Fiber Recession / Protrusion Study

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Introduction

As part of the Navy, NAVAIR SBIR N092-118, a study was commissioned to study the effects of fiber optic recession and protrusion inside the ceramic ferrules of fiber optic connectors. The purpose of fiber optic connectors is to provide a reusable, repeatable, reliable, low optical loss method of joining two separate pieces of optical fiber. In order to achieve these goals, various standards bodies have devised recommendations for the geometry of the polished endface of these connectors.

For physical contact (PC) style connectors, where two connector endfaces are mated to make an optical connection, three aspects of the endface geometry are generally specified:

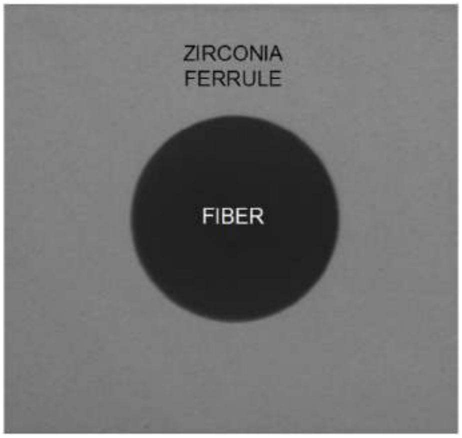
- Radius of Curvature
- Linear Apex Offset
- Spherical Fiber Height

These parameters are related to the three-dimensional shape of the fiber optic endface. A standard microscope cannot measure these parameters, so a device called an optical interferometer is most often used to examine the connector endface. Interferometers provide numerical three-dimensional data that is used to calculate the values of the above three parameters.

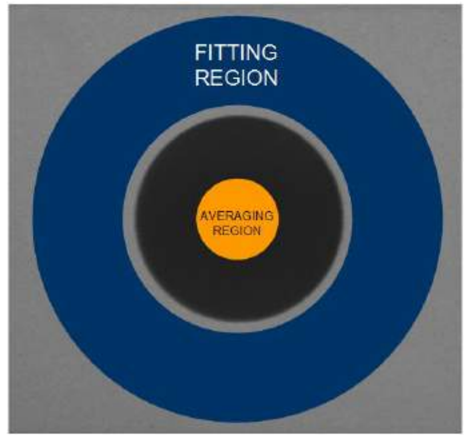
Radius of Curvature

In order to find the Radius of Curvature, an ideal sphere is numerically fit to an annular region of the ferrule surrounding the fiber (called the fitting region). The TIA-455-218 standard (and others) recommends using a region that has an outer diameter of 250 microns and an inner diameter of 140 microns. 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.

The following microscope images show a connector endface with, and without, the Fitting Region displayed.



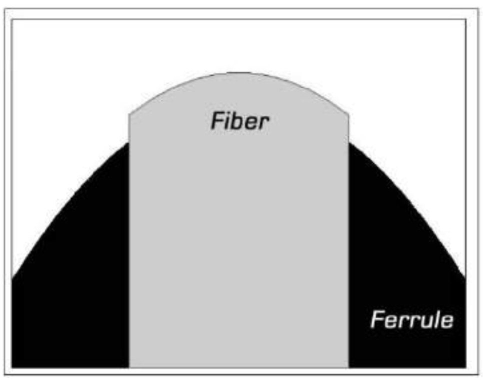
Fiber Optic Connector Endface



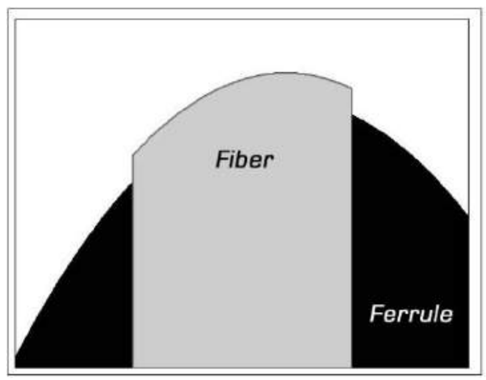
Fitting & Averaging Region

Linear 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 following exaggerated cross-sectional diagrams of a connector endface illustrate a connector with no apex offset (left) and with excess apex offset (right).



No Apex Offset



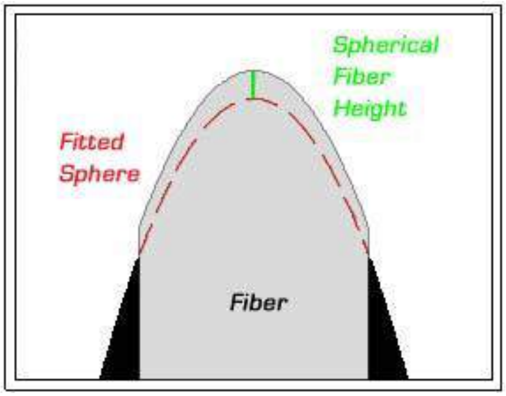
Excess Apex Offset

Linear 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.

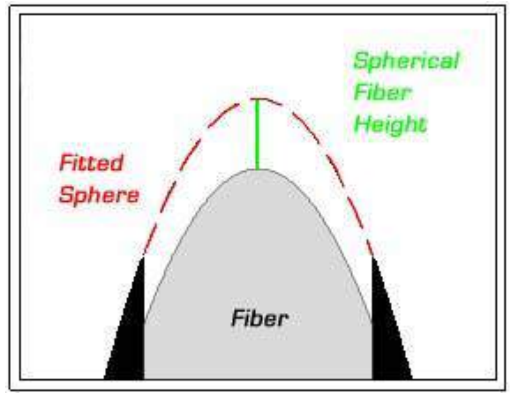
Spherical Fiber Height

Spherical Fiber Height is calculated by first subtracting the fitted sphere from the measured data. The heights in a central area of the fiber called the averaging region are then averaged together. The diameter of this circle, centered on the center of the fiber, is typically specified in the standards as 50 microns. The average height in the fitting region 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 acceptable range for fiber height is from -125 to +50 nanometers.

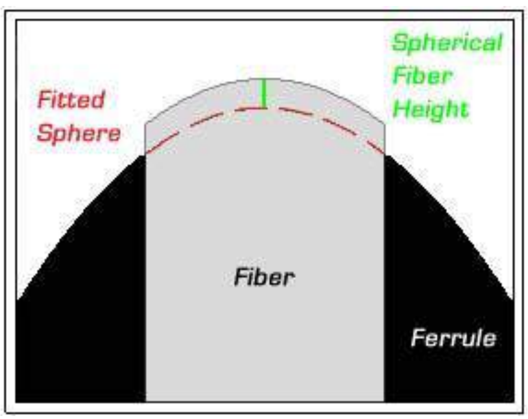
The following images (not-to-scale) illustrate examples of cross-sections of different combinations of fiber radius and spherical fiber height. The gray area is the fiber, the black area is the ferrule, the dashed red line is the fitted sphere, and the solid green line is the spherical fiber height distance.



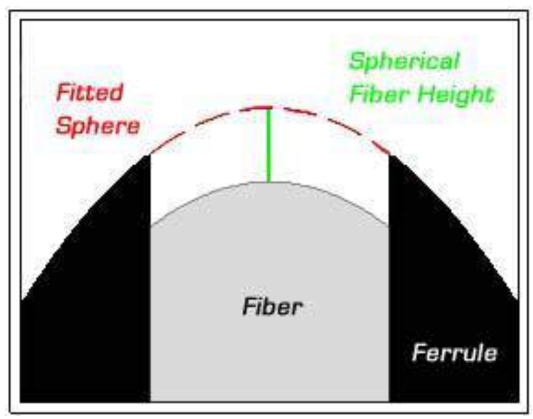
Radius = 7mm
Spherical Fiber Height = +50nm



Radius = 7mm
Spherical Fiber Height = -125nm



Radius = 25mm
Spherical Fiber Height = +50nm



Radius = 25mm
Spherical Fiber Height = -125nm

The purpose of this study is to examine what happens to the optical performance, as well as to the physical properties of the fiber, when the Spherical Fiber Height is not within the recommended range.

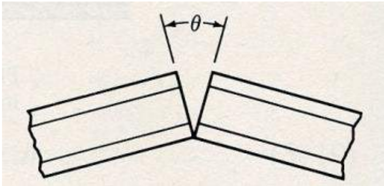
Theoretical Background

There are many papers and books that describe the theoretical optical performance of two mated optical fibers (e.g., Keiser, Thiel & Hawk, Bisbee). The main optical parameter that is measured is called Insertion Loss. It is the amount of light that is lost when transferring between the first fiber core to the second fiber core and is affected by how the two fibers are aligned to each other. It is usually stated in decibels (dB) as a ratio of two optical powers.

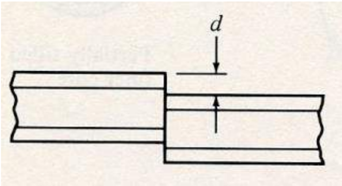
Alignment Issues

The three main alignment issues between two fiber cores are given as (Keiser, page 130):

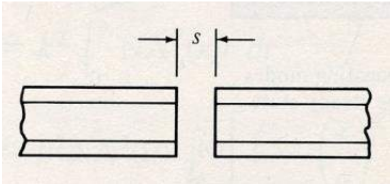
1. Angle Misalignment



2. Lateral (axial) Displacement



3. Longitudinal Displacement



We examine the third issue, assuming the other two alignment conditions are controlled by the quality of the connectors and mating alignment sleeves.

Longitudinal Displacement

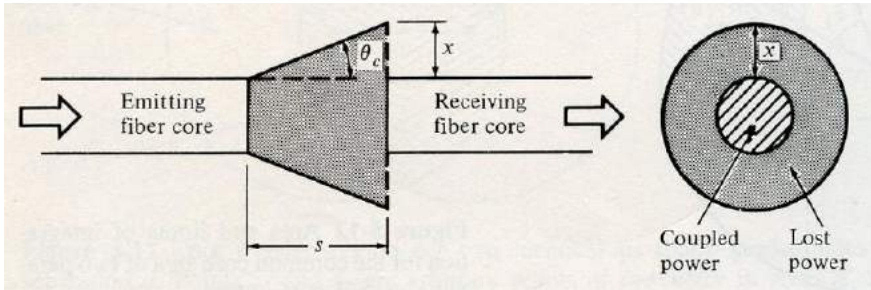
For Longitudinal Displacement, there are three theoretical insertion loss problems:

1. Separation loss from numerical aperture (NA) of fiber
2. Fresnel loss at both air/glass interfaces of the fiber when they are not in physical contact
3. Fabry-Perot interference effects from light bouncing back and forth between the connector endfaces when they are no longer touching.

When a fiber protrudes, there is not a displacement problem because the two fibers will be touching. The main problem is seen to be fiber damage because the fiber is not protected by the ferrule when it is sticking out.

Separation Loss from NA of Fiber

When two fibers are separated, the light from the emitting fiber expands and not all of it is captured by the receiving fiber as shown in the following diagram (Keiser, page 134):



Showing power loss from separation (s)

Thiel and Hawk studied this problem and derived the following equation for the loss:

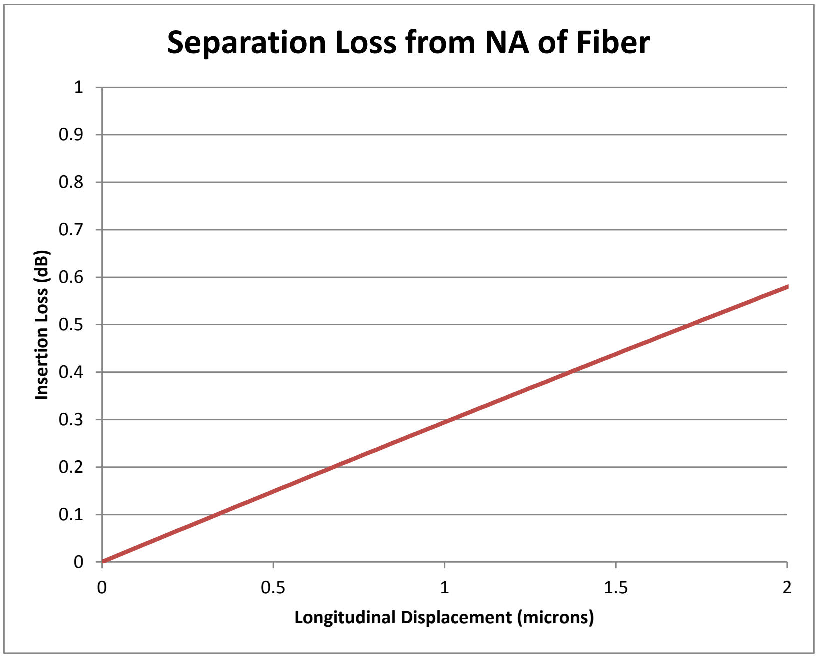
$$L_{NA} = -10\log_{10}\left(\frac{a}{a + s\tan\theta_c}\right)^2$$

where:

$$\theta_c = \sin^{-1}\frac{NA}{n}$$

a is the fiber's core radius (4.1µm for SMF28 type fiber (Corning)), *s* is the separation distance, *NA* is the numerical aperture of the fiber (0.14 for SMF28) and *n* is the index of the material between the fibers (n = 1 for air).

Ignoring any other losses, plotting the formula above produces the following graph:



Power loss from separation from NA of fiber only

Fresnel Loss

When light travels from one media to another with an index of refraction mismatch, a portion of the light is reflected. This reflection loss is given by the Fresnel equations as (Hecht, page 102):

$$L_{Fres} = -10\log_{10}\frac{4n_t n_i}{(n_t + n_i)^2}$$

where n_t is the index of refraction of the transmitted medium and n_i is the index of refraction of the incident medium.

For an optical fiber (n = 1.4682 for SMF28 at 1550nm) in air (n = 1), there is a loss of 0.177 dB at each fiber endface when they are no longer touching for a total loss of **0.355 dB** for the pair.

Fabry Perot Interference

The Fresnel loss above is true for incoherent light, but when the light is coherent (such as from a laser) and travels between two separated plane parallel mirrors, a Fabry-Perot etalon is created. We have a very similar case when the two optical fibers are no longer touching. The result of this etalon is that constructive and destructive optical interference can occur between the two fibers depending on the space between them. This loss is described by (Hecht, page 367):

$$L_{F-P} = -10\log_{10}\frac{1}{1 + Fsin^2\left(\frac{\delta}{2}\right)}$$

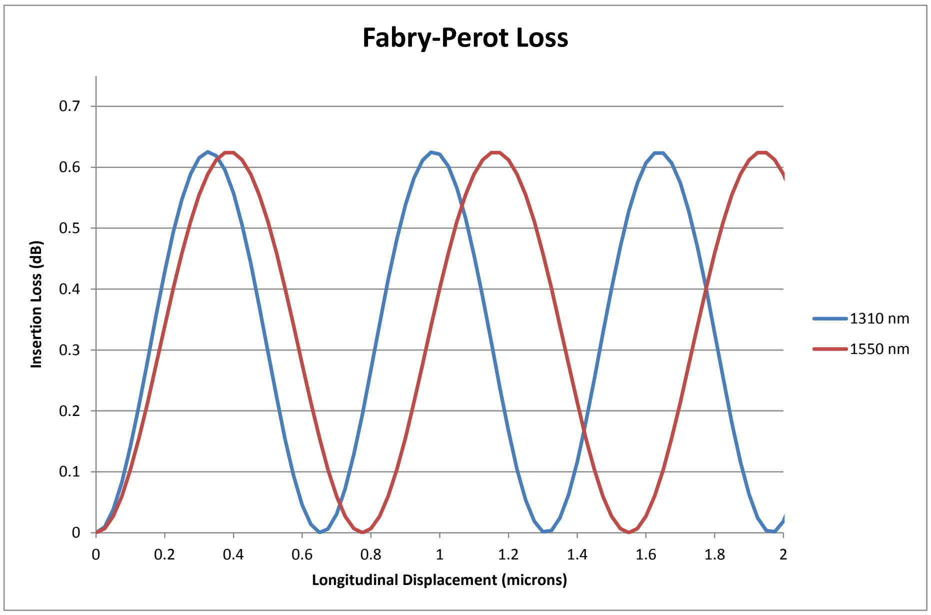
where:

$$F = \frac{4R}{(1-R)^2}$$

$$\delta = \left(\frac{2\pi}{\lambda}\right) 2ns$$

R is the Fresnel reflectance of the fiber in air (0.03598 for an index of 1.4682 for SMF28), *s* is the separation distance, λ is the wavelength of the light used (e.g. 1550nm) and *n* is the index of the material between the fibers (n = 1 for air).

Ignoring any other losses, plotting the formula above generates the following graph for 1310 and 1550 nm:

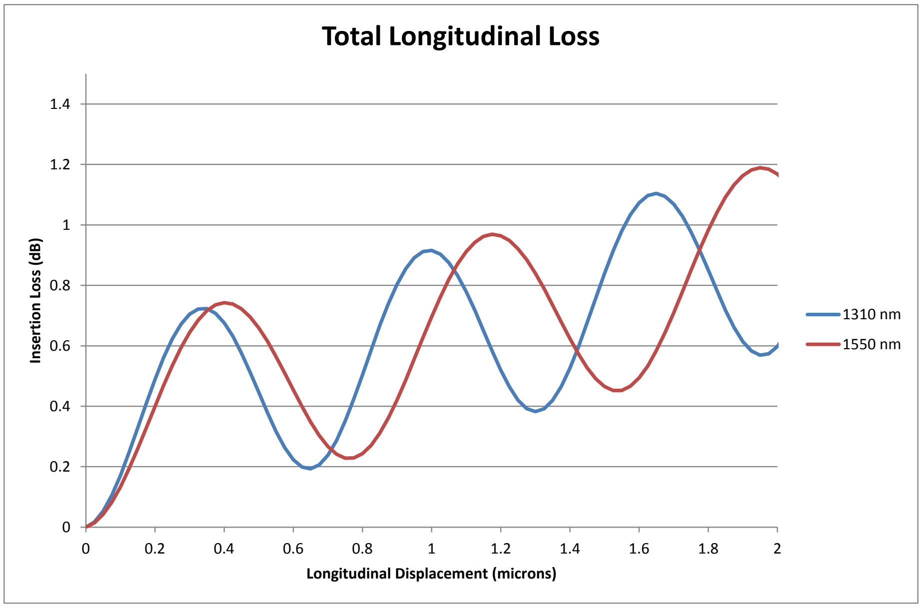


Power loss from separation from Fabry-Perot interference only for 1310 and 1550 nm

We can see in this graph that the Fabry-Perot loss can actually go to zero at the correct distances.

Total Theoretical Loss

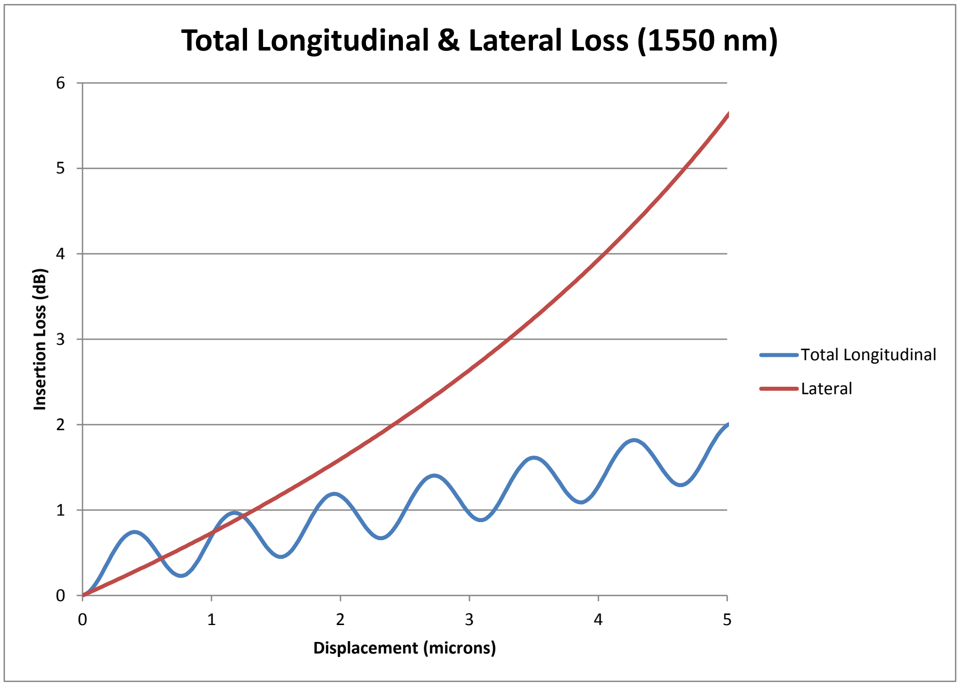
If a laser is used for illumination, the NA loss and Fabry-Perot longitudinal losses can be added together and result in the following graph:



Power loss from adding NA and Fabry-Perot losses for both 1310 and 1550 nm

As indicated in this graph, when the fibers no longer touch a sharply increasing loss occurs from primarily the Fabry Perot loss. In only a few hundred microns, the loss can increase > 0.6 dB. It can also decrease just as rapidly.

As a note, Insertion Loss increases more rapidly for Lateral Displacement than Longitudinal Displacement for the same amount of distance displaced. If the data above is plotted along with Lateral Displacement loss (using equations from Thiel & Hawk), the following graph results:



Comparison of Total Longitudinal Displacement Loss & Lateral Displacement Loss

Sample Preparation Methodology

Due to the unique requirements of this study, it was determined that off-the-shelf connectorized fiber optic patch cables would not give enough fiber height variation because they are made to fall within "good" specifications. Equipment and supplies to connectorize fiber optic cables and polish connector endfaces were therefore purchased.

SC/PC connectors from Seikoh Giken Co., Ltd. were chosen for their reputation of quality construction and widespread availability. The raw connectors consist of several parts:

Boot *Crimping Sleeve* *Ceramic Ferrule* *Connector Body* *Dust Cap*

Assembling a completed connector requires several steps including fiber stripping, expoxying, heat curing and crimping:

Completed connector before polishing

The Krell Technologies Inc. Rev polisher was used to perform the polishing steps. It is a small fiber optic connector polisher that polishes one connector at a time:

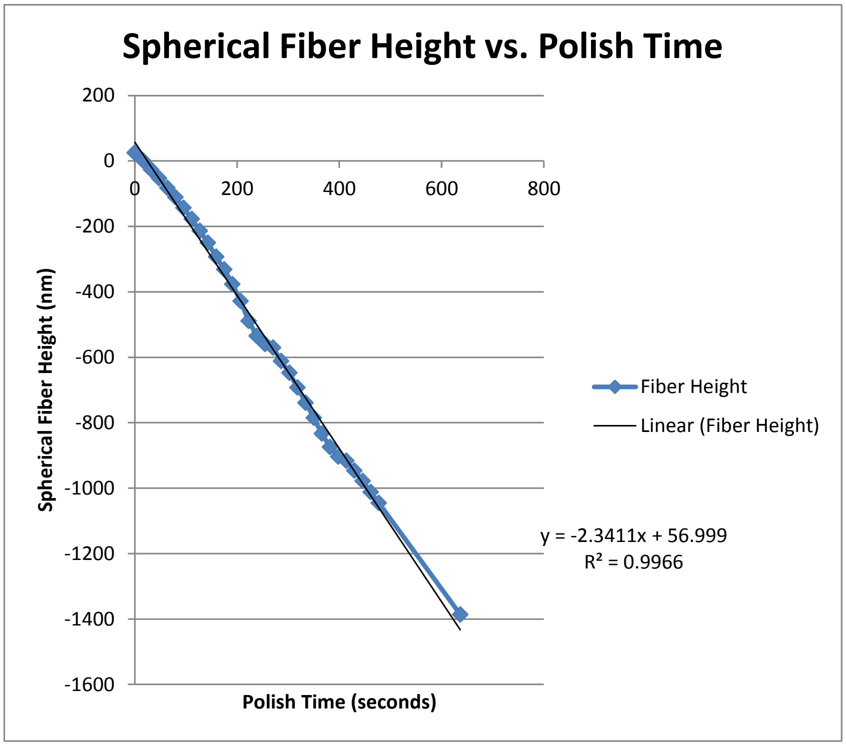
Krell Rev Polisher

The system comes with polishing pads of different hardness as well as different polishing sheets of varying grit sizes. It also comes with recommended polishing steps for different types of connectors using these sheets and pads.

Some time was spent learning the process to make “good” connectors using Krell’s recommended polishing steps and polishing pads. Experiments were then performed to create connectors with “bad” amounts of fiber height.

Making excess negative fiber height (undercut)

A customer of PROMET’s shared their proprietary polishing method used to undercut the fiber height of a connector after it has been normally constructed and polished. Using this method, a connector endface was polished many times in ~15 second long polishing steps (the timer setting of the Krell polisher) and its fiber height was measured on a FiBO interferometer after each step:



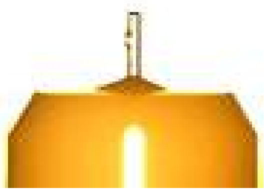
Spherical Fiber Height as a function of polishing time

A linear fit to the data gives a fiber height polishing rate of 2.3 nm per second.

Using this technique, the Radius of Curvature and Linear Apex Offset are only slightly affected during the subsequent polishing steps.

Making excess positive fiber height (protrusion)

As part of the connectorizing procedure, the fiber is epoxied into the ferrule of the connector and it protrudes above the surface of the ferrule with a small epoxy bead surrounding it:



Fiber protruding above surface of ferrule (Sagitta)

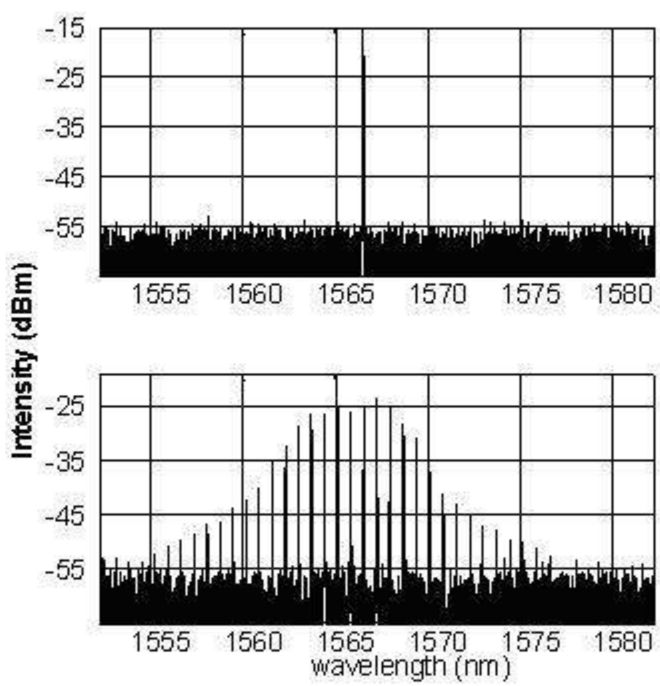
We want to have a small amount of polished fiber sticking out from the endface. A procedure was developed where the ferrule was pre-polished without the fiber so that the surface of the ferrule would be smooth and only the fiber that was sticking out would need to be polished. The process involved removing most, but not all, of the epoxy and fiber sticking above the endface surface with gentle polishing. The remaining thin layer of epoxy was then removed chemically using a mixture of Methylene Chloride and Methanol.

This process is not well controlled (variation in how much epoxy was on the surface of the ferrule, an unknown starting fiber height, etc.) like the process for undercut, but did lead to a variety of different fiber heights (from several hundred nanometers to many microns) for testing.

Primary Measurement Equipment

Light Sources

Historically, most insertion-loss measurements have been made with sources that have fixed wavelengths, mostly Fabry-Perot (FP) lasers. These lasers are well-suited for measuring the losses of broadband optical components such as fibers, connectors, attenuators, etc., because they produce high power (>1mW) with a spectral window larger than several nanometers. This large spectral spread reduces the chance of having optical interference problems. Here is a comparison between the spectra of a single-wavelength mode laser and a FP laser (University of New Mexico):



Laser Spectra: Single Longitudinal Mode (top) and Fabry-Perot multimode (bottom)

There is continuous competition between the different longitudinal modes in the Fabry-Perot laser, so the power in each individual mode fluctuates continuously, but the total power stays the same. For insertion-loss measurements, only the total power is important. In addition, some averaging is usually implemented in the measuring power meter which also reduces noise.

The Light Sources used in this study do not have a free-space output, but are fiber pigtailed with one end of the fiber at the laser and the other connectorized at a panel interface. They are bench-top Fabry Perot lasers from Thorlabs with wavelengths of 1310nm and 1550nm:

Thorlabs Fabry-Perot Benchtop Laser

Optical Power Meter

The Power Meter used in this study has an integrating sphere type input rather than just a flat detector. It is the Newport 818-IS-1 Universal Fiber Optic Detector paired with the 1830-C Meter electronics:

Newport Optical Detector and Power Meter

This detector uses a symmetrical integrating sphere design to ensure the most accurate calibration possible regardless of the fiber type measured. The integrating sphere uses a novel dual detector design with special optics that improve temperature sensitivity markedly from ordinary detectors. It can operate over the wavelength range of 410–1650 nm.

Measurement Methodology

Insertion Loss

Instructions for accomplishing Insertion Loss measurement were primarily extracted from the book **Fiber Optic Test and Measurement** by Dennis Derickson. Chapter 9 of this book is entitled *Insertion Loss Measurements* (page 339).

Insertion loss measurement is a two-step procedure:

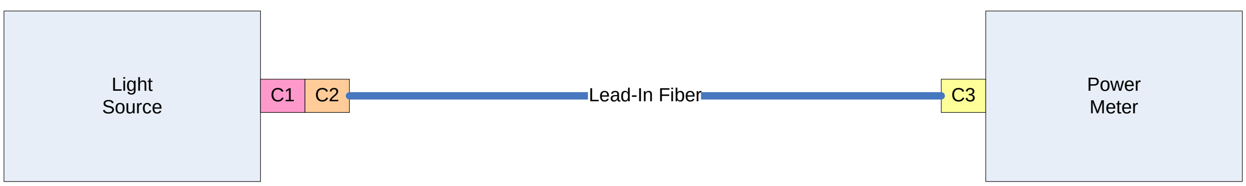
1. Calibration. The reference power is measured (without the test device).
2. Measurement. The test device is inserted and the power is measured again.

The ratio of the two measured powers is calculated and the attenuation is usually expressed in dB:

$$Insertion\_Loss = -10 \cdot \log\left(\frac{Power\_with\_Test\_Device}{Calibration\_Power}\right) dB$$

Calibration Step

In the calibration step, a lead-in fiber (or golden standard), preferably of the same type as the Device Under Test's (DUT) fiber pigtails, connects the source and power meter directly:

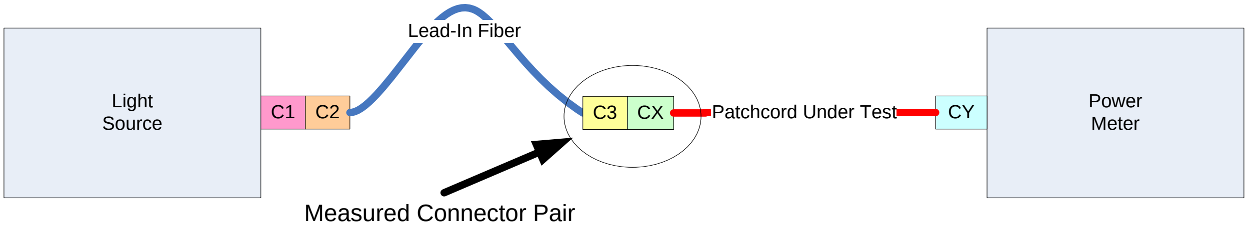


Insertion Loss Calibration Step

Each connector is represented by a box with a C in it. A mandrel wrap of a single turn was added to the lead-in fiber to strip any higher order modes travelling down the fiber for this, and all other measurements.

Measurement Step

In the measurement step, the patchcord's input connector CX is mated with the system's connector C3, and the patchord's output connector CY is inserted into the Power Meter:



Insertion Loss Measurement Step

Details of the Measurement

The measurement step adds another connector interface to the measurement (C3 to CX). Therefore, the measurement adds the insertion loss of the fiber of the patchcord and the insertion loss of the input connector pair C3/CX. If the patchcord has just a short length of fiber, then the loss due to the fiber is very low and the measured loss is almost all due to the C3/CX interface. According to Derickson, even good connector pairs can have a loss of 0.3dB (6.7% loss).

Ideally, exchanging connectors C3 and CY at the input port of the Power Meter should not influence the power measurement results, especially with a Power Meter using an integrating sphere.

The Insertion Loss measurement is not the measurement of a single connector, but is the measurement of a mated pair.

Return Loss

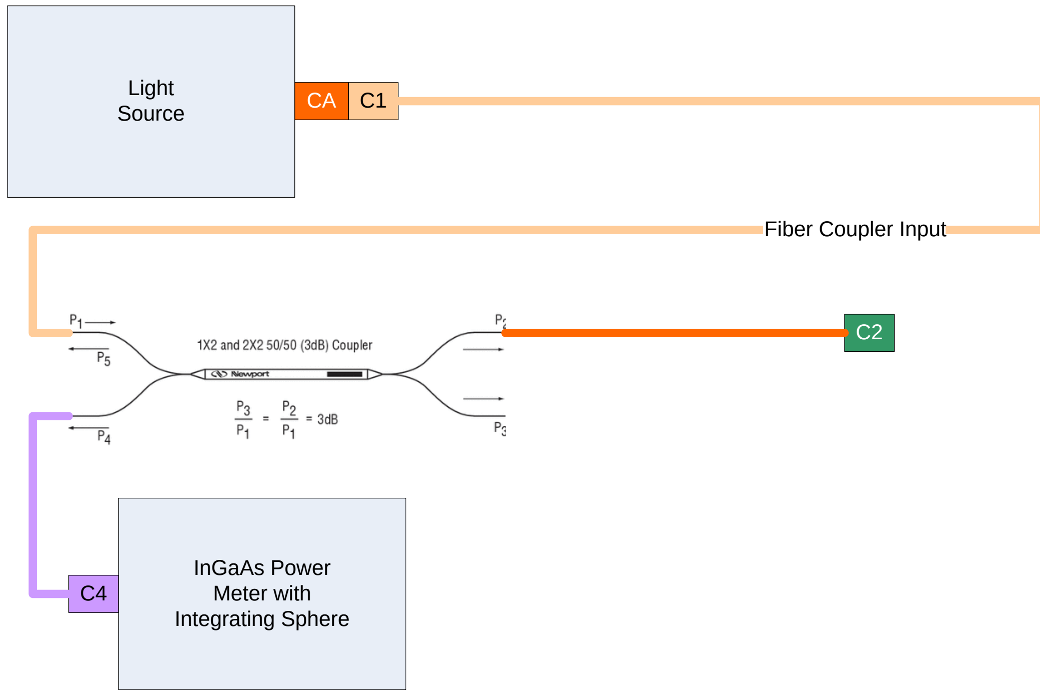
The information for accomplishing the Optical Return Loss (ORL) measurement is also primarily from the Derickson book starting on page 387. Return Loss represents the total fractional power that is reflected from a test device. It is performed by sending a continuous wave optical signal to the test device and then measuring the total reflected power. There are some variations in test methods, but the procedure primarily consists of 3 measurement steps:

1. ORL Reference Measurement
2. ORL Zero Measurement
3. ORL Measurement

The setup is similar to the Insertion Loss measurement, with the addition of a 50/50 coupler which allows the measurement of light reflected backwards from the device under test.

Step 1- ORL Reference Measurement

The first step is to take a reflected power measurement from the endface of an unmated ferrule and equate this to a reflection value from the Fresnel reflection occurring at the endface of -14.7dB (3.388%).

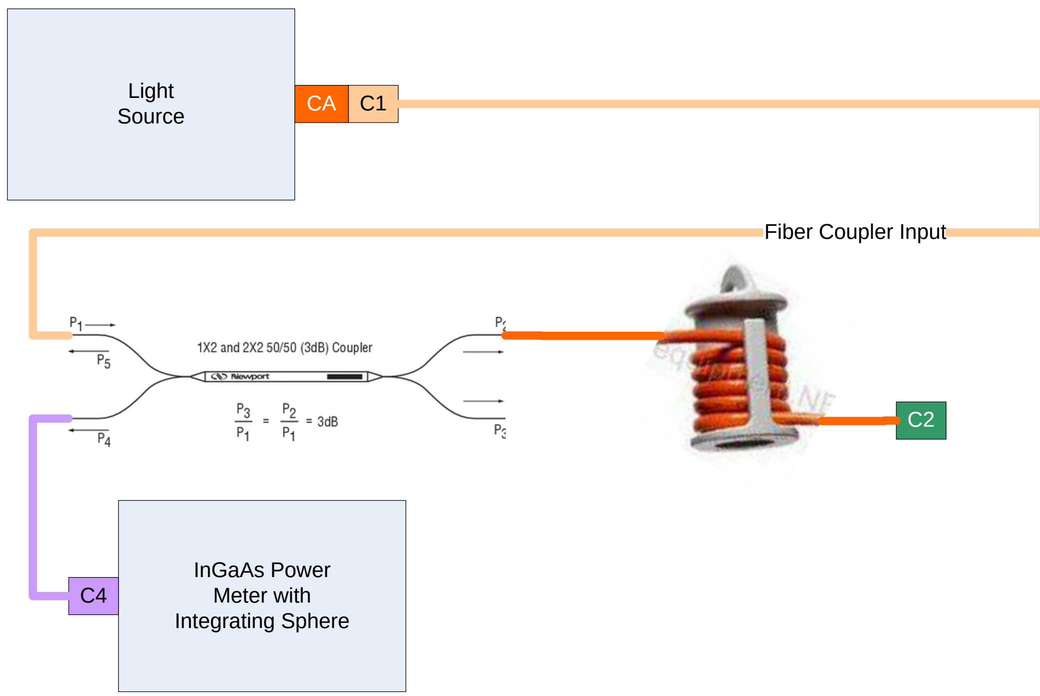


ORL Reference Step

The measurement is taken with connector C2 providing the glass-to-air back-reflection to the measurement system.

Step 2- ORL Zero Measurement

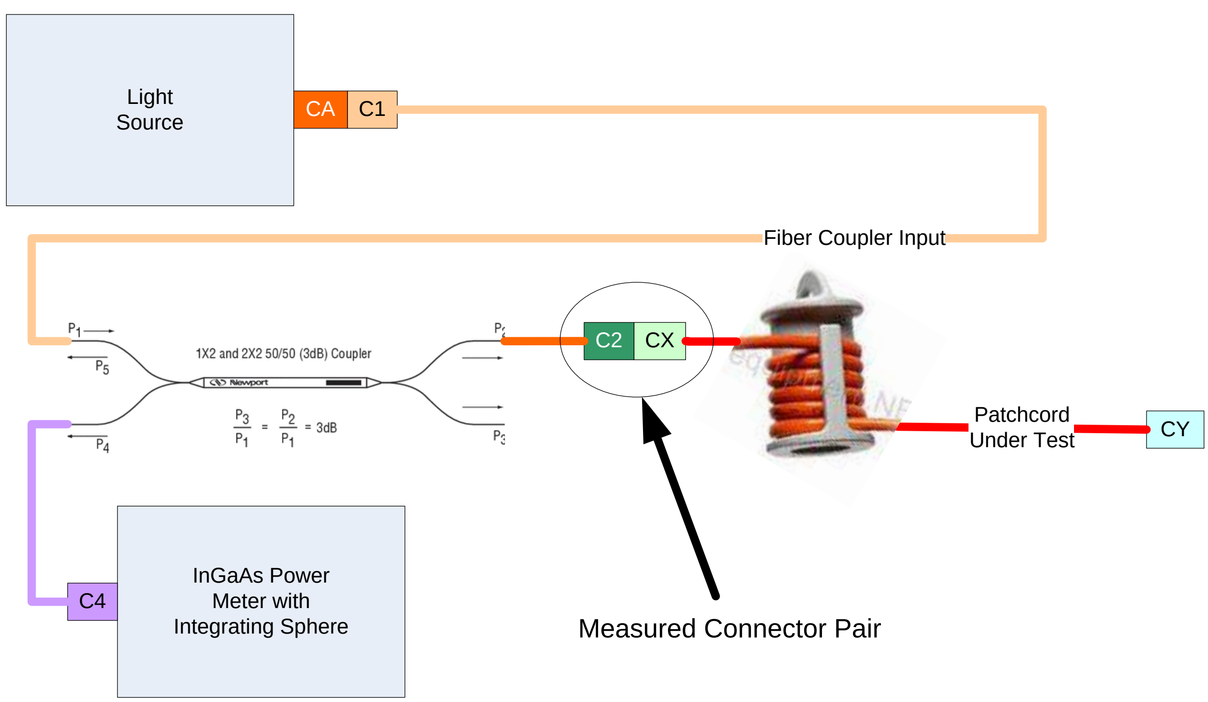
For this measurement, a mandrel wrap is performed on the Lead-In Fiber just before its output connector (C2). A mandrel wrap is performed by wrapping the fiber tightly around a small diameter cylinder so that all of the light in the core of the fiber leaks into the cladding and doesn't get back to the detector.



ORL Zero Step

Step 3- ORL Measurement

For the actual measurement of the connector interface, a mandrel wrap is performed right after the connector interface that is to be measured (C2 to CX):



ORL Measurement Step

The measured Optical Return Loss is then:

$$Return\_Loss = 14.7dB + 10\log\left(\frac{P_{REFERENCE}}{P_{MEASURED} - P_{ZERO}}\right)dB$$

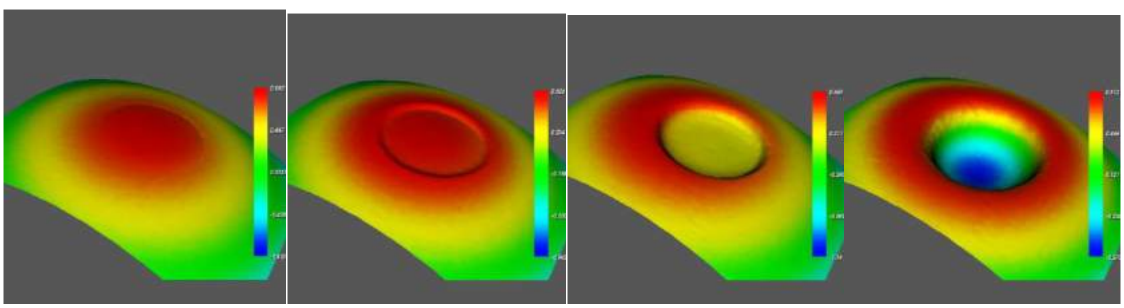
Details of the Measurement

This Return Loss number will be positive, and the bigger the number, the less light is reflected from the C2 to CX interface. A high Return Loss value is better. APC connector matings can have Return Losses > 60dB.

Return Loss can be a noisy measurement because it depends on the reciprocal of the difference between the measurements of two small optical powers ($P_{Measured}$ and P_{Zero}).

Recession Measurement Results

For the recession (undercut) measurements, the polishing method described above was used to polish down the fiber in a series of steps. After each polishing step, the connector end was cleaned (which proved to be not a trivial challenge), and then measured on a FiBO interferometer to determine the spherical fiber height. Here are 3D examples of a few of these polish steps:



+21 nm *-123 nm* *-509 nm* *-1202 nm*

Spherical Fiber Heights

After being visually inspected and cleaned again if necessary, the polished connector was mated to a reference connector using a connector mating sleeve like the following:

SC to SC Connector Mating Sleeve

The SC connector ferrules are spring-loaded and the mating sleeve pushes and holds the two connectors together so that the springs exert their forces towards the ferrule endfaces. According to the TIA FOCIS-3 Standard for SC connectors, the spring force should be between 7.8 and 11.8 Newtons.

Insertion Loss

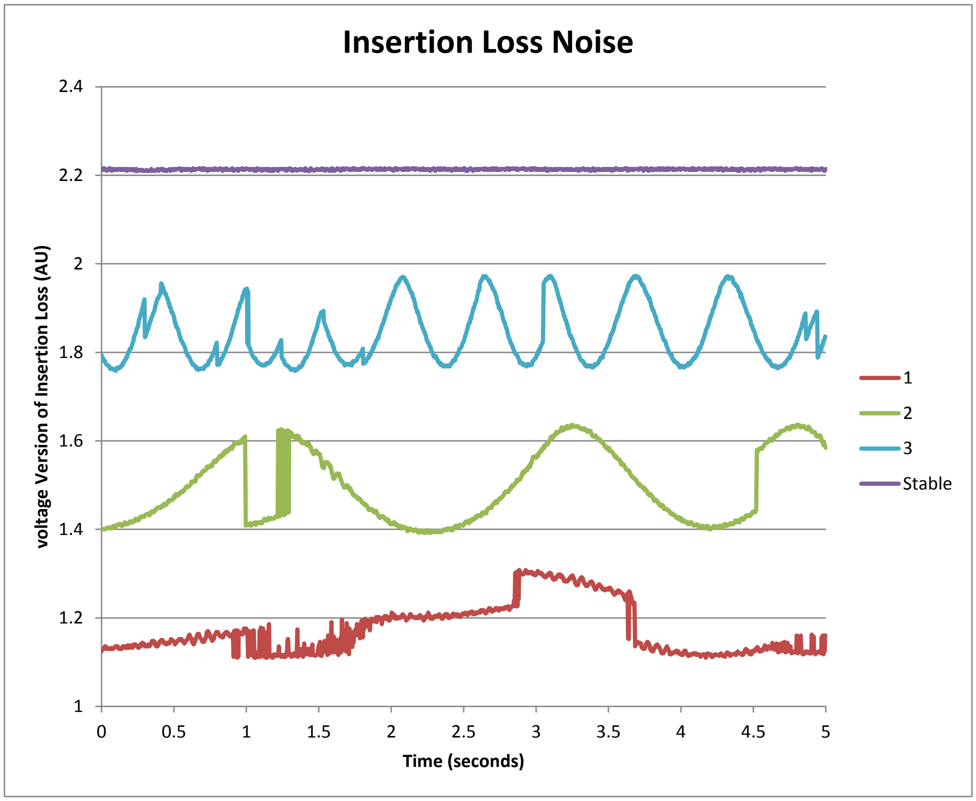
A connector with approximately zero fiber height and a radius of curvature of 14.4mm was used as the reference connector to which the connector under test was mated for all of the insertion loss measurements.

For each measurement point, three measurements were averaged.

Use of an Optical Isolator

For the initial three sets of insertion loss measurements, a polarization independent optical isolator was inserted in between the laser and the patchcord under test. According to the Thorlabs website, an isolator "protects laser sources from back reflections and signals that can cause instabilities and damage to fiber coupled laser sources. It is an optical device that allows light propagating in the forward direction to be transmitted, while absorbing or displacing light propagating in the reverse direction." The thought was that the isolator would prevent back reflections from the test connectors getting back into the laser and causing measurement instabilities. As we will see, it actually caused strange measurement behavior.

For these first measurements, the insertion loss measurements seemed normal and were low until the fiber recess reached ~-500nm. At this point the loss readings began to oscillate, sometimes slowly and other times quickly, in strange patterns over periods of seconds. In order to capture these phenomena, an oscilloscope was attached to the analog voltage output of the Newport power meter. Here are some example traces:



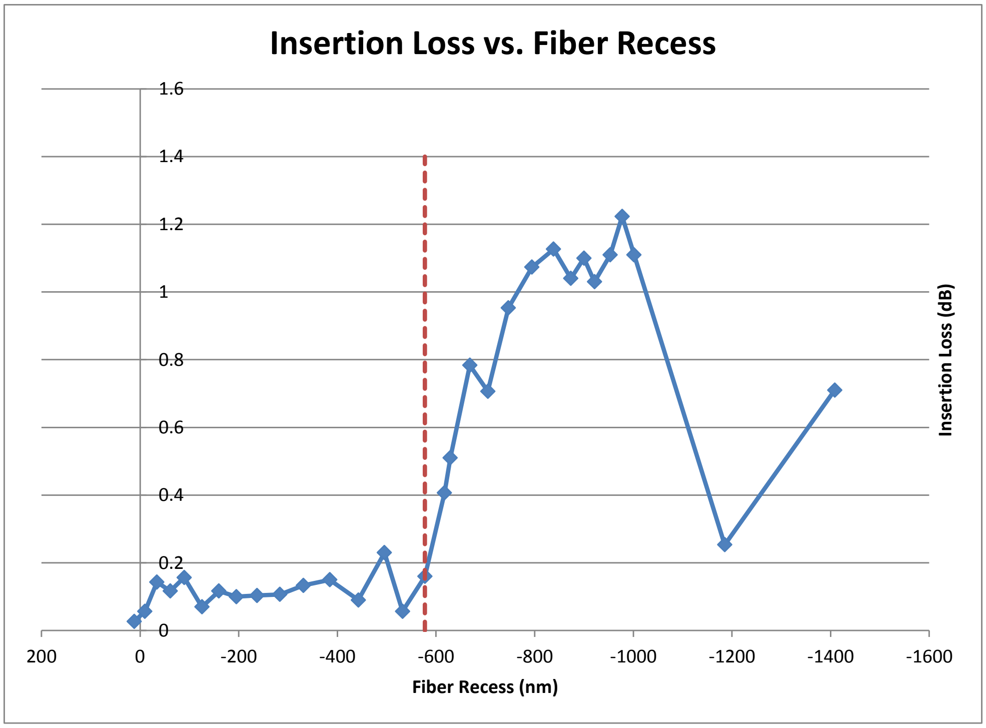
Examples of Insertion Loss Noise, each shifted for clarity

It was initially thought that this was strictly Fabry-Perot phenomena between the two separated connector endfaces that were somehow relaxing and changing the space between them. It was later discovered that by removing the isolator, this strange feedback mechanism disappeared. It is postulated that when the fiber recess reaches approximately -500nm, the two fiber ends no longer touch and interference phenomena occur between the isolator and the connector endface in conjunction with the different modes of the Fabry Perot laser, perhaps involving polarization. It is not really clear what happens, but it seems to be a real problem when using an isolator and fiber recess is large.

IL Measurement 1

This data was taken with the 1550nm laser. The radius of curvature of the test fiber was initially 14.7mm which is similar to the reference connector.

The points beyond ~-500nm were taken by using the largest insertion loss seen during the oscillations described above. The dashed line in the plot shows the point where these oscillations started to occur.

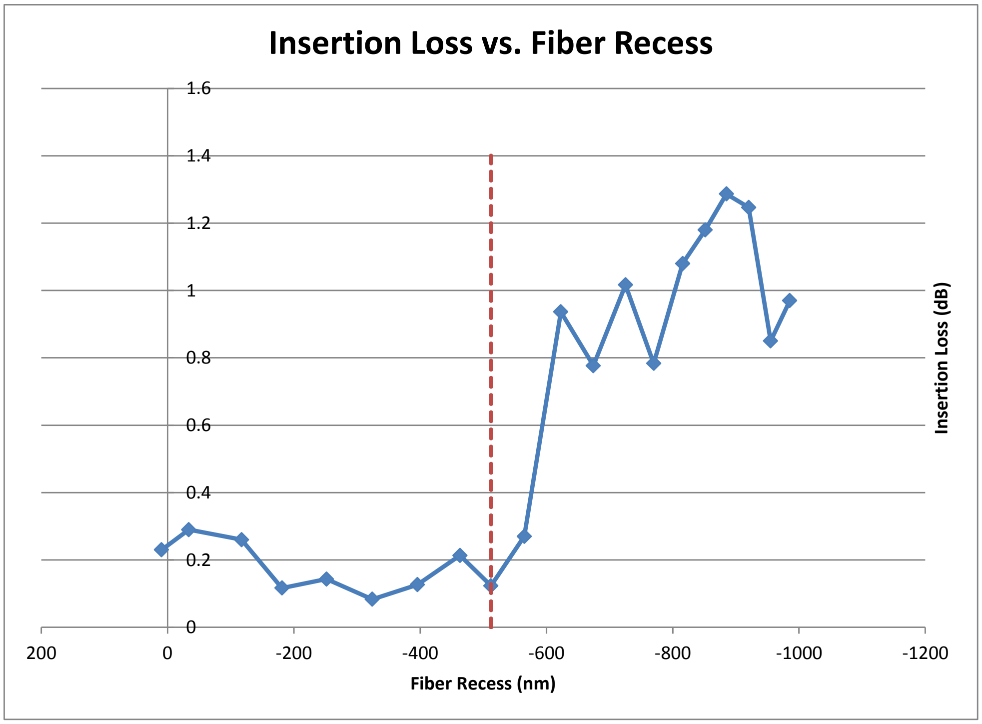


Insertion Loss Test 1, 1550nm

Below -500nm, the insertion loss stays low and because of that, implies that the two fiber endfaces are still touching, probably due to the compressive force applied by the springs in the connectors. Above -1000nm there is a hint that the insertion loss is actually improving.

IL Measurement 2

These data were taken with the 1550nm laser. The radius of curvature of the test fiber was initially 20.6mm, a radius larger than that of the reference connector.

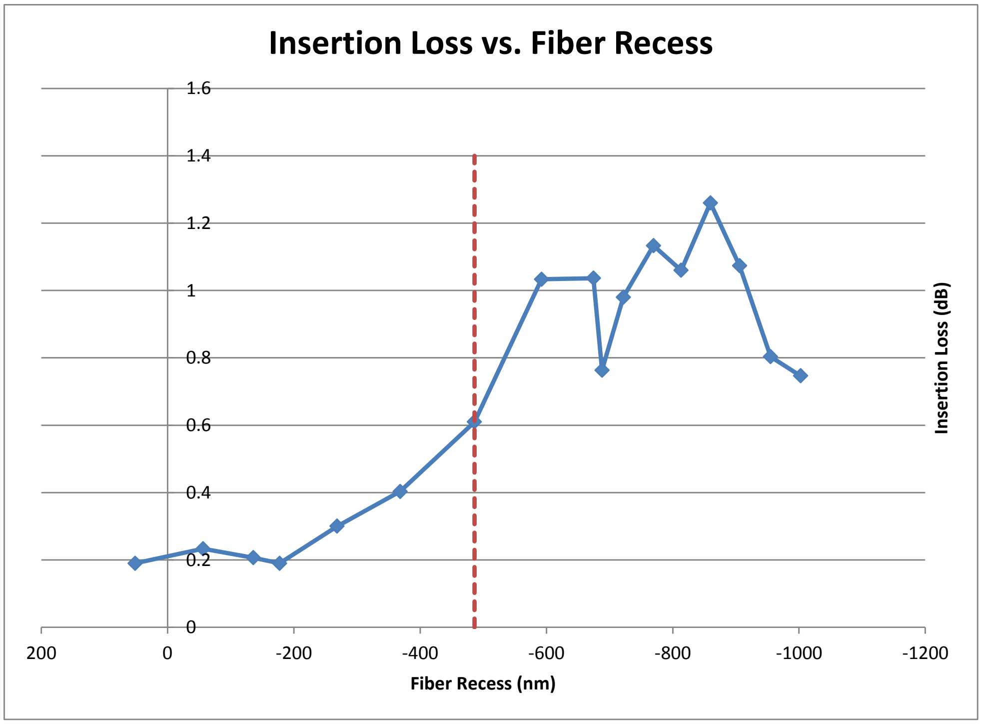


Insertion Loss Test 2, 1550nm

These data show similar results to test 1 with the insertion loss rising when the recess gets larger than -500nm. Again, the dashed line in the plot shows the point where the oscillations started to occur.

IL Measurement 3

These data were taken with the 1550nm laser. The radius of curvature of the test fiber was initially 13.7mm which is slightly smaller than that of the reference connector.

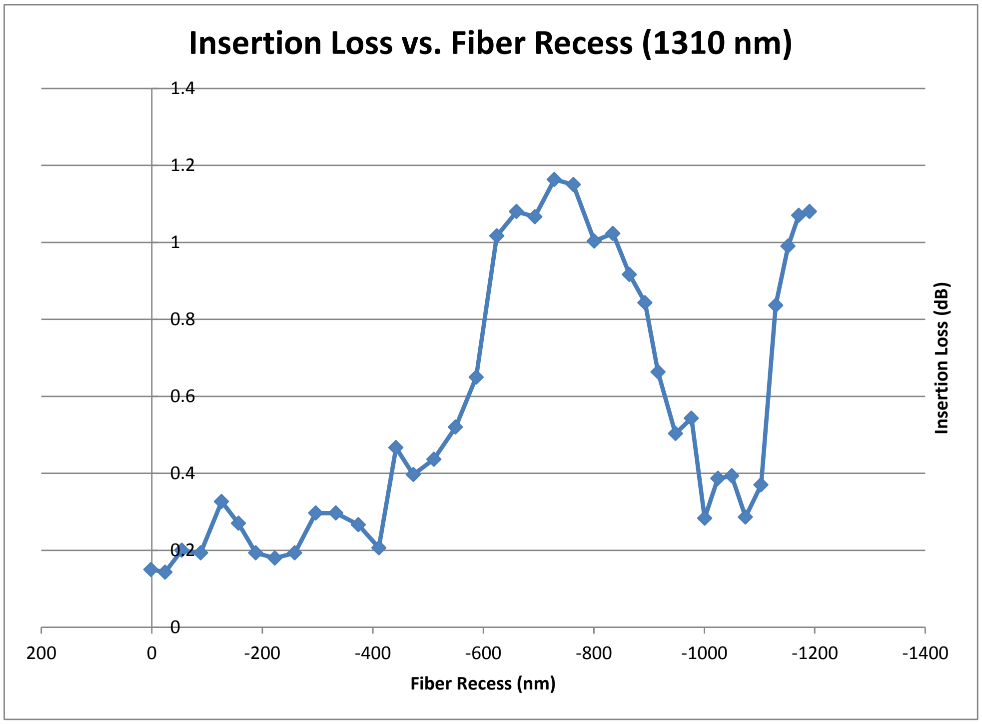


Insertion Loss Test 3, 1550nm

These data show a more gradual increase of insertion loss. Again, at the end, there is indication that the insertion loss is improving.

IL Measurement 4

These data were taken with the 1310nm laser without an optical isolator between the test connector and the laser to prevent strange oscillations. The radius of curvature of the test fiber was initially 14.0mm, similar to that of the reference connector.

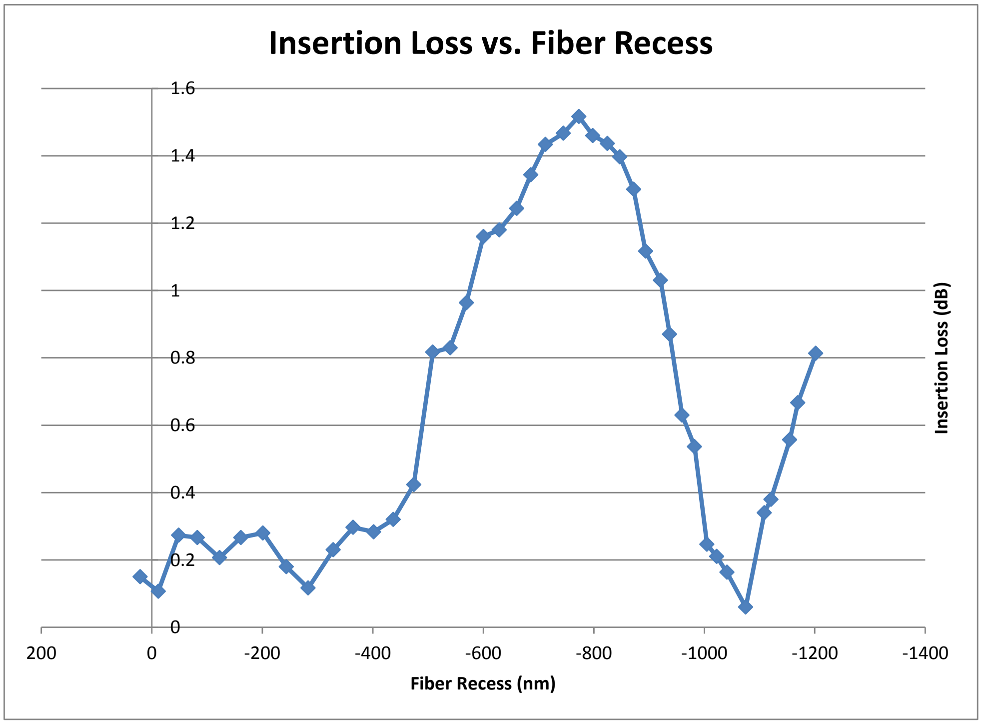


Insertion Loss Test 4, 1310nm

These data show a fairly constant insertion loss until the recess exceeds -400nm. Above -800nm, the insertion loss actually improves to almost the same level as with no recess. Above -1000nm, the insertion loss increases again. This matches the Fabry-Perot etalon effect that was discussed in the theory section. It appears to have a period of ~650 nm which is about half the laser wavelength of 1310nm, as expected.

IL Measurement 5

These data were taken with the 1550nm laser without an optical isolator between the test connector and the laser. The radius of curvature of the test fiber was initially 16.5mm.



Insertion Loss Test 5, 1550nm

These data look very similar to the Test 5 data, but because it was tested using the 1550nm laser, the period of the Fabry-Perot phenomena is slightly longer. It is very interesting that the insertion loss can actually improve with large recess, but is probably not something that should be counted on as a design idea.

Return Loss

The return loss measurement turned out to be very noisy because of the low optical powers involved, so it was not repeated more than once because it was hard to see small variations in the measurement.

These data were taken with the 1550nm laser without an optical isolator between the test connector and the laser. The radius of curvature of the test fiber was initially 15.2mm.

Return Loss Test

The return loss is basically the inverse of the insertion loss measurements. When the insertion loss is good (low), then the return loss is also good (high). When the insertion loss is bad (high), then the return loss is bad too (low). This measurement also shows the Fabry-Perot phenomena where the return loss improves beyond ~-1000nm.

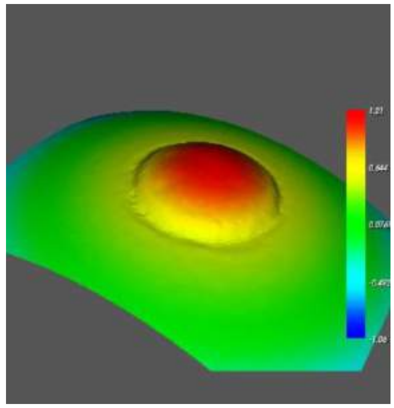
Protrusion Measurement Results

The main concern with excess protrusion is not that insertion loss will be reduced, but that the protruding fiber will be easily damaged by the force encountered during the mating process. To examine this expected problem, connectors with large protrusions (many hundreds of nanometers, measured with a FiBO interferometer) were mated and unmated one hundred times with a standard endface. During this repeated mating and unmating, their endfaces were examined with the FiBO every ten matings and their insertion losses were constantly measured.

Surprisingly, during the 100 measurements, the insertion loss did not change much, and only slight damage was seen on most of the connector endfaces. To get something major to happen, some of the connector endfaces were compressed together by hand without a sleeve and ground together. This caused damage on both the protruding fiber as well as the flush fiber.

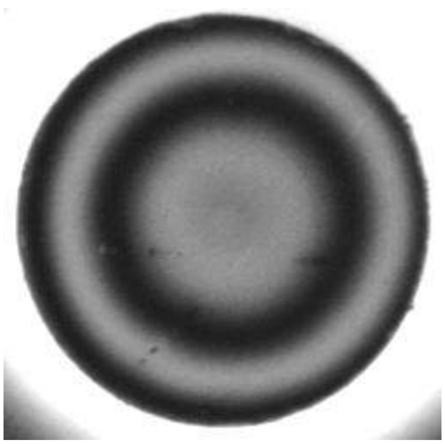
RL Measurement 1

Measured Fiber Height: +507nm. Measured Insertion Loss: 0.11 dB.

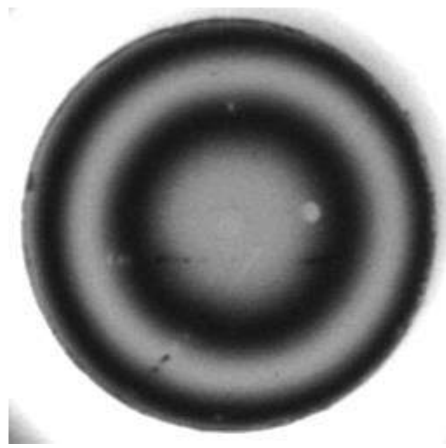


3D Image of Endface

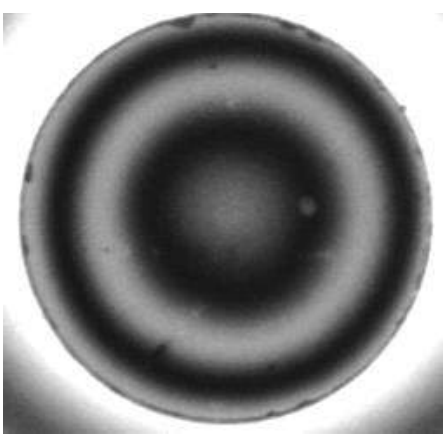
Images of the fiber during the mating process (images taken in interferometric mode to show contour-map-like fringes and enhance defects on the dark fibers):



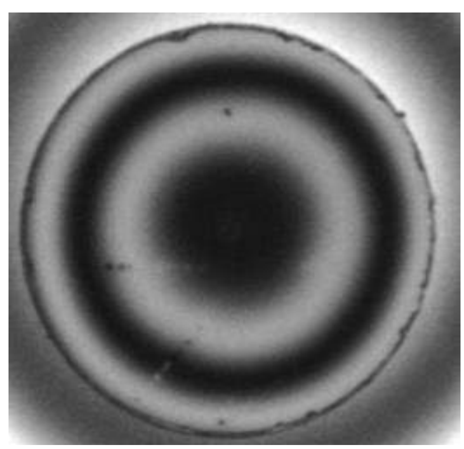
Before mating



After 30 matings



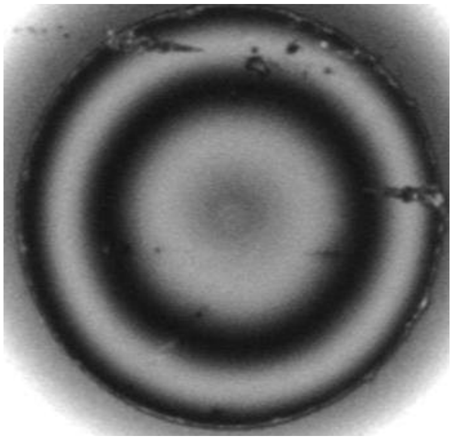
After 60 matings



After 100 matings

Looking at the edges of the fiber, chipping occurs as a result of the repeated mating.

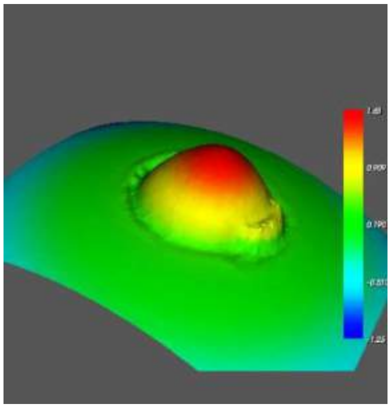
Mashing the connectors together by hand induced more damage, but that is probably unrealistic:



After hand mating

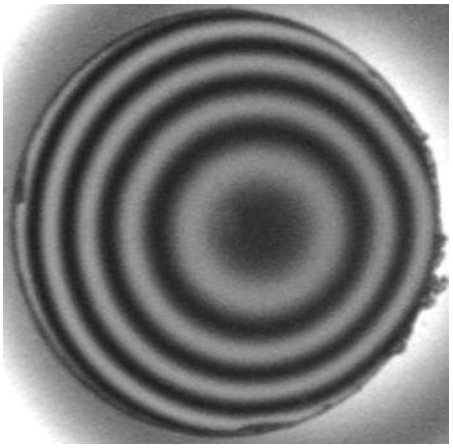
RL Measurement 2

Measured Fiber Height: +936nm. Measured Insertion Loss: 0.08 dB.

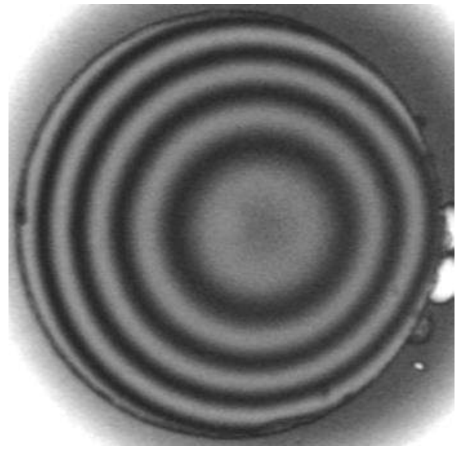


3D Image of Endface

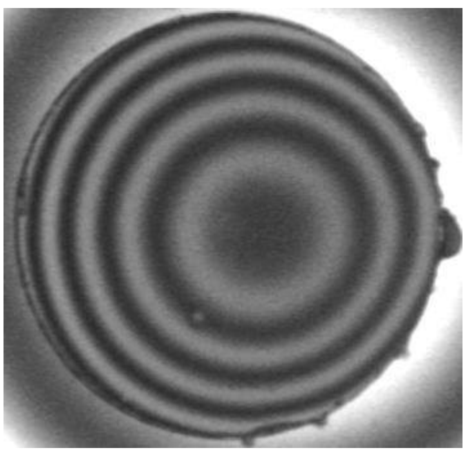
Images of the fiber during the mating process:



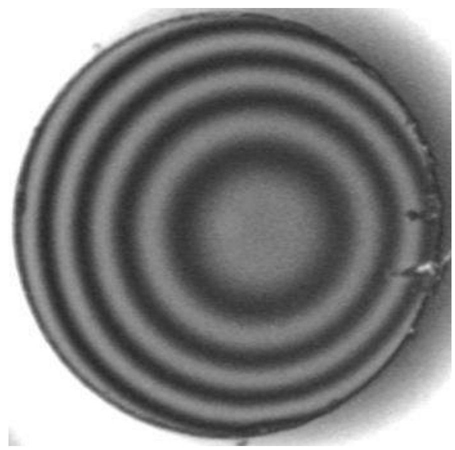
Before mating



After 30 matings



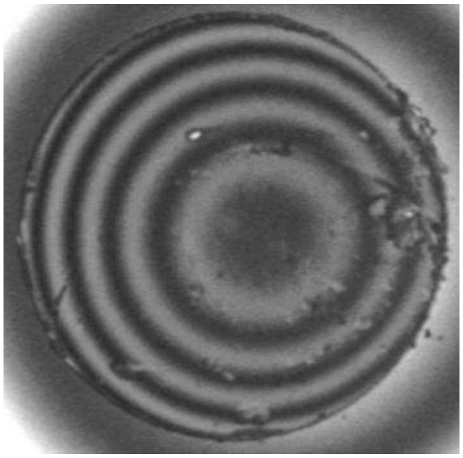
After 60 matings



After 100 matings

Looking at the edges of the fiber, there seems to be only a slight change on the right side.

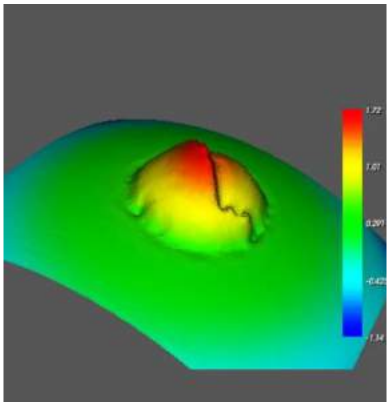
Mashing the connectors together by hand induced more damage:



After hand mating

RL Measurement 3

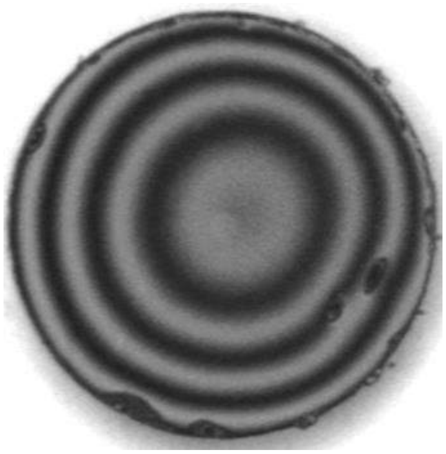
Measured Fiber Height: +868nm. Measured Insertion Loss: 0.07 dB.



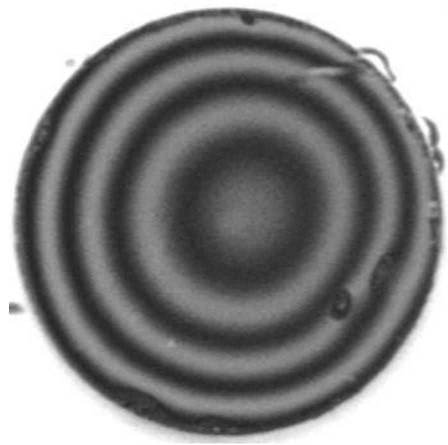
3D Image of Endface

The line in the above 3D image is not real, but an artifact of the phase unwrapping procedure of the interferometer due to the protruding fiber height.

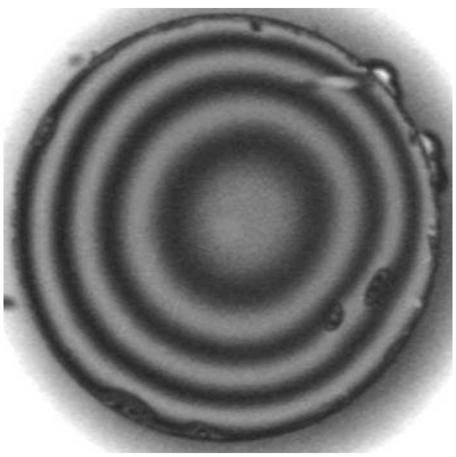
Images of the fiber during the mating process:



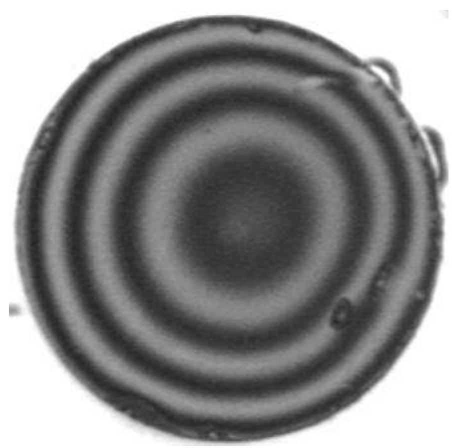
Before mating



After 30 matings



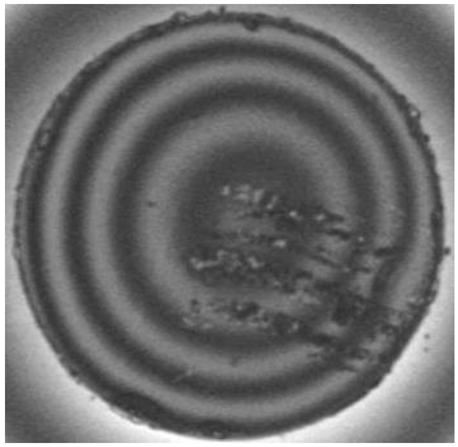
After 60 matings



After 100 matings

Looking at the edges of the fiber, there seems to be only a slight change on the right side.

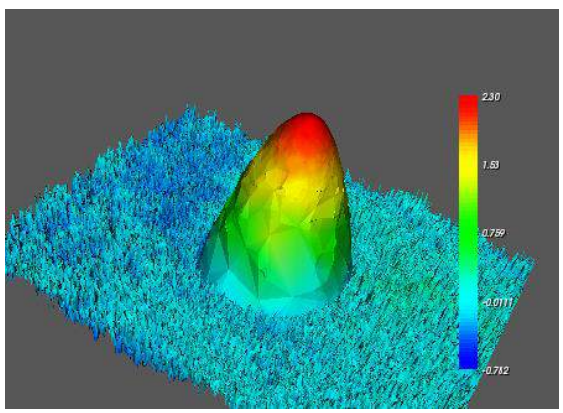
Mashing the connectors together by hand induced more damage:



After hand mating

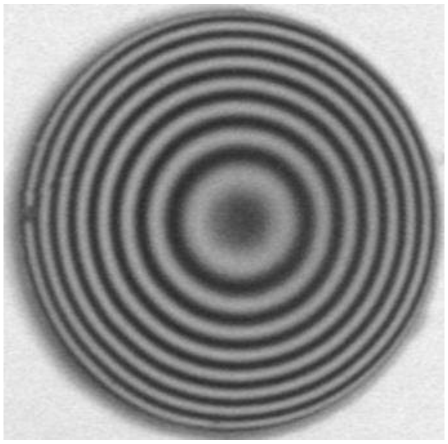
RL Measurement 4

For this measurement, a connector with an extreme fiber protrusion was used. The height was too great for the interferometer to measure, so it was estimated by using the stepper motor counts between focusing on the ferrule and focusing on the fiber. Estimated Fiber Height: +55 microns. Measured Insertion Loss: 0.05 dB.

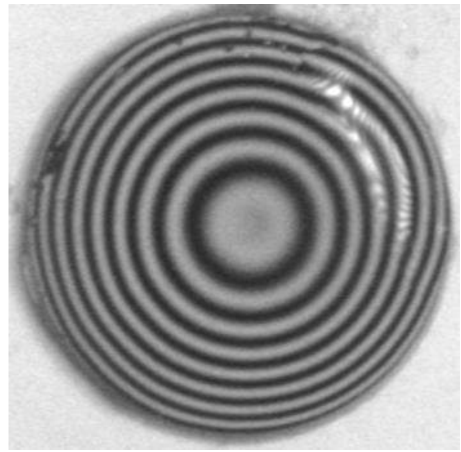


3D Image of Endface

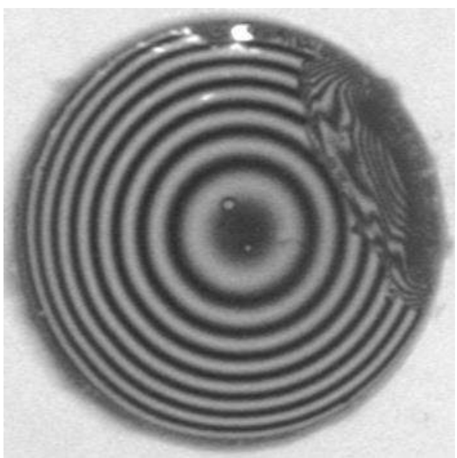
Images of the fiber during the mating process:



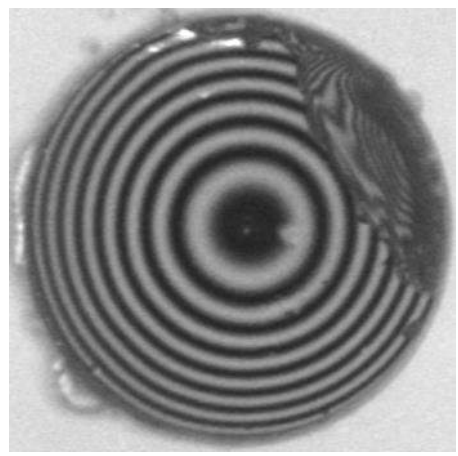
Before mating



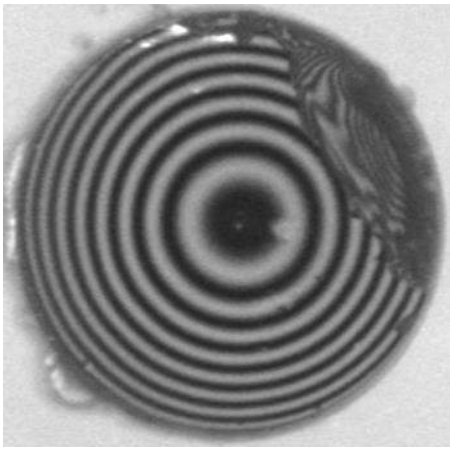
After only 10 matings



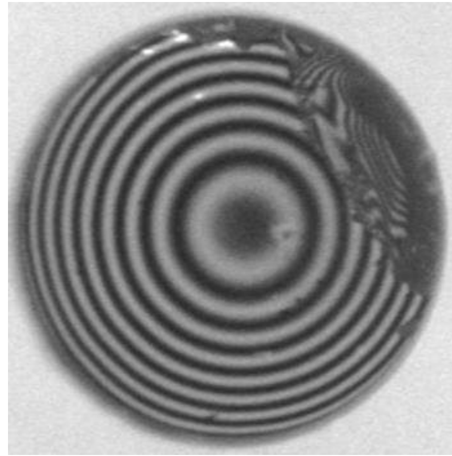
After 20 matings



After 40 matings



After 60 matings



After 100 matings & cleaned

In this extreme case, a chunk of the fiber was damaged almost immediately and, in subsequent matings, it broke off completely. Despite this, the insertion loss was still acceptable after 100 matings at 0.2 dB. After 100 matings, there did not seem to be additional significant damage.

Perhaps over time with more matings, this is the kind of damage that can be expected for connectors with smaller protrusions.

Summary

This paper describes the primary optical fiber connector endface 3D geometrical properties. It then discusses the theoretical background of what happens when two connector endfaces become separated longitudinally. The sample preparation steps to create fiber undercut and fiber protrusion are depicted, and the measurement techniques used to measure insertion loss and return loss are detailed. The measurement results are then described.

Physical endface separation does not start immediately when one endface has a slight amount of negative spherical fiber height and the other is zero, but occurs after it reaches several hundred nanometers because of the compression of the two endfaces by the connector's spring forces. When the endfaces are no longer in physical contact, they demonstrate Fabry-Perot interference as shown in the theoretical section. This etalon effect causes the insertion loss to initially rise much more rapidly than would be expected with strictly NA calculations, but then can go almost back to zero after the initial peak in insertion loss.

Using different wavelength lasers showed the wavelength effect upon the etalon. As the wavelength decreases, the peaks of the etalon effect get closer together because they are spaced at half of the wavelength.

When using an isolator to protect the laser, strange insertion loss effects can be seen when the connector endfaces are no longer in contact. At times, the insertion loss looked almost periodic over many seconds while sometimes it varied erratically.

The measurement of return loss showed the same etalon effect as seen with insertion loss. When the endfaces were in contact, return loss was high. As the endfaces separated, the return loss degraded quickly, but then got better.

During the entire measurement process, cleanliness of the endface played a very important role in measurement uncertainty. The endfaces needed to be inspected each time after cleaning, because cleaning them the same way every time did not always result in a clean endface. Any debris can affect the mating of the two connectors, and therefore the measurement, but especially if the debris is near the core of the fiber.

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