REPORT

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Fiberoptic sensors for high-voltage applications

(1 appendix)

Summary

1. Background

SP has experience in the field of fiberoptic communication and expertise in research in the field. Also, SP has expertise in the high-voltage field and there is currently a large interest in developing the high-voltage network in order to accommodate new small producers of electric power (wind mills, solar power, etc.)

In this report we describe efforts to find areas of interest to develop fiberoptic sensors for offshore monitoring of high-voltage equipment.

A large number of research papers and review articles have been collected and reviewed in order to investigate what possibilities are at hand for SP to provide support for development of new or existing fiberoptic sensor technologies. The background material has been divided based on the monitored property, as evident from section 2.

2. Monitoring

In order to reduce costs and increase the reliability of high voltage networks, monitoring systems are used to keep track of performance and predict maintenance.

Power, voltage and current transformers, cables, rotating generators, solid-state substations and finally renewable energy production facilities are among the most important power system components. This is due to the substantial investments in them and their key effects in the system reliability. Unscheduled outages of these high voltage components due to unexpected failures are catastrophic in many cases.

Online condition monitoring equipment is vital for increasing the reliability of the high voltage network. Over the past few years many monitoring techniques and systems have been developed offering a variety of advantages for the transformer operator and asset manager. With introduction of HVDC solid-state facilities, all these techniques and systems should be reviewed, reconsidered, adopted, and also new methods defined and developed. The same challenge exists for the high voltage cables which have to withstand higher voltages at longer lengths and harsher installation conditions.

Some typical examples of monitoring and diagnostics methods for evaluation of condition of an oil filled power transformer are shown in Figure 1. The exact origin of the picture is unknown.

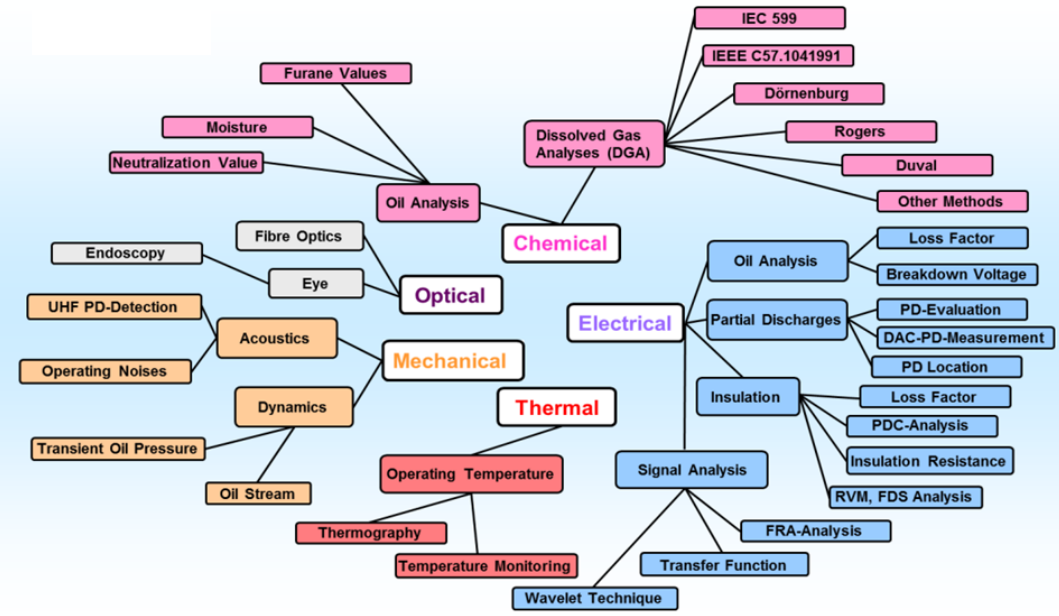

Figure 1. Examples of monitoring and diagnostics methods for evaluation of condition of an oil filled power transformer.

2.1. Monitoring by the use of optical fiber

A fiberoptic sensor is a sensor that uses optical fiber either as the sensing element or as a means of relaying signals from a remote sensor to the electronics that process the signals. Fibers have many uses in remote sensing. Depending on the application, fiber may be used because of its small size, or because no electrical power is needed at the remote location, or because many sensors can be multiplexed along the length of a single fiber by using light wavelength shift for each sensor, or by sensing the time delay as light passes along the fiber through each sensor. Fiberoptic sensors are also immune to electromagnetic interference, and do not conduct electricity so they can be used in places where there is high electric field strengths or flammable material. Fiberoptic sensors can be designed to withstand high temperatures as well. Light weight, large bandwidth and high sensitivity are among other advantages that can be mentioned.

2.2. Fiberoptic sensor market

The global market for fiberoptic sensors is expected to reach $2.2 billion by 2018, representing a compound annual growth rate (CAGR) of 4.5 percent since 2013, according to a BCC Research analysis[1].

The firm said the defense industry is the largest consumer in the market but is set to shrink, representing negative growth, due to spending cuts in the U.S. However, other fiberoptic sensor applications should see a CAGR of 10.4 percent.

Medical applications show the greatest potential, but growth depends on regulatory approval for new devices, BCC said.

Fiberoptic sensors “found a lucrative niche in the oil and gas market, as they opened an entire new revenue stream for service providers,” said BCC Research analyst Lori Weisenbach Cornett. “However, improvements in sensor robustness will be required for (fiberoptic sensors) to realize their potential in this market”.

2.3. Some exclusive properties of offshore sea-bed high voltage equipment

Offshore sea-bed high voltage equipment introduces several new requirements for any applied monitoring system due to its different electromagnetic, electrostatic and thermal behaviour. Examples of such requirements are:

- The equipment's quality and reliability are very important in a project because it is extremely expensive to raise equipment up from the sea bed for repair
- New types of insulation; conductive, magnetic and constructive materials
- Different installation environmental condition (deep sea water instead of ambient air)
- Innovative cooling system required for dissipation of losses
- Reinforced mechanical structure in and out of equipment
- Mechanical and electrical parameters affecting the monitoring system components inside sea water

2.4. Fiberoptic sensor examples

Fiberoptic sensors have already been proposed for the following applications:

- Detection of AC/DC voltage in the middle and high voltage range (100–2000 V)
- Detection of high frequency (5 MHz–1 GHz) electromagnetic fields
- Measurement of electrical power
- Transmission of light from an electrical arc flash to a digital protective relay to enable fast tripping of a breaker in electrical switchgear
- Measurement of current and voltage for high-voltage substations
- Measurement of temperature
- Strain measurements in electrical welding jaws
- Position sensor which provides absolute angular measurement
- Sensing of individual electric field components
- Transmission of control and measurement information, as well as optically powering of remote microelectronic sensory system
- DC and low frequency AC measurements
- High current surge measurements
- Measurement of sound and vibration
- Detection and measurement of partial discharges
- Detection of oil leakage
- Measurement of electrification in power transformers
- Dissolved gas analysis for insulating oils
- Oil-paper insulating system monitoring

The main parameters of the lightwave that can carry information and be used as a sensor are; intensity, polarization state, phase, and frequency. Based on these sensor parameters the measurands can include geometrical (e.g. displacement), mechanical (e.g. strain), dynamical (e.g. acceleration), physical (e.g. temperature, voltage, current), and chemical (e.g. flammable gases) quantities[2].

An overview of the different types of fiberoptic sensors developed has been given in ref. 3:

- Fiber acts as transmission medium for light out of or in to sensing region: extrinsic sensors, see Figure 1

- Fiber acts both to power an electronic sensor and to carry the data back to the data link: hybrid sensors, see Figure 2
- Sensing takes place inside the fiber itself: intrinsic or all-fiber sensor
- The most important type of high performance intrinsic sensors: interferometric sensors, see Figure 3

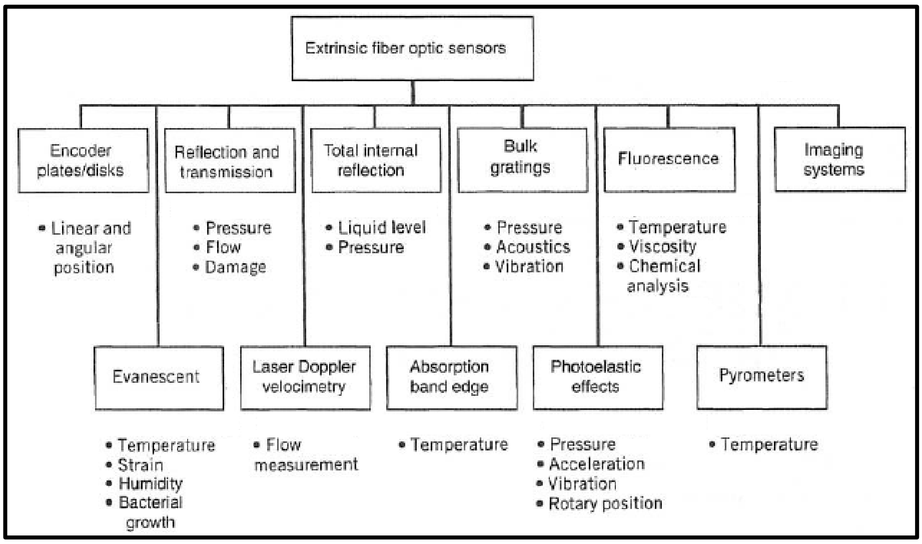

Figure 2. Extrinsic fiberoptic sensors.

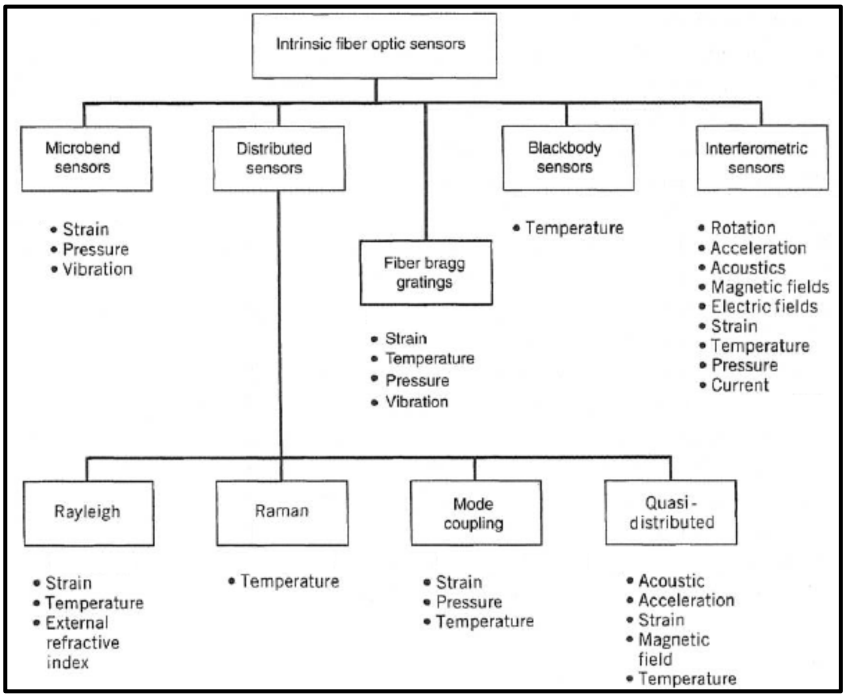

Figure 3. Intrinsic fiberoptic sensors.

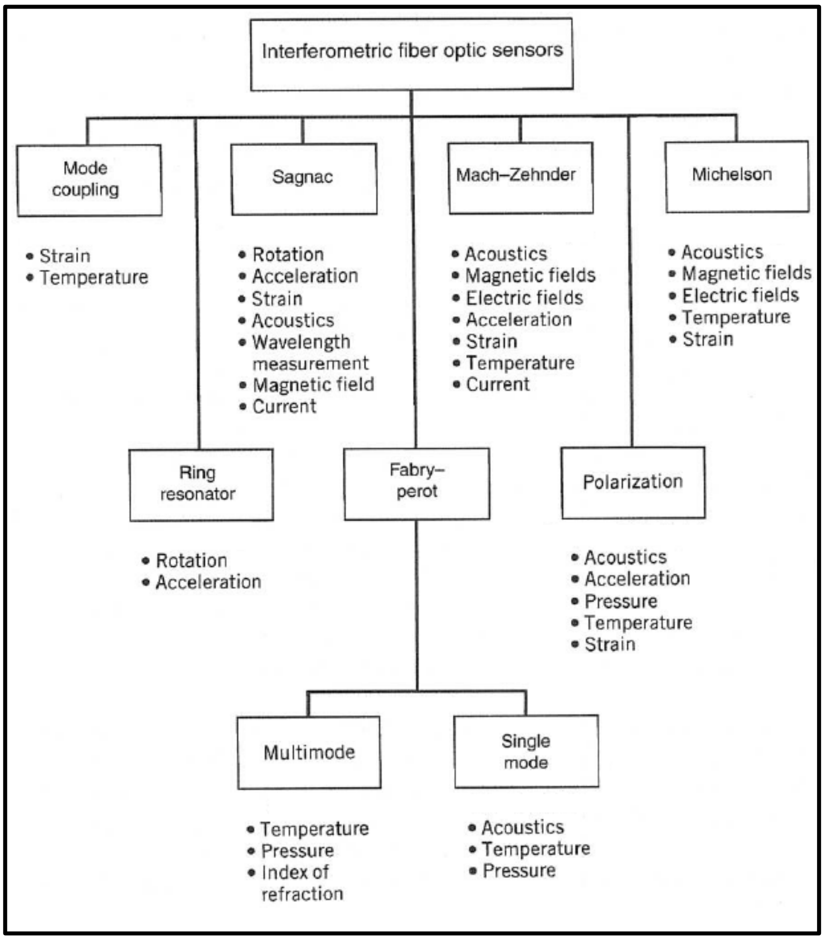

Figure 4. Interferometric fiberoptic sensors.

3. Monitored parameters

A large number of published papers and reports in the field of optical sensors and high-voltage equipment have been collected during the project. Each report has been examined and the technical possibilities have been evaluated, as recorded in an Excel file. The file is shown in Appendix 1 and commented also in this section.

3.1. Examples of Monitored equipment

The table shows examples of monitored high-voltage related equipment and monitored parameters found in literature.

Table 1. Examples of monitored equipment.

Monitored equipment	Monitored item	Ref.
Regular high-voltage AC metering and protection, accurate wide dynamic range metering, high voltage DC, high current DC, portable calibration reference, generator monitoring, generator protection, and high-current AC applications where conductors are quite large or far from one another	Current	4

Monitored equipment	Monitored item	Ref.
Two types of electrical current conductors: a typical conductor with circular cross-section and a bus duct based on inducing voltage in the coil	Current based on magnetic field arising around the conductor due to the current passing in it	5
Oil-filled power transformers or equipment	Three types of dissolved fault gases, acetylene (C2H2), methane (CH4) and ethylene (C2H4)	6
Transformer oil	Dissolved hydrogen gas	7
Transformer oil	Monitoring of traces of fault-gas (C_2H_2)	8
High-voltage transformers	Real time monitoring of dissolved gases in the insulating oil (C_2H_2 & CO)	9
Power Transformers	Static Electrification of oil	10
Wind turbine rotor blades	Lightning-safe condition monitoring	11
Wind turbine Structure	determine the parameters of lightning strikes, and localize the impact point	12
Wind turbine	Lightning discharge current	13
Transformer oil	Moisture	14
Oil-Paper insulated High voltage equipment	Humidity in oil-paper insulation	15
High-Voltage Power Equipment	Ultrasonic pressure waves PD detection	16
Oil-Paper Insulated Electrical Systems	Acoustic detection of partial discharges	17
Oil-Paper Insulated Electrical Systems	Acoustic detection of partial discharges	18
High-Voltage Equipment	Ultrasonic pressure waves PD detection	19
Oil insulated high-voltage equipment	Internal temperature, sound pressure and vibration due to partial discharge	20
High voltage cable	Optical fibre system for PD signal transmission	21
High voltage cable joints	Optical fibre system for PD signal transmission	22
High voltage transformers	Optical fibre system for PD signal transmission	23
Oil insulated high-voltage equipment	Formation of sludge	24
High Voltage Power Cable in Seafloor	Inner temperature and outside strain damage monitoring	25

Monitored equipment	Monitored item	Ref.
Transformers	Direct temperature measurement	26
Transformers	Direct temperature measurement	27
High-Voltage Equipment	Isolated voltage monitoring for high-voltage sensing applications	28
High voltage systems	Vibration measurement in the vicinity of electrical fields	29
Power transformers	Multiplex distributed Temperature Monitoring and Acoustic detection of PD	30
Power transformers	Humidity, Temperature, Vibration and Acoustic detection of PD	31
Power transformers	Vibrations and Partial discharge induced Ultrasonic pulses	32
Wind turbine blades	Mechanical damages	33
Generator end-winding	Vibration monitoring	34
High voltage power generators	-The cooling air flow temperature of a power plant generator within the cooling slots of the stator -Distributed magnetic field near the end windings -End winding vibrations	35
Turbo Generators	Thermal movement and vibration of the stator end windings (Temperature, vibration and Strain)	36
Oil filled Equipment	State of purity of machine oils	37
Oil filled Equipment	-Identification of different kinds of oils or mixtures of them -Tracing oil aging with use	38
Oil filled Equipment	Oil aging	39
Power transformers	Distributed acoustic location of partial discharges	40
High voltage equipment	Temperature, Displacement and Vibration	41
High voltage equipment	Current	42
Power transformers, Gas insulated substations (GIS), and Cable installations	Partial discharges	43
Transformer, Switch gear, Power cable, Overhead transmission line, Rotating machine and Substations	Temperature, Pressure, Moisture and other	44

3.2. Acoustic monitoring of partial discharges

In a transformer small partial discharges are a certain indication of a problem and if each and every one of the discharges can be detected it is a powerful method to determine the status of the transformer.

It is known that the discharge will produce detectable acoustic emission inside the transformer. Several methods are presented where the ultrasonic pressure wave is detected by running an optical fiber through the transformer and using phase-modulation or interferometric techniques to detect the discharge.

The methods are possible to implement using standard equipment. Since it is a measurement based on ultrasound, there is a risk that it is sensitive also for vibrations and other mechanical disturbances. The false-alarm probability may be high, but it is not clear from the studied material.

3.3. Cable properties

It is a simple task to run an optical fiber along an installed high-voltage cable. In modern cables it may be incorporated already during manufacturing.

There is a technique to continuously monitor both temperature and mechanical stress along the entire fiber length, up to 160 km cable length can be monitored by using BOTDR/BOTDA technique available from companies e.g. OZ Optics (www.ozoptics.com) and Sensa (www.sensa.org).

The technology seems to be available, but there is a possibility that SP can be active in interpreting and/or developing the requirements for a real high-voltage cable installation.

3.4. Current measurement

Fiberoptic current sensors are available from ABB and other companies. It is also studied in an EMRP research project where SP has an active part, so it is not further investigated here.

3.5. Dissolved gas monitoring

Partial discharges and other processes in an oil-filled transformer will eventually lead do detrimental gases becoming dissolved in the oil. Detection and concentration measurement of such gases are already the standard method for determining the status of a transformer. However, the measurement techniques needed are difficult and in many cases the testing entails taking an oil sample and sending it to a laboratory for analysis. Consequently, continuous monitoring is generally available only for monitoring dissolved hydrogen.

Research papers in the field describe techniques where optical methods are indeed used for analysis of the dissolved gases, but only few papers present all fiber-based solutions. Some of the interesting fiberoptic probes use a specially fabricated sensor in the fiber end. This makes a good sensor, but it is rather complicated for SP to get involved in making such sensors. Other sensors requires the oil being pumped out of the transformer and into an analysis instrument placed nearby.

3.6. Partial discharge in oil filled high voltage equipment

Failure of high voltage equipment normally starts with partial discharges in the weak points of their insulation system. These discharges can lead to the insulation system dielectric instability which causes a major electrical breakdown in the system if not treated in the right period of time.

Some inevitable and unwanted substances like water and gas can contaminate the transformer oil. As a result, insulation strength of the oil reduces and this can lead to partial discharge or a complete breakdown in the insulation system.

Partial discharge can cause creation of light and sound, increase in dielectric losses, propagation of electromagnetic waves, chemical reactions, creation of high gas pressure and generation of electrical pulses caused by charge transfer.

The chemical measurements for detecting PD are based on monitoring gases released during the partial discharge process. DGA is an important and well known chemical measurement method based on analyzing the dissolved gas in the transformer oil during any discharge activity.

Several reports show achievable solutions for the detection of the acoustic waves emanating from PD in oil-filled equipment, using fiberoptic sensors. The sensors detect ultrasonic pressure waves or similar, using interferometric technique. Sensors seem to be feasible but complex, and a major drawback is the sensitivity to vibrations and other sound-like sources.

3.7. Partial discharges in dry transformers

Research papers report on measurement of partial discharges in dry transformers and using sensors to pinpoint the position of such discharges. However, no fiberoptic sensors were reported.

3.8. Moisture and sludge in transformer oil

The water content in the transformer oil is an indicator of quality, and the refractive index is dependent on the same. Papers present measurement of this property but there is no study on the sensitivity and durability of such a system. It also requires special sensitization of the fiber which cannot be easily achieved within SP.

A similar technique can be used to measure the amount of sludge present in the oil. It has the same drawbacks with a treated fiber which probably affects the durability. It is also a power measurement which is susceptible for permanent contamination.

3.9. Temperature

Fiberoptic temperature sensors are commercially available, but they normally rely on a special sensor fiber tip. As mentioned before it is difficult for SP to produce new technology here. In addition, the sensor is highly localized and measures the temperature only at the fiber end. Distributed temperature sensors more suitable for continuous monitoring of larger areas/volumes are mentioned in section 2.2.

3.10. Oil condition

A few papers report on the sensitive dependence of resonance peaks of a long-period grating in a fiber. The technique is feasible with instruments available at SP, but it requires fibres with fabricated gratings. The resonance is influenced by the refractive index in the oil which surrounds the fiber cladding. The sensitivity needs to be further studied, and also which parameters are dependent on the refractive index.

Another approach is the leakage of light from within the fiber, through the cladding. It depends on the refractive index of the surrounding oil. The paper contains weak evidence, but the sensor is simple to setup and use, so further studies are needed.

Early suggestions for monitoring the oil quality is measurement of colour, which is feasible at SP with available techniques and expertise. The need, achieved sensitivity, and commercial availability was not studied in more detail.

4. Research in the field

4.1. Active research centers in Sweden:

Fiber Optic Valley (fiberopticvalley.com/en/) is Sweden's leading innovation environment in broadband, sensor technology and innovative leadership designated by innovation agency VINNOVA.

Fiber Optic Valley’s operations are conducted on the basis of Hudiksvall / Gavle / Sundsvall headquartered in Hudiksvall.

The institute’s sponsors are VINNOVA, the Growth Board and Gävleborg Region.

Acreo Fiber Optic Center (www.acreo.se/) is a cross disciplinary competence center, which gathers competence and resources in fundamental material science and components technologies in fiber optics to industrial applications and sensing solutions.

The Center was created in 2007, based on the competence and resources at Acreo, four university partners, and around 20 industrial partners.

The Center carries out several research projects including fiber sensors.

The Center's industrial partners represent different industrial sectors, including telecommunications, medical technologies, defence, manufacture and instrumentation including:

- Bergsäker AB
- Bäcken Industrifysik AB
- Cobolt AB
- EPiQ Life Science AB
- Ericsson Network Technologies AB
- Fiberson AB
- Fibertronix AB
- Inmec Network Technologies AB
- LKAB
- Nyfors Teknologi AB
- OptoNova AB
- Optoskand AB
- Parans Solar System AB
- Proximion Fiber Systems AB
- Saab AB (Electronic Defence Systems)
- Samba Sensor AB
- Sensible Solutions Sweden AB
- Swedelase Photonics AB

- System 3R International AB
- The Center's University partners include:
- Mid Sweden University, Electronics Design Division
- Royal Institute of Technology, KTH, Dept. of Laser Physics
- Royal Institute of Technology, KTH, Dept. of Microelectronics and Applied Physics
- Karolinska Institute, KI, Div. of Haematology

The Center's Funding partners include:

- Vinnova
- Swedish Foundation for Strategic Research (SSF)
- Knowledge Foundation (KKS)
- European Regional Development Fund (Tillväxtverket)
- Region Gävleborg

The Center's Supporting partners include:

- Hudiksvalls Sparbanks sysselsättningsstiftelse
- Fiber Optic Valley

4.2. Active organizations in the world:

Society of Photo-Optical Instrumentation Engineers (SPIE), is an international society for optics and photonics, was founded in 1955 to advance light-based technologies. Serving more than 256,000 constituents from approximately 155 countries, the not-for-profit society advances emerging technologies through interdisciplinary information exchange, continuing education, publications, patent precedent, and career and professional growth. SPIE annually organizes and sponsors approximately 25 major technical forums, exhibitions, and education programs in North America, Europe, Asia, and the South Pacific.

The Optical Society of America (OSA) was founded in 1916, is the leading professional association in optics and photonics, home to accomplished science, engineering, and business leaders from all over the world. Through world-renowned publications, meetings, and membership programs, OSA provides quality information and inspiring interactions that power achievements in the science of light.

4.3. Active in Fiberoptic industry:

Opsens (www.opsens.com/en/industries/) offers key solutions for life sciences, medical, transformer, defense, aerospace, semiconductor, civil engineering, microwave chemistry, food, industry, and laboratory sectors.

The company offers industrial solutions for:

- Fiber optic transformer hotspot temperature monitoring
- Circuit breaker fiber optic pressure monitoring
- Switchgears and high voltage apparatus fo temperature sensing

OPSENS white light polarization interferometry technologies is shown in Figure 4[45].

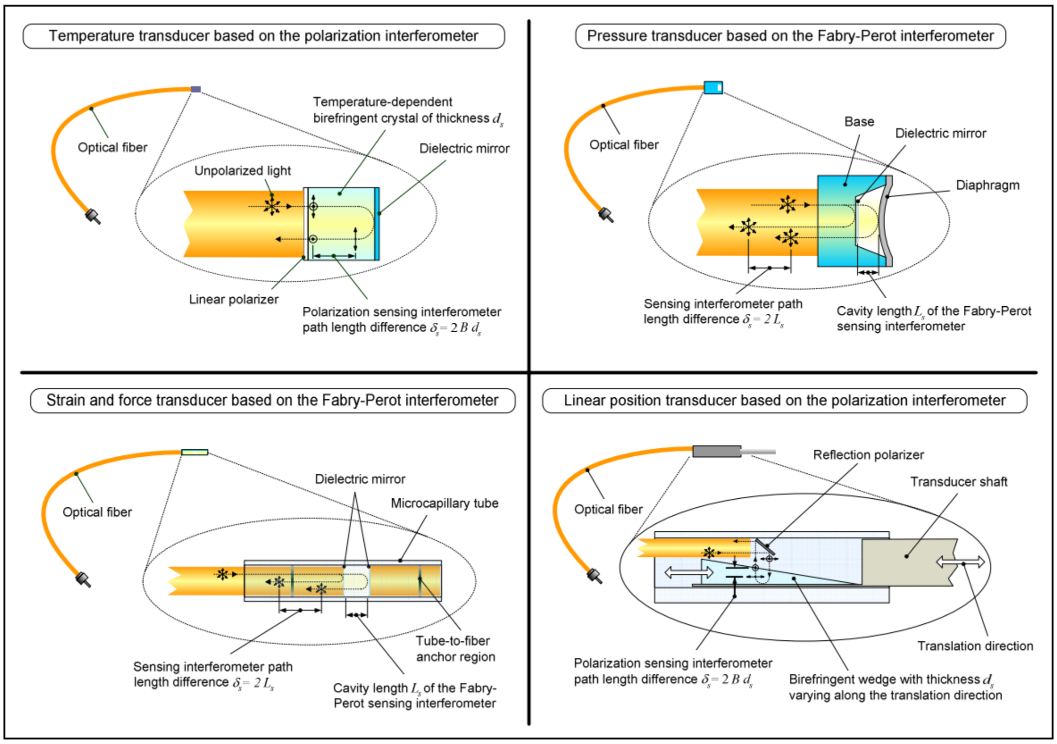

Figure 5. OPSENS sensors technology.

5. Discussion

The goals of the project were specified as the following;

- Study of applications of optical fibers for detection, measurement, sensing and condition monitoring of different physical and chemical properties for high voltage applications
- Evaluation of feasibility and reliability of proposed applications of optical fibers in normal high voltage, high power transformers comparing the proposed methods and equipment specifications with well approved scientific and technological facts
- Proposal for design considerations of an optical fiber sensor prototype to be used as Smart sensors for global condition monitoring of sea bed transformers

These goals have been partially fulfilled during the project. A large number of fiberoptic sensors have been identified and their application for high-voltage equipment studied. The feasibility of certain applications have been studied and evaluated in the light of knowledge and equipment available within SP. However, it has not been possible to identify a specific type of sensor which we consider suitable for development. Instead our conclusions are some areas where further work can be performed in possible collaboration with interested parties. The most promising are:

- Oil colour – relatively simple but the achievable sensitivity is not known
- Cable temperature and stress – commercially available but complicated so SP can find work as consultant/expert
- Oil refractive index – directly affects the oil insulation properties (dielectric constant), simple distributed sensors possible

We propose to find a suitable partner among the companies mentioned in section 4.1, in order to perform a project on development of a fiberoptic based monitoring system for high voltage equipment. The project could be financed via Vinnovas *Innovationsprojekt i företag*.

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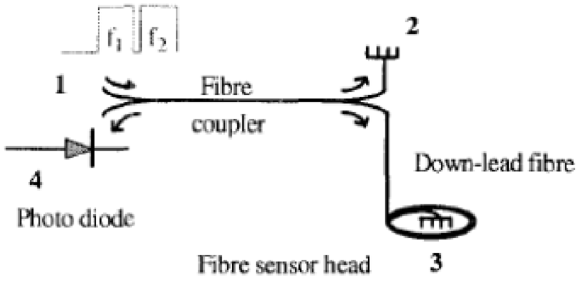
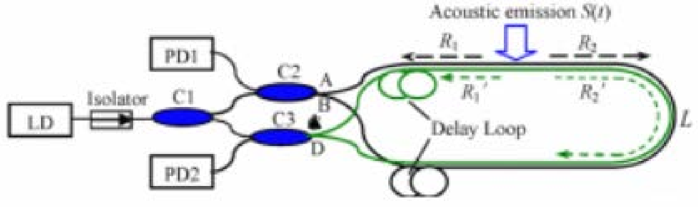
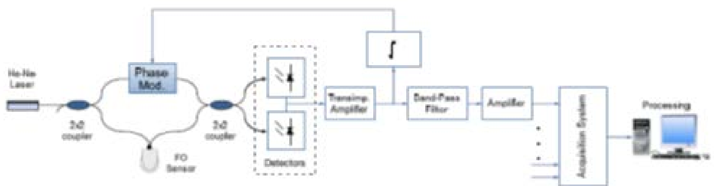
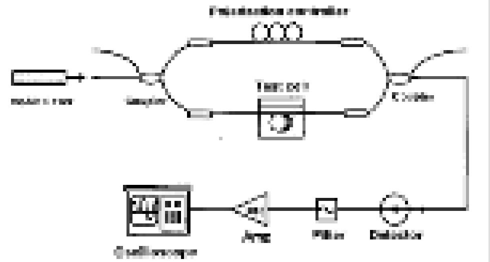
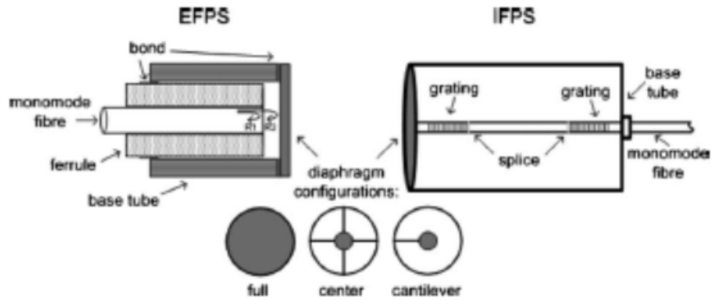
Appendices

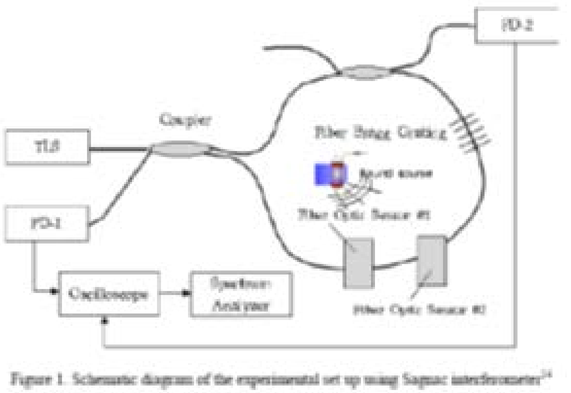
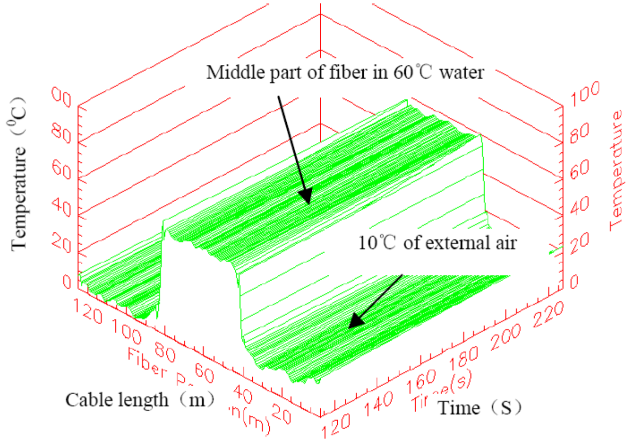
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
Acoustic PD discharge	Modified Optical Fibre Sensor for PD Detection in High-Voltage Power Equipment	Detection of electrical partial discharges (pds) Ultrasonic pressure waves are produced by partial discharges By using interferometric techniques the optical phase shift caused by the perturbation can be detected accurately with a phase-modulated type optical sensor **Achievable with standard equipment**	
	Dual-Sagnac Optical Fiber Sensor Used in Acoustic Emission Source Location	Dual-Sagnac optical fiber sensor is introduced to locate the acoustic emission(AE) source embed optical fiber sensors into concrete and other materials to monitor the structural integrity **Achievable, but not very interesting**	Figure 2. Dual Sagnac optical fiber interferometer
	Fiber Optic Sensor for Acoustic Detection of Partial Discharges in Oil-Paper Insulated Electrical Systems	A fiberoptic interferometric sensor with an intrinsic transducer along a length of the fiber is presented for ultrasound measurements of the acoustic emission from partial discharges **Achievable with standard equipment**	Figure 3. Diagram of the optoelectronic instrumentation system.

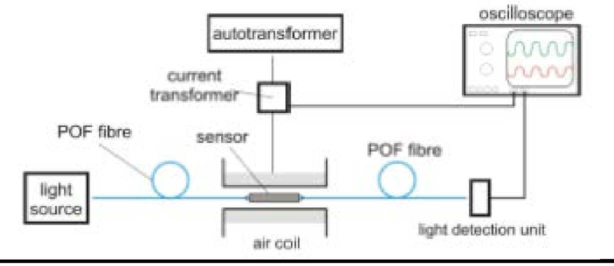
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
	Acoustic monitoring of hv equipment with optical fiber sensor	An all-optical-fiber-sensing system using a Mach-Zehnder interferometry technique **Achievable with standard equipment**	
	Extrinsic and intrinsic fiber optic interferometric sensors for acoustic detection in high-voltage environments	This paper describes the use of extrinsic and intrinsic Fabry-Pérot FP interferometers the interferometric structure is produced between the end face of a fiber and a mirrored diaphragm. Two identical FBGs are used as mirrors to produce the in-fiber FPC **Requires specially made FP cavities in the fiber end**	

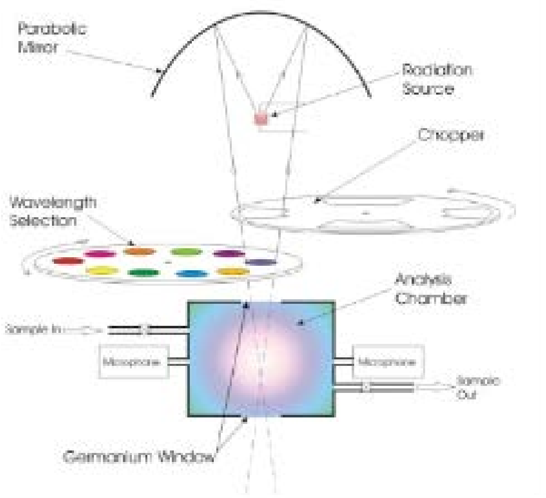
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
	Sound detection monitoring in the transformer oil using fiber optic sensor	Very poor english, hard to understand… fiberoptic sensor array, i.e. the case of two sensors in the Sagnac loop **Achievable with standard equipment**	
Cable Monitoring	Technological Study on Distributed Fiber Sensor Monitoring of High Voltage Power Cable in Seafloor	Find feasible technologies and approaches for seafloor cable fault detection. Examples of such faults include submarine power cable short circuit and cut faults We use distributed brillouin scattering optical fiber sensing technology to detect inner temperature and outside strain damage of submarine power cables **botdr required, special instrument which we do not have**	 Fig.7 Temperature online monitor in cable from distributed optic fiber sensor

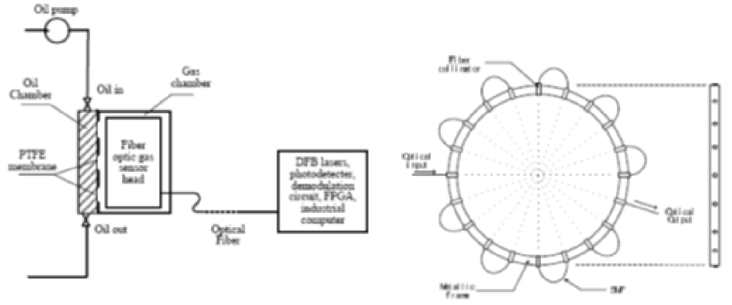
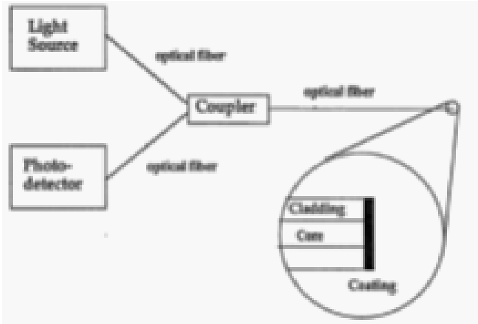
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
Current measurement	Optical fibre current sensor for electrical power engineering	Optical fibre current sensors with an external transformation. The head of the sensor is made of the glass which has a high value of the Verdet constant. **Requires special doped glass and connection studied in Alf's project also**	

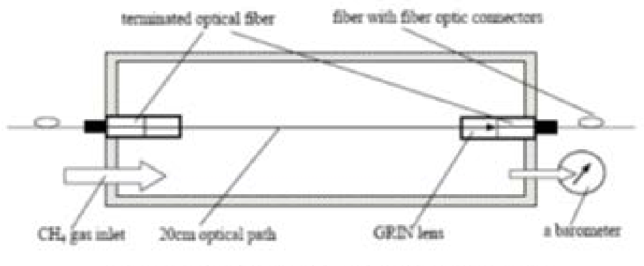
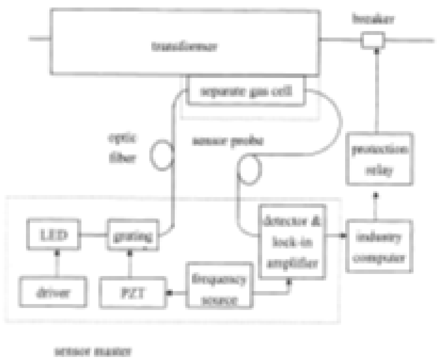
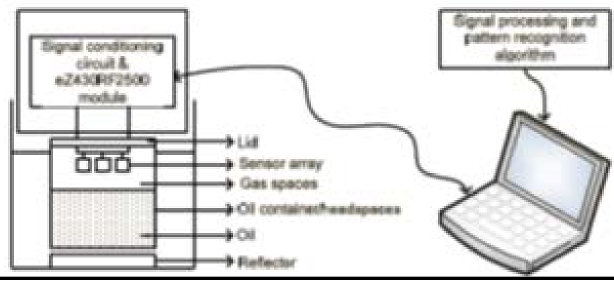
Appendix 1

Para-meter	**Title**	**Description and evaluation**	**Typical figure**
Dissolved Gas monitoring	Some applications of infrared optical sensing	Lubricating oil quality - FTIR Gas in coal mines by fiber probe **Possible but not specifically described here**	
	Dissolved Gas Analysis & Monitoring	On-line dissolved gas analysis systems can now continuously monitor dissolved gas content and relative saturation of moisture employ Infra-red spectroscopy and headspace gas extraction No technique allows for measurement of the gas while it is still a component of the oil. **No fiber solution presented**	

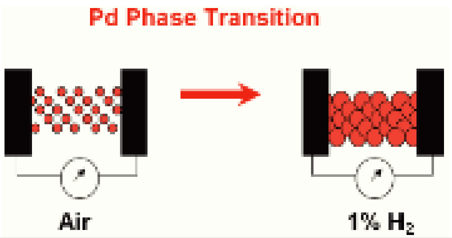
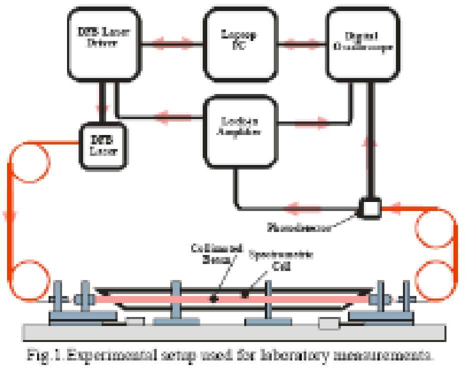
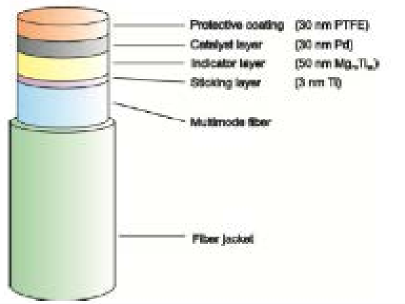
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
	Fiber optic gas detection system for health monitoring of oil-filled transformer	Fiber-optic gas detection system capable of detecting three types of dissolved fault gases in oil-filled power transformers or equipment. The system is based on absorption spectroscopy and the target gases include acetylene (c2h2), methane (ch4) and ethylene (c2h4). Fiber coupled micro-optic cells are employed **Feasible, but requires oil pumping**	 Fig.2 Configuration of the dissolved fault gases detection for oil-filled power transformer. Fig.3 Sensor head structure
	Fiber Optic Hydrogen Sensor	Micromirror chemical sensor configuration **Requires special fiber end coating, slow response**	

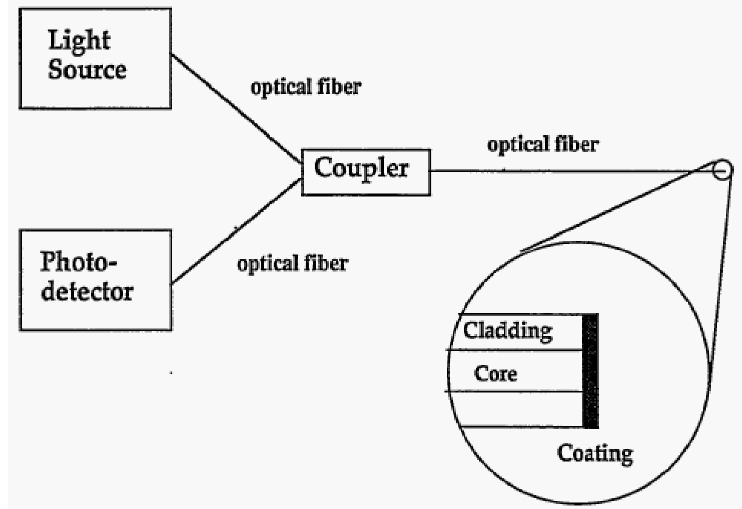
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
	Optic-fiber network sensor system for monitoring methane concentration	Methane concentration measurement system Requires special cell with open air path **Not all-fiber**	Fig.1 The detector heads of long optical path absorbent cell
	A Fiber Optic Multigas Monitoring Technique by Fiber Grating Model Filter in Transformer Oil Due to Fault	Gas absorption is measured by sweeping the laser wavelength and monitoring absorption peaks. Complex home-made sweeping and separate gas-cell **Not all-fiber**	
	Gas and Optical Sensing Technology for the Field Assessment of Transformer Oil	Specially designed measurement apparatus, does not use fiber. Special oil container for field use **Not fiber-based**	

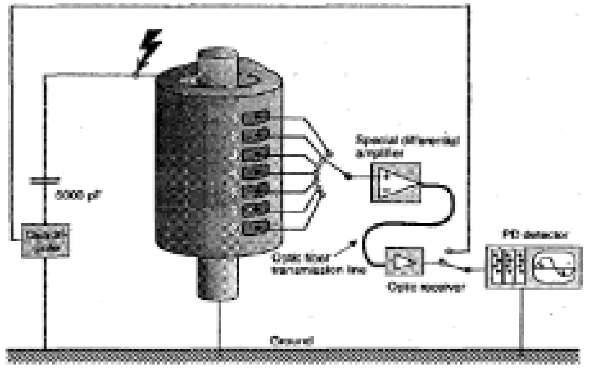
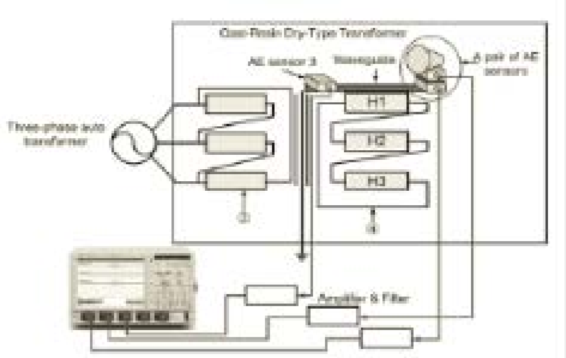
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
	Hydrogen Sensor for Oil Transformer Health Monitoring	Hydrogen sensor based on palladium nanoparticles. **No optical readout**	
	Sensor System for Fault Detection of High Voltage Transformers	Using a separate spectrometric cell to measure C2H2 and CH4. A prototype portable sensor head was demonstrated, but it still requires oil pumping. **Feasible with standard fiberoptic components**	
	Optical hydrogen sensors based on metal-hydrides	Fiberoptic probe for hydrogen, can be used immersed in oil, but requires special material deposition on the fiber end **Fiber-end processing required**	

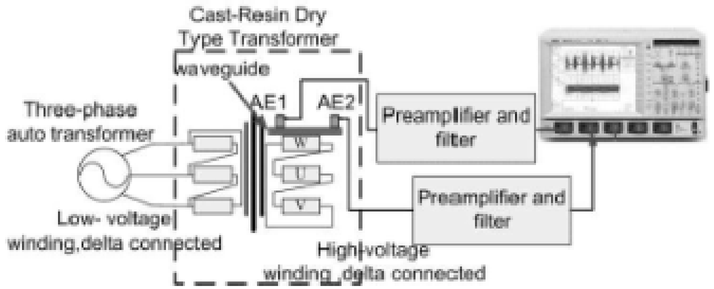
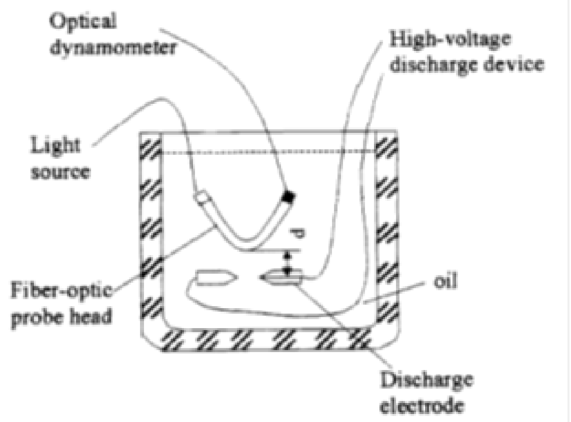
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
	Contributions to the Optimization of an Optical Sensor for Acetylene and Carbon Monoxide	Same as *"Sensor System for Fault Detection of High Voltage Transformers"*	
	Fiber Optic Hydrogen Sensor	Fiberoptic probe for hydrogen, can be used immersed in oil, but requires special material deposition on the fiber end **Fiber-end processing required**	
	The Palladium-Hydrogen System	**No fiber solution presented**	

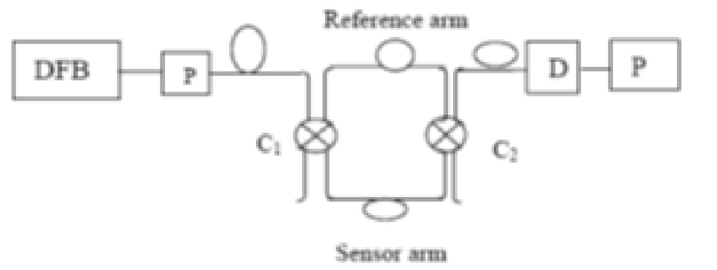
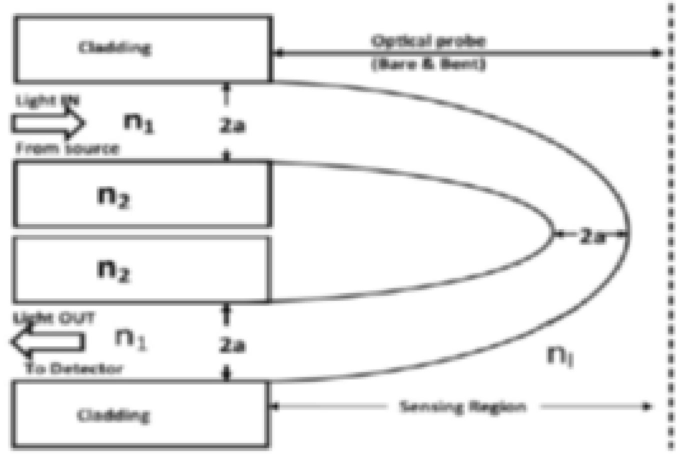
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
Dry Transformers PD	Diagnosing the Insulation Condition of Dry Type Transformers using a Multiple Sensor Partial Discharge Localization Technique	Partial discharge is measured electrically and the results are transferred via fiber **No fiber sensor**	
	An Operating Procedure for the Detection, Identification, and Location of Partial Discharge in Cast-resin Dry-type Transformers	PD is measured by acoustic emission technique, fiber is not used **No fiber sensor**	

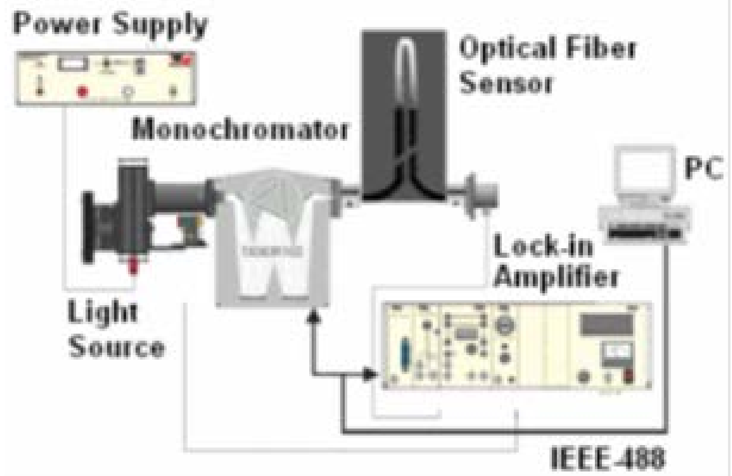
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
	New Designed Wideband Amplifier and Waveguide for Partial Discharge Location in Cast-Resin Dry-Type Transformer	PD is measured by acoustic emission technique, fiber is not used **No fiber sensor**	
Electrification	An optical fiber sensor for electrification measurement in power transformers	Measure the leakage of light from an exposed fiber core in oil. Depends on refrative index which depends on dielectric constant. Weak evidence but simple probe. **Simple but not sensitive enough?**	

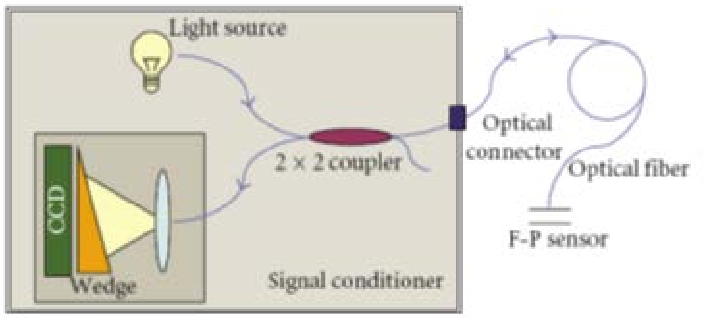
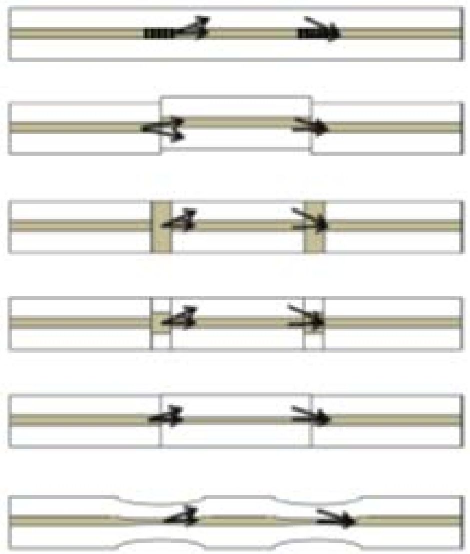
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
Leakage	Leakage detection of oil pipeline using distributed fiber optic sensor	Interferometer setup to measure position of leak in pipeline. Sensitive (to everything). **Only useable for leakage detection.**	
Moisture	Monitoring of moisture in transformer oil using optical fiber as sensor	Water content of the oil is measured by calculating the refractive index. Intensity-based measurement, stripped bent fiber in the oil and processing. **Technically feasible, some special fiber. Sensitivity and durability?**	

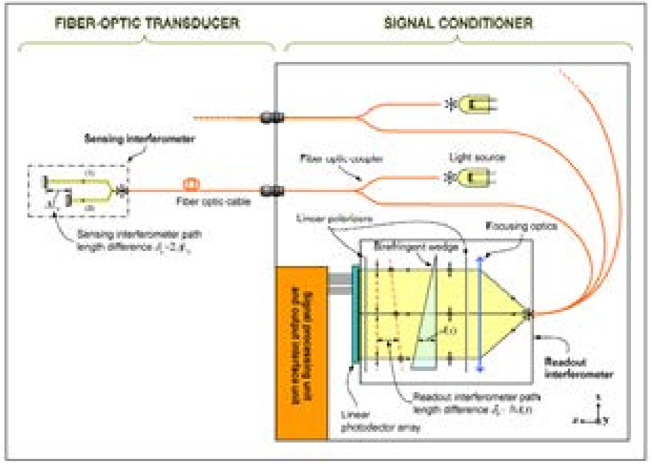
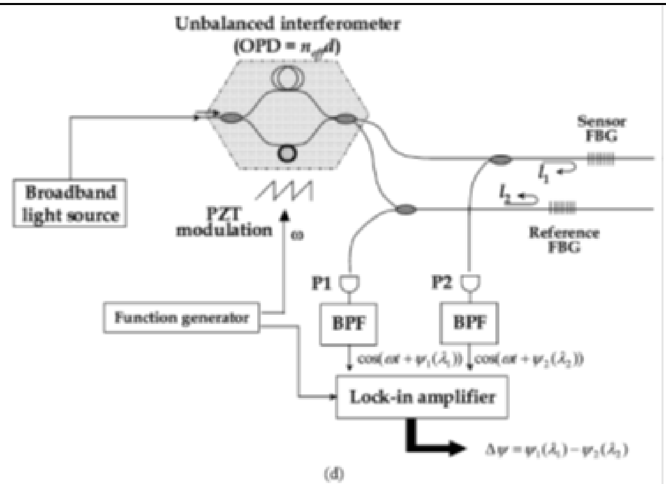
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
	Polymer optical fiber moisture sensor based on evanescent-wave scattering to measure humidity in oil-paper insulation in electrical apparatus	Bent fiber for evanescent field. Coating by PVA for moisture sensitization. Embedded into paper-insulation (proposed). Intensity-based meaasurement. **Technically feasible but special fiber treatment needed. Sensitivity? Point measurement.**	
Optical fiber for condition monitoring	Optical Fiber Sensor Technologies: Opportunities and—Perhaps—Pitfalls	Tutorial paper E. Fiberoptic Systems for Gas Detection: Wavelength modulation spectroscopy, requires special D-fiber or open path. F. Distributed Sensors: Unique feature, but how to use? **No directly feasible sensors**	

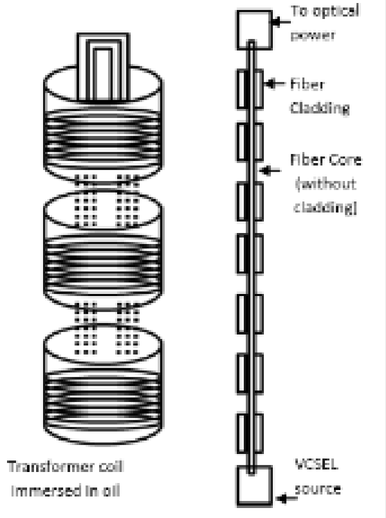
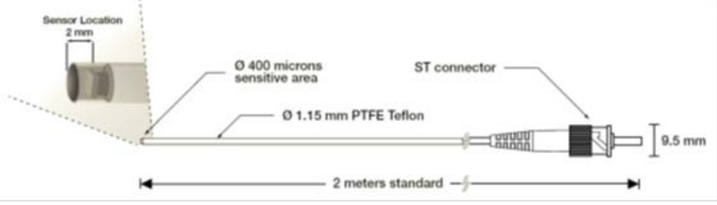
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
	Fabry-Perot Fiber-Optic Sensors for Physical Parameters Measurement in Challenging Conditions	Sensors for temperature, strain, and refractive index based on F-P cavity and white-light interferometry **Interesting but requires fabricated sensor cavities**	
	Interferometric Fiber Optic Sensors	Review of interferometric sensor principles Refractive index FPI sensor MZI with two paths in the same fiber (core/cladding) MI with two paths PCF is less temp-sensitive **Good review of interferometer principles, ref to sensors**	

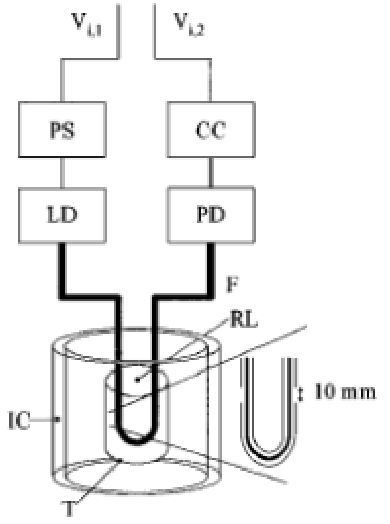
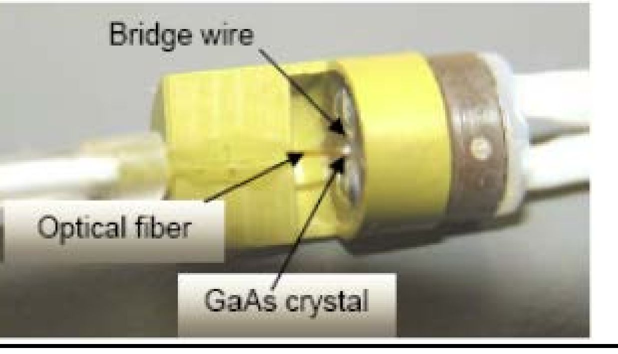
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
	OpSens white-light polarization interferometry technology	Description of white-light interferometer signal conditioner Excellent idea for receiver **Temp, pressure, strain sensor ideas which require fiber end tranducer**	
	Review of the present status of optical fiber sensors	2. Fiber grating sensors - primarily strain 3. Fiber-optic gyroscopes - Feedback system for slowly varying 4. Fiber-optic current sensors - futuregrid project Distributed temperature sensor, acoustic sensors, chemical sensors with LPGs **Most sensors require special transducers.**	

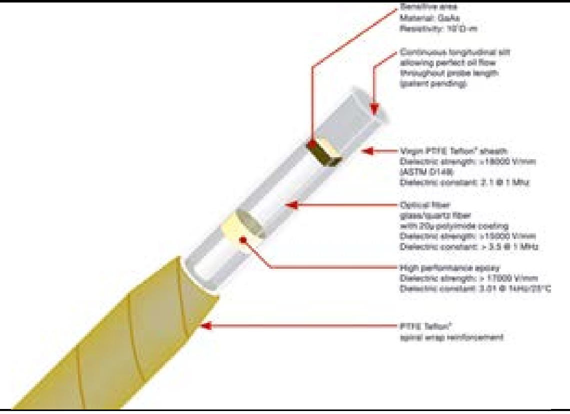
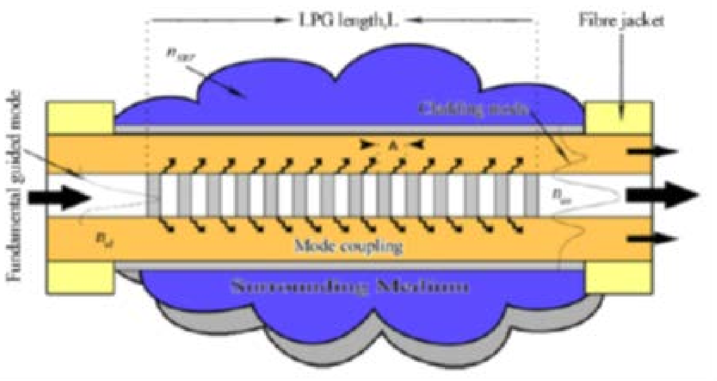
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
Sludge	Sludge Detection in The Oil Of An Electrical Transformer Using OM4 Optical Fiber	Fiber cladding is partially removed to allow the evanescent field to interact with the oil in which the fiber is immersed. Measurement of absolute power transmission **The fiber with removed cladding is weakened and power measurement is susceptible to contamination**	
Temperature	Toward increased reliability in the electric power industry: direct temperature measurement in transformers using fiber optic sensors	Nortech fiber-optic (FO) thermometer is a direct-contact type point sensor whose operating principle is based on temperature dependant variations in the absorption shift of GaAs. Now sold by Neoptix. **Requires a GaAs chip attached at the end of the fiber as the sensitive volume, no distributed sensing**	

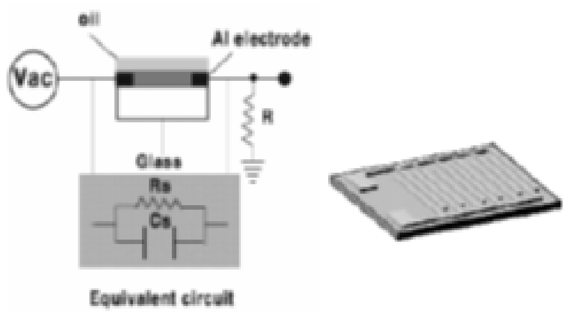
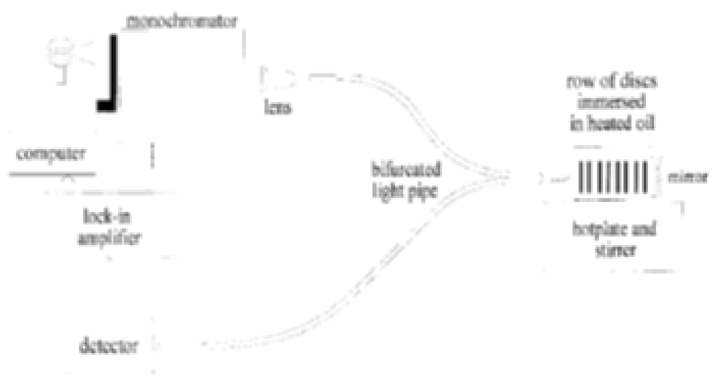
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
	An Enhanced Fiber-Optic Temperature Sensor System for Power Transformer Monitoring	Cladding is removed from a portion of multimode fiber. The unclad fiber is bent and enclosed in a tank, filled with a reference liquid, whose temperature-dependence of the refractive index is known or calibrated. The tank is small, centimeter-size, and permanently sealed. Optical power transmission is a measure of the temperature. **Requires a specially-made sensor filled with liquid, simple measurement scheme.**	
	Mark-1 EED instrumented with OTG-R fiber optic temperature sensor – calibration and injected current response report	Sensor based on a GaAs crystal bonded to the fiber end Sold by Opsens **Requires crystal bonded to fiber end**	

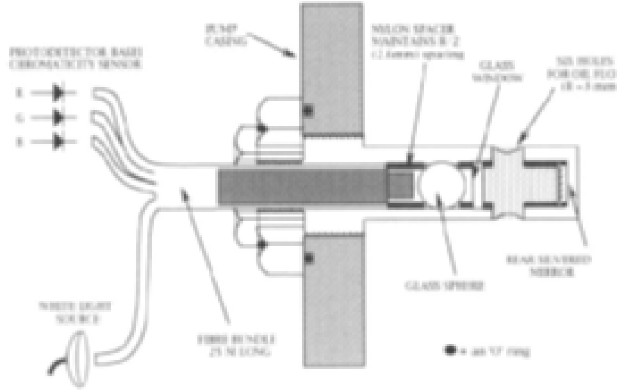
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
	Transformer temperature monitoring and control - US Patent	The end of the fiber is coated with a phosphorus material. The persistence of afterglow is temperature dependent, so by measuring it the temperature can be determined. Qualitrol Corp. **Requires phosphor-coating on the fiber end.**	
Transformer oil	Detection and analysis of paraffin oil adulteration in coconut oil using fiber optic long period grating sensor	Based on the sensitive dependence of the resonance peaks of a long period grating (LPG) on the changes of the refractive index of the environmental medium surrounding the cladding surface of the grating. The wavelength shift of the attenuation bands of the LPG was measured with the sensor immersed in paraffin oil. **Spectral measurement, fiber with grating and cladding but without coating, feasible.**	

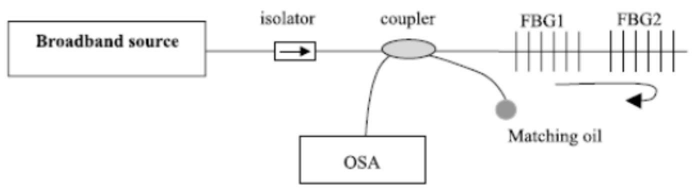
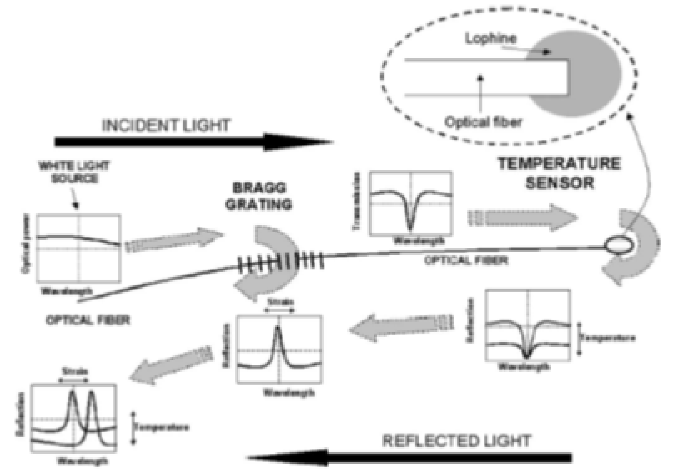
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
	Design and fabrication of the degradation level monitoring sensor for power transformer insulating oil	Capacitive sensor. **No fiber solution.**	
	A Novel Optical Sensor for the Measurement of Furfuraldehyde in Transformer Oil	The optical sensor is based on the use of a novel solid state material which is formed using the sol-gel process. Color-change of centimeter-size disks. **Not suitable for miniaturization and modern fibers.**	

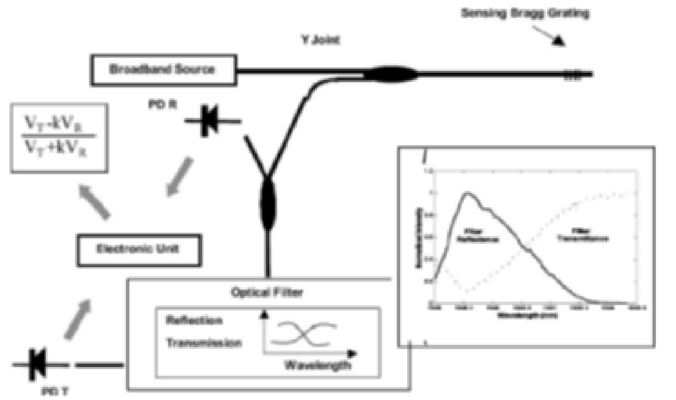
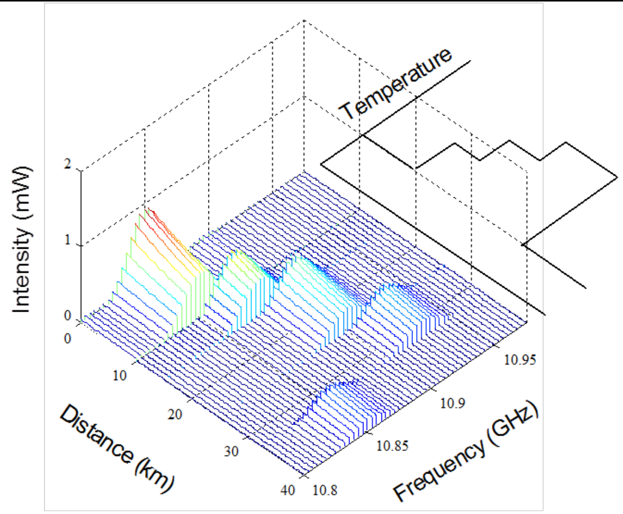
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
	A fibre-optic oil condition monitor based on chromatic modulation	Tri-stimulus color measurement. **Simple measurement of color, but it is not enough to determine oil quality.**	

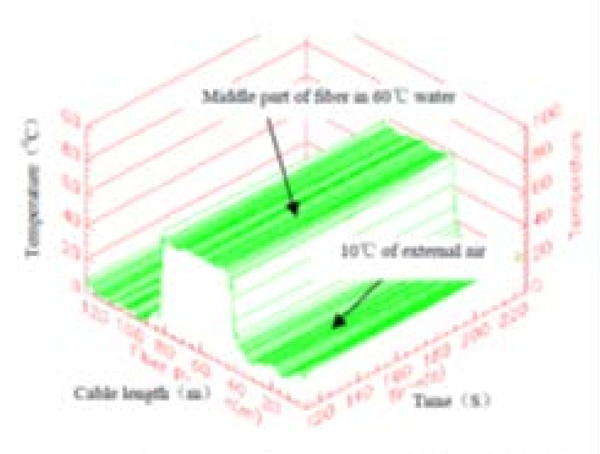
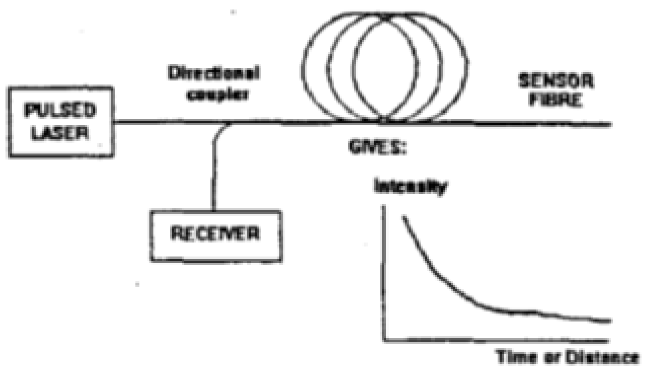
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
Temperature and strain	Strain and temperature sensor using a combination of polymer and silica fibre Bragg gratings	Fiber bragg grating is used as the sensitive element, for both temperature and strain. Reflected wavelength changes due to T and/or s. Discrimination between the two by using polymer and silica fibers. **Sensitive only where the grating is positioned.**	
	Simultaneous measurement of strain and temperature using a fiber Bragg grating and a thermochromic material	Fiber bragg grating is used as strain sensor, a thermochromic material is used as temperature sensor, to compensate for the FBG temp sensitivity. The TC material is placed as a drop on the fiber end. **Localized sensors only.**	

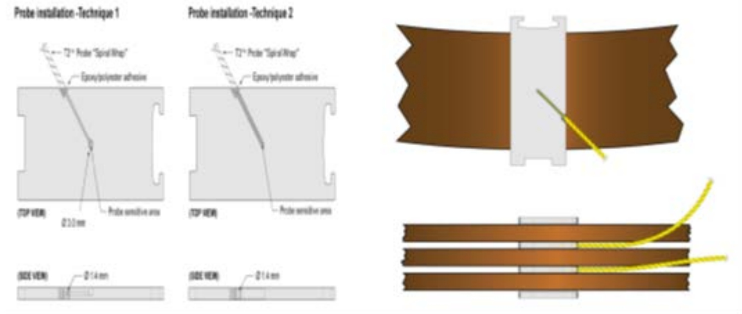
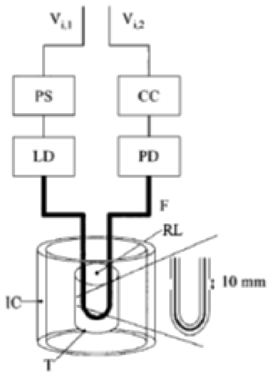
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
	Dynamic strain measurements by fibre Bragg grating sensor	Fiber bragg grating is used as strain sensor. No temperature compensation. **Localized sensor only.**	
	Fiber Optic Brillouin Optical Time Domain Analysis Sensor	Distributed sensing of temperature; 40 km, 10 m resolution, 1 deg resolution **Requires BOTDA instrument, available from OZ Optics.** **www.ozoptics.com/products/fiber_optic_distributed.html**	

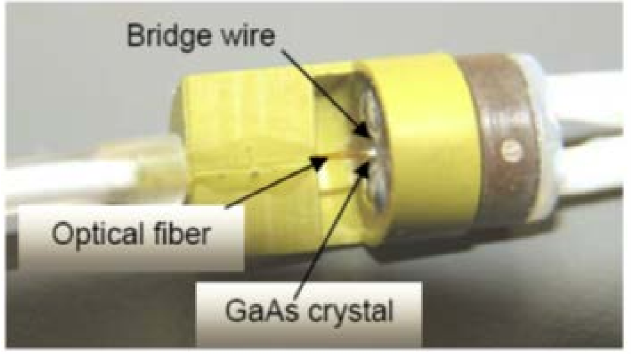
Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
	Technological Study on Distributed Fiber Sensor Monitoring of High Voltage Power Cable in Seafloor	Three fibers integrated into 35 kV subsea cable, distributed temperature and strain sensing through BOTDR. **Requires BOTDR instrument.**	 Fig.7 Temperature online monitor in cable from distributed optic fiber sensor
Temperature	Technical aspects of optical fibre distributed temperature sensing	Fiber for temperature measurement, based on BOTDR. **Available from SENSA company www.sensa.org/products-and-technology/linear-heat-detection.html**	

Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
	Toward increased reliability in the electric power industry: direct temperature measurement in transformers using fiber optic sensors	The Nortech sensor's measurement principle is based on variations in the spectral absorption of a fiber-mounted semiconductor chip. Total length of probe + extension can be up to several hundred meters. **Localized sensor, Nortech Fibronic (1998), Neoptix**	
	An Enhanced Fiber-Optic Temperature Sensor System for Power Transformer Monitoring	Temperature measurement in fluids, bent fiber. **Localized sensor**	

Appendix 1

Para-meter	Title	Description and evaluation	Typical figure
	Mark-1 EED instrumented with OTG-R fiber optic temperature sensor – calibration and injected current response report	Temperature measurement with GaAs crystal at fiber end. **Localized sensor**	
	Transformer temperature monitoring and control US Patent 7 377 689	Qualitrol Corp. Now used in Neoptix instruments. **Localized sensor**