OPTICAL CONNECTOR CONTAMINATION AND ITS INFLUENCE ON OPTICAL SIGNAL PERFORMANCE

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ABSTRACT

The thrust of the NEMI project on Fiber Optic Signal Performance was to develop fiber optics inspection criteria, which may support differing requirements based on application. The tests' resulting data would provide OEM incoming quality and cable suppliers with specific cleanliness requirements with supporting data. Potentially, the inspection criteria could be used as an enhancement to existing TIA, Telcordia and other standards bodies.

The influence of the contamination/scratches on connector optical performance, that is, Insertion Loss (IL) and Return Loss (RL), as well as on the system level performance using the Bit Error Rate Test (BERT) were investigated. It was shown that the effect of contamination / scratches on optical signal performance is dependant on the contamination type (fingerprints, carbon, metallic particles, etc.), the size of the contamination / scratches and their location on the connector end face. The influence of the contamination / scratches becomes more evident if they are located in the core / cladding areas. It was shown that particle contamination may cause a significant increase in IL (up to ten times), decrease in RL (up to 3 times) and increase in BERT results (2- 10 times). The significant degradation in BER performance occurred when the core of the fiber was blocked: the BER signal increased by more than 100 times compared with a clean fiber at average power -12 dBm. Scratches applied to the fiber MFD (Mode Field Diameter) resulted in an increase of up to 25% of RL while scratches located in the cladding layer showed little effect on IL, RL and the BERT results. Multiple heavy scratches passing through the core caused severe performance degradation (IL, RL) and catastrophic BERT failures. Further investigations, such as mathematical modeling, are required to understand the influence of contamination and scratches on optical signal performance.

The other objective of the project was to determine methods for improving the cleaning process and preventing recontamination of fiber optic connectors. This would result in the minimization of inspection and cleaning processes, elimination of false failures during test due to contaminated connectors, reduced cycle times and associated cost reductions.

Key words: Fiber optics, fiber optics connectors, contamination, scratches, optical performance, insertion loss, return loss, Bit Error Rate

INTRODUCTION

Within the fiber optics industry, the typical attitude toward fiber terminations is to ensure no visible contamination exists on a fiber optic connector prior to termination. This has developed an opinion within the industry that each connector or port must be inspected, and cleaned if necessary, prior to termination to ensure the interface will operate as efficiently as possible.

Contaminated fiber optic connectors affect system optical performance by causing an increase in BER and could even cause catastrophic failures [1,2]. It was shown that contamination increases the IL of the connector especially if the contamination is located in the core and cladding areas [3]. The problem becomes more severe for high power applications. It was found that contamination of SC / PC connectors with carbon black-doped acrylate particles showed failures at 50 mW of incident power [4]. It was also shown that the cleaning of connector end faces while the laser is on and the optical power levels higher than 15 dBm can cause damage to the connector end face [5]. Many efforts are concentrated on the improvement of the cleaning process. It is also important to develop ways to prevent contamination especially for non-removable types of contamination. There are two aspects to contamination prevention, elimination of the sources of contamination and prevention of contamination transfer from the source to the connector end face. Recently the PVC (Polyvinyl Chloride) dust cap has been recognized as one of the main sources of (cross-)contamination for fiber optics connectors [2]. In order to reduce the test time, debug time and the associated cost due to false failures, a better understanding of the transfer mechanisms of contamination to the fiber end face is needed. The ESC (Electrostatic Charge) effect due to connector cleaning process was recently reported in [6].
Scratches are another example of a fiber end face anomaly. Scratches can be caused by an improper polishing process or poor handling. The effects of scratches on the RL performance were analyzed using a Gaussian distribution of

the incident power [7, 8]. Based on the proposed model, it was found that the performance depends on the number of scratches, their location and the relative reflectivity of the scratch [7]. Furthermore, additional experimental data on the influence of scratches on optical signal performance is required.

Many fiber optic cable connectorization companies have created inspection criteria for their products which are very strict in terms of the allowable quantity and size of non-removable contamination and scratches. This is rather a common sense approach since many terminations may exist within a fiber optic link and the cumulative loss of contamination or scratches, etc. at each interface may drive the link budget beyond an acceptable level for reliable signal transmission.

The dilemma for systems manufacturers is that if the typical industry attitude of inspecting the connector prior to each termination is followed, the test time for high density port systems dramatically increases and thereby increases test and product cost. A happy medium must be found where minor non-removable contamination is considered acceptable as long as there is no significant, negative impact to the link performance under test and to the integrity of the products' optical port.

The influence of different types of contamination and scratches on IL, RL and BER has not been investigated in detail. This paper presents the results of a study performed to determine the impact of connector end face defects such as scratches, particles and oil contamination (finger prints) on optical connector performance parameters. The optical connectors chosen for this study were SC Single Mode (SM) 2.5mm ceramic-ferrule type. The optical performance parameters measured for SM connectors are IL, RL and BERT measurements. Results from the testing for the various combinations of defect-free and scratched / contaminated connector end face are included. The correlation between the level of cleanliness of the connector end face and optical performance is investigated.

EXPERIMENTAL METHODOLOGY

In order to understand the influences that contamination (any foreign anomaly such as scratches, particles etc.) has on signal performance, the traditional methods of connector performance (IL, RL) verification will be used. An attempt will then be made to correlate this data to performance of the connector in a simulated traffic test such as the BERT. When using a stable platform with pristine interconnects as a reference, repeatable results should be easily attained and compared to results received when an anomaly is introduced. At this time a reasonable conclusion may be drawn to support or discount the theory being brought forth that minor end face anomalies may be acceptable.

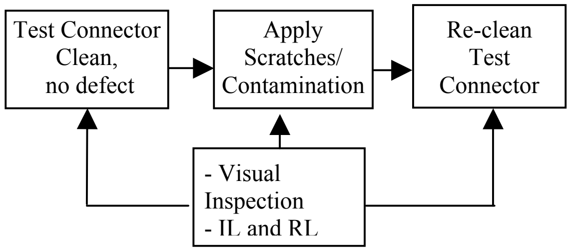


Figure 1. Flow Chart of Scratches/Particles or Oil Contamination Experiment

Three groups of cables with SC/SC simplex connectors were tested as shown in Figure 1. The first group of cables was used for the scratch experiment, the second group was contaminated with carbon particles and the third group was contaminated with oil. Each group consisted of 20 to 24 cables (device under test - DUT) and launch cables which were all polished to UPC performance using a standard polishing process. To ensure that the optical connector end faces were free of any fixed contamination such as scratches and pits, the optical cable assemblies and launch cables were visually inspected after polishing and initial optical performance parameter measurements were taken.

Each cable connector was initially cleaned, inspected and the image was saved. Each cable was then measured to determine its performance in pristine condition using the IL, RL and BERT equipment. Then scratches, removable particles or oil contamination were applied and the image of the contaminated connector was saved. Further, the scratched or contaminated connector was mated with clean reference fiber and IL, RL and BERT were measured again.

The connectors were de-mated / mated again and IL and RL were measured again after the second mating. While all connectors were inspected after each mating / de-mating process, the reference connector was cleaned before the first contact with a contaminated connector using standard Cletop or CleanCheck cleaning cassettes. The connectors were inspected using 200x or 400x fiberscope (Westover FVDW-2409P or FVW-409). Oil contaminated fibers were inspected using a 200x EXFO FIP-USB4 Fiber Inspection probe. IL and RL measurements were performed using standard experimental set up [9]. A JDS Uniphase Backreflection Meter (RM3750) or EXFO test system were used for IL & RL measurements for the scratches and particle contamination experiment.

A pre-experiment study showed that the measurement difference between the JDS Uniphase and EXFO tester was relatively small (<0.2 dB max for IL and <5dB max for RL. On average the difference is about 0.04dB for IL and 1dB for RL). In the case of oil contamination IL and RL were measured using the IQS 12001B test system which is based on time domain reflectometry technology with a wide-aperture integrating cavity detector [10]. The IL uncertainty was +/- 0.04 dB and RL uncertainty was +/-1 dB from 30 dB to 60 dB. IL & RL measurements were performed at 1550 nm wavelength for group 1 (scratches) and at two different wavelength values: 1310 nm and 1550 nm for groups 2 and 3, particle contaminated and oil contaminated connectors, respectively.

The BER performance of the contaminated fiber is evaluated using the setup shown in Figure 2. The pattern generator supplies the 10Gbps pseudorandom sequence to the optical transmitter to modulate the laser output. Further, the optical signal passes through a variable optical attenuator that is used to set the input power into the UUT, followed by a beam splitter that sends 90% of the input to the reference optical receiver and 10% to an optical power meter, calibrated to measure the input power to the reference receiver.

The reference receiver recovers the Clock from the incoming optical signal and sends it electrically, together with the received data, to an error detector for BER measurement.

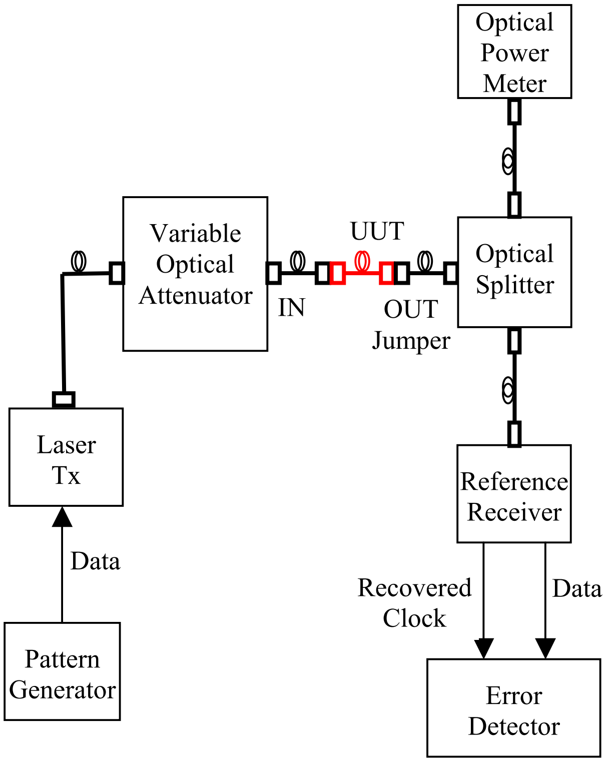


Figure 2. BER Measurement Setup

The error detector synchronizes to the received data and it evaluates the received bits for any errors. Both the decision threshold and sampling phase in the error detector are optimized for the received signal since it is known in the literature that these values affect the BER performance of the receiver; furthermore it can be said that the measurement was conducted with an optimized receiver. To obtain accurate BER values it is necessary that at least 50-100 errors be recorded by the error detector for each measurement. At the transmission rate of 10Gbps it is possible to measure BER in the range of 10^{-10} and higher fairly quickly. To confine BER to such values, the optical input power to the receiver is set from –12dBm to –16dBm by using the variable optical attenuator. There were four categories of fiber patch cable samples: clean (considered for reference), carbon contaminated, scratched and oil contaminated. For each sample, the optical input power into the reference receiver together with the BER curve consisting of three points: -12dBm. –14dBm and –16dBm were recorded.

Meanwhile, a better understanding of the impact of contamination needs to be developed to determine if minor contamination can be tolerated and not significantly impact the test process or the product being tested. With regards to fiber optic interface contamination, some of the concerns within the manufacturing environment are:

- Accurate absolute optical power measurement
- Traffic flow verification (Bit Error Rate Testing)
- Optic end face cosmetic appearance (workmanship violations)

Sample preparation has proven to be the greatest challenge. While many approaches were considered, only a few have proven to be financially viable within the scope of this project. A trial and error approach was adopted for inflicting scratches and contamination until a suitable sample batch size was reached.

THE INFLUENCE OF SCRATCHES ON OPTICAL PERFORMANCE

Cosmetic or functional defects on the end face of optical connectors are often associated with degradation of optical performance parameters of the mated optical connectors. Such defects usually occur either during the manufacturing process, or system installation.

To organize the experiment, the samples were divided into two groups: A and B. Scratches were induced only within the cladding region of Group A, while for Group B, the scratches were applied to the fiber mode field diameter (MFD).

Group A - Effects of Scratches within the Fiber Cladding Region (outside the Fiber MFD) on Optical Performance Parameters.

Group B - Effects of Scratches within the Fiber MFD on Optical Performance Parameters.

Figure 3 and 4 shows the IL and RL distribution, respectively, for mated pristine cables, and the combination of:

- Pristine launch cable mated with DUTs scratched across the fiber-cladding region only, not crossing the fiber MFD, and
- Pristine launch cables mated with DUTs scratched across the fiber MFD.

The average insertion loss difference between pristine mated connectors and mated connectors with scratches across the cladding region only, was 0.004dB; the mean RL difference between pristine mated connectors and the combination of pristine launch cable with DUTs scratched across the fiber cladding was 0.9dB. Both the average IL and RL changes are well within the uncertainty of the test equipment used.

The average insertion loss difference between pristine mated cables and cables having connectors with scratches across the fiber MFD was 0.004dB. However, the average RL difference was significant, 4dB.

The results of this study indicate that:

1. Polishing scratches and scratches made during connector cleaning, outside the fiber MFD, have no impact on IL and RL of the mated optical connectors,
2. Scratches, 2um wide or less within the mode field diameter, have no impact on insertion loss; the insertion loss change observed is within the measurement uncertainty of the test equipment.
3. Scratches, within the fiber MFD, can degrade the RL of the mated connectors. The level of degradation depends on the size (width and depth), and the number of scratches crossing the fiber MFD.

Figure 3. IL of the connectors from groups A and B , wavelength is 1550 nm

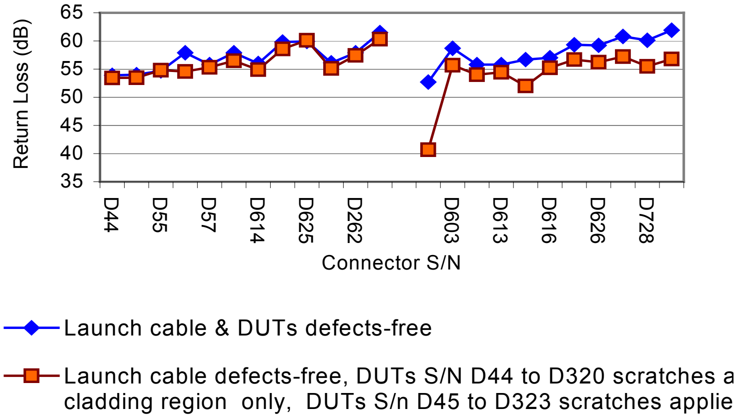


Figure 4. RL of the connectors from groups A and B (wavelength is 1550 nm)

Figure 5 provides the pictures of the connector end faces used for the study.

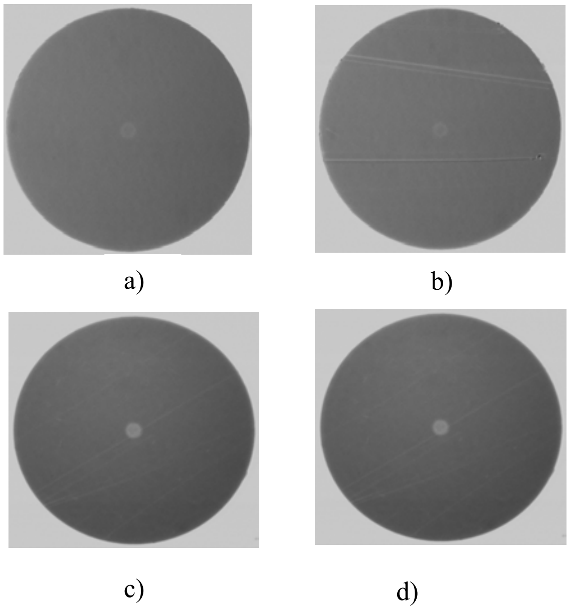


Figure 5. The fiberscopic images of pristine (a) and scratched (b-d) connector end faces. (a)-FC #55 clean, IL=0.14dB, RL=54.7dB; (b)-FC #55 scratched connector, IL=0.11dB, RL=54.8dB; (c)-FC #626 scratched connector, IL=0.09, RL=56.2dB; (d)FC #45, scratched connector, IL=0.10dB, RL=40.7dB

PARTICLE CONTAMINATION

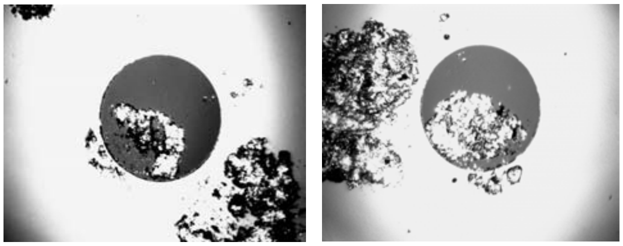
One of the challenges when working with particles is to deposit a defined particle quantity on the precise end face location. Several deposition methods such as SEM, Pt coater, use of dye material and UV recoating material were investigated, but none of them gave satisfactory results. Finally carbon particles were used for contamination of connector end faces. Particles can be trapped on any of three basic areas of the connector end face: the core, the cladding and the ferrule area. Seven possible anomaly conditions may exist, that is, anomalies existing on:

- the core only
- the cladding only
- the ferrule only
- the core/cladding
- the cladding/ferrule
- the core/ferrule
- the core/cladding/ferrule

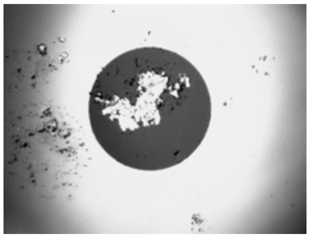
By studying the effects of particles on the optical connector at these locations we can learn the “hot” spots on the end face where the presence of particles can result in critical optical losses.

The study showed that the particles (loose contaminants) were spreading during mating. Through connection, a significant amount of the particles were transferred from the contaminated connector to the clean reference connector in a similar pattern as seen on the contaminated connector.

Figure 6 shows the spreading and transferring pattern after the connection.



a) Before Test b) After Test



c) Reference Connector

Figure 6. Loose Particles Transferring Pattern (through SC-SC adapter connection)

The study also showed that particles blocking the core cause a tremendous increase in IL and decrease in RL. The IL and RL measurements are shown in Figure 7. When most of the core was blocked (case JSC1, blocked ~90% core), an increase of 33dB IL and decrease of 46dB RL were seen. In JSC2 connector, approximately 5-10% of the core was blocked, and an increase of 1.26dB IL and the decrease of 34dB RL were observed. Particles blocking approximately 20-40% of the core would cause 7 times increase in IL (from 0.51 dB to 3.61 dB), and the RL decreased from 54.6 dB to 34.5dB (see case TSC138 and Figure 7). The proportion of increase in IL and decrease in RL and the blocked core area is going to be investigated in a future study.

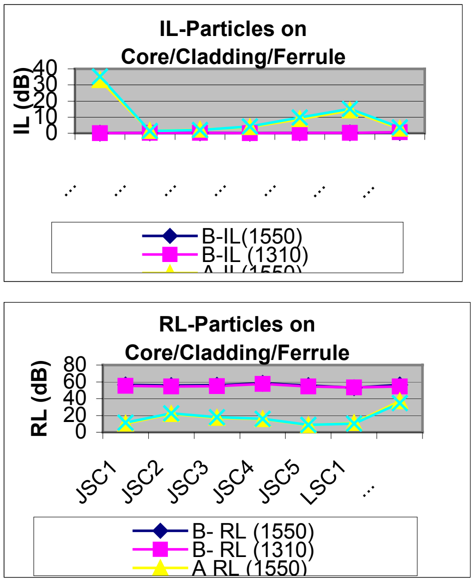


Figure 7. IL and RL Measurements- Particles blocked core. In the JSC1 case, most core region was block (>90%). In JSC2, approximately 5-10% of the core was blocked. In JSC4, approximately 60-70% of core was blocked. In TSC138, approximately 20-40% of the core was blocked.

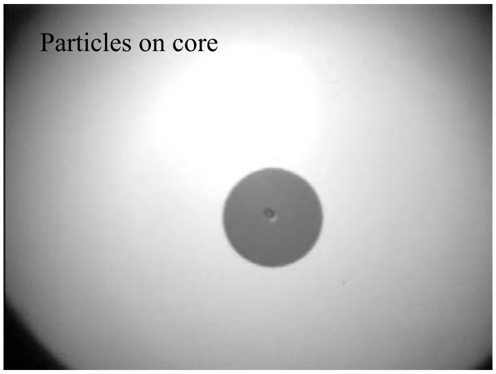


Figure 8. Particles blocked the core (connector TSC138). IL-1550nm/1310nm (clean connector)=0.39/0.51dB; IL-1550nm/1310nm (contaminated connector) =2.88/3.61dB. RL-1550nm/1310nm (clean connector)=56.2/54.6; RL-

1550nm/1310nm (contaminated connector) =37.1/34.5dB.

Figure 8 shows the IL and RL measurements when the particles were located at the ferrule of the connector. A relatively large amount of particles were presented at the ferrule area (See Figure 10). The difference between the measurements of the clean and contaminated connectors were small and showed no degradation on the optical performance. The maximum difference of the measurements before and after the contamination was less than 0.05dB for IL and 4dB for RL as shown in Figure 9.

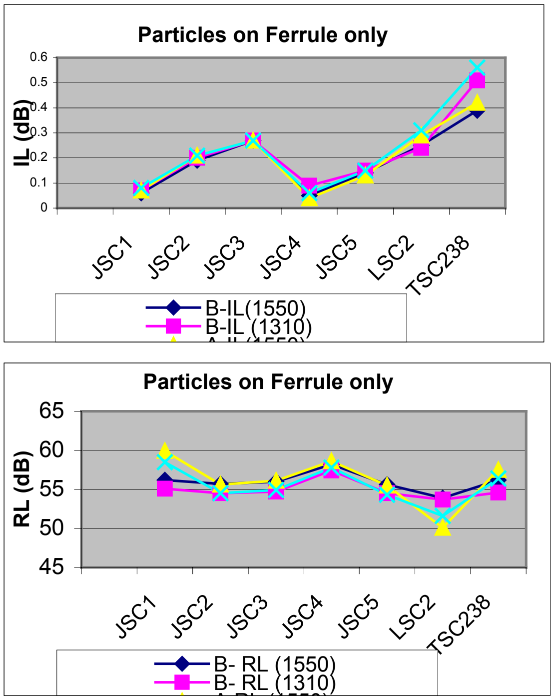


Figure 9. Particles on Ferrule Area- IL and RL measurements

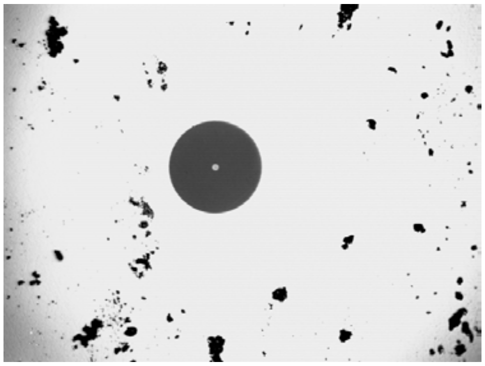


Figure 10. Typical amount of particles on Ferrule (JSC2 Connector). IL-1550nm/1310nm (clean connector)=0.19/0.2dB; IL-1550nm/1310nm (contaminated connector) =0.21/0.21dB. RL-1550nm/1310nm (clean connector)=55.7/54.5dB;RL-1550nm/1310nm (contaminated connector) =55.6/54.5dB.

When particles exist on the ferrule and the cladding area, a mixed result was seen (see Figure 10). In many cases there were no significant changes in the IL and RL measurements between the clean and contaminated connectors. However, a few exceptions show that the presence of the particles on the cladding but very close to the core (see JSC5, LSC5 and TSC152 connector) increased the IL and/or RL. In the case of the connector JSC5, the particles spread out during mating and blocked a small portion of the core. This would explain why both the IL and RL increased significantly (See Figure 11,12). In the case of connector TSC152, there was no evidence of particles blocking the core, but the IL increased from 0.25dB to 1.07 dB. Its RL didn't change significantly (see Figure13)

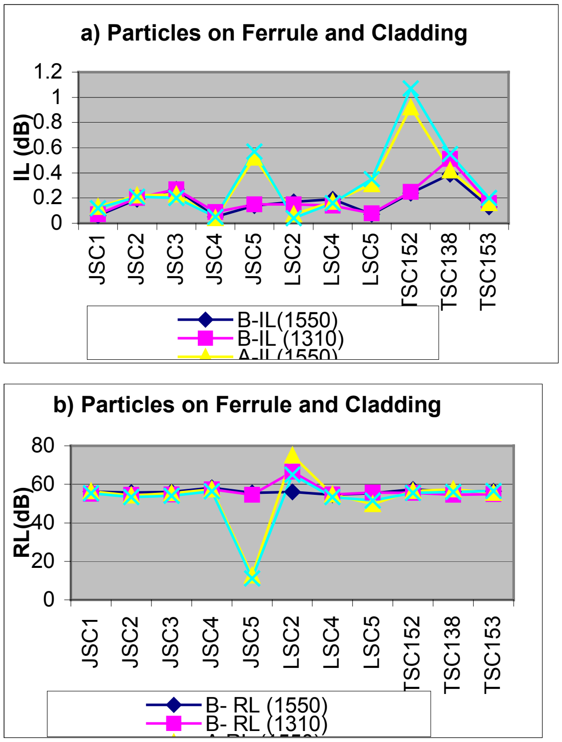
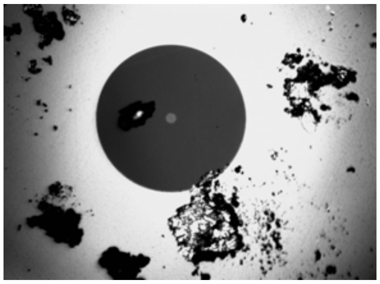
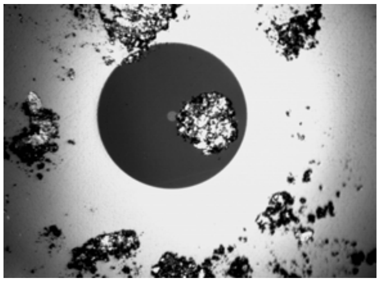


Figure 11. Particles on Ferrule and Cladding. a) IL measurements b) RL measurement



a) Before Test



b) After Test

Figure 12. Case Study JSC5: Particles on Ferrule and Cladding. IL-1550nm/1310nm (clean connector)=0.14/0.15dB; IL-1550nm/1310nm (contaminated connector) =0.52/0.57dB. RL-1550nm/1310nm (clean connector)=55.6/54.5dB; RL-1550nm/1310nm (contaminated connector) =12.7/11.2dB.

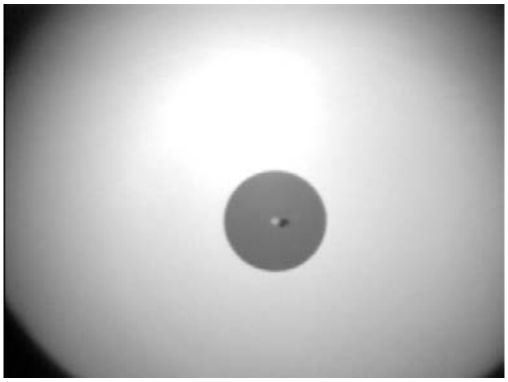


Figure 13. Case Study TSC152:Particles on Ferrule and Cladding. IL-1550nm/1310nm (clean connector)=0.24/0.25dB; IL-1550nm/1310nm (contaminated connector) =0.92/1.07dB. RL-1550nm/1310nm (clean connector)=57.3/55.5dB; RL-1550nm/1310nm (contaminated connector) =56.5/55.6dB.

OIL CONTAMINATION

A typical image of an oil contaminated connector is shown in Figure 14.

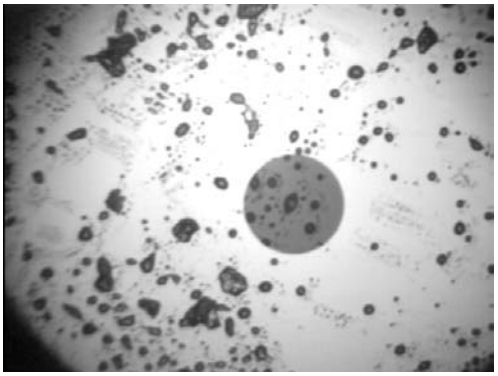
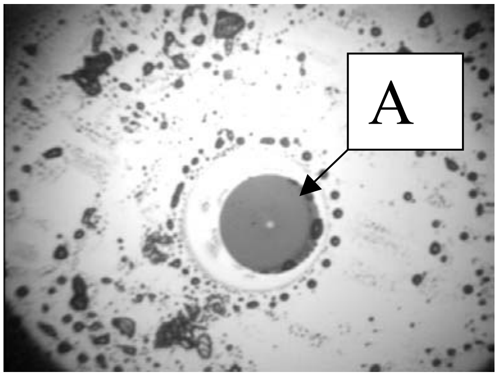
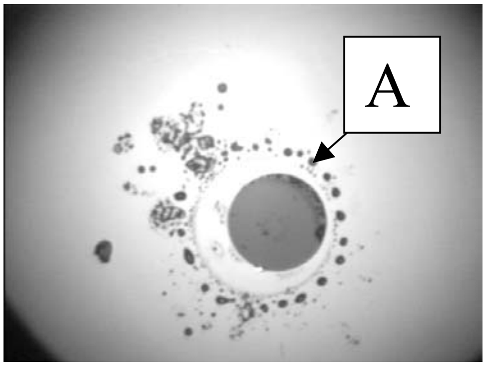


Figure 14. The typical images of contaminated test connector before the mating.



(a)



(b)

Figure 15. The typical fiberscopic images of the connector, contaminated with finger prints after mating with clean reference connector (a), fiberscopic image of the reference fiber after mating with oil contaminated fiber (b). IL (clean connector)-1550nm/1310 nm= 0.22dB/0.27dB, RL (clean connector)-1550/1310nm= 58.1dB /56.9 dB,
IL (contaminated connector)- 1550nm/1310 nm =0.23 dB/0.27 dB , RL (contaminated connector)-1550 nm/1310 nm=41.2/39.8 dB

Usually, before mating with the reference connector, the location of the oil contamination has a 2-D random distribution. Small oil drops of 2-60 µm in size covered the core, cladding layer and ferrule as shown in Figure 14. The oil distribution was changed after the mating with clean test connector as shown in Figure 15 (a), the contamination having been transferred partially from the test connector to the reference connector. The circle area A made from the oil drops was clearly identified after de-mating the contaminated connector with the test fiber. The estimated diameter of the area was approximately 182+/- 2um; furthermore the fiberscopic image did not reveal oil drops located at the core and close to the core cladding area. The oil drops were re-located from the core/cladding area to the location outside of A after mating with the reference connector. The reference connector became contaminated as shown in Figure15 (b).

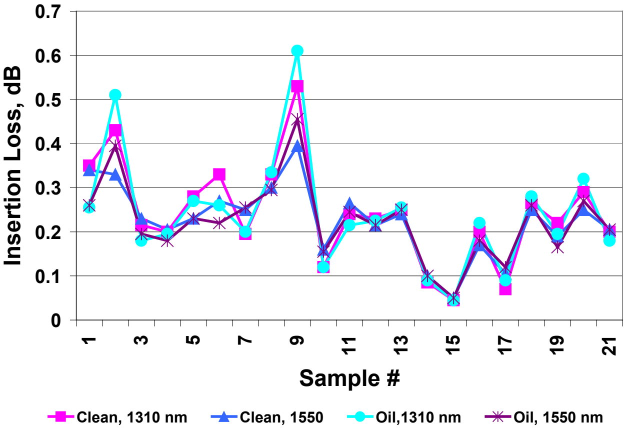


Figure 16. The IL measurements for clean and contaminated at λ= 1550nm/1310 nm

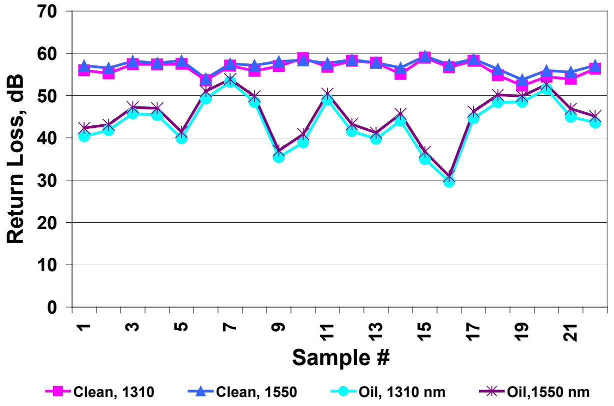


Figure 17. The RL measurements for clean and contaminated connectors at 1550nm/1310nm

The IL measurements for clean and oil-contaminated connectors are shown in Figure 16. The average IL for group of clean connectors was 0.24 dB for 1310 nm and 0.23 dB for 1550 nm. The group of contaminated connectors has an average IL of 0.24 dB at λ= 1310 nm and 0.23 dB at λ= 1550 nm. Based on our results, the oil contamination didn't affect the IL of the connector; however the application of oil contamination resulted in a significant decrease of the RL as shown in the Figure 17.

The average RL was decreased from 56.37 dB to 43.64 dB at λ= 1310 nm and from 57.18 dB to 45.15 dB at λ= 1550 nm. It is important to note that the standard deviation was significantly higher for the group of contaminated connectors than the group of clean connectors.

Based on our results the oil contamination has a significant effect on RL and causes only a small change in IL. The reflective index of the finger prints (oil) is 1.4602 [11]. It was shown that the reflective index of polished silica varies between 1.46 and 1.6 [12]. It was found experimentally that the reflective index of the high-index polished fiber core fiber core is 1.476 [13]. The small difference (0.0158) between the reflective indices of finger prints and fiber indicates that the behavior of oil contamination is similar to the behavior of the reflective index matching material. It is known that index matching material is applied to fill the gap between the two fiber end faces to reduce the Fresnel reflection due to the discontinuity in propagation medium. This idea can explain why IL didn't change after the application of oil contamination. The reflectance of perpendicular optical fiber connectors employing index matching material was discussed in [13], where it was shown that the RL depends on the high index layer thickness of the polished connector as well as by the gap and the reflective index of index matching material. Further development of the mathematical model for the oil contamination is a needed research direction.

BERT MEASUREMENTS

The first order statistics of the results are shown in Figure 18, where the average BER for each group is plotted versus the input power. As the graph shows, the group containing scratched fiber reveals a BER curve that is almost superimposed on the clean fiber group, suggesting that there is little effect from the scratches under consideration. On the opposite side, the other two groups, contaminated 1 (particles) and oil, resulted in degraded BER over the clean group.

Similar conclusions can be drawn from the second order statistics of the results. As seen in Figure 19, Std. Dev. BER vs. Power, the oil group exhibits a larger variance than all other groups, which can evidentiate the fact that oil based contamination has a more pronounced impact than the other contamination groups investigated. The remaining groups (clean, contaminated 1 and scratches) have identical variance curves. One possible interpretation of this behavior is that other factors (for instance the end face geometry of the connector) can be the dominant ones and not the contamination. In other words, the effects of the scratches and contaminants 1 could not be clearly separated from the effects of the geometry factors, which are more pronounced.

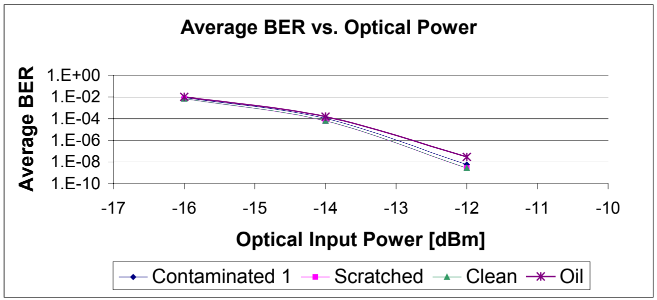


Figure 18. The dependence of average BER from Optical Input Power

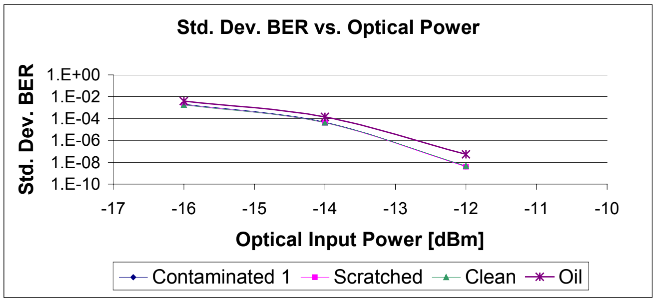


Figure 19. The dependence of BER standard deviation from Optical Input Power

One interesting perspective of the results can be obtained by investigating the correlation between the BER and the input power to the reference receiver. As seen in Table 1, the correlation coefficients between the power and BER vectors result in the high range, 0.84 to 0.85, revealing underlying mechanisms by which BER and the power are correlated. Similar conclusions can be drawn from the coefficient of determination, shown in Table 1.

Table 1. The correlation and determination coefficients between the power and BER vectors

	Correlation BER - Pwr	Coefficient of determination
BER@-12dBm	-0.84	71%
BER@-14dBm	-0.86	73%
BER@-16dBm	-0.84	71%

The squared correlation coefficient is called the coefficient of determination. The magnitude of the coefficient of determination indicates the proportion of variance in one variable, explained from knowledge of the second variable. Multiplied by 100, this proportion of variance indicates the percentage of variance that is known, accounted for, determined. The coefficient of determination is the primary information measure within the general linear model. Correlation of 0.86 explains 73 percent of variance and this brings a particularly interesting note: the BER that was measured in our experiment is, to a very large degree, the reflection of the input power to the optical receiver, which in turn its variability dictated by the IL of the sample under test. Furthermore, the prevalent mechanism by which contamination affects the BER of a simple optical transmission system, as the one considered herein, appears to be the IL created by the contaminant. This conclusion has a strong impact on the overall investigation, since knowing the effects of the contamination over the IL then the BER can be predicted based on the correlation between two variables, which graphically is reflected in the scatter plot in Figure 20.

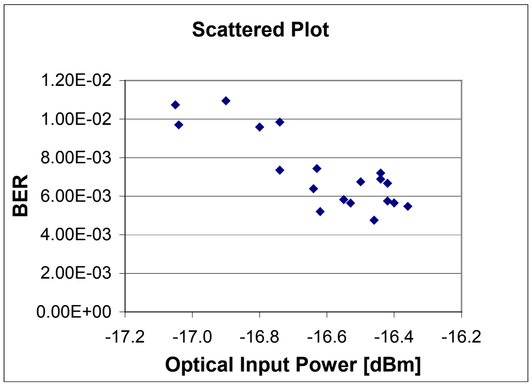


Figure 20. BER dependence from Optical Input Power for clean and scratched / contaminated connectors

CONCLUSIONS

The influence of scratches, particles and oil contamination of simplex SC connectors was investigated via IL, RL and BERT measurements. It was shown that:

- Polishing scratches and scratches made during connector cleaning, outside the fiber MFD, have no impact on IL & RL of the mated optical connectors.
- 2um wide or less scratches within the mode field diameter, have no impact on IL; the IL change observed is within the measurement uncertainty of the test equipment.
- Scratches within the fiber MFD can degrade the RL of the mated connectors.
- The scratches located in the cladding layer show little effect on BERT results.
- The level of degradation depends on the size (width and depth) and the number of scratches crossing the fiber MFD.
- The particles on the core resulted in catastrophic failures while the presence of particles on the ferrule did not show any degradation of its performance.
- Application of the oil contamination resulted in significant changes of RL (10-12 dB) and didn't result in any significant changes of IL.
- Results can be explained by considering the oil as index matching material.

- The groups of connectors with particles and oil contamination show significant degradation in BERT performance.

The development of mathematical modeling for scratches, particles and oil contamination is the subject of the further research. Future studies will also investigate the effects of particles when they locate at the cladding (and close to the core) area as well as focusing on particle size, quantity and different particle types.

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