Applications of Bragg grating sensors in Europe

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I. Introduction

Fiber Bragg gratings (FBG) are now recognized as very important optoelectronic components for guided-wave optics owing to the large number of device functions they can facilitate [1]. They are of widespread use either in telecommunications, in instrumentation and sensors for the measurement of strain, temperature and hydrostatic pressure [2] as well as many other measurands (*i.e.* magnetic fields [3, 4]) *via* appropriate transducing mechanisms [5] and have unique advantages over classical electrical strain gauges (*e.g.* in smart structures). These advantages are at first conveyed by OFS intrinsic features such as electromagnetic interference (EMI) immunity, light weight and small size, high temperature and radiation tolerance, flexibility, stability and durability against harsh environments. FBGs have the advantages of being absolute, linear in response, interrupt-immune and of very low insertion loss so that they can be multiplexed in series along a single monomode fiber. Also, any specific network (star, series, fish-bone, ...) can be implemented and modified a long time after the setting-up, thus increasing the return on investments. As the spectral signature renders the measurement free from intensity fluctuations, it guarantees reproducible measurements despite optical losses (bending, ageing of connectors) or even under high radiation environments (darkening of fibers) [6]. Moreover, FBGs may be easily embedded into materials (*e.g.* composite materials) to provide local damage detection as well as internal strain field mapping with high localization, resolution in strain and large measurement range. The FBG is therefore a major component for the development of smart structure technology. It offers the promise of undertaking 'real-time' structural measurements with built-in sensor systems expected to be cost-effective when the number of sensors to be multiplexed is large.

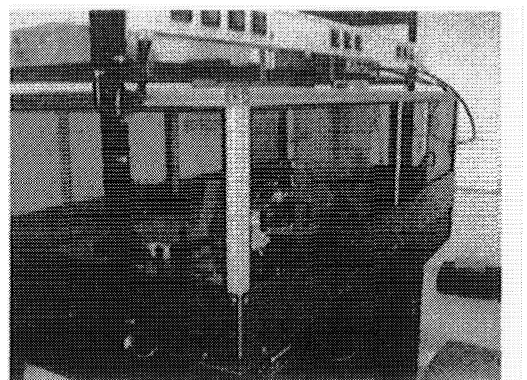

Fig. 1 : Bragg grating facility at CEA-LETI

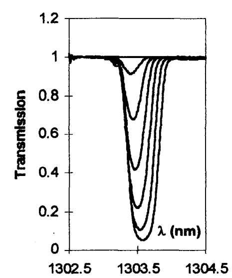

Fig. 2 : kinetics of FBG photo-writing (CEA-LETI).

Efforts are now engaged in laboratories to realise integrated and cost effective demultiplexing devices. For instance, ALENIA Research Department (Roma - Italy) has developed a pigtailed tunable high resolution filter (FMWH < 0.45 nm @1.3 µm) [7]. Moreover, FBG with piezo-electric cylindrical or thermo-electrical coating have been successfully developed and used as spectral demodulators [8].

FBGs are wavelength-selective reflectors at the Bragg wavelength : $\lambda_g = 2\ n.\Lambda$, where Λ is the grating period and n is the effective index of the propagating mode (LP_{01}) [1]. A linear response is obtained with limited change in temperature (T), pressure (P) and strain ($\varepsilon = \Delta L/L$) : $\Delta\lambda_g = (10\ pm/K).\Delta T + (-\ 5\ pm/MPa).\ \Delta P + (1\ pm/\mu strain).\varepsilon$ at $\lambda = 1.3\ \mu m$.

For all these reasons, BG is actually the most exciting and ever progressing sensing topic of this decade. This stimulated emulation could be compared to that of the « Gyro » in the eighties. Many European countries are now involved in FBG sensors and systems development. Laboratories are in Universities (as Lille in France very active in FBG photowriting and physical understanding of phenomena ; Kent, Hull, Southampton in UK, EPFL in Switzerland, ...) or in government centers (so is CEA-LETI working to achieve industrial transfers), and others are private manufacturers (as Identity in Belgium). Besides national approaches, European projects are launched in the purpose of strengthening the European industry.

In UK for instance, the University of Hull is very active in grating and in LIPSS (Laser Induced Periodic Surface Structures) formation and characterisation, in glasses and polymers [9]. The University of Kent is largely involved in grating R&D [10], in collaboration with Aston University [11]. The former collaborates with the INESC in Porto (Portugal) [12], which works on a potentially low-cost detection system based on a 'minimum configuration' principle [13].

Today, many Companies in the world are selling FBGs and phase masks as well as FBG-based components for the telecommunication market. Phase masking is compatible with photolithographic techniques and offers good repeatability and low cost. FBGs are currently photowritten in many laboratories by UV holography as well (Fig. 1 and 2) due to the high versatility of the technique. Gratings have also been successfully written directly on draw tower [14]. All these breakthroughs enable a very cost-effective mass production and has interesting consequences on reproducibility of their metrological characteristics and contributes to a downward trend of price, cheap enough to compete with traditional strain gauges enabling us to realise large demonstrations in a near future.

II. Main domains of applications

Four great functions in which OFS are a paramount for structure monitoring can be identified (see table 1).

	Monitor key Manufacturing Process	Non Destructive Control, Evaluation	Health Monitoring or Health Diagnostic	Active Control
Final technical & economical Objectives	- Qualify a new process, - Optimise process to improve yield & quality of products, or works - Reduce costs and risks	- Qualify old structures, new lighter or more technical ones, - Damage assessment	- Assess structural integrity to improve safety, life cycle & performances, - Reduce down time, diagnostic/ maintenance, and life-cycle cost, - Provide maintenance schedule	- Adapt the structure in real time *versus* external conditions - Control damping, - Shape control
Main Domains	- Civil engineering, - Composite fabrication	- Composite qualification - Extensometry	- Soils, mining, civil engineering - Aeronautics, space	- Aeronautics, space

Table 1 : Identified sectors of application of FBGs for structure monitoring.

II.1. Soil and mining applications

At the end of 1992, a consortium was formed with partners from Portugal (Pirites Alentejanas), Belgium (Identity E.E.I.G.), France (CEA-LETI and Framatome), Switzerland (CSEM) and Germany (GSF) to launch the European Brite STABILOS project (Accurate *STABIL*ity Control in Mining with Fiber *O*ptic *S*ensing Technology - ref. BE 5553). The aim was to provide mine works with an accurate stability control system based on OFS, together with an improvement in safety for working conditions [5]. It led to the development of a new geotechnical FBG-based instrumentation applied to measurements in mines, tunnels or storage caverns. An optoelectronic system based on a broadband erbium-doped fiber source associated with a Fabry-Perot Interferometer has been designed and tested [15]. The final system is made up with a 3 dB single mode coupler with two gratings devoted to spectral calibration on one end, and on the other end an optical switch connected to lead fibers and sensor gratings. Such configuration allows reflection measurements in both directions for redundancy. A user-friendly Control Software running under Lab-view application has been developed by CEA-LETI ; peak locations are measured after inter-correlation. Any extensometer is composed of a central metallic rod on which the FBG is attached. The extensometers were designed to define a 10 cm long measurement base. This innovative sensor developed by Identity, with the help of CEA-LETI, includes a mechanical lever arm in order to adapt the displacements (~ cm per month) to the FBG strain range (< 1 %). The overall configuration is an easy-to-install and compact housing. The sensing network installed in April 97 in a German mine is composed of several extensometers for wall monitoring as depicted in fig. 3.

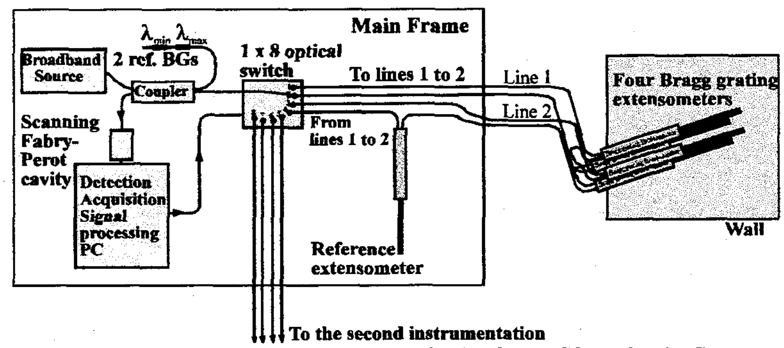

Fig. 3 : Bragg sensing wall monitoring in the GSF-ASSE Mine in Germany

II.2. Applications for fiber Bragg sensors within the nuclear and traditional electricity power industries

From mining to waste disposal, OFSs provide new functionalities to improve safety and monitoring in the nuclear industry both for revamping Nuclear Power Plants (NPP) and for new generations of NPP. In countries where a large part of the energy production is based on nuclear power industry (France, USA, Japan), the instrumentation has ever been one of the essential aspects of the R&D in this sector due to the crucial need to improve both safety of operations and the monitoring of equipments. Studies have been done in a recent past (EPRI in the USA [16 to 18], CEA-EDF-Framatome in France) to evaluate the impacts of OFS use in NPPs. The French prospective Task Force CORA 2000 showed that OFSs could improve availability and safety of many strategic equipments (generator, transformer,...) and structures (containment shells, cooling towers, steam pipes), (fig. 4), [6]-[19]. OFSN and Bragg transducers can meet this challenge [20].

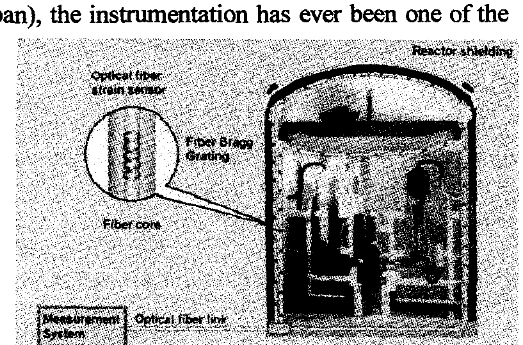

Fig. 4 : Containment building monitoring concept based on FBG extensometers

II.2.1 Nuclear shield monitoring. The nuclear containment building is the ultimate barrier. It is designed to withstand an hypothetical H_2 risk in case of a nuclear accident. The ultimate pressure level is about 12 bar for 900 MW NPP (single shield) and 9 bar for 1300 MW NPP (double shield). An integrity test is periodically performed. Nevertheless, a quasi-distributed OFS remote structure monitoring approach would considerably enhance reliability, safety and save maintenance costs. An important project launched in 1995 conjointly with CEA-LETI, EDF and Framatome in France concerns the development of an extensometric instrumentation for concrete monitoring, for both *in situ* and external measurements (fig. 5). Extensometers are surface-mounted onto or embedded into the large walls of the nuclear shield, made of high performance pre-strained concrete. The FBG extensometer is able to operate under traction and compression in the range of 2500 μstrain. When connected to the CEA-LETI instrumentation, the extensometers exhibit a detection threshold of 2 μstrain.

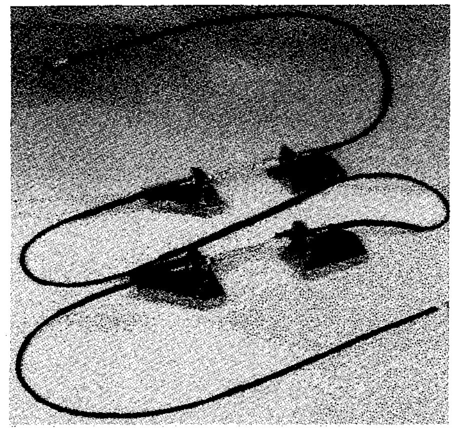

Fig. 5 : FBG extensometers for concrete monitoring

An experimental surface measurement campaign has been done in 1996. The reproducibility of the measurement is evaluated to be 0.05 % FS (30 s averaging). A campaign, in 97, has consisted in measurements inside concrete elements. Satisfactory results are obtained for both strain measurements and preventive cracks detection. Further objectives might be monitoring of real structures in the NPP as well as civil engineering or public works.

II.2.2 Steam pipe monitoring. In a Pressure Water Reactor (PWR) NPP, breaks may occur between elements of a complex circuitry (vessel, pump, pressurizer, steam generator) with large number of solder joints ageing under thermo-mechanical cycling. Although safety factors of pipes are large and safety rules take into account a complete breakage of a pipe (*i.e.* the Loss Of Coolant Accident - LOCA), an early detection of leakage is an important issue for safety. Early location of small cracks could avoid any fissuration or even breaks necessitating an emergency situation. Classical approaches exist to detect such leaks, but they are global (water balance, dose level), and local detection would be highly desirable for redundancy. A Raman OTDR could be used for quasi-distributed temperature sensing. Unfortunately, such system is costly and spatial resolution is limited to about 1 m. FBGs located at specific parts of pipes (soldering, elbow, ...) is an alternative solution.

Since integrity of ageing components in power plants is a major problem, a consortium of 9 partners led by BICC Cables Ltd. (UK) has launched, in January 1996, a 3 years Brite Project, the 'Fiber Optic Strain Monitoring at Elevated Temperature' (FOSMET) project (ref. BE 1432). Its primary objective is to develop a quasi-distributed monitoring system with fully integrated temperature compensation able to multiplexed several strained FBG gauges and to provide 'real time' (1 s scanning per sensor) life prediction for high temperature components (~ 550 °C) [21]. Expected thermal and spatial resolutions are 2 °C and 10 cm respectively. Of course, development of armoured, specific cabling, interconnections and methods for sensor attachment is an important goal. The demonstration will take place in an operating fossil fuel plant at the end of 1999. The aim of this project is very close to that of a former Brite one : the 'Distributed Strain Monitoring on High temperature Pipework' (FORMS) project (ref. BRE20965) launched by ERA Technology Ltd. (UK) and a 10 partners consortium, in February 1995 and scheduled to end in August 1998.

II.2.3 Waste conditioning and disposal monitoring. There are three kinds of radioactive wastes corresponding to the level of activity : low, intermediate and high. High activity waste must be kept over a long time by underground storage. ANDRA, the 'French National Radioactive Waste Management Agency' is currently studying underground repository concepts and monitoring equipments jointly with CEA. A future concept could consist in a network of disposal interconnected galleries. Such site should be decommissionnable (reversibility). This implies to define concepts and instrumentation that help anticipating such decision. In the same way, many European repository concepts have arisen. For example, the Belgian concept initiated by SCK-CEN Mol Research Center [22]. Current research activities are led in the underground laboratory HADES. In Germany, experiments will certainly be under investigations in a near future in salt mines. In underground repositories, FBG-based sensors can ensure strain and temperature measurements, and they are very well suited for the measurement of high hydrostatic pressure (ranging from several bar to several hundreds bar).

II. 3 Civil engineering monitoring

II.3.1 Application to tunnels. A second application, within the STABILOS project frame, concerns the monitoring of the Mont-Terri tunnel (Switzerland) conducted by CSEM. This tunnel, devoted to the Transjurane N16 highway, addresses problems often encountered within tunnels. The stratified rock is composed of anhydrite materials (marles), which after excavation start to absorb water, and therefore high non-symmetric stresses induce changes of the tunnel section (fig. 6). In turn, maintenance should take place for preventive purposes. In tunnels where similar phenomena occur, this causes the tunnel to timely close. Therefore, just-in-time repair based on continuous monitoring would have considerable economical impacts. Special openings have been left in the concrete in order to integrate the sensors at the end of the building of the tunnel. The

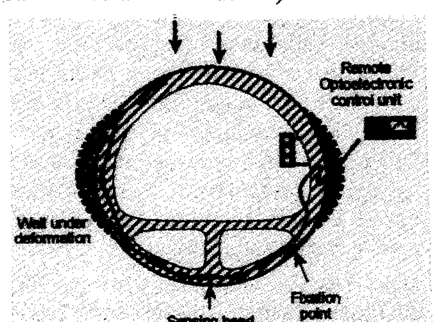

Fig. 6 : Mont-Terri tunnel FBG-based instrumentation

sensing fiber is prestrained, to half measurement range (to operate both in compression and traction). In this STABILOS application, the spectral analyser is a rotating interference filter instead of the Fabry-Perot interferometer. The sensing network is composed of bare FBGs strained between 2 anchoring points and connected in series (Fig. 6).

II.3.2 Application to civil engineering maintenance. A FBG-based system, designed at EMPA (Dubendorf-Switzerland), is made up of FBGs in series along a fiber illuminated with a SuperLuminescent diode @ 830 nm. Light reflected back from FBGs is sent to a 0.5 m focal-length grating spectrometer equipped with a 1024-elements CCD-array. An argon lamp is also used for continuous spectral calibration purpose. Resolution after signal processing is 1 µstrain at 10 Hz. This system has been tested on two civil engineering structures, the Storck's cable-stayed bridge in Winterthur and the dam of Luzzone in the Swiss Alps. Traditional sensors and FBGs were either inserted at the periphery of two CFRP cables on the Storck's bridge or bonded on a 2 m long steel rod for embedding in concrete [23].

II.3.3 Other application to civil engineering and electrical Power generating Industry. In Spain, the Photonics Engineering Group (PEG) of the Univ. of Cantabria is coordinator of a project named 'Development of OFS for Intelligent Structures' (ref. TIC95-0631-C04-01) funded by the *Spanish Comisión Interministerial de Ciencia Y Tecnología*. Four Teams are working on this project to develop FBG sensors for civil engineering and electrical power generating structures. Up to now, they are focused in concrete strain monitoring, and in the development of new techniques for magnetic field monitoring [4]. In the frame of this project and in collaboration with the University of Navarra, the PEG started recently the development of a reflective quasi-distributed fibre sensor network with distributed optical fibre amplifiers using WDM techniques [24].

II.3.4 Application to underground civil works. A European Brite project named COSMUS (Real-time Modeling & *CO*mpensation of *S*oil *M*ovements on *U*nderground *S*ites ; ref. BRPR960235) has been launched for 3 years in Dec. 1996 to improve safety in civil works. The consortium includes Soletanche and CEA-LETI (France), Tractebel (Belgium), Glötzl (Germany), Cambridge Univ. (UK) and EPFL (Switzerland). The construction of underground transports is a potential source of damage to existing buildings and structures. In order to face the growing need for underground transports in overcrowded city, and to reduce the social risk, an intelligent public work method, the « Compensation grouting », is studied to assess and control the induced movements and to keep their variations within ± 1 mm range (fig. 7). So, 2 D and 3 D prediction models will be developed, and an 'intelligent' grouting will be used on sites. Sensors currently used in civil engineering do not allow to reach the objective. So, a high accuracy instrumentation and control system is currently under development to control the grouting plant every 30 s and new civil engineering FBG-based sensors are designed. These are quasi-distributed strain sensors (accuracy ~ 10 µstrain) and high resolution tiltmeters (10 arc.sec), both temperature-compensated. Therefore, an important part of COSMUS project concerns the development of an handable, low-cost and ruggedized acquisition unit.

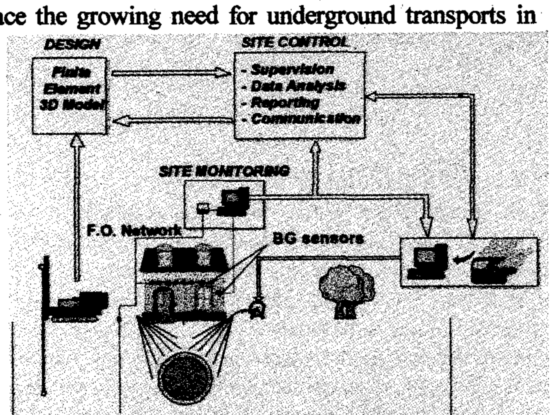

Fig. 7 : COSMUS expected achievements

II.4 Composite materials

II.4.1. Aerospace applications. Advanced fibre reinforced composites are being extensively used by the Aerospace Industries because they offer superior specific properties such as high stiffness to weight and high strength to weight ratios. Moreover, by contrast to metallic pieces, there is no corrosion, higher fatigue resistance and complex shapes can be obtained at reasonable cost (*e.g.* by Resin Transfer Molding). The increase in composite content have advantageous effects on the structural weight of aircrafts and space structures and consequently on the direct operating costs. In this perspective, the aeronautic industry currently faces different challenges concerning the composite manufacturing and the operating structure maintenance. However, a major concern with composite materials is the significant difficulties associated with detecting damages. In other words, an ideal sensor system should be capable of providing information in real-time which can then be used to fulfill a number of functions, as follows :

- **Intelligent manufacturing process monitoring** such as in-process temperature-profiling and strain release monitoring of composites in autoclave, in order to improve real-time manufacturing control & quality of products.
- **Design of Smart structures & skins** for the purpose of 'operating structure monitoring' for distributed strain/temperature measurements. This monitoring applied to wing, empennage, ... would enable to guarantee an 'Integrity control & structural maintenance' (health monitoring of ageing aircraft and modern composite structures as well as prediction of residual life of repaired systems), the 'Impacts & cracks detection', and an 'Active structural control' to provide information to actuators (vibration damping of flexible structures, shape control of structures under thermal/mechanical loads). These last applications are of significance for Aeronautics and Space, as well as for the Naval sector.

II.4.1.1 Curing process monitoring and Impact detection in a composite material. In France, a project with DRET/AIA-Cuers-Pierrefeu/ONERA-L3C and CEA-LETI is currently running in order to define a method able to assess the integrity of a fighter aircraft radome. The project deals with the possibility to detect consequences of invisible impacts within the composite structure (delaminations, cracks). High resolution OTDR and quasi-distributed FBG sensor techniques are under evaluation. Sophisticated embedding processes have been developed and FBGs are used for curing process monitoring (strain and temperature). Moreover, several composites samples have been tested with an impact testing machine. Results are encouraging, as relatively low energy impacts can be detected in the surroundings of the FBGs.

AEROSPATIALE - Aquitaine, the French Aerospace Company, largely involved in the design and/or manufacturing of advanced composites structures for new engines and high pressure tanks, started recently developments with the CEA-LETI in order to equip a high pressure tank (diameter 304 mm) with embedded BG strain gauges. One of the first aim of this project is to check the compatibility of fibers and sensors embedding with the state-of-the-art manufacturing technology such as wrapping and electron beam curing [25].

II.4.1.2 Application to on-line Health & Usage Monitoring (HUM). A European Brite Euram 3 years project named MONITOR (ref. BRPR960181) concerning 11 partners and managed by British Aerospace (UK) has started in May 1996. The objective of the 'Monitoring On-line Technologies for Operational Reliability' project is to develop an on-line HUM System based on advance load monitoring and damage detection technologies. The aim is to achieve a reduction in inspection of 20% within the 5 years of project completion, *i.e.* about 2 M$ per aircraft if related to 20 years life. To achieve these goals, several sensing technologies are currently under investigations, one of them is Bragg grating technology [26]. In Sweden, the Institute of Optical Research (IOF) in involved in a national project named 'SMART' together with the FFA to develop a Time Multiplexed strain/temperature measurement system, for composite monitoring in military aircraft [27].

II.4.1.3 Application to adaptative structures. In Germany, since the beginning of 1996, the Daimler-Benz Research Center, with the Daimler-Benz Aerospace Airbus and the DLR (Institute for Aerospace studies) is investigating the development of an adaptative wing equipped with BGs. The technical aim of this 7 years project is to find a structural-dynamic solution to optimise aerodynamism of aircraft, while the economical objective is to induce lower fuel consumption, higher payload and lower operating costs. These goals may be realised by local contour modifications at the wing surface and with variable trailing edges. The structure geometry changes are expected to be monitored by quasi-distributed embedded strain/temperature FBG sensors scanned by a tunable laser in the vicinity of 1.55 μm [28].

In Spain, ETSI Aeronauticos (Madrid, Spain) coordinates a European JOULE III project called SMART BLADES aiming at developing an optical fibre-BG based monitoring multisensors system (with a tunable filter as scanning device) devoted, for instance, to wind energy conversion systems with structural health monitoring capability [29].

II.4.2. Marine applications

II.4.2.1 Application to Lock Gates. A new concept of Glass Reinforced Plastic (GRP) lock gate has been developed by the *Direction des Constructions Navales* (DCN-Lorient-France) for use on navigable French waterways. Each set consists of two 'mitre-type leaves' rotating around a vertical axis. Conventional steel gates currently in use require a major maintenance effort. The leaves are made from thick, single skin GRP panels, strengthened by horizontal stiffeners. Advantages of this new approach are : reduced through-life costs (good ageing of GRP, ease of maintenance : gates quick to install/remove (lightness), standardisation of components ; good integration into landscape). An optical line made of five FBGs (1 for temperature compensation and 4 for strain measurement) have been embedded by the CEA-LETI into a gate (fig. 8). Measurement of initial strains, and during operation have been recorded, in real time, with the system of CEA-LETI. Results are in good agreement with water level and with expected strain at specific sensor locations. Measurement data will be used by designers to scale finite element models and to optimise conception.

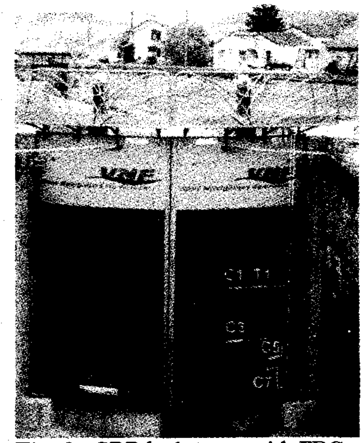

Fig. 8 : GRP lock gates with FBGs

II.5 Other domains In the scope of making strain measurements using gratings, FBG rosettes can also be designed (fig. 9) [30]. They are made of 2 or 3 non-collinear strain gauges, mounted on a common substrate at 45° or 60° to form 'rectangular' or 'delta' rosettes respectively. They are extensively used in experimental stress analysis to measure the two principal strains (and stresses) and the orientation of the principal axis whenever it is not known *a priori*. Beside this classical application, we described also an innovative way to use this rosette as an uniaxial strain gauge rigorously independent of temperature effects as well as the orientation of the sensor onto the structure. The uniaxial strain, the angular orientation and the temperature are accurately measured.

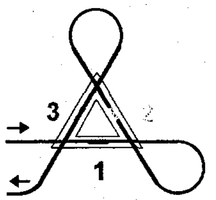

Fig. 9 : Delta strain Rosette with 3 BGs

BGs may also be used in microsystems such as accelerometers [31] designed by MIC (MikroElectronik Center) in Lyngby (Denmark) in collaboration with Brüel & Kjær. Planar waveguides are formed by

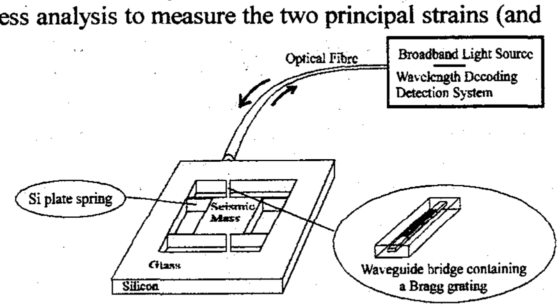

Fig. 10 : Accelerometer based on a BG in a planar waveguide bridge, from [31]

Plasma Enhanced Chemical Vapor Deposition (PECVD). The seismic mass (4.2 mg) is suspended by waveguide bridges containing a BG @ 1.55 μm (L= 3 mm) -thus acting as strain gauge- and is revealed by chemical anisotropic etching of the silicon wafer (fig. 10). Dynamic strain resolution is $6.\ 10^{-10}\ Hz^{1/2}$.

Conclusion Bragg grating sensors are mainly used in Europe for « Structure monitoring » applications. Most applications are civil engineering (mining, tunnels, public works, bridges, dams), nuclear industry (containment barriers, steam pipes, storage sites), aeronautics (curing process monitoring, impact detection, health monitoring, shape control & vibration damping) and marine applications (lock gates, ...). Moreover, in a near future, other fields of application will be covered (high temperature measurements, extensometry, magnetometry, civil and nuclear robotics, medical sensors, chemical/biochemical sensing ...). FBGs, mainly used as transducers in the sensors, are also increasingly integrated in instrumentation as in the demultiplexing unit itself (tracking FBGs, linear discriminator). Although the price of FBGs is continuously decreasing, the total cost of the system is still dominated by the cost of the acquisition unit so that the higher the number of transducers, the lower the cost per measurement point due to multiplexing capabilities. Letting alone special applications where BGs are surpassing transducers (*e.g.* measurement of temperature or strain in electromagnetic environment), FBGs are competitive only on large scale demonstrations. A key development is therefore the integration of the acquisition unit so as to decrease its cost and increase the market share. So, in Europe, the level of innovation is good and the first R&D demonstrators are leaving the laboratories to perform field trials in collaboration with industrial partners. Reliability of FBG transducers and systems is a great matter of concern as well and European collaborations act through COST Projects (BGs reliability addressed through COST 246 and managed by H. Limberger (EPF - Lausanne, Switzerland)). Current issue is the influence of BG manufacturing process on high temperature erasure and mechanical reliability (static & dynamic fatigue stress).

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