Optical Backscatter Reflectometry (OBR) – Overview and Applications

Optical Backscatter Reflectometry (OBR), with ultra-high resolution and no dead zones, delivers unprecedented visibility into optical components and systems

Introduction

Optical communications technology is rapidly evolving to meet the ever-growing demand for ubiquitous connectivity and higher data rates. As signaling rates increase and modulation schemes become more complex, guaranteeing a high-fidelity optical transmission medium is becoming even more critical. Additionally, modern networks are relying more on photonic integrated circuits (PICs) based on silicon photonics or other developing technologies, introducing additional variables into the design and deployment of robust high bandwidth optical systems. Measurement and full characterization of loss along the light path is a fundamental tool in the design and optimization of these components and fiber optic networks.

Different types of reflectometers are available to measure return loss, insertion loss, and event location for different types of optical systems. While optical time domain reflectometers (OTDRs) are a standard tsool for medium to long span fiber optic networks, optical backscatter reflectometry (OBR) offers a unique combination of ultra-high spatial resolution and sensitivity that make it a very important tool for shorter fiber spans, modern photonic integrated circuits (PICs) and silicon photonics.

Reflectance and Return Loss

Whether characterizing a miniaturized PIC or troubleshooting a long-haul fiber optic span, understanding and quantifying the loss along the optical path is a very important step when optimizing performance or resolving transmission problems.

Return loss (RL) is defined as the ratio of light reflected back from a device under test (P_R) to the light launched into that device (P_{in}). RL is typically expressed as a negative number in decibels (dB).

$$RL = 10 \log\left(\frac{P_R}{P_{in}}\right)$$

High levels of optical return loss can lower signal-to-noise ratios, contribute to higher bit-error rates (BER), interfere with the operation of the light source, and generally compromise the performance of the optical component or system.

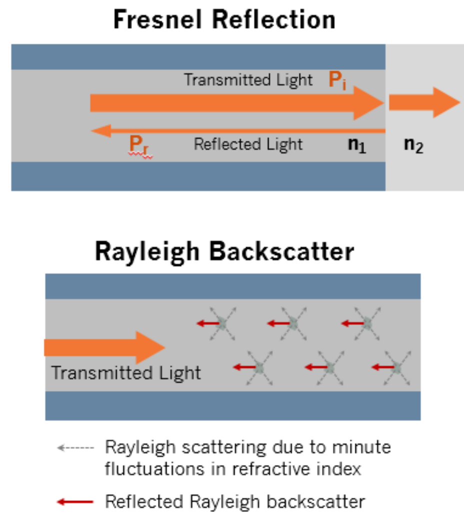

Figure 1. Two primary sources of reflection

The two primary phenomena that cause return loss are Fresnel back reflection and Rayleigh backscatter (Figure 1). Fresnel back reflection occurs when light transitions through different media with different refractive indices (n_i). In an optical fiber, for example, Fresnel reflections are caused by air gaps, cracks in the core, misalignment of fiber cores in splices, macro bends, etc. Rayleigh backscattering, on the other hand, is an intrinsic property of optical media and is caused by the natural impurities and imperfections in the optical fiber core or media. Rayleigh backscattering occurs along the entire length of the optical fiber or light path.

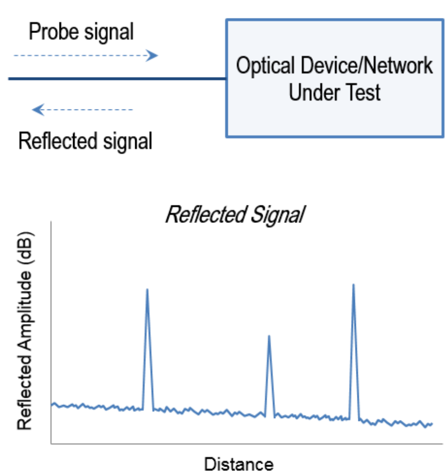

Figure 2. Measurement of return loss using reflectometry

Measuring Return Loss

Reflectometry is a general method of measuring return loss and consists of launching a probe signal into the device or network, measuring the reflected light, and calculating the ratio of the two (Figure 2). The measurement may either quantify the total amount of light reflected or map the loss along the length of the optical path. Measuring the aggregate or total amount of optical return loss (ORL) in a fiber network or optical component is relatively straightforward and consists of injecting a known level of light into the device or network under test and measuring the reflection with an optical power meter. A popular tool for this type of measurement is the optical continuous-wave reflectometer (OCWR). While measuring the total end-to-end optical return loss is often useful, it gives no indication or insight into where the attenuation occurs or where a problem may be in the optical system.

With a time-domain or frequency-domain based reflectometer, however, the return loss can be measured along the length of the device or network under test. There are three established technologies available for spatially-resolved reflectometry - optical time domain reflectometry, optical low-coherence reflectometry, and optical frequency-domain reflectometry.

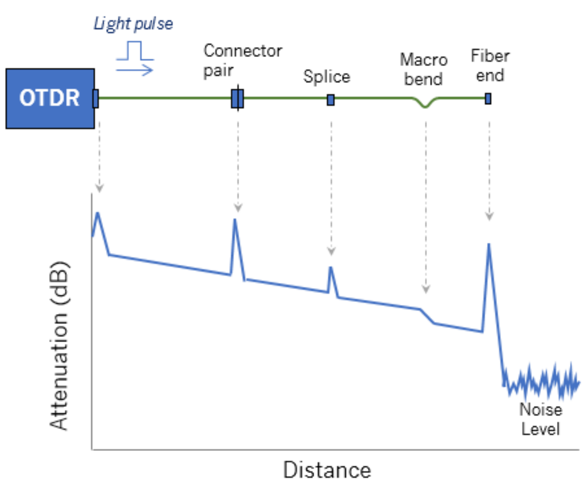

Figure 3. Example OTDR trace for a simple network, mapping loss versus distance

Optical Time-Domain Reflectometers (OTDRs)

The OTDR is the most familiar and popular instrument used for reflectometry measurements of fiber optic networks. OTDRs work by launching optical pulses into the optical fiber and measuring the travel time and strength of the reflected and backscattered light. These measurements are used to create a trace or profile of the returned signal versus length. An example OTDR trace is shown in Figure 3.

Precisely and accurately detecting and characterizing all sources of loss along the optical path is critical to optimizing signal transmission.

The dynamic range of the OTDR determines the total length of the network link that can be traced. It is common for OTDRs to have measurement ranges reaching hundreds of kilometers, making them useful for long-haul fiber optic links. The spatial resolution of the OTDR, defined as the smallest distance over which one can resolve two distinct reflection events, is generally determined by the optical pulse width. A shorter pulse width enables higher resolution (more closely spaced points) but limits the dynamic range and distance range of the OTDR. Typical OTDRs have the ability to reduce the pulse width enough to resolve adjacent reflection events in the range of 1 or 2 meters.

The spatial resolution of an OTDR is also limited by its dead zone. An OTDR dead zone is the distance after a reflection that the OTDR cannot detect or measure a second reflection event. The OTDR dead zone is generally determined by the pulse width as well as the recovery time of the detector within the OTDR. The dead zones are most prevalent at the connector to the OTDR and any other strong reflectors.

Standard OTDRs are well suited for relatively long network spans, reaching hundreds of kilometers or more. For shorter networks and when higher resolution is needed, high-resolution OTDRs employ techniques to decrease the dead zone and reduce the spatial resolution to tens of centimeters.

Optical Low-Coherence Reflectometry (OLCR)

Optical low-coherence reflectometry (OLCR) is an optical measurement technology that can deliver very precise detection. OLCR is an interferometer-based measurement that uses a wideband low-coherent light source and a tunable optical delay line to characterize optical reflections.

While an OLCR measurement can achieve high spatial resolution down to the tens of micrometers, the overall measurement range is limited, often to only tens of centimeters. Therefore, the usefulness of the OLCR is limited to inspecting individual components, such as fiber optic connectors.

Optical Frequency Domain Reflectometry (OFDR)

Falling somewhere in between OTDR and OLCR with regards to measurement range, optical frequency domain reflectometry (OFDR) is an interferometer-based measurement that utilizes a wavelength-swept laser source. Interference fringes generated as the laser sweeps are detected and processed using the Fourier transform, yielding a map of reflections as a function of the length.

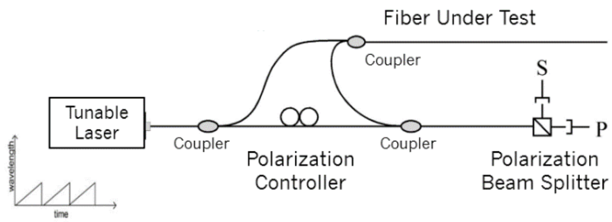

Figure 4. The simplified diagram for an optical backscatter reflectometry (OBR) system

OFDR is well suited for applications that require a combination of high speed, sensitivity, and resolution over short and intermediate lengths.

Optical Backscatter Reflectometry (OBR)

Optical backscatter reflectometry (OBR) is a polarization-diverse implementation of OFDR that further improves the sensitivity and resolution without sacrificing the usable measurement range.

A simplified diagram of the OBR measurement method is shown in Figure 4. Light from a tunable laser source (TLS) is split between the reference and measurement arms of an interferometer. A

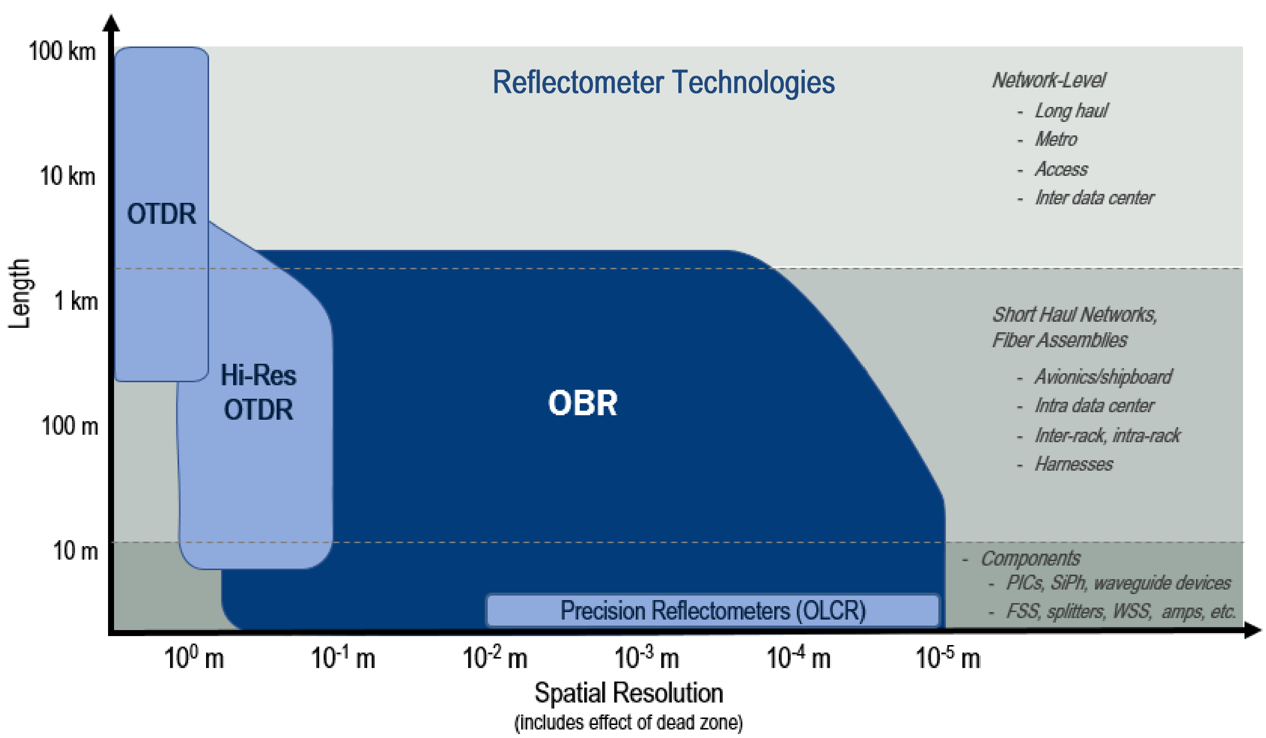

Figure 5. Established methods for optical reflectometry, comparing length (range) and resolution

polarization beam splitter and a polarization controller split the reference light evenly between two orthogonal polarization states. The interference between the measurement field and these two polarization states is then recorded at detectors labeled S and P. The complex reflection coefficients are obtained, and a Fourier transform converts the data into reflectivity as a function of length.

OBR systems can scan optical fiber and components with zero dead zones and ultra-high sampling resolution down to 10 µm for a 30 m range.

The very high resolution of OBR extends the capabilities of OFDR to levels that make it a very useful tool for characterizing PICs, silicon photonics, and other small optical components. With measurement ranges able to extend up to 2 km, OBR is also very useful for troubleshooting short fiber networks and cable harnesses, and even measuring transmission latency, or length, with sub-nanosecond precision. Figure 5 summarizes the landscape of established technologies for optical reflectometry. By mapping the measurement range and spatial resolution of the most common technologies, the plot illustrates the unique application coverage of OBR.

Ultra-High Spatial Resolution and No Dead Zones

The biggest advantage of OBR over other reflectometers is its ability to achieve unprecedented spatial resolution, completely avoiding the limitations of OTDRs caused by large dead zones.

Because OBR instruments are frequency-based, they do not suffer from dead zones. Reflection events in very close proximity to each other can be detected and measured with an OBR. An OBR instrument also can achieve ultra-high spatial resolution, as low as 10 µm for 30 m measurement ranges and 1 mm resolution for 2 km ranges.

OBR Measurement Capabilities	
Measurement Range	Sample Resolution (glass optical fiber)
30 m	10 µm
70 m	20 µm
2 km	1 mm

Table 1. Sampling resolution of OBR

The resolution of the OBR increases for materials with a higher refractive index. For example, silicon photonics waveguides can be scanned with a resolution of about 5 µm.

Additional Measurement Capabilities of OBR

In addition to the measurement of spatially-resolved RL, an OBR system can simultaneously measure other important characteristics of the light path. For example, insertion loss can also be measured along the optical path and at specific locations using the Rayleigh backscatter levels, as shown in Figure 6.

An OBR can also be used to make the following measurements, in addition to Return Loss (RL):

- Insertion Loss (IL)
- RL Spectrum
- Latency
- Group delay (delay versus wavelength)
- Phase derivative (local wavelength vs. distance)
- Polarization state evolution

Because it can measure spectral shift in the Rayleigh backscatter with high precision, OBR can also be used to measure strain (deformation) or temperature in the core of the optical fiber. Luna has developed this capability into a dedicated sensor measurement platform (ODiSI) that can measure strain or temperature along an optical fiber with a spatial resolution of less than 1 mm.

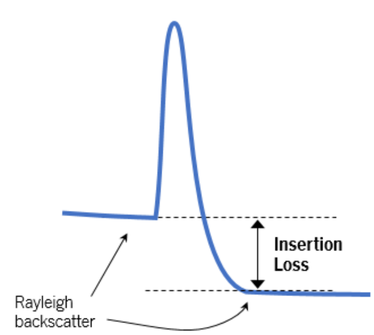

Figure 6. Measuring insertion loss (IL) using backscatter levels

Applications of OBR

The unique precision and resolution of OBR make it a useful tool for many applications involving short fiber networks and PICs. This white paper will describe three general applications that illustrate the value of the OBR's measurement capabilities:

- Characterization of Short Fiber Networks
- Component and Waveguide Characterization
- Latency (or Length) Measurement

This set of example applications is not exhaustive, of course, but illustrates how OBR delivers important insight into a variety of optical design, validation, characterization and troubleshooting applications.

Characterization of Short Fiber Networks

The range and high resolution of OBR are well suited to characterizing or troubleshooting shorter fiber optic networks. As optical data communications rates continue to increase, higher speed optical links are becoming prevalent within data center buildings and campuses (Figure 7) and in fiber to the premise (FTTP) applications. Optical networks are also being deployed for onboard communications on aircraft, ships and other vessels. These applications utilize relatively short high-performance optical links that can be precisely characterized using OBR.

An example of measuring and characterizing a relatively short network is illustrated in Figure 8. An OBR system scans the simple fiber network and generates a detailed trace of loss versus length which is similar to an OTDR. However, the location of the reflection events can be very precisely located due to the ultra-high resolution and lack of any dead zone. For example, the second connector reflection appears to have an abnormal amount of loss, and one might assume this is a misaligned connector. However, with the resolution of an OBR system, we are able to zoom into this area and see that this reflection actually includes a second reflection just behind the connector interface. This second reflection, located only about 8 mm from the connector face, is caused by a crack in the fiber core due to stress where it exits the connector ferrule.

Only an OBR system has the combination of spatial resolution and range to detect and quantify these types of defects and issues.

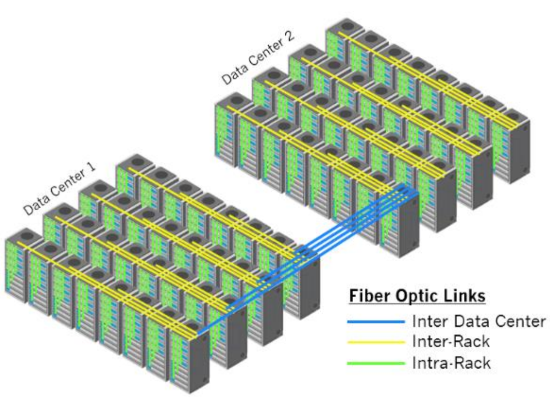

Figure 7. Data centers incorporate many high-bandwidth, relatively short-range fiber connections

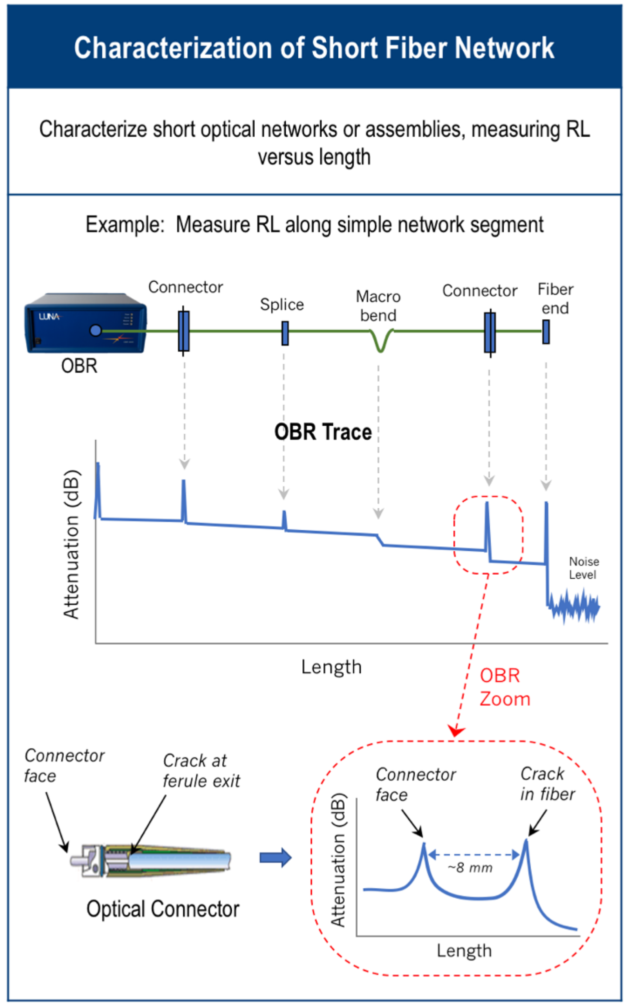

Figure 8. Example OBR measurement of short fiber network

Component and Waveguide Characterization

As silicon photonics and other technologies evolve to pack more functionality into smaller packages, limiting power loss and dispersion becomes even more critically important. The ability to see deep inside a photonic integrated circuit (PIC) and map out the entire loss profile, including the coupling of light into and out of the component, can be invaluable for improving optical waveguide designs.

For example, Figure 9 illustrates the use of OBR to scan a planar lightguide circuit (PLC). The OBR trace shows the RL at the input and output coupling, the insertion loss along the waveguide path, as well as the small reflections due to optical interaction occurring at path crossings internal to the device.

The reflection from the far end of the PLC device demonstrates some broadening of the peak. This is indicative of dispersion in the PLC device. Using standard OBR analysis tools, we are able to also examine group delay versus wavelength. The slope of the group delay indicates the presence of chromatic dispersion, a common phenomenon in these types of photonic components.

As an additional example in silicon photonics, Figure 10 shows a scan using Luna's OBR system of a silicon photonics waveguide. The trace clearly shows the 50 reflections spaced at about 50 µm within the integrated device.

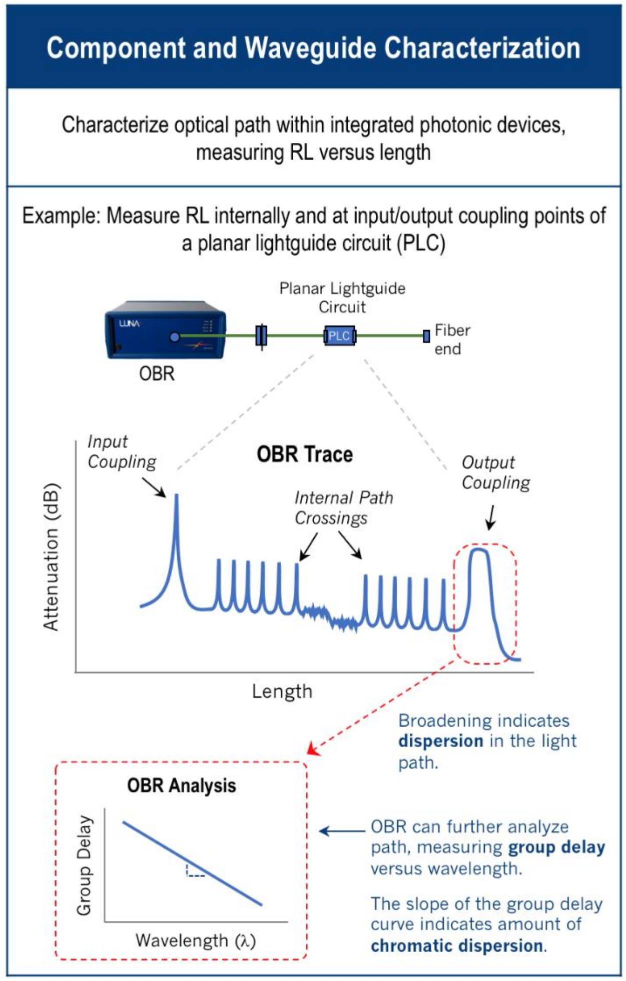

Figure 9. Example OBR measurement of PIC component

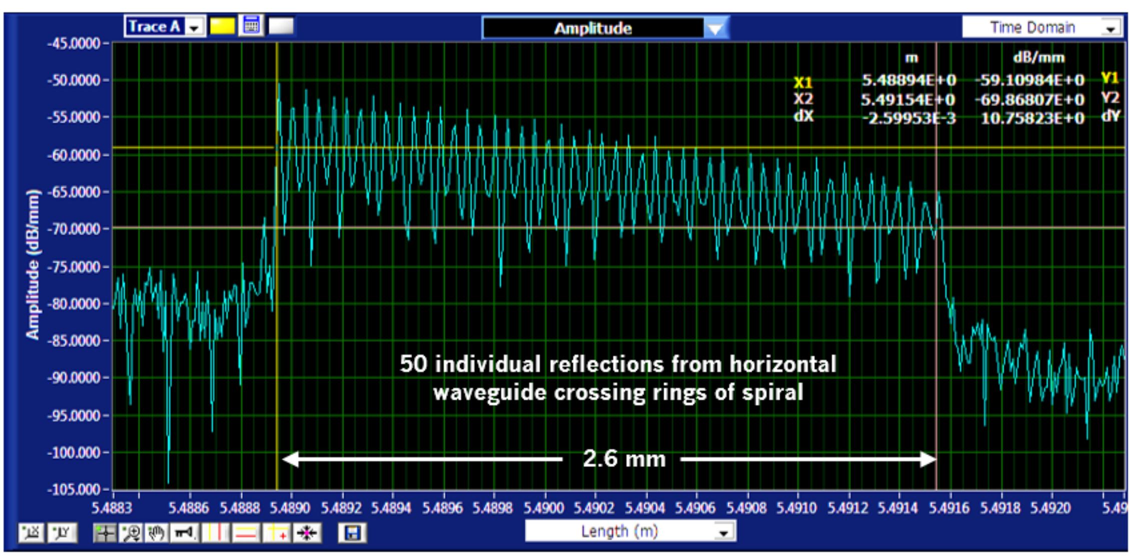

Figure 10. OBR scan of silicon photonics waveguide device

Latency and Length Measurement

The length of a fiber optic segment, and also the physical transmission latency, can be very precisely measured with an OBR system. This is useful for quality control in the production of precision length fiber links, diagnosing latency issues in a fiber network, and certifying link latency in time-critical transmissions, such as in financial data centers.

With its ultra-high sampling resolution, OBR can measure latency with sub-picosecond resolution. The example in Figure 11 illustrates a measurement of two fibers, each approximately 50 m in length. An OBR system measures the difference in latency between the two links as 95 ps, which for this fiber is equivalent to a difference of 19.3 mm in length. Luna's OBR 4600 can measure latency with an accuracy of <0.0034% of the total length (or latency). For a 30 m optical fiber, this corresponds to an accuracy of around 5 ps; for a 2 km fiber, this corresponds to an accuracy of about 0.34 ns.

Signal latency can be measured using OBR with an accuracy of about 5 picoseconds (for 30 m range), or 0.34 ns for a 2 km length of optical fiber.

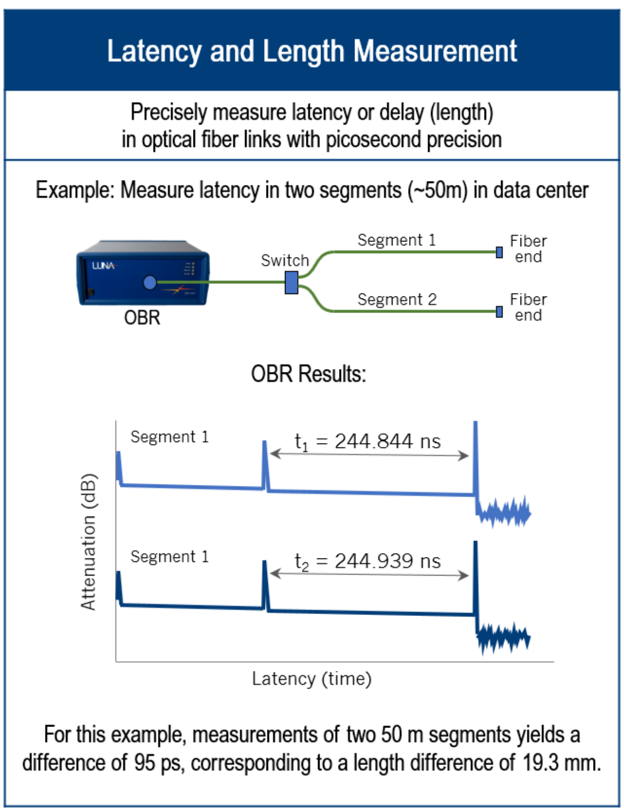

Figure 11. Example measurement of latency/length of optical fiber

Luna OBR Reflectometers

Luna Innovations' line of OBR reflectometers delivers the unique performance and capabilities of OBR to R&D labs, production floors, quality control labs, and to the field. OBR options include:

- OBR 4600: 10 µm resolution and range up to 2km. Great for labs and production floors.
- OBR 6200: Portable OBR for field maintenance applications.
- Luna 6415: Component analyzer with OBR mode - streamlined for the production floor with an update rate of >10 Hz.

The OBR 4600 has the highest measurement performance, working over either the C & L (1525-1610 nm) or O (1270-1340 nm) bands, and featuring 80 dB of dynamic range for RL measurement.

The OBR systems include an intuitive and powerful software platform for interactive measurements and analysis, as well as tools for easily integrating the OBR into your test platform or production line.

Please visit lunainc.com to learn more about all of Luna's solutions for testing fiber optics and photonic components.