Ultra-Low Loss (ULL) Interconnects – supporting advancements in Quantum Photonics

Quantum photonics has emerged as a rapidly advancing field with enormous potential for various applications including quantum computing, quantum cryptography, and quantum communication. As the demand for efficient and reliable transmission of quantum information increases, the role of fiber optics connectors becomes more critical. The purpose of this white paper is to provide an overview of the results of Diamond's efforts to develop a class of ultra-low-loss connectors that can help quantum photonics players improve the efficiency of emitters, detectors and other components, thereby facilitating the development of robust quantum technologies.

1. Introduction

The unique characteristics of quantum signals, such as entanglement and superposition, make them highly susceptible to environmental disturbances. The success of quantum applications thus depends on reliability of the transmission and manipulation of single photons. Ultra-Low Loss fiber optics connectors play a key role in this context, serving as the crucial link between quantum devices. Standard connectors may introduce significant losses, compromising the fidelity of quantum communication. Ultra Low-Loss connectors address this challenge by minimizing signal degradation and maintaining the integrity of quantum states.

2. Fiber optics connectors in quantum photonic

Quantum applications demand components that combine precision, durability, and high performance to function reliably under extremely specialized conditions. Diamond's E-2000® and Mini AVIM® connectors stand out as industry-leading solutions due to their exceptional optical performance, robustness, and adaptability even when subjected to challenging environmental factors. The E-2000® is particularly renowned for its integrated shutter mechanism, which protects the fiber end-face from contamination and damage, ensuring consistent performance over time. On the other hand, the Mini AVIM® is highly valued for its compact, lightweight design combined with rugged reliability, making it the connector of choice for challenging environmental conditions such as extreme temperatures and vibrations.

Additionally, Diamond's Vacuum Feedthrough provides a critical interface solution for quantum systems operating under ultra-high vacuum (UHV) and cryogenic conditions. Designed to enable precise and efficient light transmission across vacuum barriers, this feedthrough ensures minimal signal loss and optimal performance when integrating optical components into quantum environments. Diamond's advanced technology and engineering ensure that these solutions meet the stringent demands of quantum research and development, offering unmatched reliability and optical precision.

3. The causes of insertion loss

The optical performance of a connector can only be guaranteed by controlling several parameters such as:

- Ferrule properties: diameter, form and precision hole diameter and concentricity;
- Polishing parameters;
- End face imperfections (scratches, pits and contamination);
- Lateral and angular misalignment of the fiber cores.

These parameters have to be measured and kept under control during the all manufacturing and assembly process.

Lateral misalignment is the most significant contributor to insertion loss in single-mode connectors. Fiber manufacturers typically specify a core-to-cladding eccentricity of max. 0.5 micrometers and a cladding diameter precision within ±1 micrometer.

State-of-the-art ceramic ferules available on the market offer precision holes with 1 micrometer tolerance above nominal fiber cladding diameter and eccentricity value within 0.5 microns, thus leading to a worst-case lateral misalignment of the fiber cores in regard to outer ferule diameter of up to 2 micrometers.

While orientating the connectors towards each other can mitigate the impact of core misalignment, it is not possible to entirely get rid of it. As a result, even low-loss connectors may therefore show a residual loss of potentially 0.2 to 0.3 dB.

For this reason, taking an approach that aims to reduce, if not completely void, these intrinsic residual deficiencies in the materials used is the way forward for to achieve ULL performance.

4. Diamond's ferrule and active core alignment

Diamond has introduced an innovative termination method that actively places the core precisely in the ferrule center. In contrast to ceramic ferrule designs, Diamond's method utilizes a two-component element comprising a tough zirconia ceramic sleeve and a malleable titanium insert. Precision-ground and lapped to a tolerance of 0.2 µm or less, these ferrules intentionally have overdrilled bores, typically 127 micrometers for standard 125 micrometers fibers. A circular crimping tool with a wedge profile then plastically deforms the titanium insert in order to adapt the bore diameter to the diameter of the fiber. After the fiber has been mounted into the ferrule, another crimping tool is used to plastically deform the insert and to shift the fiber and thus reduce the core eccentricity to less than 0.125 micrometers. This is achieved thanks to a real time computer assisted eccentricity measurement setup. The active core alignment process offers precise positioning, reducing fiber pistoning (axial displacement of the optical fiber within the ferrule) and enhancing thermal stability. Furthermore, this approach eliminates the need for meticulously sorted ferrules to accommodate cladding diameter variations, offering a more reliable and efficient alternative to unaligned ferrules.

This technology allowed Diamond to launch the 0.1 dB class of connectors that did revolutionize the market for telecom fiber optics connectors more than 20 years ago.

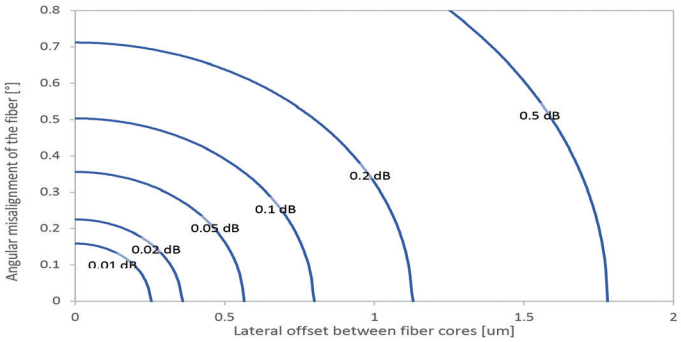

Figure 1: Contour lines showing the theoretical influence of lateral and angular misalignment on the insertion loss of single mode connectors.

5. The path towards Ultra-Low Loss connectors

By leveraging their extensive experience with this proprietary technology, and taking into account the customers' specific requirements, particularly in the field of quantum photonics, Diamond has recently improved its unique active core alignment process to achieve lower losses. This has been achieved by reducing manufacturing tolerances, taking advantage of the latest advances in imaging systems and introducing a new alignment software that enables the operators to work in a highly accurate, reproducible and repeatable manner.

With the new process, Diamond is able to manufacture single mode E-2000® connectors with average insertion losses as low as 0.017 dB in random mating measurements, and a max value of 0.04 dB on 95% of the connections[1].

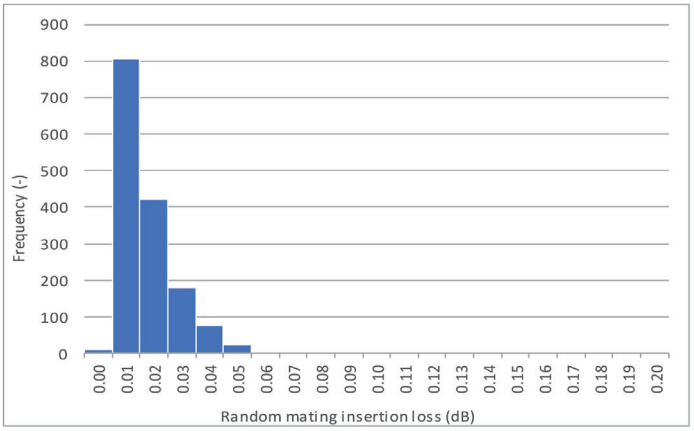

Figure 2: Random mating insertion loss measurements at 1550 nm on a batch of 40 E-2000® Ultra-Low Loss connectors.

The Ultra-Low Loss technology is not limited to a specific wavelength. While typical applications focus on 1550 nm, the technology has demonstrated excellent performance across non-standard wavelengths, such as visible light. To validate its reliability and determine the achievable optical losses, extensive testing has been conducted on different types of fibers and at different wavelengths. These tests provide critical data for assessing the technology's adaptability and ensuring optimal performance in diverse applications.

The test results are summarized in the table below:

FIBER NAME	FIBER TYPE	MEASUREMENT WAVELENGTH (nm)	AVERAGE IL (dB)	MAX 95% IL (dB)
Ultra-low loss fiber (compatible with G.652.D)	SM	1550 nm	0.017	0.04
Corning SMF-28e+	SM	1550 nm	0.034	0.07
Nufern 780-HP-HYT-BK	SM	800 nm	0.057	0.10
Fujikura SM.15-P-8/125	PM	1550 nm	0.050	0.09
Thorlabs UHNA3 (ultra high Na)	SM	1550 nm	0.070	0.15

Table 1: Results of random insertion loss measurement on Diamond's ULL connectors on different fiber types.

Each specific configuration requires a distinct process that leads to different results. Diamond's team of experienced engineers is ready to discuss tailor-made solutions with customers aiming at defining the products that best suit their specific needs.

[1] Prodution data for ULL connectors assembled using a singlemode fiber at 1550nm.

6. Measurement uncertainties

The result of insertion loss measurements is highly influenced by major measurement uncertainties (quality of reference connector and adapters, variations in fiber mode field diameter, uncertainties related to the measurement instrument) and cannot therefore be used as the unique criteria for the definition of performance grades for optical connectors. This is especially true for Ultra-Low Loss connectors, since their insertion loss values are in the same order of magnitude of the measurement uncertainty. For this reason, the measurement of insertion loss should be treated as a mere statistical representation of a batch of random mated connectors, and not as absolute values of individual connectors.
Since the most significant parameter affecting attenuation is the lateral misalignment of the fiber cores, the performance of a batch in a random mating measurement can be guaranteed by maintaining specified limits on this parameter, which is rigorously taken under control and measured at 100% during the termination process.

7. Other technologies

For quantum applications, Diamond offers a range of other relevant technologies that address specific needs. Power Solution connectors are designed for high power applications, ensuring reliable performance under demanding conditions. Diamond also specialize in polarization maintaining, enabling precise control and manipulation of light polarization in quantum systems. When it comes to high and very low temperature environments, such as cryogenic applications, Diamond's connectors are designed to withstand extreme conditions while maintaining optimum performance. Diamond's technologies perform - exactly where you need them to.

8. Conclusion

As quantum photonics continues to advance, the importance of Ultra-Low Loss (ULL) fiber optics connectors will be further emphasized. Fiber optics and connectors are more than simple contributors - they are enablers of transformative quantum technologies, embodying the essential link between theoretical understanding and real-world quantum applications. Diamond's experience and willingness to always stay at the front of development put us in a position to best meet customers' needs and help them pave the way for the realization of advanced quantum technologies.

About Diamond

Diamond SA is an international company with a solid know-how in the design, manufacture and assembly of components for precision optical fiber optical components. Diamond is known for its repeatable very low insertion loss through the use of its patented Active Core Alignment technology. Diamond SA is also the inventor of the globally established E-2000® connector.
To find out more about Diamond's connectors and technologies, please contact +41 58 307 45 45 or visit www.diamond-fo.com.