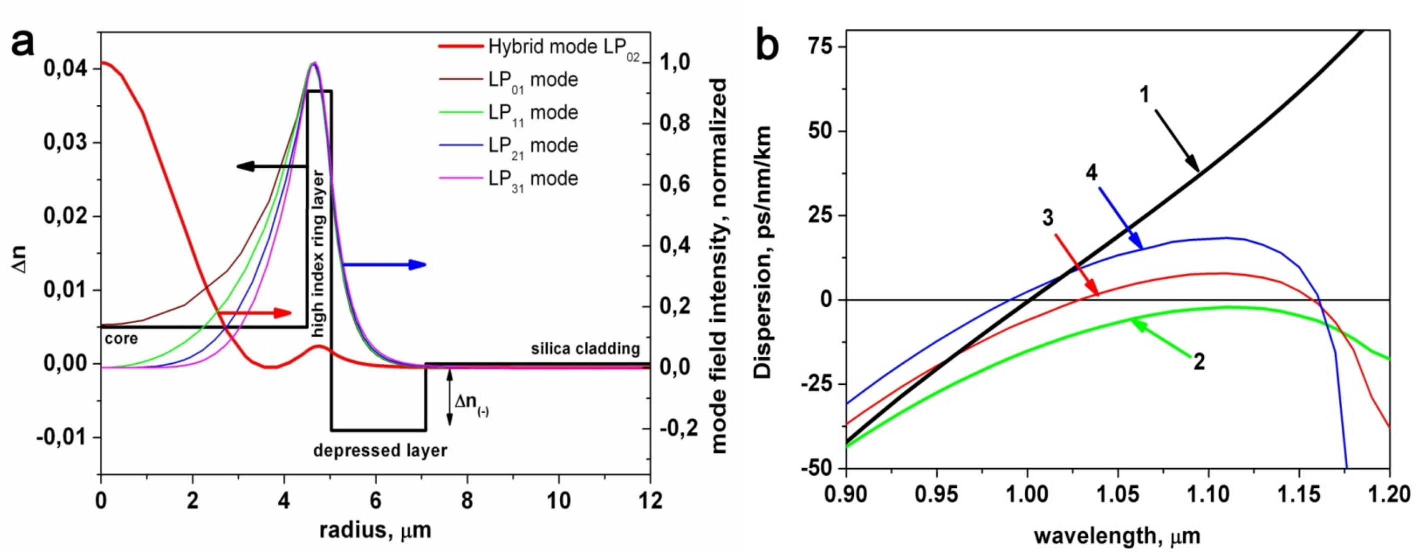
2 – Dispersion of the fiber without depressed layer

3 – Dispersion of the fiber with $\Delta n_{(-)}=0.005$

4 – Dispersion of the fiber with $\Delta n_{(-)}=0.010$

Svetlana S. Aleshkina, et.al, Opt. Express 21, 23838-23843 (2013)

# Guiding mechanism




1 – Dispersion of the Bragg fiber

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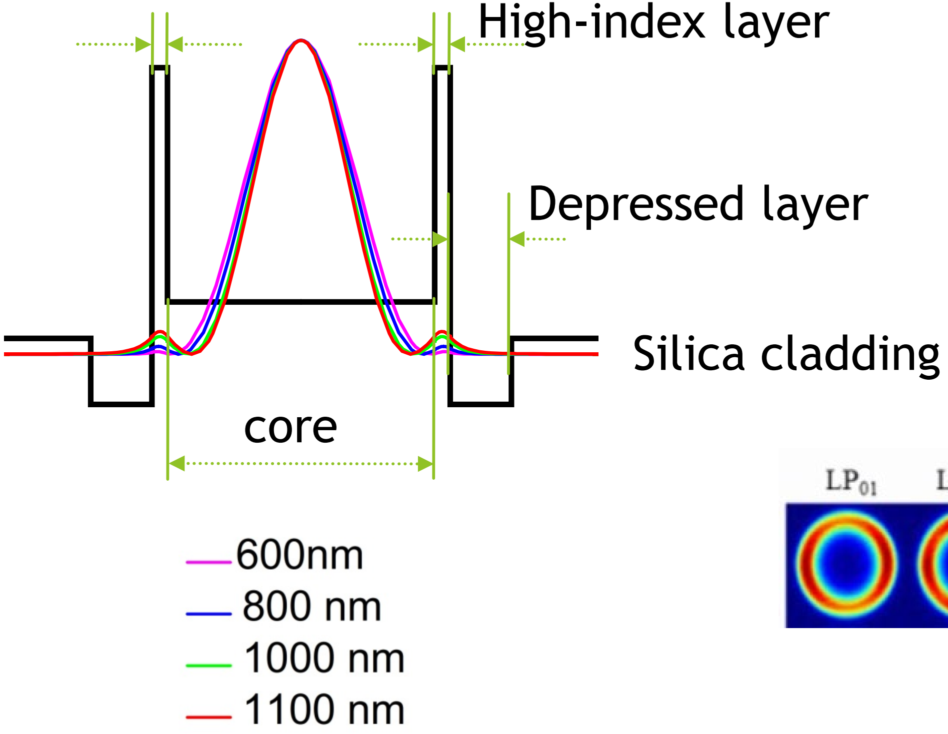
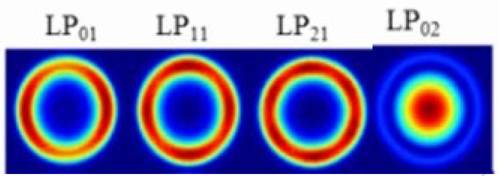
Svetlana S. Aleshkina, et.al, Opt. Express 21, 23838-23843 (2013)

# Hybrid fiber:



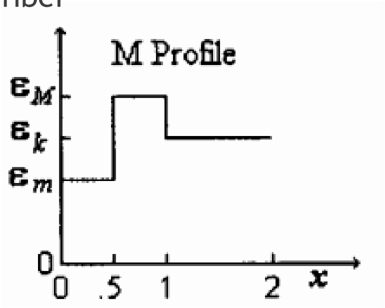

- ❖Operating mode $LP_{0i}$ ($HE_{1i}$), $i=N+1$
- ❖The most part of the mode confined in the weakly-doped core
- ❖The operating mode can have anomalous dispersion at the desirable wavelength region
- ❖Multimode mode structure
- ❖The other modes is localized in the high index ring layer predominantly.

Svetlana S. Aleshkina, et.al, Opt. Express 21, 23838-23843 (2013)

# The pioneering work (theoretical)

- M-type fiber

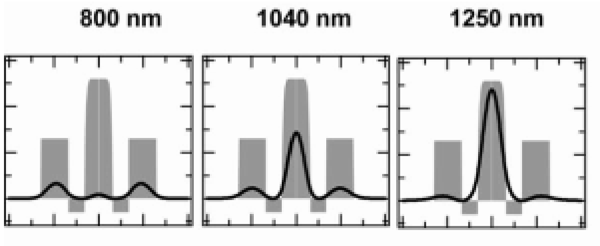
M



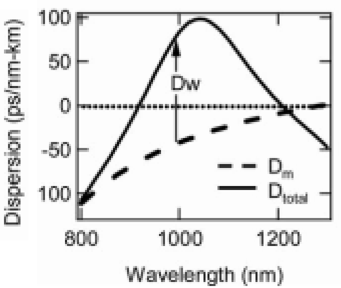

❖The fundamental mode was considered as the operating one
❖Dispersion was **NOT** studied

Neves, I. and A. S. C. Fernandes. “MODAL CHARACTERISTICS FOR W-TYPE AND M-TYPE DIELECTRIC PROFILE FIBERS.” (1999).

## Few-mode fiber




1. The core is truly multimode




2. For desirable mode excitation it is necessary to use specific techniques

S. Ramachandran, et.al, Opt. Lett. 31, 2532-2534 (2006)

# Content:

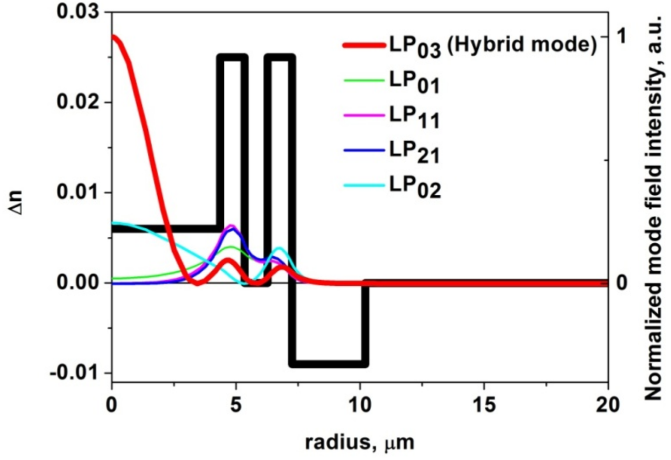
1. Motivation

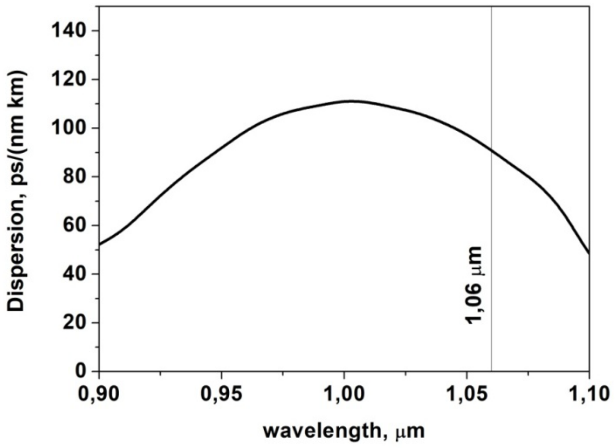
and

History of hybrid fiber development

2. Modeling aspects

# Modeling aspects

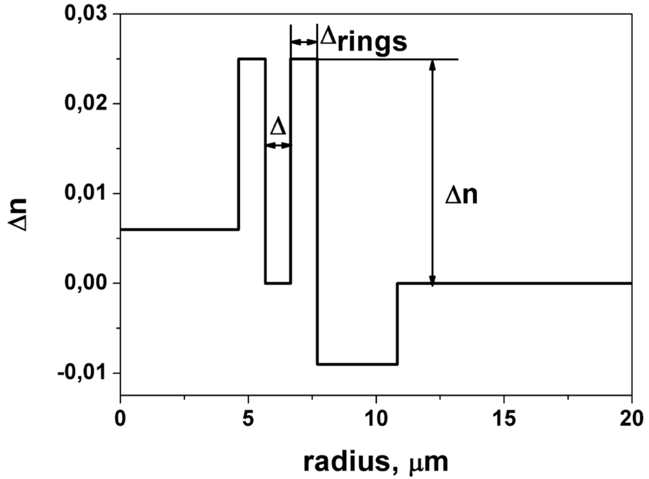


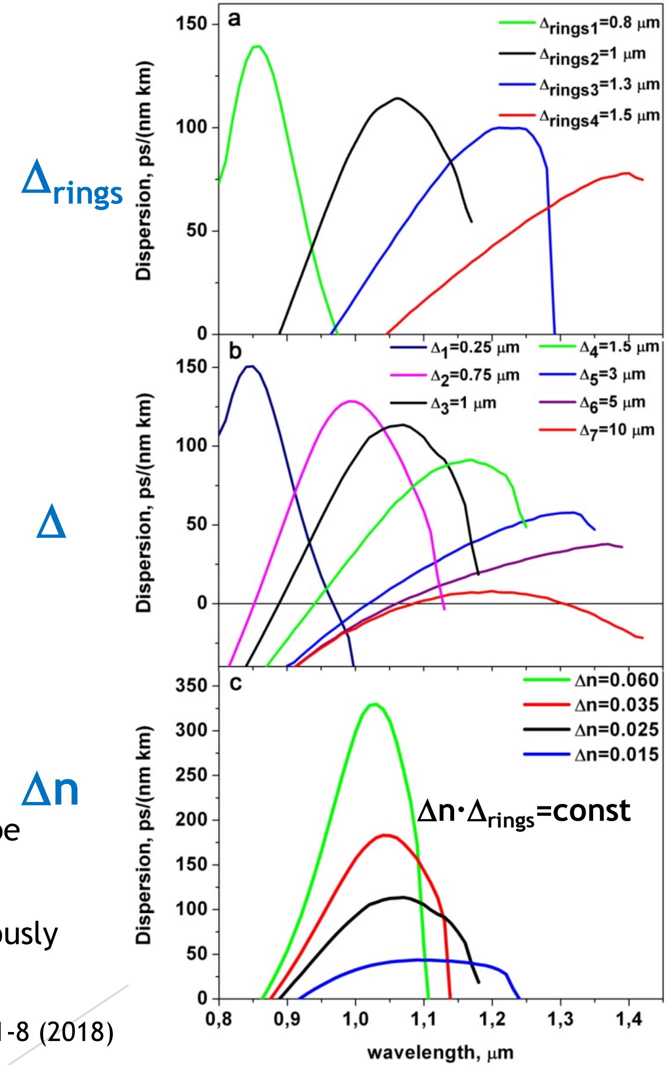




- ❖A design with two rings is optimal compromise between HF fabrication simplicity and achievable parameters
- ❖HF is the most flexible both in terms of the MFD variations and in terms of the value and slope of the anomalous dispersion

S. S. Aleshkina et al., "Assymptotically single mode-hybrid fiber with a high anomalous dispersion in the 1μm wavelength region," Proc. SPIE, vol. 9344, Mar. 2015, Art. no. 934405

# Modeling aspects




- dispersion curves have well-defined maximums
- breaking of the dispersion curves corresponds to hybrid mode cutoff
- the position of anomalous dispersion maximum, its value and slope could be adjusted by appropriate choice of $\Delta$ and $\Delta_{rings}$
- An increase of the fiber's maximum anomalous dispersion value simultaneously reduces the dispersion peak's spectral width

Aleshkina S. S., et.al, in IEEE Journal of Selected Topics in Quantum Electronics, **24**(3), 1-8 (2018)

# Content:

1. Motivation

and

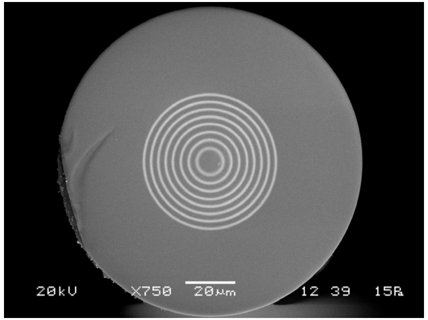
History of hybrid fiber development

2. Modeling aspects

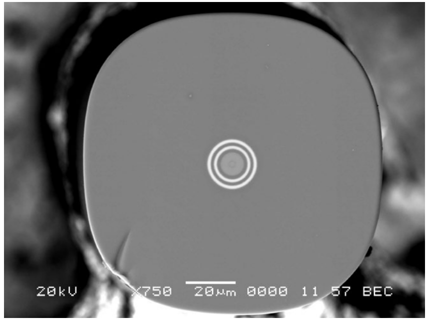
3. Fabrication aspects

# Fabrication aspects

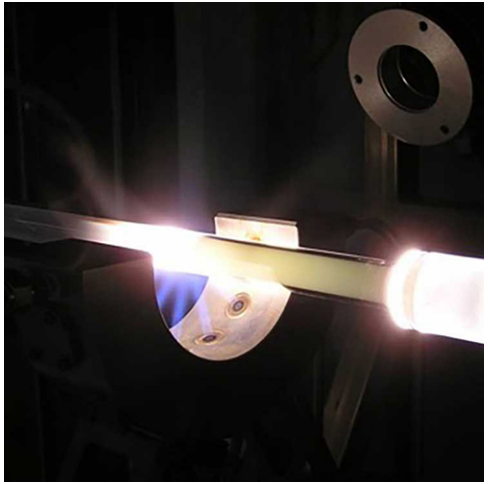
Bragg fiber




Hybrid fiber




MCVD



The RIP can be formed by $GeO_2$ doping of silica glass

# Hybrid fiber advantageous

- In the core only hybrid mode is propagated
- It can be easily excited
- Appropriate design of the fiber allow dispersion management and its sign management
- The structure can be easily created by standard fabrication technique

**What's wrong?**

# Content:

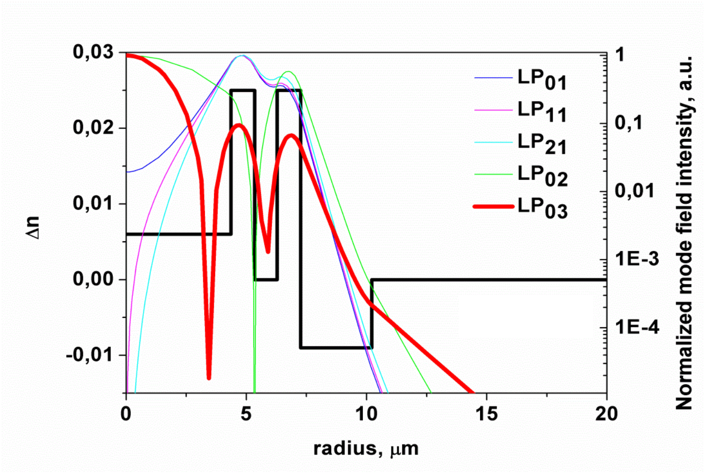
1. Motivation
and
History of hybrid fiber development

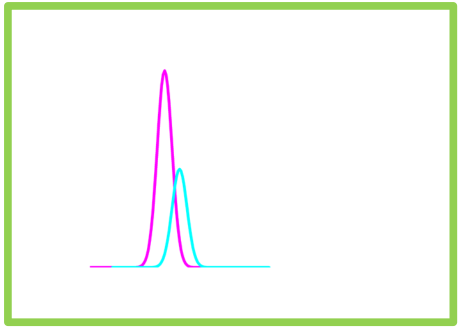
2. Modeling aspects

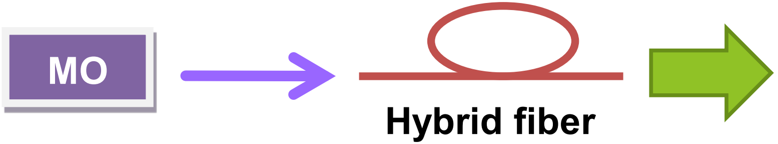
3. Fabrication aspects

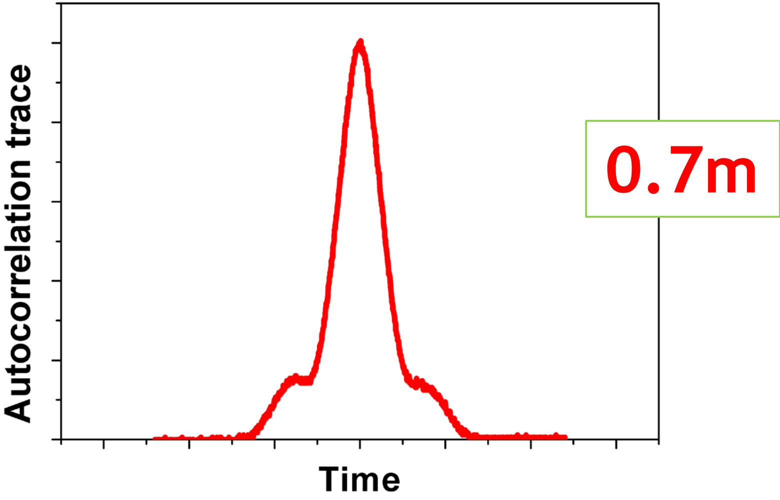
**4. Limitations of the hybrid fibers**
and
**The ways to overcome them**

# Limitations of the hybrid fibers



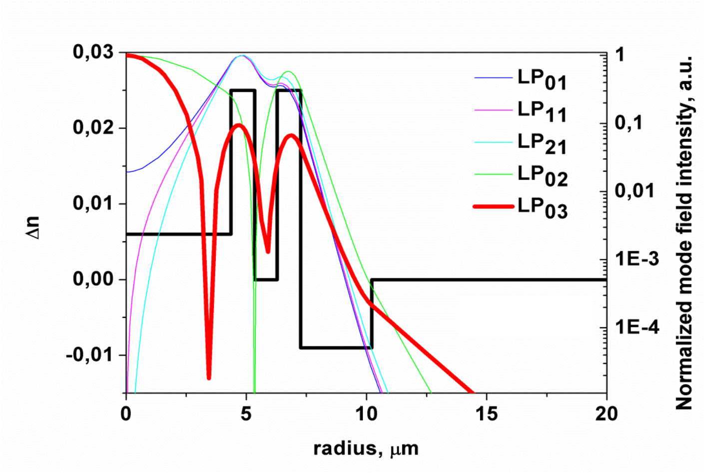



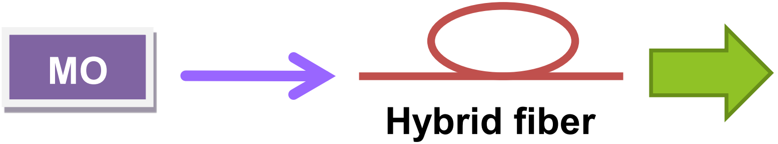


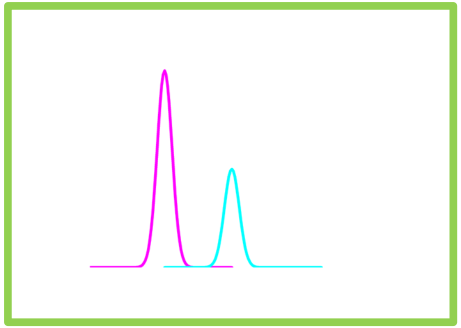



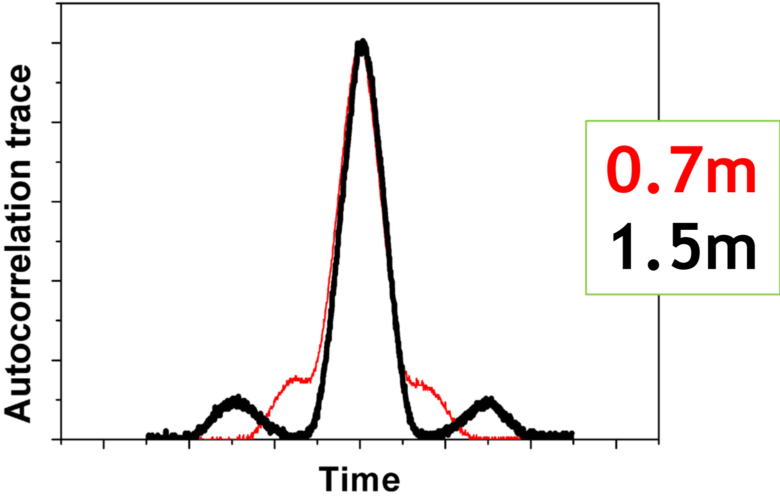

S. S. Aleshkina et al., Quantum. Electron., vol. 46, pp.738–742, 2016.

# Limitations of the hybrid fibers






S. S. Aleshkina et al., Quantum. Electron., vol. 46, pp.738–742, 2016.

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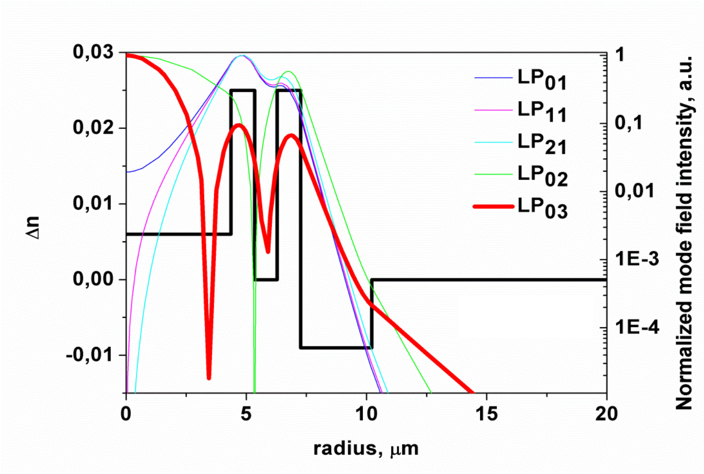
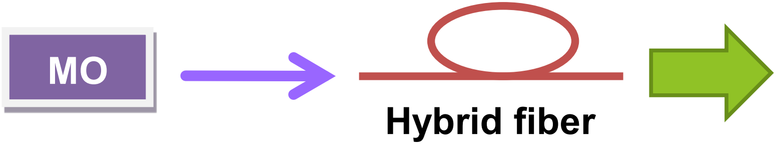
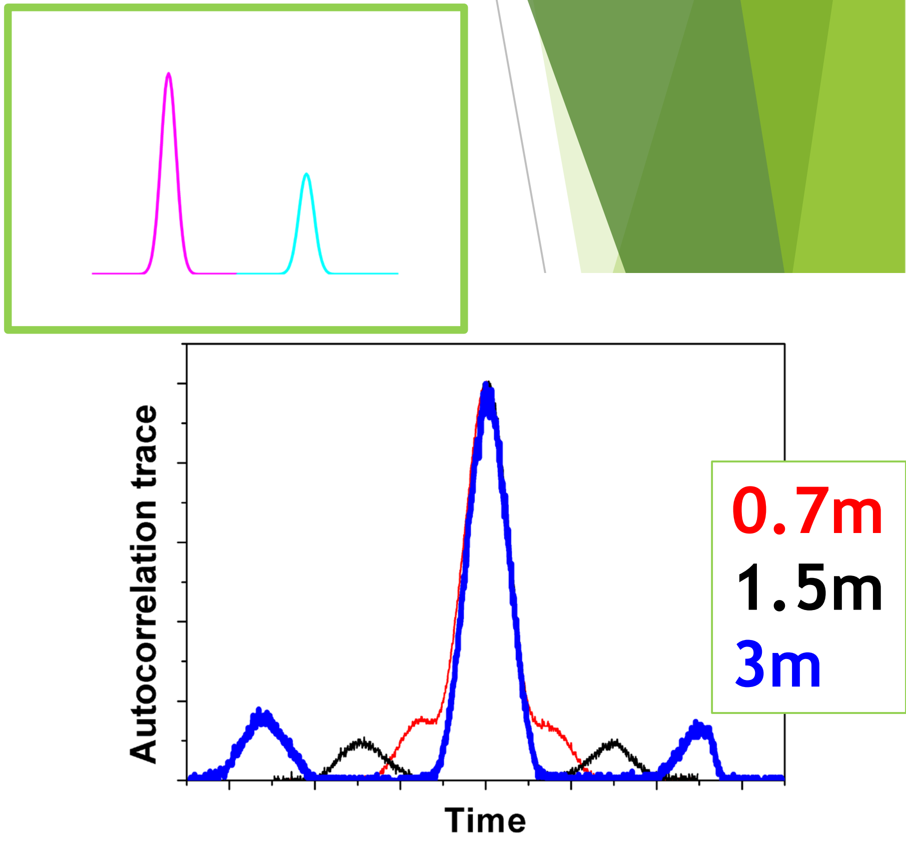
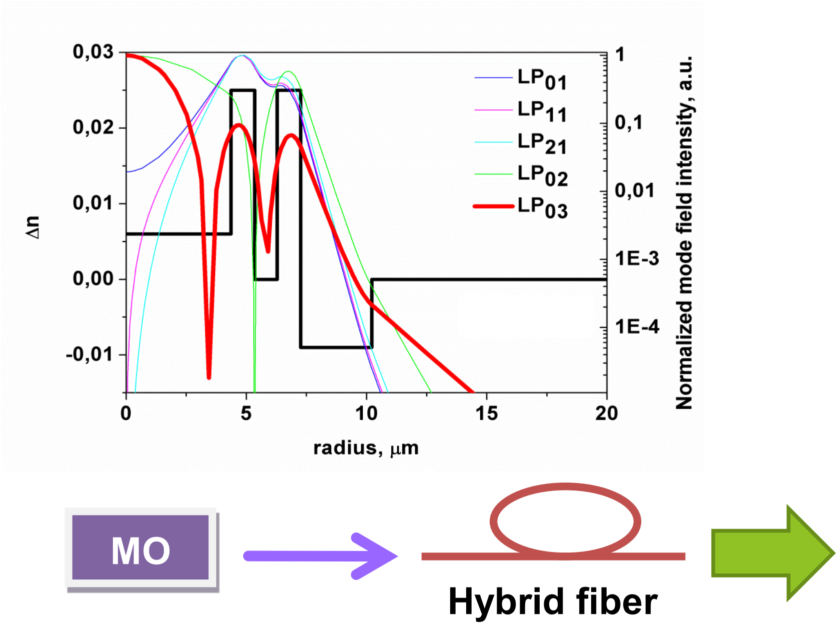


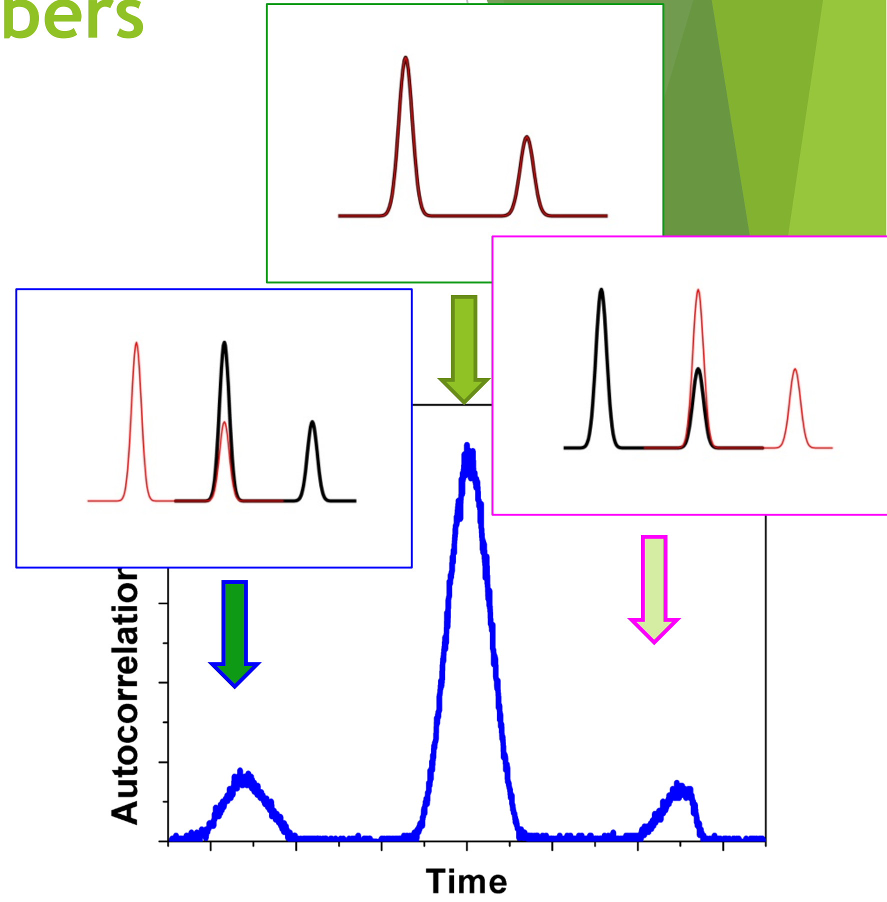




S. S. Aleshkina et al., Quantum. Electron., vol. 46, pp.738–742, 2016.

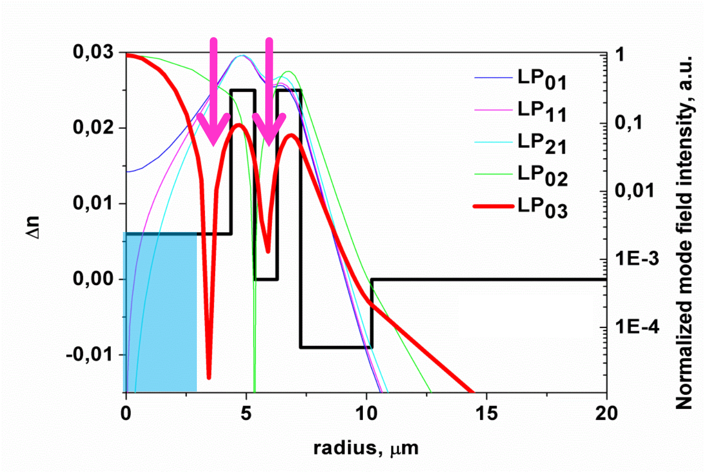
# Limitations of the hybrid fibers




S. S. Aleshkina et al., Quantum. Electron., vol. 46, pp.738–742, 2016.

# Asymptotically single-mode propagation of the hybrid fiber




**The operating mode and the undesired modes have a different mode field intensity distribution**

**1. The method of selective undesirable modes SUPPRESSION**

**Introduction of an additional absorbing ring layer into position of the hybrid mode minimum**

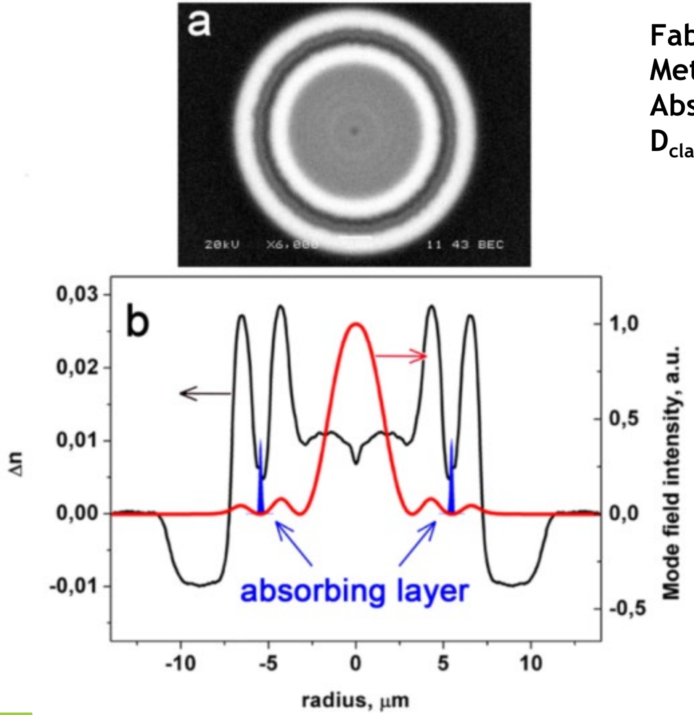
Aleshkina S. S., et.al, in IEEE Journal of Selected Topics in Quantum Electronics, **24**(3), 1-8 (2018)

**2. Method of selective mode AMPLIFICATION**

**Partial doping of the fiber core**

S. S. Aleshkina *et al.*, in *IEEE Photonics Journal*, vol. 11, no. 5, pp. 1-11, Oct. 2019

# 1. The method of selective undesirable modes SUPPRESSION




Fabrication method: MCVD
Method of absorbing layer creation: solution doping
Absorbing element: $Sm^{3+}$
$D_{clad}$=125 μm

**Estimated losses**

**Measured:**

$LP_{03}$ (Hybrid mode) = 0.8 dB/m

**Calculated:**

$LP_{02}$ = 22 dB/m
$LP_{01}$ = 43 dB/m

Aleshkina S. S., et.al, in IEEE Journal of Selected Topics in Quantum Electronics, **24**(3), 1-8 (2018)

# 1. The method of selective undesirable modes SUPPRESSION

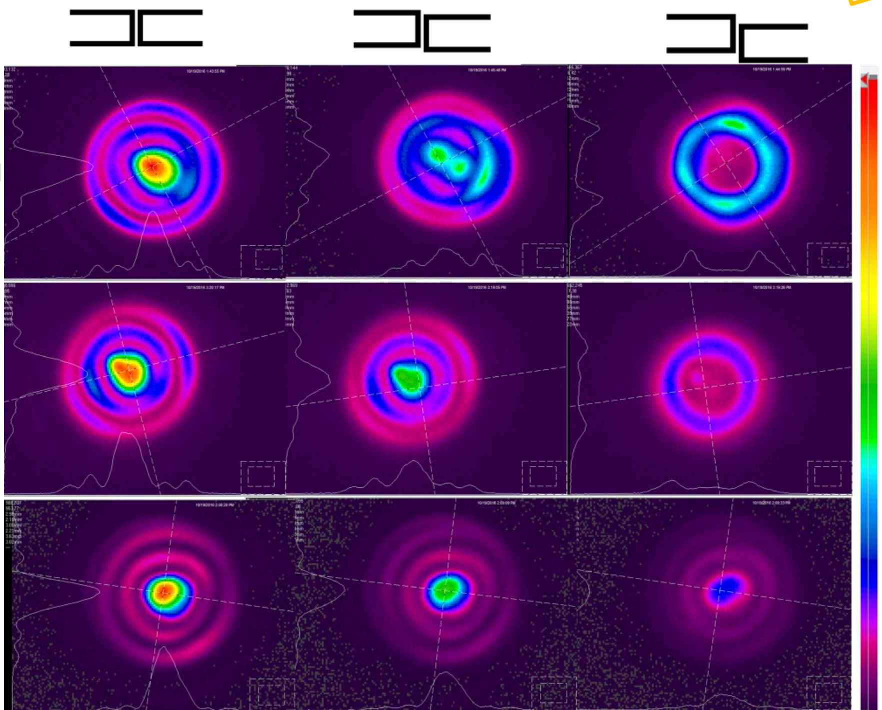
Hybrid mode

Mode content

0.5 m

3 m

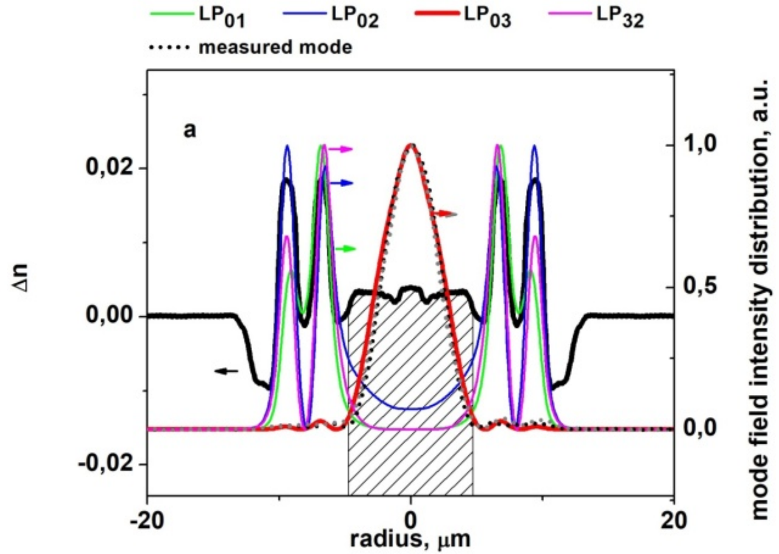
6 m

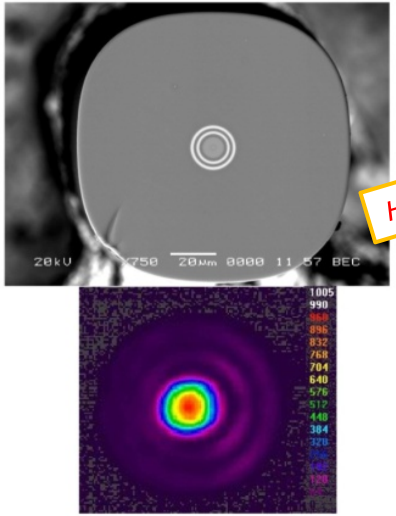


| $\alpha(LP_{03})$, dB | $\alpha(LP_{02})$, dB | $\alpha(LP_{01})$, dB |
|---|---|---|
| 0.4 | 11 | 21.5 |
| 2.4 | 66 | 129 |
| 4.8 | 132 | 258 |

Aleshkina S. S., et.al, in IEEE Journal of Selected Topics in Quantum Electronics, **24**(3), 1-8 (2018)

# 2. Method of selective mode AMPLIFICATION



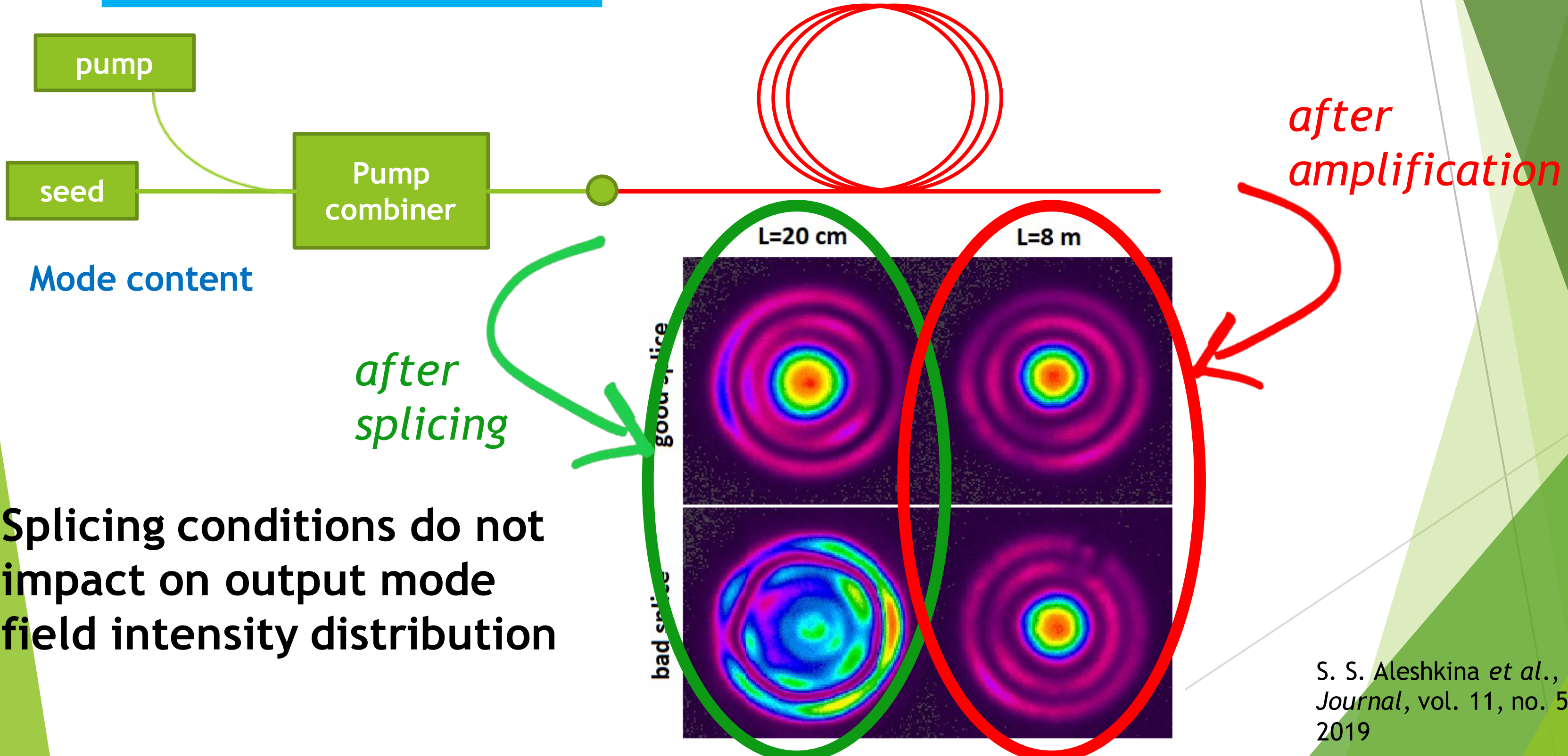




Hybrid mode

| mode | Overlap with doping region at 1.03 μm (1.06 μm) |
|---|---|
| $LP_{03}$ | 90% (87%) |
| $LP_{02}$ | 6.6% (9.5%) |
| $LP_{01}$ | 1% |

S. S. Aleshkina *et al.*, in *IEEE Photonics Journal*, vol. 11, no. 5, pp. 1-11, Oct. 2019

# 2. Method of selective mode AMPLIFICATION




**Splicing conditions do not impact on output mode field intensity distribution**

S. S. Aleshkina *et al.*, in *IEEE Photonics Journal*, vol. 11, no. 5, pp. 1-11, Oct. 2019

# Sub conclusion

## 1. The method of selective undesirable modes <u>SUPPRESSION</u>

**Introduction of an additional absorbing ring layer into position of the hybrid mode minimum**

Aleshkina S. S., et.al, in IEEE Journal of Selected Topics in Quantum Electronics, **24**(3), 1-8 (2018)

- ❖High hybrid mode losses
- ❖Low nonlinearity

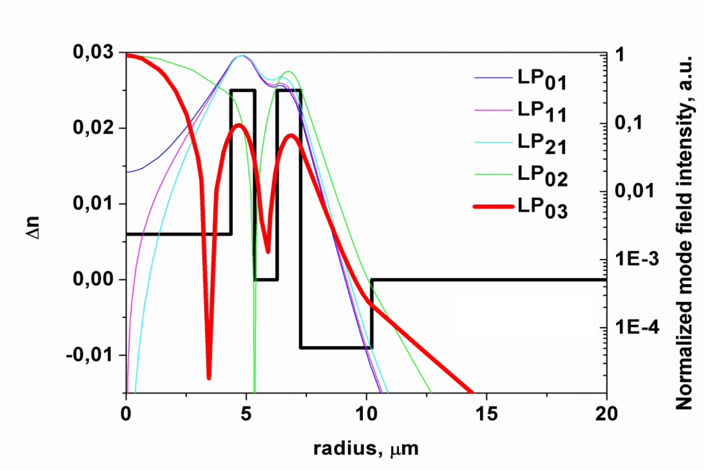
## 2. Method of selective mode <u>AMPLIFICATION</u>

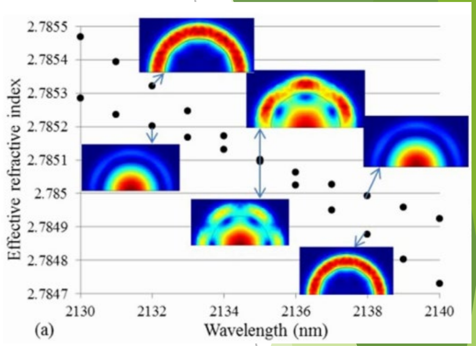
**Partial doping of the fiber core**

S. S. Aleshkina *et al.*, in *IEEE Photonics Journal*, vol. 11, no. 5, pp. 1-11, Oct. 2019

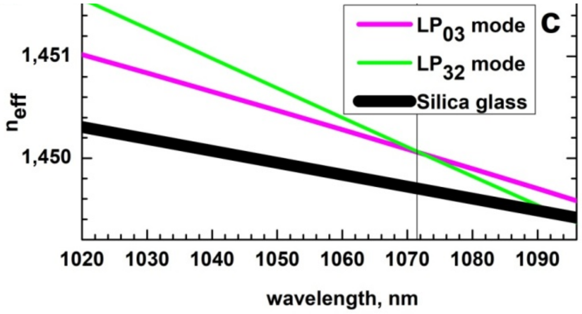
- ❖Low hybrid mode losses
- ❖High nonlinearity

# Resonant modes coupling effect



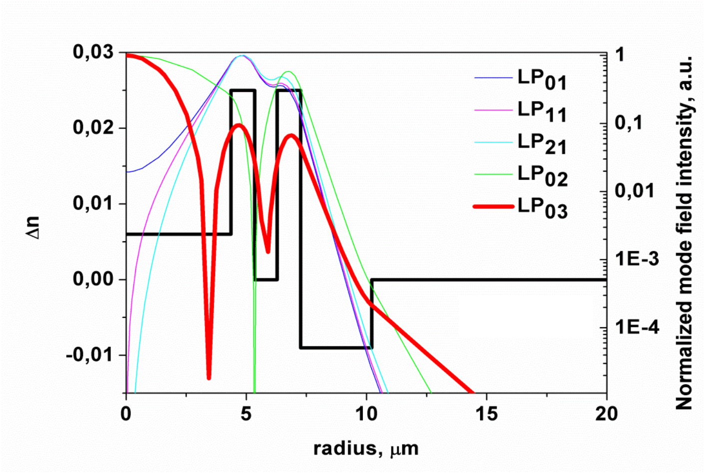



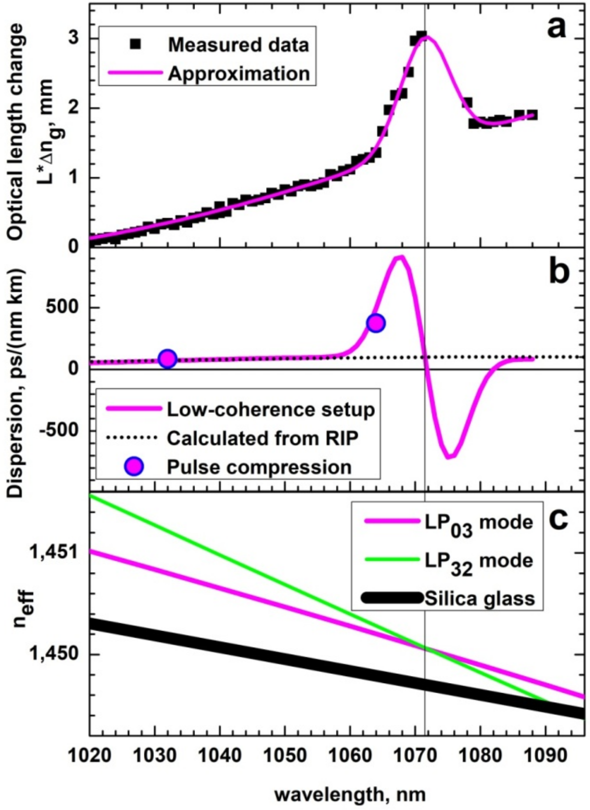

Jain, D., et.al, *Sci Rep* **9**, 8536 (2019)

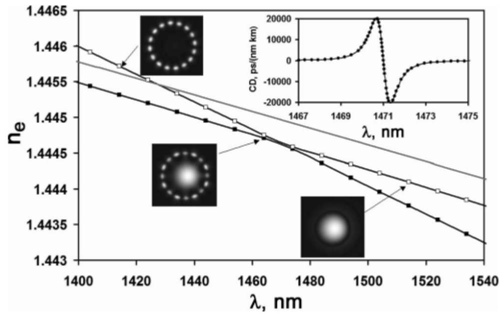


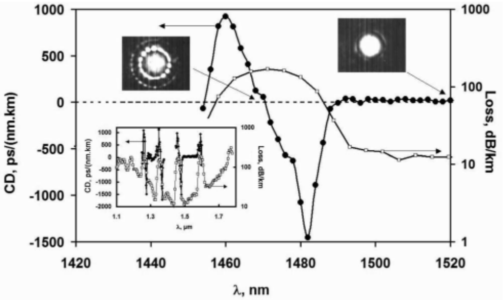

S. S. Aleshkina *et al.*, in *IEEE Photonics Journal*, vol. 11(5), pp. 1-11, 2019

# Resonant modes coupling effect



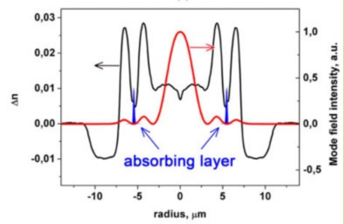
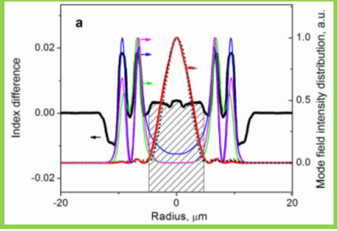

Frédéric Gérôme, et.al, Opt. Lett. 32, 1208-1210 (2007)

S. S. Aleshkina *et al.*, in *IEEE Photonics Journal*, vol. 11(5), pp. 1-11, 2019

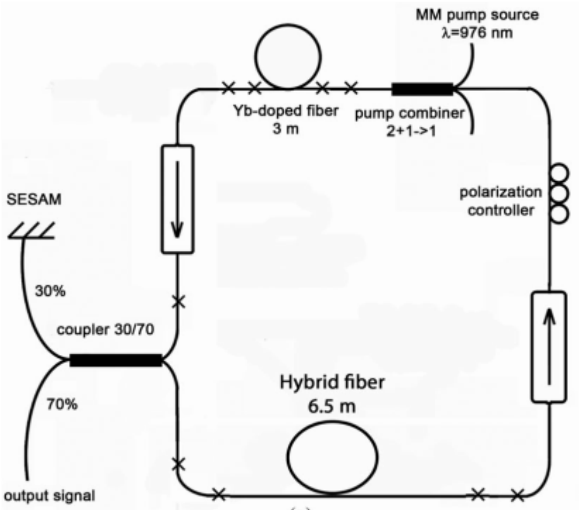
## Content:

1. Motivation and History of hybrid fiber development
2. Modeling aspects
3. Fabrication aspects
4. Limitations of the hybrid fibers and The ways to overcome them
5. Applications

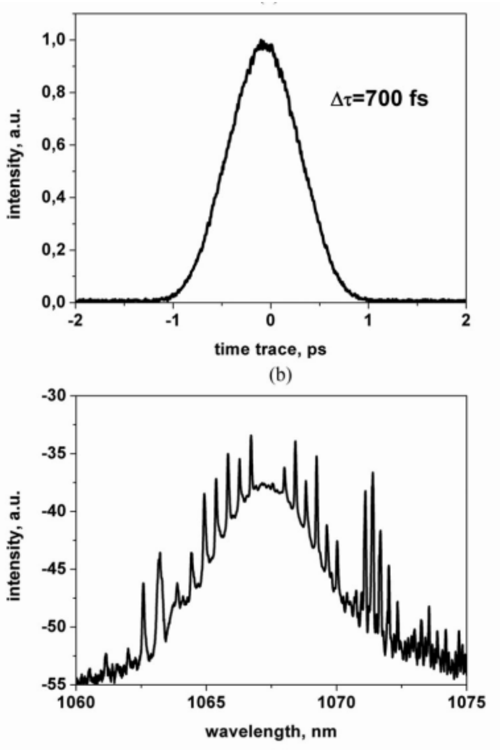
# Application

| Application | Approach | |
| --- | --- | --- |
| | undesirable modes <u>SUPPRESSION</u><br> | hybrid mode <u>AMPLIFICATION</u><br> |
| master oscillator | +<br>Aleshkina S. S., et.al, in IEEE Journal of Selected Topics in Quantum Electronics, 24(3), 1-8 (2018) | /high nonlinearity/ |
| pulse compression | /high propagation losses/ | +<br>S. S. Aleshkina *et al.*, in *IEEE Photonics Journal*, vol. 11(5), pp. 1-11, 2019 |

# Pulse generation



(a)



(b)

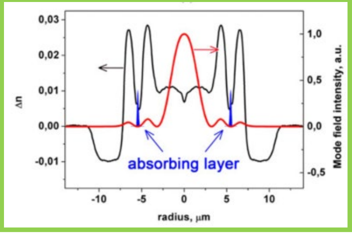
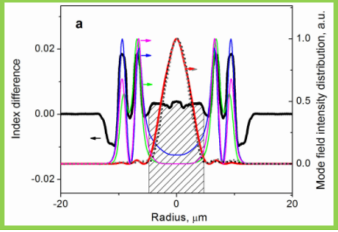

(c)

Pout=8.6 mW
ν=15.75 MHz
T=63.48 ns

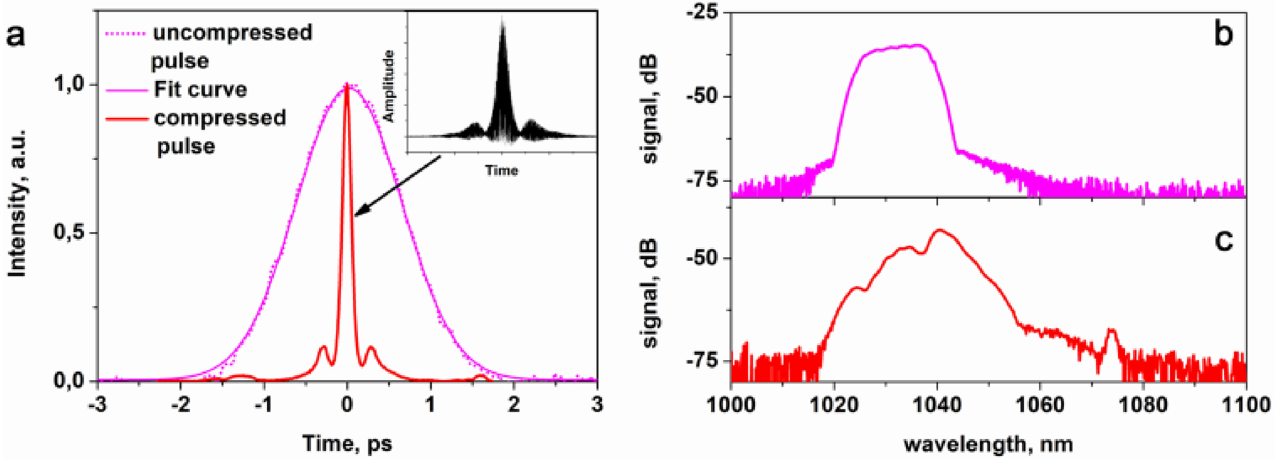
Ppeak~800 W
E=0.55 nJ

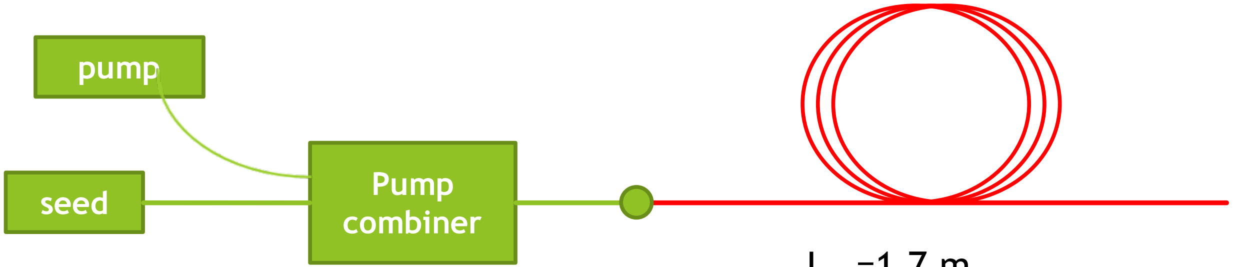
Aleshkina S. S., et.al, in IEEE Journal of Selected Topics in Quantum Electronics, 24(3), 1-8 (2018)

# Application

| Application | Approach | |
|---|---|---|
| | undesirable modes **SUPPRESSION**   | hybrid mode **AMPLIFICATION**   |
| master oscillator | + Aleshkina S. S., et.al, in IEEE Journal of Selected Topics in Quantum Electronics, 24(3), 1-8 (2018) | /high nonlinearity/ |
| pulse compression | /high propagation losses/ | + S. S. Aleshkina *et al.*, in *IEEE Photonics Journal*, vol. 11(5), pp. 1-11, 2019 |

# Chirped pulse compression



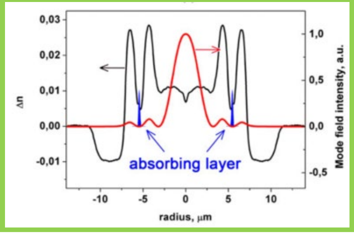
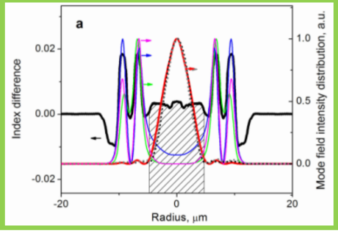




**Input pulse parameters:**
$\Delta\tau$=1 ps; $\Delta\lambda$=11 nm; Pav=1 mW

**Output characterisics:**
$\Delta\tau_{in}$=90 fs
E=0.9 nJ (Pav=40 mW)
Peak~10 kW

S. S. Aleshkina *et al.*, in *IEEE Photonics Journal*, vol. 11(5), pp. 1-11, 2019

# Application

<table>
<tr><th rowspan="2">Application</th><th colspan="2">Approach</th></tr>
<tr><th>undesirable modes<br><u>SUPPRESSION</u><br>
</th><th>hybrid mode<br><u>AMPLIFICATION</u><br>
</th></tr>
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<tr><td>pulse compression</td><td>/high propagation losses/</td><td>+<br>S. S. Aleshkina et al., in IEEE Photonics Journal, vol. 11(5), pp. 1-11, 2019</td></tr>
</table>

## Potential Applications

**Raman soliton generation**

S. S. Aleshkina *et al.*, in *IEEE Photonics Journal*, vol. 11, no. 5, pp. 1-11, Oct. 2019

**SC generation**

Mid-infrared spectral range

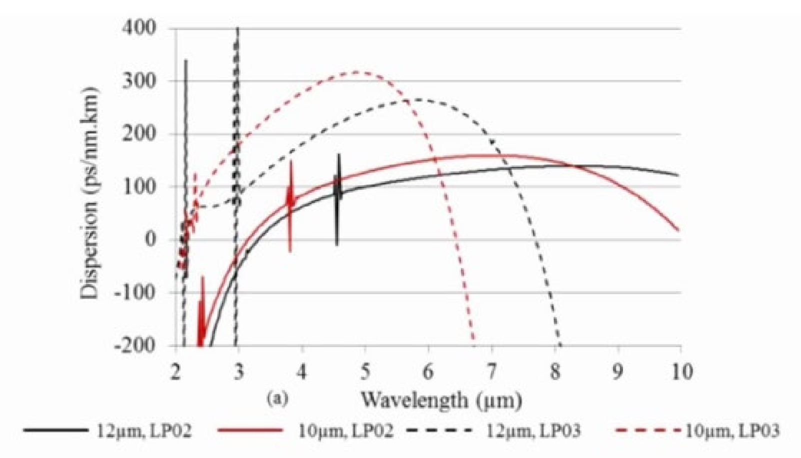
ZDW shifting to the spectral range of available pump sources

Jain, D., et.al, *Sci Rep* **9**, 8536 (2019)

# Supercontinuum generation

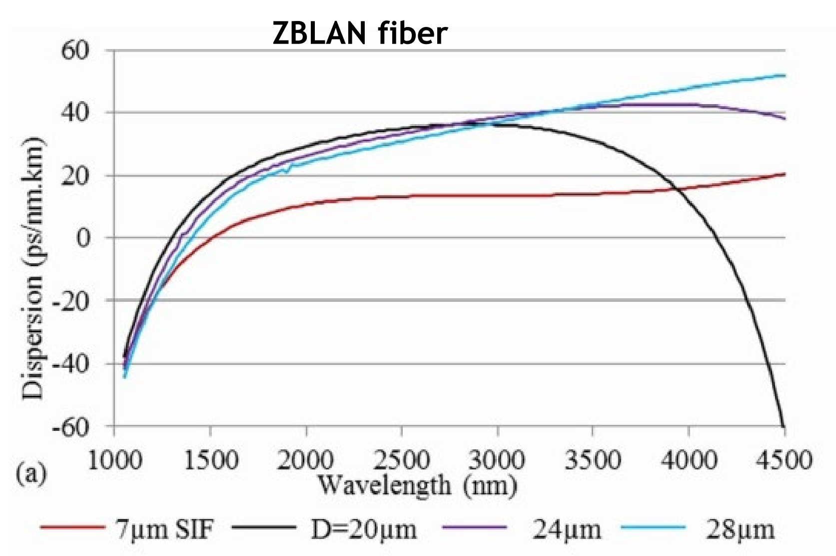
## Mid-infrared spectral range ($\lambda$>2 $\mu$m)

**Chalcogenide fiber**




**Pump source: Er-ZBLAN at 2.94 $\mu$m**

Jain, D., et.al, *Sci Rep* **9**, 8536 (2019)




**Possibility to increase MFD compared to standard SIF**

Jain, D., et.al, *Sci Rep* **9**, 8536 (2019)

# Conclusion

- Hybrid fibers (also called as M-type fibers) is perspective structure for dispersion management  due to
  - all-glass  structure
  - Possibility to control the dispersion sign and its slope.
- The main features of the hybrid fiber correspond to Bragg fibers characteristics that are due to the similar nature of operating mode formation.
- Appropriate choice of the fiber parameters and glass matrix allow to provide dispersion management in the different spectral regions.

# Thanks

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ICHPS RAS

Senatorov Andrey
FORC RAS

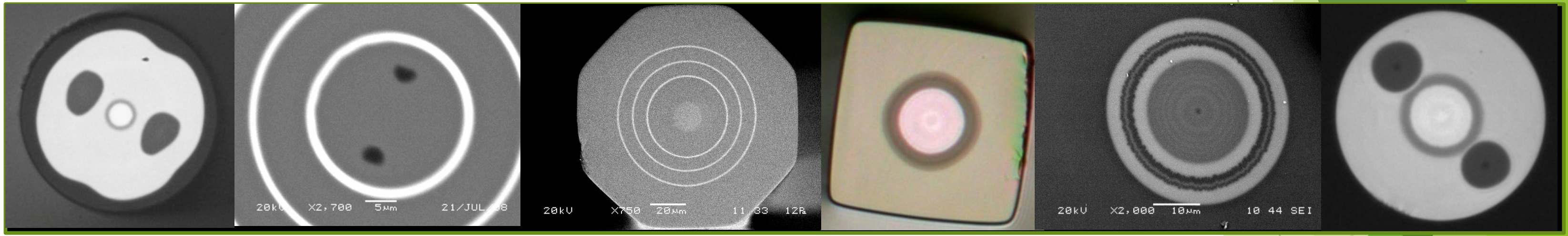
Yatsenko Yuri
FORC RAS

Bubnov Mikhail
FORC RAS

Guryanov Alexey
ICHPS RAS

# Our fibers are commercially available through FORC-Photonics

http://www.forc-photonics.ru/en/



# Questions: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Dianov Fiber Optics Research Center
Specialty Optical Fibers Lab

FORC RAS


FORC RAS

# Thank you for your attention!