Advancements in Quantum Photonics: The Crucial Role of Ultra Low Loss (ULL) Fiber Optics Connectors

Abstract *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 crucial. This white paper aims to provide a glance at the latest advancements in Diamond's effort to decrease connection losses in single-mode fiber connectors, so as to provide players in the field of quantum photonics with a new class of Ultra Low Loss connectors that can assist them to improve the efficiency of coupling of quantum emitters, detectors, and other components, 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. Application of fiber optics connectors in quantum photonic

Fiber optics and connectors are used in many fields of quantum photonics. Some use cases are cited below:

- Quantum Communication: Fiber optics enables long-distance, high-speed quantum communication, allowing the transmission of quantum states and quantum information reliably and securely.
- Quantum Computing: Fiber optics is essential for interconnecting qubits in quantum computing systems, enabling high-speed data transfer and efficient quantum information processing.
- Quantum Sensing: Fiber optic sensing systems are utilized in quantum sensing applications for accurate measurements of physical quantities, such as magnetic fields or gravitational waves, with high precision and sensitivity.
- Quantum Key Distribution (QKD): Fiber opticsserves as the medium for secure quantum communicationthrough QKD protocols, ensuring the distribution of cryptographic keys with ultimate security.
- Photon Counting: Fiber optic interfaces are integral to photon counting applications, enabling the detection and measurement of individual photons for quantum ex periments and precise quantum information processing.

Typical connectors used in quantum applications include Diamond's E-2000® and Mini AVIM®, known for their reliability and performance, even under the very specific operating conditions, such as those recurring in this field of application. In addition, Diamond's Vacuum Feedthrough serves as an ultra-high vacuum and cryogenic system, enabling seamless integration into quantum setups.

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 0.5 micrometers and a cladding diameter precision of 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 to 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 will 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 seems 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 polished to a tolerance of 0.5 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 over 20 years ago.

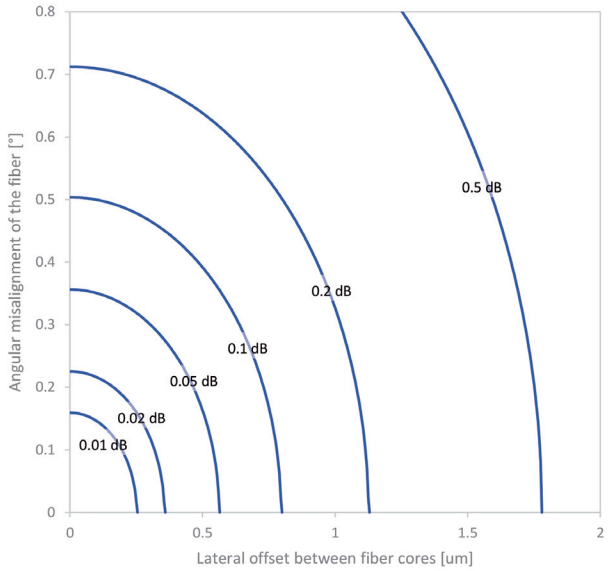

Figure x: Contour lines showing the theoretical influence of Lateral and angular misalignment on the insertion loss of single mode connectors.

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 recently improved their active core alignment process to yield lower losses. This result was achieved by reducing manufacturing tolerances, taking advantage of recent advancements in imaging systems and introducing a new alignment software that enables the operators to work in a very precise and reproducible way. With the new process, Diamond was able to manufacture single mode E-2000® connectors with average insertion losses as low as 0.045 dB in random mating measurements, and a max value of 0.06 dB on 95% of the connections[1].

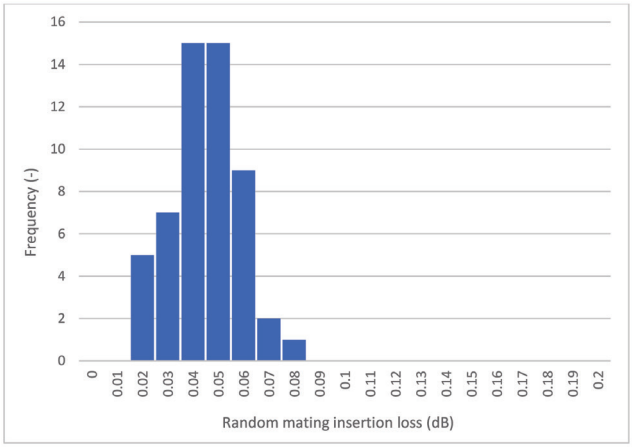

Figure x: Random mating insertion loss measurements at 1550 nm on the first prototypes of E-2000® Ultra Low Loss connectors (SMF-28e+ fiber).

The results are highly dependent on the fiber, wavelength and connector type. Furthermore some prototypes using a 1550 nm polarization maintaining fiber were manufactured. In this configuration it was possible to produce connectors with an average IL of 0.05 dB on random mating and a max value of 0.09 dB on 95% of the connections, while still yielding very high polarization extinction ratio values. Low wavelength fibers are more critical, as the losses increases exponentially with the decrease of the mode field diameter. By interpolating the results that were achieved at higher wavelength, the following distributions can be estimated:

- 630 nm: mean of 0.15 dB on random mating, with a max value of 0.25 dB on 95% of the connections;
- 780 nm: mean of 0.11 dB on random mating, with a max value of 0.18 dB on 95% of the connections.

Every specific configuration does require a different process and yields different results. Diamond's experienced engineering team is ready to discuss with customers about tailor-made solutions and to develop the products that would best fit their unique requirements.

[1] *Preliminary data derived from prototypes assembled using SMF-28e+ fiber @ 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 serve as more than simple contributors - they stand as 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, manufacturing and assembly of components for precision optical fibers. Diamond is known for their repeatable very low Insertion Loss due to usage of their patented Active Core Alignment Technology. Diamond SA is also the inventor of the world-famous 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.