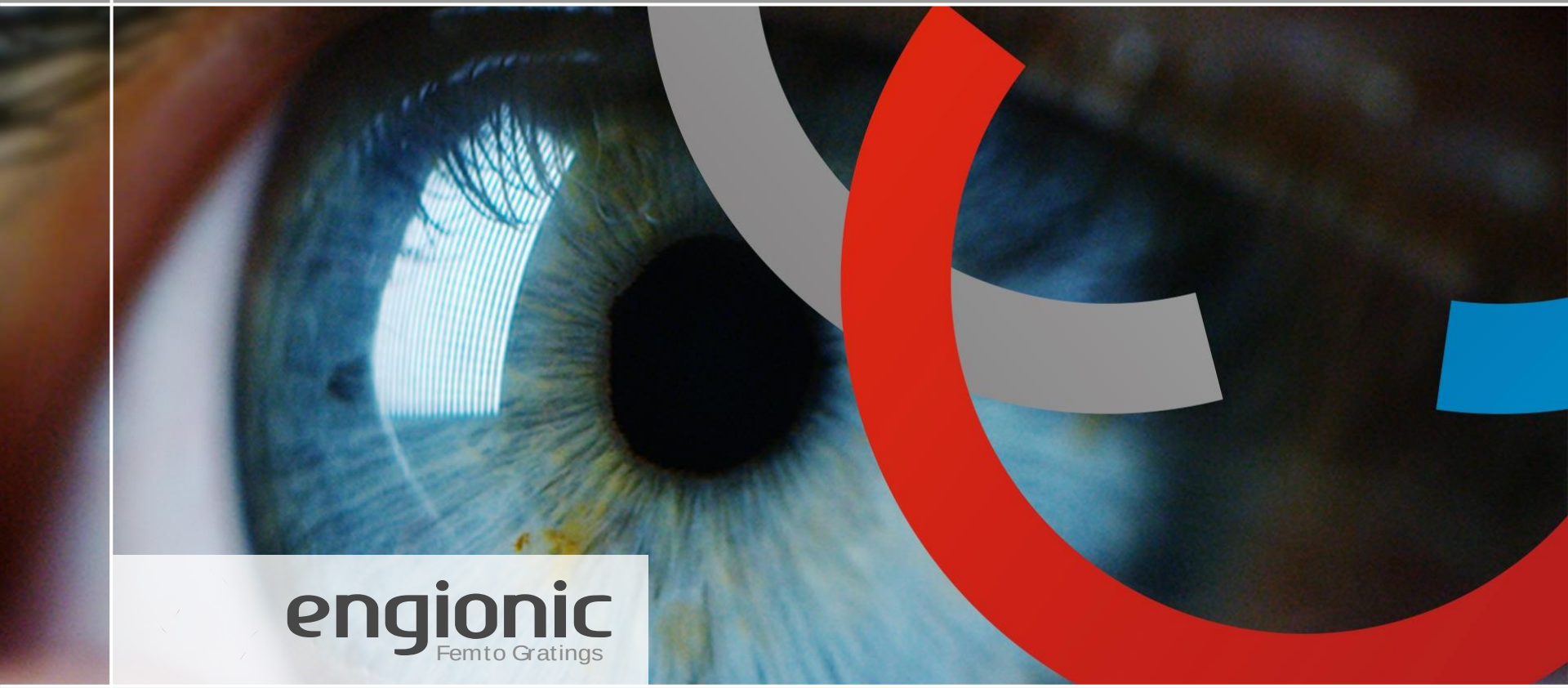


Gold-Coated Femtosecond FBGs for expanded temperature sensing

EPIC, Porto, 19.04.23

member of engionic group

The group focuses on fiber bragg gratings, fiber optic sensors and systems as well as CNC precision parts

Business approach engionic group companies

engionic Femto Gratings

- **Founded** in **2013**
- **Manufacturing** of **Fiber Bragg Gratings (FBG)**
- Worldwide **first** commercial **supplier** of **fs-point-by-point** inscription **FBGs**
- From single FBG to FBG arrays with thousands of sensors in one fiber
- Unrivalled **large range** of available **fibers** and **coatings**
- Certified **DIN ISO 9001**

engionic Fiber Optics

- Successful **>30 years**
- Fiber Optic **Light Guides**, **cross section converters**, **probes**, **medical components**
- **FBG** based **sensor solutions and assemblies**
- FBG **system solutions covering all** available **interrogation technologies**
- Customer-specific **OEM manufacturing**
- From prototyping to efficient serial production
- Certified **DIN ISO 9001**

engionic CNC

- **Successful >20 years**
- **High precision mechanics** for customer-specific parts
- Focus on **medical applications** (for example heart pumps)
- **Broad technology base** – CNC milling and drilling, honing, sand blasting, coating, laser marking
- Certified **DIN ISO 9001**

∑ approx. 40 employees

All engionic group companies are managed from the international headquarter in Berlin

Business locations engionic group

BERLIN

- In January 2017 the **new company headquarter** has been finished in Berlin Adlershof - one of the most successful **high-technology sites** in Germany
- The headquarter hosts the **complete production** of engionic Fiber optics and engionic CNC, as well as the **management and sales office** for all engionic group companies

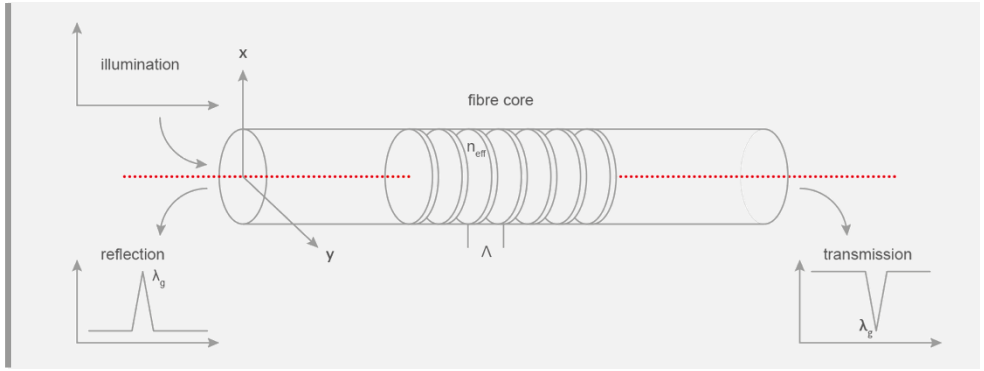
GOSLAR

- engionic Femto Gratings **production facility** for **fs-Laser written FBGs**
- Since its foundation in 2013, **production capacity** has been **doubled every 2-3 years**

Measuring with Light by Means of Fiber Bragg Technology

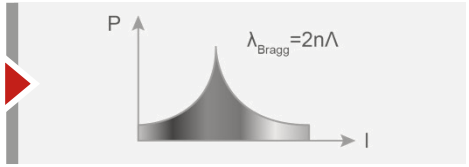
Fiber Bragg Gratings as Wavelength Selective Mirrors

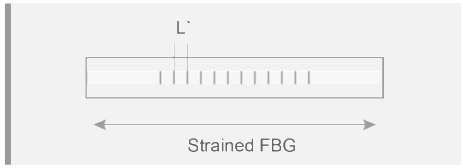
Principle of the fiber bragg grating sensor

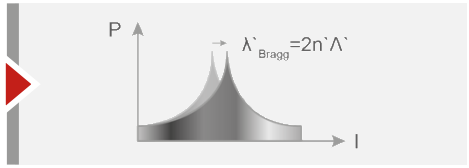


- A **periodic refractive index change** in the **fiber core** in the order of magnitude of 10^{-3} to 10^{-4} with the distance of L leads to a formation of a **wavelength selective mirror** at $\lambda=2*n*L$ in the fiber core

Details on measurement principle





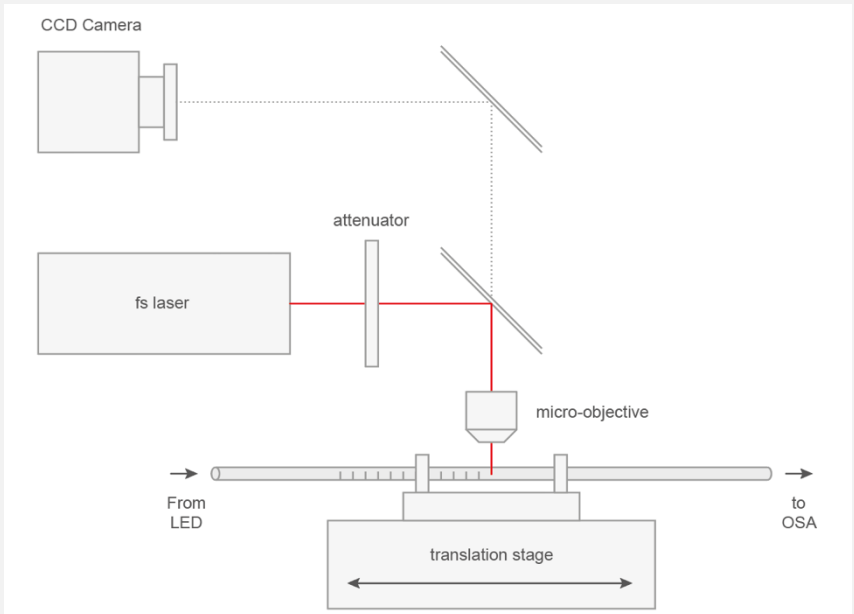


- **Strain** and **Temperature changes result** in **wavelength change** $\Delta\lambda$, which is within a large interval relatively linear and in the order of: **~ 12pm /°C** and **~ 1pm/µe**
- From this a wide range of derived variables like **pressure, curvature** or **acceleration** can be measured

fs-Point-by-Point Writing Technology Allows Flexible Writing of Extremely Stable Gratings through Coating

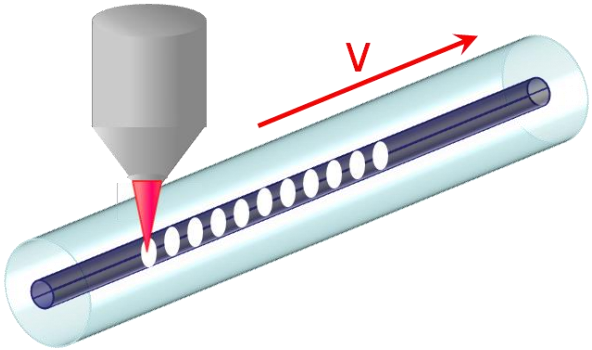
fs-Writing Technology at engionic

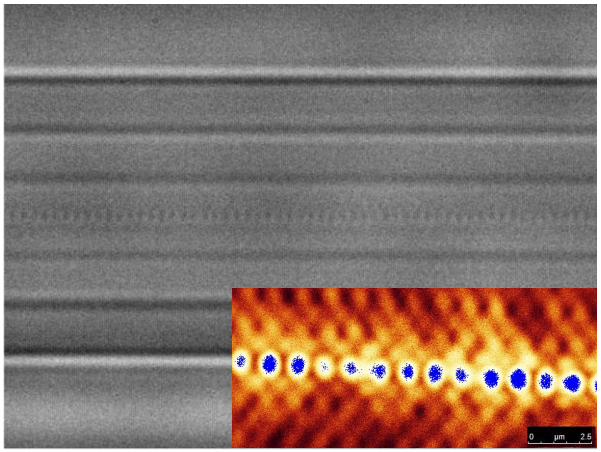
Writing set-up with fs-laser (point-by-point)



- Highly flexible point-by-point inscription without phase-mask allows writing of any wavelength
- Pulsed fs-IR laser beam is focused strongly into fiber core into a small area of ~0.5 µm
- Writing through the coating is possible due to high transmission of typical coatings for IR light and low laser intensity at coating
- Highly flexible array configurations with distances between a few mm and several km in customized fibers are possible

fs-Point-by-Point Writing Technology Allows Flexible Writing of Extremely Stable Gratings through Coating

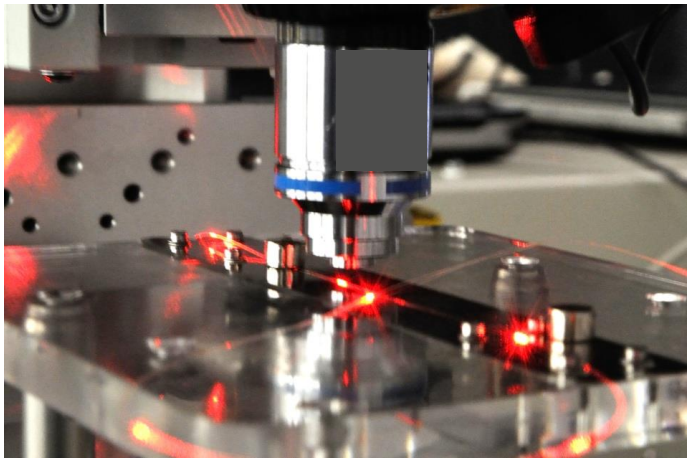




FBG SPECIFICATIONS

- Bragg wavelength 1,460-1,640nm (others on request) / Wavelength tolerance <0.2nm
- FWHM: 0.1nm to several nm / Reflectivity: 10^{-4} to 99%
- Sideband suppression (apodized): up to 20dB / FBG length: 0.06 to 12mm
- Low polarization dependence option from 0-5pm
- Low scattering loss option of <0.2dB

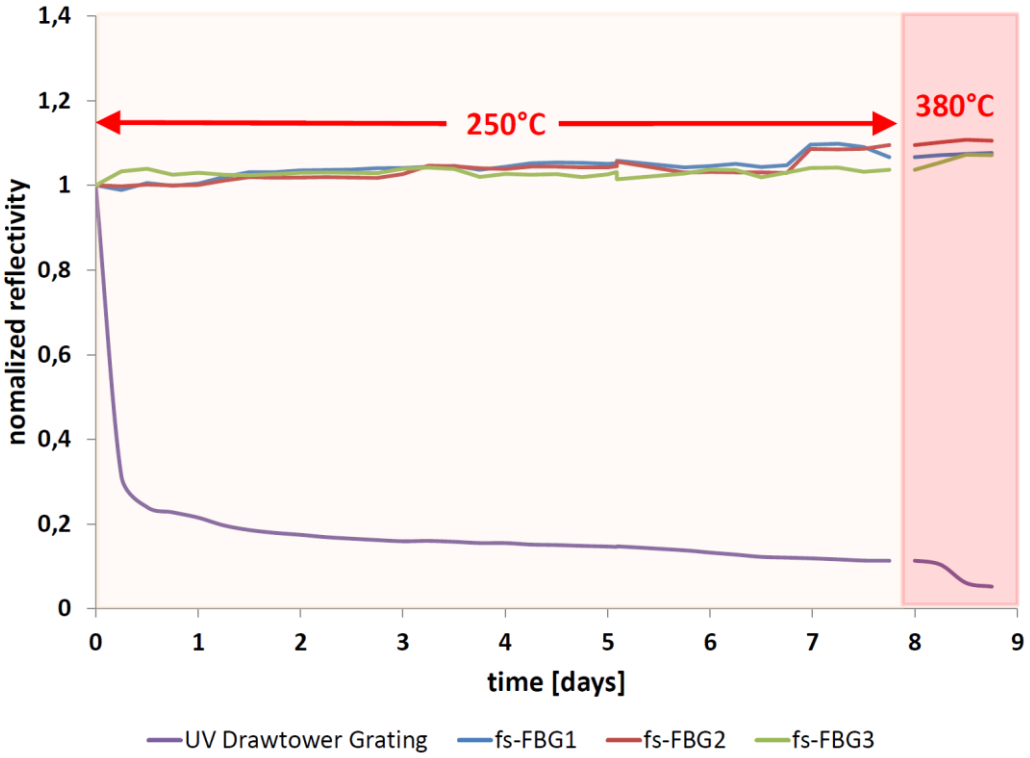
fs-Point-by-Point Writing Technology Allows Flexible Writing of Extremely Stable Gratings through Coating



- **Maximum temperature stability** due to the generation of **Type II FBGs** produces temperature-stable grids **up to 1000 ° C**
- Direct writing **through the coating** - **full** flexibility in the **choice of materials** and sensor configuration allows **use under extreme conditions**
- **Automated manufacturing** process for **efficient** high-volume **production**
- **Highly flexible** array configurations with distances of **a few mm** to **several km** possible.

Maximum Temperature Stability due to the Generation of Type II FBGs

Comparison of Draw Tower Gratings vs. engionic fs-Laser Written Gratings



At 250°C

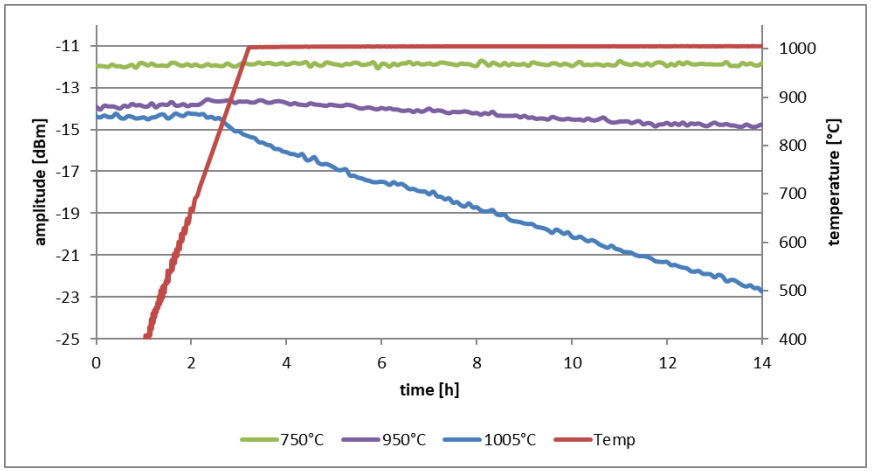
- **FFTs** IR fs-laser written **type II gratings** show **no decline** in **amplitude** (even a slight gain)
- **Steep decrease of the amplitude seen for UV written type I conventional phase mask written gratings** already within ½ day. Slow down of the decrease at ~10% nominal amplitude.

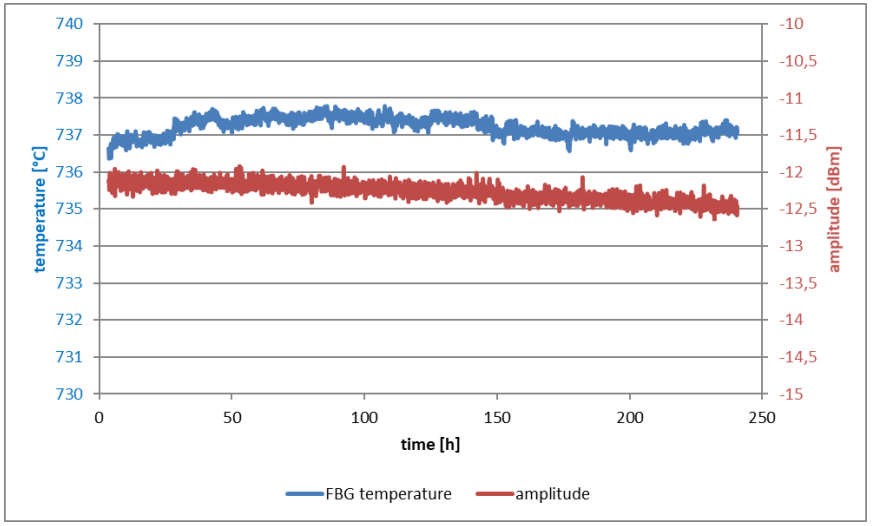
At 380°C

- **fs-FBGs show no** further **temperature dependence**
- **Conventional phase mask written gratings bleach completely**

Maximum temperature stability due to the generation of Type II FBGs

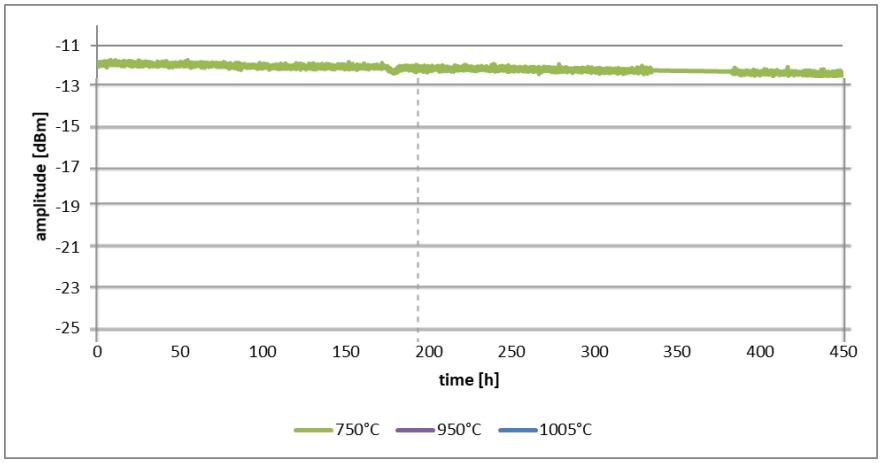
Long-term customer data at different temperature zones up to 1000°C





Temperature profile at different positions within the furnace

- **At 1005°C** the **gratings bleach** within a day
- **At 950°C** the **gratings** show a **decay** in amplitude **but do not bleach** within the observed period of 19 days
- **At 750°C the gratings are stable** over the period of 19 days

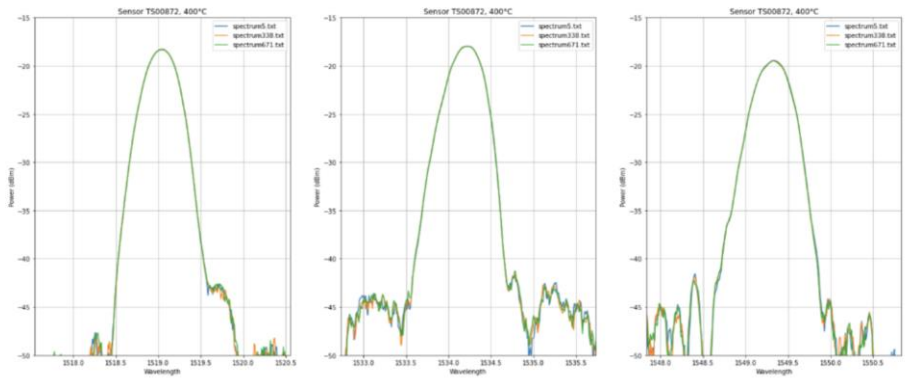


Maximum temperature stability due to the generation of Type II FBGs

Long Term Test of engionic written fs-Laser Written Gratings

At 400°C

Now if we look at the data after the furnace has settled to 400°C (spectrum5) and compare that with (spectrum338) captured 14 days later and (spectrum671) captured 28 days later:



The spectrums overlay one another almost perfectly showing no change in peak shape or position.

At higher temperatures fs-FBGs show a temperature dependent drift.

At 400°C

- **Long term soak tests show** that **FFTs** IR fs-laser written **type II gratings** show **no change in peak shape or spectral position**

At 500°C

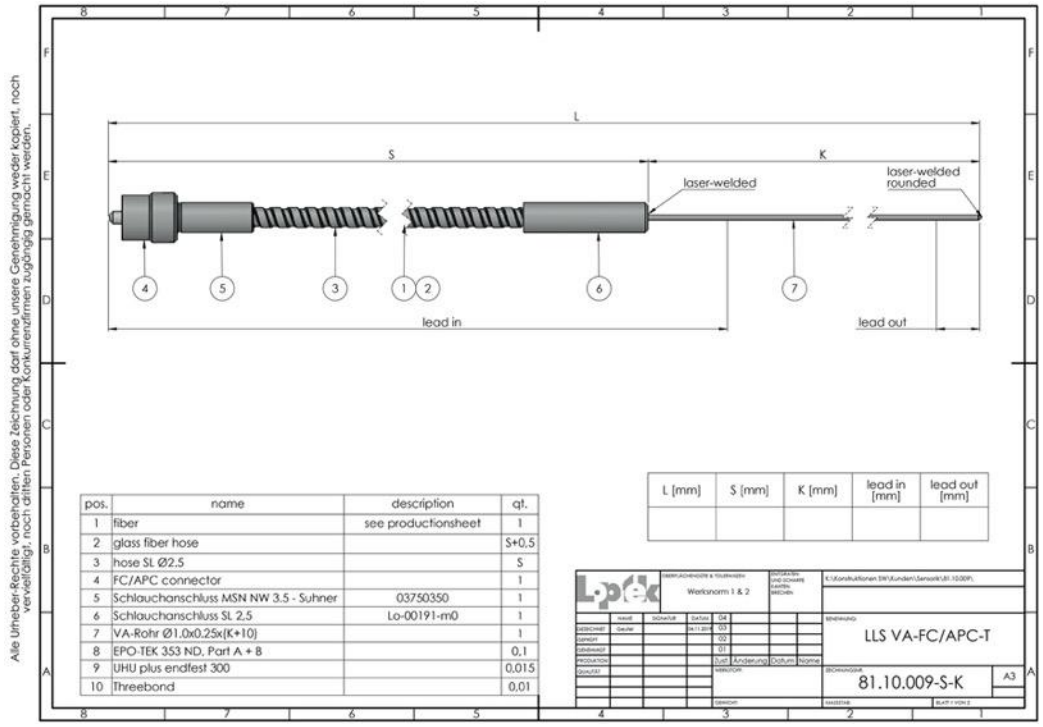
- **No** apparent **peak distortion**
- **temperature dependent drift** of **~1,5K/months.**

High temperature stability does make **fs-laser written typ II gratings** ideally suited for **long term operation** in **demanding applications.**

The sensor design has proven its design and measurement reliability in hundreds of installations

Sensor drawing and calibration

DESIGN DRAWING



pos.	name	description	qt.
1	fiber	see productionsheet	1
2	glass fiber hose		S+0,5
3	hose SL Ø2.5		S
4	FC/APC connector		1
5	Schlauchanschluss MSN NW 3.5 - Suhner	03750350	1
6	Schlauchanschluss SL 2.5	Lo-00191-m0	1
7	VA-Rohr Ø1.0x0.25x(K+10)		1
8	EPO-TEK 353 ND, Part A + B		0,1
9	UHU plus endfest 300		0,015
10	Threebond		0,01

L [mm]	S [mm]	K [mm]	lead in [mm]	lead out [mm]

LLS VA-FC/APC-T

81.10.009-S-K

A3

CALIBRATION

- Individual sensor **calibration according** to **DIN EN 60751 Class B standard for Pt100** temperature probes and fiber optic temperature probe guideline **VDI/VDE 2660** (currently in preparation)
- Highest calibration accuracy through **high-end calibration equipment**: FLUKE 1586A-2588 DAQ-STAQ Multiplexer incl. 1586A Super DAQ Precision Temperature Scanner and Platinum Resistance Thermometer (PRT) reference, Model 1913-4-7/SN:4546, Calib. 03/2018
- To achieve specified accuracy, a reference measurement with customer measurement unit in installation condition within sensor calibration range for absolute temperature reference is required

Our standard temperature sensor range offers numerous individualization possibilities

Our standard temperature sensor range

SENSOR TYPE	TEMPERATURE RANGE	ACCURACY[1)]
ST150 Standard	-30 to 150°C	+/- 0,5°C
ET300 Elevated	20 to 300°C	+/- 2,0°C
HT500 High temp.	up to 500°C	+/- 3,0°C
XT700 Xtra high temp.	up to 700°C	+/- 4,0°C

DESIGN OPTIONS

SENSORS: 1-20 sensor points distributed over a maximum length of 200cm, allocation according to customer request

HOUSING: Steel probe up to 200cm (standard), longer length upon request

CONNECTORS: LC/APC | FC/APC | FC/PC | E2000

PIGTAILS: Custom length and buffer | PVC | PTFE | flexible steel

INTERROGATION UNITS / FBG SPECIFICATIONS

Our FBG specifications are suitable for all commercially available interrogation units

Wavelength:	1,460nm to 1,620nm
Reflectivity:	~ 50%
SLRS:	~ 15dB
FWHM:	0,1nm to 1nm

1) For HT500 and XT700 at elevated temperature operation, regular recalibration will be required, due to expected drift at continuous maximum operation temperature of about 1K per month.

Why Gold-Coated FBGs?

- Improved performance in high-temperature environments
  - In order to have a coated FBG that works in an environment > 300°C, metal is the only reasonable option
  - Otherwise, the coating needs to be removed entirely, and uncoated silica fibers are fragile and not suitable for long length >10m

- AFL introduced gold-coated optical fibers in 2019
  - Low attenuation (< 5 dB/km)
  - Proprietary treatment prevents “cold welding” to other metals
  - Available in long lengths (longest to date, > 5km, prooftested)

- Gold has a high melting point and doesn’t oxidize – exposure to high temperatures won’t make the coating brittle and hard

- Gold coated fs-laser written FBGs able to withstand temperatures up to 500°C would be suitable for a variety of industrial processes and aerospace applications

Exclusive Partnering of engionic Fiber Optics and AFL: Development of metal-protected fiber optic sensors

Facilitating Temperature-Stable FBG Sensors

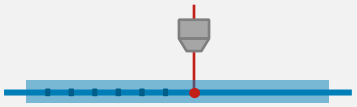
Production process (schematic)

AFL

1. Coated fiber

engionic

2. PbP-FBG inscription

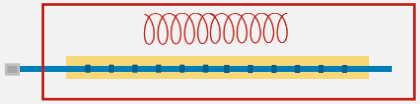


AFL

3. Au coating

engionic

4. Sensor confectioning + calibration

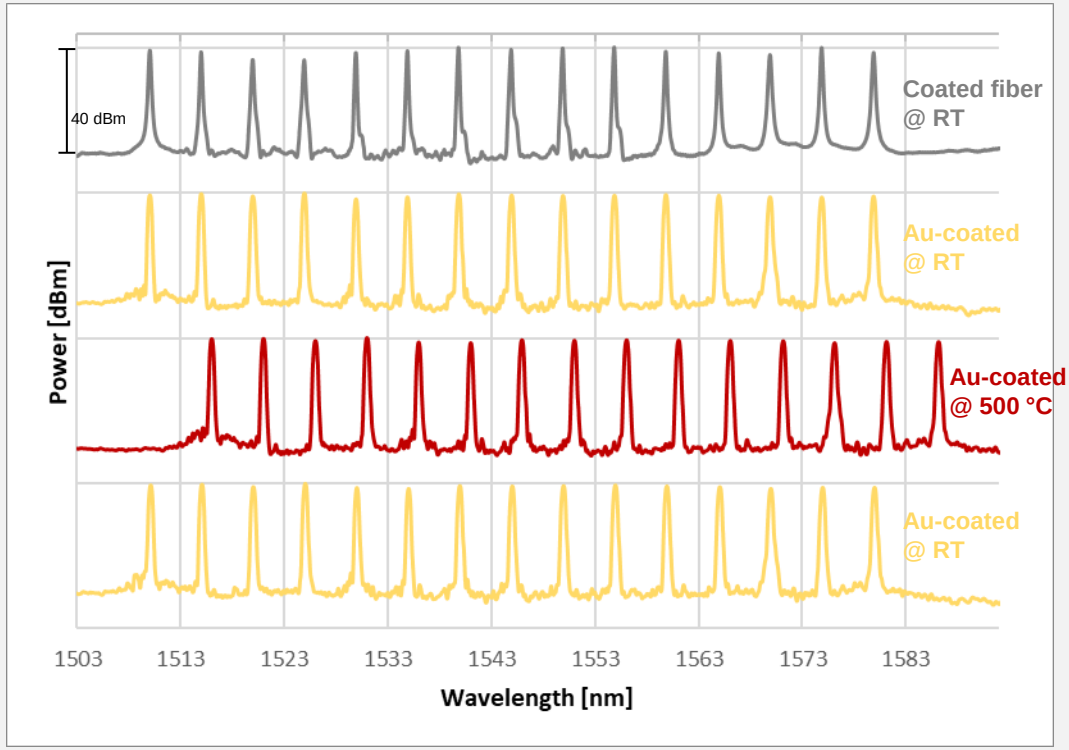


- Highly flexible point-by-point inscription allows **writing of any wavelength**
- Writing through coated fiber with optimized parameters
- Highly **flexible array configurations** with distances between a few mm and several km in customized patterns are possible allowing for the creation of probes **with multiple sensing points**, which can be used to measure **temperature or strain** at different locations simultaneously
- Inscribed fibers are **sealed with Au-coating** to yield temperature-stable FBG-sensors according to customer specifications

FBGs Retain Full Functionality in Au-Coated Fiber

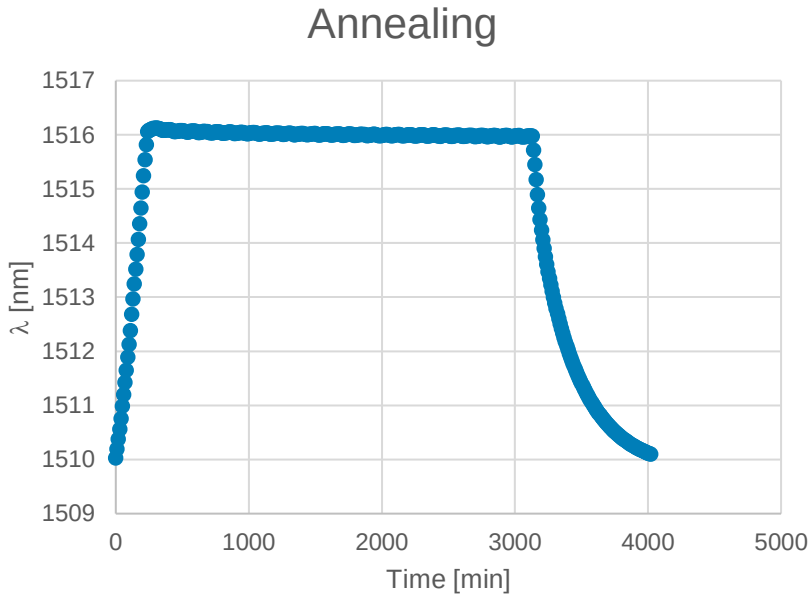
Initial Experiments demonstrate Sensor Integrity up to 500 °C

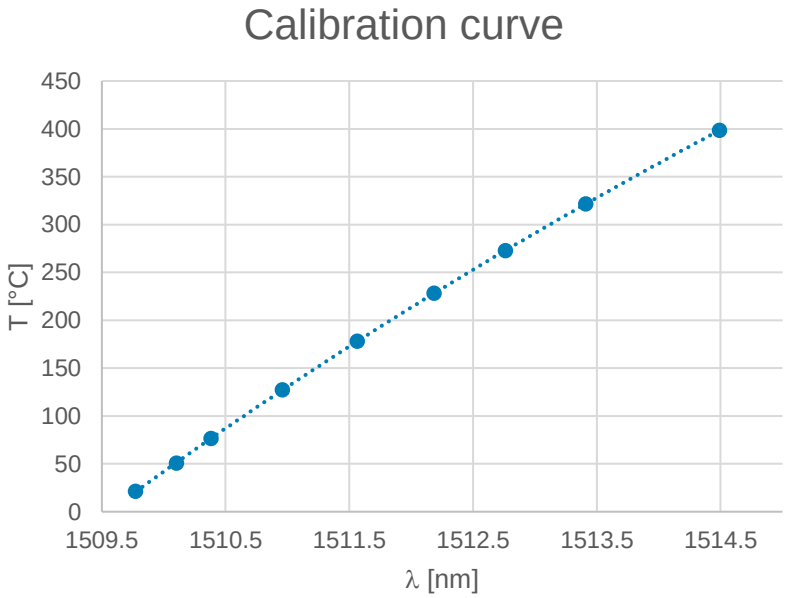
FBG array spectra



- **Au-coating** of laser-processed fibers **retains FBG characteristics**. A **blueshift of ~300pm** is observed **after** the **Au-coating got applied**. **No** further **spectral changes** are observable.
- **Annealing at 500 °C** and subsequent temperature cycling possible **without loss** in **signal intensity** and with **expected FBG** shifting **behavior**.

Annealing and Subsequent Calibration Steps Ensure Exact Functionality of Sensors



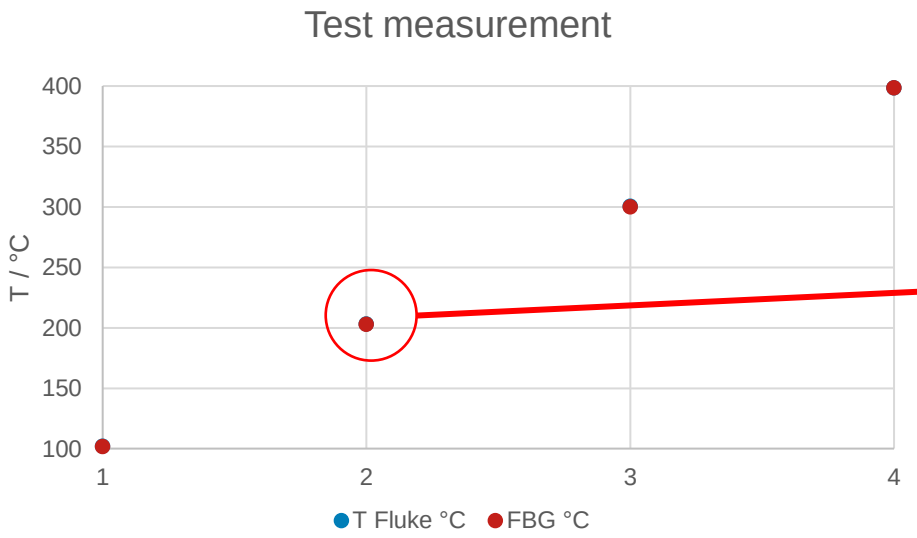


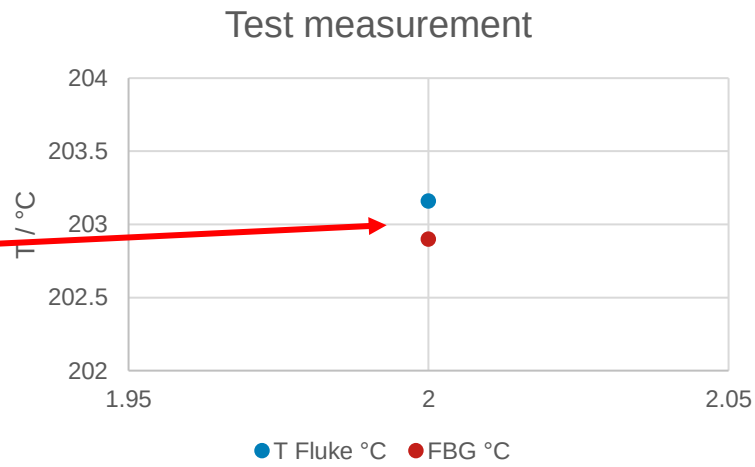
- 48h annealing at 500°C leads to a small blueshift of the central Bragg wavelength
- Fast stabilization and no further wavelength shift is monitored

- Stepwise temperature increase RT -> 400°C
- Sensitivity coefficent ~12,4 pm/°C is in the expected regime.

Temperature ramping

First results: Test measurements and referrencing





	T Fluke °C	FBG °C	Δ °C
1	101,89	101,8	0,09
2	203,16	202,9	0,26
3	300,5	300,1	0,4
4	398,4	398,5	0,09

- First results of **temperature measurements** show a **good agreement** with a **calibrated** temperature probe
- Individual sensor **calibration according** to **DIN EN 60751 Class B standard** for **PT100 temperature probes.**
- Highest calibration accuracy through **high-end calibration equipment**: FLUKE 1586A-2588 DAQ-STAQ Multiplexer incl. 1586A Super DAQ Precision Temperature Scanner and Platinum Resistance Thermometer (PRT) reference, Model 1913-4-7/SN:4546, Calib. 03/2018

fs-Laser Point-by-Point Written FBGs in Au Coated Fibers Convince with a Variety of Benefits

Benefits compared to **conventional FBGs and compared to conventional fiber options**

- Type II gratings with **temperature stability up to 1,000°C**
- **Gold coated FBG fiber** is ideal for **conventional** and **special applications up to 500°C**
- Extended temperature sensing **length up to 5km for temperatures up to 500°C** possible
- Potential for **strain sensors at elevated temperatures** above 200°C in evaluation with soldering processes

Thank you.

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