

OFDR measurement using the CTP10 test platform

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Introduction

This application note describes how optical frequency domain reflectometry (OFDR) measurements can be performed using the CTP10 component test platform. OFDR is primarily used to create a map of reflections within the optical path of a device under test (DUT), usually as a function of distance. OFDR measurement relies on a sweeping tunable laser and a high-speed power meter to acquire an interference pattern as a function of optical frequency.

OFDR complements two other reflectometry techniques: optical time domain reflectometry (OTDR) and optical low coherence reflectometry (OLCR). All three approaches provide a different measurement range and resolution, OFDR being somewhere in the middle, with a typical measurement range of 1 meter and a spatial resolution of a few tens of microns. These specifications make OFDR suitable for photonic integrated circuits (PICs) and optical subassembly testing.

OFDR: measurement principle

OFDR relies on optical interference resulting from the laser light travelling through two different optical paths: a reference arm of fixed length and a measurement arm including the device under test. Several experimental setups are possible and have been reported in the literature. Two setups based on Mach-Zehnder and Michelson configurations are presented below in Figures 1 and 2.

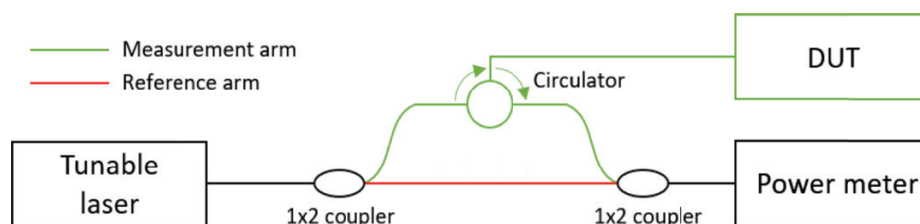


Figure 1. Mach-Zehnder configuration using a circulator. A 1x2 coupler could also be used instead of a circulator.

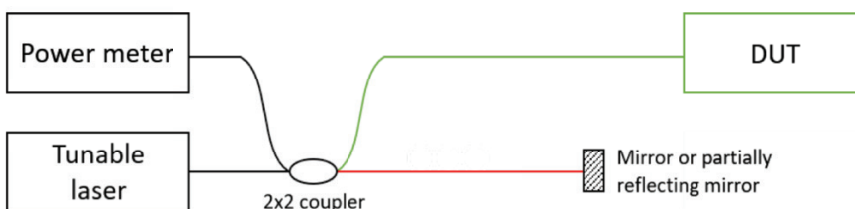


Figure 2. Michelson configuration where a mirror or partially reflecting mirror is used in the reference arm.

It can be shown that a reflection in the measurement arm will result in a sinusoidal interference pattern detected on the power meter as a function of the optical frequency of the laser.

$$P(\nu) = P_0 [1 + \cos(2\pi \tau_0 \nu + \varphi_0)]$$

With:

- P the power detected on the power meter
- ν the optical frequency
- P_0 a factor related to the laser power and polarization alignment
- τ_0 the time delay between the reference and the measurement arms
- φ_0 a constant phase term

This interference signal has a periodicity, also called free spectral range (FSR), constant in the frequency domain. Additionally, the FSR is directly related to the time delay τ_0 experienced by the light between the reference and measurement arms: $FSR = 1/\tau_0$.

The interference pattern, recorded during the laser sweep as a function of optical frequency can then be transposed to the time domain by means of a Fourier transform. A sinusoidal pattern in the frequency domain results in a Dirac peak in the time domain located precisely at the time delay τ_0 experienced by the light.

OFDR is essentially a delay measurement between both optical paths, but it is usually more convenient to display the data as a function of distance. This can be easily done if the refractive index of the propagation medium is known. Since the time delay is relative to the reference arm, distances are also relative to the reference arm.

Figure 3 below shows how an interferogram (120 GHz FSR, 960 pm at 1550 nm) acquired in the frequency domain can be displayed in the time and spatial domains by means of a FFT.

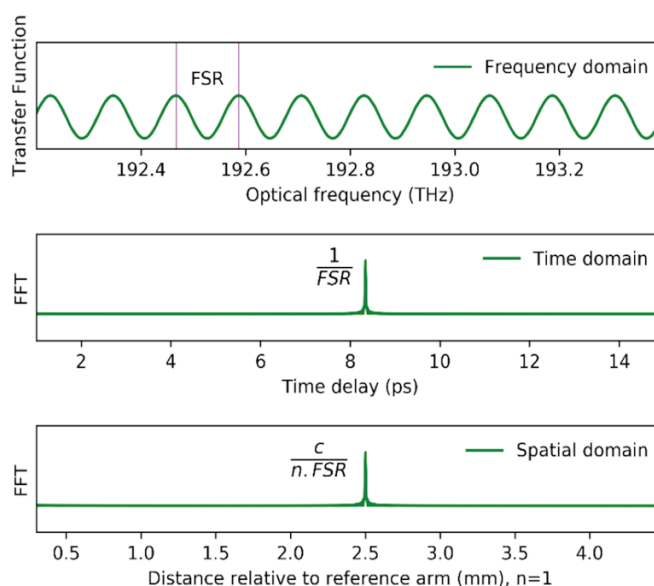


Figure 3. The different representations of the acquired data: in the frequency domain (top), in the time domain (middle) and in the spatial domain (bottom). A sinusoidal signal with 120 GHz FSR was used in the frequency domain. In the time and spatial domains, the peaks are located at 8.3 ps and 2.5 mm, respectively.

In general, several reflections will be present at different locations within the DUT. The back-reflected light will experience different time delays depending on the position of the reflections, giving contributions at different frequencies in the interference pattern. In the time and spatial domain, those reflections will appear as separate peaks and can be used to accurately characterize interfaces or defects within a DUT.

Temporal and spatial resolutions

The temporal and spatial resolutions characterize the minimum time delay or distance above which two reflections can be properly resolved by the system.

The temporal and spatial resolutions can be calculated as follows:

$$\delta\tau = \frac{1}{\Delta\nu}$$

$$\delta l = \frac{c \cdot \delta\tau}{n}$$

With:

- $\delta\tau$ the temporal resolution
- $\Delta\nu$ the frequency range used for the swept measurement
- δl the spatial resolution
- c the speed of light in vacuum
- n the refractive index of the propagation medium

The following table provides the theoretical values using the wavelength ranges of the T100S-HP-CL and T100S-HP-SCL swept tunable lasers.

Wavelength range [nm]	Temporal resolution [ps]	Spatial resolution [μm] ($n=1$)
1500–1630 nm	0.0627	18.8
1440–1640 nm	0.0394	11.8

Measurement range

OFDR systems have a maximum measurable time delay that results in a maximum measurable range. A given time delay τ_0 produces an interferogram with an FSR equal to $1/\tau_0$, which can only be properly detected with a sampling resolution in the frequency domain of $1/(2 \cdot \tau_0)$, based on the Nyquist–Shannon sampling theorem.

The maximum measurable range is calculated from the maximum time delay using the speed of light in the propagation media. It corresponds to the maximum distance that can be investigated in a single measurement.

The maximum time delay and measurement range can be calculated as follow:

$$\Delta\tau = \frac{1}{2.\delta\nu}$$

$$\Delta L = \frac{c.\Delta\tau}{n}$$

With:

- $\Delta\tau$ the maximum measurable time delay
- $\delta\nu$ the sampling resolution in the frequency domain
- ΔL the maximum measurement range
- c the speed of light in vacuum
- n the refractive index of the propagation medium

The table below provides some example values based on different sampling resolutions.

Sampling resolution [GHz]	Maximum time delay [ns]	Measurable range [m] (n=1)
0.01	50	15
0.1	5	1.5
1	0.5	0.15

Since the time delay is relative to the reference arm, the optical path being investigated within the measurement arm depends on the length of the reference arm. This means the path being measured can be shifted by adjusting the length of the reference arm, as shown in Figure 4 below.

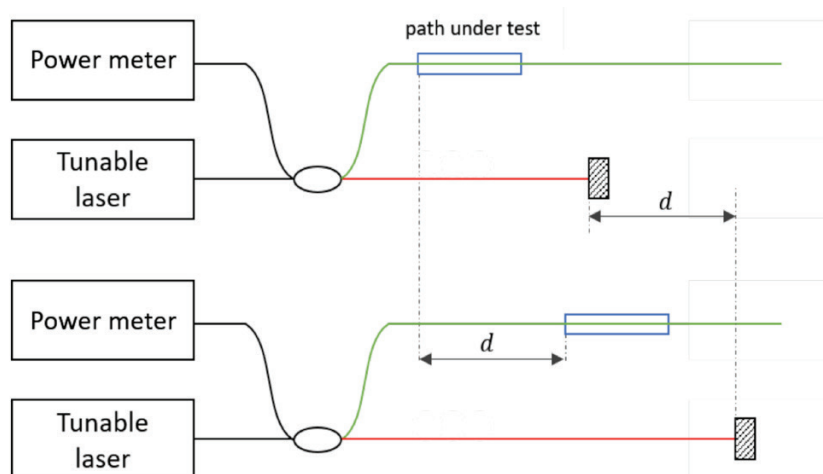


Figure 4. The length of the reference path affects the path being measured within the measurement arm. The length of the reference arm is increased by a distance (d) in the bottom configuration, shifting the path under test by the same amount as compared to the top configuration.

Distance measurement

Distance measurement within the measurement arm can be performed either if the length of the reference path is known, or if a reflection in the measurement arm can be used as a reference. Typically, a ferrule or the entrance interface of a photonic integrated circuit (PIC) can be conveniently used as a reference for distance measurements within the DUT. It should be noted that the configurations shown in Figures 1 and 2 are used in reflection. Consequently, the time delay and path difference (relative to the reference arm) always include the fact that the light makes a roundtrip to reach a given reflection in the measurement arm. This is shown in Figure 5 below.

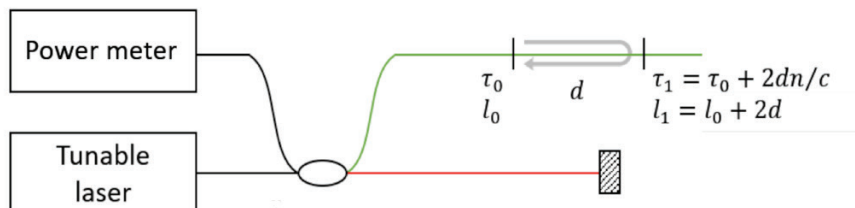


Figure 5. The values τ and l represent, respectively, the time delay and distance relative to the reference arm. Relative distance measurements in the measurement arm must consider the roundtrip of the light.

This results in a twofold increase in resolution (both temporal and spatial) and a twofold decrease in the measurement range, as compared to the formulas given in Paragraphs 2.1 and 2.2. The distance values displayed in Section 3 are corrected to account for this and reflect distances in the measurement arm.

CTP10 component test platform

The CTP10 test platform is a high-performance multiport detection system. It is used in conjunction with a swept tunable laser to perform insertion loss and return loss measurements with high dynamic range and picometer resolution. In the context of OFDR measurement, the measured transfer function corresponds to the interference pattern.

The sampling resolution of 1 μm gives a measurable range of roughly 1.3 m in air (0.65 m in reflective configurations), providing a sufficient range for photonic integrated circuits and most optical subassemblies. Additionally, the T100S-HP swept laser sources have a wavelength range between 100 and 200 nm, providing a theoretical spatial resolution between 12 and 20 μm in air (8 and 13 μm in glass).

The configuration shown in Figure 2 was used to perform several OFDR measurements. An unconnected PC connector was used at the end of the reference arm, yielding a 14.7 dB return loss from the glass-air interface.

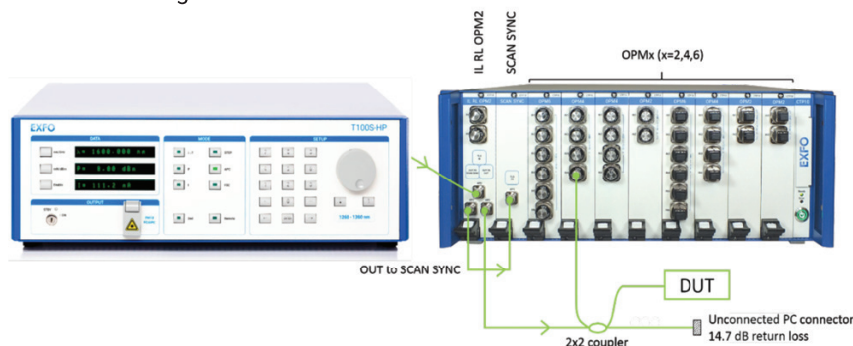


Figure 6: Michelson configuration used with the IL RL OPM2, SCAN SYNC and OPM modules.

The IL RL OPM2 module serves as an interface between the tunable laser source and the DUT for real-time power monitoring of the laser, whereas the SCAN SYNC module optically measures the wavelength during the laser sweep and triggers the power acquisition based on the desired sampling resolution.

The measured transfer function (interferogram in the case of OFDR measurements) is given as a function of wavelength, with a constant resolution in wavelength. Consequently, the data should first be resampled using a constant interval in the frequency domain. Resampling is required by the Discrete Fourier Transform (DFT) algorithm, which works with data acquired with a constant resolution in the frequency domain.

Unmated PC connectors

A fiber adaptor was used so that two unmated PC connectors could face each other in the measurement arm. The distance between the two connectors was gradually changed from 3.5 mm to close contact.

Figure 7 below shows a zoomed view of the results obtained with a single PC connector and facing PC connectors with different distances.

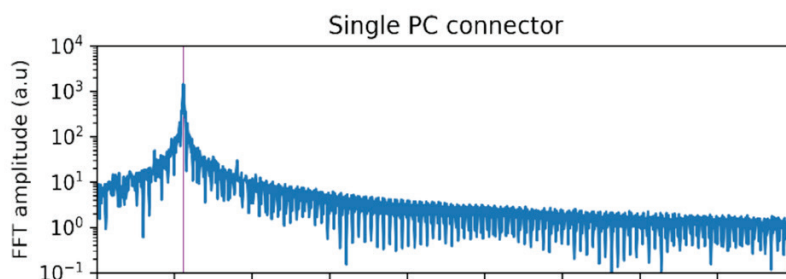


Figure 7a. Single PC connector without any facing connector. A single peak is detected in the spatial domain at 7.05 mm.

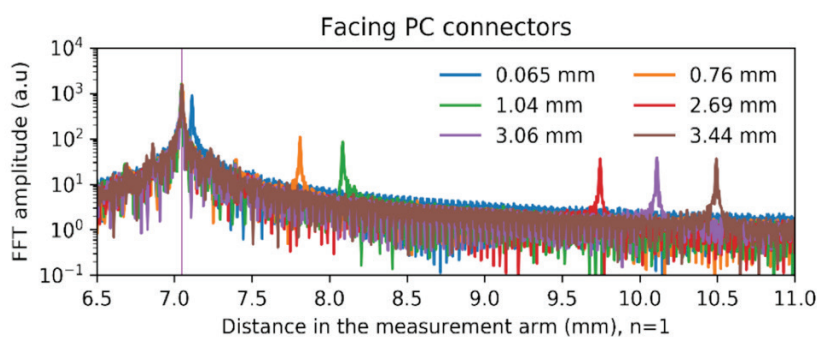


Figure 7b. Facing PC connectors at several distances. Each measurement consists of two peaks: one located at 7.05 mm, corresponding to the fixed PC connector, and another peak corresponding to the unmated PC connector.

A screenshot of the GUI showing the zoomed view of the measured interferograms is shown in Figure 8 below.

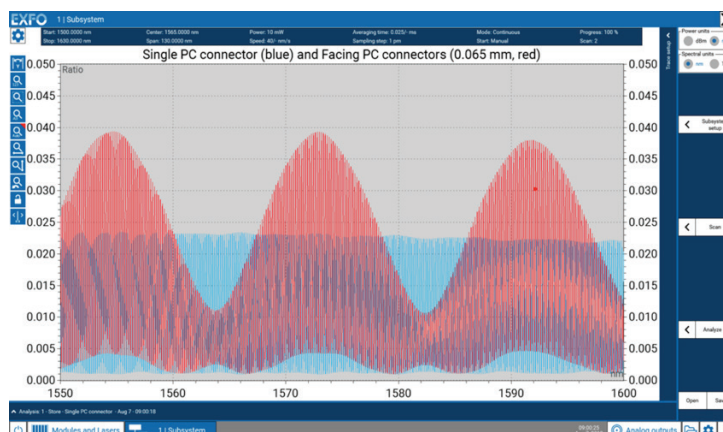


Figure 8. Screenshot of the CTP10 GUI showing the interferograms measured for a single PC connector (in blue) and facing PC connectors (in red, $d=0.065$ mm).

Achromatic doublet

We characterized an optical subassembly consisting of a ferrule aligned with a commercially available achromatic doublet lens. The ferrule was precisely aligned beforehand to obtain a collimated beam after the doublet.

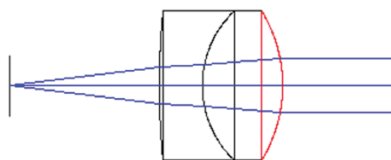


Figure 9. Schematic representation of the ferrule aligned with the achromatic doublet lens.

Figure 10 shows the results obtained using the CTP10 and a dedicated commercial low coherence reflectometer. The relative position of the peaks shows an excellent ± 0.01 mm agreement between both measurements, validating how accurately the CTP10 platform performs OFDR measurements.

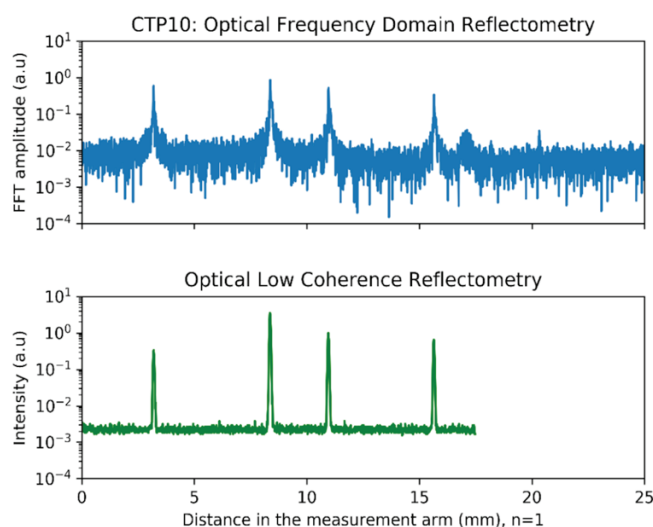


Figure 10. Zoomed view of the results obtained using the CTP10 platform and a dedicated OLCR system.

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[CTP10 - Passive optical component testing platform](#)

The 8° polished ferrule and both air-glass interfaces of the achromatic doublet were AR coated to minimize back reflections but remain visible with the CTP10. This measurement gives some insights about the lens characteristics but also allows users to monitor the back focal length with high resolution, possibly helping the alignment procedure.

	Theoretical values based on design		
	Distance [mm]	Optical distance [mm]	Measured value [mm]
Back focal length (n=1)	5.2	5.2	5.18
Lens 1 (N-SF6, n=1.763)	1.5	2.64	2.59
Lens 2 (N-LAK22, n=1.631)	2.5	4.08	4.68

Conclusion

This application note describes how OFDR measurements can be performed using the CTP10 platform and T100S-HP swept tunable laser. The configuration featured a single 2x2 coupler in a Michelson configuration and was simple yet powerful.

The results showed excellent resolution and sensitivity. Reflections spaced by 0.065 mm were easily distinguished in the case of facing PC connectors, thanks to a theoretical spatial resolution in the order of 10 μm . In addition, measurements performed on AR-coated interfaces showed that weak reflections were properly detected and allowed distance measurement with excellent accuracy, showing a ± 0.01 mm agreement with another reflectometry instrument based on OLCR.

The OFDR configurations in figures 1 and 2 could be further improved by implementing the polarization diversity method to mitigate the effect of polarization fading. By using a polarization beam splitter and an optical detector for each polarization, more accurate back reflection values can be achieved.

The CTP10 platform's high-performance multiport detection system can be leveraged to perform highly resolved OFDR measurement. This is particularly useful for applications such as photonic integrated circuits, which require both spectral characterization (insertion loss, return loss) and reflectometry measurements, eliminating the need for a separate reflectometry system.