# FBG and FBG-Sensors for use in Difficult Environmental Conditions

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EPIC World Photonics Technology Summit 2019
29-30 August, Berlin

## Founded in 2005

FORC RAS

FORC - Photonics

### Main business:

Manufacture different type of Fiber Bragg Gratings

Development and production of fiber-optic sensor systems

Development and production of ASE and high power amplifiers

Optimization design specialty fibers for fiber optics devices

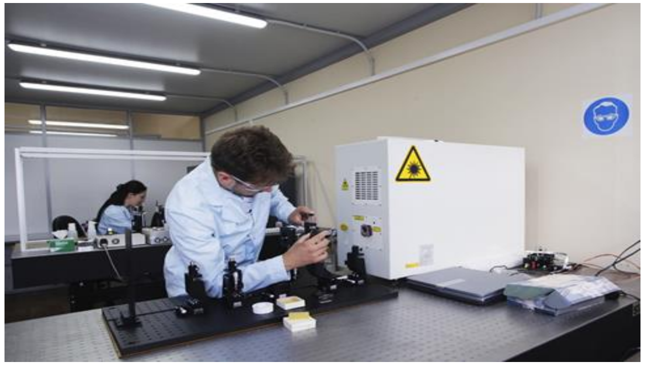
ISO 9001-2015

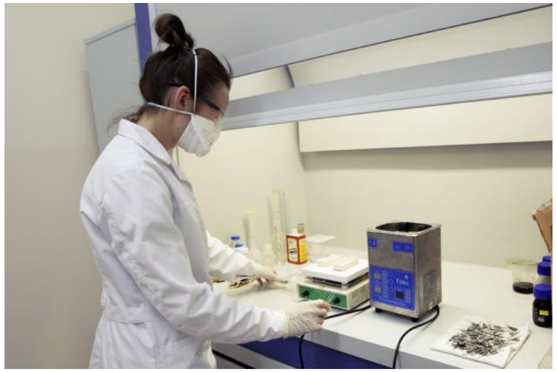
ISO 14001-2015

Intellectual property - 10

# About FORC-Photonics

- 500 square meters area
- 35 specialists (6 PhD)
- 4 groups
  - R&D group
  - FBG group
  - Production group
  - Metrological support group





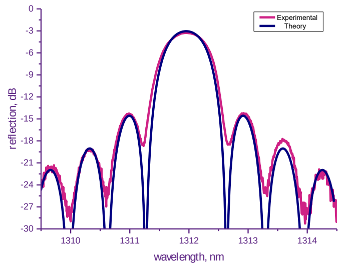
# FBG MANUFACTURED METHOD

- INTERFEROMETRIC METHOD
- MASKS METHOD
- FEMTOSECOND METHOD

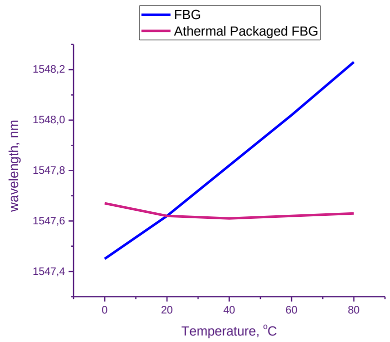
| FBG MANUFACTURED METHOD | INTERFEROMETRIC METHOD | MASKS METHOD | FEMTOSECOND METHODS |
|---|---|---|---|
| Wavelength range, nm | 600 ÷ 2300 | 633, 780, 794, 797, 799, 801, 852, 940, 976, 1030, 1057, 1060, 1064, 1080, 1125, 1150, 1178, 1310, 1510 ÷ 1580, 1650, 1900, 1908, 1952, 2300 | 700 ÷ 2000 |
| FBG types | Uniform, fiber laser matched pairs, π-phase shifted, tunable, athermal packaged | Uniform, apodized, fiber laser matched pairs, chirped, tilted, π-phase shifted, tunable, athermal packaged | |
| Types of fiber | Single-Mode, PM, Double clad, LMA | | Single-Mode, PM, Double clad, LMA, Radiation resistant, Active and Passive fibers |
| Reflectivity, % | 0.2 ÷ 99.9 | 0.2 ÷ 99.9 | 0.2 ÷ 95 |
| Bandwidth (WFHM), nm | 0.05 ÷ 1.2 | 0.05 ÷ 1.2 | 0.1 ÷ 7 |
| FBG Recoating | None, Acrylate, Polyimide, Aluminium, Copper | | |
| Chirp Rate, nm/cm | no | 0.01 ÷ 33 | 0.01 ÷ 33 |
| FBG inscription thought the fiber protective coating | no | no | Acrylate, Polyimide |

# FBG technology

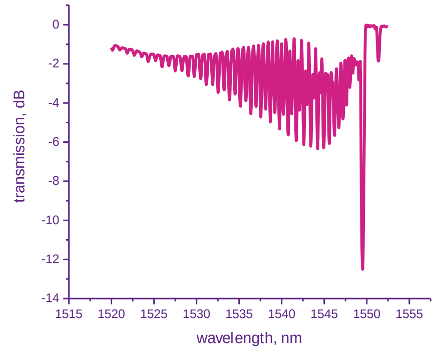
UNIFORM FBG



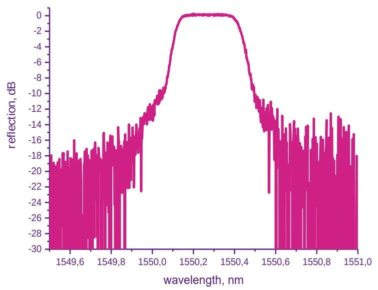

ATHERMAL PACKAGED FBG



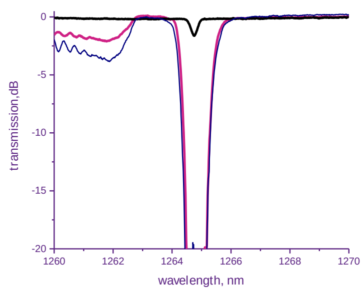

TILTED FBG



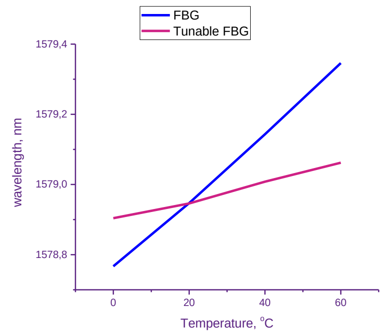

APODIZED FBG



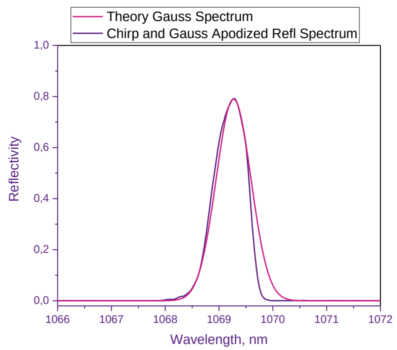

FIBER LASER MATCHED FBG PAIRS



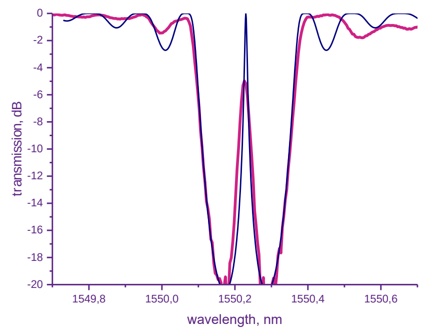

TUNABLE FBG



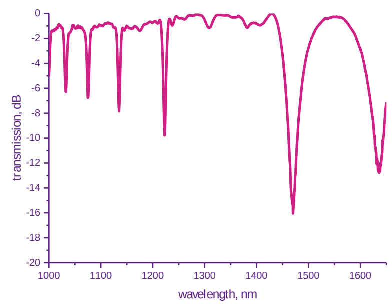

CHIRPED FBG




π-PHASE-SHIFTED FBG

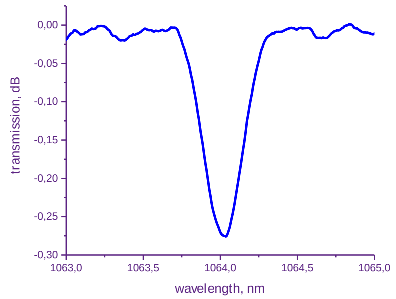


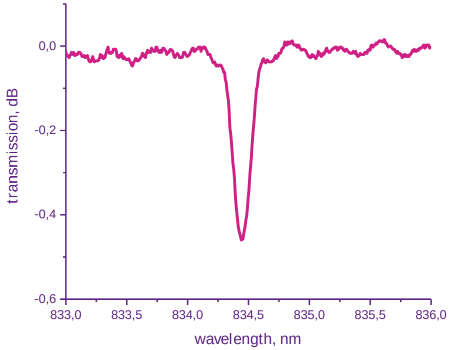

LONG PERIOD FIBER GRATINGS (LPFG)



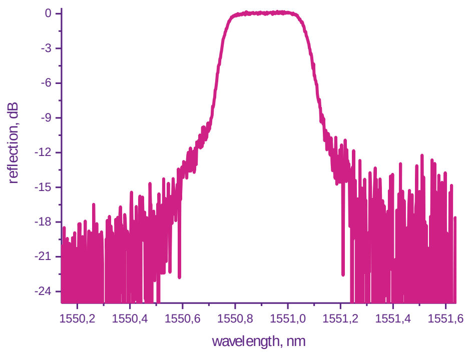
# FBG specific application type

**FBG WAVELENGTH LOCKER**



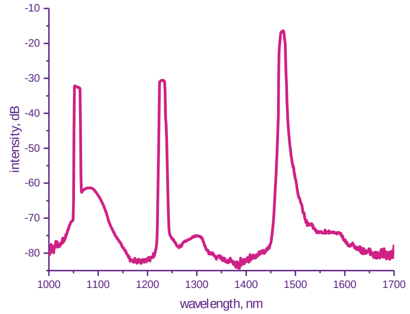




**FBG WDM ITU FILTER 100/200GHZ**

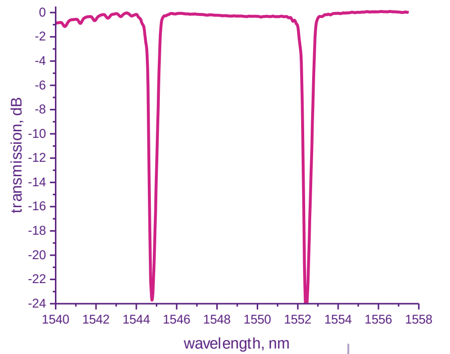



**FBG FABRY-PEROT INTERFEROMETER**


**FBG RAMAN LASER (NOT REMOVING COATING)**

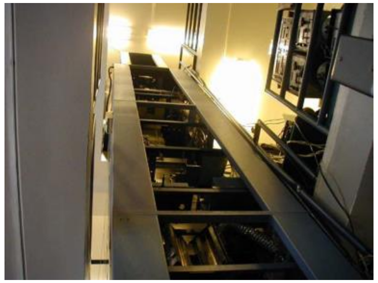


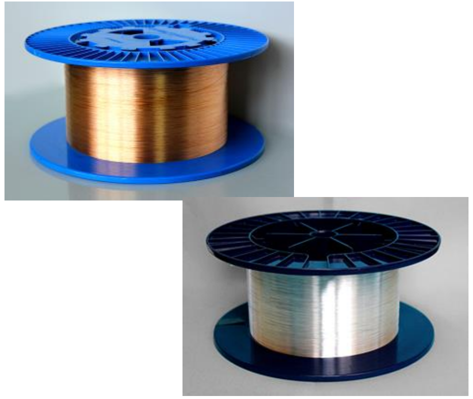

**RADIATION HARD FBG**



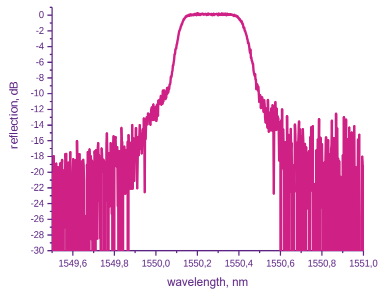
# FBG sensors

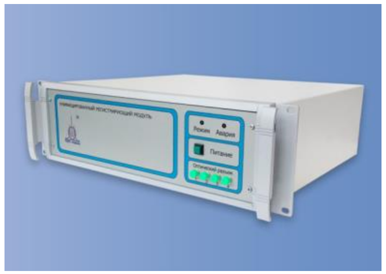
FORC RAS





FORC - Photonics



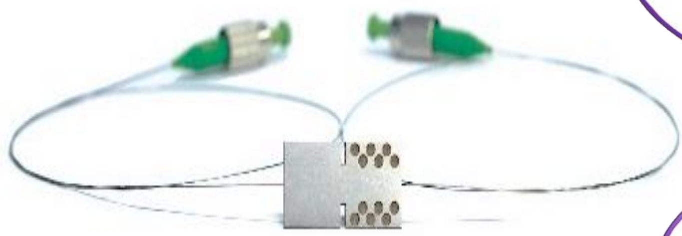



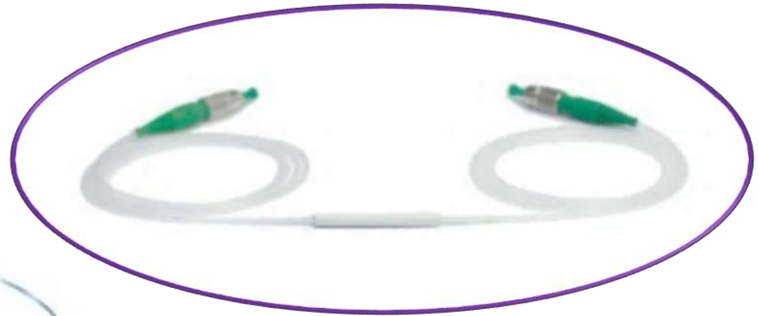
✓Sampling frequency of sensors 8 kHz

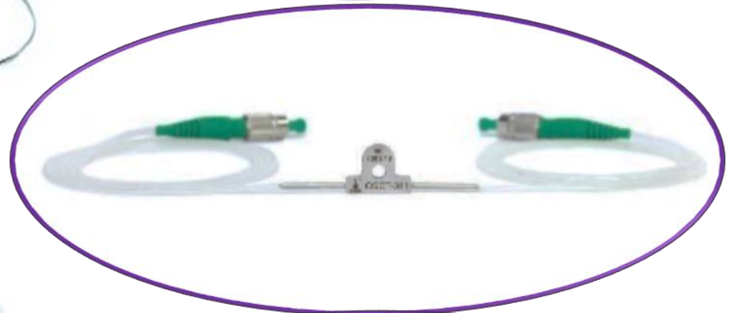
## FBG sensors

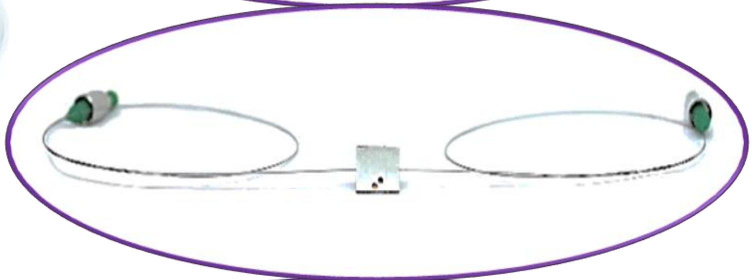
## High temperature and radiation resistance sensors

- Temperature sensor
- Strain sensor
- Displacement sensor
- Acoustic sensor









**Operating temperature up to +500 ºC**

**Radiation resistance condition:**

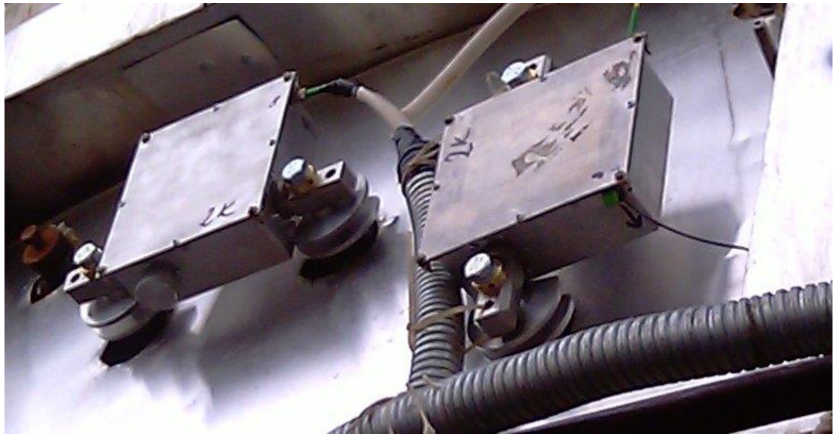
- **absorbed dose of γ-irradiation 2,9*10^7 Gy** (IVG-1M nuclear reactor).
- **fluence of fast neutrons 4.5*10^17 n/cm^2** (WWR-K reactor)

## Application of the sensors

### Control of the coke column at the refinery

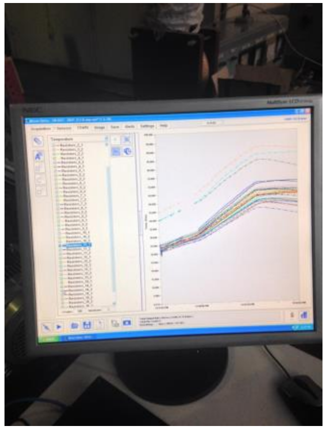
T $_{inside}$=500C

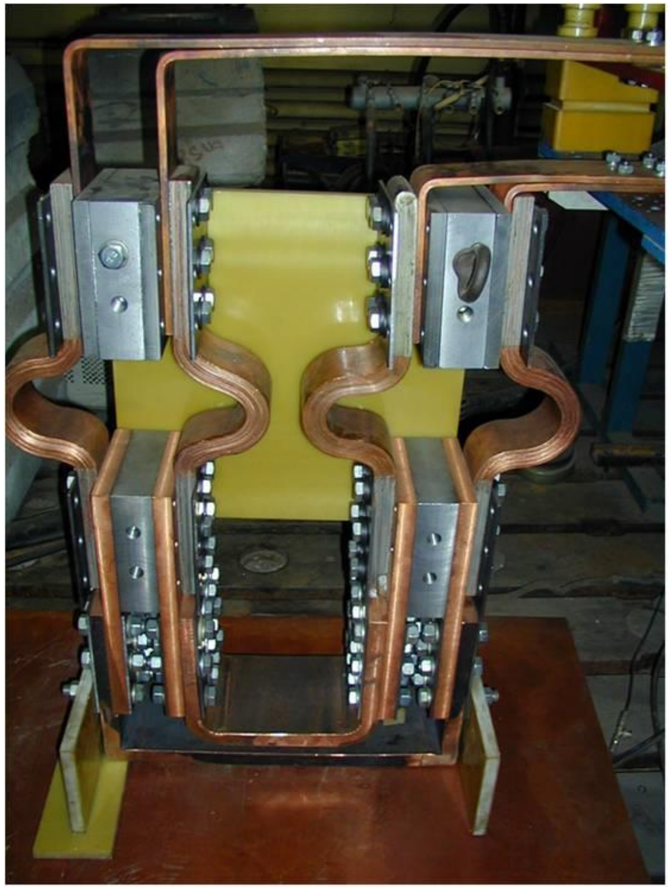
T $_{outside}$=230C



## The temperature control resistors and basbar contact connection of the power supply system

$T_{inside}$ = 400C





T = 150C

Q-ty › 3500pcs

## Application of the sensors

Temperature, strain, acoustic and displacement sensors for Blanket and Divertor of vacuum vessel

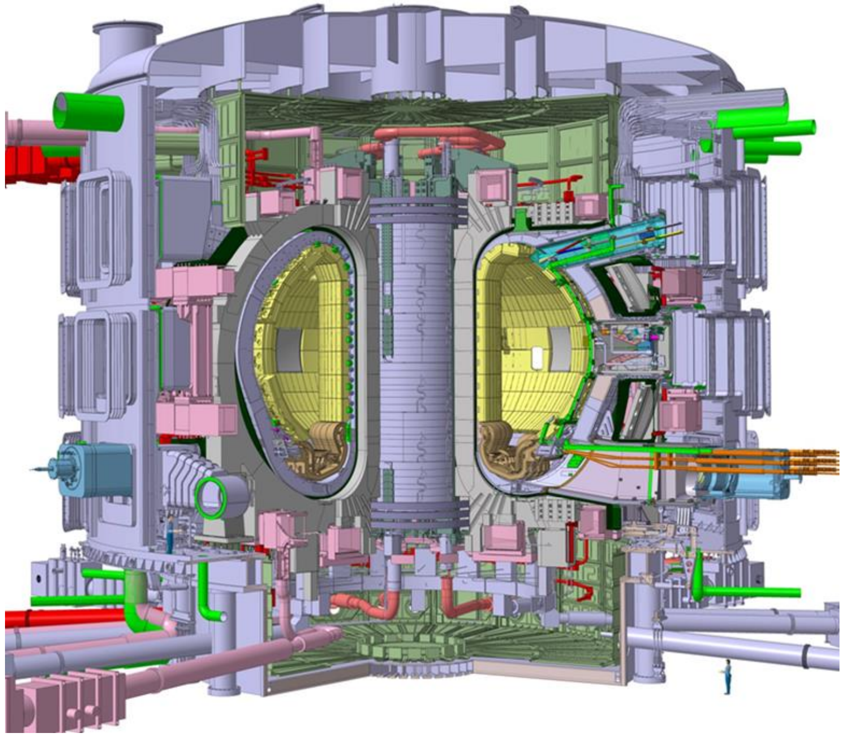
- Divertor and Blanket directly face the thermonuclear plasma and cover an area of about 210 + 620 $m^2$, respectively.

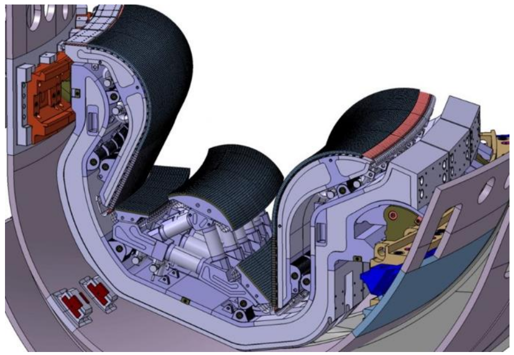
- All these components are mechanically attached to the Vacuum Vessel.

- All these components are designed to be replaced by RH tools

- Max heat released during nominal pulsed operation: ~850 MW

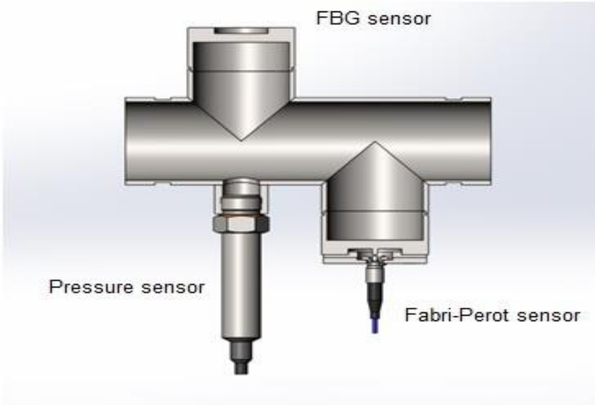
- Removed by four independent water loops (~1300 kg/s each), at 4 MPa water pressure, ~70 (inlet), ~130 (outlet) °C



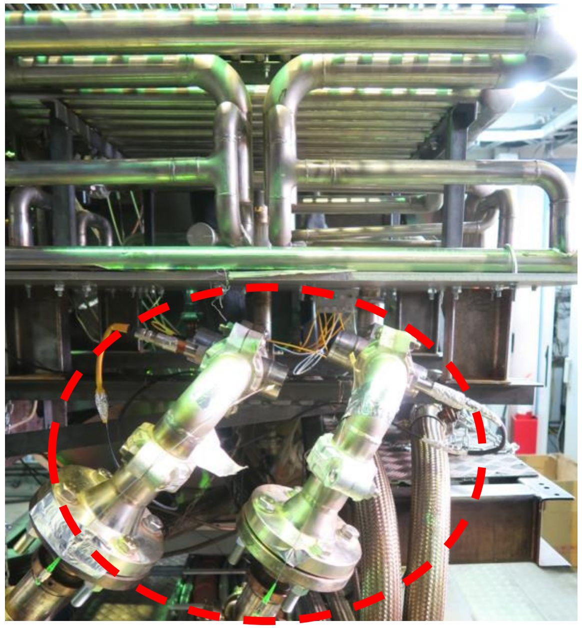


**T = 350C** **Q-ty › 2000pcs**

## Optical fibre acoustic sensors for the early detection of "Critical Heat Flux" events




**T = 250C**



## Test program

Table matches the technical requirements applied to each sensor type with certain tests, which have to be performed to satisfy these requirements.

| Technical requirement | Temperature sensor | Strain sensor | Displacement sensor | Acoustic sensor | Test |
|---|---|---|---|---|---|
| **Operating temperature , °C** | 20-350 | 250-350 | 250-350 | 250-350 | Accelerated temperature aging test |
| **Temperature limit, °C** | 600 | - | - | - | |
| **Fatigue life** | ~ $10^3$ cycles, 70 → 350 → 70°C | - | - | - | Thermocycling test |
| | - | ~ $3*10^5$ cycles, ± 2000 με (Strain limits ± 2500 με) | - | - | Combined cyclic & static strain test |
| | - | - | ~ $10^5$ cycles, ± 5 mm (Displacement limits ± 8 mm) | - | Combined cyclic & static displacement test |
| | - | - | - | ± 400 m/s2 peak (± 40 g) | Acoustic test |

## Test equipment

**Servohydraulic fatigue testing system INSTRON 8802** equipped with a high-temperature climatic chamber INSTRON SFL 3119 - 408, which allows operating in the temperature range from -70ºC to + 600ºC.

**Vibration testing system THV–216–A–600C** equipped with high-temperature climatic chamber which allow operating in the temperature range up to +600°C.

## Certificates

### Verification certificates of the test equipment

# Specialty fibers

### YTTERBIUM DOPED FIBERS (PHOTODARKENING FREE)

| | |
|---|---|
| **YDF-SM-6/125** | **operation without power degradation in core-pumped laser and amplifier schemes (optimal fiber length ~ 0.5-1 m)** |
| **YDF-DC-6/125** | highly efficient high-reliability lasers operating in the 1.03-1.08 µm spectral range. |
| **YDF-DC-10/125** | high-peak-power cladding pumped amplifiers. |
| **YDF-DC-40/400-PM-TPR** | operation without any power degradation in extremely high-peak-power cladding-pumped amplifiers |

### BISMUTH DOPED FIBERS

| | |
|---|---|
| **BiDF-SM-7/125** | **highly efficient ASE sources, lasers and amplifiers operating near 1440 nm** |

### ERBIUM DOPED FIBERS

| | |
|---|---|
| **EDF-4/125-10** | **highest efficiency of telecommunication amplifiers** |
| **EDF-4/125-25** | amplifier length without pump-to-signal conversion efficiency degradation |
| **EDF-4/125-50** | amplification of ultra-short pulses, when high efficiency, a short amplifier length and a high negative dispersion are required |
| **EDF-14/125-35** | low-nonlinearity amplifiers |

### THULIUM - YTTERBIUM DOPED FIBERS

| | |
|---|---|
| **TYDF-DC-7/125** | **highly efficient pumping with MM pump sources at 915/975nm. Pumping with conventional sources near 790 nm is also possible, as well as core pumping with EDFL operating at 1550-1600nm** |

### PHOSPHOROUS DOPED FIBERS

| | |
|---|---|
| **P-SM - 5** | **highly efficient Raman lasers and amplifiers operating in the 1.1-1.6 µm spectral range** |
| **P-SM – 5 PM** | specially designed with ability to maintain polarization |

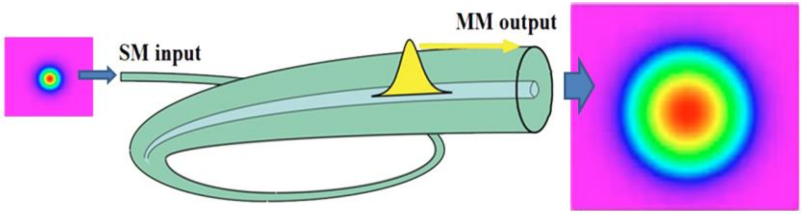
### HIGHLY NONLINEAR FIBERS (GERMANIUM-DOPED)

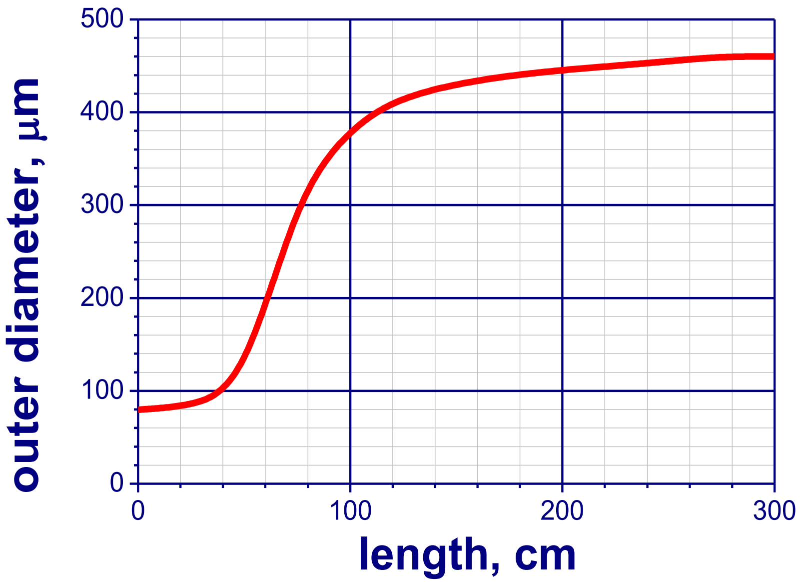
| | |
|---|---|
| **HNLF** | **constructing highly efficient Raman lasers and amplifiers, dispersion compensators** |
| **HNLF DS** | shift of the zero dispersion wavelength to the 1550 nm spectral region: supercontinuum generation, parametric conversion and etc. |

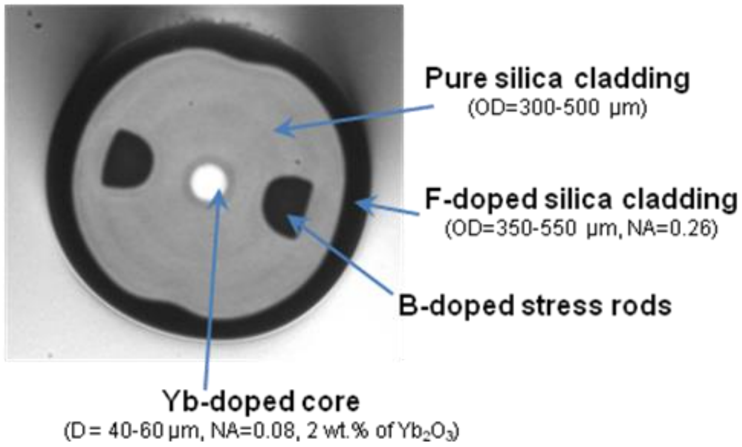
### METAL-COATED SILICA FIBERS

| | |
|---|---|
| **Aluminum coated fibers** | **High OH/ Low OH. Excellent long life fibers for harsh environmental applications** |

## Tapered fiber YDF-DC-40-400-TPR




| Fiber specifications | YDF-DC-40/400-PM-TPR | |
|---|---|---|
| **Signal type** | **Signal input end** | **Signal output / pump input end** |
| Core diameter, µm | 9 ± 1 | > 40 |
| Clad diameter, µm | 90 ± 10 | 450 ± 100 |
| Cutoff wavelength, µm | < 1.0 | - |
| MFD, µm | 10.0 ± 2.0 | > 20 (25-30 typical) |
| Inner clad shape | PANDA with F-doped second cladding | |
| Core NA | 0.085 ± 0.01 | |
| Clad NA | > 0.26 | |
| Clad absorption (915 nm), dB/m | > 2.5 | |
| Clad absorption (976 nm), dB/m | > 10 | |
| Grey loss (1150 nm), dB/km | < 50 | |
| Photodarkening resistance | > 20 times better compare to the $Al_2O_3$-$SiO_2$ Yb-doped fiber | |

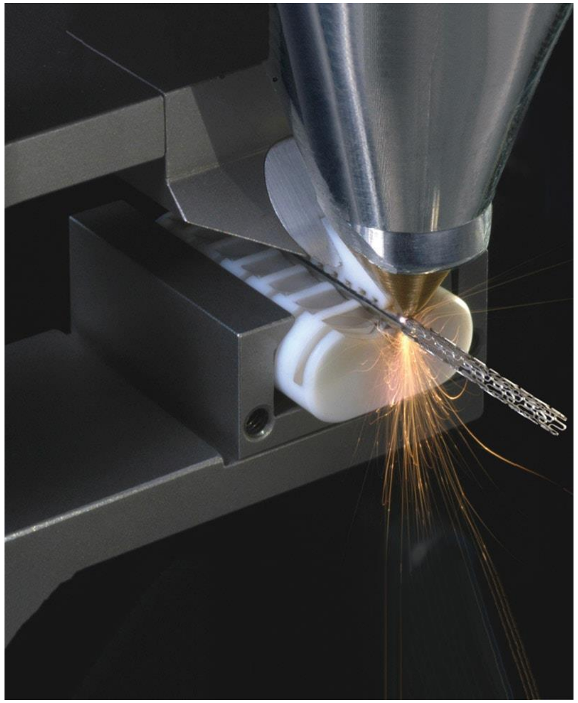
**! NO high order modes excitation**

**beam quality factor is typically below 1.2**

**! Scaling of the core D up to 10 times as compare to SM fiber**

# Tapered fiber YDF-DC-40-400-TPR High peak and average power

## Application: High speed micromachining



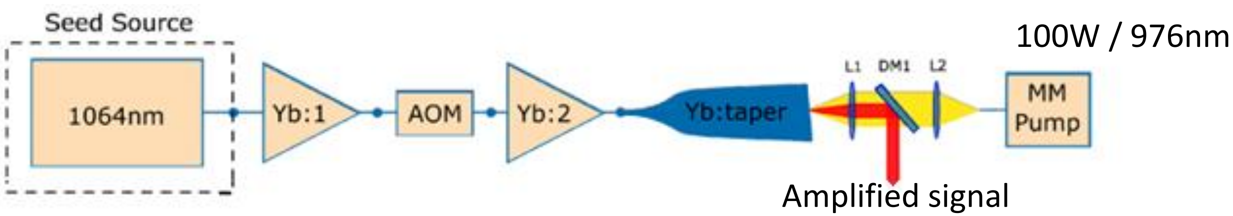
- Amplification chirped pulse up to sub-MW peak power (directly from amplifier) with following pulse compression to fs duration and few tens peak power [1]
- Simultaneous achievement of high average and peak power: 70W of average power and 0.8 MW of peak power [2]

**RECENT RESULTS [3]:**
**150W of average power and 0.9 MW of peak power**

***Additional advantages:***
- ***Diffraction limited beam quality (typical $M^2$ <1.2)***
- ***Simple in use compact monolithic laser design***
- ***Compatible with mass production***


[1] K. Bobkov et al, "Sub-MW peak power diffraction-limited chirped-pulse monolithic Yb-doped tapered fiber amplifier," Opt. Express 25, 26958 (2017)
[2] K. Bobkov et al, "71 W average power sub-MW peak power diffraction-limited monolithic tapered fiber amplifier", CLEO-Europe'2019, paper CJ-4.1
[3] K. Bobkov et al, "Generation of picosecond pulses with 150 W of average and 0.92 MW of peak power from an Yb-doped tapered fiber MOPA", was sent to Photonics West conference (2020)


**Laser scheme:** Seed source (1064 nm) ass few preamplifiers (Yb:1,2) and than to the tapered fiber (Yb:taper) which is counter-pumped by 976 nm pump through dichroic mirror (DM1). Repetition rate of the signal is controlled via acoustic-optical modulator (AOM)



## Our solutions allow easy achievement of high peak and average power

**Few world records in term of peak power were set with our solutions!**

### 1.06 µm spectral region (highest simultaneous peak and average power):

Yb-doped tapered fiber amplifiers (available product: (YDF-DC-40-400-TPR tapered fiber)

[1] K. Bobkov et al, "Sub-MW peak power diffraction-limited chirped-pulse monolithic Yb-doped tapered fiber amplifier," Opt. Express 25, 26958 (2017)
[2] K. Bobkov et al, "71 W average power sub-MW peak power diffraction-limited monolithic tapered fiber amplifier", CLEO-Europe'2019, paper CJ-4.1
[3] K. Bobkov et al, "Generation of picosecond pulses with 150 W of average and 0.92 MW of peak power from an Yb-doped tapered fiber MOPA", was sent to Photonics West conference (2020)

### 1.55 µm spectral region (highest pulse energy, highest peak power for single-frequency pulses, highest efficiency for high peak power amplifiers):

cladding pumped large mode area Er-doped (Yb-free) fiber amplifiers
(available product: OEM and bench top fiber amplifier FOA-EDFA-HP-30-1)

[1] L.Kotov, et al, "Millijoule pulse energy 100-nanosecond Er-doped fiber laser," Opt. Lett. 40, 1189-1192 (2015)
[2] L. V Kotov et al., “Record-peak-power all-fiber single-frequency 1550 nm laser,” Laser Phys. Lett., vol. 11, p. 095102 (2014)
[3] M.M. Khudyakovet al, "All fiber combined Er/Er-Yb amplifier for efficient amplification of high peak power single frequency pulses", accepted for ASSL'2019 conference.

# Thank you for attention!

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