Subsea Downhole Optical Sensing

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Abstract. The potential for subsea downhole optical fibre sensing to optimize hydrocarbon production and hence contribute to enhanced oil recovery is described. The components of subsea downhole optical sensing systems are reviewed and the performance of a new subsea optical fibre feed-through for downhole optical fibre sensing reported.

1. Introduction

The need to enhance the overall efficiency of oil production presents significant technical challenges for subsea oil production. Enhancement will require improvements in all aspects of the production process including; subsea equipment, subsea processing, equipment and reservoir monitoring and oil recovery technologies. The development of enhanced production systems offers the potential for increased revenue and to cost effectively extract more oil from a reservoir. For example technological limitations and economic conditions often mean that conventional oil recovery processes leave around two-thirds of the oil in the reservoir. Despite the fact that recovery of the remaining oil is challenging using current methods, due to a range of factors such as the oil being located in regions of the reservoir that are difficult to access, improvements in the production process, such as enhanced oil recovery (EOR) systems, may make the recovery of more of the oil economically and technically feasible. The potential economic benefit is illustrated in figure 1, which summaries the oil in place in the U.S.A.. It can be seen that around 58% of the known and future U.S.A. oil reservoirs fall into the category of being already discovered but unrecoverable using current oil production technology. Enhanced oil recovery (EOR) methods have the potential to recover much of this oil. For example in the U.S.A. this could amount to some 200 billion barrels from current discovered but “unrecoverable” reservoirs. Consequently there are a wide range of new technologies being developed for EOR applications. Examples include new gas-injection systems, microbial strains that can produce high levels of microbial organisms that behave like detergents to sweep oil from a reservoir and high-speed, and oil-free, intelligent motor compressors. The generation of better information on the status of a reservoir is another critical aspect in the overall enhancement of the production process. This will require the use of improved sensor technology and far more downhole measurements than have traditionally been used.

2. Downhole Optical Fibre Sensors

Over the last decade optical communications and optical fibre sensor technology has been shown to be capable of generating the real time reservoir data required for effective optimisation of the oil production process and hence EOR. [1-3]. This period has seen significant investment and
increasing adoption of optical technologies by the oil and gas industry. This growth is illustrated in figure 2, which shows the trend in fibre and optical technology patents applied for each year, by a selection of major oil and gas industry companies, in the period 1999-2005.

Optical fibre sensors have a number of advantages over traditional electronic systems for downhole sensing including:

- Being made of electrically insulating materials and immune to electromagnetic interference
- The materials are chemically resistant
- Wide operational temperature range
- Multiplexing capabilities

Optical fibre technology also provides new sensing formats, highly suited to downhole sensing applications (2-4). There are many and varied types of optical fibre sensors, however in general they can be divided into two basic types namely; intrinsic and extrinsic and two sensor formats; point and
distributed sensing. Intrinsic sensors utilise properties of the optical fibre, such as light scattering, as the basis of the measurement. Extrinsic sensors utilise properties of a separate component, for example a fluorescent material or flexible membrane, which is coupled to the optical fibre, as the basis of the measurement. The two basic sensing formats are illustrated in figure 3. In the point sensing format the optical fibre serves only to transmit light to and from a component possessing a suitable measurement property. It is also possible to have a number of such sensing components distributed along a length of optical fibre, which may be individually accessed, by for example wavelength selection.

One of the most widely adopted point sensing technologies for downhole measurements is in-fibre Bragg gratings. Optical fibre Bragg gratings form the basis of number of sensor systems, including displacement, temperature, strain sensors. The Bragg gratings comprise periodic variations in the refractive index along a small length of the optical fibre, typically produced by illumination with a periodic high intensity light pattern, which causes a photo-induced periodic change in the refractive index in the fibre. The grating is a highly selective reflector within the optical fibre, with the reflective wavelength being dependent on the period of the grating. Optical fibre Bragg grating sensors are capable of high sensitivity measurements, for example, for strain sensing, the resolution can be in the range of a few µε. There are a number of techniques, including the use of reference gratings that are not subject to the strain that can be used to differentiate between temperature and strain thus allowing both parameters to be measured. It is also possible to have more than one Bragg grating sensor in an optical fibre allowing measurements to be made at discrete points along the optical fibre, which may be meters or kms apart. Such a measurement system is called quasi-distributed sensing. There are different techniques to address the single gratings and hence the discrete locations along the optical fibre, including Wavelength Division Multiplexing (WDM) and Time Division Multiplexing (TDM), as illustrated in figure 4. Bragg grating sensors have been used for downhole temperature measurements, for permanent seismic sensors in a wellbore to detect the movement of fluids over time in the surrounding reservoir and in downhole flow monitors (5).

![Figure 3: Basic optical fibre sensing formats.](image)

True distributed sensing along the entire length may be achieved using optical time domain reflectometry (OTDR) [6]. In this technique a pulse of light is propagated through an optical fibre and the backscattered light detected at the launch end. The time-of-flight information is used to identify the point along the fibre from which the backscatter originated and the nature of the backscattered signal is used as the basis of the measurement. By analysing the OTDR Raman backscatter light from an optical fibre it is possible to derive the temperature of the fibre at a given point along it’s length. Distributed sensors employing Brillouin backscatter can perform temperature and strain measurements [6,7]. Improvements in the spatial resolution of the distributed measurement may be achieved by employing stimulated Brillouin scattering. Such schemes involve a pulse pump and a CW probe.
launched from both ends of the fiber. Other systems incorporate a pre-pump pulse to stimulate phonon waves in optical fibre prior to the arrival of the measuring pump pulse and claim a 10cm spatial resolution. Distributed pressure and strain sensing may also be performed using Polarisation Optical Time Domain Reflectometry (POTDR). Such sensors utilise the fact that the polarisation of light propagating in an optical fibre is influenced by the birefringence of the optical fibre. The birefringence of an optical fibre is due to the different refractive indices of the “fast” and “slow” axes. The technique may be enhanced by using special optical fibres with characteristics designed to increase the change in birefringence for a given force. Downhole sensing systems based on all the above approaches have been proposed, however only Raman and Brillouin scattering based systems have seen significant take up.

Figure 4: Schematic of the WDM and TDM techniques used to perform quasi-distributed sensing along an optical fibre with multiple Bragg gratings

Figure 6: a) Overview of the subsea downhole optical fibre sensing system, b) downhole optical fibre cable
3. Subsea Downhole Optical Fibre Sensing Systems

The basic scheme for a subsea downhole optical fibre sensor system is shown in figure 6a. As can be seen the scheme comprises a remote monitoring and control facility, which may be situated locally on an offshore platform or remotely in a land based facility and the downhole sensor data relayed to this facility using appropriate communications systems. One end of the optical fibre incorporating the downhole sensors are connected to a sensor optoelectronics driver and processing system. In some applications the optoelectronics driver and processing unit may be located topside on a platform, typically within the remote control and monitoring facility, and an optical fibre run from this directly to the subsea XT. The other approach is to locate the optoelectronics driver and processing unit within the subsea control module located on the XT and the optical fibre connected from here to an optical fibre feed-through.

The downhole optical fibre and sensors of the system are designed to have a prolonged life in downhole conditions, which may include temperatures up to 150°C and pressures to 15,000psi, as well and production fluids loaded with abrasive sand and rock fragments. A typical multi-optical fibre cable construction used to access downhole optical sensing systems such as point temperature, pressure, flow, phase-fraction, distributed-temperature-sensing, and seismic systems is shown in figure 7b. As shown the cables may have an outer encapsulation material, which depending on the operating temperature may for example be made of Polyamide (90°C), EPDM/propylene copolymer (130°C) or Polyvinylidene fluoride (140°C). There is also an outer stainless steel tube and inner jacket, with the optical fibres housed within the inner stainless steel tube. This inner tube is filled with a hydrogen scavenging gel to counter the effects of hydrogen in the well. Multiple optical fibres may be incorporated into the cable. In developing a downhole optical sensing system it is necessary to ensure that the downhole gauge dry mate connector component of the overall feed-through system will readily interface with the downhole optical fibre cable.

![Diagram of XT Optical fibre feed-through system](image1)

Figure 7: a) Schematic of the XT Optical fibre feed-through system, b) photograph of a sub assembly of the subsea optical fibre feed-through.
4. Subsea Optical Fibre feed-through
The optical fibre feed-through system developed specifically to meet the requirements of subsea downhole optical fibre sensing systems is shown schematically in figure 7a. Single- and multi-mode optical fibre versions of this unit have been developed, with the single-mode unit tested for 1310nm and 1550nm and the multi-mode for 850nm and 1300nm. The feed-through comprises a downhole gauge dry mate optical connector, a tubing hanger wet mate optical connector; a stem wet mate optical connector and a stem dry mate optical connector. Each optical connector component of the overall feed-through has appropriate pressure barriers built-in. The feed-through is capable of multiple in-service re-matings without degradation of the optical performance, is designed to be compatible with standard XT penetrators and function in the high temperatures and pressures found on the inside of the XT for 25 years. The feed-through has been comprehensively tested including, thermal, pressure and mechanical integrity testing and found to be capable of withstanding the conditions likely to be found in operation and to maintain an effective pressure barrier under the test conditions, with the wetmate rated to 150°C and the drymate at the bottom of the tubing hanger to 177°C. The important parameters in determining if the feed-through can be used with downhole optical sensors are the optical loss and back reflection. The optical loss through the individual connectors components of the system were measured as part of the above tests and found to be \( < 0.5 \text{ dB} \) per mated connection pair at 1310 nm and 1550 nm for single-mode and 850nm and 1300nm for multi-mode optical fibre systems and the back reflection per mated connection pair \( < -45 \text{ dB} \). The fully assembled feed-through has been shown to have an optical loss of less than 1.5dB. These figures comply with the performance requirements identified in an industry-wide draft SEAFOM spec for a subsea optical fibre feed-through to be used with downhole optical sensors. Figure 7b shows a photograph (reproduced with permission from Company Deutsch) of a sub assembly of the subsea XToptical fibre feed-through developed as part of a collaborative project with Company Deutsch.

6. Conclusions
Subsea downhole optical fibre sensing offers the potential to greatly enhance the monitoring of subsea hydrocarbon production. The increase in monitoring should facilitate optimisation of the process and lead to enhanced oil recovery. The components of subsea downhole optical systems are now available, including a subsea optical feed-through system with a total feed-through loss of less than 1.5dB.

7. References
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