Low Phase Noise Lasers:

Fiber Optic Seismic Sensing Systems & The Missing Link

Sensilaser Technologies Inc.

Abstract

Permanent seismic monitoring is a new and emerging application with the potential and capability to significantly increase the amount of hydrocarbons ultimately recovered from an oil or gas reservoir. Permanent monitoring systems typically comprise a series of ocean bottom cables containing thousands of electronic geophones and hydrophones. However, once installed on the ocean bottom electronic systems are prone to leaks, corrosion, sensor degradation all of which lead to reliability problems which are difficult and costly to maintain. On the other hand optical systems are totally passive (no moving parts) and require no subsea electronics or high voltage cables, as such are ideal for permanent reservoir monitoring. Fiber optic systems are not new. For many years they have been deployed by the military in similar applications for antisubmarine warfare and area surveillance. The technology is proven and well understood. In addition to reliability, fiber optics offers the potential for improved data quality and lower costs.

Key components in a fiber optic permanent monitoring system are **low phase noise laser** sources and highly **sensitive fiber optic sensors** (e.g. hydrophones & geophones). The performance of the sensors is largely dependent on the phase noise level (frequency jitter) of the light source as well as the source's insensitivity to environmental vibrations, particularly at low frequencies. With today's laser sources these two attributes tend to be mutually exclusive, hence industry's tendency to focus on finding ways to reduce the sensitivity of fiber lasers to vibration, which is easy at high frequencies, but next to impossible at low frequencies, the seismic region of interest. **Sensilaser** has overcome this issue and developed a compact laser source that combines vibration insensitivity and low phase noise into a single and scalable package.

Keywords: laser phase noise, vibration sensitivity, fiber optic seismic sensing, oil/gas exploration, Life of Field Seismic, Ocean Bottom Cables, Permanent Reservoir Monitoring, 4D & 4C seismic.

1. Introduction

Over the next 50 years, the world's energy needs will double or triple thus increasing the pressure on exploration companies to increase their reserves, which is possible through more efficient production and finding undiscovered hydrocarbons. Compounded by the fact that all the easy oil has been found, the exploration industry is constantly challenged to push its boundaries and explore for new hydrocarbons in ever more challenging and remote environments. According to Dr. Fatih Birol, Chief Economist at the International Energy Agency, meeting this challenge, over the next 30 years, will require investment of as much as

$16 Trillion in areas such as infrastructure (new and old) and the research and development of new and improved exploration and production techniques. (Fatih et al, 2003).

A key need is the management of existing reservoirs, which once depleted still contain, on average, 65%-75% of the oil and gas originally found. Therefore, the simplest, most cost effective, quickest and least risky way to increase the supply of hydrocarbons is to improve the ultimate yield from existing reservoirs, as well those yet to be discovered. These are some of the main factors driving the interest in permanent seismic reservoir monitoring (PRM). However, PRM itself brings a unique set of challenges, which is the reason for the move to and the growing interest in fiber optic based systems.

Seismic surveying is a technique to determine the detailed structure of the subsurface. It involves sending acoustic shock waves (seismic energy) into the subsurface and measuring the weak seismic energy (Figure 1) reflected by each of the different layers of rock. Until recently seismic had been viewed and used primarily as an exploration tool, rather than a reservoir management tool. However, over the last decade or so it has been clearly demonstrated that seismic is a valuable reservoir management tool which can be used to significantly increase ultimate yield, while at the same time lowering costs. In terms of PRM, Ocean Bottom Cables (OBC) are deployed permanently on the ocean bottom and used to acquire 4D and/or 4C seismic data, pretty much on demand throughout the life of the field. Hence the term, Life of Field Seismic (LoFS). The benefits of PRM speak for themselves; fewer wells required, fewer dry holes drilled, faster production rates, significant increases in ultimate recovery and lower costs. PRM is foremost about better and more efficient management of a scarce and finite resource. According to Van de Vijver, moving forward, innovation in seismic technology is now recognized as the crucial area for exploration and production (Van de Vijver et al, 2003).

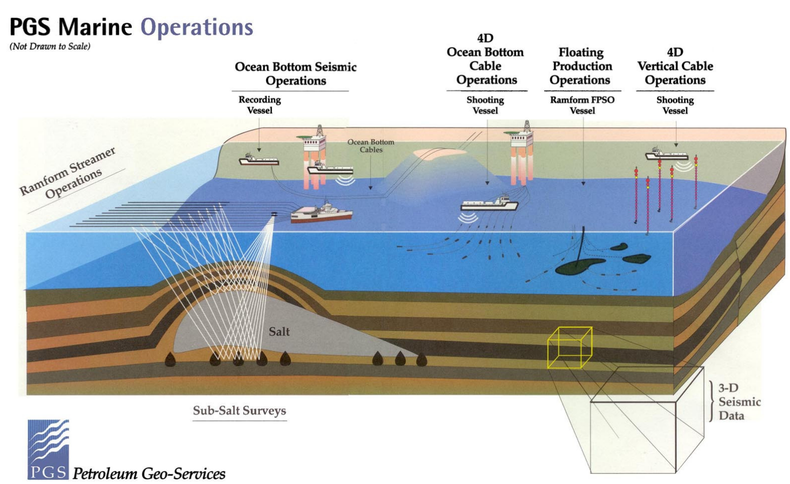


Figure 1: Illustration of Fiber Optic Sensors In Oil & Gas Applications (Source: PGS)

2. Fiber-optic Based Seismic Sensor Systems

One might ask why fiber optics, when incumbent electronic systems work well and have been around for years. Well the answer lies in the fact that electronic systems are expensive to build, and in water susceptible to failure making them very expensive and difficult to maintain. Additionally, electrical seismic systems are not well suited for in-well installation due to the hostile environment (high temperature, corrosive and extremely high pressure environment). Fiber-optic systems don't suffer the limitations of electronics and as a result are emerging as the future technology. Fiber optics offer many advantages: light weight sensors, no subsea electronics or high voltage cables; and, scalability that can accommodate tens of thousands of sensors. Since they are passive optical arrays maintenance is lower, reliability higher they can be towed behind a boat, permanently installed on the ocean bottom, on land, or in-well.

The core components in a fiber optic seismic system are sensitive fiber optic sensors (e.g., accelerometers/geophones and hydrophones) which sense based on **interferometric** principals, and the **laser source** which serves as a signal carrier.

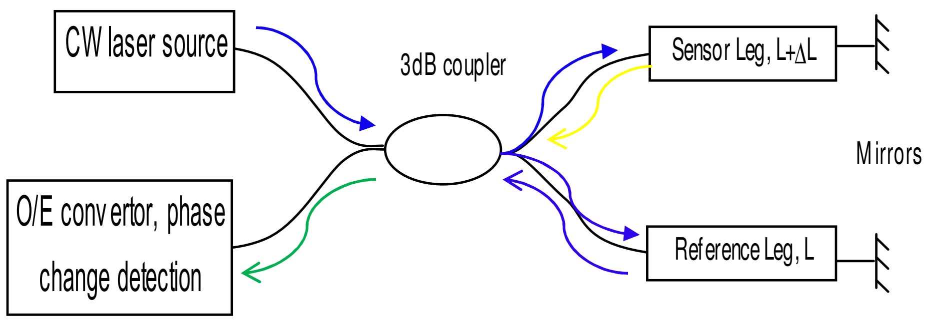


Fig. 2: Typical fiber optics sensor based on a Michelson interferometer

The lasers and sensors can be as much as 60% of the system costs. Hydrophones and geophones are typical interferometric fiber optic sensors. The hydrophone is typically a Mach-Zehnder or Michelson fiber optic device (Figure 2). Laser light enters the sensor and is split into two arms: one sensing and the other reference. The sensing arm consists of fiber wound onto a hollow air-backed cylinder, and the fiber on the reference arm is wound around a solid mandrel that is insensitive to pressure variations. As the pressure changes around the hydrophone, the hollow cylinder changes its diameter (very slightly), resulting in changes in the length and refractive index (to a much less degree) of the sensing fiber. Any variation in the relative path length between the sensor and the reference sides will show up as **PHASE CHANGE** in the recombined light signal emerging from the sensor. Hydrophones (geophones to a lesser degree) are also used for military applications (antisubmarine warfare), where they are used as seabed arrays for area surveillance, towed arrays behind surface ships or submarines (seismic streamers), and submarine hull mounted arrays (Cranch et al).

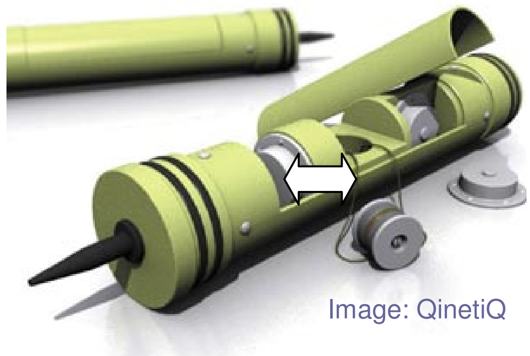


Figure 3: Interferometer based fiber optic sensor

3. Application Requirements

Obviously the laser needs to be CW (continuous wave), single frequency and single polarization. In addition its coherence length needs to be sufficiently long in order for the sensor to show high contrast output interference patterns. For seismic sensor applications, the phase noise of the laser source in the low frequency range is of critical importance (Nash et al) since the seismic signal is usually collected between 1 Hz and 500 Hz. A laser source with high phase noise in this frequency range reduces the seismic sensor's useful dynamic range. Laser phase noise is characterized simply by sending laser light into an ultra-stable interferometer and measuring any changes in phase in the output from the interferometer

Laser suppliers measure the laser linewidth and provide linewidth specifications to their customers. Industry is accustomed to the terminology of linewidth which is useful for seismic applications since linewidth is directly related to phase noise. The narrower the linewidth, the lower the laser's phase noise. However, the relationship between linewidth and phase noise is complicated at low frequencies due to significant contributions from 1/f or 1/√f noise (Little et al).

The phase noise level of telecom grade semiconductor lasers is too high and as a result they have not been considered as a potential source. Today only solid-state lasers and fiber lasers have phase noise levels low enough to be used with seismic systems. However, even though phase noise levels are very low, they are highly susceptible to environmental perturbations (vibration, noise, temperature), which has the detrimental effect of increasing phase noise levels. The optimum laser source has low phase noise and vibration insensitivity, is compact, has high output power (e.g., 30mW), tunable and low cost. Neither solid-state lasers, nor fiber lasers meet these requirements.

While package size and power consumption requirements for seismic, are not as critical as for telecommunications applications, compact and low power consumption are important from the perspective of efficiency and the limited space available on a rig.

Available Lasers	**Phase Noise**	**Vibration insensitivity**	**Linewidth**
GeoLaser	☺ ☺ ☺ ☺ ☺	☺ ☺ ☺ ☺ ☺	☺ ☺ ☺ ☺ ☺
Fiber Laser (DFB type)	☺ ☺ ☺ ☺ ☺	☺	☺ ☺ ☺ ☺ ☺
Fiber Laser (FP type)	☺ ☺ ☺ ☺ ☺	☺ ☺	☺ ☺ ☺ ☺
Fiber Laser (other type)	☺ ☺ ☺ ☺ ☺	☺	☺ ☺ ☺ ☺
Extended Cavity Laser	☺ ☺ ☺ ☺	☺ ☺	☺ ☺ ☺
Telecom DFB laser	☺	☺ ☺ ☺ ☺ ☺	☺

Phase noise requirements are demanding, with typical linewidth requirements below a few KHz or better. Many applications or system designs require even lower phase noise (i.e., linewidth of <1 KHz) with fiber lasers and Nd-YAG solid-state lasers considered the only options. Unfortunately, once in the field, these types of laser source tend to be unstable and problematic due to reasons described earlier.

The other option is the semiconductor laser developed for telecom applications. Telecom lasers are proven in terms of reliability and have many of the key properties required by fiber optic seismic applications and described above. They are insensitive to vibration, compact, have high power output, and are very efficient, tunable, as well as cheap. In addition, these are high reliability devices, having been designed for twenty years of uninterrupted service life. However, most semiconductor lasers do not meet the low phase noise performance demanded by interferometric applications.

4. Sensilaser Low Phase Noise Lasers

4.1 Technical Performance

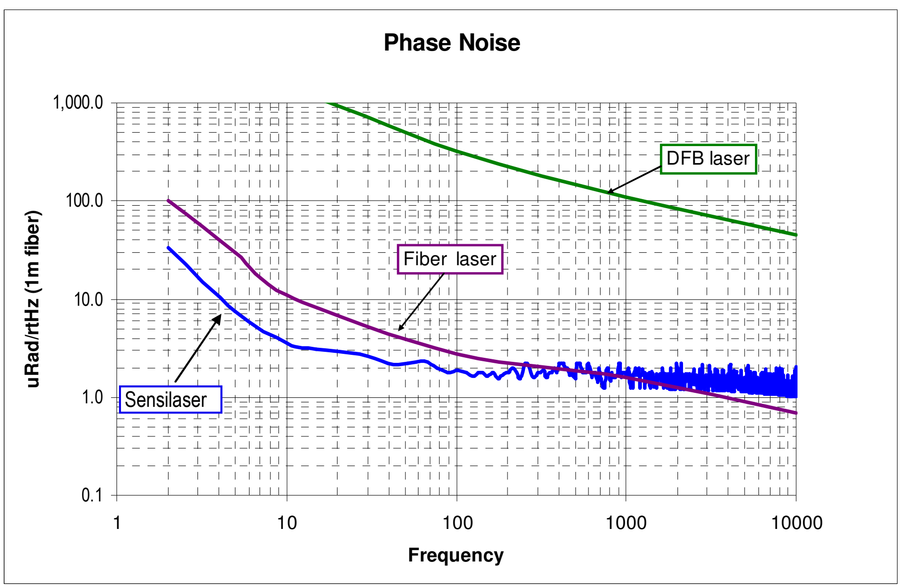
In order to satisfy the requirements for seismic systems and with a focus on reliability, Sensilaser developed a low phase noise laser **(GeoLaser)** source with very low sensitivity to environmental disturbances.

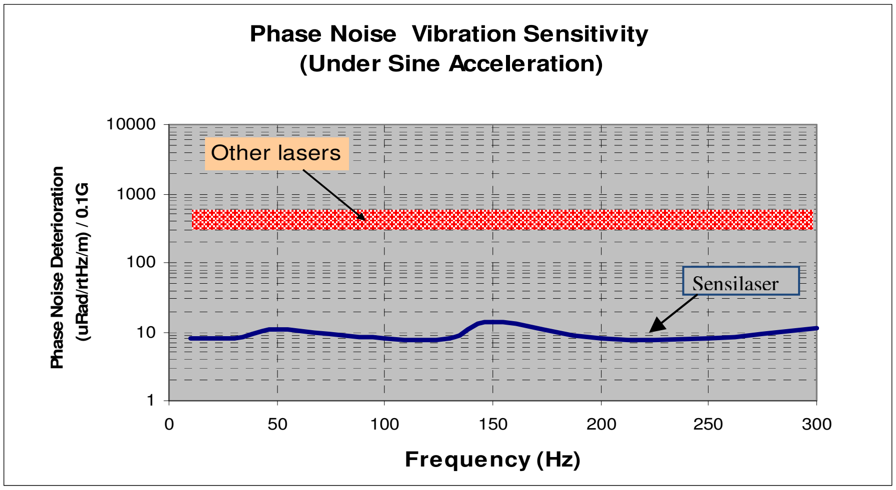
The key characteristics of Sensilaser's GeoLaser are:

- Very low phase noise level: <3 uRad/√Hz/m.
  - Equal or better than the best fiber lasers and 40-60 dB lower than telecom DFB lasers.
- Insensitive to environmental noise (temp & vibrations) -
  - orders of magnitude better than fiber lasers
- Low power consumption.

4.2 Experimental Results

The graph below shows the phase noise of a GeoLaser compared with the typical phase noise level of a 500 kHz DFB laser and 1 kHz fiber laser.





The graph above demonstrates quite clearly the exceptional robustness of un-damped GeoLaser in a noisy environment, showing vibration insensitivity orders of magnitude better than any other low phase noise laser.

5. Conclusions:

Sensilaser's unique vibration insensitive low phase noise laser (GeoLaser) is the first laser available offering both vibration insensitivity and very low phase noise in a single package. It meets performance and cost requirements, and is therefore expected to make a significant contribution to the performance and reliability of fiber optic seismic systems and accelerate adoption by the exploration and production industry.

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