Sensing - lab01
Strain measure
Prof: Luca Palmieri

Teammates:
Federico Berra, Gaia Arienti
Lab Date: 06/12/2018

1 Introduction

The aim of the experiment is to locally determine the strain applied to an optical fiber through the measurement of the spectral shift. More specifically, an Optical Frequency Domain Reflectometer (OFDR), which includes a swept-frequency laser, is employed to measure the spectral shift of the distributed Rayleigh's backscattering generated along the fiber under strain.

The refractive index of a fiber is not homogeneous, hence a signal transmitted is scattered. A small part of the signal is backscattered elastically (i.e., it preserves the same frequency of the incident signal) in a process named Rayleigh's backscattering. The scattering centers are localized in well-defined positions since they are originated in the production phase of the fiber. For this reason, a characteristic feature of the Rayleigh's scattered signal is that it is constant and unique for each fiber under equal conditions of input signal and surrounding environment. The backscattered spectrum depends on the local properties of the fiber in the physical point where the scattering is generated, consequently it is possible to map a physical property of interest (applied strain in our case) in a distributed manner, that is along the entire length of the fiber. When the fiber is mechanically under strain the scattering centers change their relative position and hence the characteristic fingerprint changes. The backscattered signal results shifted in frequency, and the resulting strain can be calculated as:

$$\delta f = K_\epsilon \delta \epsilon$$

where δf is the spectral shift, $\delta\epsilon$ the resulting strain, and the strain constant $K_\epsilon = -0.15$ GHz/μstrain. Temperature is assumed almost constant during the experiment and consequently its effect on the spectral shift has been neglected.

1.1 Experimental setup

The experimental setup consists of an OFDR and a fiber sensor made coupling mechanically the fiber with a metal plate where the weights are applied. The fibre forms a coil, as outlined in Fig. 1: in this way the external points of the fiber are most affected by the weight applied than the internal points. The fiber coil is also under the board: when the upper coil is compressed, the coil under the board is stretched, and viceversa.

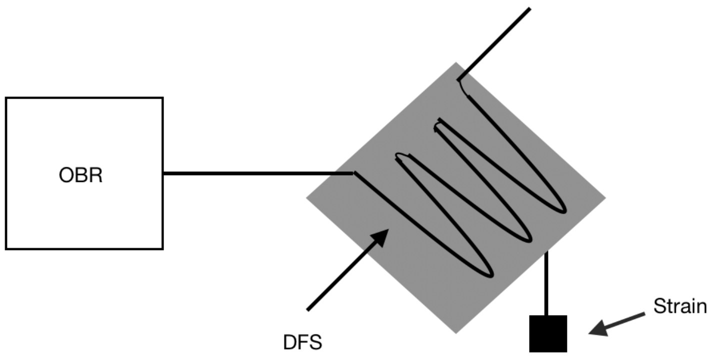

Figura 1: A commercial OFDR (Luna OBR 4600) measures the backscattering signal of the Distributed Fiber Sensor (DFS)

The measurements are taken increasing the weight applied as summarized in Tab.1. The measurements are taken also in the opposite direction, i.e. the weights have been removed.

measure number	weight [g]	ymax [$\mu\epsilon$]	ymin [$\mu\epsilon$]
1	0		
2	60		
3	120		
4	180	84.9	-72
5	240	112	-95
6	300	138	-118
7	359	165	-138
8	418	189	-164
9	476	213	-182
10	534	238	-202
11	591	261	-220
12	686	300	-256
13	782	339	-289
14	686		
15	591		
16	534		
17	476		
18	418		
19	359		
20	300		
21	240		
22	180		
23	120		
24	60		
25	0		

Tabella 1: Measurements performed.

Electrical sensors are used to check whether the measurements conditions are suitable, for example that the board is not moving.

2 Analysis

The row data collected consist in the complex envelope (amplitude and phase) of the electric field as a function of the position along two orthogonal polarization: polarization S and polarization P as can be seen in Fig.2, where the magnitude of the two polarization is depicted.

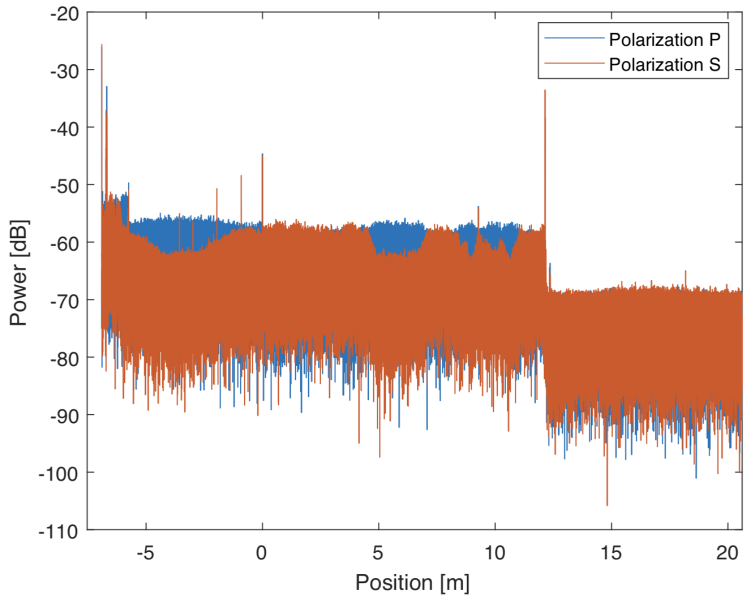

Figura 2: Raw data

The portion of the fiber of interest goes from 6,77 m (start of the sensor) to the final reflection peak at 12,1 m.

2.1 Numerical results

Given the reference measurement and the measurement with the weight applied, we want to find the spectral shift between the two: it is therefore necessary to work in the frequency domain. To pass in the frequency domain maintaining a local information of the signal, it has been decided to perform the Discrete Fourier Transform (DFT) on a sufficiently small interval (window). The choice of the size of the window is a trade-off between ensuring local information, i.e., two points that are affected by a significantly different strain must belong to two different windows, and an adequate accuracy. We decided for a window size of 5 cm since it resulted as the best solution in terms of results after some tests. The signal we have considered for our analysis is given by the sum of the amplitudes squared of the S and P spectra, in the selected window. At this point, one can proceed to define the frequency shift between the signal with the applied weight and the reference signal. The spectral shift is given by the position of the cross-correlation peak (phase lag index) between the reference spectrum and the measured spectrum, properly converted in frequency. If in a selected window there are w samples spaced dt seconds apart, the frequency resolution dF of the spectrum is given by the opposite of the signal duration T, with $T = w\ dt$.

The cross-correlation between the two signals has been calculated, and in Fig.3 is represented an example. We can then proceed with the detection of the peak.

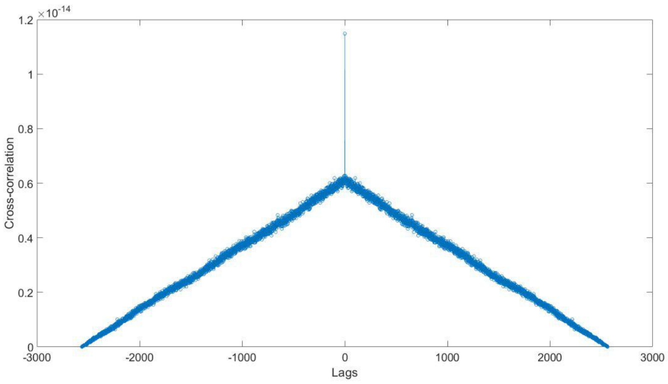

Figura 3: Cross-correlation

To make the analysis easier, it has been decided to subtract the mean value to each signal used to make the cross-correlation, as can be seen in Fig.4

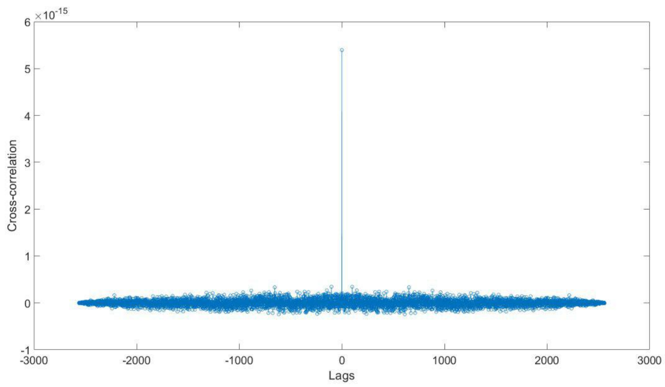

Figura 4: Cross-correlation minus mean

To find the location of the maximum value with a finer resolution, we apply a quadratic fitting using a parabolic approximation. Unfortunately, as can be noticed in Fig.5, in the peak region we have only of 3 points, that are not sufficient to obtain a good estimate. In fact, we need at least 4 points of analysis that correspond to one point more than the degrees of freedom of the parabola.

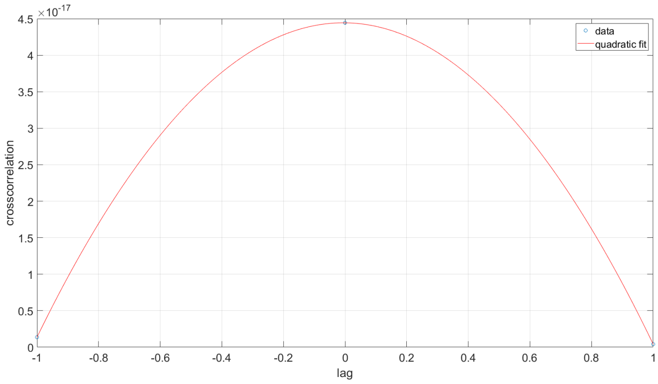

Figura 5: Cross-correlation peak zoom

For this reason, we have interpolated the DFTs by zero padding, fixed at 10. The spectral resolution does not vary. Data can hence be fitted with the quadratic interpolation, as represented in Fig. 6.

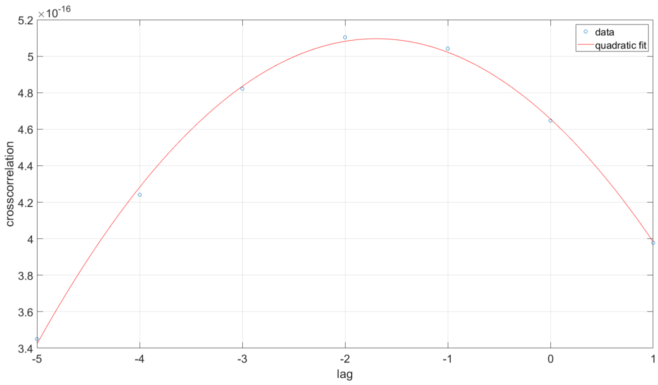

Figura 6: Cross-correlation with padding

The lag is then extracted and converted in a frequency shift, using the relationship we previously recalled and accounting for zero-padding. The two windows (one for the reference and one for the strain measure) have been shifted together in order obtain a strain measurement for each centimeter (window-step of 1 cm). In this way, it has been possible to obtain the spectral shift δf (in GHz) as a function of the position along the fiber. As already mentioned, strain and spectral shift are related by:

$$\delta f = K_\epsilon \delta \epsilon$$

with K_ϵ = -0.15 GHz/$\mu\epsilon$, and the strain measured in microstrain ($strain * 10^{-6}$). The results are firstly shown for a particular weight applied (782 g, the maximum weight), in order to highlight the different features applied during the processing of the data. In Fig.7, in fact, are compared the microstrains when the fitting is not performed and the final result obtained with the quadratic fitting.

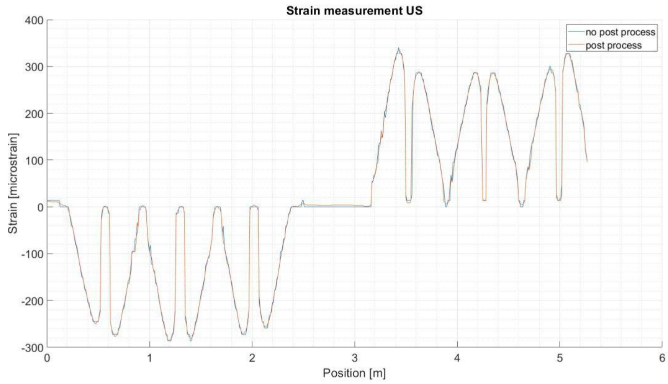

Figura 7: Raw strain compared with the quadratic fitted strain.

The processed results are smoother than the raw ones. The final results for all the weights applied are shown in Fig. 8

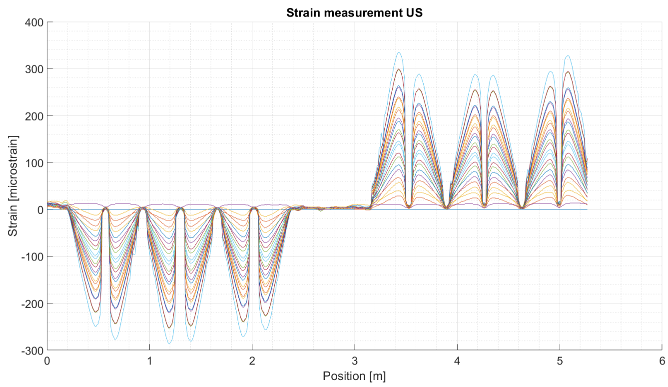

Figura 8: Distributed strain measurements for each applied weight.

It is clear that the signals obtained comply with the setup scheme: the first portion of the fiber sensor has a negative value of strain and corresponds to the compression of the fiber under the table, while the final part is positive and corresponds to the lengthening of the fiber on the upper side of the board. The values of strain deduced from the graphs correspond to the values taken during the laboratory experience and reported in the third and fourth column of Table 1.

3 Discussion and Conclusions

To verify the quality of our measurements, we have plotted in Fig. 9 the microstrains as a function of the applied weight, in a specific position in the fiber. The position chosen was the point of maximum strain to obtain the highest possible sensitivity of the device, estimated as the slope of a linear fitting. In red, the measurements obtained applying increasing weight (forward direction), while in blue the ones in the opposite direction (removing the weights). The values of sensitivity obtained are $S_f = 0.42\ \mu\varepsilon/g$ for the forward direction, and $S_b = 0.41\ \mu\varepsilon/g$ for the backward direction.

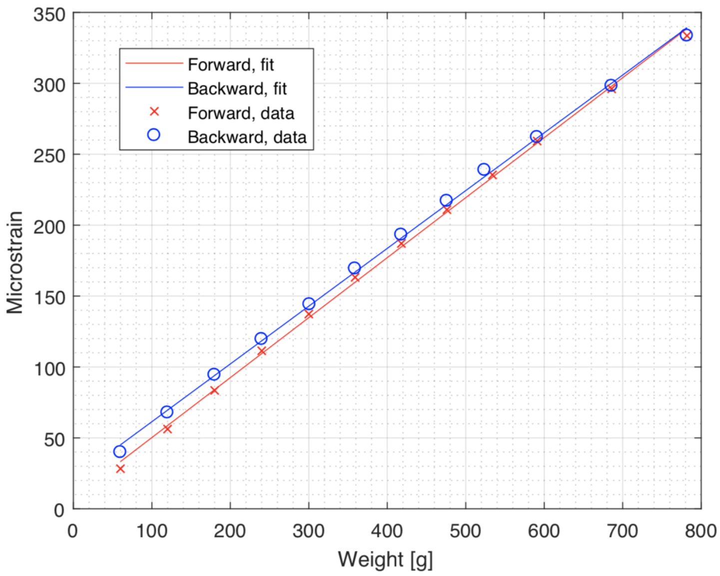

Figura 9: Microstrain versus weight applied

It can be noticed that the forward and backward curves are not overlapping: supposedly, this is due to the change in temperature occurred during the experiment that is more evident comparing the first and the final measurements.

Our final results have been compared with the ones of the device, that are plotted in Fig. 10.

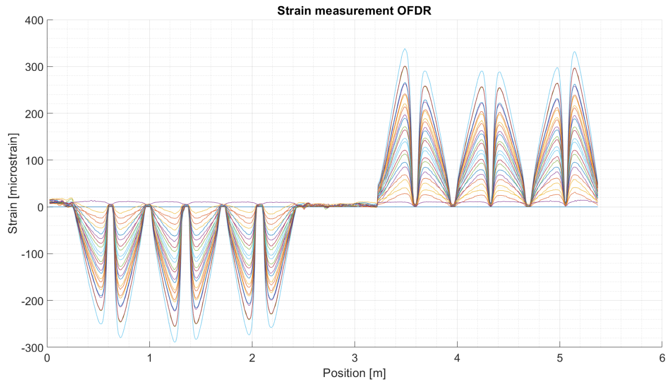

Figura 10: Strain measurement for each weight applied, measured by the OFDR

The superposition of the two results are represented in Fig. 11. Considering that the OBR processing of the data is not known, the results obtained seem satisfactory.

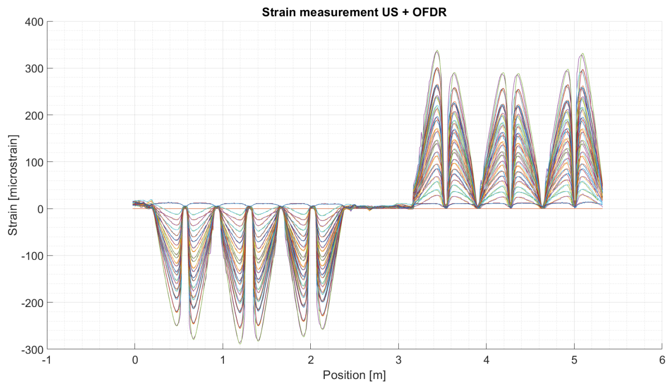

Figura 11: Comparison between ours and OBR's processed data

In conclusion, this report presents the processing of the OFDR data acquired and a measurement of the sensitivity of the sensor. The quality of the results obtained was determined by comparing them with the measurements of the commercial device.

4 Further analysis

Despite of the use of the same data, our analysis resulted different from the automatic one performed by the device due to the non-identical processing procedure. To quantify this difference we have estimated the distance between the two spectral shifts. The spectral shift resulted from our analysis is depicted in Fig. 12.

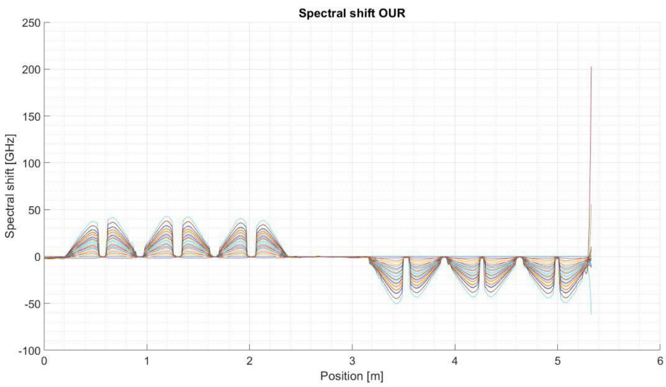

Figura 12: Spectral shift obtained with our processing of the data

We have defined the distance between the two functions as

$$d(x) = |f_2(x) - f_1(x)|$$

To accomplish the point-to-point difference we needed the two graphs to have the same number of samples, so it was decided to perform a spline interpolation on both in order to have 1000 points for each signal. The resulting signal of the difference is shown in Fig.13

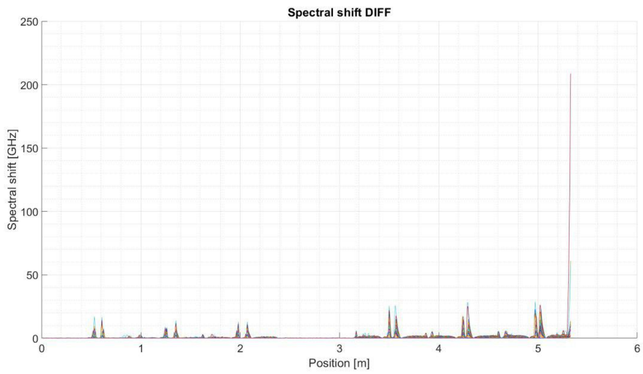

Figura 13: $d(x)$ for each signal.

The last part of the signal in Fig.13 (about 7 points) presents some peaks introduced by the edge effects of the spline interpolation, therefore it has not be considered. At a first impression, the pattern of Fig.13 seemed to suggest a shift between the two spectral shifts. For this reason, the cross-correlation between the two signals was performed but no shift was found. We then proceed with a numerical evaluation of the difference, and in this respect we have chosen to consider the mean and the maximum values of $d(x)$ as benchmarks. The values obtained are collected in Table 2.

measure	mean	max	shift in number of samples
1	0	0	0
2	0.17	1.4	0
3	0.29	4.2	0
4	0.40	6.2	0
5	0.54	8.4	0
6	0.66	11.1	0
7	0.77	13.9	0
8	0.88	13.1	0
9	1.03	18.5	0
10	1.22	20.2	0
11	1.31	22.6	0
12	1.55	25.9	0
13	1.83	28.9	0
14	1.56	26.1	0
15	1.29	22.9	0
16	1.24	20.8	0
17	1.08	18.8	0
18	0.89	13.2	0
19	0.79	14.4	0
20	0.68	12.1	0
21	0.54	9.8	0
22	0.44	6.6	0
23	0.32	5.2	0
24	0.20	1.9	0
25	0.11	0.5	0

Tabella 2: Numerical evaluation of the difference between our final signal and the OBR final signal.

Looking at the maximum values of difference between the two signals, the latter seems significant, but comparing it with the mean values that turned out to be low we can deduce that that maximum value is not descriptive of the general behavior.