Phase-sensitive reflectometer using a single-frequency laser diode and an Er-doped fibre amplifier

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Abstract. We report on the observation of phase-sensitive Rayleigh backscattering from a single-mode fiber excited by light pulses obtained from a highly coherent single-frequency laser diode and an Erbium doped fiber amplifier (EDFA). The laser diode stability was tested using a highly imbalanced fiber optic Mach-Zehnder interferometer. The CW laser light was first modulated using fiber-optic EO modulator which formed 100ns to 500 ns pulses that correspond to 20 to 100 m of pulse length in the fiber. The backscattered light power is estimated to be about -51 dB lower than the launched power at the input and about \( N=500 \) averages are needed for a sensing length of \( L_s = 40 \) km to be in the useful dynamic range.

1. Introduction

Fiber optic distributed sensing has emerged as a highly perspective technology in a number of applications especially those related to perimeter intrusion sensing [1,2] and pipe-line monitoring [3]. The alternative of this approach is to use a combination of a Mach-Zehnder and a Sagnac fiber interferometer [4]. For similar applications a phase-sensitive optical time domain reflectometer (\( \phi \)-OTDR) is of particular interest since it allows the detection of weak acoustic pressure waves by a sensing cable buried underground [1] or attached to a pipeline. A phase-sensitive OTDR is in essence a fiber optic interferometer in reflectometric arrangement and requires high power, single-frequency lasers and low-noise avalanche photodiodes (APD) in combination with signal averaging equipment.

In [1] a single-frequency fiber laser is used in combination with and EDFA as a high coherence high power source to observe phase-sensitive response while a combination of a single-frequency laser diode and an EDFA is reported in [2].

In this paper we estimate the required signal-to-noise ratio (SNR) and the usable dynamic range (UDF) needed for the proper functioning of \( \phi \)-OTDR and report on the observation of phase-sensitive Rayleigh backscattering from a single mode fiber using single frequency laser diodes and Erbium doped fiber amplifier.

2. Optical time domain reflectometry

2.1. Rayleigh scattering in optical fibres
Optical fibres are made of fused silica (SiO₂) and by adding different doping materials a desired index profile can be obtained so that the fibre acquires the desired transmission characteristics. Since the material is amorphous, its local density fluctuates which causes loss along the lightguiding structure caused by Rayleigh scattering. The scattering coefficient α is given as:

\[
\alpha_s = \frac{(2\pi)^3}{3} \frac{1}{\lambda^4} n^8 p^2 k T_f \beta
\]

where \( p \) is the photoelastic coefficient of glass, \( k \) Boltzmann’s constant and \( \beta \) is the isothermal compressibility of the material, while \( T_f \) is a fictive temperature, representing the temperature at which the density fluctuations are "frozen" in the glass material.

2.1.1. Rayleigh back-scattering in single mode optical fibres. In optical fiber reflectometers a series of light pulses are injected into the fibre, which in the ideal case are rectangular. If at the initial moment \( t = 0 \) a pulse of width \( dt \) is injected into the fibre its length along the fiber will be \( dz = v_c dt \)

As an approximate estimation of the group velocity a value of \( v_c \approx 2 \times 10^8 \text{ m/s} \) can be assumed which means that a pulse of a duration \( dt = 1 \text{ ns} = 10^{-9} \text{ s} \) will span over \( dz = 0.2 \text{ m} \) along the fiber. The elementary backscattered optical power \( P_{bs} \), obtained at the fiber input is given as \([5]\)

\[
dP_{bs} = 0.5P_0 \alpha_s S dz
\]

where \( P_0 \) is the peak optical, \( \alpha_s [1/\text{km}] \) is the attenuation caused by Rayleigh scattering (see (1)), \( S \) is a scattering coefficient. The total optical power is obtained after integration over the physical length of the light pulse which is twice the one-way length.

\[
P_{bs} = \frac{1}{2} P_0 \alpha_s S \int_0^\alpha \exp(-\alpha z) dz
\]

In the above equation \( \alpha [1/\text{km}] \) is the attenuation in the fiber, which for single-mode fibers is practically the same as the scattering coefficient \( \alpha \approx \alpha_s \) over the 1.3 µm to 1.55 µm range. The solution of (3) can be written as \( P_{bs} = 0.5P_0 \alpha_s S / [1 - \exp(-aD)] / \alpha_s \). In the above specified spectral region \( a \ll D \) which is of the order of meters or tens of meters, so \( D \ll 1/\alpha \). Expansion into series of the exponent in (5) \( (e^t \approx 1 + t) \) yields:

\[
P_{bs} = 0.5S \alpha_s D P_0 = A P_0
\]

which means that the back-scattered signal is proportional to the peak power \( P_0 \), the scattering coefficient \( \alpha_s \) and the pulse length \( D \) and the scattering coefficient \( S \) given as:

\[
S = [NA/n]^2 / q
\]

For single mode communication fibers \( n = 1.465-1.468, Na = 0.13, q = 4.55, \) so \( S = 1.76 \times 10^{-3} \). For \( \lambda = 1550 \text{ nm} \), \( \alpha \approx 0.26 \text{ dB/km} \), \( \alpha_s = 0.2 \text{ dB/km} \). Taking into account that

\[
\alpha_s [1/\text{km}] = 0.23 \alpha_s [\text{dB/km}]
\]

we obtain for \( D/2 = 0.02 \text{ km} \) (20 m) \( A = S \alpha_s D/2 \) the value \( A = 1.619 \times 10^{-6} \), i.e. \( A \approx 58 \text{ dB} \)

Since the resolution of a reflectometric sensor is defined by the pulse length \( \delta t \) in the fiber the value of the coefficient \( A \) will have different values as summarized in Table 1.

| \( \delta t [\text{ns}] \) | \( \delta l [\text{m}] \) | \( A \)  | \( A [\text{dB}] \) |
|-----------------|-----------------|--------|--------|
| 200             | 40              | 3.24E-06 | -54.9 |
| 300             | 60              | 4.86E-06 | -53.1 |
| 400             | 80              | 6.48E-06 | -51.9 |
| 500             | 100             | 8.10E-06 | -50.9 |

Table 1. Attenuation coefficient \( A [\text{dB}] \) for different values of the pulse duration \( \delta t [\text{ns}] \) and the corresponding spatial resolution of the sensor \( \delta l [\text{m}] \).
Thus for a 100 m spatial resolution, and a 1 mW of input peak power, the peak power of the back-
scattered Rayleigh light will be 8 nW (for a 500 ns pulse duration); for 10 mW - 80 nW, while for a 25
mW peak input power there will be correspondingly 200 nW at the receiver.

2.1.2. Phase sensitive OTDR. In the traditional OTDR scheme, which is used to detect losses and
reflections along a fibre communication line which is as long as possible, it is desirable to avoid noise
due to laser’s high coherence. With a coherent laser, noise is generated because of the interference of
two consecutive backscattered pulses (1) and (2) which arise at some small perturbation \( \delta n \) of the fibre
refractive index induced, for example by an external pressure wave.

The intensity of the superimposed waves with individual backscattered intensities \( I_{bs,1} \) and \( I_{bs,2} \) would
be described by the well known interference equation

\[
I_{bs} = I_{bs,1} + I_{bs,2} + 2 \sqrt{I_{bs,1} I_{bs,2}} \cos \phi
\]

where \( \phi \) is the phase accumulated by wave (1) before it interferes with (2). So the intensity of the
backscattered light will fluctuate in the case of a coherent source if the coherence length is \( L_c \gg D \). To
suppress this type of noise a lower coherence laser having a large number of longitudinal modes is
used in conventional reflectometry.

In phase-sensitive OTDRs what is a noise in the conventional OTDR is a useful signal to detect
small local modulations of the fibre refractive index caused by external fields such as sound pressure
waves. Signals reflected at different consecutive moments will vary as shown in Figure 1 due to the
phase changes \( \delta n \) over time. Taking the phase difference \( \Delta \phi(t) \) of two consecutive moments will produce a signal that will bear information on external influences:

\[
\Delta \phi(t) = \phi(t) - \phi(t_0)
\]

If at a given position the fibre has experienced an index perturbation \( \delta n \) from an external cause,
then a difference \( \Delta I_{bs} \) of the backscattered intensities will be observed:

\[
\Delta I_{bs}(t) = I_{bs,1}(t) - I_{bs,1}(t_0) + I_{bs,2}(t) - I_{bs,2}(t_0) + 2 \sqrt{I_{bs,1}(t) I_{bs,2}(t)} \cos \phi(t) - \sqrt{I_{bs,1}(t_0) I_{bs,2}(t_0)} \cos \phi(t_0)
\]

If the total backscattered intensities do not change considerably over time, i.e.

\[
I_{bs,1}(t) \approx I_{bs,1}(t_0) \approx I_{bs,1} \quad \text{and} \quad I_{bs,2}(t) \approx I_{bs,2}(t_0) \approx I_{bs,2},
\]

then we obtain

\[
\Delta I_{bs}(t) \approx I_{bs,1} + I_{bs,2} - 4 \sqrt{I_{bs,1} I_{bs,2}} \sin \phi(t) \sin[\Delta \phi(t) / 2]
\]

with \( \overline{\phi(t)} = [\phi(t) + \phi(t_0)]/2 \).

Thus the differential signal is proportional to the phase difference between two sequential moments.

2.2. Signal-to-noise ratio and Dynamic Range
2.2.1. Signal-to-Noise Ratio (SNR) and Dynamic Range (DR). Since the received optical power is too low (Figure 2) and subject to fluctuations averaging over as large a number of pulses should be performed to increase the SNR defined as the ratio of the average optical power $\bar{P}$ to the noise level. Assuming the noise follows a Gaussian distribution of expectation $\mu$ and standard deviation $\sigma$,

$$f(x, \mu, \sigma) = \left[\frac{\sigma}{\sqrt{2\pi}}\right]^{-1} \exp\left\{-\frac{(x-\mu)^2}{2\sigma^2}\right\}$$  \hspace{1cm} (11)

the SNR can be defined as

$$\text{SNR} = \frac{\bar{P}}{\sigma}$$  \hspace{1cm} (12)

Averaging over $N$ pulses will yields a standard deviation of the sampled mean as:

$$\bar{\sigma} = \sigma / \sqrt{N}$$  \hspace{1cm} (13)

SNR in the case of averaging over $N$ pulses will be

$$\text{SNR}_N = \frac{\bar{P}}{\bar{\sigma}} = \frac{\bar{P}}{\sqrt{N} / \sigma} = \sqrt{N}.\text{SNR}$$  \hspace{1cm} (14)

Since SNR increases, this leads to an increase of the dynamic range (DR) which is the ratio of the scattered signal to the noise level. If SNR is expressed in dB, then

$$\text{DR}_{\text{db}} = 10 \log \text{SNR} = 5 \log \text{SNR}$$  \hspace{1cm} (15a)

From (17) the SNR in dB after averaging over $N$ pulses we obtain:

$$\text{SNR}_{N,\text{db}} = \text{SNR}_{\text{db}} + 5 \log \sqrt{N} = \text{SNR}_{\text{db}} + \Delta(\text{DR})_{\text{db}}$$  \hspace{1cm} (15b)

The factor $\frac{1}{2}$ in (15a) accounts for the fact that propagation is considered only in one direction – back to the input. For example averaging over $N = 10$ signals raises the SNR by $2.5$ dB, that is 1.77 times, but averaging over $N = 100$ signals increases SNR by 5 dB, i.e. 3.16 times.

2.2.2. Usable dynamic range (UDR). The usable dynamic range is the range within which measurements are done on signal that exceeds a definite level above noise. When peak-to-peak noise becomes close to the signal level obtained as the difference between two averaged signals of the phase-sensitive OTDR. This means SNR $\geq 1$. Signals greater than this value are in the so called usable dynamic range (UDR). In analogy with conventional OTDRs, the UDR can be defined relative to a 0.2-dB losses as follows [5]:

$$0.2\text{dB} = 5 \log \frac{I_s + N}{I_s - N}$$  \hspace{1cm} (16)

$I_s$ being the signal level, while $N$ is the noise level. The SNR is then obtained as:

$$\text{SNR} \approx 6.68\text{dB}$$  \hspace{1cm} (17)

which means that the UDR is practically 7 dB above the level, below which are 98% of noises.

2.2.3. Maximum number of averages $N_{\text{max}}$. Since increasing the UDR needs averaging over $N$ signals we need to evaluate what would be the maximum possible number $N_{\text{max}}$ of signal averages for a phase-sensitive OTDR.
Unlike conventional OTDRs in which millions of pulses can be averaged in the course of several minutes, phase-sensitive OTDR used as a distributed sensor has severe limitations coming from the integration time, sensing distance and the spatial resolution. To evaluate $N_{\text{max}}$ we must assess the averaging time $T_{\Sigma}$. If we set as $L_{\text{crit}}$ as the critical distance from the sensing cable to an intruder, approaching at a velocity $v$, the time period over which the critical distance would be covered is $L_{\text{crit}} / v$ which we set as the time $T_{\Sigma}$ available for integration. So we let $v L_{\text{crit}} / T_{\Sigma} = \sum$.

(18)

Should we accept $L_{\text{crit}}$ as 10 m, which is of the order of the detectable signals [1], and the intruder’s speed within the limits of $v_{\text{min}} = 3.6 \text{ km/h} = 1 \text{ m/s}$ (calm walk) and $v_{\text{max}} = 72 \text{ km/h} = 20 \text{ m/s}$ (car speed), the integration time would correspondingly vary from $T_{\Sigma, \text{min}} = 0.5 \text{ s}$ to $T_{\Sigma, \text{max}} = 10 \text{ s}$. Reducing $L_{\text{crit}}$ to 2 m would then yield $T_{\Sigma, \text{min}} = 0.1 \text{ s}$ to $T_{\Sigma, \text{max}} = 2 \text{ s}$. Thus for $2 \text{ m} \leq L_{\text{crit}} \leq 10 \text{ m}$ and $1 \text{ m/s} \leq v \leq 20 \text{ m/s}$, the integration time would vary over two orders of magnitude and be $0.1 \text{ s} \leq T_{\Sigma} \leq 10 \text{ s}$.

Denoting by $L_{\text{sens}}$ the sensing length of the fiber and $v_g$ the group velocity of light along the fiber, the round-trip time $T$ for the signal is $T = 2 L_{\text{sens}} / v_g$.

And for $L_{\text{s}} = 1 \text{ km}$, then $T = 2 \mu \text{s}$. So the maximum possible number of averages can be determined from the ratio of the averaging time $T_{\Sigma}$ to the round-trip time which is the pulse repetition period with a duration of $\delta \tau < T$.

$N_{\text{max}} = T_{\Sigma} / T$

(21)

For $\delta \tau = 500 \text{ ns}$ with $\delta l = 100 \text{ m}$, we obtain the following possible averaging numbers and the corresponding addition to the dynamic range $\Delta(DR)_{\text{dB}}$. Figure 3 shows that if the signal level is close to the noise level (SNR = 1) then the maximum possible sensor length (no other restriction factors excluded) is about $L_{\text{s}} = 40 \text{ km}$ so that it can be within the usable dynamic range. This length is satisfactory for distributed optical fiber intrusion sensor. Other limiting factors are input optical signal level, ADC response time, APD sensitivity. The graph in Figure 3 shows that we need at least 500 averages to be in the usable dynamic range.

![Figure 3](image)

**Figure 3.** Dependence on the fiber length of the minimum and maximum SNR after averaging

### 3. Experimental scheme and results

#### 3.1. Experimental scheme

So far we have considered only the issue of SNR and the length restriction caused by the maximum possible number of averages. It follows that to obtain a satisfactory signal level of 100 nW or above
for a sensing length of \(L_s \leq 40\) km light pulses of duration \(\delta \tau = 500\) ns should be generated to obtain a resolution of \(\delta l = 100\) m. We can have a SNR within the UDR if pulses of tens of nW can be detected. The input peak optical power in this case must be greater than 10 mW.

However, to ensure high coherence a highly stable single-frequency laser diode must be used. During operation the center wavelength of the laser must be stable within tens of kHz/s drifts. Since direct modulation causes chirp, external modulation must be applied. External electro-optical modulators typically introduce additional losses of up to 6 dB, which would reduce the input power level to unacceptably low levels. Therefore optical amplifiers should be used at the fiber input.

The basic experimental set up is shown in Figure 4. A single-frequency thermally stabilized laser diode with a \(\Delta \nu = 20\) kHz bandwidth was used as highly coherent source. The output CW power at 1550 nm provided is 10 mW. Prior to tests the stability of the laser was tested using a highly imbalanced fiber Mach-Zehnder interferometer with a fiber length in the signal arm of 9.7 km. The results obtained showed that a stability was better than 24 kHz/s.

A 10 GHz in-line fiber optic modulator (Photline Technologies) was used as an external electro-optic modulator. (EOM). Since modulator performance is polarization-dependent, two in-line fiber polarizers were used before and after the EOM. An Er-doped fiber amplifier (EDFA) providing 14 dBm (25 mW) output optical power that was launched into port (1) of an optical circulator and through port (2) into the test fiber with \(L_s = 3\) km. An avalanche photodiode model HCA-S-200M-IN (Femto) was used and responses were observed using a digital scope.

Figure 4. Experimental set-up.

3.2. Obtained results

We have varied the pulse duration from 100 ns to 500 ns and have observed the phase sensitive backscattered light on the oscilloscope. Figure 5 a-f) shows several responses for different sensitivities and number of averages. As we see on increasing the number of averages the noise level significantly reduces and at \(N = 16\) (Figure 5e) we can see the back reflection from the end of fiber at a 15 \(\mu\)s time delay which corresponds to the 3 km fiber length. Even with this level of peak input optical power (25 mW), it was still insufficient to reduce noise below the level so as to enter in the usable dynamic range. As calculated in the first part to obtain a good performance responses, at least \(N = 500\) signals must be averaged, for which purpose an ADC and a signal averaging scheme is under development.

4. Conclusions

We have estimated the signal averaging requirements for the normal functioning of a phase-sensitive OTDR and have considered intruder to fiber distances ranging between 2 m to 10 m and approaching
Figure 5. Observed responses: a) Pulses injected of duration 100 ns at 250 ns resolution and the backscattered light; b) same as a) but at 10 µs resolution and no averaging observed Rayleigh backscattered response with N = 16 averages; c) same as b) but with N = 4; d) same as c) but with N = 16; e) and f) same as c) and d) but with 2 mV/div vertical scale.
speed between 1 m/s and 20 m/s and have estimated the minimum number of averages as close to 500 so as to be in the usable dynamic range. We have also tested an optical scheme using a highly coherent single-frequency laser and an EDFA providing a 25 mW peak output power in combination with an APD detector with which we have observed the backscattered phase-sensitive response.

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