Understanding How the Appearance of Optical Fiber Splices Relates to Splice Quality

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Factors That Affect Fusion Splice Appearance

- Contamination or bubble
- Poor arc conditions (especially “cold splice” due to weak arc power)
- Dissimilar left & right fibers
  - MM spliced to SMF
  - Different left & right SMF types
    - G.652D spliced to G.654C
    - G.652D spliced to G.655D (NZDS)
    - G.652D spliced to G.657 (Bend Insensitive)
    - Etc.

Factors That Affect Fusion Splice Loss

- Poor alignment (especially core alignment for SMF)
- Bubble, or other ***actual*** splice defect
- Difference in left/right fiber core size (for MM fiber)
- Difference in left/right MFD (for SM fiber)
  - MFD (Mode Field Diameter) defines the size or diameter of the area in which the single mode optical power propagates down the length of a SM fiber
- Improper arc parameters or heating

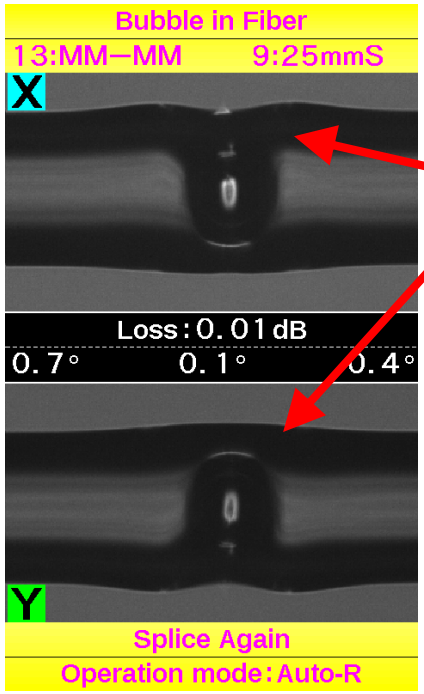
Bubbles at the Splice Point

- Typically seen as a dark spot in the fiber image
  - May not be an actual bubble, could be contamination on the fiber surface
- Causes of actual bubble
  - Contamination on cleaved fiber end
    - Contamination “outgasses” during arc to form a gas pocket or bubble, trapped inside the glass
  - Insufficient “Prefuse” heating time for MM fiber
    - Large core of MM fiber may melt back and form a cavity at beginning of arc.
    - Longer initial heating before stuffing fibers together solves this problem
- Preventing actual bubbles
  - Avoid cleave contamination / load fibers carefully / maintain the cleaver
  - For MM fiber, ensure sufficient “Prefuse” time

Fusion Splicer Bubble Detection / Alarm

- A dark spot in the splice image may trigger a “Bubble” error message
- Alarm is triggered for any dark spot larger than error limit threshold
- The alarm may also be triggered by a vertical line or shadow at the splice point, but this does **NOT** indicate an actual bubble
- An actual bubble usually appears as a somewhat round dark spot, and is often accompanied by an enlarged and distorted fiber cladding
- If a splicer “Bubble” error message is triggered by a vertical shadow or line at the splice point, it may be possible to adjust the alarm threshold to eliminate the error message

Bubble Versus Vertical Line at Splice Point



Actual Bubble

This is a severe bubble, with enlarged and distorted fiber cladding

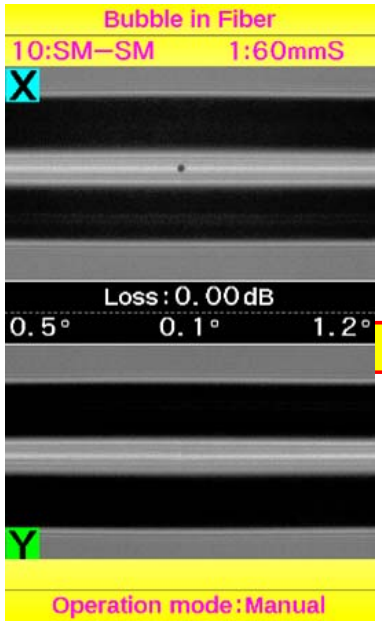
In this case, the vertical line is dark on right fiber side, and lighter on the left fiber side

Vertical Line at Splice Point

Determination of Actual Bubble

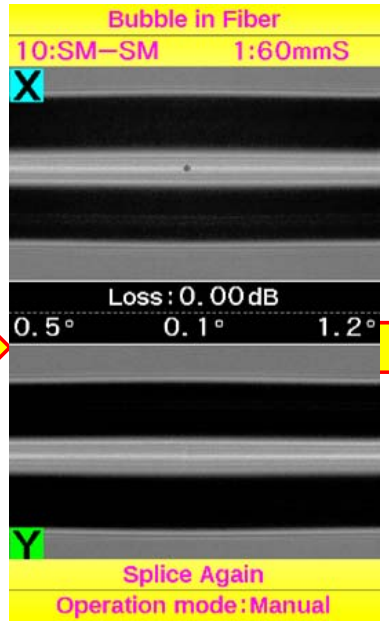
- Re-arc to see what happens to the dark spot
- An actual bubble or gas pocket usually expands when heated again
  - The cladding may be enlarged and distorted due to the bubble
  - When reheated, the black spot and the cladding may expand more as the bubble expands
  - If heated enough, the bubble may blow out through the side of the spliced fiber
- If the black spot decreases in size when re-arced, it is probably a surface defect
  - A dimple on the fiber surface from a cleaved end chip will “heal” we re-heated sufficiently
- A vertical line at the splice point will not change due to re-arcing

Bubble Error Caused By Cleave Defect on Fiber Surface



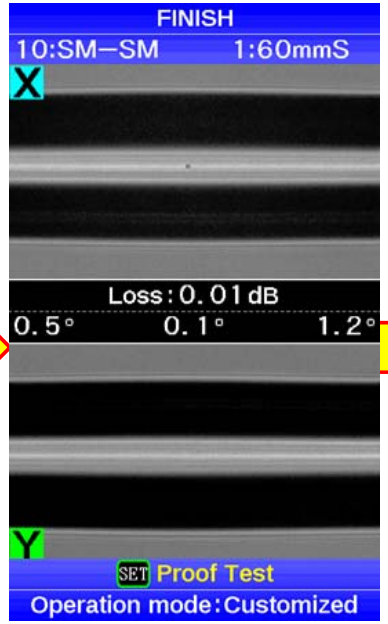
Initial Appearance
After Splicing

Re-Arc



After 1 Re-Arc
Black Spot Is Smaller

Re-Arc



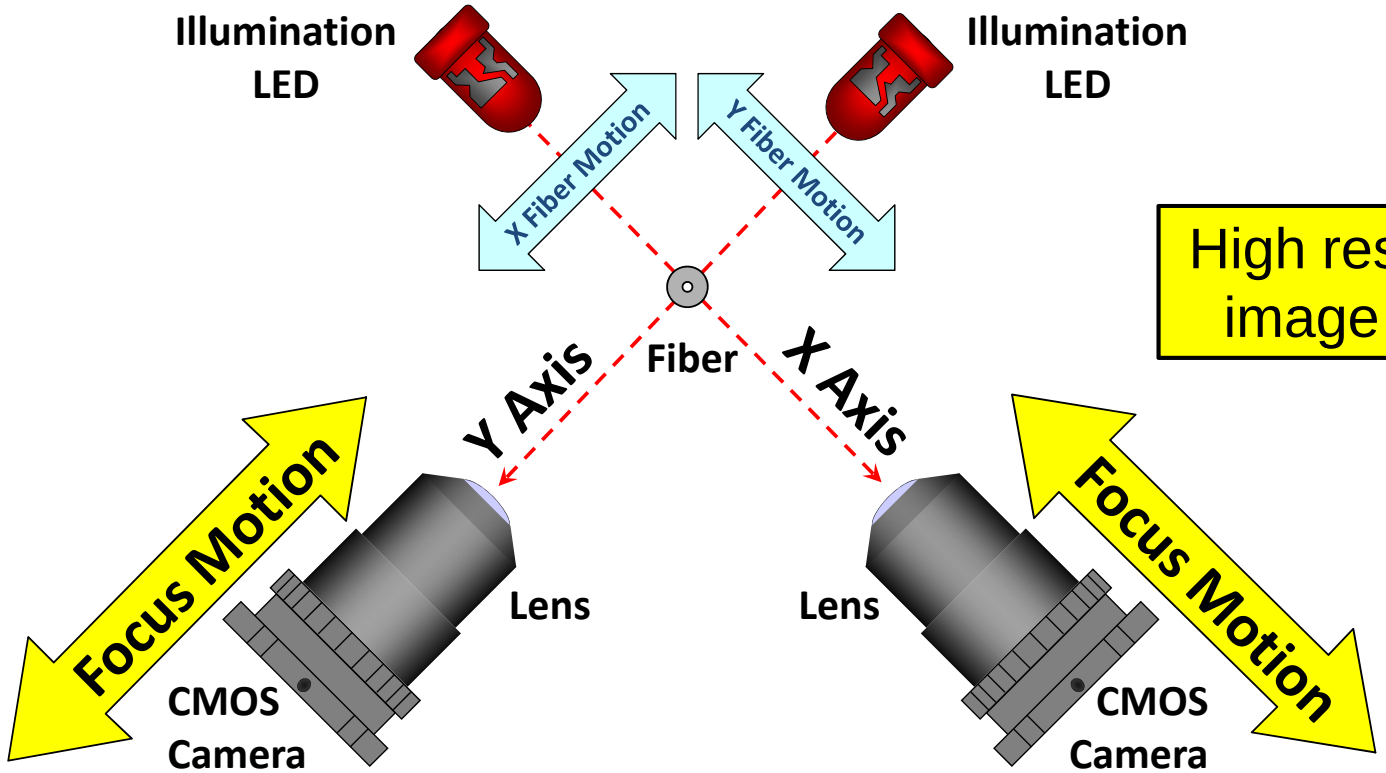
After 2nd Re-Arc
Spot is Almost Gone
No Error Message

Re-Arc

After 3rd Re-Arc
No Spot
No Error Message

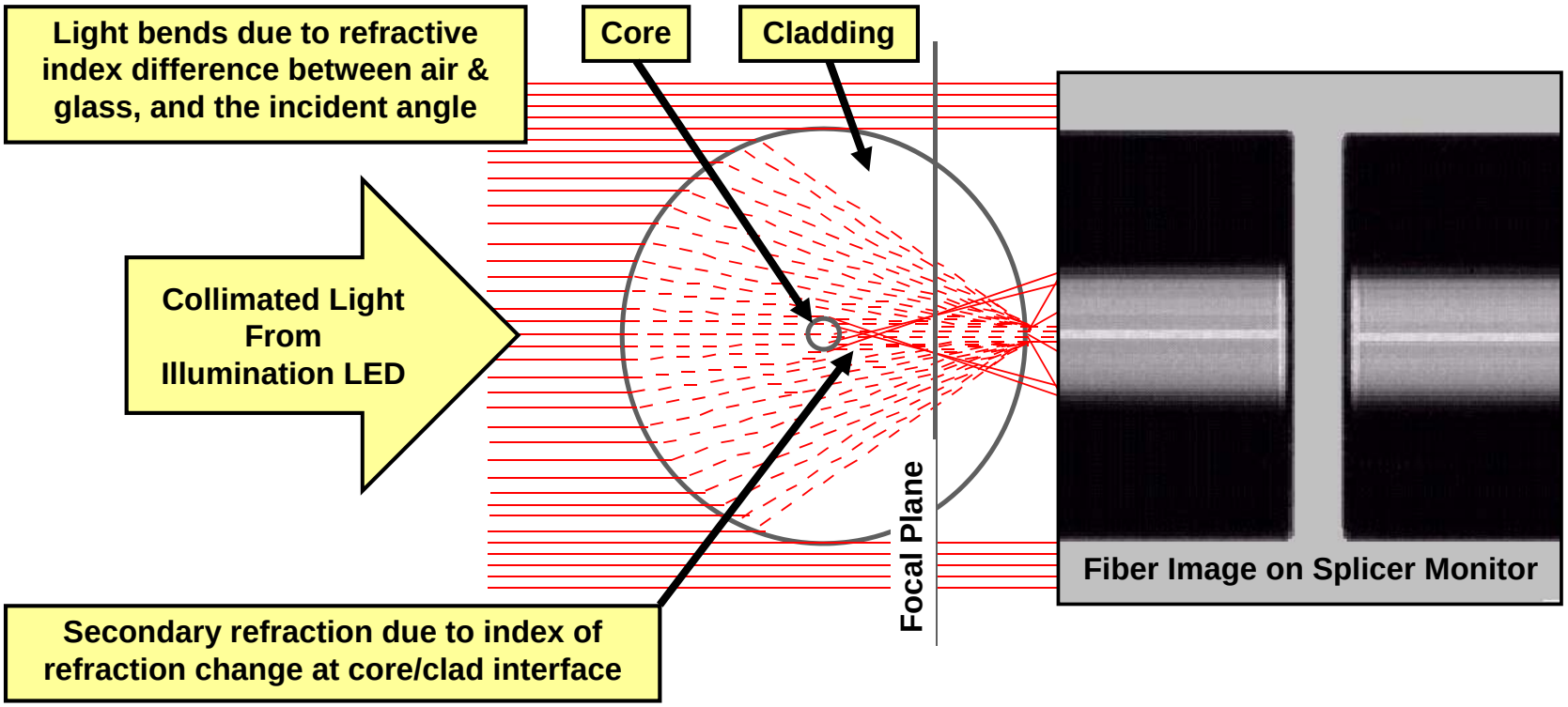
Details of PAS Core Alignment Splicer Optical Analysis

PAS Core Alignment Splicer Optical System

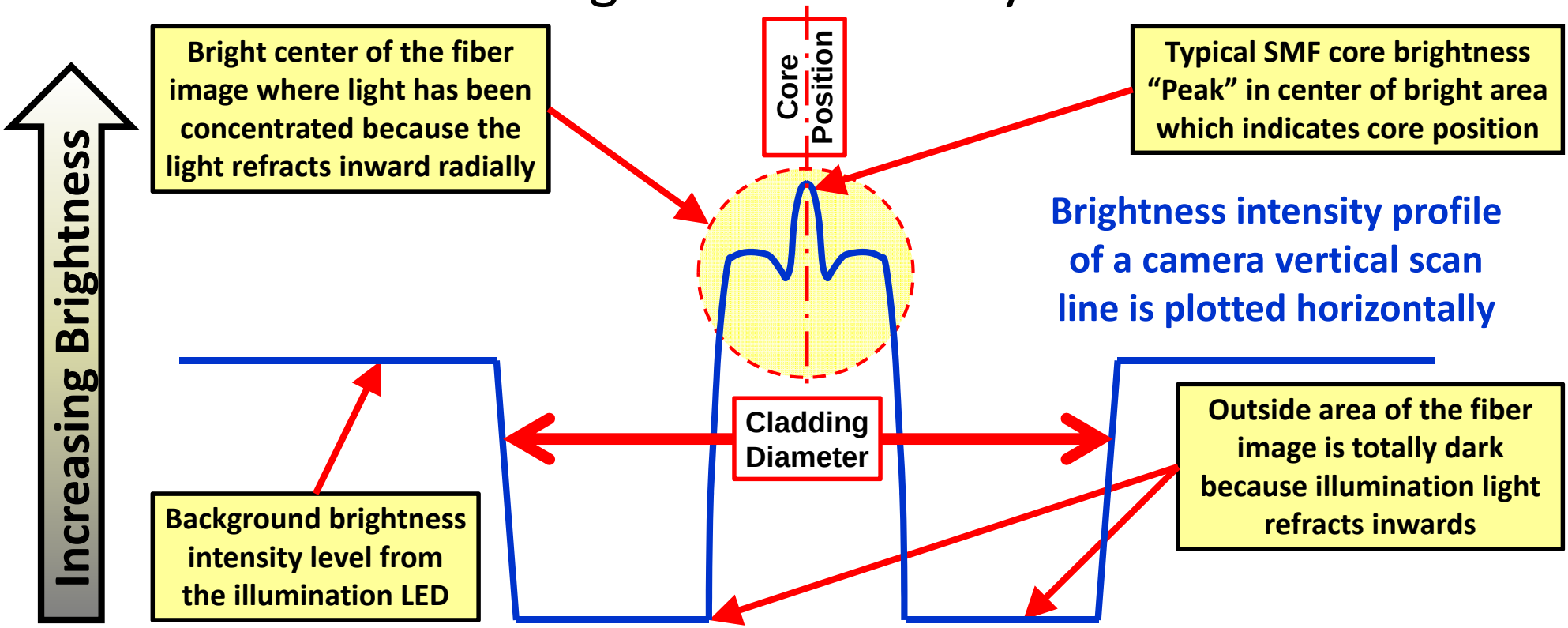


High resolution fiber image is required

Function of PAS Optical System



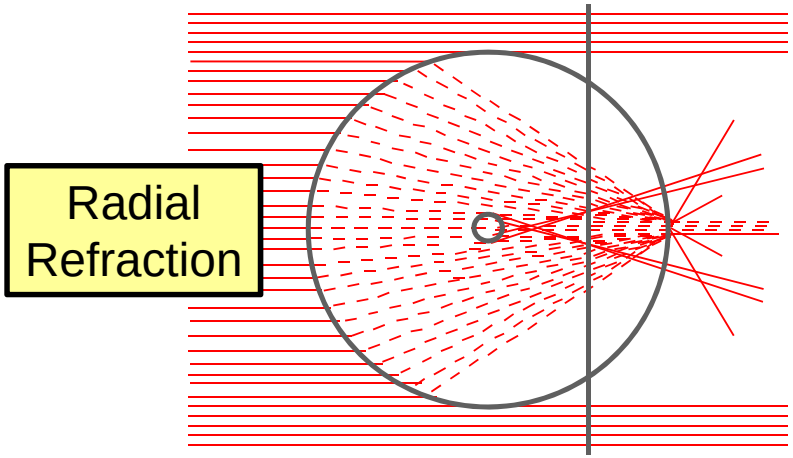
PAS Brightness Intensity Profile

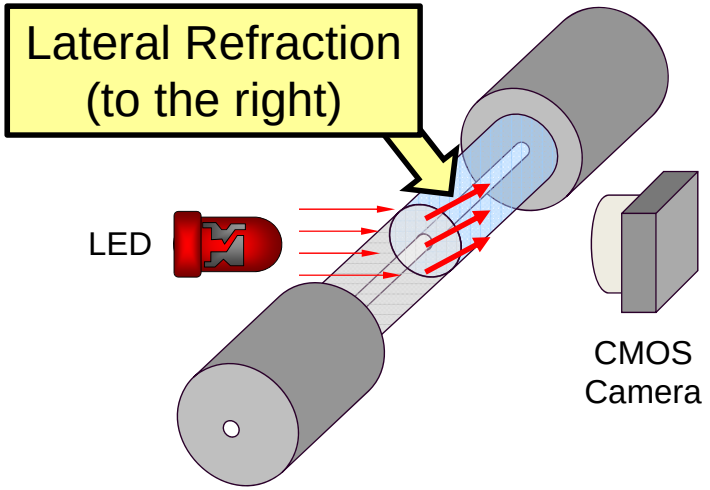


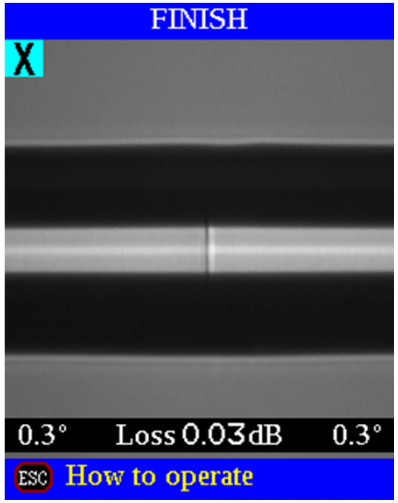
Radial vs. Lateral Refraction of PAS Splicer Illumination Light

Radial refraction of PAS splicer illumination light towards the center of the fiber enables core position detection & alignment, as shown below

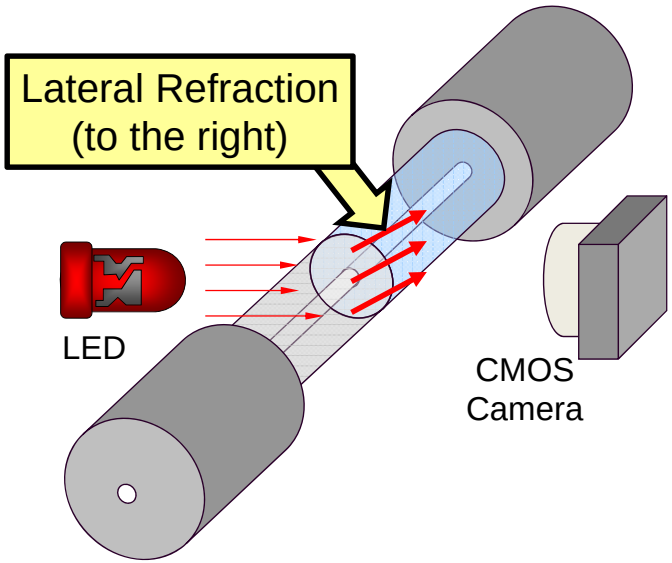
When the refractive index profiles of the left & right fiber are different, the illumination light may also refract laterally, towards the left or right.



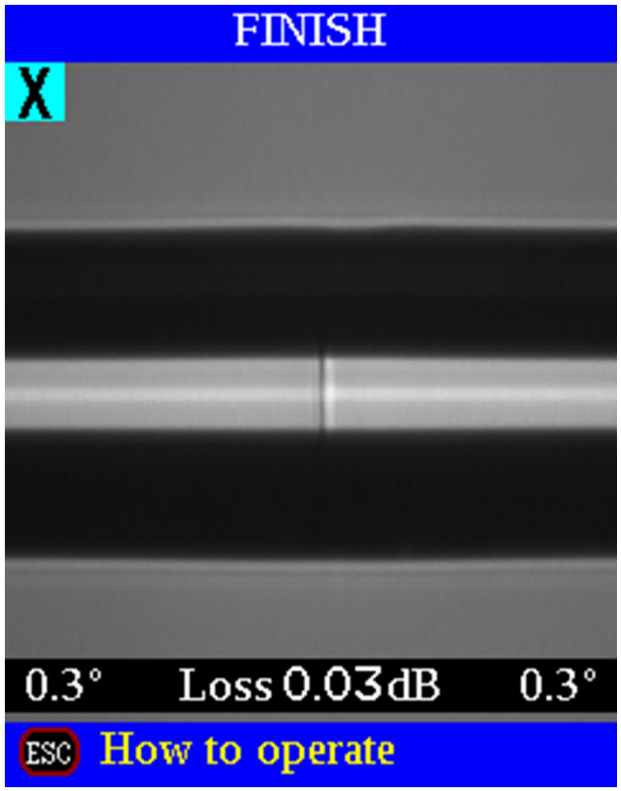




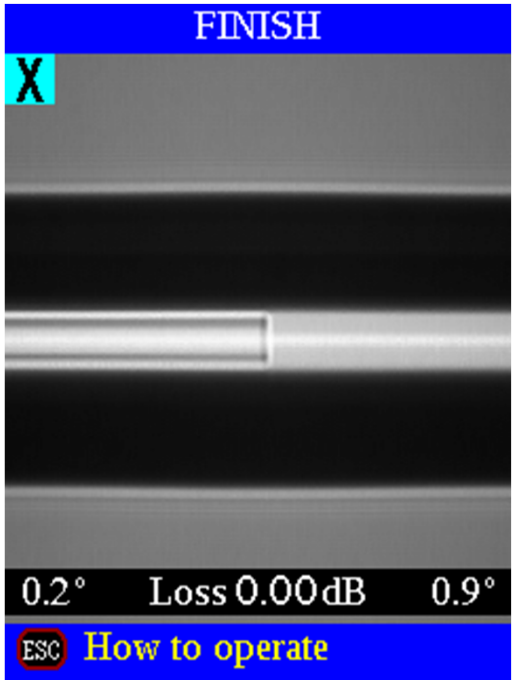
Lateral Refraction of Illumination Light



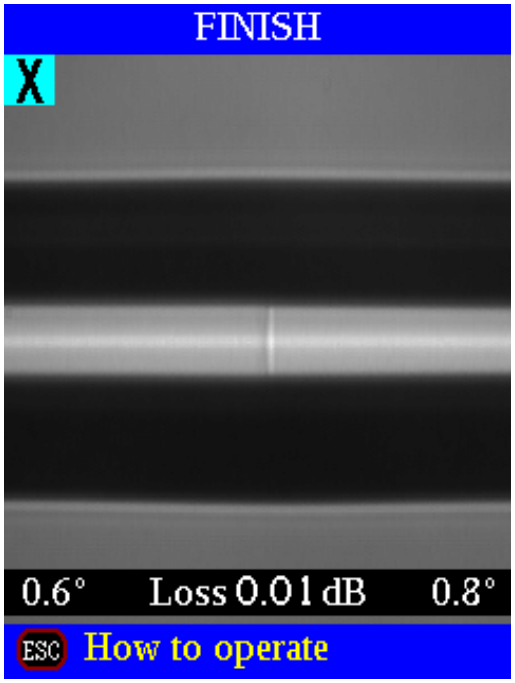
- The illumination light from the splicer's LED bends (refracts) in the direction of the higher index of refraction
- In this case, the right side fiber has a higher index than the left fiber
- Therefore the illumination light bends towards the right fiber
- This results in a vertical line where the fibers meet that is bright on the right side and dark on the left



Examples of Dissimilar SMF Splices

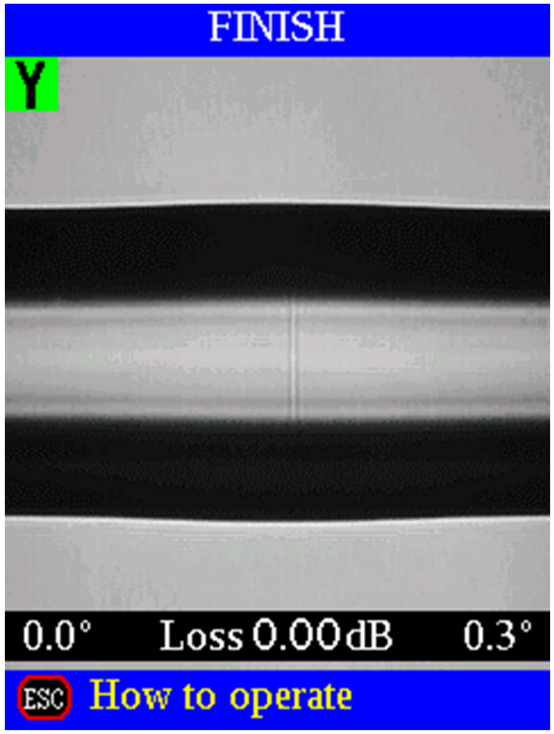


Bend Insensitive to
Standard SMF



Matched Clad to
Depressed Clad SMF

Multimode Fiber Spliced to Identical Multimode

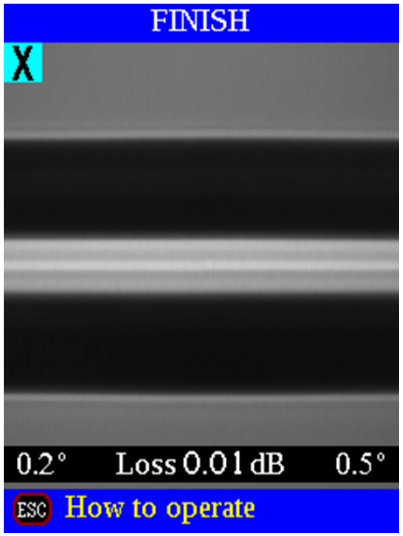


- MM fiber typically has a huge core which is heavily doped with Germanium
- The core therefore has a very high index of refraction compared to the silica cladding, and also a lower melting temperature
- During the fusion splice, Germania from the core diffuses outward into the cladding at the splice point
- This diffusion raises the cladding index of refraction at the splice point
- Therefore, light from both the left and right of the splice point refracts inwards towards the center of the splice
- This results in a slight bright vertical line at the splice, with a faint darker line to both left & right
- This same effect can happen with some SMF-SMF splices

Dissimilar SM Fiber Case Study

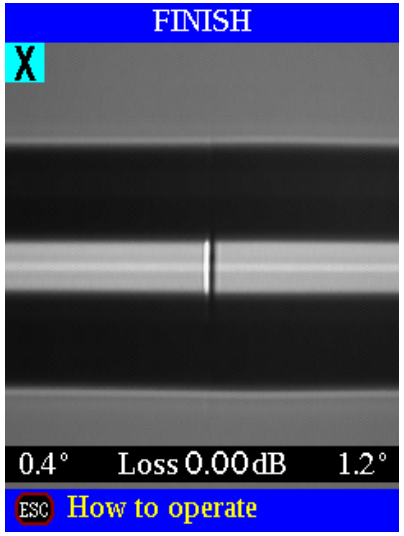
Dissimilar SM Fiber Case Study

G.652D to G.652D



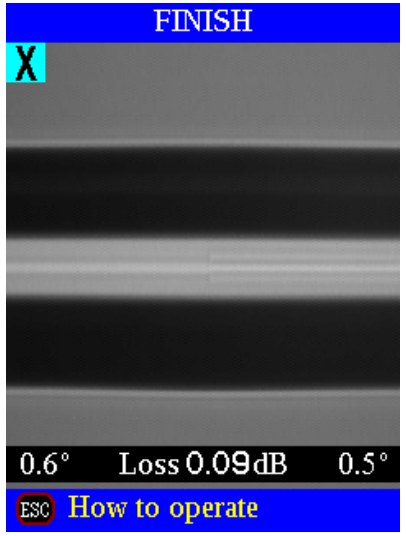
Baseline SMF-SMF
(Not Dissimilar)

G.652D to G.654C



Huge Refractive Index Contrast
Small MFD Difference

G.652D to G.655D



Small Refractive Index Contrast
Large MFD Difference

Measurement of Fiber Characteristics

- Fiber characteristics were carefully & accurately measured
- MFD Measurement:
  - Photon LD8900 HDR Far Field Profiler
  - Agilent stable laser diode
- Refractive Index Measurements:
  - Interfiber IFA-100 refractive index measurement system
  - This system enables mapping refractive index down the length of a fiber, and across a splice point
  - This is helpful for dissimilar fiber splice analysis, and is shown in this presentation

Mode Field Diameter Measurements

- The measured MFDs for each fiber are as follows:

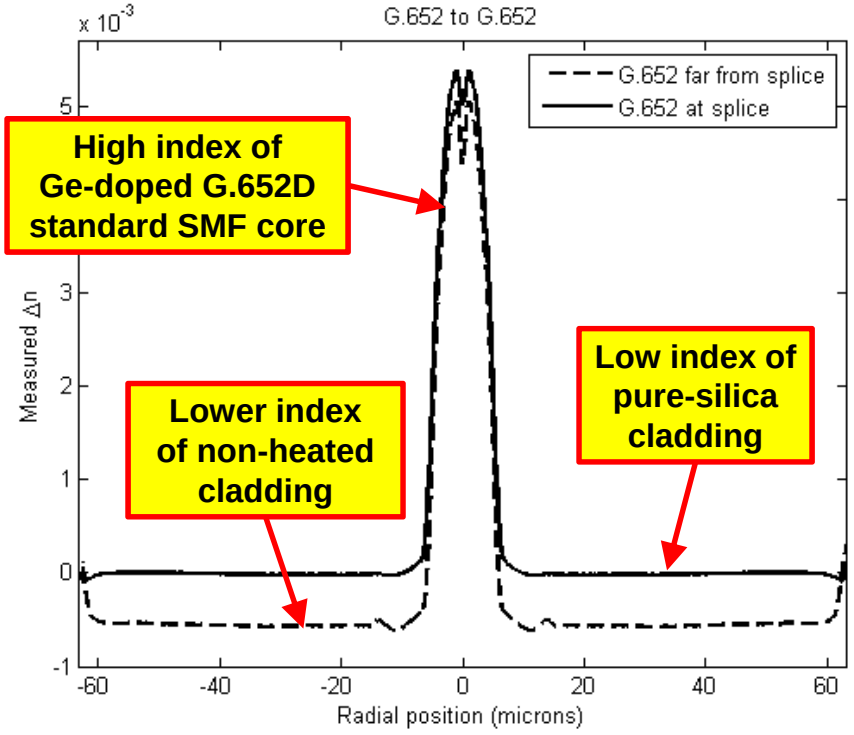
Fiber Type	G.652D	G.654C	G.655D
MFD (µm) (Measured at 1550 nm)	10.46	10.13	9.25

- The loss due to MFD difference may be calculated by the following equation:

$$Loss_{\text{due to MFD Mismatch}}\,[dB] = -20\,Log\left(2\,\frac{MFD_1 . MFD_2}{MFD_1^2 + MFD_2^2}\right)$$

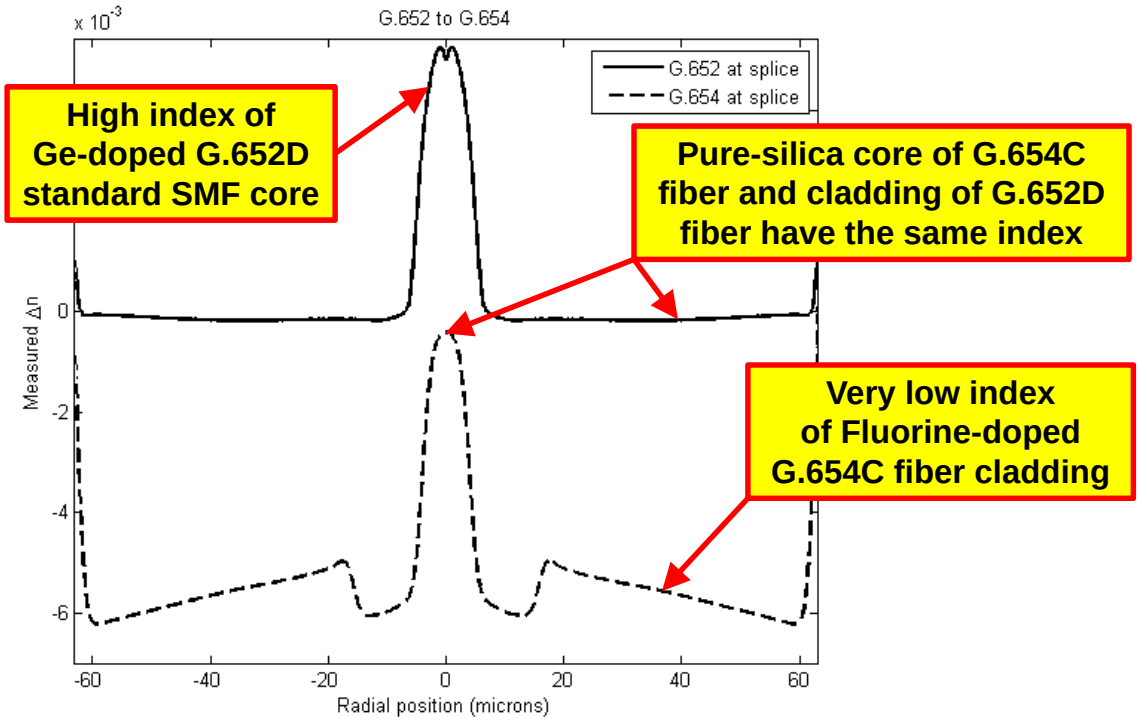
Fiber Combination	G.652D to G.652D	G.652D to G.654C	G.652D to G.655D
Splice Loss Predicted by MFD Difference [dB]	0.000	0.004	0.065

Refractive Index Profiles For Spliced G.652D SMF

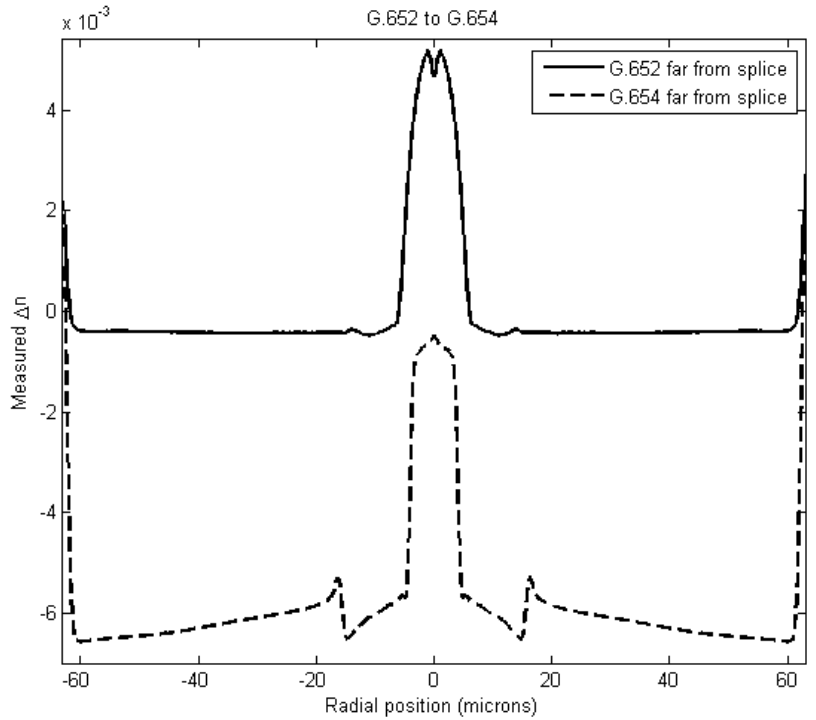


- This shows the refractive index profile of standard G.652D SMF
- The higher index of the Ge-doped core relative to the pure-silica cladding is easily seen
- There are 2 refractive index plots:
  1) One shows the refractive index profile far from the splice where the fiber has not been heated
  2) The other shows the refractive index profile of the fiber at the splice point
- The refractive index in the heat-affected zone at the splice point is somewhat higher because as the fiber is heated, residual strains in the glass (induced during drawing of the fiber) are relaxed

Refractive Index Profiles For G.652D Spliced to G.654C

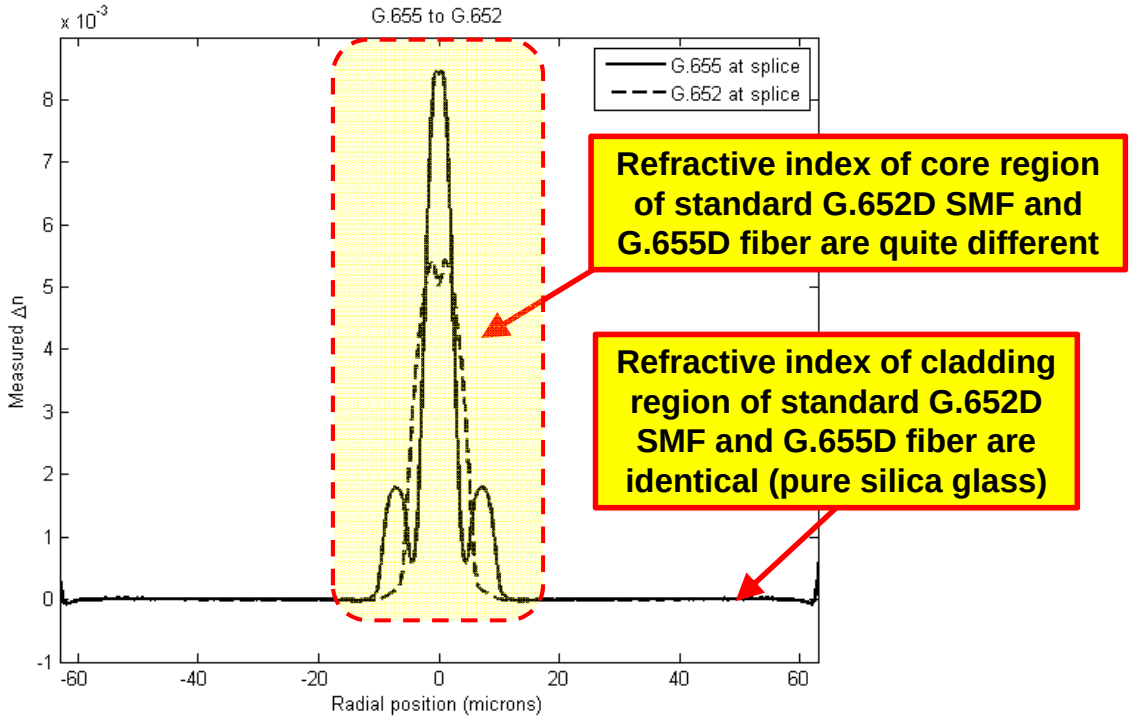


Refractive index Profile in Heat-Affected Zone at Splice Point

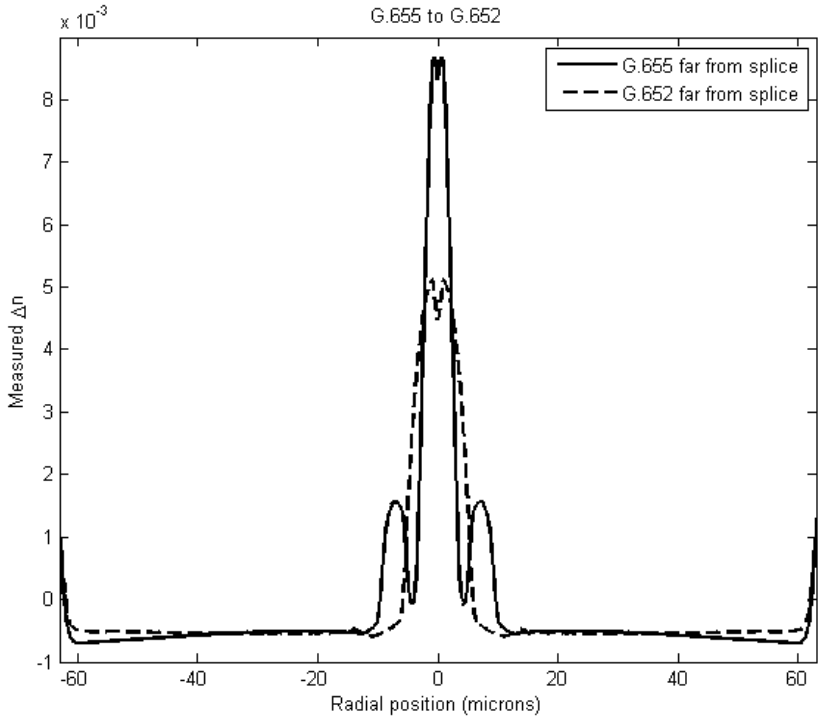


Refractive index Profile of Non-Heated Fibers

Refractive Index Profiles For G.652D Spliced to G.655D

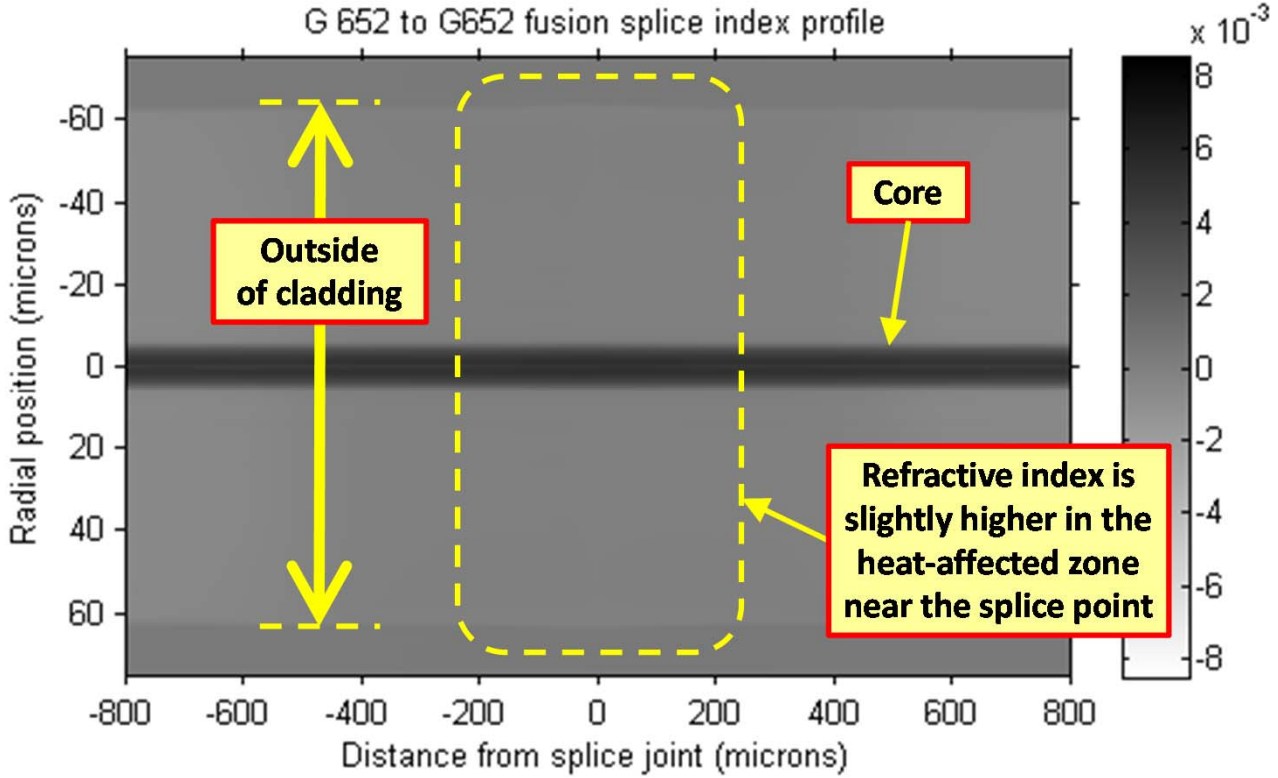


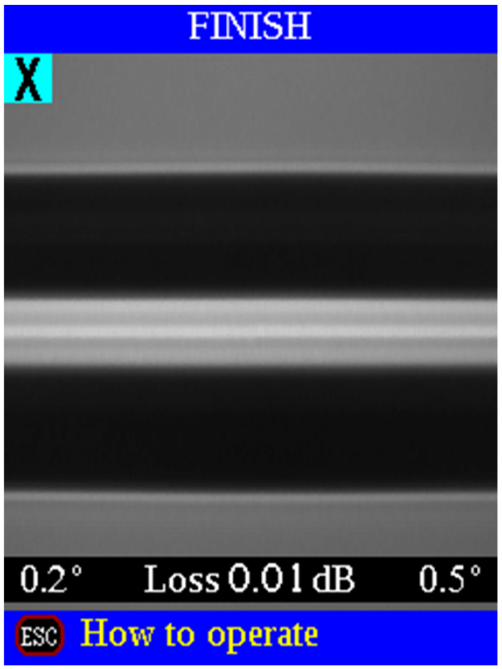
Refractive index Profile in Heat-Affected Zone at Splice Point



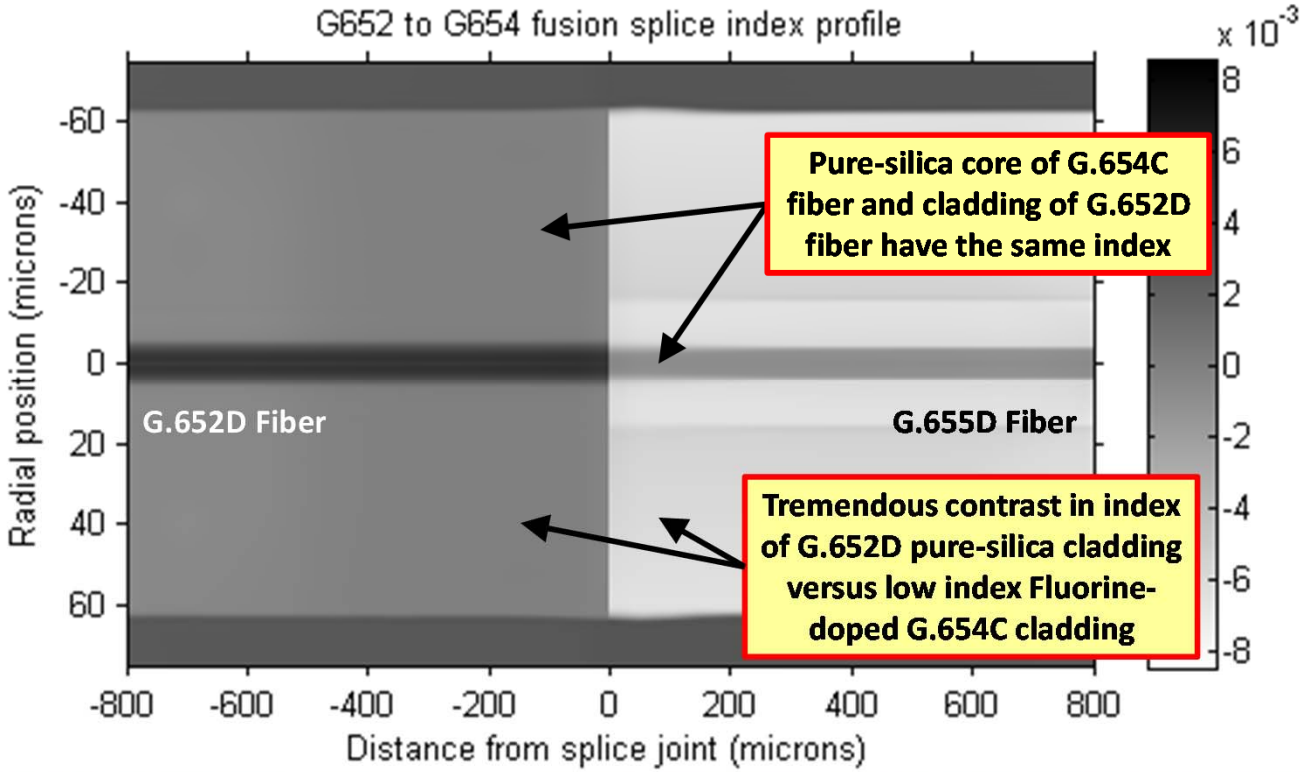
Refractive index Profile of Non-Heated Fibers

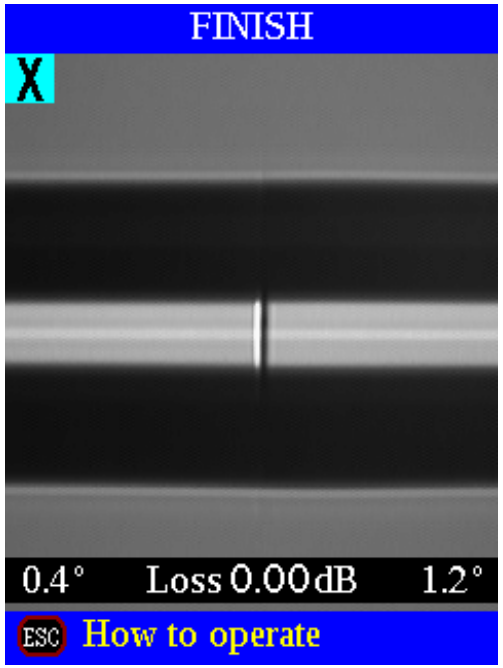
Refractive Index Map: G.652D Spliced To G.652D



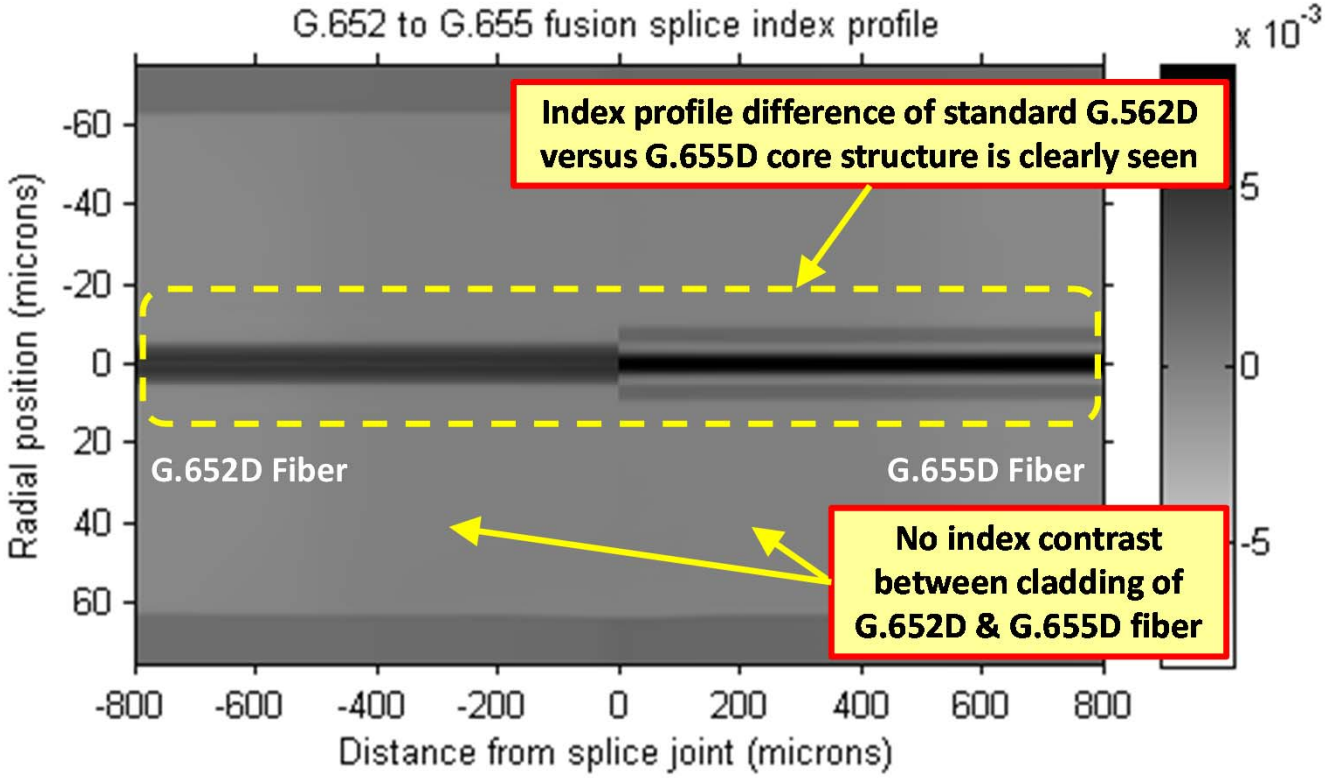


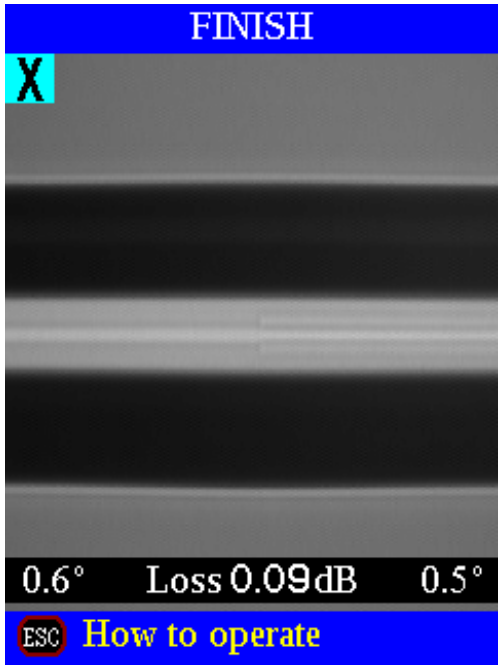
Refractive Index Map: G.652D Spliced To G.654C



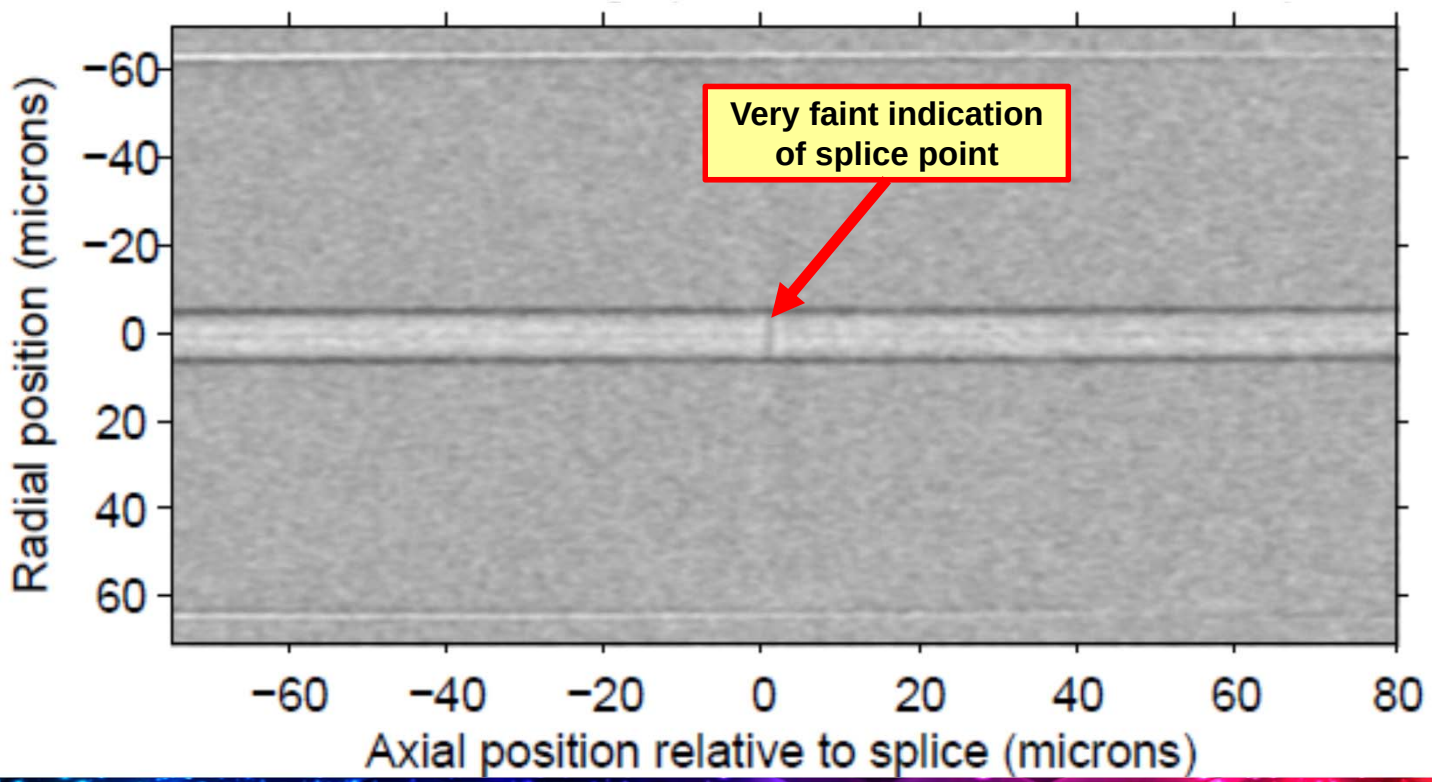


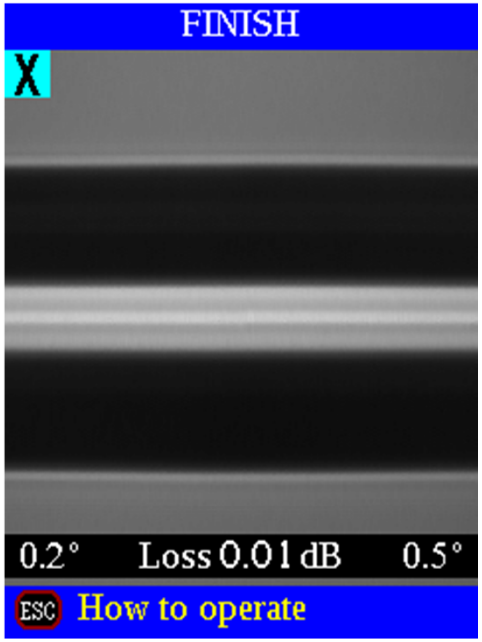
Refractive Index Map: G.652D Spliced To G.655D



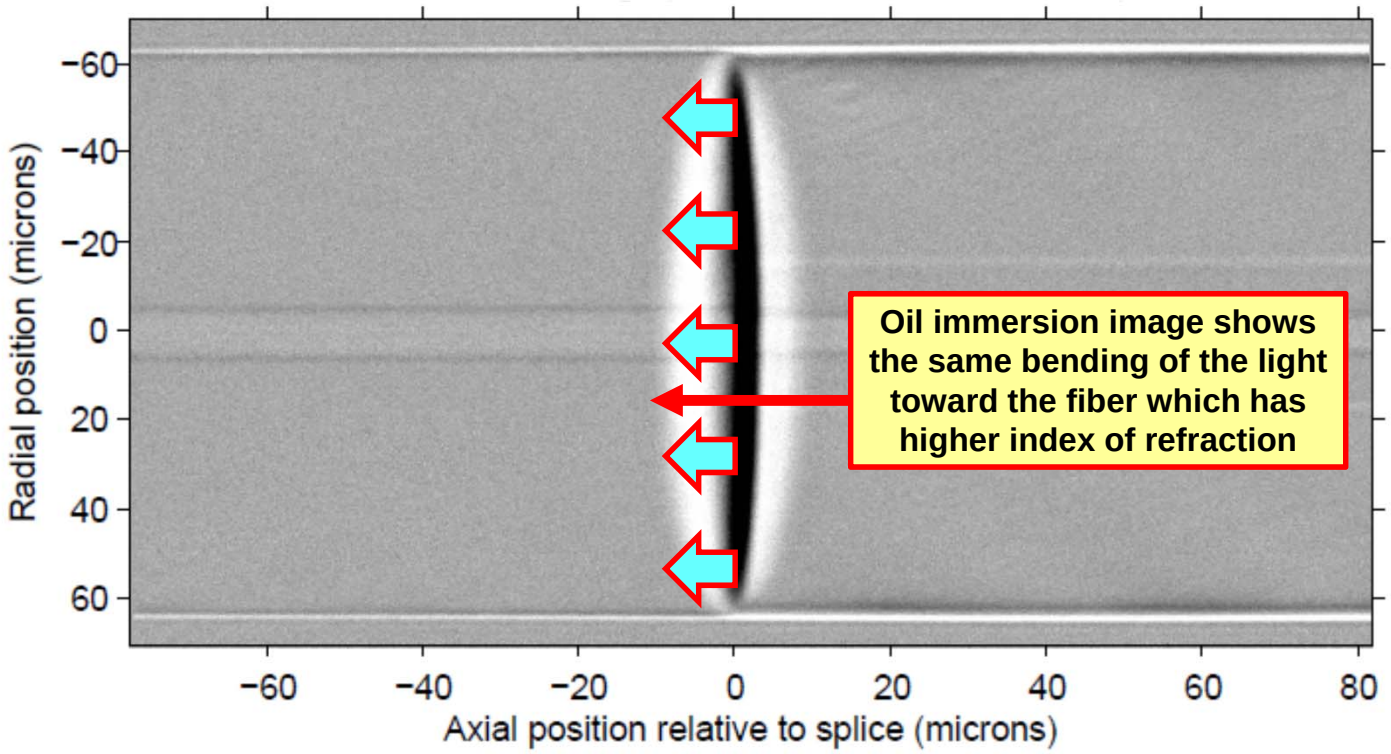


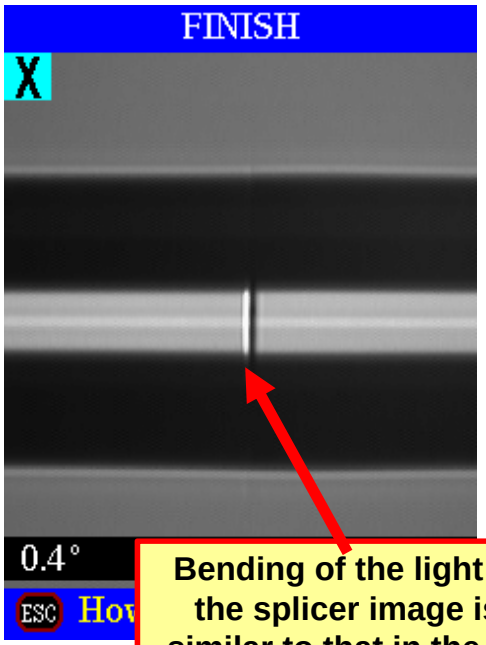
Oil Immersion Micrograph: G.652D To G.652D Splice



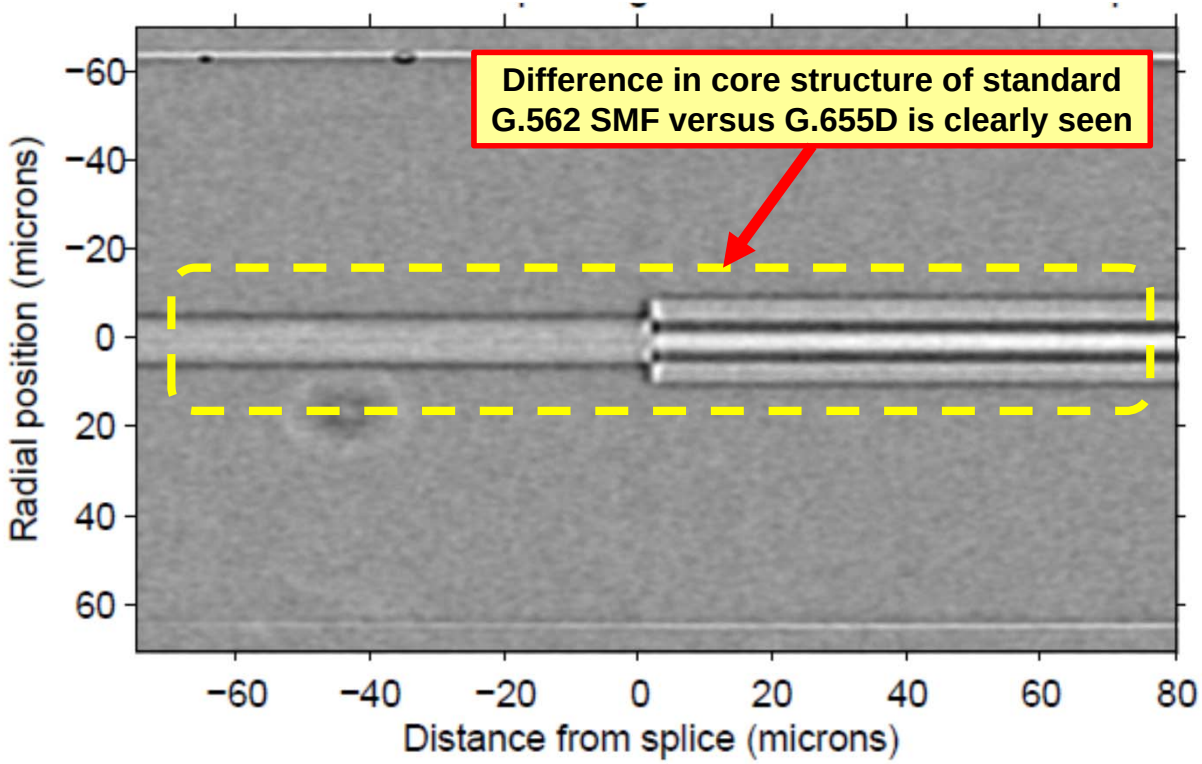


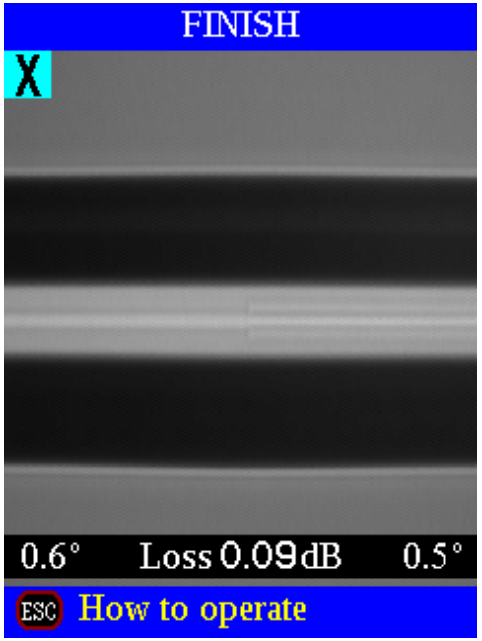
Oil Immersion Micrograph For G.652D To G.654C Splice





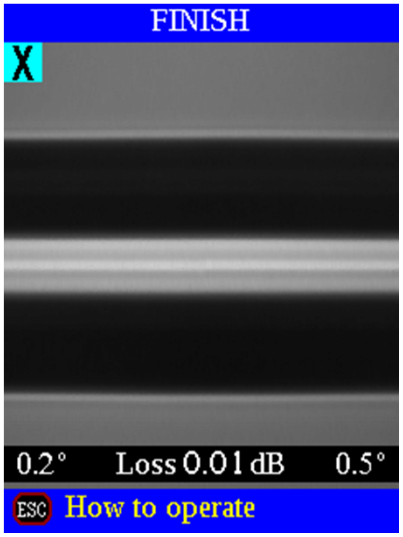
Oil Immersion Micrograph For G.652D To G.655D Splice





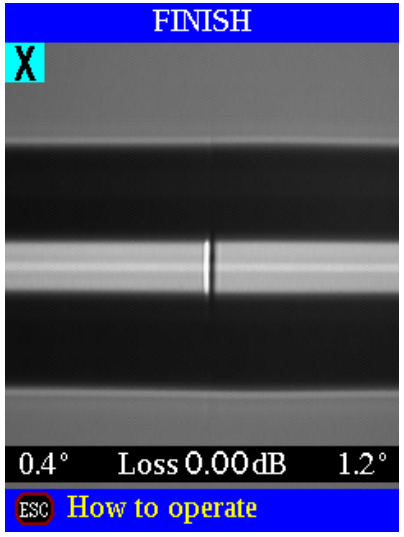
Dissimilar SM Fiber Case Study

G.652D to G.652D



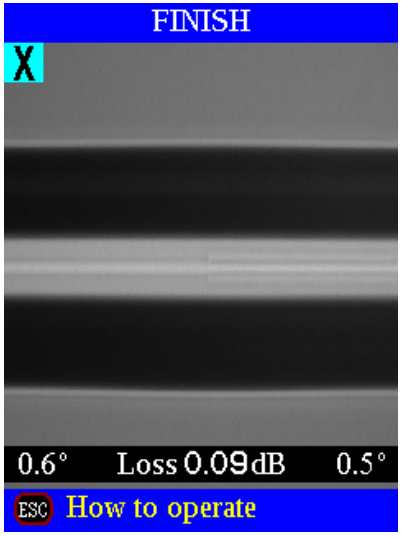
Baseline SMF-SMF
(Not Dissimilar)

G.652D to G.654C



Huge Refractive Index Contrast
Small MFD Difference

G.652D to G.655D

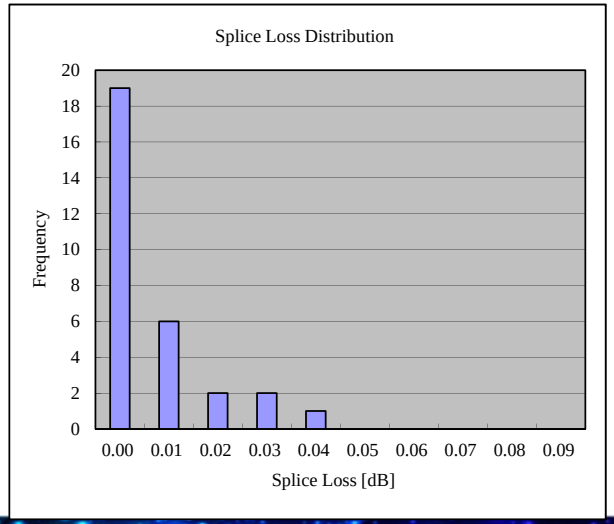


Small Refractive Index Contrast
Large MFD Difference

Dissimilar SM Fiber Case Results: Splice Loss

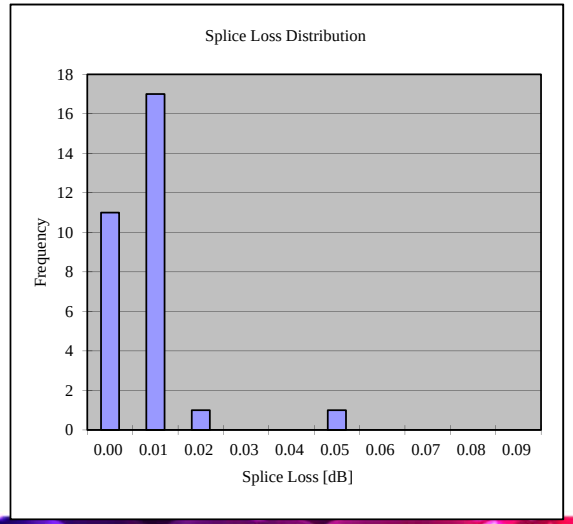
G.652D to G.652D

Average Loss [dB]	0.01
Standard Deviation	0.01
Maximum Loss [dB]	0.04
Minimum Loss [dB]	0.00



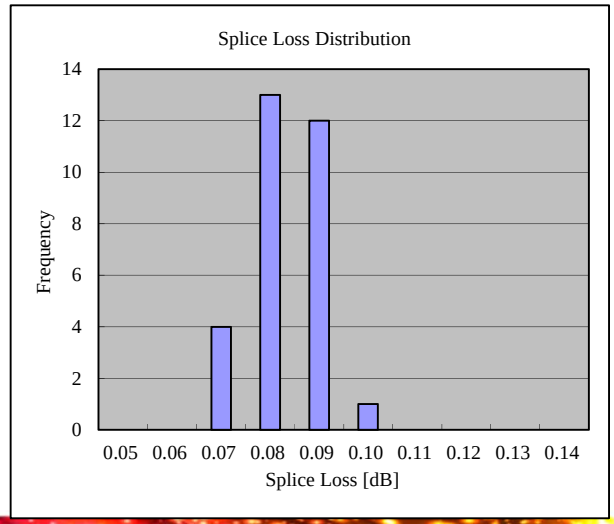
G.652D to G.654C

Average Loss [dB]	0.01
Standard Deviation	0.01
Maximum Loss [dB]	0.05
Minimum Loss [dB]	0.00



G.652D to G.655D

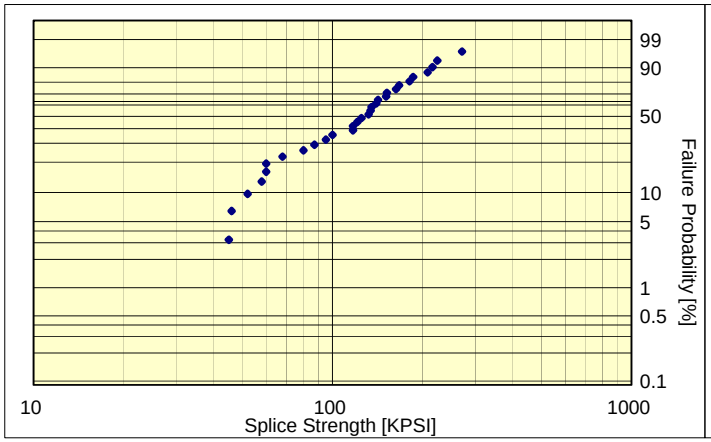
Average Loss [dB]	0.08
Standard Deviation	0.01
Maximum Loss [dB]	0.09
Minimum Loss [dB]	0.07



Dissimilar SM Fiber Case Results: Splice Strength

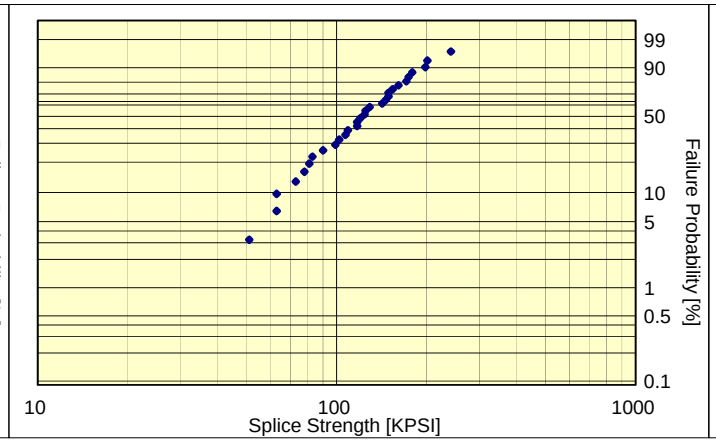
G.652D to G.652D

Average Strength [kpsi]	128
Standard Deviation	58
Maximum Strength [kpsi]	271
Minimum Strength [kpsi]	45



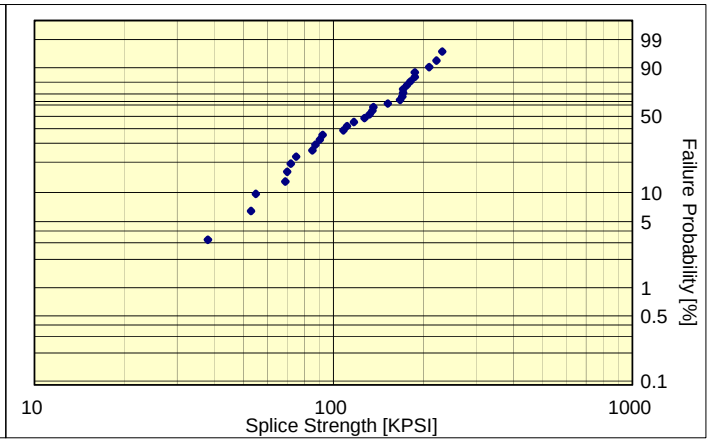
G.652D to G.654C

Average Strength [kpsi]	127
Standard Deviation	46
Maximum Strength [kpsi]	241
Minimum Strength [kpsi]	51



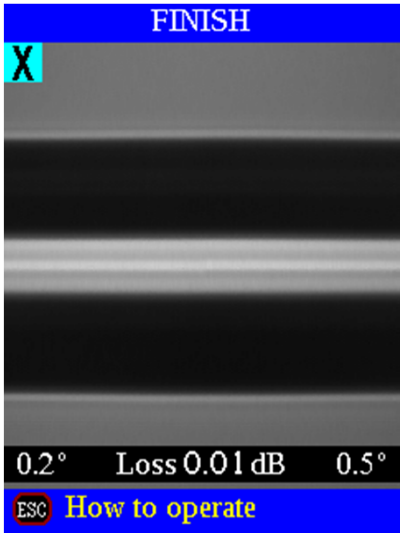
G.652D to G.655D

Average Strength [kpsi]	129
Standard Deviation	54
Maximum Strength [kpsi]	231
Minimum Strength [kpsi]	38



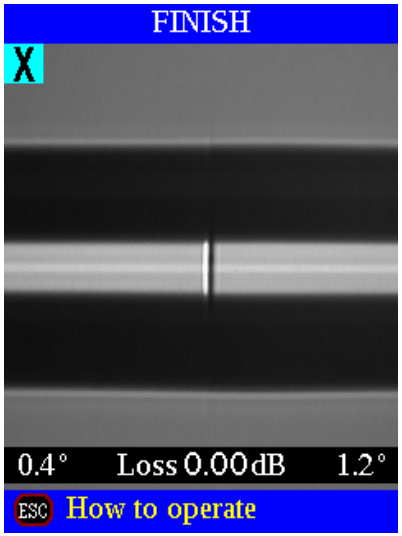
Dissimilar SM Fiber Case Study: Results Summary

G.652D to G.652D



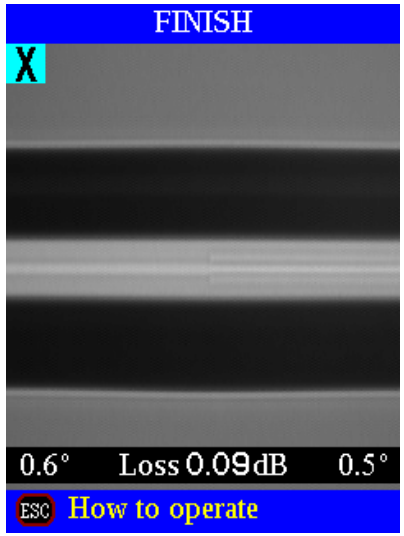
Average Strength [kpsi]	128
Average Loss [dB]	0.007
Loss Predicted by MFD Δ [dB]	0.000

G.652D to G.654C



Average Strength [kpsi]	127
Average Loss [dB]	0.008
Loss Predicted by MFD Δ [dB]	0.004

G.652D to G.655D



Average Strength [kpsi]	129
Average Loss [dB]	0.080
Loss Predicted by MFD Δ [dB]	0.065

Dissimilar SM Fiber Case Study Conclusions

- A large difference in refractive index profiles of two fibers results in a visible line at the splice point
  - The fusion splicer optical system illumination light bends due to refractive index contrast between 2 fibers and this results in the line at the splice point
  - Large refractive index difference affects how the splicer's optical system illumination light behaves
  - Refractive index contrast does not affect the light intensity of the optical signal propagating through the fiber
  - Therefore, refractive index contrast between fibers **is not** related to splice loss

Dissimilar SM Fiber Case Study Conclusions

- A visible line at the splice point between two dissimilar fibers is ***not*** a reliable indicator of splice loss or strength
  - G.652D spliced to G-654C has a prominent line, but low loss
  - G.652D spliced to G.655D has almost no visible line, but loss is high
  - There is no relationship between splice strength and a visible line
- MFD difference between two fibers ***is*** good predictor of splice loss
  - MFD is a measure of the area in which optical signal power propagates through the fiber
  - MFD difference dominates splice loss, especially if core alignment is used

Conclusions Concerning Appearance of Fusion Splices

- A visible line between dissimilar fibers should generally be ignored
  - In ***RARE*** cases, a line at the splice point may be due to improper arc heating
    - Perform arc calibrations regularly
  - If the line triggers a splicer “Bubble” error, it may be possible to reduce the error sensitivity
- A dark spot at the splice point may or may not indicate a bubble
  - Typically, a bubble gets larger when a re-arc is performed
  - If the spot is a surface defect such as from a cleave chip, it may “heal” and disappear if enough re-arcs are performed
- To prevent bubbles:
  - Avoid cleave end contamination/ load fibers carefully / ensure proper cleaver maintenance
  - Use proper arc parameters for MM fiber, especially “Prefuse” time