THE AMERICAN OIL & GAS REPORTER®

JANUARY 2014

The "Better Business" Publication Serving the Exploration / Drilling / Production Industry

Multiparameter Fiber Sensors

Enabling New Capabilities In Production Optimization

By Lun-Kai Cheng, Micha Boering and Richard Braal

HOUSTON–Fiber optic data transmission already has led to revolutionary developments, and ongoing research in fiber optic sensing technology for applications in extreme operational conditions will boost the development of fiber optic multiple-parameter sensing systems further. Such innovations will be of particular benefit to the oil and gas industry in situations where conventional electronic sensors are not technically feasible or cost efficient.

It was an eye opener for the oil and gas industry when fiber optic-based distributed temperature sensing was introduced two decades ago. Suddenly, temperature profiles over the entire length of the wellbore could be monitored to deliver data for troubleshooting and production optimization. Judging the speed of developments today, a second fiber optic sensing revolution can be expected in the oil and gas industry in the near future.

In the multiparameter sensing systems of the future, different types of fiber optic sensors (flow, pressure, acoustic, chemical, vibration, gravity, etc.) can be manufactured and read through a single optical fiber. Data from the different types of sensors will be merged and processed through special data mining algorithms to generate unambiguous information for faster and better decision making.

Well and production strategies are becoming increasingly complex, requiring accurate and reliable input for decision making. Maturing assets develop complex "time critical" process dynamics such as production decline, liquid loading and salt precipitation that create the need for real-time monitoring and control. Measurement and control technology must give a more accurate understanding of the key processes involved. It also should improve asset diagnostics to lead to enhanced production control and recovery strategies without compromising reliability or safety. Furthermore, the industry has to deal with increasingly complex environmental and safety regulations, and an increasing shortage of expert personnel.

Innovations in fiber optic sensing technology potentially can provide data to help better understand the key processes behind decision making in the oil and gas industry. This insight is based on many projects both inside and outside the industry related to monitoring, process modeling and data processing. These insights are essential to control and optimize the "new" oil and gas industry, when one considers the challenges that lie ahead.

To assess the shape of future fiber optic technologies for the upstream industry, it is helpful to examine the versatility and potential of fiber optics based on applications in other industries and their applicability to oil and gas. Fiber optics is a proven technology, but one that needs to be adapted and modified to the restrictions and challenges of oil and gas applications. The demands of applications in the upstream sector will give rise to further technological innovations.

Fiber Optic Sensing

Fiber optic sensor has gained increasing acceptance. Among the different fiber sensor types, fiber Bragg grating (FBG) is used most widely. An FBG is a periodic modulation of the refractive index in an optical fiber. This modulation is realized by exposing the optical fiber to a periodic pattern of ultraviolet light.

Like a conventional grating, the reflection of an FBG depends on the wavelength. Any physical parameters that affect either the refractive index of the optical fiber or the period of the grating will cause a change in the wavelength of the reflected light. The wavelength shift is a measure of the physical parameter of interest (i.e., temperature and strain). By coupling a mechanical transducer to the FBG sensor, physical parameters such as pressure, flow, acoustic signal and gravity can also be measured.

An extra benefit of FBG sensors is that each sensor can have a different Bragg wavelength to enable easy wavelength domain multiplexing of an array of FBGs in a single optical fiber. The multiplexing capacity can be further extended by combining time domain multiplexing technology.

In extreme environments such as cryogenics or space, new-generation fiber Bragg grating fibers are capable of surviving temperatures from <-200 to 800 degrees Celsius, giving FBG sensors the ability to measure temperatures across a broad working range. However, the FBG has to be integrated into a transducer to monitor other physical parameters. Proper bonding materials and processes are required to ensure stable attachment to the transducer and proper operation of the FBG sensor.

Conventional high-temperature adhesives for temperatures higher than 300 degrees are based on a two-component system with solid fillers. This inhomogeneous material generates uneven mechanical forces on the FBG that lead to unpredictable distortions of the FBG reflection spectrum (resulting in large measurement errors). New, special fiber/FBG technology suitable for temperatures up to 500 degrees is under development to solve this problem in the oil and gas industry.

In the aerospace sector, composite materials are essential because of their superior strength-to-weight ratios, compared with metal alloys. Consequently, a large number of aircraft parts are made from composite materials. The most important failure modes of composite materials are impact by an object, delamination and debonding. These failure modes can be monitored by FBG strain sensors at appropriate locations in the structures.

Embedding the FBG in the composite structure has the added benefit of protecting the fiber and increasing its lifetime. However, the inhomogeneity of composite materials means that embedding standard FBGs will lead to unpredicted distortions of the FBG reflection spectrum. Different solutions to this challenge, ranging from using small-diameter fibers to novel fiber/FBG concepts, are under development.

The cost and performance of FBG sensor systems are determined largely by the type of interrogation system. Custom systems under development can both extend the frequency range and lower the wavelength detection noise level by a factor of 100. Another direction of interrogator development is to reduce system cost (high-performance, commercial interrogators cost about $25,000). Low-cost interrogators with only the necessary specifications can be used to avoid an overly complex sensor network and enable system redundancy.

Other fiber optic sensing technologies are developed for special applications. In the defense industry, interferometric-type fiber optic acoustic sensor arrays are used to detect threatening objects or intruders. This technology has been transferred successfully to acoustic measurement in ocean-bottom cable system for seismic application. For applications such as aerospace and nuclear fusion, special fiber optic technologies and components have been developed to function under extreme operating conditions. Furthermore, new fiber optic sensing technologies with extreme sensitivity are being developed, some of which will be beneficial in oil and gas applications.

Developments in distributed acoustic sensing systems and quasi-distributed FBG-based sensors for measuring acoustic pressure, flow, steam quality and chemical composition are being demonstrated successfully at an ever-increasing pace. Technology is becoming more cost effective and more versatile through multiparameter monitoring using only one fiber. Combining (quasi-) distributed sensing with proper signal processing schemes and data mining technology will provide valuable information about well and reservoir conditions that is not available today.

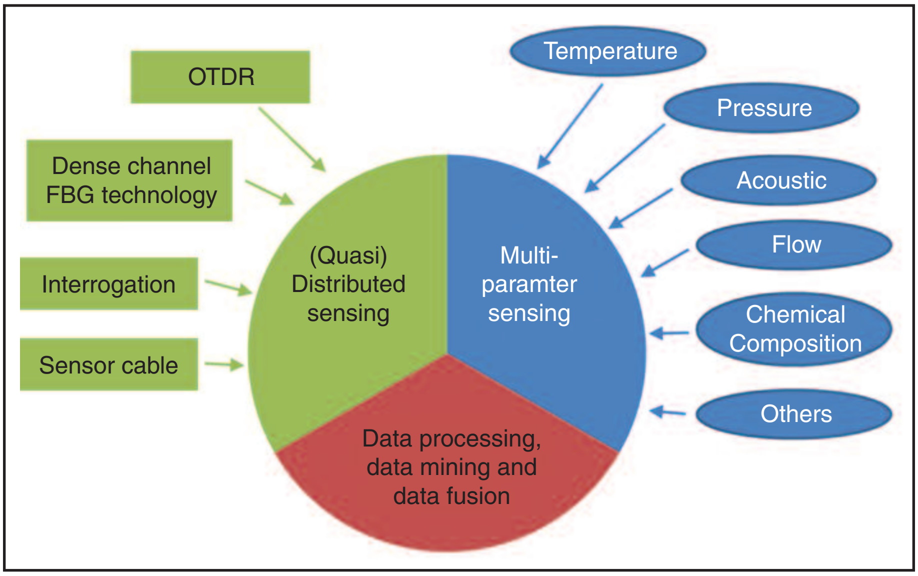
And this information will be more than the sum of the data derived from the individual sensor systems; the extensive developments in system reliability, deployability, data mining, signal processing and information visualization are creating revolutionary changes in fiber optic sensing and decision making in the oil and gas industry.

Next-Generation Systems

Fiber optic components and sensing technologies have been developed/demon-

FIGURE 1

Next-Generation Fiber Optic Sensing System



strated that are able to operate in harsh conditions, monitor concentrations of different chemical substances, and detect microseismic events, pressure and inflow patterns over the full length of a well. Combining distributed technology with multiparameter sensing and proper data fusion will be the basis of the next generation of fiber optic systems for oil and gas (Figure 1).

The technical breakthroughs necessary to spark this revolution should come from three directions. The first is ease of system installation. Conventional systems have been complex to install and hinder production. Also, practical problems related to splicing methods, wet connects and making perforations without the risk of damaging preinstalled fibers will have to be solved.

The second factor is related to system robustness and reliability. Implementing additional fiber optic systems is sometimes put on hold by operators because of lack of reliability statistics. Early failures and degradation are attributed to leaking connectors and nipples, or to mechanical stress caused by poor fiber immobilization. Fiber optic monitoring systems are configured from sourced components and are not tested as a system. These components are tested individually by the supplier, but against criteria developed mostly for telecom applications. Standardized test protocols for oil and gas applications have to be developed for both components and systems to increase confidence and acceptance.

The third factor is the ability to handle the vast amounts of data generated by a system. Sampling strategy and data processing are critical factors in utilizing a monitoring system. Being able to process the data coming from different sources into tangible information at an early stage, or filtering raw data and only keeping the interesting events can facilitate easy data transport, storage, processing and interpretation. Special electronics for parallel data processing to reduce process time and translate multiparameter data into unambiguous information for decision making are being used already in other industries.

The smart wells of the future will be equipped with a variety of sensors that can operate under extreme environmental conditions. Lifetime, stability and reliability are the most important requirements for downhole sensors. For conventional electrical sensors, the failure rate increases significantly as operational temperatures rise. Optical fiber-based sensors have no electrical components in the sensing element and the glass fiber is stable up to several hundred degrees, making the technology ideally suited for permanent well monitoring and high-operational temperature applications such as stream-assisted gravity drainage.

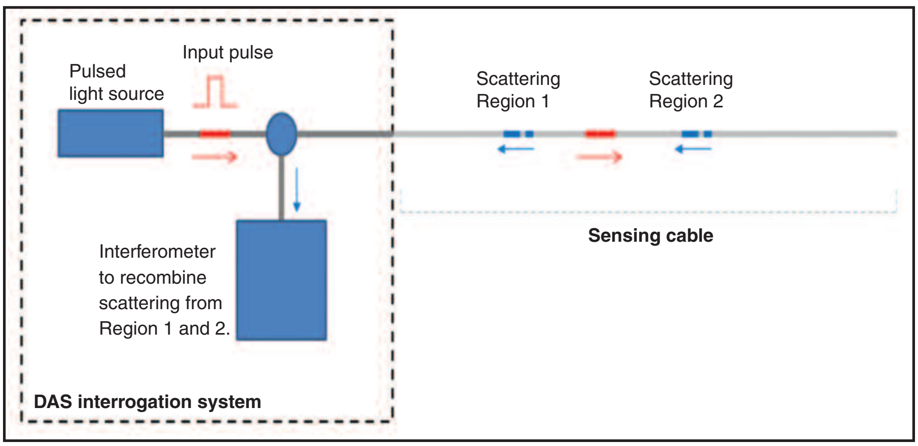
Oil And Gas Solutions

Optical time domain reflectometry (OTDR) is a light scattering technique that measures the condition of a fiber network and pinpoints local optical loss, which is an indication of the condition of the fiber. A short optical pulse is launched into the fiber and the optical properties of the reflection are measured as a function of time to achieve a relation between the distance and the local scattering.

The different types of scattering–Rayleigh scattering (amplitude is a function of composition and density variations in the fiber), Raman scattering (amplitude is a function of temperature), and Brillouin scattering (the wavelength is a function of temperature and strain)–are related to the different physical parameters. Measuring scattering as a function of time results in distributed sensing of the particular parameter.

FIGURE 2

Optical Fiber Distributed Acoustic Sensing System



The most well-known distributed sensing technology for oil and gas is distributed temperature sensing (DTS) systems. DTS is based generally on Raman scattering. Several commercial systems are available. The optical fiber in a downhole DTS system has to be optimized to ensure a long lifetime. The development of pure silica core fiber greatly reduces the problem of hydrogen darkening of conventional optical fiber with a germanium-doped core. Furthermore, the fiber has to be protected by a cable to survive installation and downhole operations.

By continuously monitoring and logging DTS data, changes in the well can be observed. Field applications using DTS data in production and completion scenarios include:

- Gas lift monitoring/optimization;
- Production/inflow monitoring;
- Injection profiling and water management;
- Well integrity and monitoring;
- Electric submersible pump optimization;
- Fracture height monitoring; and
- Real-time stimulation monitoring.

Multiparameter Sensing

Single-point fiber optic sensors can be designed to measure a range of physical parameters. Initial single-point sensors for oil and gas applications were developed mainly with Fabry-Perot interferometer technology. Single-point sensors generally provide higher sensitivity and resolution than distributed sensing technology, and measurements of pressure, temperature and acoustic signal have been demonstrated.

The main disadvantage of Fabry-Perot sensors is the lack of multiplexing potential. Making multiple-point measurements with single-point fiber optic sensors required a fiber optic network with multiple fibers. FBG technology, with its unique multiplexing capability, solves this problem. Even sensors for different physical parameters can be multiplexed in the same fiber to enable multiparameter sensing. Multiple-drop downhole pressure and temperature sensing with nine sensing points has been demonstrated by Shell and SmartFibres.

By mounting an array of FBG strain sensors on a construction, the deformation-induced strain distribution can be measured. For a construction with known mechanical design and material properties, the shape and deformation of the construction can be calculated. This quasi-distributed strain sensing technology with FBGs has been used by Shell and Baker Hughes in a fiber optic, real-time compaction monitoring system to measure casing deformation (i.e., axial compression, bending, buckling, etc.). The multiplexing capacity of an FBG sensor system depends largely on the interrogation technology and the sensor network topology.

DAS, Vortex Flow Sensors

Distributed acoustic sensing (DAS) is a new monitoring technology with many potential applications, including gas lift, ESP monitoring, 3-D vertical seismic profiling, and hydraulic fracturing. DAS technology is basically a combination of Rayleigh scattering-based OTDR with a fiber optic interferometer for acoustic signal detection.

High-performance acoustic sensor arrays developed for naval defense applications based on fiber interferometer technology have demonstrated noise levels even below the ambient noise level of the sea, and have been used in towed arrays and hull-mounted arrays on submarines. In oil and gas, this same technology has been used in ocean-bottom cable seismic data acquisition as well as reservoir monitoring.

In a DAS system, local Rayleigh scattering is used as a reflector in the fiber, and OTDR technology enables real distributed measurement of disturbances (e.g., acoustic sensing along a long optical fiber). The extremely sensitive interferometric detection technique can measure acoustic signal-induced changes of fiber length at a very high resolution level.

DAS systems can operate with fiber lengths to 10 kilometers, spatial sampling down to about one meter, and a frequency range up to about 10 kilohertz. Figure 2 shows a basic block diagram of a DAS system. In comparison to a standalone fiber optic interferometric acoustic sensor, a DAS system has a simple sensing cable and is compatible with single-mode optical fibers in a well. The trade- off is a lower signal-to-noise ratio (lower detection limit).

In enhanced recovery operations such as steam-assisted gravity drainage with multiple injection and production points, it is important to measure the flow distribution between the various points to optimize production. Achieving this would require installing flowmeters at various intervals in injection wells to measure the amount of fluid injected at each location. Flowmeters suited to the HP/HT operating conditions at the bottom of injection wells are expensive, making deploying multiple meters very costly.

One solution is a robust, simple flow sensor based on the proven mechanical concept of vortex shedding (Figure 3). An obstruction placed in the flow will generate a periodic pressure fluctuation (vortex) at a frequency that is proportional to the flow. The FBG vortex flowmeter consists of a shedder bar as an obstruction and a tail plate with an embedded FBG to pick up the vibration.

Using proper fiber optic components and optimized mechanical design results in a rigid fiber optic flow sensor that can be used at temperatures to 335 degrees Celsius and pressures to 140 bar. FBG vortex flowmeters offer a much larger turndown ratio than orifice plate meters, and

FIGURE 3

Vortex Shedding from Flow Obstruction

have the ability to accurately measure the density of the medium, making it ideal for steam quality measurements.

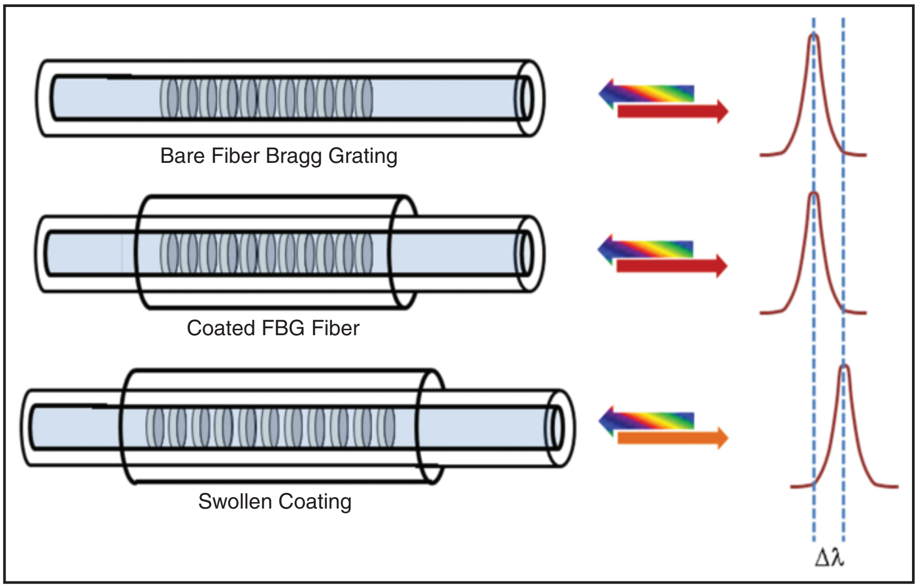
Chemical Sensors

Although FBG sensors generally are used to measure physical parameters, the technology has been extended to include chemical sensing functionality. FBG-based chemical sensors in an array configuration can be developed into a distributed chemical sensing (DCS) system to detect specific molecules along the full inflow area of a producing well. Possible applications are detecting formation water and/or water breakthrough. The sensors also can detect small quantities of chemical compounds such as hydrogen sulfide. Another interesting application is monitoring carbon dioxide concentrations in carbon capture and storage reservoirs.

There are different technologies for fiber optic chemical sensing. One approach is to use a chemically responsive coating to generate an axial strain in the fiber/FBG under the influence of the presence of a chemical compound (Figure 4). Applying different coatings on different FBGs makes the DCS system suitable for measuring chemical compositions.

FIGURE 4

Coating-Based Fiber Bragg Grating Chemical Sensor



When measured properly, the strain-induced FBG wavelength shift can provide quantitative information about an environment's chemical composition. The challenges of such distributed chemical sensors include the sensitivity of the coating, the

LUN-KAI CHENG

Lun-Kai Cheng is a senior research scientist in the optics group at TNO in the Netherlands. He is involved in developing interferometric systems, optical sensors for process control and fiber optic sensors for extreme environmental conditions. Cheng is inventor of more than 10 patents on fiber optic technologies, including a high-speed interrogation system for Fiber Bragg Grating sensor arrays and a fiber optic vortex flowmeter for oil and gas applications, both of which are commercialized under license. His research interests are fiber laser sensors, special optical fibers, and fiber optic distributed sensing. Cheng holds an M.S. in physics from Delft University of Technology.

MICHA BOERING

Micha Boering is business development manager for upstream oil and gas at TNO. He is the liaison between researchers and future end-users. Through constant iteration, he feeds the engineering process with requirements and paves the way for successful product development, including funding field trials and licensing. Through presentations of papers at conferences and trade shows, Boering proactively informs future stakeholders about the latest innovations and developments in relation to current and emerging applications in the oil and gas industry.

RICHARD BRAAL

Richard Braal is manager of innovative reservoir management and production optimization at TNO, with the objective of assisting operators and manufacturers in developing technologies that increase recovery and production efficiency. This includes illuminating wells and reservoirs by means of novel monitoring techniques and sensor systems. Developing new instrumentation concepts has played a major role since early in his career, first for downstream and then upstream oil and gas applications. As a business development manager, he was responsible for acquiring projects for developing innovative sensor systems such as distributed chemical sensors, the fiber optic vortex flowmeter, and other game-changing technologies.

processing of the coatings onto the FBG, and optimizing chemical selective responsive polymeric coatings for different chemical elements.

To date, the sensitivity of various coatings for humidity, CO_2 and H_2S have been demonstrated. Figure 5 shows the stability of the humidity coating after periodic temperature (from 23 to 80 degrees Celsius) and humidity cycling (50 to 100 percent) in a climate chamber for about six months. No degradation of the coating response was observed.

Combining multiparameter sensing and quasi-distributed sensing with signal processing and data mining technology is providing game-changing capability that represents the foundation of the new generation of monitoring systems for controlling and optimizing well efficiency and production. ❐

Editor's Note: The authors acknowledge Shell, SmartFibres, Hong Kong Polytechnic University, and colleagues at TNO for their contributions to developing the FBG-based sensor concepts discussed in this article.

FIGURE 5

Sensor FBG Reflection Wavelength Change (Multiple Temperature/Humidity Cycles)