Optical noise of a 1550 nm fiber laser as an underwater acoustic sensor.

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Abstract.

The goal of this presentation is to provide first results concerning the optical noise of a fiber laser used as an underwater acoustic sensor: hydrophone. The main sensor characteristics are: -1): A sensitivity allowing to detect all noise levels above background sea noise (the so-called *deep-sea state 0*). Among other applications, one may mention: seismic risk prevention, oil prospection, ship detection, etc. –2) : An optical noise reduced to its minimal value: it is the lower bound below which no acoustic pressure variation is detectable.

We therefore present here the first results for the expected sensitivity of the acousto-optic sensors, the frequency and amplitude of optical noises induced by the fiber laser and all the devices on the optical line. These results exemplify the possible detection of signal levels as low as the *deep-sea state noise 0*, especially for low frequency bandwidths, from several Hertz up to several kiloHertz.

Keywords: **Distributed FeedBack Fiber Laser, Optical Noise, Underwater, Acoustic Sensor, Deep Sea State Zero.**
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INTRODUCTION

The detection of underwater signals and noises has a large number of applications in geological observations [1,2]. It can be used for the observation of geologic movements, associated to seismic events. Underwater acoustic testing is of primary importance for off-shore oil prospection. It can also be used to detect the motion of ships. Piezoelectric systems have been used since several decades as hydrophones. Their main qualities for this application are their small volume and their mechanical simplicity, leading to robust sensor elements. However, their sensitivity is limited, of the order of 1mV/Pa, when the deep-sea state noise 0 is in the µPa range [2].

Sensors based on optical fibers have well known advantages over conventional electromechanical sensors. They offer electrically passive operation and immunity from electromagnetic fields because the fiber is entirely made with dielectric materials. The principle of the commercial passive fiber optic hydrophones is to measure the change of length of an optical fiber which is induced by a variation of hydrostatic pressure associated with the acoustic waves. To achieve the necessary

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sensitivity, a fiber of a few hundred meters must be used. This fiber must be supported by a mandrel producing a large deformation with hydrostatic pressure. With such hydrophones, high sensitivity and wide dynamic measurement range can be achieved allowing the detection of the deep-sea state noise 0. They have multiplexing capabilities for a quasi-distributed measurement configuration by using a single optoelectronic control unit. Remote measurement is also possible. Indeed, the very low signal attenuation (0.2 dB/km from 1.48μm up to 1.55μm) makes it possible to place the optoelectronic control unit several kilometers away from the measurement point. However, the mechanical system allowing achieving the required sensitivity is complex, which reduces the durability and makes it difficult to use the hydrophone under elevated hydrostatic pressures in deep sub-marine investigations. This also leads to an elevated cost. More recently, laser fiber hydrophones have been proposed. They have very small dimensions (diameter of 125 μm and length varying from 5 cm up to 10 cm for a standard bare fiber)[2]. One of the problems to be solved is to reach the necessary sensitivity for deep sea state noise 0 detection with simple mechanical systems. Moreover, the free running relative intensity and frequency optical noise of the laser can limit the performance of deep sea detector systems [2,3].

For the first time, the dependence on relative intensity and frequency optical noise detected of distributed feedback fiber laser (DFB FL) used as sensor versus acoustic frequency is shown. We also discuss the acousto-optic sensitivity of the sensor. We show that the performances that can be reached make fiber lasers suitable for acoustic detection of seismic risks, tsunami prevention and oil prospection with large deep-sea detectors.

DISTRIBUTED FEEDBACK FIBER LASER

The studied sensor we are concerned with is a fiber-laser based deep-sea hydrophone. Its basic principle lies in the measurement of a laser emission frequency from an erbium-doped optic fiber, with two imprinted mirrors acting as an optical cavity. The length variations of the fiber, proportional to the acoustic pressure levels, induce a change in frequency of the emitted light. To allow for an accurate detection of these length variations, the fiber laser is embedded into an acoustic/mechanical device whose aim is to amplify strains arising from acoustic waves. Such a device is shown in Figure 1.

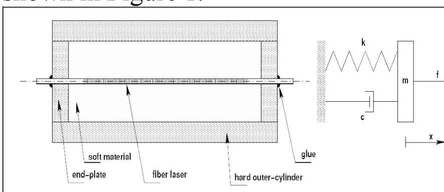

FIGURE 1(a) Acoustic amplification after [1]

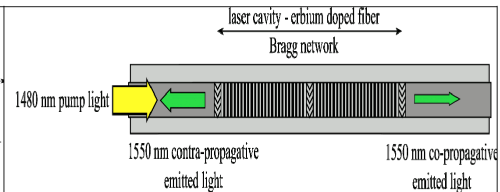

FIGURE 1 (b) DFB FL sensor

<u>Acousto-optic sensitivity S_{AO}</u>

The deformation of the DFB fiber laser is small when a bare fiber laser is placed directly in water. Its sensitivity can be increased by using an acoustic amplification as shown in figure 1 [2]. Typically we have calculated that for underwater surveillance applications, an amplification of the sensitivity of about 500 – 1000 times is required to approach the deep sea state zero noise level in the sea.[1,2] The sensitivity can be expressed for the general case of an acousto-optic amplification by:

$$S_{OA} = \frac{\delta\lambda_B}{\delta p} = (\frac{\mathrm{A}}{\mathrm{k}}).(\mathbf{0,78}.\frac{\lambda_B}{L_{FL}}) \quad (1)$$

where A is the sensitive surface area, k is the fiber stiffness, λ_B is the wavelength and L_{FL} is the DFB laser length equal to 5 cm, S_{AO} is the sensitivity parameter of the overall device. Indeed, the sensitivity S_{AO} depends both on the DFB grating distortion due to axial strain, and to the dependence of the optical properties of the material on the strain state, due to the elasto-optic couplings [2]. The mechanical amplifier can be made at least with two technologies: (i) for medium-range depth (up to 500 m), a suited compliant mechanism with a large amplification capability, such as the one in Figure 1 can be used (several devices are mentioned in the literature [3,4]); (ii) for large-range depth (up to 5000 m), a more robust design, though less sensitive must be constructed. The mechanical device that we have designed provides the necessary amplification[2].

EXPERIMENTAL SETUP

The experimental apparatus is described in Figure 2. The excitation power is produced by a laser pump located on an emission/reception station on shore. A transmission fiber, whose length may be up to several dozens of kilometers, guides the pump power (with a 1480 nm wavelength) up to the fiber lasers acting as sensors. These fiber lasers emit a backtracking beam with a different wavelength. In order to increase the detection area, several sensors may be located on the same line, provided that they all respond with different wavelengths, close to 1550 nm. Once they reach the reception station, the different signals are first separated with a wavelength demultiplexer, and second, driven to a Mach-Zehnder interferometer (MZI) shifted by using a line of 300m optical fiber that detects both the acoustic signal frequency and the optical noise generated by the fiber laser. To improve the phase detection, the two separated beams in the interferometer are modulated with an oscillator which delivers a frequency of 100 MHz and we use a phase-meter and a fast Fourier transform (FFT) analyzer for low frequency analysis of the main signal and optical noise for homodyne detection. The oscillator is connected to both the acousto-optical modulator (AOM) and phase meter to fix the phase to that of the AOM in Figure 2 [2, 3]. The MZI converts the pressure-induced wave-length shift of the radiation emitted by the DFB fiber laser, into a phase delay which is a function of the FL output wavelength shift $\Delta\lambda$ and of the optical path difference OPD = n_{eff}. L, where L is the length unbalance between the two interferometer arms.

$$\Delta\phi = n_{eff}.(\Delta k).L = \frac{\mathbf{2}\pi n_{eff} L}{\lambda^{\mathbf{2}}}.\Delta\lambda \qquad (2)$$

$\Delta\phi = \phi_s + \delta\phi$, where ϕ_s is the phase delay related to the pressure induced wave length shift and $\delta\phi$ is the noise component associated with the signal.

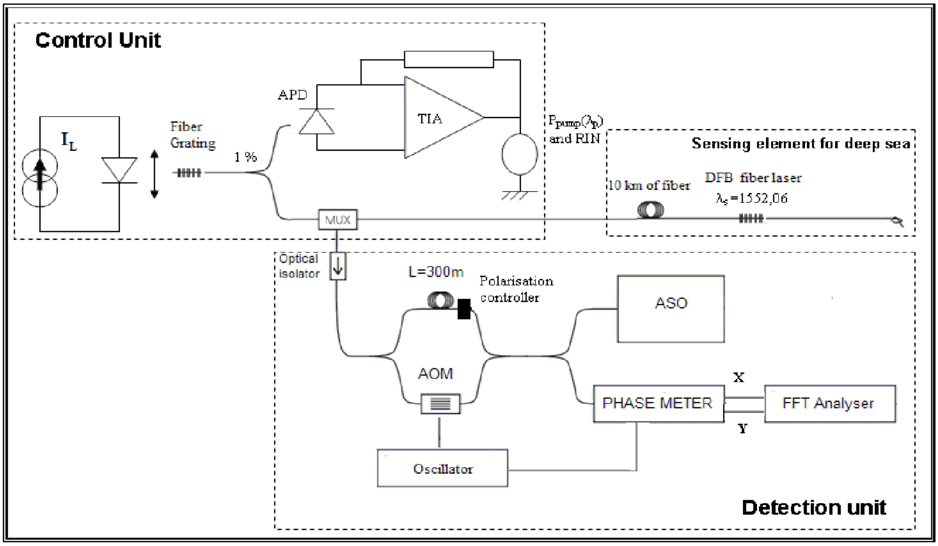

FIGURE 2: Experimental Setup

The optical intensity detected by two photodiodes PIN at the input of the phase-meter is in the form eq 3:

$$I = I_0 \ (1 + V \cos(\Delta\Phi)) \qquad (3)$$

where I_0 is the mean optical intensity, $V = \dfrac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$ is the visibility. The interferometer must be in quadrature (multiples of $\pi/2$) to provide linear responses; hence we must use a sinusoidal phase carrier signal to carry the phase delay created in the interferometer [1].

The sensitivity of the interferometer to the frequency modulation by the carrier is obtained by differentiating eq 2:

$$\Delta\Phi = \frac{2\pi n_{eff} L}{c} \sin(\omega t) - \Delta\phi \qquad (4)$$

The expression gives the following by using the Bessel functions eq 5:

$$I(\Delta\phi) = \underbrace{I_o V \cdot \left[J_0(\alpha) + 2\sum_{k=1}^{\infty} J_{2k}(\alpha) \cos(2k\omega t) \right] \cos(\Delta\phi)}_{\mathrm{Y}(\Delta\phi)} + \underbrace{I_o V \left[2\sum_{k=1}^{\infty} J_{2k+1}(\alpha) \sin((2k+1)\omega t) \right] \sin(\Delta\phi)}_{\mathrm{X}(\Delta\phi)} \qquad (5)$$

The even harmonics of the carrier are all amplitude modulated by the cosine of the phase delay while the odd harmonics are amplitude modulated by the sine of phase delay. The phase meter gives Y($\Delta\phi$) and X($\Delta\phi$) as outputs. Both signals can be connected to two channels of a FFT analyser from which the phase delay can be extracted both in time and frequency domain in order to plot frequency noise $\delta\phi$ versus acoustic frequency f at different hydrostatic pressures is given by eq 6 [2].

$$\arctan\left(\frac{\sin(\delta\phi)}{\cos(\delta\phi)}\right) = \delta\phi \qquad (6)$$

OPTICAL SENSOR NOISE SOURCES

A noise source refers to any effect that generates a random signal which is unrelated to the acoustic signal of interest and interferes with precise measurement. In the remote interrogated optical hydrophone sensors, there are several optical noise sources that contribute significantly to the total sensor noise[5]. The main are: i) laser intensity noise, ii) laser frequency noise. Other noise sources such as optical shot noise, obscurity current noise, oscillator phase noise and fiber thermal noise and input polarization noise are generally less significant and will be ignored [2].

<u>DFB fiber laser frequency noise:</u> A typical RMS frequency noise $S(f,\lambda)$ (Hz/√Hz). is shown in figure 3 at 1552.06 nm. The frequency noise of the laser was measured using the experimental set up described in figure 2. The frequency noise of the DFB fiber laser was found to exhibit an $f^{-\gamma}$ relationship where $\gamma = 0.5$ for frequencies up to 1 kHz. Between 3 kHz and 10 kHz, the frequency noise spectrum detected was flat at 7Hz/√ Hz at 5 kHz. These results are comparable with those given by Cranch et al [5].

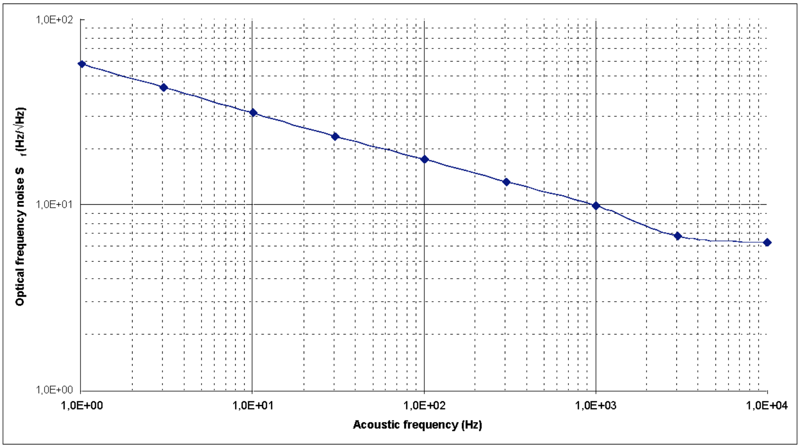

FIGURE 3: RMS Frequency fluctuations of a DFB FL at 1552.06 nm

<u>Laser intensity noise</u>: Fluctuations in the intensity of the laser contribute to the sensor noise and generate a noise photocurrent on the detection indistinguishable from the sensor phase signal by the phase-meter and FFT analyser. Measurements carried out on a single DFB FL pumped at 1480 nm with a power of 140 mW, are obtained by using the relationship given by the experimental set up[2]. This is characterized in terms of the relative intensity noise spectral density (RIN) eq 7 where

$$RIN(f,\lambda) = \frac{S_{\delta I_{ph}}(f,\lambda)}{I_{ph}(\lambda)^2} = \frac{S_{\delta P}(f,\lambda)}{\langle P(\lambda)\rangle^2} \qquad (7)$$

$S_{\delta P}$ is the spectral density of the optical power fluctuations and $\langle P \rangle$ is the mean optical power generated by laser near $\lambda = 1.55\mu$m. For the case where the RIN occupies a bandwidth much narrow than the heterodyne beat frequency, RMS induced phase fluctuation is given by eq 8 [5]:

$$\delta\phi_{RIN} = \sqrt{RIN(f,\lambda)} \qquad (8)$$

A typical $\delta\phi_{RIN}$ RMS fluctuations is shown in Figure 4. It was found to exhibit an $f^{-\gamma}$ relationship where $\gamma = 0.5$ for frequencies up to 10 kHz. Our measurements have given that $RIN(f,\lambda)$ levels less than –110 dB/Hz between 10kHz and 100kHz thanks to a $RIN_{Pumplaser}$ lower than 10^{-13} s [5,6].This behavior proves that sufficiently low RIN can be obtained from DFB FL with a good choice of pump lasers powered with a very low noise current source[2,6]. Generally, the laser frequency-induced phase noise arises from the small path imbalance present in each sensor. The frequency noise is converted into phase noise by the interferometer and is proportional to the path imbalance in the interferometer. The optical phase fluctuations shown in Figure 4, are given eq 9 by:

$$\delta\phi_{freq} = n_{eff}(\delta k)L = \frac{2\pi n_{eff}L}{c}\delta\nu = \frac{2\pi n_{eff}L}{c}.(\ \pi.S_f^{\ 2}(f,\lambda)\ ) \qquad (9)$$

$\delta\nu$ is due to the RMS frequency fluctuations or line-width [7].

In our interferometer fiber sensor, the detected RMS phase resolution can be degraded by both RMS intensity noise $RIN(f)$ and $S_f\,(f,\lambda)$ RMS frequency noise fluctuations given by eq 8 and eq 9 respectively.

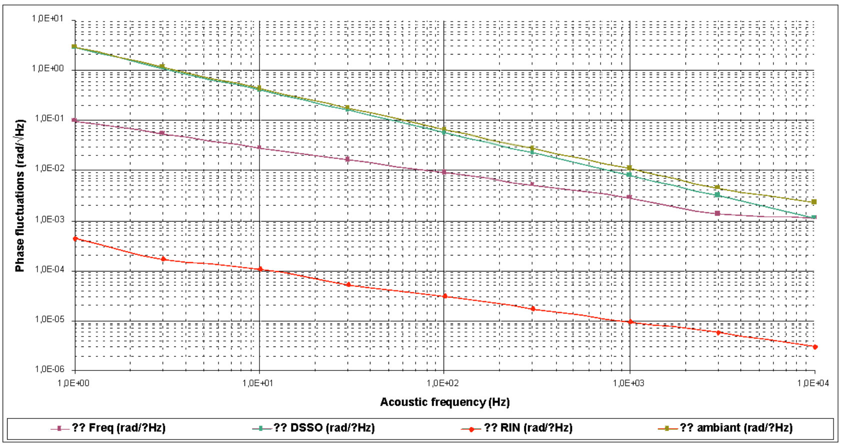

FIGURE 4: Detected RMS phase fluctuations $\delta\phi_{RIN}$, $\delta\phi_{freq}$, $\delta\phi_{DSSO}$, $\delta\phi_{ambient}$ versus acoustic frequency.

Deep sea state Noise (DSS0) :When a hydrophone is placed in the ocean, the background acoustic noise contributes to the total noise. This has been empirically determined for the quietest sea state, referred to as deep sea state zero (DSS0) in Figure 4, such as the root mean square amplitude of the pressure fluctuations in Pa/√Hz can be approximated by the Knudsen relationship eq 10[1,2,5]:

$$\delta P_{DSS0} = \delta P_0.10^{2,2} \bullet (\frac{f_0}{f})^{0,85}\text{, with } \delta P_0 = 10^{-6}\,Pa/\sqrt{Hz} \qquad (10)$$

For f=f_o, $\delta P_{DSSO}(f_o$=1kHz) = 158.48 μPa/√Hz; and at f = 0.3kHz, δP_{DSSO}(0.3kHz) = 441 μPa/√Hz. The frequency fluctuations due to the pressure fluctuations detected by the fiber laser are given eq 11 by:

$$\delta\lambda_{DSS0} = \delta P_0 .10^{2,2} \bullet (\frac{f_0}{f})^{0,85} \bullet S_{AO} \qquad (11)$$

where S_{AO} is the acousto-optic sensitivity, equal to 4 10^{-5} nm/Pa. At f = 0.3kHz $\delta\lambda_{DSSO}$(0.3kHz)=6.61 10^{-9} nm/√Hz.

INTERFEROMETRIC PHASE RESOLUTION

The detected RMS phase fluctuation due to sea state is given eq 12 by:

$$\delta\Phi_{DSS0} = \delta P_0 .10^{2,2} \bullet (\frac{f_0}{f})^{0,85} \bullet S_{AO} \bullet G_{MZI} \qquad (12)$$

where f is the acoustic frequency and G_{MZI} is the gain of imbalanced interferometer given by the relationship eq 13:

$$G_{MZI} = \frac{\partial\phi}{\partial\lambda} = \frac{2\pi\, n_{eff} L}{\lambda^2} \qquad (13)$$

with the values λ = 1552 nm, n_{eff} = 1.465, L = 300m, G_{MZI} = 1.149 10^{6} rad/nm. Between 3 kHz and 10 kHz, the RMS phase fluctuation $\delta\phi_{ambient}$ detected was flat at 5 kHz equal to 1.2 10^{-3} rad/√ Hz for L= 300m. These results are comparable with those given by Cranch et al [5]. In this case, the RMS phase noise fluctuation due to local oscillator and thermal fluctuation of imbalanced interferometer fiber respectively, are negligible [2] and are not shown in the Figure 5.

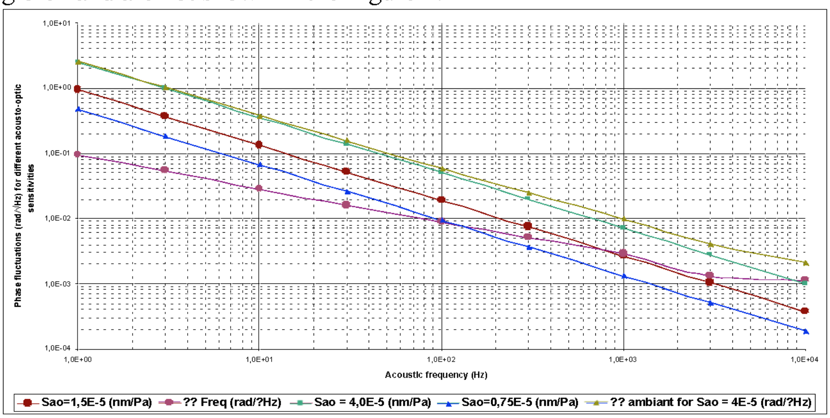

FIGURE 5: Phase fluctuation resolution $\delta\phi_{ambient}$ versus acoustic frequency at various acousto-optic sensitivity S_{AO}

NOISE EQUIVALENT PRESSURE

Noise equivalent pressure δP_{PEB} (Pa/√Hz) can be computed, it is given by the model eq 14:

$$\delta P_{PEB} = \frac{\delta\phi_{self}}{S_{AO} \bullet G_{\text{int}}} = \frac{\sqrt{\delta\phi^2_{RIN} + \delta\phi^2_{freq}}}{S_{AO} \bullet G_{\text{int}}} \qquad (14)$$

In order to compare it with sea noise equivalent pressure δP_{DSSO} (Pa/√Hz). The acoustic pressure resolution of the hydrophone can be computed for the two cases limited by the sensor self noise and acoustic noise $\delta\phi_{DDSO}$ using eq14 and eq15, respectively versus sensitivity S_{AO}.

$$\delta P_{DSSO} = \frac{\delta\phi_{DSSO}}{S_{AO} \bullet G_{\text{int}}} \qquad (15)$$

The results are plotted in Table 1 when $\delta\phi_{PEB} = \delta\phi_{DDSO}$.

TABLE 1..

Sao(nm/Pa)	**Frequency (Hz)**	$\delta\phi_{PEB} = \delta\phi_{DDSO}$ **(rad/√Hz)**	δP_{PEB} **(µPa/√Hz)**
1.5 10^{-6}	1	0.1	57900
3.0 10^{-6}	10	0.03	8690
5.0 10^{-6}	38	0.015	2600
7.5 10^{-6}	100	0.01	1150
1.0 10^{-5}	**300**	**0.005**	**434**
1.5 10^{-5}	800	0.0032	185
4.0 10^{-5}	10000	0.0012	26

When the sensitivity is higher than 1.5 10^{-5} nm/Pa, the acoustic limit of detection is only due to the deep sea state zero (DDSO). When the sensitivity is lower than 1.0 10^{-6} nm/Pa at 1Hz, the limit of detection is only due to the laser noise.

CONCLUSION

In this paper, we have shown the first noise measurements (detected) of a single mode DFB FL used as an underwater hydrophone. The low frequency pressure resolution in water becomes limited by Deep Sea State zero ambient acoustics if the acousto-optic sensitivity is sufficiently high (> 1.5 10^{-5} nm/Pa). If the sensitivity is lower, then the frequency resolution is limited by self noise which is nearly equal to DFB FL frequency noise when the phase noise related to relative intensity noise is negligible because the DFB fiber laser is pumped with a 1480 nm laser with a very low $RIN_{Pump} < 10^{-13}$ Hz^{-1}. This type of system can be adapted for any applications requiring networks of sensor elements to be efficiently multiplexed. In particular, for seismic surveying arrays such as those positioned on ocean floor, for instance plugged to the Deep Sea Net used by Ifremer.[2]

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