Enhanced optical performance for small form factor LC connectors

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Abstract

Design considerations, performance data, and a theoretical simulation of the data are presented that describe how insertion losses (*IL*'s in units of dB) are reduced in small form factor LC connectors. *IL* results show that eight position tuning on the average gives 2.4 times lower *IL's* and smaller variations, compared to no tuning. Measurements were also made on fiber core misalignments. Simulations, based on those measurements, are shown to have acceptable correlations with the *IL* results. These simulations were used to predict that on the average 8 position tuning, compared to 6 position tuning, gives significantly lower *IL*'s, compared to the minimum possible *IL* results. A practical LC connector is described that can be readily tuned in the field, yielding improved optical performance.

1. Introduction

Increasing data rates in optical networks translate into requirements for lower insertion losses (*IL*'s) in connections[1]. Our experience and theoretical analysis are consistent with the technical literature. Given tight but economically achievable tolerances on connector components and given currently available single mode fiber, the dominant cause of *IL* is fiber core to ferrule OD (outside diameter) misalignment or concentricity[2,3] which translates into fiber core misalignments across the connection. This is called lateral offset.

The construction of real fiber networks involves mating connectors that are randomly selected. Due to lateral offset such connector pairs can produce greater *IL*, compared to either one connected to a reference connector. While mated to another connector, tuning a given connector reduces *IL* and improves overall network performance.

The process of tuning is used where the ferrule of one connector is rotated relative to the other mated ferrule. This reduces the lateral offset of one fiber core relative to the mating fiber core. Without tuning such axial alignment in a connector is difficult due to tight component tolerances of the connector and small dimensions. For example, a tolerance that results in a 1.0 μm (0.001 mm) fiber core misalignment translates into an *IL* increase of 0.2 dB. Without tuning the same optical performance would require that connectors be more expensive and impractical.

Given the correlation between tight tolerances of the connector components and their associated costs, a near zero *IL* has a near zero probability of occurring in cost effective connectors. What is required is a fine adjustment for each installed mated-pair that will reduce the *IL* to its near minimum value. Tuning accomplishes this. A summary is given of a unique design and the associated performance details of a tuned LC connector that (1) improves optical performance (reduced *IL*), (2) is easily tuned during field installation, and (3) requires only a single installation tool.

2. Design considerations

The entire tunable connector meets the LC intermateability standard[4]. Within the connector a modified ferrule holder is rigidly attached to the LC ferrule. The ferrule and that portion of the fiber located by the ferrule can be rotated ±180° about their initial set position. Extensive twisting of fiber is avoided by limiting the rotation to ±180°. A modified LC housing contains the connector assembly. The network installer uses a tuning tool that engages the ferrule holder. The tuning tool is rotated to various preset angles, set 45° apart, which rotates the fiber and ferrule by the same angles within the tuned connector. In this manner the minimum *IL*, IL_{min}, is determined for that pair of connectors. After this procedure the fiber in this connector is tuned so that IL_{min} is achieved for the given connection.

3. Materials and procedures for performance testing

Refer to Figure 1 where A_1 and A_2 are adapters and C_1 – C_4 are connectors. The reference *IL* reading does not include the LC adapter. C_1 is an FC/APC (angle polish). The others are LC connectors. The repeatability of the meter was determined to be 1xSD = 0.002 dB. (SD is standard deviation.) There were 4 digits of display to the right of the decimal point for the *IL* reading. All cables were 3-m long. All fiber was Corning SMF-28[5] with a 1.6-mm jacket. The LC adapter was pre-selected and included a ceramic split sleeve. The procedure for making *IL* measurements as a function of tuning angle included these steps: Zero the launch cable by connecting C_2 to A_2 in Figure 1 and saving that *IL* reading in the memory of the meter. Connect C_3 and the tuning tool to the LC adapter. Connect C_4 to A_2. Make an *IL* reading, temporarily designating this tuning angle 0°.

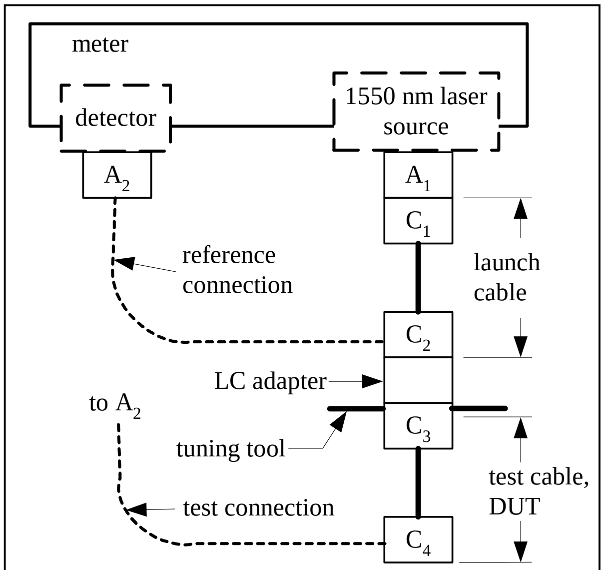

Figure 1. Summary of how IL was measured as a function of tuning angle. See the text for details.

Observing the tuning tool from the C_2 side (top to bottom in Figure 1), rotate the tuning tool in a clockwise direction with increments of +45° up to and including +180° to the temporary angles of 0°, 45°, 90°, 135°, and 180°. Rotate the tool back to 0° in a counter clockwise direction. Continue to rotate the tool in a counter clockwise direction with increments of -45° up to and including -180° (temporary angles: -45°, -90°, -135°, and -180°). The readings at 180° and -180° are at the same tuning angle. The average of those two readings was used for that angle.

In this manner nine *IL* readings were determined for each of the 38 C_3 connectors under test. All temporary angles were adjusted to corresponding final angles with the lowest *IL* reading corresponded to the final 0° angle. The tuning angles were quickly and conveniently set.

The concentricity, index angle, and other parameters were measured for each completed connector with an optical instrument, designed for this purpose. Concentricity here refers to the diameter of the path that the fiber core makes about the center of the ferrule OD. Index angle here refers to that angle where the fiber core is closest to the ferrule's outside surface (maximum lateral offset). Before the connectors were assembled (ferrule, fiber, and housing components), the concentricity and index angles were measured from blank LC ferrules. Each connector was manually rotated to complete a concentricity and index angle measurement. The concentricity of connector C_2 on the launch cable was somewhat larger than the mean concentricity of connector C_3 on the test cables.

The results were automatically saved in a file for subsequent data analysis. The repeatability of a connector's concentricity was measured and found to be 1xSD = 0.04µm. The accuracy of this measurement is ±0.2µm. Several

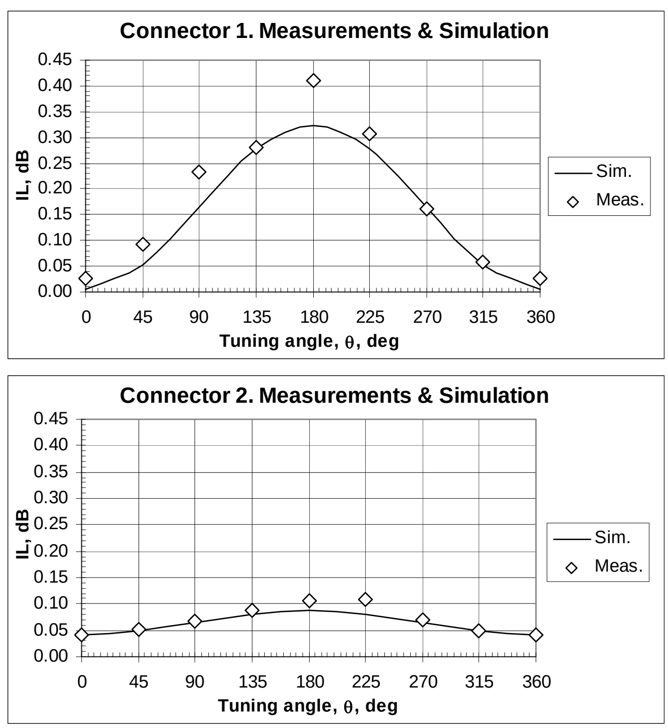

Figure 2. Two typical examples of tuning measurements, "Meas", compared to the simulation, "Sim".

comparisons were made between the results from this instrument and an equivalent, but different, instrument. Agreement was shown to be within the accuracy and precision of the two instruments.

4. A simulation for tuning

Based on our experience and the literature, the measured concentricity is assumed to be the only source of *IL* (see Section 1). This gives a reasonable description of the measurements (see Figure 2).

Consider the top sketch in Figure 3. This represents the plane where the end face of the ferrule and fiber in connector C_2 mate with the end face of the ferrule and fiber in connector C_3 (see Figure 1). The bore of the ferrule depicted as ID (inside diameter) and concentricity of two ferrules are greatly exaggerated for the sake of clarity. The *x*-axis passes through the center of the fiber core of the fixed ferrule (the one for connector C_2) and the center of the ferrule's OD. The *y*-axis, also passing through the center of the fiber core of the fixed ferrule, is perpendicular to the x-axis. The center of the fiber core of the tuned ferrule circularly moves about the center of the ferrule's OD. The diameter of that circle is called the concentricity of connector C_3 and its radius is called the eccentricity.

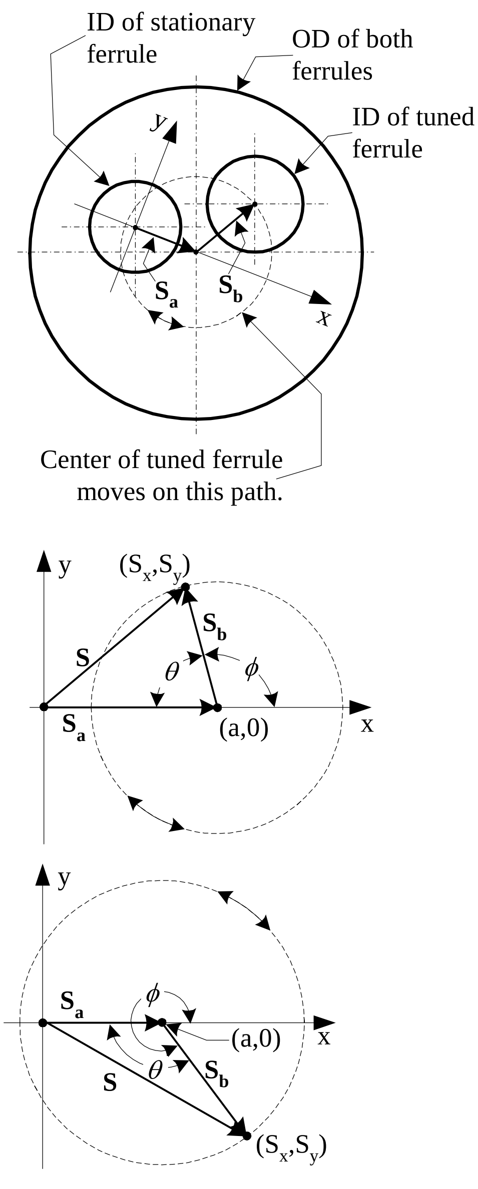

Figure 3. Diagrams for the simulation. See associated text for explanations.

As the tuned ferrule moves about the center of the ferrule's OD the distance between the center of the fiber core of the fixed ferrule and that of the tuned ferrule changes. Let the vector $\boldsymbol{S}$ represent this distance and associated direction of the lateral offset where $\boldsymbol{S}$ is the sum of its two component vectors, $\boldsymbol{S_a}$ and $\boldsymbol{S_b}$.

$$\boldsymbol{S} = \boldsymbol{S_a} + \boldsymbol{S_b} \tag{1}$$

Refer to the middle and bottom sketches in Figure 3 which show two cases: (1) The path of the center of the fiber core of the tuned ferrule is inside the coordinate origin ($|\boldsymbol{S_b}| \le |\boldsymbol{S_a}|$, center). (2) The path of the center of the fiber core of the tuned ferrule is outside the coordinate origin ($|\boldsymbol{S_a}| < |\boldsymbol{S_b}|$, bottom).

From these relationships we can see that the magnitude of $\boldsymbol{S}$, lateral offset, $|\boldsymbol{S}|$, is given by

$$|\boldsymbol{S}| = \left[\left(|\boldsymbol{S_a}| + |\boldsymbol{S_b}|\cos\phi\right)^2 + \left(|\boldsymbol{S_b}|\sin\phi\right)^2\right]^{1/2} \tag{2}$$

where θ is the tuning angle and $\theta = \pi - \phi$. The insertion loss, *IL*, due to lateral offset is given by

$$IL = -10\log_{10}\left[\exp\left(-U^2\right)\right] \quad \text{where} \quad U = 2|\boldsymbol{S}|/(MFD). \tag{3}$$

Here *MFD* is the mode field diameter of the fiber. For SMF-28 the nominal *MFD* = 10.4μm at 1550nm, the wavelength used in this study.

Notice that in this approach $|\boldsymbol{S_a}|$ is half the concentricity of connector C_2 and $|\boldsymbol{S_b}|$ is half the concentricity of connector C_3. Note $|\boldsymbol{S_a}|$ and $|\boldsymbol{S_b}|$ are measured (see Section 3) quantities.

The parameters required for this simulation are all measured: the final tuning angle, θ, and the magnitudes of $\boldsymbol{S_a}$ and $\boldsymbol{S_b}$. There are no adjustable parameters in this simulation. The simulation curves in Figure 2 have no adjustable parameters.

How much *IL* improvement does 8 position tuning provide, compared to 6 position tuning? Assume that the uncertainty of the *IL* measurement is sufficient that tuning angle, θ_{min}, for the minimum *IL*, IL_{min}, can be off by one half of the step size. For this situation the angular uncertainty for θ_{min} is ±45°/2 = ±22.5° for 8 position tuning and ±60°/2 = ±30° for 6 position tuning. The simulation was applied to the mean *IL*'s at each tuning angle for all the test cables. For θ_{min} = ±22.5° *IL* = 0.044 + 0.006 dB and for θ_{min} = ±30° *IL* = 0.044 + 0.010 dB where IL_{min} = 0.044 dB. Consider the worst case *IL*'s for both situations which typically would be done in fiber network design. With these assumptions 8 position tuning yields worst case *IL's*, compared to IL_{min}, that are 0.010/0.006 = 1.8 times smaller (accounting for rounded-off values), compared to 6 position tuning.

5. Comparison of test results with a simulation

Measurements, using the above procedures, were made on each tuned connector under test (C_3 in Figure 1). A simulation was used to predict the effect of tuning (see Section 6) for each connector. Two typical results are given in Figure 2.

The top plot shows a test connector with larger tuning amplitude, maximum *IL* minus minimum *IL*. The bottom plots shows test connectors with a smaller tuning amplitude. Each of these two sets of results is reasonably well described by the corresponding simulation for that connector.

6. Summary of all the results

A summary of all the *IL* measurements is given in Figure 4. The height of the bars represents the mean *IL* readings and the error bars represent ±1xSD. The connectors were assembled, polished, and their *IL*'s measured; those results are labeled "Random, no tuning". This represents what would be expected, on the average, from newly made LC patch cords without tuning.

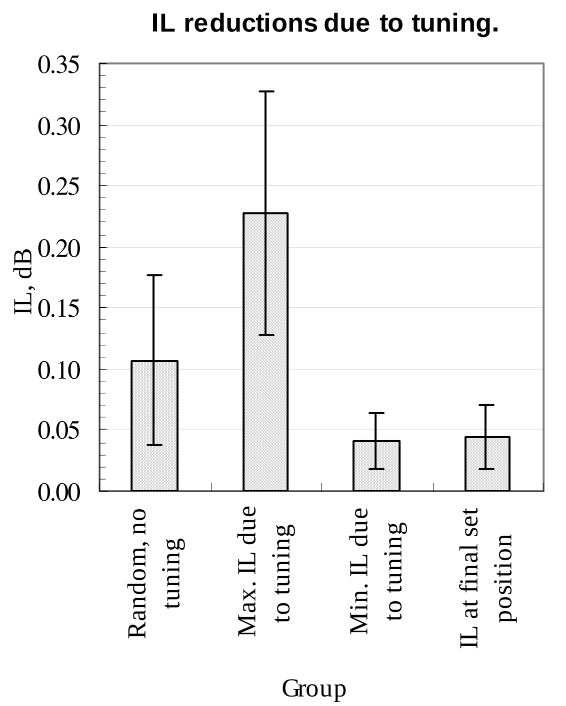

Figure 4. Summary of all the *IL* results showing the benefits of tuning.

When the maximum *IL*'s are grouped due to 8 position tuning, we obtain the results labeled "Max. *IL* due to tuning". This represents worst case *IL*'s from newly made LC patch cords with tuning. When the minimum *IL*'s are grouped due to 8 position tuning, we obtain the results labeled "Min. *IL* due to tuning". This represents the best case *IL*'s from newly made LC patch cords with tuning.

After the tuning angle that corresponds to the minimum *IL* is determined, the connector is reset to that angle with the tuning tool. Those results are labeled "*IL* at final set position". This represents the nominal best *IL* that might be expected with routine 8 position tuning. From Figure 4 we see the "Min. *IL* due to tuning" and the "*IL* at final set position" bars and variances are nearly identical.

Mean *IL* values were used to make the following comparisons. Compare a randomly mated LC connector to the nominally best *IL* ("Random, no tuning" divided by "*IL* at final set position") and we find that the tuned results are 2.4 times better. If we compare the worst case, "Max. *IL* due to tuning", with "*IL* at final set position"; we find the results are 5.2 times better for 8 position tuning.

From Figure 4 the *IL* error bars are smaller for the tuned connectors, compared to connectors that were not tuned. This means that the tuned connectors not only have lower *IL*'s, they are more predictable in *IL*. Fiber networks built with such tuned connectors can be designed with lower link loss budgets and with greater predictability.

7. Discussion and conclusions

It was determined that lateral offsets, *i.e.*, misalignment of the two fiber cores across the connection boundary, are the dominant source of *IL* for the types of connections described in this paper. A tuning procedure and associated components were described where the fiber core of the given connector is rotated around the center of its ferrule's OD. A modified ferrule holder and tuning tool is used. This method lowered (improved) *IL*'s by a factor of 2.4 on the average, compared to the same kind of connectors which are not tuned. From worst case *IL* to best case *IL* the improvement factors averaged 5.2.

The concentricity (fiber core to ferrule outside diameter misalignment) of each connector was measured with an accuracy of ±0.2-μm and a repeatability of 0.04-μm (1xSD). A simulation used those measurements to estimate *IL* as a function of tuning angle. The simulation depends only on connector concentricity and uses no adjustable parameters. Acceptable correlations were computed in comparison to the tuned *IL* measurements.

Based on these measurements, assumptions, and analysis 8 position tuning as presented here can translate into uncertainties in final *IL* values that are 1.8 times smaller compared to 6 position tuning.

8. Acknowledgements

Encouragement from and discussions with Rick Pimpinella were most helpful. Eline Gilmack made many of the measurements for this and related work.

9. References

1. See, for example, the link loss specifications in IEEE 802.3ae, "Part 3: Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications Amendment: Media Access Control (MAC) Parameters, Physical Layers, and Management Parameters for 10 Gb/s Operation", 2002.

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5. Corning data sheet, "Corning SMF-28 CPC6 Single-Mode Optical Fiber", issued April 2002.