Field Test and Fading Measurement of a Distributed Acoustic Sensor System over a 50 km-long Fiber

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ABSTRACT

In this study, we present a direct detection distributed acoustic sensor based on phase-sensitive optical time domain reflectometer (\(\phi\)-OTDR) with long sensing range and high signal-to-noise ratio (SNR), which is field-tested over a 50 km-long fiber. Due to the random nature of Rayleigh backscattered light and fading phenomena, it is hard to characterize the performance of the system. For this reason, the performance of our sensor is specified in a statistical manner in which the mean SNR is determined using the histograms of the SNR. The SNR values are measured for identical acoustic signals in five different days, total of 48 hours and the SNR histograms are obtained for fiber distances of 100 m, 12 km, 21 km, 30 km, 40 km and 50 km. The system is field-tested using external disturbances that are generated from a 50-Hz vibrator. The SNR values are extracted from the power spectral density (psd) of the collected data over the monitored fiber span. Our results show that the \(\phi\)-OTDR system exhibits a mean SNR of 22.5 dB at 50 km distance.

Keywords: Distributed acoustic sensor, optical time domain reflectometer, \(\phi\)-OTDR, Rayleigh scattering, fading.

1. INTRODUCTION

\(\phi\)-OTDR based distributed acoustic sensing (DAS) systems have attracted increasing attention in recent years due to its remarkable advantages in a wide range of industrial applications including health monitoring and security of civil infrastructures, railways, oil and gas pipelines, borders, and more [1]. They measure vibrations and detect perturbations along a section of fiber. Different approaches have been adopted to realize the \(\phi\)-OTDR system and several efforts have been made to improve the performance. These methods include coherent detection for increased sensitivity [2], hybrid distributed amplification for longer range [3, 4], phase demodulation based on phase generated carrier algorithm, 3 x 3 demodulation method, frequency division multiplexing, and digital coherent detection schemes for increased linearity and SNR [5-8]. However, regardless of the interrogation scheme, it is hard to characterize the performance of the system due to the random nature of multipoint interference of Rayleigh backscattered light and fading phenomenon [9]. Since fiber-optic DAS technologies are based on coherent interference of Rayleigh backscattered light from discrete scatterers within the pulse duration, they experience signal fading, which includes interference fading and polarization fading [9]. The former is caused by randomness of Rayleigh scattering and is one of the most important factors that limit the performance. It also raises difficulties in specifying the system performance, particularly SNR. Different techniques were implemented in order to have a reduced interference fading and relatively stable phase sensitivity [10-12]. Additionally, many studies were done to overcome the polarization fading such as adoption of polarization diversity scheme [13], interrogation with orthogonal-state of polarization pulse pair [14] and polarization-maintaining configuration [9]. Even though fading induced noise effects were remarkably mitigated in these studies, the system still suffers from fading behaviors and random fluctuations. These are even more observable in the field tests where the environmental factors such as temperature, humidity as well as soil hardness become relevant. Therefore, considering the randomness of the system, SNR should be statistically presented instead of a single value in order to provide a more complete and indicative figure of merit for the sensor. In the literature, limited attention was given to the statistical parameters such as mean SNR and the variance, to define the performance characteristics of the system. In a recent study, by taking into consideration the random characteristics of the system, a new figure of merit (mean SNR) was introduced to characterize and compare DAS systems.
[15, 16]. However, the analysis is limited to laboratory tests and coherent detection schemes; in this manuscript we extend the analysis to field tests and direct detection systems. In this work we experimentally show the statistical characteristics of the SNR of a direct-detection DAS system, calculated over five days and 48 hours of data acquired from the field. We also demonstrate the distribution patterns of SNR in different distances and the change in mean SNR over distance.

2. BASIC PRINCIPLE

We first review the basic principle of a φ-OTDR before assessing the performance of our DAS system. In the φ-OTDR technique, repeated optical pulses from a highly coherent light source are injected into the sensing fiber. As the pulse propagates along the fiber, the Rayleigh backscattered light waves interfere with each other within the pulse duration. The coherent superposition of the light scattered from randomly placed scatterers yields a φ-OTDR trace exhibiting a jagged appearance. When the launched pulses have a pulse width of \( W \) and optical frequency of \( v \), the backscattered wave at the input end at time \( t_0 \) will be the coherent summation of the fields backscattered from \( N \) scatterers [17, 18]:

\[
E(t = t_0, z = 0) = E_0 \exp(-2\alpha z) \exp(j2\pi vt_0) \sum_{i=1}^{N} r_i \exp(j\phi_i)
\]

where \( \alpha \) is the optical fiber attenuation constant, \( r_i \) and \( \phi_i \) are the reflectivity of the \( i \)th scatterer and relative phase of the reflected wave, respectively. They are random parameters and uniformly distributed over \([0, 1]\) and \([0, 2\pi]\), respectively. The fields interact with each other when they spatially overlap, corresponding to the half pulse width. Therefore, \( z \) defines the positions of the scatterers inside the half pulse width, i.e. \( W/2 \) region, and expressed by \([t_0c/n_f - W/2]/2\). Here \( c \) is the velocity of light in vacuum, and \( n_f \) is the refractive index of the fiber.

The only random parameter, which affects the statistics of the signal and contributes to fading, is \( \sum_{i=1}^{N} r_i \exp(j\phi_i) \) [17]. For φ-OTDR systems, the backscattered signal intensity is observed, which is proportional to the square of the electric field. The intensity of the backscattered signal can be expressed as:

\[
I = |\exp(j2\pi vt_0)|^2 \left| \sum_{i=1}^{N} r_i \exp(j\phi_i) \right|^2
\]

\[
= \left[ \sum_{i=1}^{N} r_i \exp(j\phi_i) \right]^2
\]

\[
= \sum_{i=1}^{N} r_i^2 + \sum_{j=1}^{N-1} \sum_{k=j+1}^{N} r_j r_k \cos(\phi_j - \phi_k)
\]

where the last term describes the multipoint interference between the scattered light from numerous scatterers within the half pulse width and results in a speckle like time domain pattern of the φ-OTDR trace.

If a perturbation is applied in the \( q \)th scatterer among \( N \) scatterers, which introduces a phase difference \( \theta \), then the corresponding expression for the intensity, \( \Delta I \), will be given by the intensity difference between two consecutive traces with and without perturbation:

\[
\Delta I = I_{\text{perturbed}} - I_{\text{non-perturbed}} = 2 \sum_{j=1}^{q-1} \sum_{k=q}^{N} r_j r_k \left[ \cos(\phi_j - \phi_k) - \cos(\phi_k - \phi_j - \theta) \right]
\]

This final expression models the non-linear response and fading behavior of the system.
Different factors affect the performance of a fiber optic-based DAS system such as laser frequency drift, amplified spontaneous emission (ASE) noise, optical pulse extinction ratio and so on. Among the most remarkable ones, the effect of laser frequency drift on phase-sensitivity OTDR based distributed intrusion sensor has been investigated in Ref. \cite{19} and \cite{20}. Zhong et al. have shown that trace- to- trace fluctuation increases with increasing laser frequency drift rate and the laser with minimum frequency drift should be chosen for better performance \cite{20}. In this regard, before testing and characterizing the performance of our DAS system, we characterized the frequency drift / stability of four different lasers and integrated the one with the lowest frequency drift / highest stability into our fiber optic-based DAS system.

As shown in Fig. 1(a), the laser under test and the reference laser are combined with a 50-50% polarization maintaining optical coupler (OC), and then the signal passes through the variable optical attenuator (VOA) and reaches to the photodetector (PD). The data acquisition (DAQ) card have been employed to acquire the signal at the output of the PD.

![Figure 1](image)

**Figure 1.** (a) Experimental setup for laser frequency drift / stability characterization. (b) Beat note frequency drifts for ~20 mins are demonstrated where beat notes are obtained by separately combining four different lasers with the reference laser. The beat note frequency drift measurements are recorded for about 20 minutes after the laser frequencies are locked to their cavity (Fig. 1(b)). Besides, the extracted drift rates per minute and per 20 minutes are reported for comparison in Table 1. According to the results we have selected the Laser 1, which has the lowest short-term and long-term drifts, to be integrated into the system for the best performance.
Table 1. Beat note frequency drift rates per minute (short-term drift) and per 20 minutes (long-term drift)

<table>
<thead>
<tr>
<th>Laser pair</th>
<th>Frequency drift (kHz/min)</th>
<th>Frequency drift (MHz/20 mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref. Laser – Laser 1</td>
<td>127</td>
<td>4.11</td>
</tr>
<tr>
<td>Ref. Laser – Laser 2</td>
<td>179</td>
<td>12.98</td>
</tr>
<tr>
<td>Ref. Laser – Laser 3</td>
<td>729</td>
<td>17.10</td>
</tr>
<tr>
<td>Ref. Laser – Laser 4</td>
<td>972</td>
<td>21.96</td>
</tr>
</tbody>
</table>

After the laser frequency drift/stability characterizations, the performance of the φ-OTDR was preliminarily tested in the laboratory with the configuration shown in Fig. 2. The amplified light from the narrow linewidth continuous-wave (CW) laser is passed through an acousto-optic modulator (AOM) which generates the interrogation pulses with ~100 ns width and injected into the fiber via a circulator. The backscattered signal from the fiber is directed to the detection regime in which the signal flows through an erbium doped fiber amplifier (EDFA) and an optical band pass filter (BPF) followed by a photodetector. The optical band pass filter was primarily used for the purpose of suppressing the ASE noise and thereby improving the SNR of the backscattered signal. The detected signal is acquired by a DAQ system and then post-processed in a PC to analyze its characteristics.

Figure 2. Experimental setup for DAS system. EDFA: Erbium doped fiber amplifier, AOM: Acousto-optic modulator, Optical BPF: Optical band pass filter, PD: Photodetector, Data Acq.: Data Acquisition

Figure 3. DAS system trace exhibits a jagged appearance due to the coherence of the light source.

Fig. 3 shows the Rayleigh backscattering trace of the DAS along the fiber without disturbance, which exhibits a jagged appearance due to the highly coherent light source. The interrogation period is 515 μs, in order to cover ~51 km, and the pulse width is ~100 ns, corresponding to a ~10 m spatial resolution and 5150 samples for each interrogation.
4. FIELD TESTS AND RESULTS

A field demonstration of the DAS system over a buried cable was performed. For the field tests, the same experimental configuration as in the laboratory tests was used. A ~51 km-long single-mode fiber is used as the sensing cable of which certain portions were buried under the soil. The sensing fiber is divided into 11 sections as shown in Fig. 4. Sections B, D, F, H and J were placed in an isolated box in the laboratory, which insulates the fiber spools from thermal and acoustic effects. The sections A, C, E, G, I and K were buried with the same depth and length (100 m) in the field after their certain lengths (150 m) pass through the building. In this manner the distances of ~100 m, ~12 km, ~21 km, ~30 km, ~40 km and ~50 km were able to be monitored. To test the ability of the system of sensing a vibration event, ~50 Hz sinusoidal signal was applied to the buried fiber generated by a motor which is placed 3 m away from the buried fiber and time-domain traces of the specific samples were collected over the monitored distances.

The time-domain data (Fig. 5(a)) is then converted to frequency domain and their power spectral densities are calculated. SNR value is extracted from the ~50 Hz peak of the psd data (Fig. 5(b)). Since the amplitudes of the vibration events are varying in time due to fading, SNR values are calculated in certain time windows. The number of samples over which SNR values are calculated is selected for the sake of convenience, which corresponds to time windows of 33.75 seconds. This results in arrays of SNR values which have ~5000 elements for each monitored distance. Using these arrays, histograms of SNR values at these distances are generated and shown in Figure 6.

The results presented in Fig. 6 reveal the probabilistic nature of the system. Even though the externally applied perturbation is identical, it does not impose the same effect on the backscattered intensity due to the fading effects and non-linear response of the system. It results in different SNR values under different conditions varying in time. For example, the SNR starts from 30 dB and goes up to 80 dB at the 100 m position whereas it varies between 5 dB and 35 dB at the 50 km position. Also, it is seen that the heights of the histogram bins get smaller as the distance increases, in other words, the number of occurrences starts to distribute more uniformly and become more spread. This implies that at long distances fading becomes more significant.

The results show that the SNR value has probabilistic fashion and cannot be identified as a single value for a given distance. At least the mean and variance value of the SNR should be provided. In order to have a good estimation about the system performance, the shape of the pdf should also be taken into consideration. We measured the vibration signal within five different days over the course of about 10 hours in each day, i.e. total of 48 hours, for obtaining a single mean SNR value. Therefore, the mean SNRs are determined over the distributions shown in Fig. 6 and the change in mean SNRs over distance are presented in Fig. 7.
Figure 5. (a) Time trace and (b) spectrum of a 50 Hz vibration signal at 21 km.

Figure 6. Histograms of SNRs at distances 100 m, 12 km, 21 km, 30 km, 40 km and 50 km.

The mean SNR values show a linear decrease for longer distances as expected (Fig. 7). The decrease is around 8 dB/10km (in electronic domain), which is consistent with a fiber loss of 0.2 dB/km (in optical domain).
5. CONCLUSION

In this paper, we have presented the field demonstration of φ-OTDR based direct detection DAS system. A narrow linewidth and low frequency drift light source was preferred for a better performance. The intensities of vibration signal over the monitored regions were measured and their SNRs within certain time windows (33.75 sec) were calculated. The resulting SNR values were used to generate corresponding histograms in 6 different locations from 100 m to 50 km along the fiber. Mean SNR values were calculated over these histograms and shown to linearly decrease with the distance as expected. The φ-OTDR based DAS system has a performance of 61.7 dB at the 100 m position and 22.5 dB at the 50 km position.

REFERENCES


