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# Optical Fibre Sensor System for Multipoint Corrosion Detection

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## 1. Introduction

Over the past thirty years there has been intense research and development on optical fibre sensors for many applications, basically because of their advantages over other technologies, such as immunity to electromagnetic interference, lightweight, small size, high sensitivity, large bandwidth, and ease in signal light transmission. The applications include sensing temperature, strain, pressure, current/voltage, chemical/gas, displacement, and biological processes among others. To accomplish those, different optical technologies have been employed such as fibre grating, interferometry, light scattering and reflectometry, Faraday rotation, luminescence and others. A review on fibre sensors can be found in (Lee, 2003).
Corrosion and its effects have a profound impact on the infrastructure and equipment of countries worldwide. This impact is manifested in significant maintenance, repair, and replacement efforts; reduced access, availability and production; poor performance; high environmental risks; and unsafe conditions associated with facilities and equipment. There have been some efforts from different countries to estimate the cost of corrosion and the results indicate that it can reach 2 to 5% of the gross national product. For example, corrosion damage represented an estimated cost of US$ 276 billions in the United States of America in 2002 (Thompson et al., 2005). Therefore, corrosion monitoring is an important aspect of modern infrastructure in industry sectors such as mining, aircraft, shipping, oilfields, as well as in military and civil facilities.
Optical fibre-based corrosion sensors have been investigated in recent years mainly because of the advantages obtained by the use of optical fibres, as already pointed out. A short review of the technologies employed in the fibre-based corrosion sensors can be found in (Wade et al., 2008). The reported applications include corrosion monitoring in aircrafts (Benounis & Jaffrezic-Renault, 2004), in the concrete of roadways and bridges (Fuhr & Huston, 1998) and in oilfields.

## 2. Corrosion Monitoring in Deepwater Oilfield Pipelines

In the oil industry, to which we focus the sensing approach described in this chapter, a very challenging problem is that related to surveillance and maintenance of deepwater oilfield pipelines, given the harsh environment to be monitored and the long distances involved.

These structures are subject to corrosion and sand-induced erosion in a high pressure, high temperature environment. Moreover, the long distances (kilometres) between the corrosion points and the monitoring location make the commercially available instruments not appropriate for monitoring these pipelines. Costly, regularly scheduled, preventive maintenance is then required (Staveley, 2004; Yin et al., 2000). Electronic and electromagnetic-based corrosion sensors (Yin et al., 2000; Vaskivsky et al., 2001; Andrade Lima et al., 2001) are also not suitable in these conditions. Fibre optic based corrosion sensors are ideal for this application. However, the sensing approaches reported in the literature are either single point (Qiao et al., 2006; Wade et al., 2008) or use a stripped cladding fibre structure that requires a high precision mechanical positioning system with moving parts for light detection, which compromises the robustness of the sensor system (Benounis et al., 2003; Benounis & Jaffrezic-Renault, 2004; Saying et al., 2006; Cardenas-Valencia et al., 2007). An optical fibre PH sensor has been recently developed for the indirect evaluation of the corrosion process in petroleum wells (Da Silva Jr. et al., 2007). It employs a fibre Bragg grating mechanically coupled to a PH-sensitive hydrogel, which changes its volume according to the PH of the medium. Thus, the change in PH is translated into a mechanical strain on the Bragg grating, which can be interrogated by standard optical methods. Although it can easily be multiplexed for multipoint measurements, this technique is limited to the evaluation of the chemical corrosion due to acid attack inside the well, disregarding the combined effects of other important sources of corrosion, such as mechanical (erosion), chemical, thermic and biological (microorganisms). The oil industry can also make use of the time domain reflectometry (TDR) technique to evaluate the corrosion process inside pipelines and oil wells (Kohl, 2000). The proposed scheme involves the deployment of a metallic cable inside and along the pipeline or well. The conductor is exposed to the fluid at selected locations such that it should be susceptible to the same corrosive processes as the pipeline. A signal generator launches a pulsed electrical signal to the conductor cable and an electronic receiver measures the reflected pulses intensity and delay. The reflections come from the locations where the exposed cable was affected by the corrosion process, which changes its original impedance. This TDR technique has also been applied to the monitoring of corrosion in steel cables of bridges (Liu et al., 2002). Although this technique has the advantage of being multipoint or even distributed, it is limited in reach. For practical purposes the maximum distance covered by the sensor is about 2 km. This is suitable for standard wells, but not for deep oilfields, especially those from the recently discovered presalt regions in Brazil, which are over 6 km deep.

## 3. A Multipoint Fibre Optic Corrosion Sensor

We have recently presented for the first time the concept and first experimental results of a fibre-optic-based corrosion sensor using the optical time domain reflectometry (OTDR) technique as the interrogation method (Martins-Filho et al., 2007; Martins-Filho et al., 2008). Our proposed sensor system is multipoint, self-referenced, has no moving parts and can detect the corrosion rate several kilometres away from the OTDR equipment. These features make it very suitable to the problem of corrosion monitoring of deepwater pipelines in the oil industry. It should be pointed out, however, that the approach is not limited to this specific application and can be employed to address a number of single or multipoint corrosion detection problems in other industrial sectors.

In this chapter we present a detailed description of the sensor system, further experimental results and theoretical calculations for the measurement of the corrosion rate of aluminium films in controlled laboratory conditions and also for the evaluation of the maximum number of sensor heads the system supports.

### 3.1 Sensor Setup

Our proposed sensor system consists of several sensor heads connected to a commercial OTDR equipment by a single-mode optical fibre and fibre couplers. Figure 1 shows the corrosion sensor setup. The OTDR is connected to a 2 km long single mode optical fibre. Directional couplers can split the optical signal such that a small fraction (3 to 9%) is directed to the sensing heads. The OTDR operates at 1.55 μm, with a pulsewidth of 10 ns, which corresponds to a spatial resolution of 2 m. The OTDR is set to measure 50000 points for the total distance of 5 km (one point every 10 cm). The optical fibres and couplers are standard telecommunication devices. The sensor heads have 100 nm of aluminium deposited on cleaved fibre facets by a standard thermal evaporation process and they are numbered from 1 to 11 in Fig. 1.

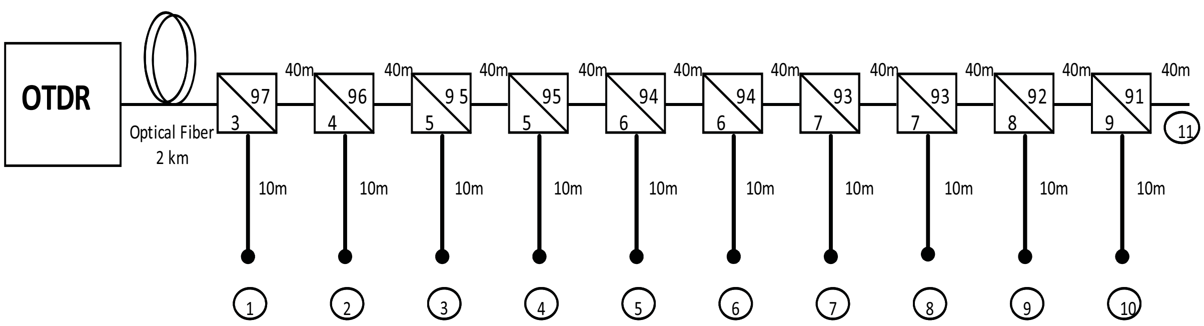


Fig. 1. Schematic diagram of the corrosion sensor. Sensor heads are numbered. Fibre lengths and split ratios are shown.

### 3.2 Results

For laboratory measurements the corrosion action was simulated by controlled etching of the Aluminium film on the sensor head. We used 25 $H_3PO_4$ : 1 $HNO_3$: 5 $CH_3COOH$ as the Al-etcher. The expected corrosion rate of Al from this etcher is 50 nm/min. Figure 2-a shows the OTDR trace where each peak, numbered from 1 to 11, indicates the reflection from the corresponding sensing head. The head number 6 is immersed in the Al-etcher. As the aluminium is being removed from the fibre facet the reflected light measured in the OTDR decreases, as shown in Fig. 2-b.

In Fig. 3 we plot the ratio of peak (point A) to valley (point B) of the reflected light shown in Fig. 2-b as a function of the aluminium corrosion time. Figure 3 shows that up to 60 seconds of corrosion there is no significant change in the OTDR measured reflected light, since the aluminium is still too thick. Further up from this point the reflection drops to a minimum and then stabilizes at a constant level. The constant level means that the corrosion process on the fibre facet has ended. We obtain the corrosion rate by taking the deposited metal thickness and the time taken to reach the constant level, as show in Fig. 3.

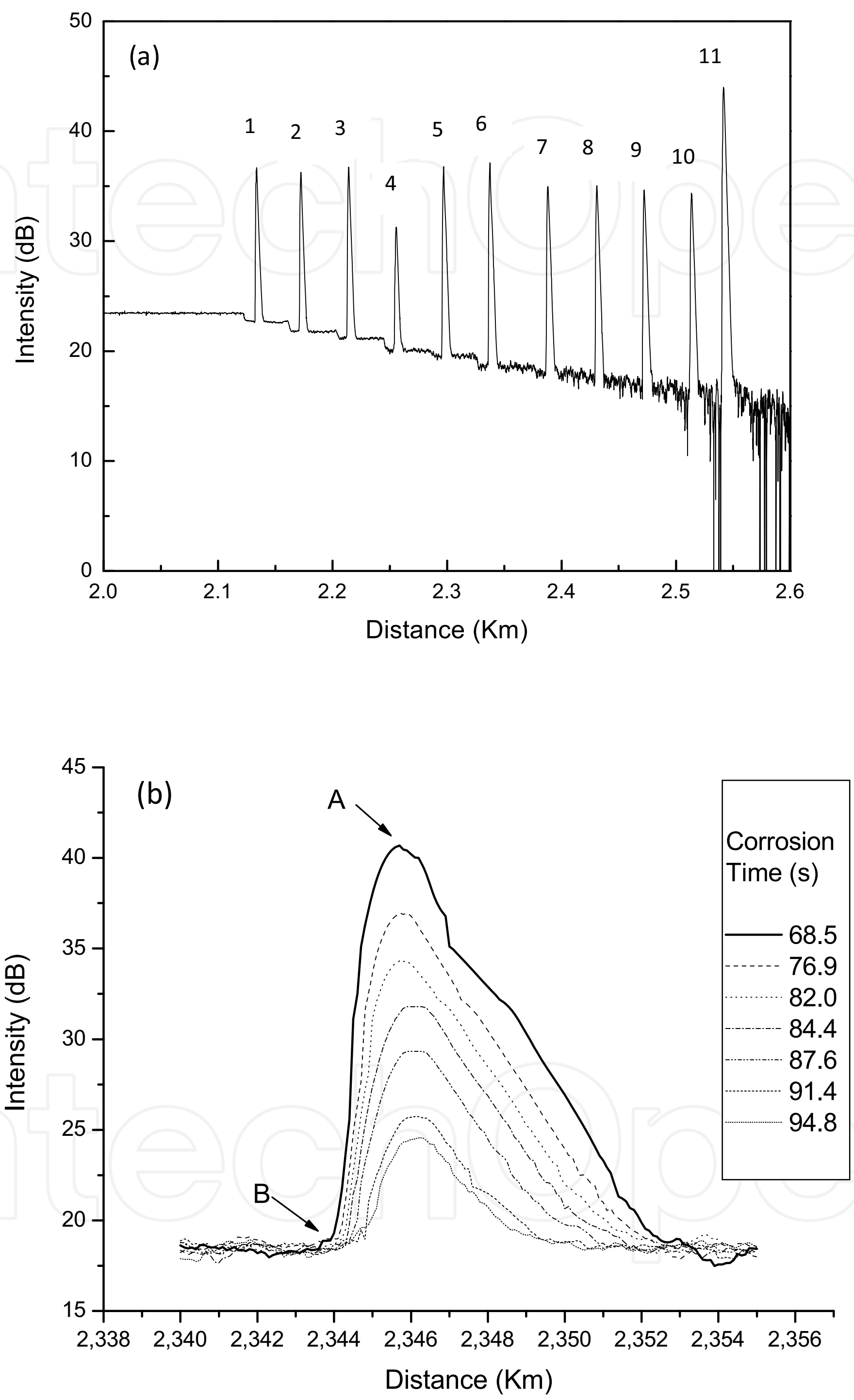


Fig. 2. (a) OTDR trace, corresponding to the intensity of the reflected light as a function of distance along the fibre. Sensor head numbers are shown. (b) OTDR traces for sensor head number 6, for several corrosion times.

The measured corrosion rate was 47.5 nm/min, which is very close to the expected value (50 nm/min). Other measurements performed using different sensor heads showed similar results. It is important to note that since the corrosion rate is obtained from the ratio of peak (point A) to valley (point B) of the OTDR trace as a function of time, this measurement is self-referenced, because the ratio is immune, to a certain extent, to small optical power fluctuations that may occur due to changes in the OTDR signal power, optical fibre and fibre coupler loss variations along the sensor system.

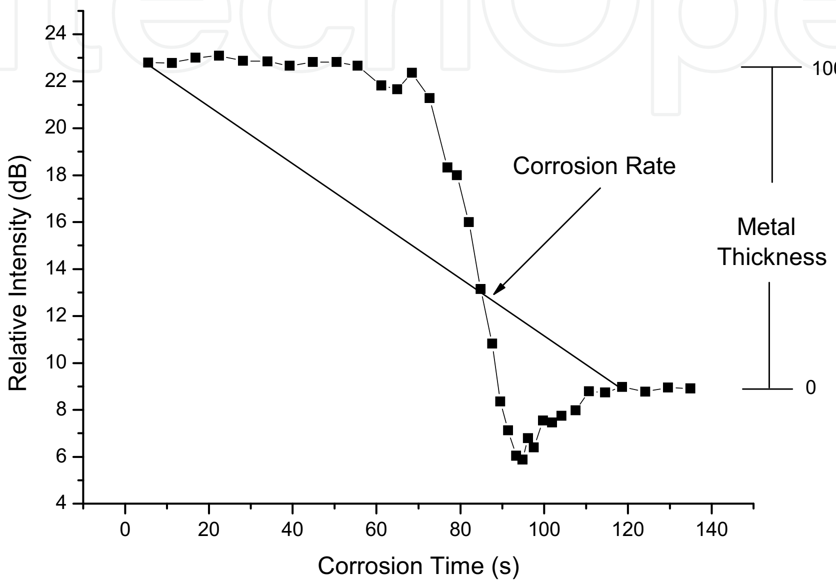


Fig. 3. Relative intensity obtained from Fig. 2-b, as a function of the corrosion time. Metal thickness and corrosion rate are shown.

Figure 3 also shows a valley in the relative reflected intensity just before the constant level used for corrosion determination. Although this feature does not seem to be important for the determination of the corrosion rate, we verified if it would be an artifact due to the pulsed OTDR operation in the multipoint (multireflection) setup scheme shown in Fig.1, by performing measurements in the single head setup show in Fig. 4. This new setup uses a CW laser source and an optical power meter, instead of the OTDR. The laser light at 1.55 μm from the CW laser with fibre pigtail is coupled to an optical isolator and then to a 50% coupler and to a 79/21 coupler. The output of this coupler has another optical isolator in one end and a sensor head in the other end. The sensor head used here is similar to those used in the multipoint setup of Fig. 1. The light reflected from the sensor head reaches the optical power meter through the optical couplers. The two isolators avoid unwanted reflections to reach the power meter and the laser source, which could cause interference effects and instabilities. For corrosion measurements we used the same Aluminium etcher as described before. Figure 5 shows the optical power as a function of the corrosion time obtained from the single head setup of Fig. 4. This result also exhibits the valley observed in the multipoint setup that uses the OTDR (Fig. 3), indicating that this feature is not a measurement artifact. Also, Fig. 5 confirms the corrosion rate obtained from Fig. 3, since the constant level starts at about 120 seconds of corrosion.

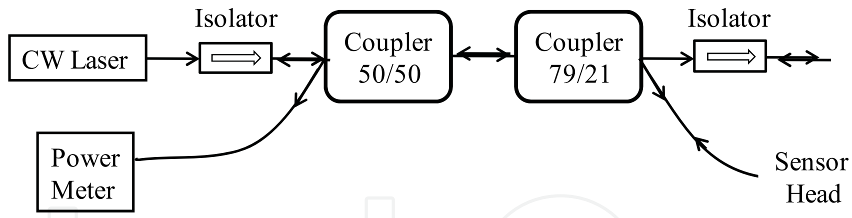


Fig. 4. Schematic diagram of the single head setup.

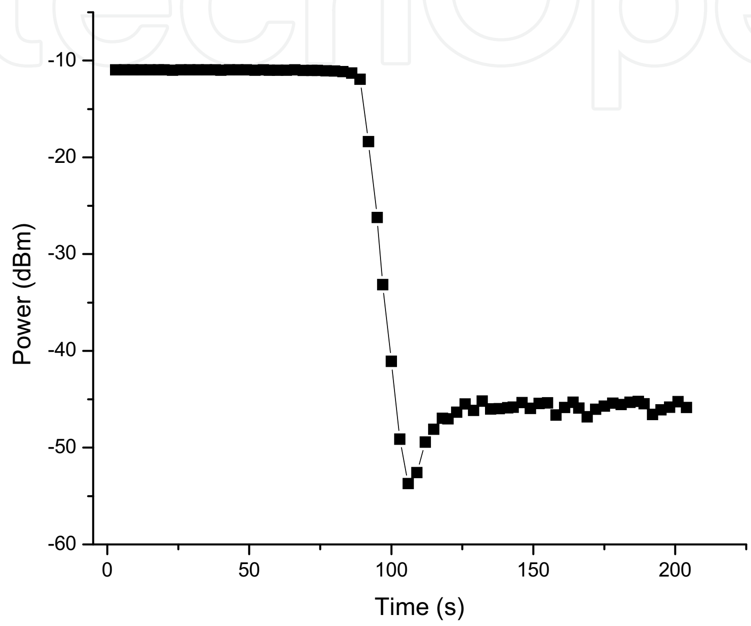


Fig. 5. Reflected optical power from a single head setup as a function of the corrosion time.

We also used the Fresnel reflection formulation (Fontana & Pantell, 1988) for a silica-Al-liquid single layer structure, as shown in Fig. 6, to study the reflection properties of the sensing head. Neglecting the small beam divergence of the guided mode, the reflectance is given by

$$R = \left| \frac{r_{12} + r_{23} \exp\left(-j2k_0\sqrt{\varepsilon_2}\,d\right)}{1 + r_{12} r_{23} \exp\left(-j2k_0\sqrt{\varepsilon_2}\,d\right)} \right|^2, \tag{1}$$

where

$$r_{i,i+1} = \frac{\sqrt{\varepsilon_{i+1}} - \sqrt{\varepsilon_i}}{\sqrt{\varepsilon_{i+1}} + \sqrt{\varepsilon_i}} \tag{2}$$

is the normal incidence reflectivity at the interface between media $i$ and $i$+1 ($i$ = 1, 2), $k_0 = 2\pi/\lambda$, $\varepsilon_i$ is the relative electrical permittivity of medium $i$ ($i$ = 1, 2, 3) and $d$ is the metal film thickness.

We assumed that the etching solution had a refractive index close to that of pure water, for the sake of simplicity. Optical parameters for silica (Malitson, 1965), pure water (Schiebener et al., 1990) and Al (Lide, 2004) at λ = 1.55 μm were used in the calculations.

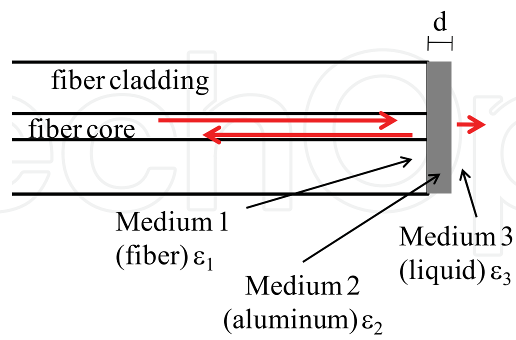


Fig. 6. Schematic diagram of the sensing head showing the Aluminium film of thickness *d* on the fibre facet.

Figure 7 shows a theoretical simulation as well as the experimental data for the reflectance at the metalized fibre facet as a function of the metal film thickness. The experimental data were obtained from Fig. 5. The theoretical result showed no evidence of a minimum reflectance with the strong depth observed experimentally at an estimated Al film thickness of 15 nm. In fact, the theoretical prediction yields almost 100% reflectance at this thickness value, as can be noticed in Fig. 7. The difference between theoretical and experimental results indicates that the valley observed in the experimental results is not due to any interference effect that could occur in the fibre-metal-liquid interfaces.

Due to the resonant nature of the reflectance minima shown in Figs. 3 and 5, it is very likely that they occur due to roughness induced, resonant coupling to surface plasmons (Fontana & Pantell, 1988) at the metal-liquid interface as a thin and rough layer of metal may result during the etching process. The coupling is thickness dependent and the strength depends on the average size of irregularities on the surface (Fontana & Pantell, 1988). Given that the dispersion relation of surface plasmons is very near that of photons in this spectral region, surface roughness could provide the required small increase in momentum for efficient coupling to the surface plasmon oscillation. A more elaborated calculation will be performed in future work taking into account the change in dispersion relation of surface plasmons due to roughness (Fontana & Pantell, 1988), to account for this effect.

It is worth noticing from Fig. 7 that the reflectance predicted theoretically with no metal film was 26.7 dB lower than that at maximum thickness, a result that differs significantly from the drop of ~ 14 dB observed experimentally in Fig. 3 and ~ 35 dB in Fig. 7. This is probably due to the residual clusters left on the fibre facet that form an absorbing, non-homogeneous interface that changes the reflectance relative to that predicted theoretically for a single glass-liquid interface. In fact we observed from a direct inspection with an optical microscope that some clusters of material still remained on the fibre facet, which were no longer affected by the Al-etcher. As can be seen from Figs. 3 and 7, the resonant features in the experimental results are similar, although the minima occur at different time points. There is, however, a significant difference from 14 to 35 dB in the final reflectance drop obtained from the data of Figs. 3 and 7, respectively, which may be due to the distinct procedures used to carry out the experiments. For the data shown in Fig. 3, obtained with the OTDR, since the equipment is somewhat slow to execute several measurements to average them in time, the head was placed in the etcher for a given time and then in water for OTDR reading and averaging for each data point. For the case of Fig. 7, we used the single head setup of Fig. 4, and we attempted to avoid artifacts introduced by the use of alternate solutions and employed an optical power meter for fast data reading and averaging, and thus the sensor head could remain immersed in the etcher during the entire measurement. These distinct procedures may lead to different residual clustering in the fibre facets, which can be the cause of the difference in the results of Figs. 3 and 7. It will be further investigated in the future.

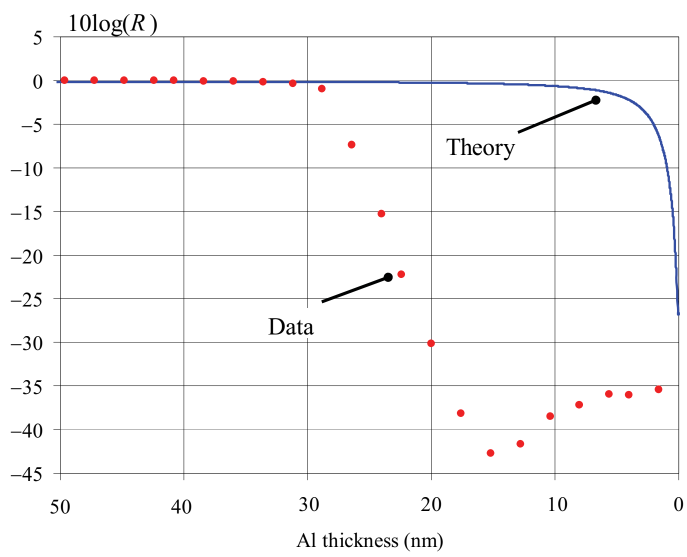


Fig. 7. Theoretical (line) and experimental data (dots) for the reflectance as a function of the Aluminium film thickness.

We also evaluated experimentally the maximum number of sensor heads our sensor system can support, and we found that it depends on the dynamic range of the OTDR. For the OTDR pulsewidth used to obtain the results shown here (10 ns) its dynamic range is about 7 dB. Since each coupler has an insertion loss of about 0.7 dB, we can have up to 10 sensor heads in this configuration. This can be verified from Fig. 2-a. One can see that as the number of heads increases along the fibre length the OTDR trace becomes noisier. This noisy trace should have impact on the accuracy of the measured corrosion rate for the heads located further away from the OTDR. On the other hand, for 500 ns pulsewidth the OTDR dynamic range is 20.4 dB, which allows the use of up to 30 sensing heads. In this case the OTDR spatial resolution is about 100 m. Therefore, the minimum separation between consecutive sensor heads should be of about 200 m. In this configuration the sensor system would cover a total length of 6 km, with a sensor head every 200 meters.

## 4. Conclusions

We proposed and demonstrated experimentally an optical fibre sensor for the corrosion process in metal (Aluminium) using the optical time domain reflectometry technique. We presented experimental results for the measurement of the corrosion rate of aluminium films in controlled laboratory conditions. The obtained corrosion rate matched the expected rate of the etcher used. We also evaluated experimentally the maximum number of sensor heads the system supports. It depends on the OTDR dynamic range and it has implications on the distance between consecutive sensor heads.

Our proposed sensor system is multipoint, self-referenced, has no moving parts (all-fibre) and can detect the corrosion rate for each head several kilometres away from the OTDR, thus making the system ideal for "in-the-field" monitoring of corrosion and erosion. This system may have applications in harsh environments such as in deepwater oil wells and gas flowlines (including from the presalt region), for the evaluation of the corrosion and erosion processes in the inner wall of the casing pipes. In this case, different materials can be deposited on the fibre facet to better match the pipe materials under corrosion/erosion. This system may enable inferred condition-based maintenance without production interruption, decreasing the cost of oil production, and substantially reducing the risk of environmental disasters due to the failure of unmonitored flowlines.

Our experimental results also revealed a feature that may indicate the occurrence of the surface plasmon effect at the metal-liquid interface. It could be due to the roughness coupling to surface plasmons at the metal-liquid interface as a thin and rough layer of metal may result during the etching process. Although we believe at this point that this effect is not vital for the operation of the proposed sensor, nor to the measurement of the corrosion rate, it will be investigated in future work.

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**Optical Fiber New Developments**
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The optical fibre technology is one of the hop topics developed in the beginning of the 21th century and could substantially benefit applications dealing with lighting, sensing and communication systems. Many improvements have been made in the past years to reduce the fibre attenuation and to improve the fibre performance. Nowadays, new applications have been developed over the scientific community and this book fits this paradigm. It summarizes the current status of know-how in optical fibre applications and represents a further source of information dealing with two main topics: the development of fibre optics sensors, and the application of optical fibre for telecommunication systems.