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Radiation-Hard and Intelligent Optical Fiber Sensors for Nuclear Power Plants

Grigory Y. Buymistriuc
Intel-Systems Instruments, Inc., St-Petersburg,
Russia

1. Introduction

Optical fiber sensors (OFS) have a number of intrinsic advantages that make them attractive for nuclear power plant (NPP) applications, including absolute explosion safety, extremely low mass, small size, immunity to electromagnetic interference, high-accuracy, self-calibration, and operation in extremely harsh environments, and it is a well-known fact. Civil nuclear industry essentially encompasses the complete nuclear fuel cycle and therefore the range of possible fiber applications both for communications and sensing is very broad (Berghmans & Decreton, 1994), (Korsah et al., 2006).

In order to expand OFS applications in nuclear engineering it was necessary to overcome a bias that some scientists and engineers used to have at the initial stage of using an optical fiber for communication, about "darkening" of a fiber and sharp growth of optical attenuation under the conditions of ionizing radiation, i.e. availability of convincing proofs of radiation hardness of optical fibers and OFS.

Safety and long-term metrological stability of OFS for NPP assumes:
- Radiation hardness of fiber optic sensors and cables;
- Absence of mechanical resonances of the gauge at frequencies up to 200 Hz;
- Immunity to electromagnetic effects in the range of frequencies 200 kHz and 18 – 20 MHz,
- High reliability of a sensitive element of the OFS ;
- Temperature-insensitive measurements of pressure in the working range of temperatures;
- Self-calibration of the gauge without stopping the process of measurement.

These requirements are satisfied by modern OFS, especially intellectual optical fiber sensors which can self-calibrate, i.e. control themselves at the level of changing their internal (own) parameters depending on the calibrated value (Buymistriuc & Rogov, 2009).

No optical measurement electronics will survive in, or near, an operating nuclear reactor core. Therefore, OFS light emission must be guided to the measurement electronics located in a well-controlled, benign environment. Several different implementations can be employed to accomplish this, each with their own advantages and weaknesses. Recently single material hollow-core optical fibers (referred to as photonic crystal fibers) have become

commercially available. All silica, photonic crystal fibers appear likely to have much larger radiation tolerance than conventional optical fiber technologies.

Monitoring signals from sensors in NPP is not only to diagnose process anomalies but also it is necessary to verify the performance of the sensors and the associated instrumentations. Tests such as calibration verification, response time measurement, cable integrity checking, and noise diagnostics are required in NPP. In-situ test methods that use externally applied active test signals are also used to measure equipment performance or for providing diagnostics and anomaly detection capabilities. Controls and instrumentation were enhanced through incorporation of optical and digital technologies with automated, self-diagnostic features.

The design of the sensitive element of interferometric pressure OFS working with the measured environment of a nuclear reactor without application of pulse tubes is such that its resonant frequency lies in the range of frequencies above 60 kHz, i.e. inadmissible resonances in nuclear reactors at frequencies below 200 Hz are structurally excluded.

Was developed also methods of realization of intelligent OFS on other principles of operation, in particular possibilities of intelligentization of the acoustic emission OFS based on intrinsic optical fiber effect of Doppler, of the strain and temperature OFS based on the fiber Bragg gratings.

Coatings of the sensitive element of interferometric OFS with enhanced adhesion to silica tips and long-term durability was obtained by a molecular layering method or atomic layer deposition. An important advantage of such interferometric pressure OFS is its enhanced reliability determined by a unitary structure of the sensor and extremely high adhesion of molecular coatings to silica optical fibers. Reliability of OFS with such nano-coatings is preserved high under different external effects, including at dose ionizing radiation up 10 MGy.

Safe disposal of spent nuclear fuel (SNF) and high level waste is currently considered a major challenge, a key element to the sustainability of future nuclear power use in most countries. A first priority is obviously ensuring safety during operation under normal and faulty conditions. With this, besides contributing to guarantee operational safety, systems reliably monitoring the repository environment over several decades of years, whenever possible maintenance free and in unattended mode, can become a key element in achieving confidence on repository performance as well as public and regulatory acceptance. Application of fiber optic technologies for monitoring SNF offers distinct advantages compared with conventional systems. Optical fibers not only withstand chemical corrosion and high temperatures much better than conventional systems, but their immunity to electromagnetic interference and their large bandwidths and data rates ensure high reliability and superior performance.

Due to this optical fibers are the preferred alternative for both: sensing and signal transmission in long-term monitoring of NPP and SNF applications.

2. Background

A NPP generally uses about 200 to 800 pressure and differential pressure sensors to measure the process pressure, level, and flow in its primary and secondary systems. For example, fig. 1 shows a typical pressure sensing (pulse) line inside a nuclear reactor containment (Lin K. & Holbert K., 2010).
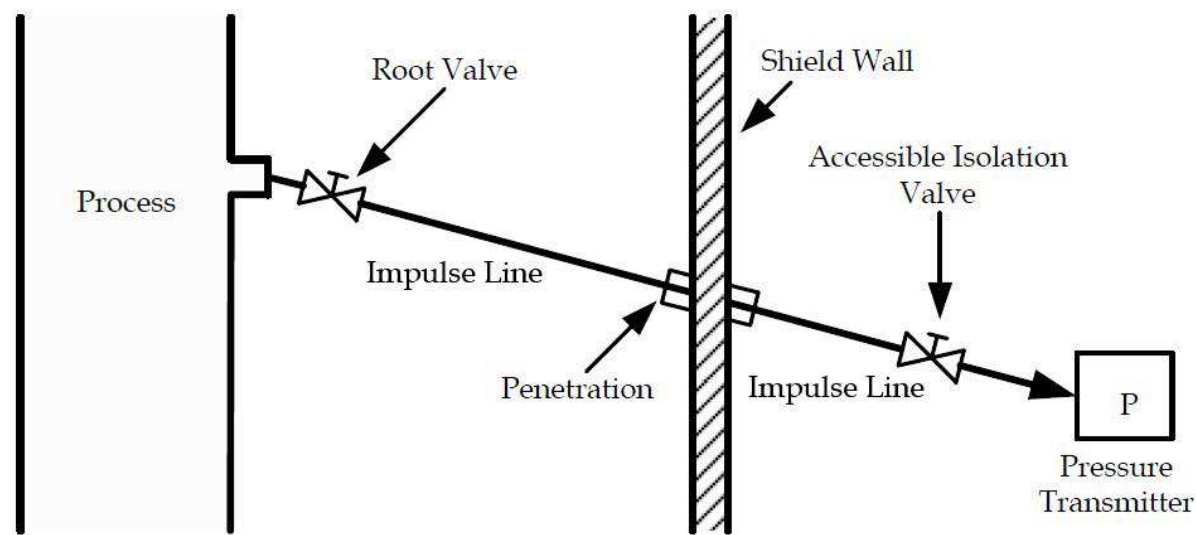
Fig. 1. Typical pressure sensing (instrument) line inside a nuclear reactor containment.

Instrument lines can encounter a number of problems that can influence the accuracy, response time of a pressure sensing system and decrease safety of NPP in consequence of mechanical resonances which appear on frequencies up 200 Hz , for example, fig. 2 shows transfer functions of a pressure sensing system (Lin K. & Holbert K., 2010).
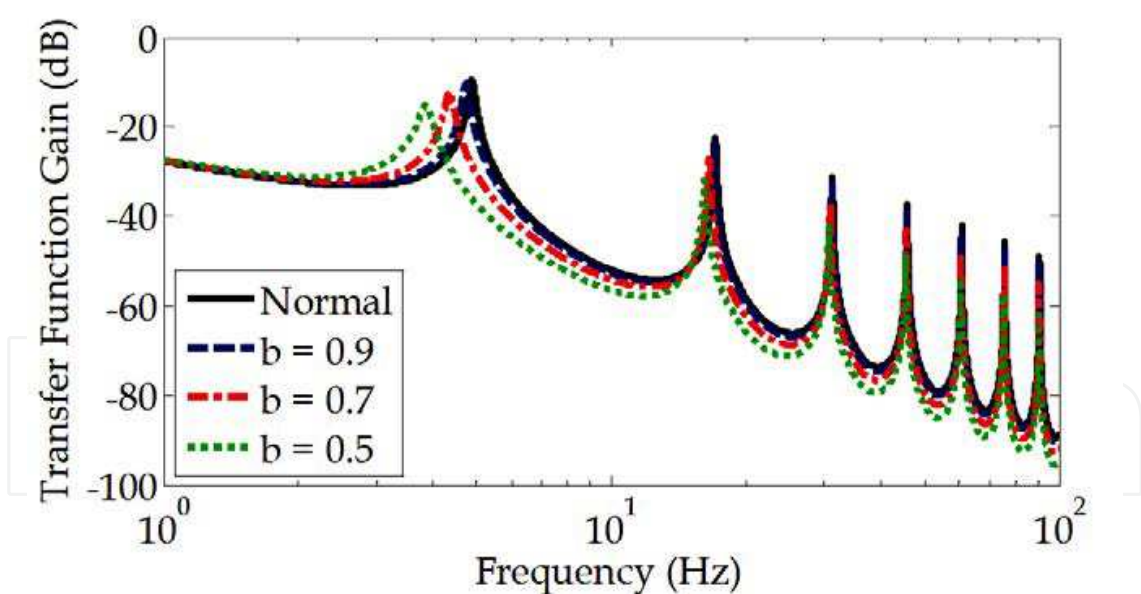

Fig. 2. Transfer functions of a pressure sensing system with resonance frequencies

Exception pulse lines from join of pressure sensors to technological equipment and pipelines in NPP is provided by Technical Regulations of the Russia (TR, 2000). Performance of this requirement became real possible only at use of fiber optic technologies. Advanced concept of construction of water-water nuclear reactors from Russian nuclear research center "Kurchatov Institute" provides use of welded joints of gages with equipment NPP instead of less reliable fitting connections that is possible with

application OFS with the big life time (up to 60 years) and with function of metrological self-calibration (Buymistriuc & Rogov, 2009).

It is important to notice that begun using fiber-optical technologies of communication and measurements in NPPs considerably improves their equipment. Really, typical NPPs used hard wired point-to-point connections from field instrumentation to control systems and panels in the control room. Essentially there is one wire per function or about 30 – 50 thousands wires coming from the field to the cable spreading room and then control room. The use of optical fiber networks, which carry substantially more information and decrease in 9 once weight of connections, instead of copper cabling, can eliminate 400 kilometers of cabling and 12500 cubic meters of cable trays (GE, 2006).

Contemporary optical fiber sensors give a unique possibility to realize the principle of remote measurement (fig. 1) .
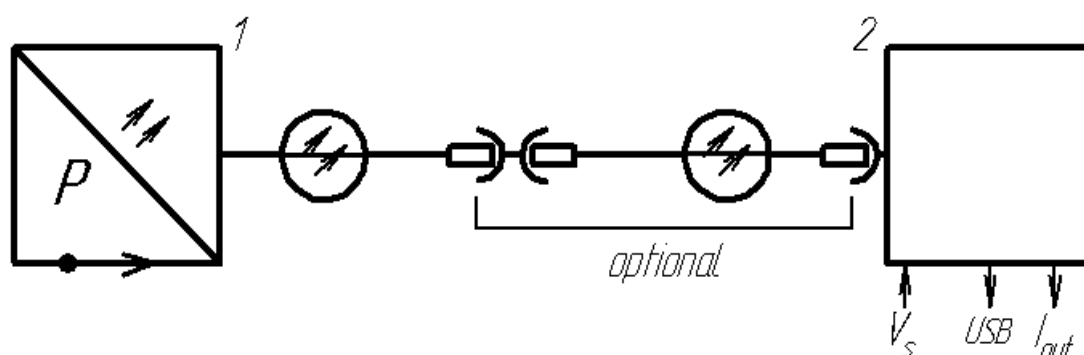

Fig. 3. Concept of remote pressure measurements
1 – OFS; 2 – optoelectronic transceiver

When sensitive element 1 of an OFS placed in harsh environment can be moved away from optoelectronic transceiver 2, which is under comfortable conditions of an equipment room, at the distance up to 3000 meters by means of an optical cable option which replaces undesirable pulse tubes very effectively.

The design of the sensitive element of pressure OFS working with the measured environment of a nuclear reactor without application of pulse tubes is such that its resonant frequency lies in the range of frequencies above 80 kHz, i.e. inadmissible resonances in nuclear reactors at frequencies below 200 Hz are structurally excluded. In fact, the resonant frequency of longitudinal vibration of optical fiber Fabry-Perot interferometer (FFPI) in the form of a quartz glass core is defined as

$$f_1 = \frac{4.91}{L}\sqrt{\frac{E}{\rho}} \tag{1}$$

where E - Young' modulus of elasticity of a glass core, Pa
ρ – glass core density, kg/m^3
E/ρ - own rigidity, in particular for silica glass, 45×10^5 m.

Thus the sensor mechanical resonant frequency is defined by its length L = 0.001 … 0.1 m and lies in the range f_1 = 10,4092 / L [kHz] = 104,092 … 10409,2 kHz.

Frequency resonant characteristic of a typical pressure OFS based on FFPI indicates Fig. 4.
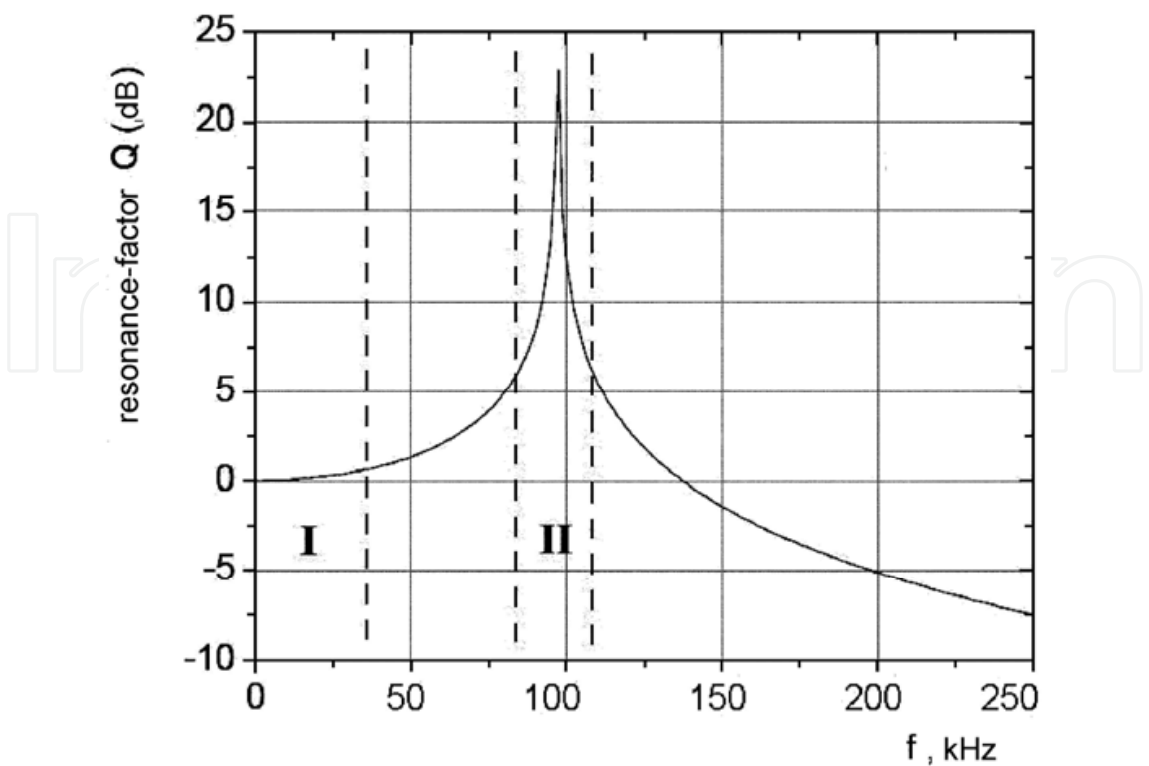
Fig. 4. A resonance frequency response of FFPI-based pressure OFS

OFS of acoustic emission, humidity and others parameters on the basis of coils of a fiber or nano-coatings of an tip of a fiber have resonant frequencies a few tens in MHz.

Use the optical fiber technologies allowing to realize a principle remote measurements changes a principle of construction of measuring systems of NPP and completely to solve a problem of resonances of pulse lines.
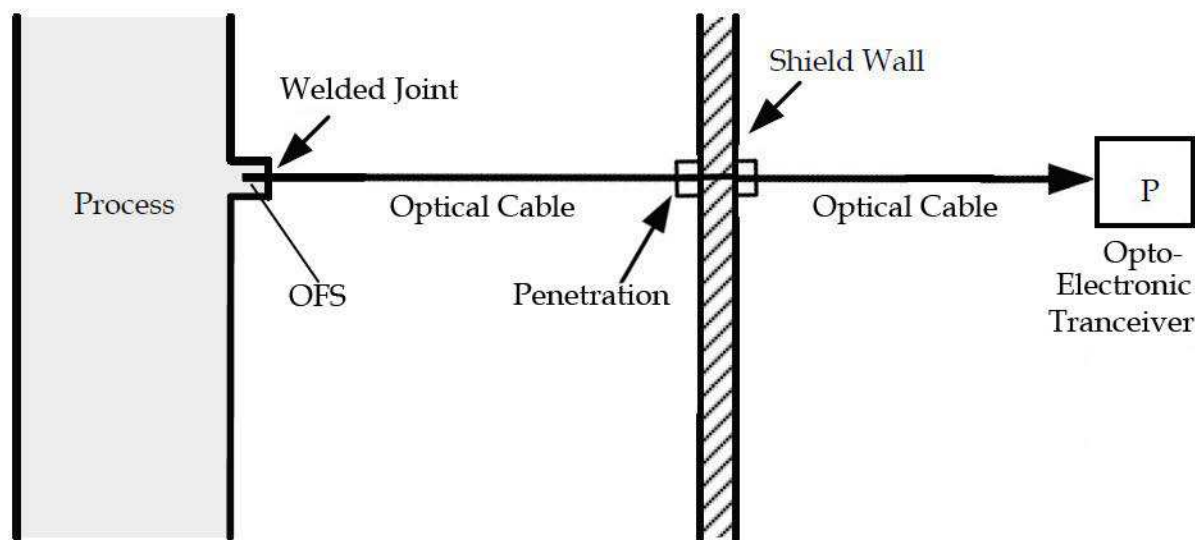

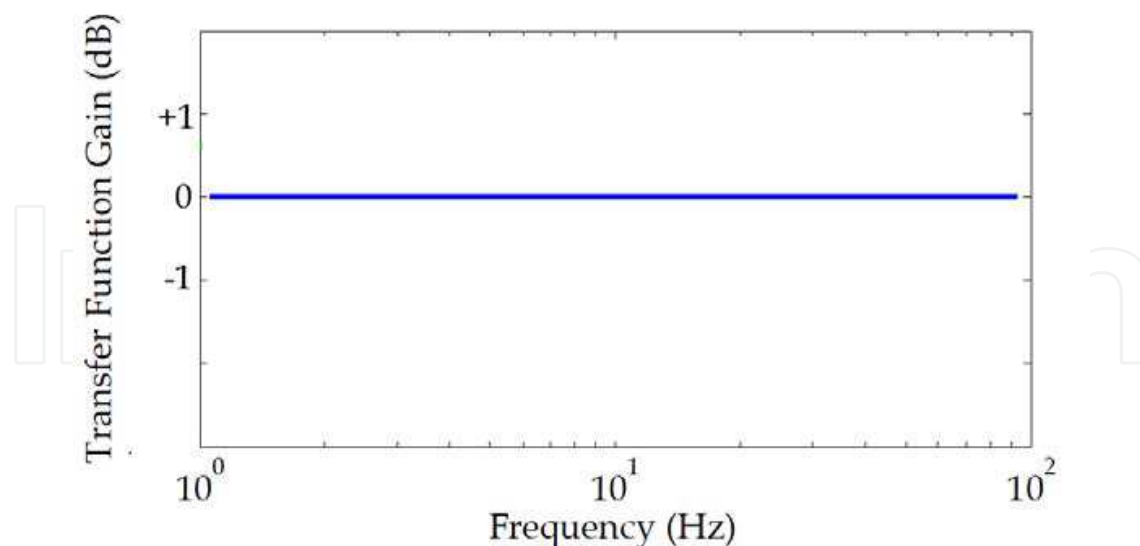Fig. 5. New advanced structure of the pressure sensing line inside a nuclear reactor containment

Fig. 6. Transfer gain-frequency function of a pressure optical fiber sensing system

On fig. 5 the new structure of system of measurement of the pressure is shown, one of which results of realization is full elimination resonances of the measuring channel as is shown in fig. 6.

For maintenance of working reliability of offered measuring system, especially in zones NPP with radiation presence, application radiation-hard optical fiber and cables is necessary (TR, 2003).

3. Ionizing radiation hardness of OFS

Use of silica as a material for fiber optic sensors and measuring communication lines is an effective solution both in terms of mechanical properties and radiation hardness of silica fibers which are reached by modern manufacturers, for example, a method of entering and retention of hydrogen in an optical fiber.

Another important factor of applying silica optical fibers under radiation conditions, in particular for OFS based on silica optical fibers, is their low radiation induced losses in the range of wavelengths between 1150 nm and 1350 nm as is shown in fig. 7 (Fiedler et. al., 2005).

Radiation hardness of OFS equaled earlier to a general dose of irradiation of about 1.2 MGy with γ-radiation and $2.6 \cdot 10^{16}$ neutrons/cm² with a neutron fluence (Berghmans F. & Decréton M., Ed.,1994) but now reaches doses of gamma radiation up to 23 MGy and neutron flux $52 \cdot 10^{16}$ neutrons/cm² (Fiedler et. al., 2005).

Photonic crystal fibers (PCFs) were also recently submitted to a number of nuclear environments applications. In hollow core PCFs the light is essentially guided in air, which may significantly decrease the radiation response of such waveguides compared to conventional optical fibers. The structure used by us hole core PCF at 1000X and 10000X imagnifying in a microscope is shown on fig. 8.

The permanent radiation induced attenuation (RIA) levels after radiation of PCF were found to be very low. This was confirmed with hollow core PCF showing at least about 30 to 100 times lower RIA than the best present conventional optical fibers at 1550 nm with theoretical

limit of total dose of gamma radiation over 1 GGy (Henschel H. et al. ,2005). Post-fabrication treatment of the photonic band gap fiber with hydrogen gas has been reported to improve the fiber's resistance to radiation (Tomashuk A.; Kosolapov A. & Semjonov S. (2006).
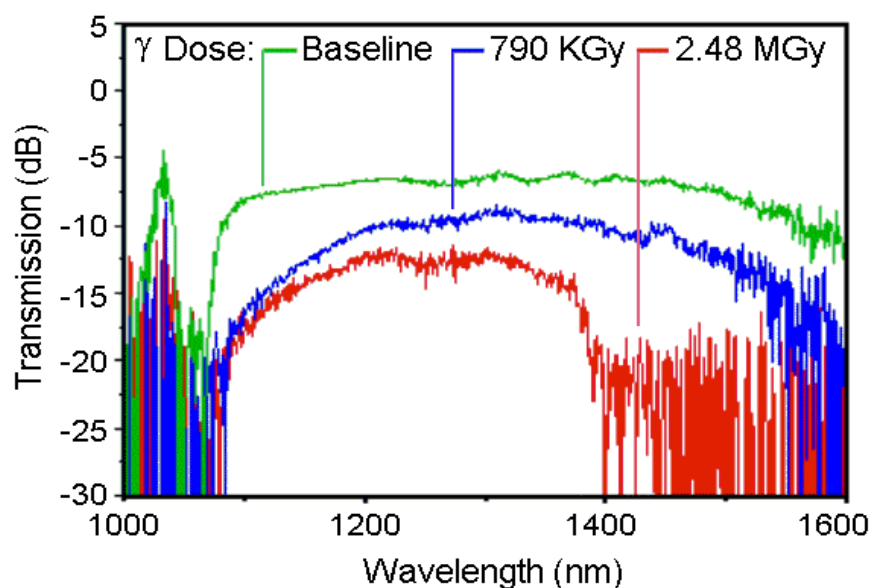

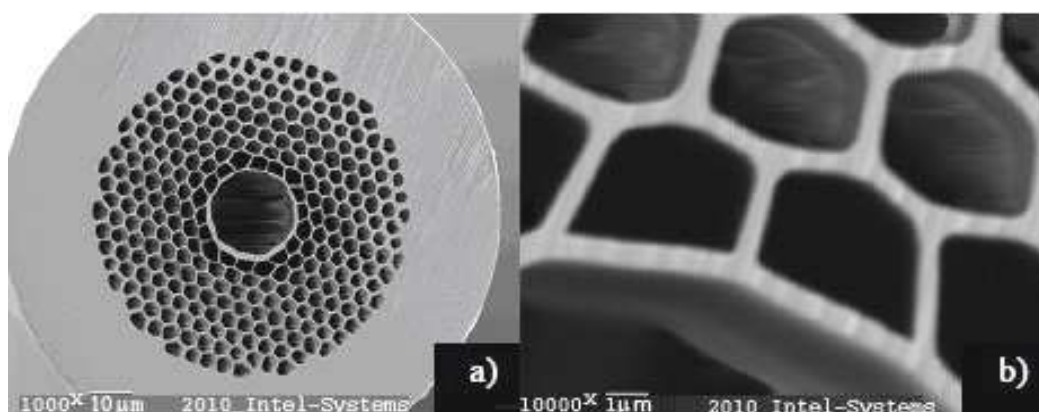Fig. 7. Spectral transmission for 20% Ge doped silica optical fiber

Fig. 8. Structure of the hollow core PCF at 1000^X and 10000^X magnifying in a microscope.

For extreme dose situations, the light must initially be guided from the measurement location using a hollow-core light guide. All known materials darken unacceptably in the intense radiation field of a nuclear reactor core. However, reflective technologies are available that have been shown to withstand comparable environments.

Conceptually, a hollow-core light guide is simply a mirror that has been formed into a polished titanium tube as shown on fig. 9. This approach was used for measurements temperature and the neutron flux in near-reactor environments (Holcomb D.; Miller D. & Talnagi J. (2005).

The principal innovation of this approach is to combine optical and fiber optical measurement components in a form suitable for deployment in a nuclear reactor core.
The main needs for in-pile concern the assessment of creep and growth of cladding materials, or nuclear fuel rod behaviour, which require elongation measurements or diameter measurements of cylindrical samples. Among others adaptations to the nuclear environment, these OFS will need a radiation resistant fixing.

Fig. 9. Hollow-Core Light Guide Concept.

As the light reaches lower radiation environments, several different optical transmission technologies become possible:
hollow core PCF or conventional radiation-hard optical fibers.
For total doses up to about 10^4 Gy, pure silica core, fluorosilica clad, multimode optical fibers are suitable light guides.

4. Enhanced reliability of OFS in harsh environments

A standard version of FFPI has no face reflecting coverings and works based on natural Fresnel reflections in the amount about 4%. For changing the sensitivity and dynamic range of the pressure OFS , we used TiO_2 reflecting coverings.
The fibers are placed in magnetron sputtering (MS) machine and coated with TiO_2 by vacuum deposition. The reason for using TiO_2 is that it has high refractive index (~2.4, vs. 1.4 for the silica fiber) over visible and infrared spectral ranges and strong bonding on glass based materials. The MS machine is filled with a mixture of 70% argon and 30% oxygen so that the titanium and oxygen atoms ejected toward cleaved fiber end and stick to the fiber until the desired film thickness is reached. However, experiments have shown that adhesion to glass and roughness of the TiO_2 coatings made by this method are not satisfactory. Apparently on fig. 10, mean-quadratic deviation of the surface profile equal about 37.8 nanometers.
A coating with enhanced adhesion and long-term durability was obtained by a enhanced method af atomic leyer deposition - method molecular layering (ML) (Buymistriuc & Rogov, 2009).
Synthesis was carried out by repeated and alternate processing of the surface of the fiber end face by H_2O and $TiCl_4$ steams removing the surplus of not reacted and formed by-products after each stage of processing. Thus, not more than one monomolecular layer with

the thickness of new structural units about 0.3 nanometers are added to the surface in each cycle of ML reactions.
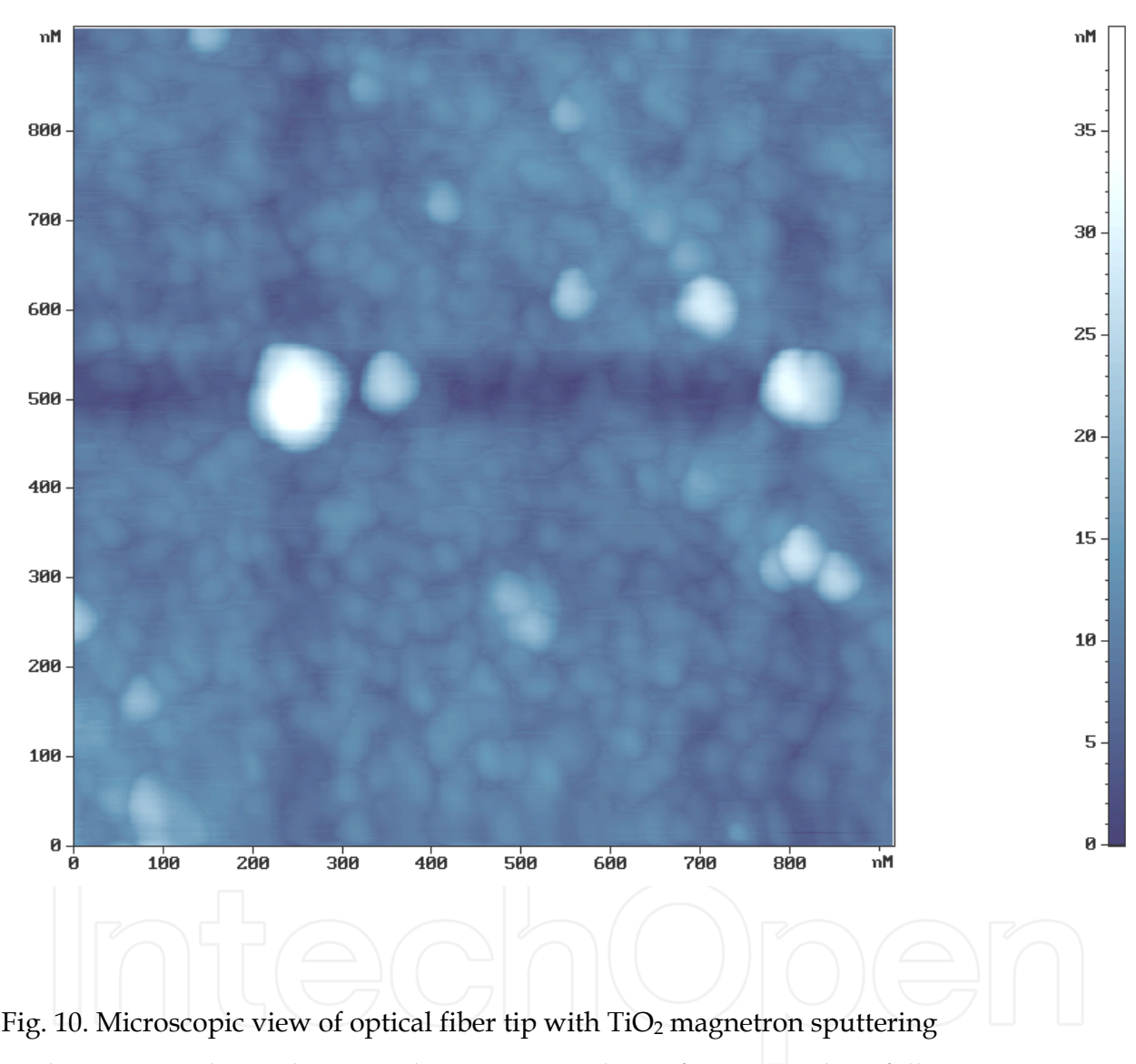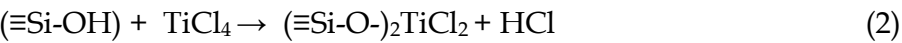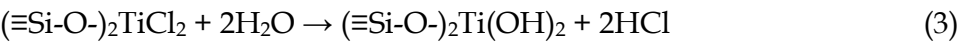

Fig. 10. Microscopic view of optical fiber tip with TiO_2 magnetron sputtering

With processing by $TiCl_4$ steams the reaction on the surface proceeds as follows:

$$(\equiv Si\text{-}OH) + TiCl_4 \rightarrow (\equiv Si\text{-}O\text{-})_2 TiCl_2 + HCl \qquad (2)$$

With processing by water steams the reaction on the surface proceeds as follows:

$$(\equiv Si\text{-}O\text{-})_2 TiCl_2 + 2H_2O \rightarrow (\equiv Si\text{-}O\text{-})_2 Ti(OH)_2 + 2HCl \qquad (3)$$

At this stage of the ML process we obtain a hydroxylated surface again but now OH-groups are linked not with the atoms of silicon of the initial matrix but with the atoms which are part of the imparted functional groups. The hydroxylated surface is processed

by TiCl$_4$ steams again. At this stage the second titanoxidechloride monolayer is formed as follows:

$$2(\equiv Si\text{-}O\text{-})_2Ti(OH)_2 + TiCl_4 \rightarrow [(\equiv Si\text{-}O\text{-})_2Ti(O\text{-})]_2TiCl_2 + 2HCl \qquad (4)$$
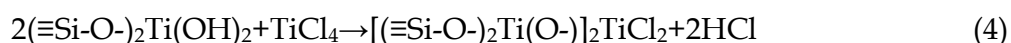
Then a reaction product is again subject to processing by water steams. The process was finished when obtaining coatings with thickness from 10 to 180 nanometers with a mean-quadratic deviation of the surface profile about 1.4 nanometers, as shown in fig. 9 which gives the view of the end faces of the optical fiber obtained by means of an atomic-power microscope.
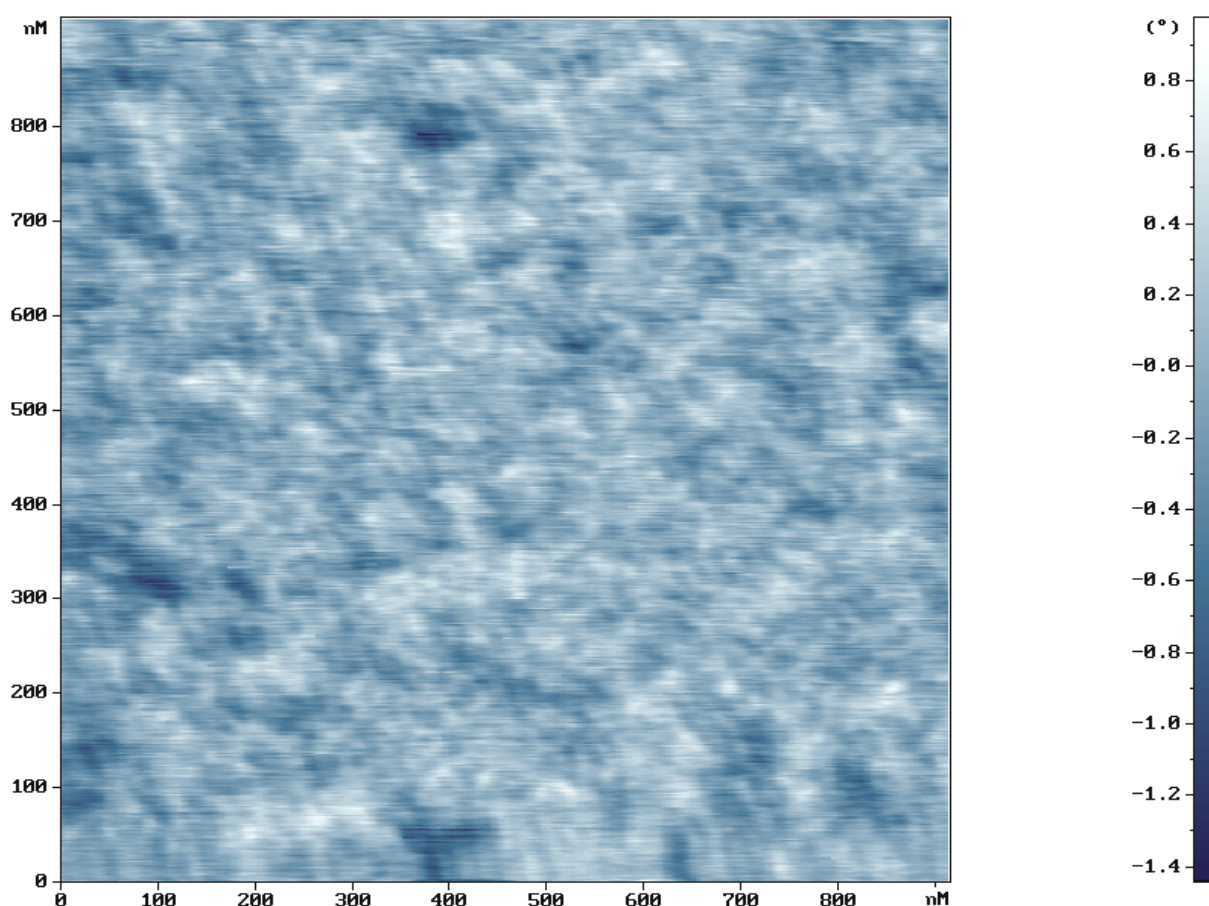

Fig. 11. Microscopic view of fiber tip with TiO$_2$ molecular layered nano-coating

An important advantage of such pressure OFS is its enhanced reliability determined by a unitary structure of the sensor and extremely high adhesion of molecular coatings to silica optical fibers. OFS fabricated with new ML technology possess the greatest reliability (on distribution of Weibull) than usual MS method as shown on fig. 12.
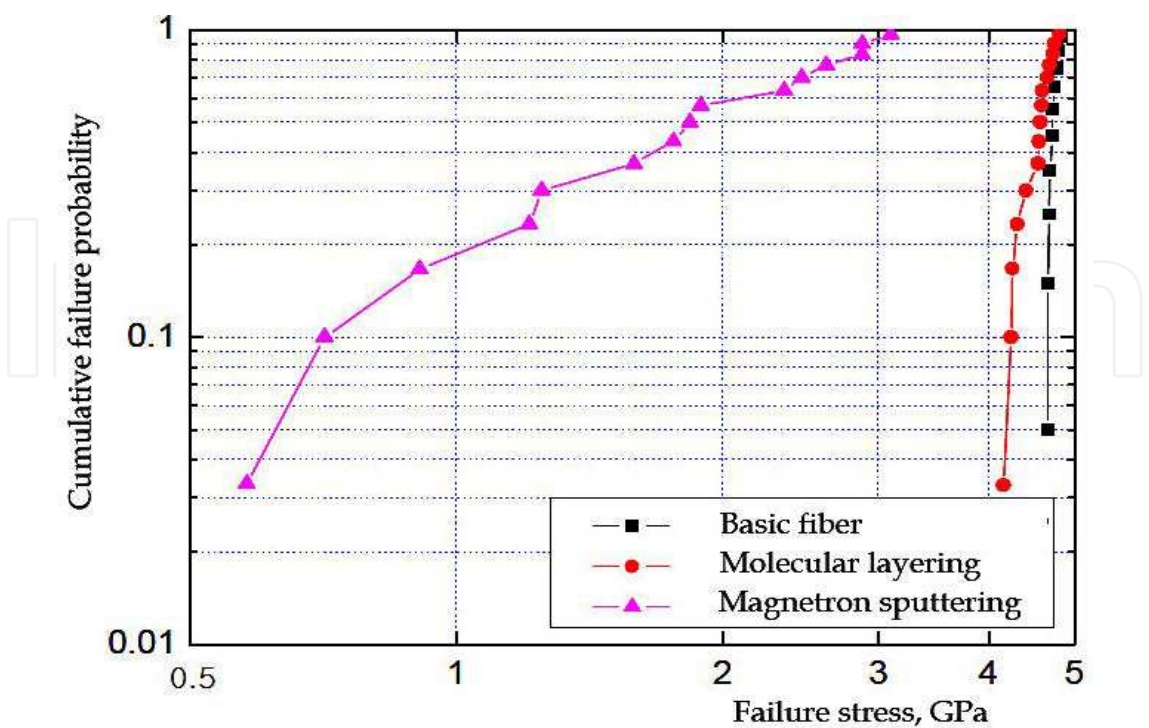
Fig. 12. Weibull distribution plots for basic fiber and fibers coated by using ML and MS technologies

5. Principles and constructions of intelligent OFS

Information redundancy of optical fiber sensors, as well as possibility to their programmable tuning in combination with a minimum structural redundancy allow to develop the so-called intelligent sensors with a function of metrological self-checking. The function of metrological self-checking of optical fiber sensors is provided with their multimodality, i.e. with their similar dependence of an output signal on several variable parameters, f.e., with their dependence on a variable pressure at a constant optical spectrum of an input signal and, accordingly, on a readjusted optical spectrum of the signal at a constant pressure. Construction of intelligent sensors of new generation assumes presence at such sensors of structural (internal) and/or information (external) redundancy (Taymanov R. & Sapozhnikova K., 2008).

Microelectronic sensors of physical quantities generate the unimodal output signal Y depending on change only of one parameter of sensor R:

$$Y = Y_0 + k \cdot \Delta R(x; t) \tag{5}$$

where Y – an output time signal, Y_0 – initial value of an output signal;
ΔR – change of parameter of a sensor, caused in the measured physical quantity x in time t;
k – proportionality factor.

That is, microelectronic sensors do not possess necessary information redundancy. To provide self-checking of such sensors by creation of information redundancy, for example giving on them influences of physical quantity of known value – it is almost impossible while in process controllable equipment in real time. Therefore intelligent microelectronic

sensors are under construction by creation of structural redundancy (embedding of the reference sensor, the additional sensor with parameters close to the basic sensor, etc.) that not always is the optimum decision.

5.1 Self-checking OFS

Application of a fiber optic Fabry-Perot interferometer for measurements of pressure and speed of pressure variation in water reactors of NPPs contributes to improving their safety and long-term metrological stability, which demands for intelligent sensors.

5.1.1 Basic principles

By means of fast tuning of the spectrum of an optical source it is possible to make self-calibration in the course of continuous work of the pressure gauge. Optical cables including connectors, splices, and other components are tested by evaluating the optical losses relationship along the cable.

OFS of physical quantity creates the multimodal output signal depending at least from two parameters of the sensor, for example for OFS based on FFPI output signal I_s depends on change of length of optical resonator G and change of a wavelength of light λ:

$$I_s = I_0 \left[1 - Cos\left(\frac{4\pi}{\Delta\lambda_0(t)} \cdot \Delta G(x;t) \right) \right] \tag{6}$$

where I_0 – initial intensity of light coupled into FFPI.

The output signal such OFS according to the equation (2) changes depending on change of length of a cavity of the resonator ΔG, caused by pressure, and depending on change of the central optical wavelength of the coherent sensing channel $\Delta\lambda_0$, provided, for example, by the tuneable spectral optical filter (TSOF) as is shown in fig. 13.
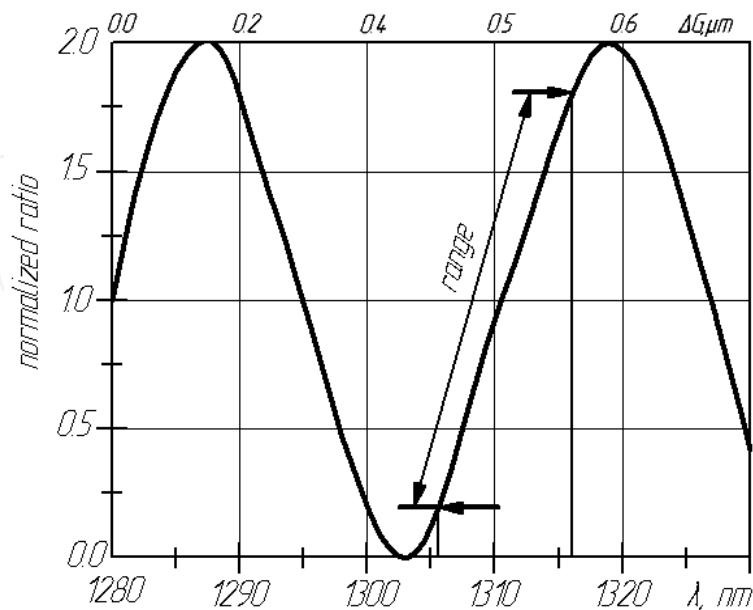

Fig. 13. Response of FFPI output from resonator cavity length and optical source peak wavelength changes

Additional possibility at such intelligent OFS is possibility of stabilization of a quiescent point (Q-point) on its linear site calibration characteristics by fine tuning of a wavelength of light on value $\delta\lambda_0$ sensing channel, compensating a deviation of initial length of a cavity of the optical resonator δG, caused by destabilizing factors during long operation of the sensor. Thus, it is obvious that for realization FMSC interferometric OFS possess necessary information redundancy.Structural redundancy of OFS at realization FMSC is minimal and is reduced to application of the TSOF, as shown on the scheme fig. 14.

On such principle has been realised the intelligent pressure OFS with function metrological self-checking (FMSC) at long operation in extreme conditions (Buymistriuc G. & Rogov A.,2009).

Speed of tuning of a modern TSOF, for example the models "FFP-TF" from "Micron Optics, Inc" or the acousto-optical tuneable filter models "AOTF" from "Fianium, Inc" is rather high also the period of tuning time T on all set spectrum. For example in sequence $T = t_3 - t_1$ on fig. 15, makes value of an order 0,1 … 0,4 microsecond that it is enough for the majority of modes of measurement of pressure, deformation, vibration, temperature, level of etc. controllable industrial equipment.
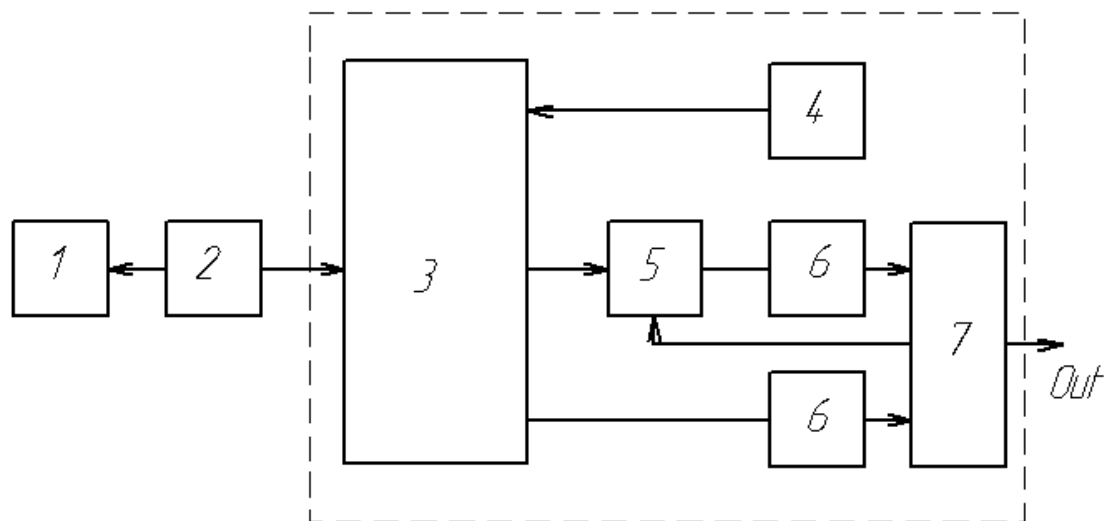

Fig. 14. Intelligent pressure OFS
1 – FFPI; 2 – optical cable; 3 – optical coupler; 4 –light emitting diode; 5 –TSOF;
6 –photodiode; 7 – microcontroller

5.2 Algorithm
Procedure of self-checking of pressure OFS on the basis of FFPI consists of the following consecutive steps.
Step 1. When OFS is manufactured, its calibration characteristic is measured:

$$I_c = f(\Delta G\{P\}) \text{ at } \lambda_0 = const$$

by means of a precision pressure calibrator (for example from DPI-610 from "Druck, Ltd") and stored as initial data in the energy-independent memory of the device.
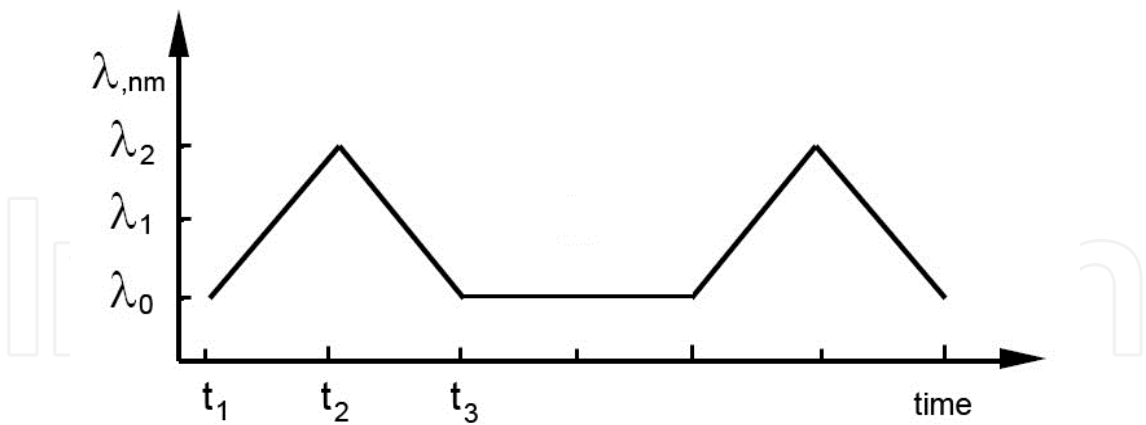
Fig. 15. A spectral peak in time change of tunable optical filter of the OFS

Step 2. While OFS is in service after a certain period of time, which may be equal to an periodic testing interval of the device, the current calibration characteristic of the gauge is measured without stopping the process of pressure measurement :

$$I'_c = f(\lambda) \text{ at } \Delta G\{P\} = const$$

by fast tuning of the central wavelength of the spectral optical filter transmission $[\lambda_0 \rightarrow \lambda_2]$ – forward scan, and $[\lambda_2 \rightarrow \lambda_0]$ – reverse scan, as shown in fig. 15. The speed of the filter tuning should exceed the rate of the measured pressure change.

Step 3. The graduation characteristic of the pressure OFS is compared with the initial data of calibration and corresponding correction factors are calculated.

Step 4. The measurement of pressure by means of OFS with using correction factors obtained at step 3 is continued.

Thus, interference OFS is internally inherent necessary information and structural in redundancy effectively to carry out FMSC.

5.3 Estimation of error

Error of measurement of the intelligent OFS, caused by instability of the central wavelength of TSOF, i.e. shifted spectra TSOF and light emitting diode and casual displacement of spectral characteristics of the filter us has been investigated by modeling and experimental check.

Distortion *s'* of an output signal *s*, is described by following expression:

$$s' = s\left[1 - \frac{\Delta I}{I_o}\right]\left(1 + \frac{\gamma_c}{2}Cos\left[\frac{4\pi}{\lambda - \Delta\lambda}G\right]\right) \tag{7}$$

where γ_c – contrast ("fringe visibility") of interference.

The normalised error of measurement of pressure *δs/s*, caused by shift *Δλ* the central wavelength of the filter, is described by expression:

$$\left.\frac{\delta s}{s}\right|_{max} \approx \left\{abs(\frac{1}{I_0}\frac{dI}{d\lambda}) + \frac{\gamma_r}{2} \cdot \frac{4\pi G}{\lambda^2}\right\}\Bigg|_{\lambda - \Delta\lambda} \cdot \Delta\lambda \tag{8}$$

A case non-centering (casual displacement) of a wavelengths of the optical filter and a source of optical radiation in the course of long operation.

By means modeling and experiences is established that spectrum mismatching of the TSOF with a light source poorly influences an error of measurements of OFS. Big shifted spectral mismatch, above 3 nm, gives metrological error less then 0.02%.

Besides by tuning TSOF with feedback included on an output signal it is possible to provide stability of a quiescent point (Q-point) interferometric OFS that is to realise the intelligent gauge with self-correction.

Possible application of adaptive OFS is their use as additional measuring transducers of the self-checking channel at construction of intelligent gauges of pressure with elastic elements and gauges of level and other physical quantities for the purpose of substantial growth of their actual interval between testing.

5.4 Intelligent acoustic emission OFS

Was investigated also methods of realization of intelligent OFS on other principles of operation, in particular possibilities of intellectualizing of the acoustic emission OFS based on intrinsic optical fiber effect of Doppler (Li F. et al., 2009).

A Doppler shift of frequency f_D under influence of a sound wave a is defined as

$$f_D = -\frac{n}{\lambda_0(t)} \cdot \frac{dL(a;t)}{dt} \tag{9}$$

where n –index of refraction of a fiber; λ_0 – wavelength of laser radiation; L – length of fiber sensing element; a – acoustic signal; t – time.

Apparently from a equation (9) and fig. 4 that frequency OFS has information redundancy – dependence Doppler shift of frequency both from change of length of fiber L, and from change of frequency of laser radiation f_0, and structural redundancy – the tunable laser diode.
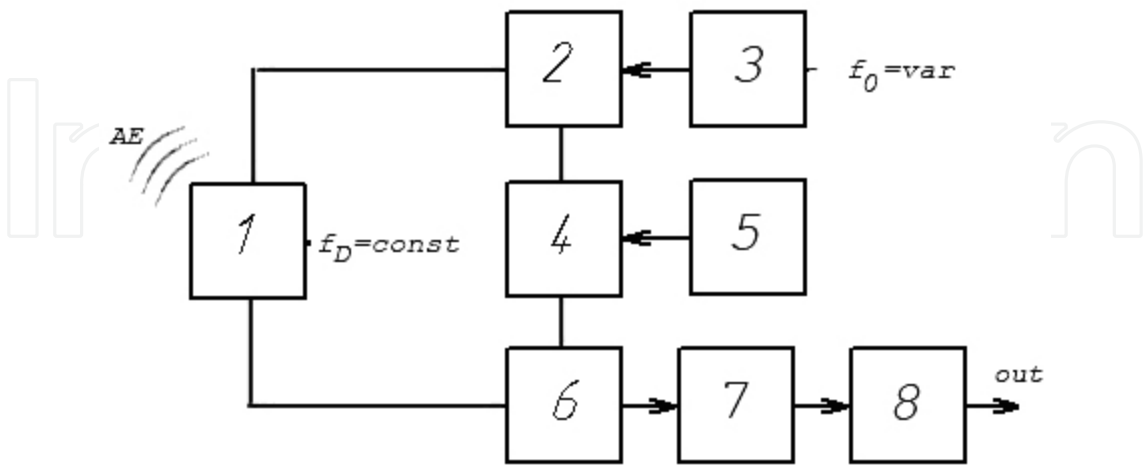

Fig. 16. Intelligent acoustic emission OFS
1-fiber coil sensing element; 2, 6 – fiber optic couplers; 3 – tuneable laser diode;
4 – acousto-optical frequency shifter; 5 – RF generator; 7 – frequency detector;
8- microcontroller

When absent an etalon device for creation, in real-time, on the OFS of acoustic emission of entrance mechanical influence with known characteristics, i.e. when f_D = *const*, self-checking of the amplitude-frequency characteristic of the OFS is made by fast tuning of acousto-optical modulator shift frequency f_M , or by fast tuning of optical frequency of laser diode radiation f_0. Modern tunable acoustic-optical modulators and laser diodes have period of tuning through all spectrum of the frequency characteristic about 1 µs that it is quite enough at frequencies acoustic emission up to 500 kHz.

This graduation amplitude-frequency characteristic of the acoustic emission OFS is compared with the initial data of calibration of OFS and corresponding correction factors are calculated. The measurement of acoustic emission by means of OFS with using obtained correction factors is continued.

5.5 Intelligent fiber Bragg grating OFS

The intelligent strain OFS design uses an induced phase discontinuity (structural redundancy) in the fiber Bragg grating (FBG) that gives information redundancy in optical spectrum which is used for self-monitoring sensor's condition .

The reflectivity at the Bragg wavelength can be estimated using the equation

$$R(\Lambda) = \tanh^2\left[\pi \cdot n\left(\frac{L}{\lambda_B(\Lambda)} \cdot \frac{\Delta n}{n} \right)\left(1 - \frac{1}{V^2} \right) \right] \qquad (10)$$

where L – the length of FBG; n – index of refraction;
V - the normalized frequency of the fiber ($V \geq 2.4$);
λ_B – Bragg diffraction wavelength that has multimodal response:

$$\lambda_B(\Lambda;t) = 2 \cdot n \cdot \Lambda(x;t) \ , \ \Lambda{=}const \ \ \forall x \in L, \ \Lambda_0 {>} \Lambda \ \text{ for } x_0 \in L \qquad (11)$$

where Λ – the period of the n modulation of of FBG; x – the fiber axis direction; x_0 – the point of phase discontinuity.

Figures 17a and 17b show the reflection spectrum of FBG-based diffraction OFS with and without a phase discontinuity respectively. The presence of a narrow pass-band in the wavelength spectrum is due forming of phase discontinuity in the FBG structure.

While a strain is applied along axis of the healthy FBG sensor with a phase discontinuity (eq. 7), optical reflection spectrum (eq. 6) shows linear shift as

$$\Delta\lambda_{BS} = \lambda_B\left(1 - \rho_\alpha\right)\Delta\varepsilon \qquad (12)$$

where ρ_α - the photoelastic coefficient of the fiber   , ε – strain (tension).

When a strain is applied along axis of the damaged FBG sensor with a phase discontinuity (eq. 7), then damage changes the photoelastic coefficient of fiber (strain sensitivity varies) and optical spectrum shows linear shift (eq. 8) and simultaneously changes her shape - the relative position of the main peak of the FBG and narrow pass-band will no longer constant: their disposition are changed that represents a damaged sensor.

It is important to note that the presence of this narrow pass-band in spectra does not add any additional complexity to the signal processing schemes to be used.

Simple tracking the phase-shift and main peak of optical spectrum allows determine technical condition (health) of the FBG strain sensor.
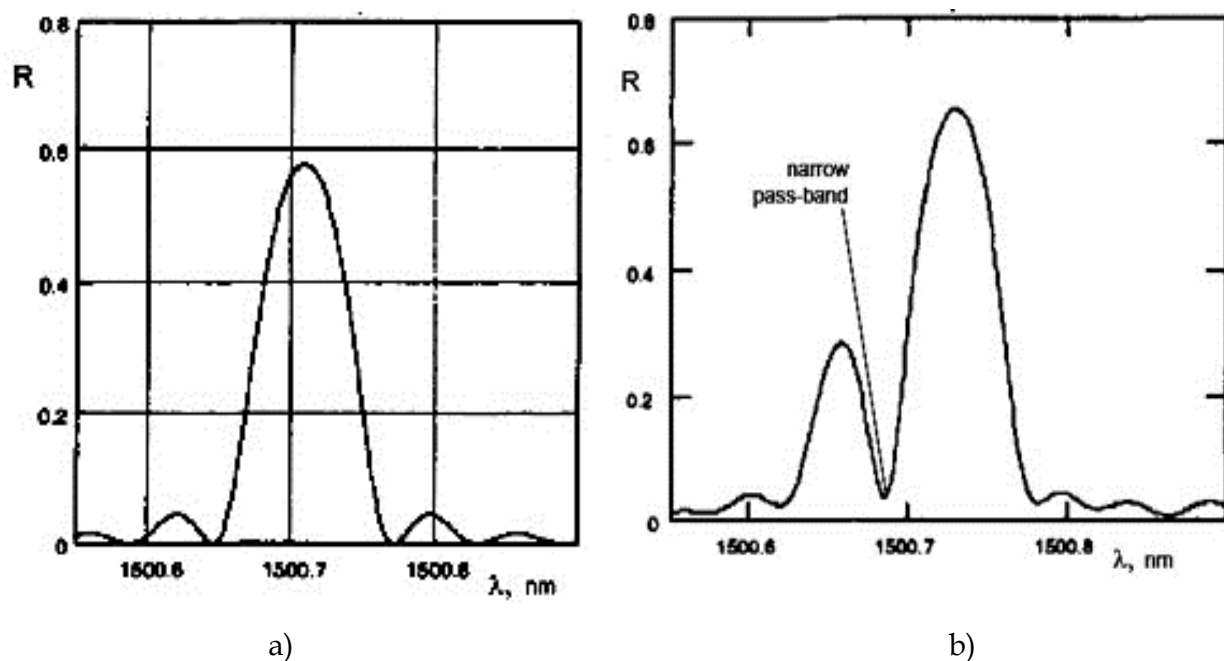

a)   b)

Fig. 17. Reflection spectra of strain FBG optical fiber sensor
a)– without discontinuity b) – with discontinuity

6. Applications OFS in nuclear power plants

The analysis of possible ways of influence of electromagnetic disturbances on pressure sensors under the conditions of factual operation on NPP units has shown that the basic influences leading to failures in work of electronic pressure gauges occur on the direct current feed circuit, the current signal output circuit and as a result of impact of electromagnetic fields.

The Russian Federal Agency of Ecological, Technological and Nuclear Supervision yearly registered a few deviations in the work of Russian nuclear stations. The causes included malfunction and false data of the electron pressure sensor.

In addition, after the inspection of electromagnetic conditions on the NPP it was established that the basic components of periodic disturbances at the output of pressure gauges have characteristic frequencies in the range of 18 – 20 MHz and 200 kHz imposed on a supply mains voltage sinusoid, which increases the value of the gauge current signal to a setting value at which emergency protection is activated.

The reason of EMI occurrence at frequencies 18 – 20 MHz and 200 kHz is the electronic circuit of the gauge in the long line operating mode when high-frequency fluctuations fade after several runs from one end of a coaxial cable to another.

This circumstance demands replacement of electronic pressure gauges by noise-proof OFS with fiber optic cable lines.

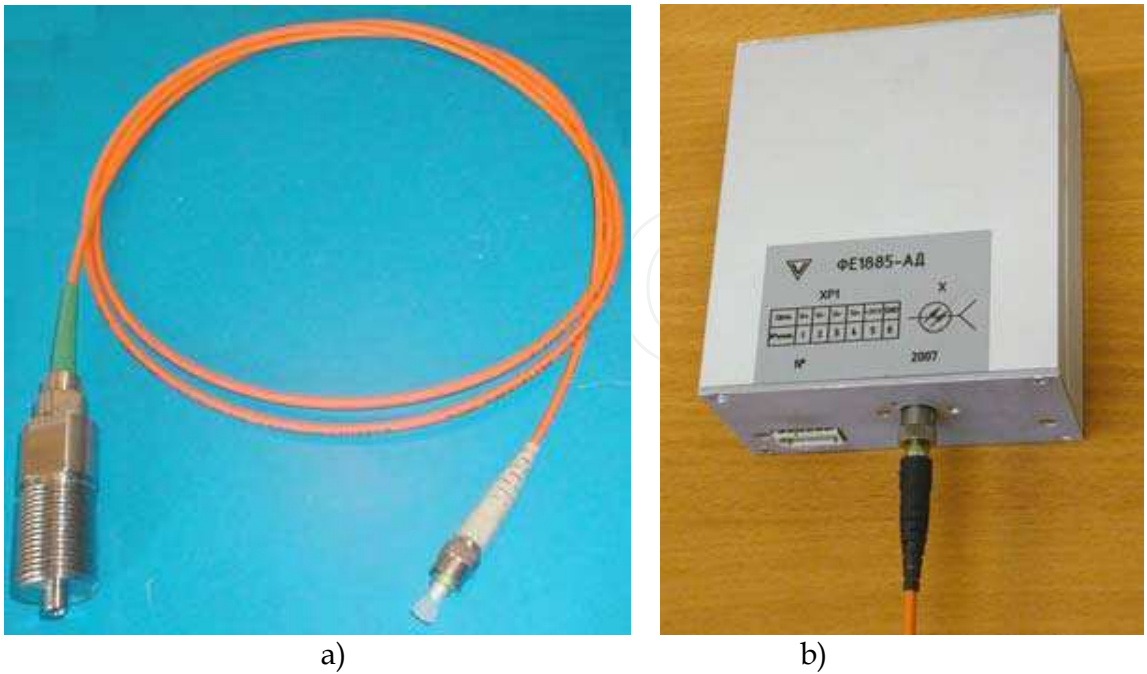A general view of intelligent pressure OFS based on FFPI is shown in fig. 18.

<div align="center">a)   b)</div>

Fig. 18. General view of intelligent pressure OFS
a)– sensing element (b)- optoelectronic transceiver

The pressure applied to a sensitive element causes blooming deformation of the FFPI glass cover. The cover radius decreases resulting in the growth of length of the L_0 resonator cavity by value ΔG up to hundred nanometers.
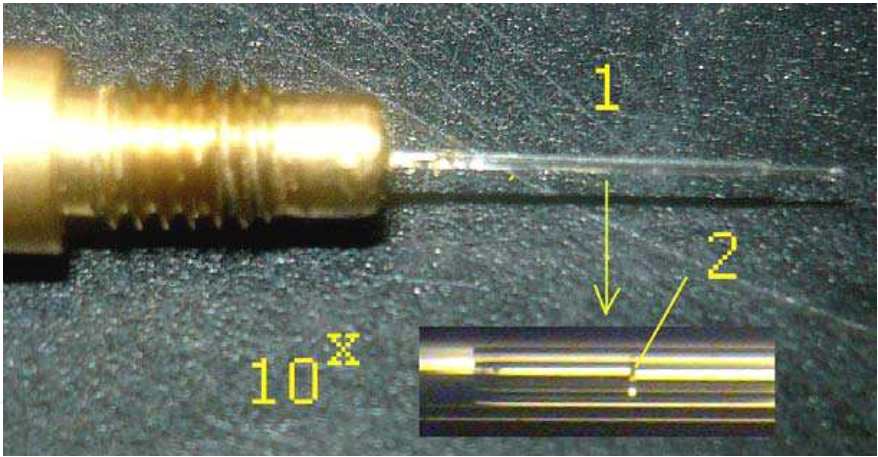

Fig. 19. General view of FFPI-based pressure sensor
1 – sensing element; 2 – FFPI cavity with ΔG length (10^x magnifying)

Analytical expression of the change of the length of the optical resonator ΔG follows from mechanics principles owing to the applied pressure:

$$\Delta G = \frac{L_o}{E}\left[\sigma_z - \mu\left(\sigma_r - \sigma_t\right)\right] \tag{13}$$

where σ_z, σ_r, σ_t - longitudinal, radial and lateral deformation of the sensor.

$$\Delta G = \left[\left(1 - 2\mu\right) \cdot k_r \cdot \frac{L_o}{E} \right] \cdot P \tag{14}$$

where P – pressure on the sensitive element;
μ- Poisson factor for quartz glass, 0.17;
E –Young modulus for silica, 73 GPa.
k_r – geometry factor of the sensitive element, 1.16.
FFPI output sensing signal is defined by ΔG value with the constant transmission peak of the spectral optical filter λo:

$$I_s = \left[1 - Cos\left(\frac{4\pi}{\lambda_0} \cdot \Delta G \right) \right] \tag{15}$$

Normalization of the FFPI output signal, i.e. relation formation

$$I_N = \frac{\int\limits_{-\infty}^{+\infty} I_s(\lambda) \cdot \left[1 - Cos\left(\frac{4\pi}{\lambda} \Delta G \right) \right] \cdot d\lambda}{\int\limits_{-\infty}^{+\infty} I_0(\lambda) \cdot \left[1 - Cos\left(\frac{4\pi}{\lambda} \Delta G \right) \right] \cdot d\lambda} \tag{16}$$

allows practically to eliminate the influence of instability of the optical source radiation (for example, ageing or change of the current rating), the influence of the induced losses of optical power in the sensor (for example, ionizing radiation) and the influence of insertion losses in the optical communication cable (for example, abrupt bends of optical cable and connectors). It is experimentally established that, for example, at an average value of relation I_N = 0.27145 and insertion optical losses up to 70% the standard deviation of the relation from the average value does not exceed 0.00063 (0,23 %) as shown in fig. 20.
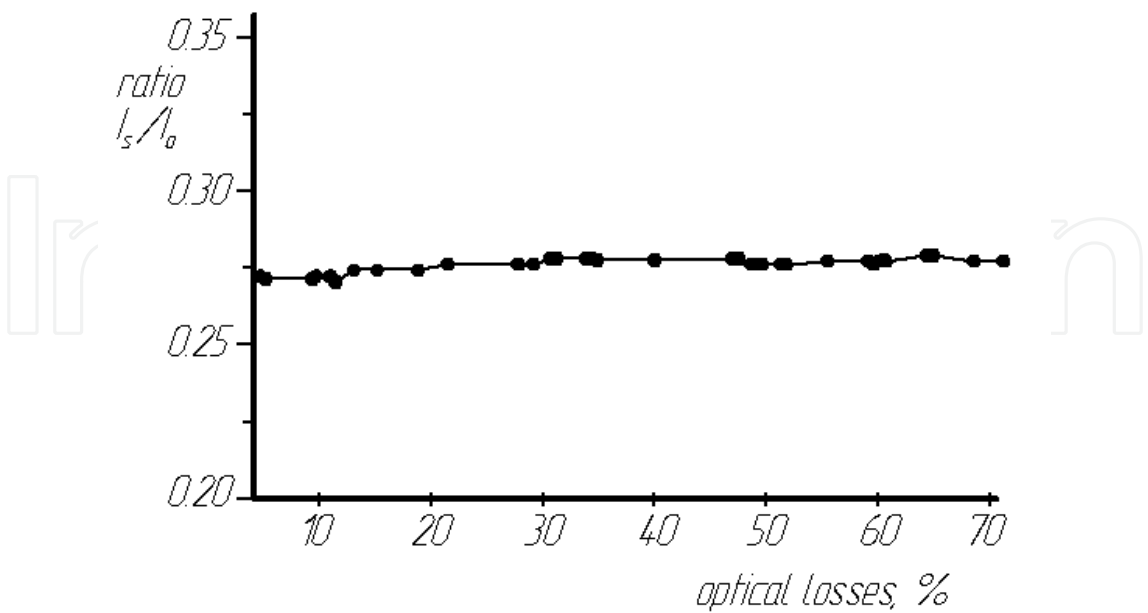

Fig. 20. Normalized output signal of the pressure OFS

The temperature dependence of the resonator cavity length is expressed by the formula:

$$\Delta G = \left(\alpha_o L_o - \alpha_1 L_1 - \alpha_2 L_2 \right) \Delta T , \tag{17}$$

where ΔT – temperature change;
α_o , α_1, α_2– CTE of capillary cover quartz glasses, input and output fibers, accordingly;
L_o , L_1 , L_2 – lengths of the sensor measuring cavity, input and output optical fibers of the interferometer accordingly.
To reduce a temperature error to a minimum, it is necessary to pick up such values of α_o , α_1, α_2, L_1 that the expression (17) of the formula in brackets almost equals zero:

$$\alpha_o L_o - \alpha_1 L_1 - \alpha_2 L_2 = 0 \tag{18}$$

at α_o = 6.1·10^{-7} K^{-1}, α_1 = 6.5·10^{-7} K^{-1}, α_2 = 5.6·10^{-7} K^{-1}, L_1 = 5.06 mm we obtain:

$$\alpha_o L_o - \alpha_1 L_1 - \alpha_2 L_2 = 0,0002 \; нм \; .$$

When the temperature ΔT of the measured environment changes by 600°C, the length of the FFPI resonator cavity will change according to the formula (17) by 0.1 nanometers, which is below a permissible threshold. That is, FFPI provides for practical temperature insensitive measurement of pressure in the entire working range of temperatures.
Fig. 7 shows calibration characteristics of pressure OFS with temperature self-compensation for working temperatures 24 °C and 250 °C. Practically, additional temperature errors are absent.
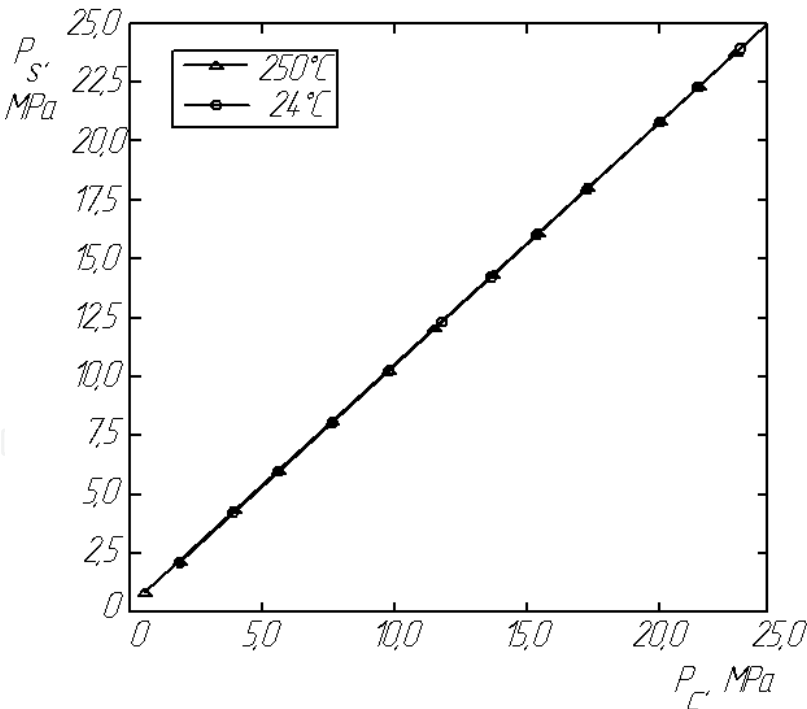

Fig. 21. Calibration characteristics of the temperature insensitive OFS

7. Application of OFS for spent nuclear fuel repository monitoring

Radioactive waste requires, due to its high hazard potential, careful handling from production to final disposal. In all waste management activities the safety objectives defined

by the authorities must be met to guarantee an adequate protection of the public. Waste management starts with the registration of the radioactive waste arising at different locations from different applications in industry, research as well as at nuclear fuel cycle facilities. The waste is then stored, conditioned into an appropriate form for further handling and disposal, intermediately stored whenever necessary over long periods of time, and eventually disposed of (Jobmann M. & Biurrun E.,2003).

Long-term effectiveness, low maintenance, reliable functioning with high accuracy, and resistance to various mechanical and geochemical impacts are major attributes of monitoring systems devised to be operated at least during the operational phase of a repository. In addition, low maintenance and automatic data acquisition without disturbing the normal operation will help reducing operational costs. Due to these reasons Russian "Krasnoyarsk SNF repository" started using of reliable and radiation-hard fiber optic technology as the basis for global monitoring systems at final disposal sites.

Series of parameters important to safety of SNF repository can be monitored by optical sensors. Sensing elements to measure strain, displacement, temperature, and water occurrence together with the multiplexing and data acquisition systems were installed at 1000m depth and the operation temperature is about 40 °C .

The configuration of experimental OFS system is shown on fig. 22.
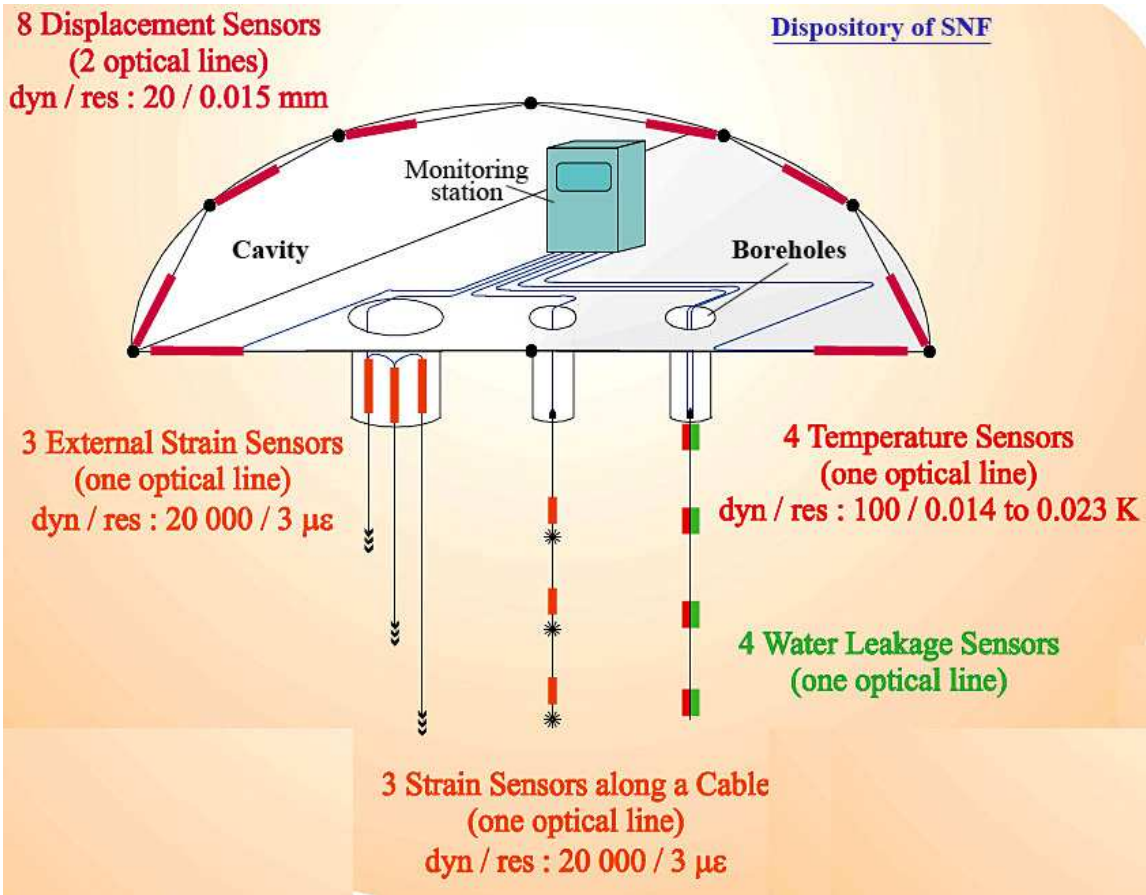

Fig. 22. Configuration of the OFS system in SNF repository

In three boreholes strain, temperature, and water detection sensors are installed, whereas the displacement sensors are fastened around the cross-section of the drift to monitor changes of the cavity geometry.

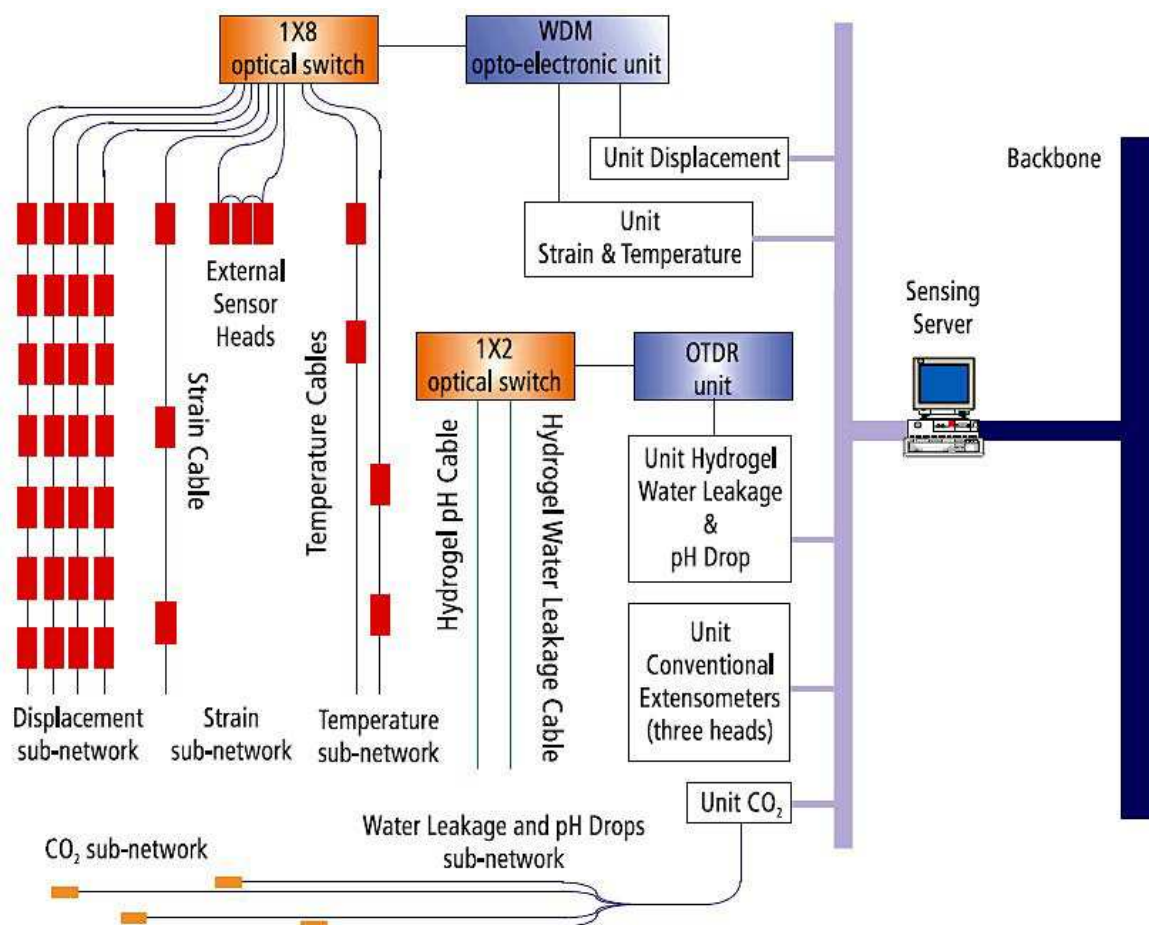The complete circuit diagram of the OFS system is shown on fig. 23.

Fig. 23. Circuit diagram of the OFS system in SNF repository

All measured data will be collected by a so called sensing server via the corresponding multiplexing units. The sensing server can be connected to a backbone providing the data in special output files to be downloaded by the user.

The presented fibre optic sensing systems which can be used in an all fibre optic network could be the basis for a high-reliability, low-maintenance, economic monitoring system for operational safety requirements in a final repository as shown in fig. 24.

Monitoring the cavities deformation at representative cross-sections will be the basis for evaluating the operational safety. Together with temperature monitoring as a function of time at different locations, data for validating the thermo-mechanical constitutive laws of the host rock will be available.

Monitoring of harmful gases as methane and carbon dioxide is an important issue in a salt environment because of the ongoing excavations during the operational period. Thus, fibre optic gas sensors at least for measuring methane and carbon dioxide was included in the global monitoring systems for spent nuclear fuel repositories. In an underground repository, the availability of appropriate monitoring tools is a major issue in order to ensure operational safety and to verify that the repository evolves as predicted. The feasibility of measuring safety relevant parameters using sensors and multiplexing systems based on fibre optic technology.

Further developments are necessary to increase accuracy in large sensing networks and to check the long term performance.
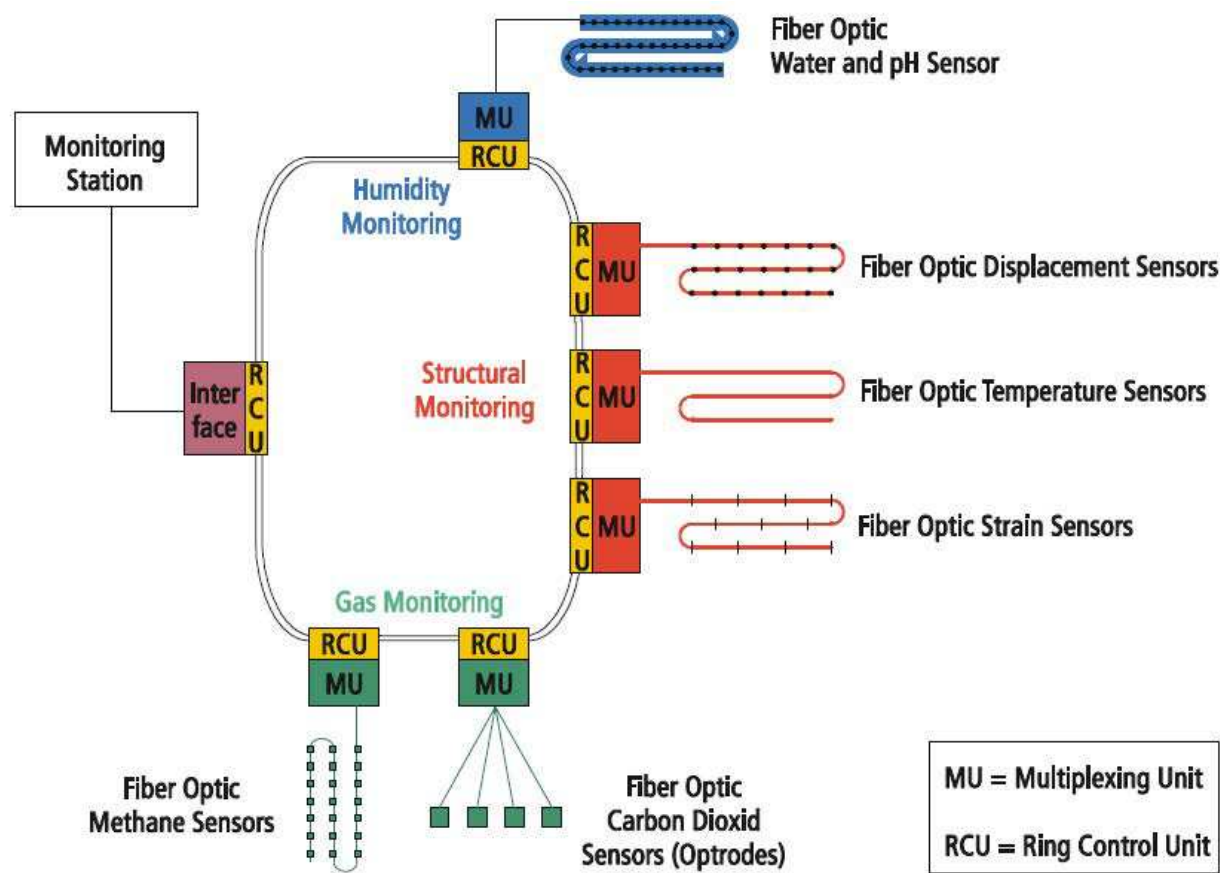

Fig. 24. All-fiber optic sensors network for SNF repository

8. Trends in developments OFS for nuclear energy an industry

In the next decade, nuclear energy is expected to play an important role in the energetic mix. Various national and international programs taking place in order to improve the performance and the safety of existing and future NPPs as well as to assess and develop new reactor concepts. Instrumentation is a key issue to take the best benefit of costly and hard to implement experiments, under high level of radiation.

OFS are contributed to improve instrumentation available thanks to its intrinsic capability of high accuracy associated with the passive remote sensing implementation allowed by fiber optic communication line. It can work under high temperature and high radiation. The small size is appreciated attending the lack of available space in research reactor, while miniaturized sensors will not disturb the temperature and radiation profile on the tested material. The ability of fiber optic sensors to provide smart sensing capabilities, detailed self-diagnostics, and multiple measurements per transducer and distributed OFS for temperature, strain and other parameters profiling are provided. These capabilities, coupled other intrinsic advantages, make fiber optic sensors a promising solution for extremely harsh-environment applications where data integrity is paramount.

The advanced fiber optic sensing technologies that could be used for the in fusion reactors, for example ITER, safety monitoring. The remote monitoring of environmental parameters,

such as temperature, pressure and strain, distributed chemical sensing, could significantly enhance the ITER productivity and provide early warning for hazardous situations.

The development of new intelligent (smart) OFS involves the design of reconfigurable systems capable of working with different input sensors. Reconfigurable systems based on OFS ideally should spend the least possible amount of time in their calibration (Rivera J., et al., 2007).

A traditional NPPs control system has almost no knowledge memory. The neural network, by comparison, learns from experience what settings work best. The system updates the network weighting factors with a learning algorithm. The neural network outputs adjusts the basic parameters (criteria) of technological processes and safety of NPP. This is an excellent artificial intelligence application. Rather than model and solve the entire process, this neural network handles a localized control challenge.

When a complex system NPP is operating safely, the outputs of thousands of sensors or control room instruments form a pattern (or unique set) of readings that represent a safe state of the NPP. When a disturbance occurs, the sensor outputs or instrument readings form a different pattern that represents a different state of the plant. This latter state may be safe or unsafe, depending upon the nature of the disturbance. The fact that the pattern of sensor outputs or instrument readings is different for different conditions is sufficient to provide a basis for identifying the state of the plant at any given time. To implement a diagnostic tool based on this principle, that is useful in the operation of complex systems, requires a real-time, efficient method of pattern recognition. Neural networks offer such a method. Neural networks have demonstrated high performance even when presented with noisy, sparse and incomplete data. Neural networks have the ability to recognize patterns, even when the information comprising these patterns is noisy or incomplete. Unlike most computer programs, neural network implementations in hardware are very fault tolerant; i.e. neural network systems can operate even when some individual nodes in the network are damaged. The reduction in system performance is about proportional to the amount of the network that is damaged.

Beyond traditional methods, the neural network based approach has some valuable characteristics, such as the adaptive learning ability, distributed associability, as well as nonlinear mapping ability. Also, unlike conventional approaches, it does not require the complete and accurate knowledge on the system model. Therefore it is usually more flexible when implemented in practice. Thus, systems of artificial neural networks have high promise for use in environments in which robust, fault-tolerant pattern recognition is necessary in a real-time mode, and in which the incoming data may be distorted or noisy. This makes artificial neural networks ideally suited as a candidate for fault monitoring and diagnosis, control, and risk evaluation in complex systems, such as nuclear power plants (Uhrig R. 1989).

The objective of this task is to develop and apply one or more neural network paradigms for automated sensor validation during both steady-state and transient operations. The use of neural networks for signal estimation has several advantages. It is not necessary to define a functional form relating a set of process variables. The functional form as defined by a neural network system is implicitly nonlinear. Once the network is properly trained, the future prediction can be interpolated in real-time. The state estimation is less sensitive to measurement noise compared to direct model-based techniques. As new information about the system becomes available, the network connection weights can be updated without relearning the entire data set. These and other features of neural networks will be exploited in developing an intelligent system for on-line sensor qualification.

We believe that researchers and instrumentation designers of new generation of NPPs will use novel approaches to conduct real-time multidimensional mapping of key parameters via optical sensor networks, distributed and heterogeneous sensors designed for harsh environments of nuclear power plants and spent nuclear fuel respository. Recent events on Japanese NPP "Fukushima-1" are characteristic that within two weeks the information from gages, as NPP was without power supplies, was inaccessible and electronic gages couldn't transmit the important measuring information for condition monitoring of NPP. Contemporary OFS, as it is known, are radiation-hard and don't need power supplies, and the optoelectronic transceiver can be installed on distance to 80 km from NPP that will allow to supervise NPP during any critical periods and to accept the right decisions on elimination of failures.

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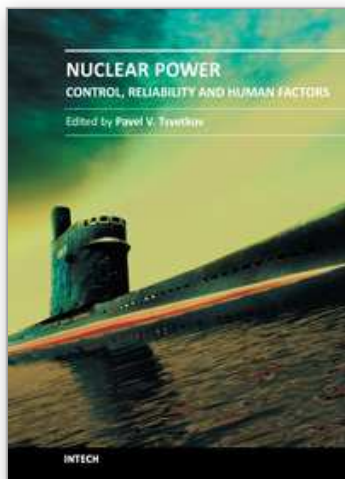
Nuclear Power - Control, Reliability and Human Factors

Edited by Dr. Pavel Tsvetkov

Advances in reactor designs, materials and human-machine interfaces guarantee safety and reliability of emerging reactor technologies, eliminating possibilities for high-consequence human errors as those which have occurred in the past. New instrumentation and control technologies based in digital systems, novel sensors and measurement approaches facilitate safety, reliability and economic competitiveness of nuclear power options. Autonomous operation scenarios are becoming increasingly popular to consider for small modular systems. This book belongs to a series of books on nuclear power published by InTech. It consists of four major sections and contains twenty-one chapters on topics from key subject areas pertinent to instrumentation and control, operation reliability, system aging and human-machine interfaces. The book targets a broad potential readership group - students, researchers and specialists in the field - who are interested in learning about nuclear power.

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