Experimental investigations of coherent optical-frequency domain reflectometry

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Coherent Optical Frequency Domain Reflectometry (C-OFDR) is a promising technique for high-resolution metrology that can find applications in DOFS (Distributed Optical Fibre Sensors). We present experimental results which are showing centimeter resolution over a few meters. Then, we discuss the prospective solutions to the problems encountered during the measurements and perspectives about the applications of the improved C-OFDR set-up.

Introduction

Optical reflectometry methods can be divided into three main groups; Optical Time Domain Reflectometry (OTDR), Optical Low Coherence Reflectometry (OLCR), and Coherent Optical Frequency Domain Reflectometry (OFDR). OLCR and OFDR implement coherent detection scheme whereas OTDR uses direct detection scheme. C-OFDR bridges the gap between the OTDR and the OLCR in terms of measurement range and spatial resolution (typically sub-millimeter spatial resolution over tens to hundreds of meters).

Principles of C-OFDR

Operation principles of C-OFDR is represented in figure 1.

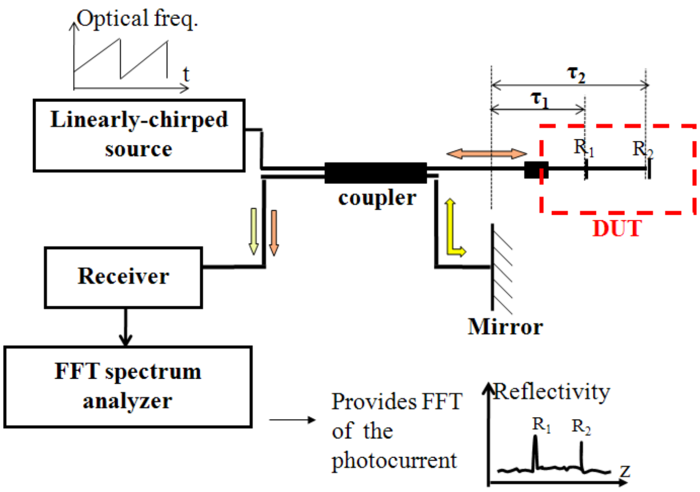


Figure 1: Operation principles of C-OFDR.

The optical frequency of the tunable laser source (TLS) is swept linearly in time without mode-hops. Then, the frequency-modulated optical signal (probe signal) is split into two paths, one of which probes the device under test (DUT) whereas the other is used as reference signal (or local oscillator). The reference signal returning from the reference mirror and test signal returning from the reflection sites in the test arm coherently interferes on the detector. This interference signal has the beat frequencies which appear as peaks at the network analyzer display after the Fourier transform of the time-sampled photocurrent. Using a linear frequency sweep, the measured beat frequencies can be mapped into a distance scale (the proportionality factor between beat frequency and the corresponding distance is determined by the rate of change of the optical frequency, γ_v), while the squared magnitude of the signal at each beat frequency reveals the reflectivity of each reflection site. This method is often called as coherent FMCW. C-OFDR has got some advantages inherent to the coherent detection scheme [1]. First of all, the measured photocurrent is not proportional to the reflected optical power but to the square root of it, which permits the system to measure signals with large amplitude differences. Secondly, the receiver bandwidth (RF frequencies) is lower compared to the OTDR techniques reducing the noise level and increasing the dynamic range. Finally, no dead zone is observed in C-OFDR since the receiver does not saturate as in pulsed OTDR methods.

Measurements

In order to determine the practical problems and limitations, we aimed at investigating our C-OFDR set-up with a typical metrology application, namely, testing of discerete reflections coming from different kinds of connectors, and patchcords. The device under test is shown in figure 2. It consists of a 1 −m fiber and three FC/PC-FC/APC adaptors creating two strong reflection sites (R1 and R2 in figure 2) which are 3 cm apart.

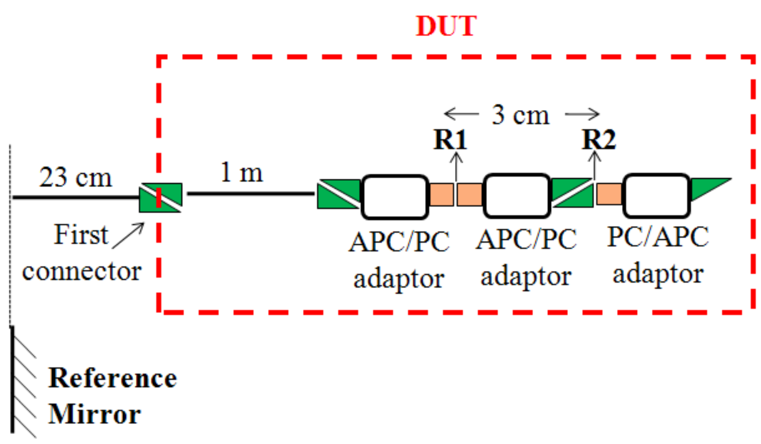


Figure 2: Device under test

In the set-up, the tunable laser source (TLS) is an external cavity laser (ECL) with a tuning range of 110 nm and linewidth of 150 kHz. It can operate in the sweep mode to ramp the optical wavelength. The sweeps are triggered by an external TTL signal. In this very early implementation, we utilised an off-the-shelf vector signal analyzer (VSA). It digitizes the detector voltage in time-domain and then uses digital signal processing

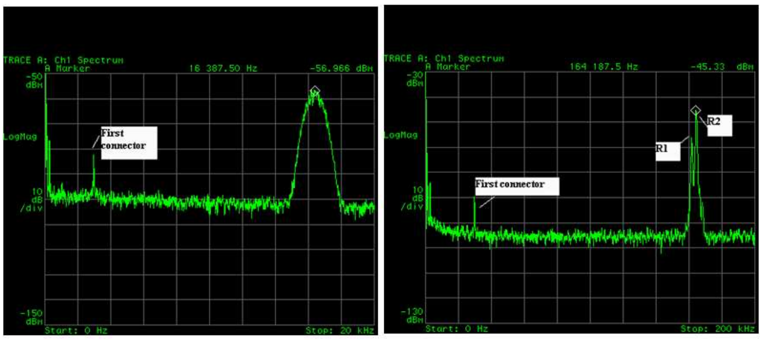
(DSP) techniques to perform a fast Fourier transform (FFT) and displays the signal in the frequency domain. The beat spectra were observed for two sets of parameters:

- CASE-1: $\gamma_\nu = 1.25$ THz/s (10 nm/s).
- CASE-2: $\gamma_\nu = 12.5$ THz/s (100 nm/s).

For both cases, the wavelength was swept between 1,550 nm and 1,560 nm. Even though, the sawtooth wavefunction sweep time is 1 s, and 0.1 s for the CASE-1 and CASE-2 respectively, the VSA uses a narrower acquisition time (*time gate*, or *main length*) in the FFT process. Time gates for the CASE-1 and CASE-2 were 127 ms, and 12.7 ms, respectively. Therefore, although the laser optical frequency is swept over 10 nm, only about 1.2 nm of this range is used for the data acquisition in both cases.

The position of the time gate with respect to the triggering signal can be adjusted by introducing a *delay* on the VSA. By changing the delay, time gate may be in the beginning, in the middle or in the end of the ramp. The best spatial resolution is determined by the frequency-resolution bandwidth of the VSA and was about 0.25 cm for both cases.

OFDR spectra are presented in figure 3. The spectra were obtained from time averaged signals (10 averages). The proportionality coefficient of the optical path difference to the optical beat frequency is estimated to be 12.5 kHz/m for CASE-1, and 125 kHz/m for CASE-2.

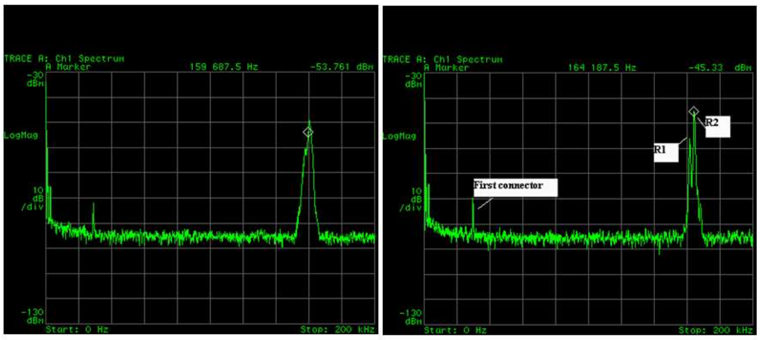


(a): CASE-1 **(b): CASE-2**

Figure 3: Comparison between two different sweep rates. a) $\gamma_\nu = 1.25$ THz/s, reflections R1 and R2 are not resolved, b) $\gamma_\nu = 12.5$ THz/s, reflections R1 and R2 are clearly resolved

As can be clearly seen in figure 3, the reflections R1 and R2 are resolved for the CASE-2 and not for the CASE-1 even though the distance between reflections is greater than 0.25 cm (the best resolution provided by the VSA). Indeed, in our system, there is a spectral broadening due to the frequency-sweep nonlinearity. This additional spectral broadening (Δf_{nl}) degrades the spatial resolution (Δz) which can be expressed as $\Delta z = \frac{c}{2n\gamma_\nu}\Delta f_{nl}$ where c is the speed of light in vacuum, n is the refractive index of the DUT [2]. Consequently, a fast γ_ν is effective for improving the spatial resolution.

The measurement for the CASE-2 was then repeated for several delay times. For each measurement, we gradually increased the delay. The purpose in doing this was to determine if there was a region on the optical frequency ramp which is more linear. It was observed that the two reflections were not resolved for delays smaller than 50 ms (over the total sweep time of 100 ms). For comparison, OFDR spectra obtained for delays of 40 ms and 50 ms are presented in figure 4. We deduce from the observation in figure 4 that the first part of the frequency sweep has got severe nonlinearities.



(a): CASE-2, Delay=40ms **(b): CASE-2, Delay=50ms**

Figure 4: Comparison between two different time gate position. a) delay = 40 ms, reflections R1 and R2 are not resolved, b) delay = 50 ms, reflections R1 and R2 are clearly resolved

Conclusions

The centimeter resolution is not as good as the performance characteristics we can expect with our TLS source. In order to obtain sub-millimeter resolution, implementation of nonlinear frequency-sweep suppression methods is mandatory [3]. We will implement an auxilary interferometer together with a data acquision system and a proper signal processing unit. Applying these improvements, the C-OFDR technique will permit us to realize optical quasi-distributed and distributed sensors.

References

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