# FIBRE OPTIC SENSING SOLUTIONS FOR REAL-TIME PIPELINE INTEGRITY MONITORING

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## ABSTRACT

Fibre optic sensors offer a relatively new technology for the monitoring and evaluation of pipeline integrity and performance. The technology is gaining wide acceptance for monitoring infrastructure and is expected to play a major role in the realisation of real-time structural integrity monitoring systems, offering an advanced new generation of engineering sensors.

The author's company has developed and successfully applied several FOS technologies which could play a vital role in pipeline integrity and performance monitoring. In this paper, the author will give a brief overview of these technologies, outline potential applications of these technologies for the petrochemical industry and detail field applications and experience in utilising these technologies in pipeline applications.

## INTRODUCTION

Pipeline integrity and disturbance are generally not monitored due to the lack of any reliable and durable techniques. Generally, if something goes wrong with a pipeline (ie., cracking, corrosion, tampering, etc.) it is usually realised when the output flow is affected or a severe impact has been made on the surrounding environment (ie., explosion, fire, spillage/contamination, etc.). No information is available as to the type and location of the fault. Obviously, this is an inefficient and potentially costly situation. Not only has the flow of goods stopped, but the pipeline has to be excavated or raised in order to locate and investigate the fault. Furthermore, the environmental consequences could be devastating.

One of the major difficulties of monitoring pipelines stems from the fact that the pipes can vary in length from a few tens of metres to several hundred kilometres. Conventional conductive sensors have difficulties surviving the environments involved and they have electrical noise problems. Furthermore, conventional sensors are generally point sensing devices, thus requiring a large number of sensors to cover a long length of pipeline. The subsequent cost and complexity of such a system would thus be impractical. On the other hand, optical fibre communication cables have proven their capabilities and survivability in long-haul applications and hence fibre optic sensors should also be reliable in this application.

Fibre optic sensor technology has progressed at a rapid pace over the last decade. Many different sensing techniques have been developed to monitor specific parameters. [1] The author's company has developed and demonstrated a number of optical fibre systems which can be used in various applications in the pipeline industry. Some of these are highlighted in this paper.

## BACKGROUND

### Fibre Optic Technology

Communications using an optical fibre have a number of attractive features and advantages over conventional communication means. These advantages include the following: [2,3]

- Greater bandwidth and capacity
- Electrical isolation
- Low error rate
- Immunity to external influences
- Immunity to interference and crosstalk
- Signal security
- Ruggedness and flexibility
- Potential low cost

The high expectations of optical fibres as information carriers in communication systems have been justified by their performance over the past two decades. Due to their high bandwidth, low attenuation and mechanical properties, each fibre is capable of replacing over 1000 copper wires in telecommunication systems. With these characteristics it is no surprise that optical fibres have become the most affordable and efficient medium available in the field of telecommunications. Furthermore, the increased capacity, ease of system expandibility, and reduced installation, operation and maintenance costs of the technology, is also making a strong impact on the pipeline industry, replacing many of the traditional communication systems.

The monitoring of fibre cable integrity and the prediction of the onset of failure and damage is critical to the reliability of fibre communication systems, and, therefore, also to the operation of a pipeline system. Most current techniques for monitoring fibre optic cable integrity are based on static or slowly varying measurements using an optical time domain reflectometer (OTDR) (ie., sharp bends, fibre fracture, fibre attenuation, connector losses, etc.). However, it would be an added advantage to be able to obtain real-time, quasi-static and dynamic information about disturbances to the fibre cable. This would have the further advantage of monitoring any structure or material near the cable or to which the cable is attached, such as the pipeline itself. Such a capability enables simultaneous, real-time fibre optic communications and sensing applications such as structural integrity monitoring, leak detection, ground monitoring, machine condition monitoring and intrusion detection.

This is possible because optical fibres can be more than mere signal carriers. Light that is launched into and confined to the fibre core propagates along the length of the fibre unperturbed unless acted upon by an external influence. Specialised sensing instrumentation may be configured such that any disturbance of the fibre which alters some of the characteristics of the guided light (ie., amplitude, phase, wavelength, polarisation, modal distribution and time-of-flight) can be monitored, and related to the magnitude of the disturbing influence. Such modulation of the light makes possible the measurement of a wide range of events and conditions, including:

- Strain/residual strain
- displacement
- damage
- cracking
- vibration/frequency
- deformation
- impact
- acoustic emission
- liquid levels
- pressure
- temperature
- load

Different configurations of fibre sensing devices have been developed for monitoring specific parameters, each differing by the principle of light modulation. Fibre optic sensors (FOSs) may be intrinsic or extrinsic, depending on whether the fibre is the sensing element or the information carrier, respectively. They are designated “point” sensors when the sensing gauge length is localised to discrete regions. If the sensor is capable of sensing a measurand field continuously over its entire length, it is known as a “distributed” sensor; “quasi-distributed” sensors utilise point sensors at various locations along the fibre length. FOSs can be transmissive or can be used in a reflective configuration by mirroring the fibre end-face.

Therefore, FOSs are actually a class of sensing device. They are not limited to a single configuration and operation unlike many conventional sensors such as electrical strain gauges and piezoelectric transducers. Hence fibres are now replacing the role of conventional electrical devices in sensing applications to the extent where we are now seeing a multitude of sensing techniques and applications being explored for practical gain.

## Pipeline Monitoring

In a sensing application, the optical fibre should be installed such that the disturbing influence is coupled from the structure of interest to the fibre, thus altering some characteristic of the light within the fibre. Such modulation of the light makes possible the measurement of a wide range of events and conditions, many of which are useful for monitoring pipelines or their operational parameters.

FOS technology can be utilised to monitor pipelines because of its high resolution and it works in real-time, without electromagnetic interference problems. Furthermore, sensor lengths can vary between different devices; between point sensing configurations to very long sensing configurations (over 50 km long). In addition, they are made from a very durable material that is corrosion resistant (pure silica). This cost effective and unique technology is currently utilised in the monitoring and evaluation of a variety of structures and machinery such as aircraft, motors, generators, bridges and pavements.

Optical fibres have the ability to detect a wide range of physical, mechanical, chemical and biological parameters. Those particularly relevant to pipeline monitoring include: **strain-stress, vibration, acoustic-emission, pressure and temperature**.

Monitoring these parameters on pipelines should enable the detection and monitoring of:

| Excellent Potential | Good Potential (Needs R&D) |
|---|---|
| strains | cracking |
| deformations | wall thickness erosion |
| impacts | coating deterioration |
| digging | stress corrosion cracking |
| tampering | ground movement |
| pin-hole leaks | slope stability |
| seam leaks | |

These parameters may be monitored with fibre optic point sensors or with distributed sensors many kilometres long. Furthermore, using an optical radar technique (OTDR) along with a distributed FOS, it is also possible to accurately pinpoint the location of a disturbance or fault on a pipe. It must be emphasised, however, that the OTDR is only capable of locating static or quasi-static effects on the cable (ie., sharps bends, fibre fracture, connector losses, etc.), while a distributed FOS monitors, in the real-time, all the static and dynamic effects on the cable.

## CURRENT WORK BY FFT ON FIBRE OPTIC SENSORS FOR PIPELINE APPLICATIONS

FOSs are applicable to most situations where traditional sensors such as thermocouples, strain gauges, and accelerometers are employed or would be employed if their limitations were to be removed. Future Fibre Technologies Pty. Ltd. (FFT) is actively involved in investigating areas in which FOSs have good potential for condition monitoring of structures and machinery.

Over the past 5 years, FFT has built-up considerable experience in the field use of its fibre optic sensing technologies, both in Australia and overseas. For example, FFT's products have been used to:

- monitor structural integrity and concrete cracking on Melbourne's West Gate Bridge;
- monitor crack activity and growth on a wing component of Australia's F-111 bomber;
- monitor crack activity and growth on the pavement of Australia's National Highway near Canberra;
- perform vibrational analysis of high-power switch gear at a Power Facility in Sydney;
- demonstrate technique for detection of small-amplitude partial discharge activity in high-voltage generator stator bars;
- monitor security perimeter fences for intrusion/escape at two prisons in Australia;
- monitor gear-mesh ratios and shaft revolutions of gearboxes and drive-trains;
- perform weigh-in-motion sensing of vehicles on two Melbourne highways using sensors embedded in the pavement;
- perform weigh-in-motion sensing and wheel flat-spot detection of trains at a National Rail shunting yard in Melbourne and a section of the National Rail link between Melbourne and Geelong;
- perform long-term monitoring of structural integrity and loading of components in the new Blanchetown Bridge in South Australia;
- successfully demonstrate technique for measuring near field strains during blastings for the Australian mining industry;
- successfully demonstrate technique for monitoring simulated gas pipeline leaks; and
- recently complete a turnkey installation of a 110 km pipeline communication/sensing system in Indonesia.

The following sub-sections detail some of FFT's current interests in the pipeline and petrochemical fields.

### Simultaneous Communications and Distributed Vibration Sensing

The Foptic™ Vibration Sensor is a unique, patented device and system, which provides a simple, effective and inexpensive technique to detect and measure both dynamic and quasi-static strain levels (disturbances) in a non-intrusive way, directly and in real-time. The sensors are supplied with any desired length, from a point sensor to a distributed sensor for operation over very long distances (in excess of 50km). Furthermore, the Foptic™ Vibration Sensor System may be operated simultaneously with a communications system within the same optical fibre or cable, adding significant value to any communications system and enabling easy integration of the Foptic™ Vibration Sensor into an existing fibre optic network.

This sensing technique is based on the modulation of the modal distribution (effectively changing the intensity) in a multimode optical fibre by external disturbances. Therefore, the sensor response is a direct function of the disturbance on the sensitised portion of the fibre. The disturbance may be in the form of physical movement (ie., compression (radially or axially), elongation, twisting, vibration, etc.) or microphonic effects (ie., travelling stress waves or acoustic emissions). The current instrumentation is designed to operate in the <0.1 Hz to 100 kHz range. The high sensitivity and wide frequency bandwidth of the system should enable the monitoring of parameters detailed above, once the fibre is installed near or onto the pipeline such that the disturbing influence is efficiently coupled to the fibre. **Figure (1)** illustrates the general configuration of FFT's Foptic™ Vibration Sensor.

The ability to vary the sensing length to fit specific applications is a major and unique advantage of this technology. This is particularly relevant if long sensing lengths are required, as is the case when combining the sensing technique with fibre optic communications in pipeline applications. [4]

**Figure (2)** illustrates the configuration for a simultaneous fibre optic communications and sensing system. A vibrational disturbance was applied to a small section (5 cm) of the fibre link using a cantilever beam arrangement. The fibre was simply taped longitudinally along the beam length. A typical sensing response is shown in **Figure (3)** for singlemode (SM) and multimode (MM) fibre links. As can be seen, very good signal quality was obtained. In addition, the Fast Fourier Transform (FFT) clearly identifies the natural frequency of the beam to be ~18 Hz.

The vibrations demonstrated may be considered to represent dynamic pressure or loading disturbances on a pipeline, such as those caused by a vehicle or machine parked or working near a pipeline, ground movement, rock slides, a person or machine digging near the pipeline or even someone constructing shelter on top of the buried pipe, thus alarming the pipeline operator of potential problems before they become serious.

**Figure (4)** illustrates results for simultaneous, non-interfering communication and sensing system with a communications data rate of 50 Mb/s. A vibrational disturbance was applied to a small section (5 cm) of the fibre link using a cantilever beam arrangement. **Figure (4a)** illustrates the processed sensing signal (in the Fourier domain) with no perturbation applied to the fibre link. The eye pattern of the simultaneously received communications signal is also shown (inset). **Figure (4b)** illustrates the typical frequency-domain response of the sensing signal with a damped perturbation applied to any small section of the fibre link. The sensing channel detects the perturbation as discrete frequency components in the Fourier domain whilst the simultaneously received communication signal is unaffected, as shown by the unchanged eye pattern (inset).

The unique capabilities and competitive edge of this technology has helped FFT to win a large contract for the turnkey installation and commissioning of a 110km pipeline communication/sensing system in Indonesia. The communications system will provide all the voice and data communications required for the operation of a large gas plant and the sensing system will be used for intrusion/tampering alert monitoring. The photograph below pictures FFT staff during the cable installation.

## Securing Communications and Infrastructure

The use of optical fibres as the main backbone of most communication systems has meant that large amounts of information can be efficiently and cost effectively transferred from point to point. Although it was initially thought that optical fibre transmission would be inherently secure, we now know that it is relatively easy to 'tap' into an optical fibre with negligible interference to the optical signal. This can have serious security implications for users of optical fibre communication systems, especially telecommunications carriers, banks, defence organisations, embassies, government organisations, museums, galleries and manufacturing plants, to name a few.

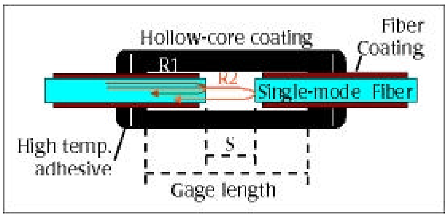
A proprietary and patented fibre optic sensing technology has been developed by FFT and is capable of simultaneously utilising a fibre optic communications cable as a tampering-alert, intrusion-alert or integrity-testing sensing cable, thus providing continuous, real-time monitoring of the fibre cable and any structure near the cable (ie., ground, tunnels, ducts, pipes, buildings, equipment, vessels, etc.).

The Fibre Optic Secure Link (FOSL™) system is a special adaptation of FFT's Foptic™ Vibration Sensor and has the capability of detecting both small and large intrusive disturbances on an optical fibre cable in real-time. This truly distributed security sensing system is unique as it also can be simultaneously retrofitted and integrated into an existing fibre optic communications cable, without requiring the installation and cost of a new cable. The FOSL™ can also be adapted for many other security applications such as perimeter fence security and pipeline infrastructure security.

The system offers real-time distributed monitoring, with dual, time-base and frequency-base alarming operation, adjustable sensitivity and event analysis, SMTP connectivity, messaging and alarming and audible alarming. The photograph below pictures a two-channel FOSL™ system in operation.

## Absolute Displacement/Strain Sensing

FFT has seen the need for point strain sensors that will work accurately in extreme conditions and for extended periods of time. As a result, it now includes the Foptic™ Absolute Displacement/Strain Sensor in it's product range. The sensor cross-section is shown in the diagram below:




This technology is self-referencing and requires no calibration to measure the absolute gap length (S) in a fibre optic interferometer cavity. If the sensor Gage Length is known, the system automatically provides absolute strain measurements.

Interferometric fibre optic sensors are very attractive measuring devices due to their high accuracy and dynamic range. The Foptic™ Absolute Displacement/Strain Sensor consists of a universal module for detection and demodulation of output signals from fibre optic interferometers. To our knowledge, FFT's Foptic™ Absolute Displacement/Strain Sensor offers one of the most sensitive and accurate point sensing systems commercially available in the world, yet is less complex and lower cost than other fibre optic sensor systems based on similar principles (due to our unique optical arrangement and signal processing). The method provides absolute, accurate, unambiguous and reliable measurement and control of different physical parameters, such as displacement (1 nm), strain (<1 $\mu\varepsilon$), pressure, force and temperature.

## Distributed Temperature Sensing for Gas Pipeline Leak Detection

Until recently, cost effective distributed temperature sensing has been limited to the use of a large array of point sensors such as conventional thermocouples. This can be costly and complicated. The Fibre Optic Distributed Temperature Sensor (DTS) system, based on OTDR and Raman analysis, allows continuous temperature measurements along the entire length of an optical fibre, and any surface or structure which the fibre is attached to. The end result is a true measurement of the temperature profile along the entire length of the sensor. Typical measurement performance is summarised in the table below:

| Range | Temperature Resolution | Measurement Time |
|---|---|---|
| 2 km | 0.5°C | 30 secs |
| 2 km | 1.0°C | 15 secs |

| | | |
|---|---|---|
| 4 km | 0.3°C | 60 secs |
| 4 km | 1.0°C | 15 secs |
| 8 km | 1.0°C | 300 secs |
| 10 km | 1.5°C | 600 secs |

A spatial resolution down to 0.25 m is possible, depending on sensor length.

The DTS sensor is robust and highly resistant to the usual environmental problems of corrosion, heat stress, and electrical and radiation interference. It is also immune to magnetic field interference, large pressure variations and even to naked flames for short durations. Conventional gauges may be badly affected by all these natural conditions.

In a gas pipeline application, Gaz de France has shown it to be possible to accurately detect and locate localised cold-spots caused by a pin-hole leak. [5] Similarly, it is feasible to be able to detect and locate a blockage in the pipeline caused by frozen contents.

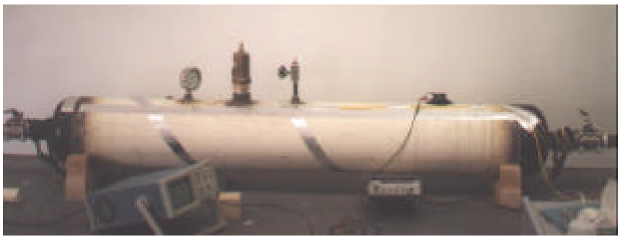
**Distributed Microphonic Sensing for Gas Pipeline Leak Detection**

The Foptic™ µStrain™ Sensor is a unique device and system providing a simple, effective and inexpensive technique which is especially well suited for high sensitivity, very wide frequency bandwidth (designed for 0 Hz to 1 MHz and tested to over 110 kHz) and low-level strain, microphonic, acoustic emission and partial discharge detection and monitoring. To our knowledge, the Foptic™ µStrain™ Sensor is one of the most sensitive distributed fibre optic sensors commercially available, it is less complex and lower cost than other fibre optic sensor systems based on similar principles (due to our unique optical arrangement and signal processing), it is simple to use and is immune to electromagnetic interference.

The sensors are supplied with any desired length, from a point sensor to a distributed sensor for operation over long distances (in excess of 5km).

The Foptic™ µStrain™ Sensor System has been shown to be have good potential to detect pin-hole leaks in gas pipelines. FFT's in-house simulated leak tests (see photograph below) have shown that a distributed Foptic™ µStrain™ Sensor can act as a very long microphone with a very wide frequency bandwidth, enabling it to be highly sensitive to high-frequency vibrations generated by pressurised gas escaping from a pin-sized hole in a pipe.

As illustrated by the frequency spectrum of actual results shown in **Figure (5)**, these high-frequency vibrations were found to occur well above the frequency range of normal environmental noise, making it possible to high-pass filter all undesired signals from the sensor response.



**Flow Sensing**

The principle of operation is to have a fibre optic Bend Sensor, mounted as a cantilever with an appropriate paddle or dragbody, to be deflected by the force of a liquid or gas flow stream. In such an arrangement, the output of the sensor varies as the square of velocity, increasing proportionally with the area of the paddle and the distance of its centroid from the sensor.

In the standard sensor configuration, a fibre bend sensor device is mounted in a very small loop configuration on a thin solid metal rod. This looped rod is then inserted inside a 1/8" OD stainless steel tube, which is filled with urethane and capped near the end with a weld. The end of this sealed tube is threaded in order that a solid rod of desired length actually extends into the flow path. This effectively comprises the bend sensor and extender, to which could be fitted a larger drag body at the end, if required. In this fashion, the sensor length may be easily modified on site to suit the application, and should the extension rod become worn or damaged over time it could be unscrewed from the sensor and replaced. The 1/8" OD stainless steel tubing extends out of the hermetically-sealed opto-electronics package. The device is then installed directly into a pipeline using a single swage lock fitting, with the sensor loops just inside the fitting, where the bend is at a maximum, and the opto-electronics cylinder outside the fitting, resulting in an inherently safe device which can withstand relatively high pressures. In this configuration, it is possible to adjust the sensor response by rotating the sensor tube, as bending will vary the response as the cosine of the rotation.

Alternate sensor configurations may also be developed for a specific application in order to satisfy a required or appropriate range, accuracy, pipe fitting, dragbody, operating temperature and linearisation scheme.

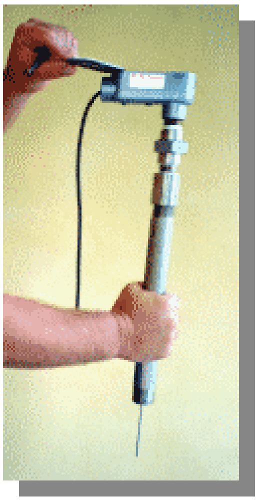
The Flow Sensor offers unique advantages over conventional flow sensors, including:

- inherent safety (no electrical current or signal present);
- bidirectionality;
- high speed of response with no time delay;
- ease of changing range;
- accuracies of 2-4 percent can be expected;
- less tendency to clog; and
- simplicity of the mechanical assembly of the device.

Example applications where these sensors have been used, include:

1. Eastman Kodak, of Rochester, NY, USA, have used the Flow Sensor to measure airflow in an explosive environment for process control. They were able to detect and diagnose turbulence and its cause. They were particularly impressed with the wide dynamic range, sensitivity, speed, and bipolar response.
2. General Motors (Delphi Engine and Energy Management Division), in Rochester, NY, USA, who used the Flow Sensor as part of a fuel cell engine development project. The sensors were prototypes destined for hydrogen flow measurement.
3. Ballard Power, of Vancouver, BC, Canada, who used the Flow Sensor to measure hydrogen flow in a fuel cell engine (world famous joint project with Daimler Benz for a fuel cell bus).
4. Milltronics Inc., of Peterborough, ON, Canada, evaluated the Flow Sensor for process flow measurement and sponsored a project to characterise them for flow in pipes. In this work, a careful comparison of the Flow Sensor vs. a conventional paddlewheel sensor was performed. Benefits included less tendency to clog, bidirectional signal, no time delay (several seconds for the paddlewheel sensor), and simplicity of mechanical portion.

Currently, the Flow Sensors are undergoing field trialing with clients in pipelines in the oil and sugar cane industries. The photograph below pictures the Flow Sensor configuration for this work.



## CONCLUSIONS

Fibre optic sensors offer a relatively new method for the measurement of many parameters. They possess several clear advantages over many existing conventional sensors and are slowly gaining attention in industry. The cost of fibre optic systems is rapidly decreasing and sensing techniques are being refined. As a result, fibre optic sensors will soon be accepted as a reliable and inexpensive measurement tool in many sensing applications.

The use of fibre optic sensing technology for the monitoring and diagnosis of the condition and performance of pipelines could provide a sound engineering and economic basis for the major decisions which will have to be made concerning the operation, maintenance, refurbishment or replacement and life extension of these items. The savings made by avoiding or delaying refurbishment or replacement could be substantial. Furthermore, their high resolution, insensitivity to electromagnetic interference, real-time monitoring capabilities and relatively low cost are characteristics expected to improve pipeline safety and operation, and provide great potential benefit to the industry and society as a whole.

Communications using optical fibres have a number of attractive features and advantages over conventional communication means, and their performance has been proven over the past two decades. The value offered by these systems has now been augmented by the ability to simultaneously monitor, in real-time, the integrity of the cable, as well as any structure or material near the cable or to which the cable is attached.

This attractive and useful new feature should increase the demand for the technology.

## ACKNOWLEDGMENTS

The author would like to thank the Australian DIST Office of AusIndustry for their valuable support.

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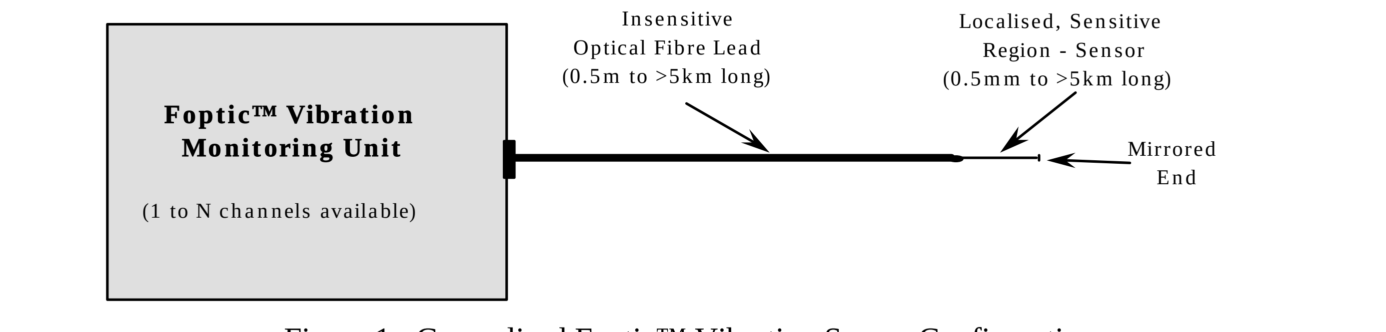



Figure 1: Generalised Foptic™ Vibration Sensor Configuration.

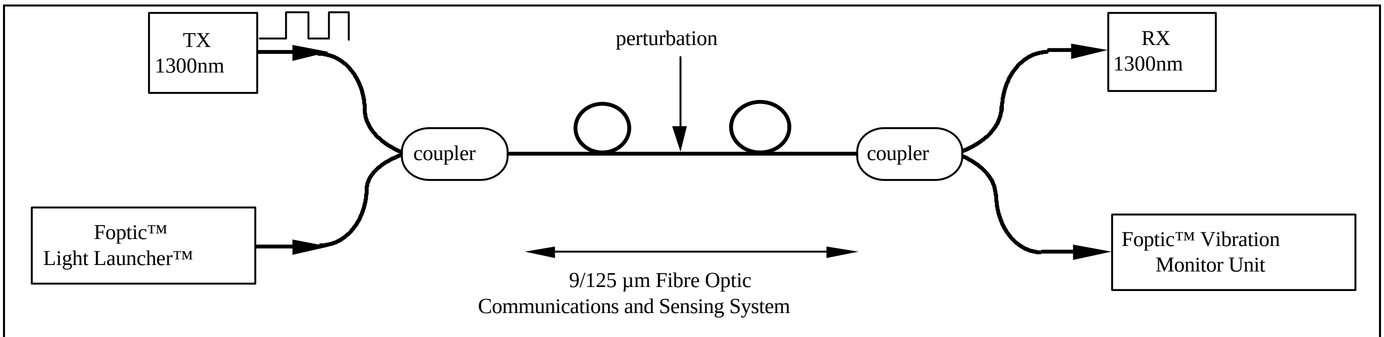



Figure 2: Simultaneous fibre optic communications and sensing system.

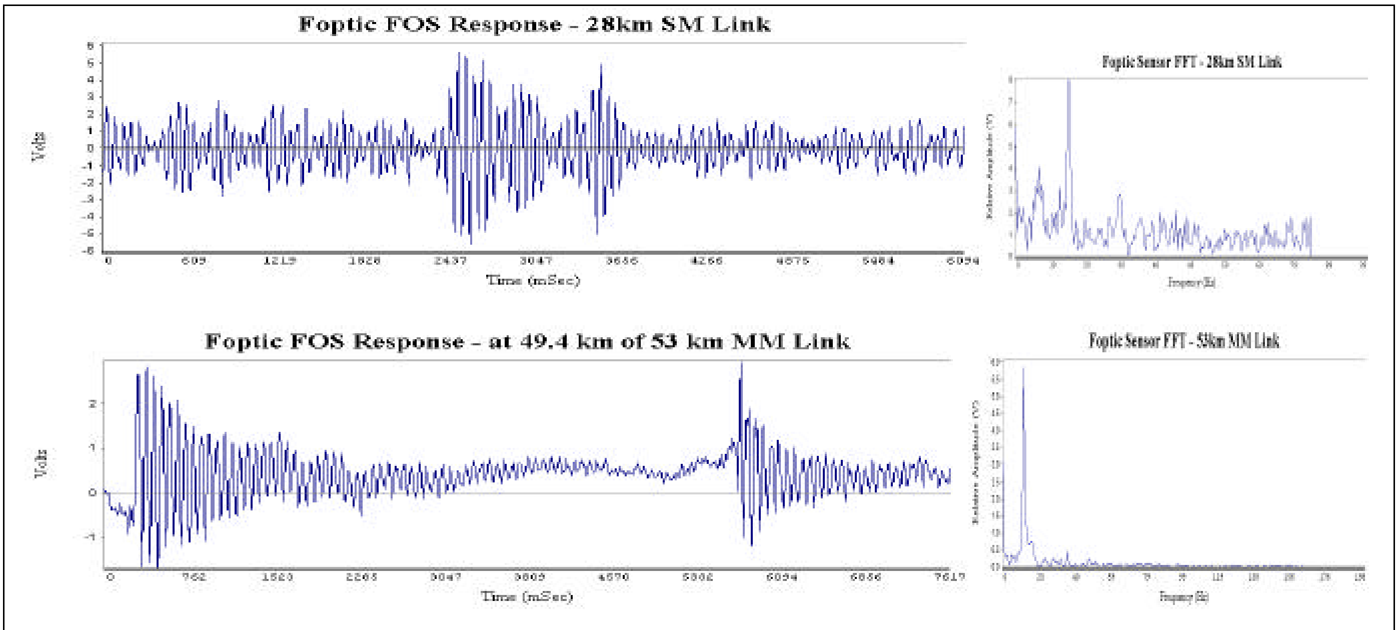
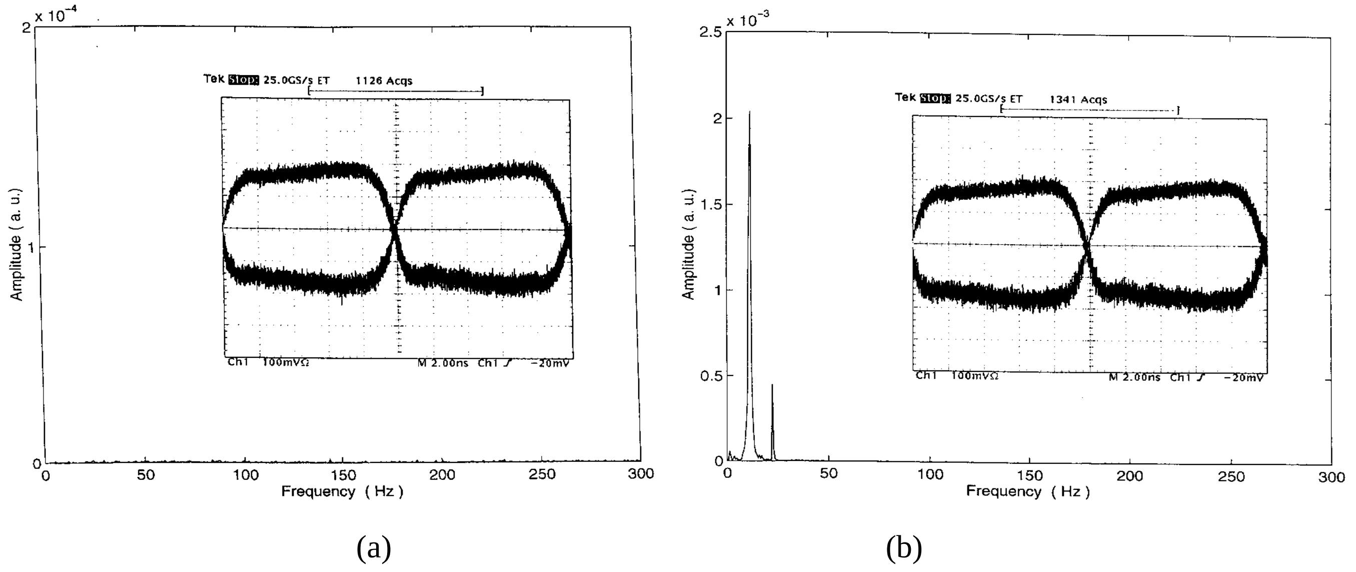
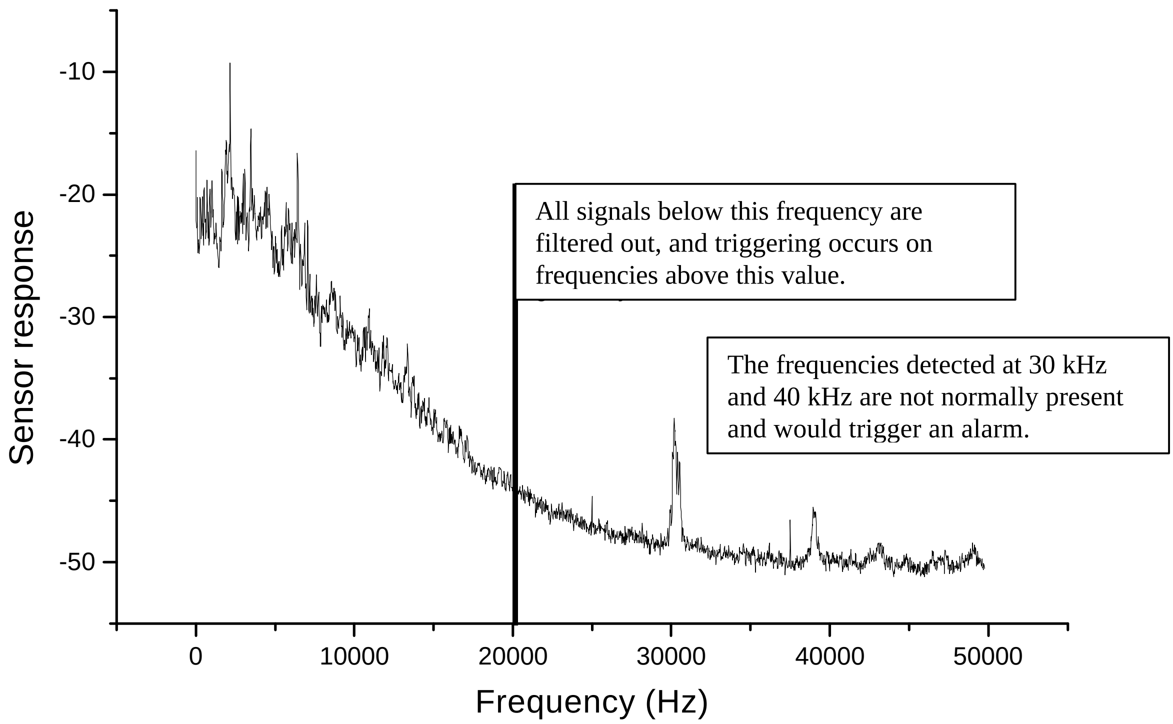



Figure 3: Foptic™ Vibration Sensor response for 28 km SM and 53 km MM link.




<u>Figure 4:</u> Response of simultaneous fibre optic 50 Mb/s communications and SM sensing system.




<u>Figure 5:</u> Frequency spectrum of actual results of simulated pipeline leaks detected with Foptic™ µStrain™ Sensor.