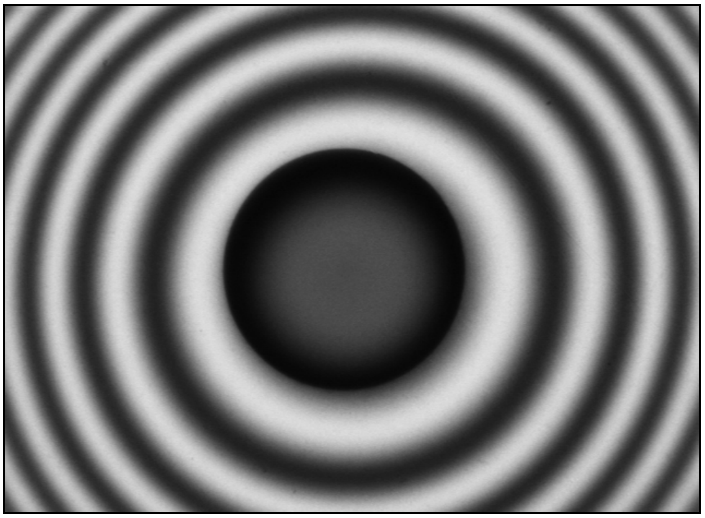
Fiber Optic Connector 3D Metrology

Theory and Practical Application



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Introduction

In theory, higher bit rate fiber optic systems tighten link-loss budgets. An important component of link-loss budgets is the loss associated with ferrule to ferrule contact between connectors. Typically, connector losses are measured by performing insertion loss and reflection loss tests. The results of these tests are relative to a reference connector that is used to perform the tests.

The endface geometry of the reference connector and connector under test has a direct influence on the results of these loss measurements. Using a reference connector that has incorrect endface geometry can give different (and misleading) loss measurements. If connectors are used in a network that have good loss performance characterized with poor reference connectors, they may not give good results when attached to connectors that were tested with a correct reference. The network performance will suffer.

To illustrate this point, Figure 1 is an example of exaggerated cross-sections of two connector endfaces making contact. The images on the left and right show connectors with different geometries making good, low-loss contact at the core of the two fibers (the colored lines in the center of the images). The third image, in the center, takes a connector from each of the other two images and shows that contact would be poor at best.

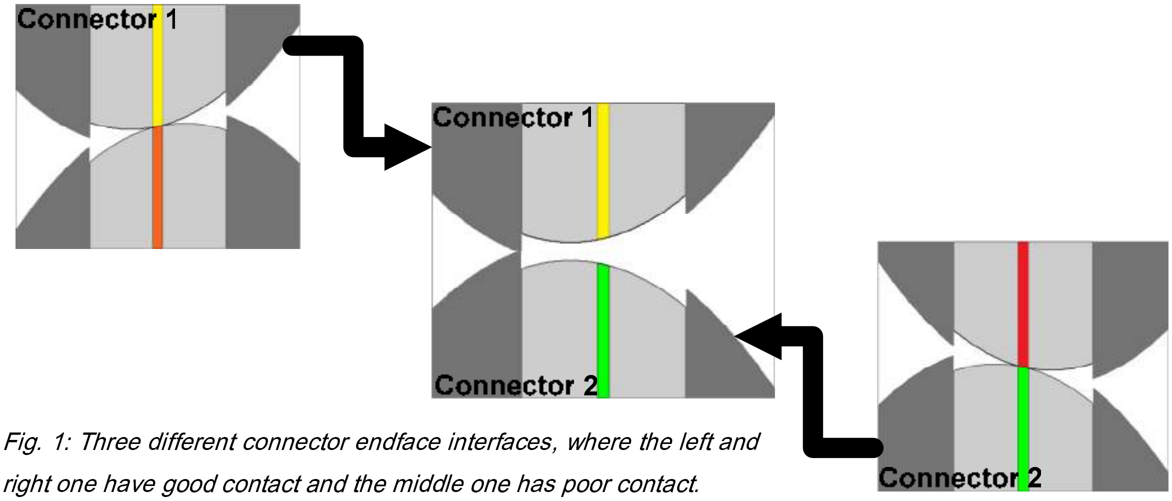


Fig. 1: Three different connector endface interfaces, where the left and right one have good contact and the middle one has poor contact.

Because the reference connector needs to have correct endface geometry to make a good connection, it follows that all of the connectors in the network need to have correct endface geometry as well.

In addition, there is a series of TIA/EIA (Telecommunication Industry Association/Electronic Industries Alliance) standards called the Fiber Optic Connector Intermateability Standards, or FOCIS, that describe the mechanical properties of various connector styles. The goal of these standards is to ensure that connectors made to specification will achieve a common level of performance. However, most of these standards only mention a recommended range for the radius of curvature for the geometry of the ferrule endface and do not mention other important endface geometrical parameters. So adhering to a FOCIS alone will not necessarily result in a robust connection.

Visual Inspection Is Not Enough

Typically, a simple visual inspection using a hand-held microscope is used to look at the endface of a connector to check for contaminants and damage. However, using a microscope only tells part of the story. As seen in Figure 2, both connector ends look free from contaminants and damage which would lead the user to believe that both connectors are acceptable for use in a network.

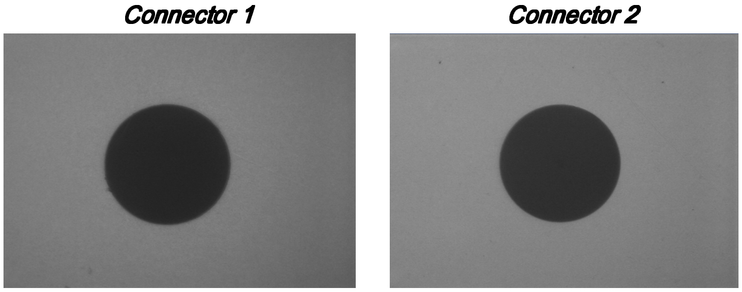


Fig. 2: Microscope image of connector endfaces

However, employing an interferometer designed specifically for connector endface measurement, such as PROMET's FiBO®, the three-dimensional shape of the endface is revealed. The interference fringe images in Figure 3 suggest that the endface geometries of the two connectors are not the same.

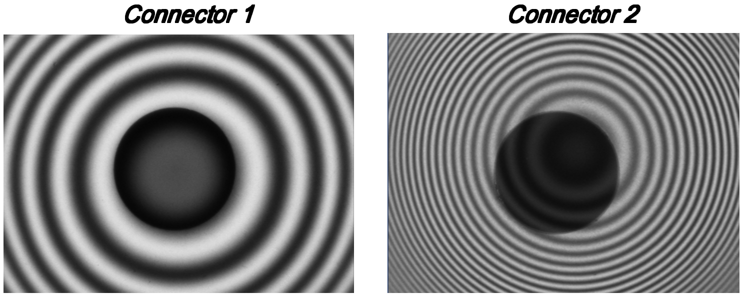


Fig. 3: Interference fringe image of connector endfaces

Taking interferometric measurements and generating the three-dimensional surface maps in Figure 4, clearly shows that the Connector 2 endface has an unacceptably small radius of curvature, only 3.5mm, while the Connector 1 endface has an acceptable radius of 14.0mm.

If Connector 2 is mated to a connector with correct endface geometry, unacceptable losses could result. In order to optimize network performance, connector endface geometries must be measured and controlled.

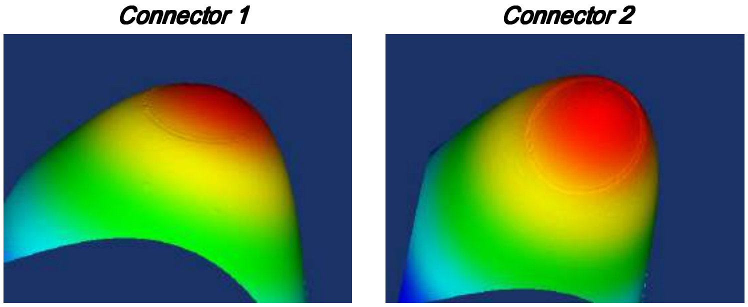


Fig. 4: Resulting three-dimensional maps

This white paper discusses the basics of how interferometry works and how it can be used to measure the geometrical parameters of a connector endface.

Interferometry

In order to measure the three-dimensional parameters of a fiber optic connector endface, optical interferometry is typically used. Optical interferometry is a well known optical phenomenon that has found uses in inertial navigation, optical metrology, holography, astronomy, and many other fields. This section will describe the very basics of interferometry and how it can be used to generate fiber optic connector three-dimensional measurements.

Optical Interference

Optical interferometry is a non-contact measurement technique that relies on the interference between two beams of light. It is preferred over contact measurement methods which can damage the connector endface. Optical interference occurs when two coherent beams of light overlap. The wave nature of the two beams can be thought of as sine waves having a period the wavelength of the illuminating light. Where the two beams overlap, they can be added together using the property of superposition. When the peaks and valleys of the two sine waves line up perfectly, bright total constructive interference occurs. When the peaks of one sine wave line up perfectly with the valleys of the other sine wave, dark total destructive interference results. When the two sine waves are lined up in neither of the previous two scenarios, various levels of gray occur, depending on the amount of phase difference between the two sine waves.

The diagrams in Figure 5 show two interfering sine waves with varying amounts of phase difference between them and their sum. As the phase difference goes from 0 to 360 degrees, the results go from total constructive interference at 0 degrees, to total destructive interference at 180 degrees, and back to total constructive interference at 360 degrees.

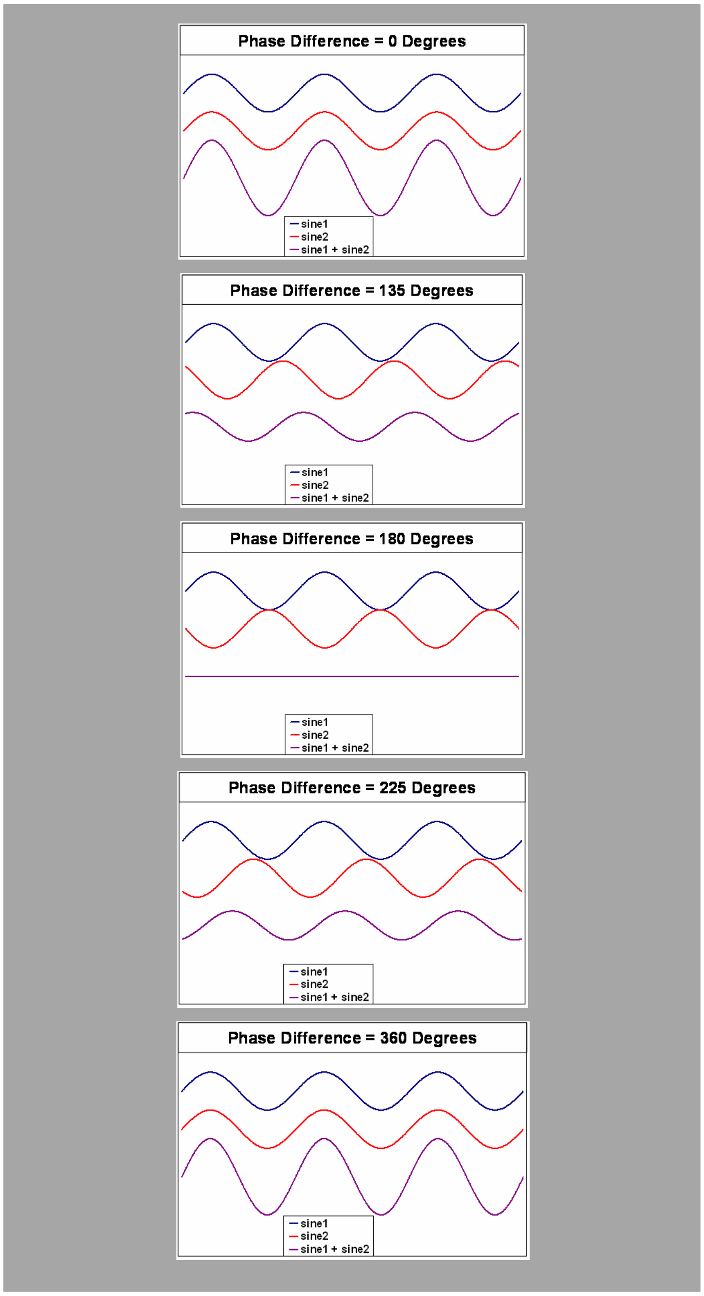


Fig. 5: Interference of two sine waves with 0 to 360 degrees phase difference

Michelson Interferometer

FiBO® is an example of a Michelson style interferometer, which forms interference fringes by dividing the illuminating light into two beams using a beamsplitter. The layout of a typical Michelson interferometer is depicted in Figure 6:

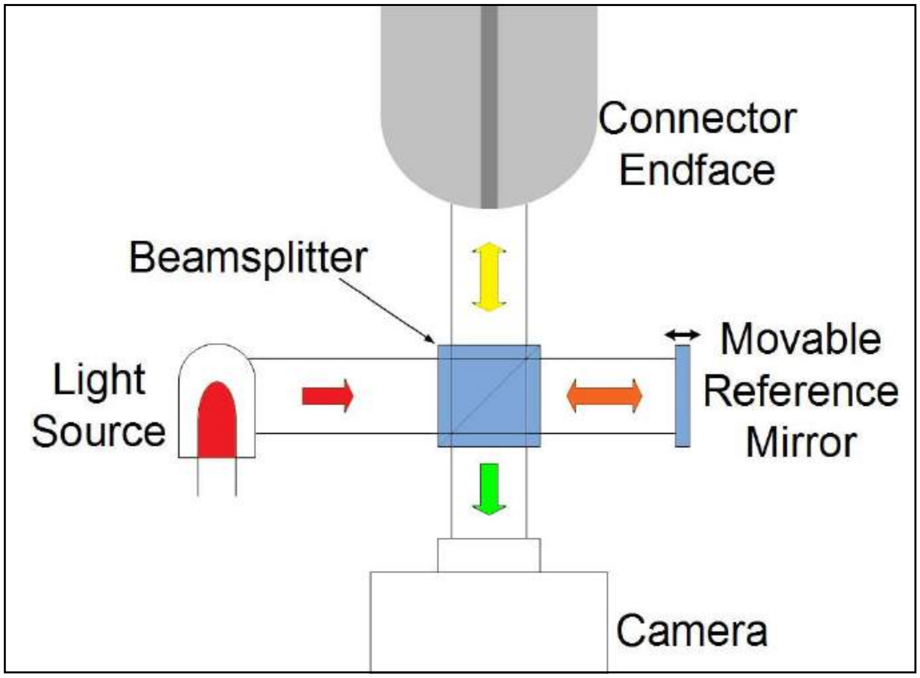


Fig. 6: Michelson interferometer

One beam bounces off of a reference mirror (orange beam) and the other beam is reflected from the connector endface (yellow beam). These beams are recombined by the beamsplitter and are imaged onto a camera (green beam). When overlapping parts of the two light beams travel distances that are multiples of the wavelength of the light, their electric fields line up and constructive interference occurs and a bright fringe is seen. When overlapping parts of the two beams travel distances that are odd multiples of half the wavelength of light, their electric fields are perfectly out of phase, and destructive interference occurs. Figure 7 shows an image with fringes that occur between a flat reference mirror and a spherically shaped connector endface. The black circle in the center is a 125 micron diameter fiber.

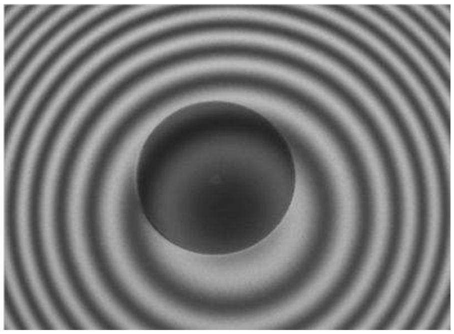


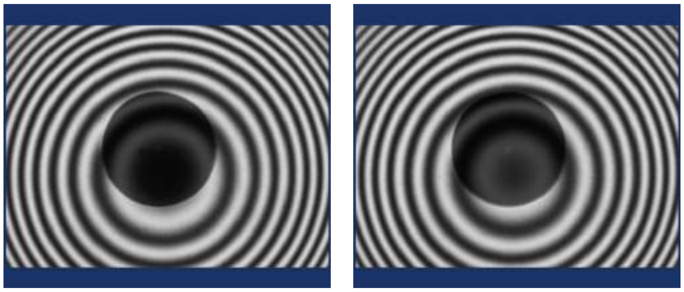
Fig. 7: Circular fringes from interference between a connector end and the reference mirror

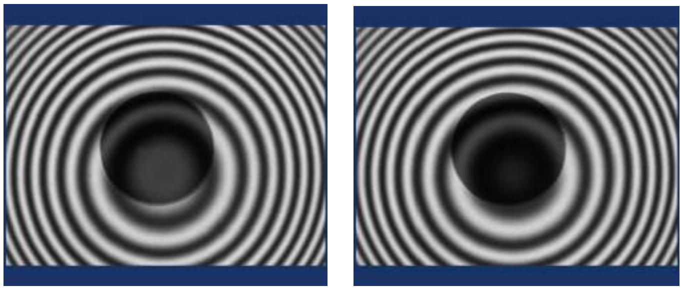
The circular fringes are like the contours of a topographical map showing where points of equal phase difference are occurring. The height difference between adjacent bright fringes corresponds to half the wavelength of light (approximately 0.32 microns).

Phase-Shifting Interferometry

A skilled operator can look at the fringes produced by a Michelson interferometer alone and get an idea of the three-dimensional shape of the connector end. However, generating quantitative information is desirable to remove the user's (in)experience from the equation and ensure objectivity. One of the most accurate techniques to obtain quantitative three-dimensional surface data is called phase-shifting interferometry.

In this technique, the reference mirror of the Michelson interferometer is mounted on a piezoelectric actuator. The reference mirror is moved by this piezo by very precise amounts, which varies the phase difference between the two arms of the interferometer. Images are taken with a series of different phase amounts, typically 90 degrees between images (see Figure 8), and then are algebraically combined to obtain a phase map of the surface. There are different algorithms that have been developed to arrive at a phase map. This phase map is then converted to quantitative three-dimensional information.


0 Degree Frame *90 Degree Frame*


180 Degree Frame *270 Degree Frame*

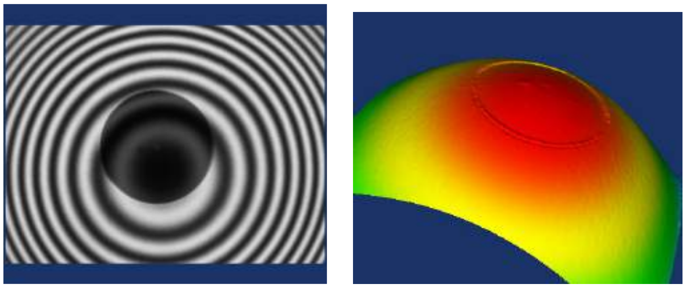

360 Degree Frame *Resulting 3D Map*

Fig. 8: Several phase-shift steps and the resulting contour map

Three-Dimensional Connector Endface Parameters

Standards such as TIA-455-218 (FOTP-218), IEC 61300-3-16, IEC 61300-3-17 and IEC 61300-3-23 describe how to measure the three-dimensional properties of a single fiber optic connector endface. The three main properties measured are:

- radius of curvature
- apex offset (offset of the polish relative to the center of the fiber)
- fiber height (relative to the ferrule surface)

Radius of Curvature

Bare Fiber Connector End

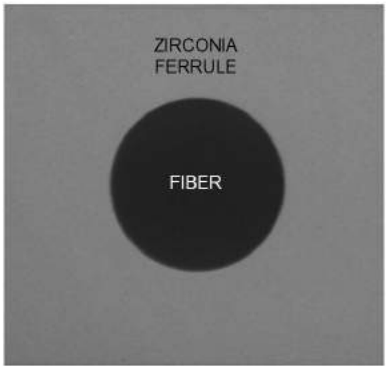


Fig. 9

Fitting and Averaging Regions

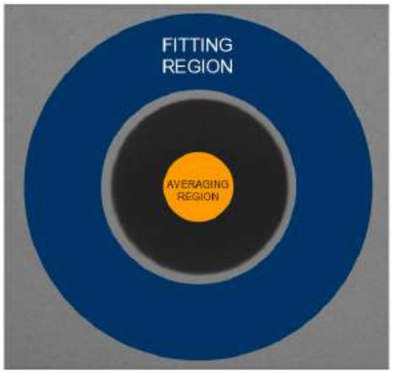


Fig.10

The first step given in these standards is to obtain a three-dimensional map of the connector surface. FiBO® obtains this map with the technique of phase-shifting interferometry described above. The next step is to numerically fit an ideal sphere to the measured data. Not all of the data is used for this fitting. Only a donut-shaped slice of the ferrule called the contact zone (or fitting region) is used. The standards recommend using a slice that has an outer diameter of 250 microns and an inner diameter of 140 microns. This fitting region is used because the endface can be aspherical and using the defined region for fitting achieves better agreement between measurements by different interferometers. The radius of this fitted sphere is then reported as the measured radius of curvature. A typical acceptable radius of curvature range is between 7 and 25 millimeters. Figures 9 and 10 show a connector endface with, and without, the fitting region displayed.

Apex Offset

The linear distance in microns between the center of the fiber and the fitted sphere in the plane of the image is reported as linear apex offset. The exaggerated cross-sectional diagrams of a connector endface in Figure 11 illustrate a connector with no apex offset (left) and with excess apex offset (right).

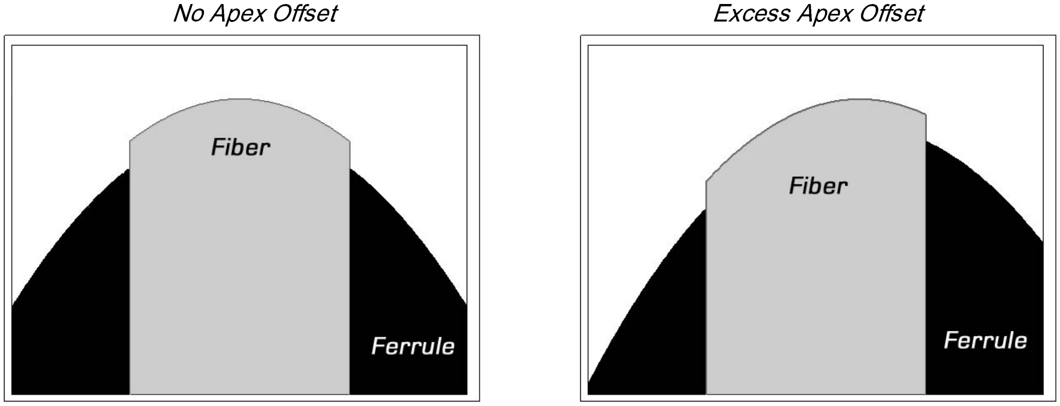


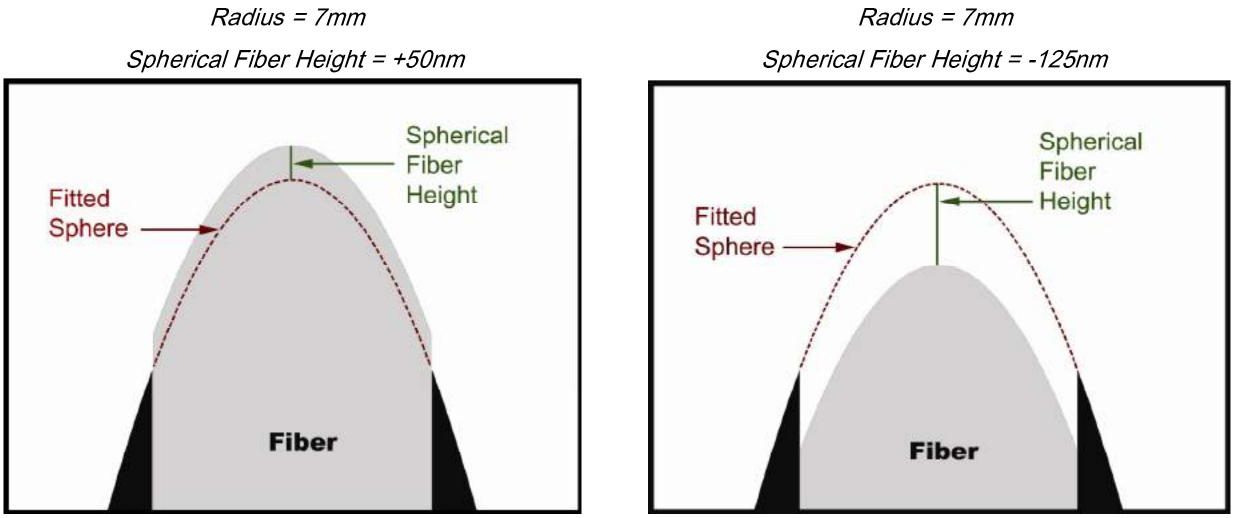
Fig. 11: Apex offset examples

Apex offset can be the result of incorrect polishing or, in the case of angle polished connectors, angle errors. The typical maximum acceptable apex offset is 50 microns.

Fiber Height

Fiber height, in nanometers, is calculated by first subtracting the fitted sphere from the measured data. The heights in a central area of the fiber, called the averaging area, are averaged together. The diameter of this circle, centered on the center of the fiber, is typically 50 microns. The average height in the contact zone is then subtracted from this average fiber height. This difference is called the spherical fiber height. We define spherical fiber height as being positive when the fiber protrudes above the fitted sphere. A typical range for fiber height is from -125 to +50 nanometers.

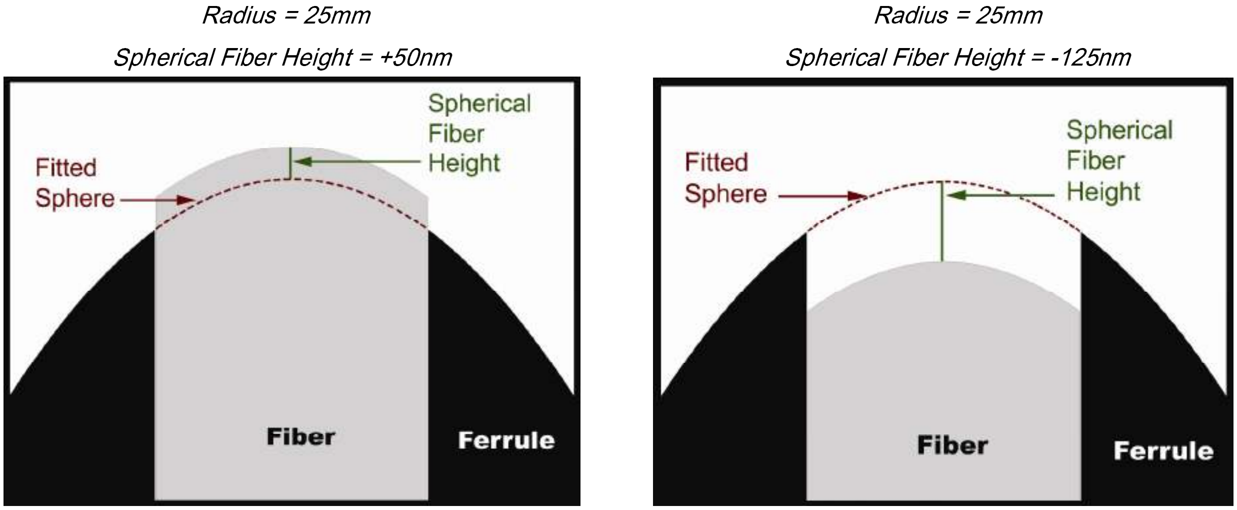
The images (not-to-scale) in Figure 12 illustrate examples of cross-sections of different combinations of fiber radius and spherical fiber height. The gray area is the fiber, the black area is the ferrule, the dashed red line is the fitted sphere, and the solid green line is the spherical fiber height distance.


Radius = 7mm

Spherical Fiber Height = +50nm

Radius = 7mm

Spherical Fiber Height = -125nm


Radius = 25mm

Spherical Fiber Height = +50nm

Radius = 25mm

Spherical Fiber Height = -125nm

Fig. 12: Examples of different combinations of radius and spherical fiber height

Summary

This white paper illustrates that to ensure a reliable and low link-loss network it is important to examine both the microscopic image of the connector endface as well as its three-dimensional properties. The basics of phase-shifting interferometry and its application to connector endface inspection are presented and discussed. Finally, the three main dimensional parameters of a connector endface that are measured with a phase-shifting interferometer (apex offset, radius of curvature, and fiber height) are illustrated and explained in detail.

About PROMET International®

PROMET International specializes in the design, manufacturing and testing of high-precision optomechanical systems for various industries including biometrics, medical, and military. Since 1993, PROMET has been providing its customers with the unique expertise, technology, and precision components that are necessary to successfully implement theoretical optical designs into real-world solutions.

The FiBO® true phase-shifting Michelson interferometers are designed and manufactured by PROMET's experienced staff of engineers and technicians. FiBO facilitates non-contact analysis of fiber optic connector endfaces and various micro-components. It sets new standards for portable, vibration-insensitive interferometry by combining **3D** surface mapping and **2D** visual inspection capabilities into compact, portable and rugged designs.

About the Author

Eric Lindmark is a Senior Development Engineer with PROMET International and has been a member of the PROMET team since 2003. He is responsible for several developmental aspects for the FiBO® line of interferometers. Eric has a Ph.D. and M.S. in Optical Sciences from the University of Arizona, as well as an M.S.E.E. from the University of Minnesota and a B.S.E.E. from Virginia Tech.