Dust Insensitive, Low Loss, and Low Mating Force Multi-Fiber Expanded Beam Optical Ferrule and Connectors

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Abstract: A new, multi-fiber, expanded beam optical ferrule, with state-of-the-art IL<0.7 dB (typical 0.34 dB), RL>55 dB for single mode (1310 nm), and IL<0.3 dB (typical 0.14 dB), RL>40 dB for multimode (850 nm), is reported. © 2024 The Author(s)

1. Introduction

A new family of multi-fiber expanded beam fiber optic (EBO) connectors [1-5] is emerging to satisfy the exploding optical interconnect demand for data centers (DCs), 5G, supercomputing, and high-performance AI servers. EBO connectors have advantages include improved resistance to dust, low mating force, high repeatability, and easy operability compared to traditional physical contact (PC) connectors. The PC connectors, including both the single fiber and multi-fiber ones, directly mate the polished fiber facets, which require high mating force to assure the seamless closing of the fiber facets with a polished convex profile. The beam spot in such facet-to-facet coupling is close to the size of the core of the fiber, which is only about 9.2 µm at 1310nm for standard single mode (SM) fibers. Dust particles and other contaminants can cause problems for SM PC connectors, such as high losses, unstable signals and possibly damages to the fiber facets. In addition, the SM PC connectors require tight tolerances at the connector level. In stark contrast, EBO connectors use micro-optic elements such as micro-lenses or micro-mirrors to generate much larger beam spots. As such, these expanded beam connectors can considerably relax the tight tolerancing requirements at the connector level, and are much less sensitive to the similar dusts.

In terms of how the light is steered by the micro-optics element of an expanded beam ferrule, there are two types of expanded beam connectors. One type of EBO connector is straight-through, where the light propagates through the micro-optics element in a direction close to the fiber direction [5]. The other type of EBO connector is light-turning, where the light is turned by an angle typically close to 90 degrees with respect to the fiber direction [6, 7]. While the straight-through version may be well-suited for fiber optic connectors with the benefits from the expanded beam optics, the light-turning version may also align well with the chip-level coupling needed for silicon photonics, VCSEL, and co-packaged optics (CPO) chips [6-8].

Here, we report a new type of injection-molded, light-turning, multi-fiber, low insertion loss (IL), high return loss (RL) optical fiber connector based on an expanded beam optical unibody ferrule, which has grooves for hosting the fibers, total internal reflection (TIR) micro-optic elements, and mating features in one piece.

2. Mechanical and optical design

As the mating features are monolithically integrated on the ferrule at the tooling and fabrication level, the reported EBO ferrule does not need external guide pins for controlling the ferrule level mating. Although the larger beam spot of the EBO ferrules doesn't require tight tolerances at the connector level, it does require ultra-high precision at the ferrule level. This precision is achieved using a fabrication process that allows sub-micron tolerances to be maintained between the fiber grooves and micro-optics elements. Furthermore, the ferrule design reduces fiber termination complexity and cost by using a fully automated, high precision fiber attachment and UV bonding process. The ferrule design and the fiber attachment process doesn't require fiber facet polishing. Fig. 1(a) shows such a 12-fiber SM EBO ferrule.

The mating of the EBO ferrule is fiber curve assisted, i.e., the 12 fibers are curved to generate forward and normal forces to mate a pair of ferrules together, as shown in Fig. 1(b). To hold the fibers in the connector cassette, a retainer is bonded to the fibers with UV adhesive. Critical ferrule-to-ferrule alignment is achieved using a pin and socket design in which the nose of the ferrule is aligned by the socket in the back of the mating ferrule. This design allows for reliable mating even with significant initial misalignment of the ferrules. In addition, the mating features in the fiber direction allows for hermaphroditic mating, eliminating the need for separate male and female connector genders.

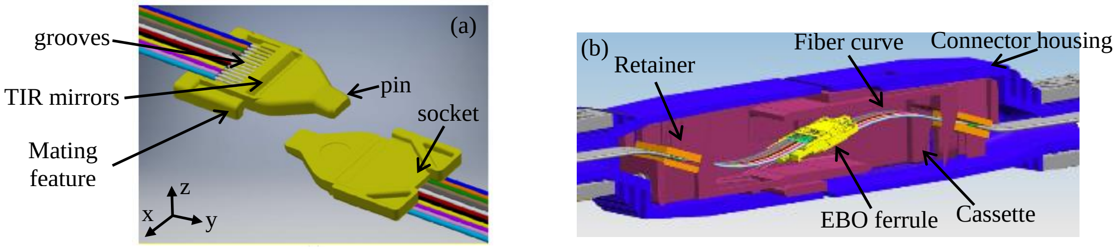

Fig. 1. EBO ferrule and connector. (a) A 12-fiber SM EBO ferrule; (b) Section view of a pair of mated EBO ferrules with fiber curve assisted mating in the connector.

The mating force at the ferrule level is less than 1 N/(ferrule pair). At the connector level, the overhead mating force is on the order of 6 N/(connector pair), in order to guarantee the ferrule cassettes are firmly mated and to provide sufficient tactile feel for insertion of the connector into its adapter. High fiber count connectors (144 fibers) can also be realized with twelve 12-fiber suspended ferrules and such connector pairs can have a mating force of only 13N.

The optical design of the EBO ferrule, as is illustrated in Fig. 2(a), is aimed to achieve IL < 0.7 dB and RL > 55 dB for SM operation. The light coming out of the fiber propagates toward the mirror at an incident angle of 46.5 degrees, like an off-axis parabolic (OAP) mirror. The light expands to a larger beam spot on the mirror and then gets total internally reflected and reshaped by the TIR mirror. In other words, the Gaussian beam waist at the fiber facet is imaged and magnified by 8 times by the TIR mirror to the output side of the EBO ferrule, exactly in the middle of the two mated ferrules, which is referred to as the output beam waist plane.

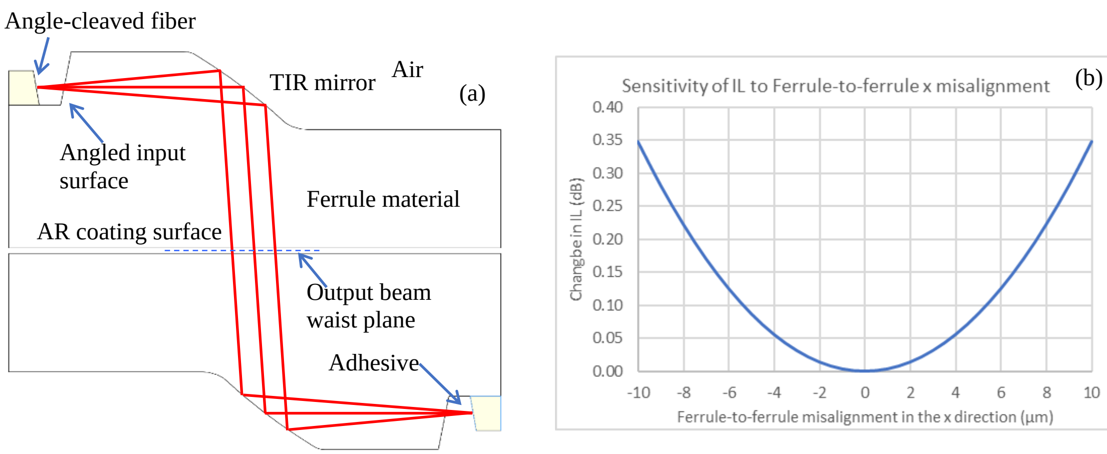

Fig. 3. (a) Schematic optical design of SM EBO ferrule. (b) Sensitivity of IL with respect to ferrule-to-ferrule lateral misalignment in the x direction

While the low ILs are achieved by the unibody design, tight tolerancing control to the sub-micron level, and optimized AR-coating at the target operating wavelength of 1310 nm, the high RL > 55 dB is realized by the angled fiber, index-matching adhesive, the tilted input surface, and the non-right-angle TIR (in other words, the output beam is tilted with respect to the bottom surface of the ferrule, such that any reflections there will not go back to the input fiber).

The EBO beam is magnified about 8 times from the SM fiber, which results in a beam spot about 74 µm at $1/e^2$ of the peak intensity. This expanded beam size is chosen to achieve good sensitivity to ferrule-to-ferrule misalignments like lateral shifts and tilting, to achieve a small size of the ferrule, and to avoid light clipping by the lenses and channel-to-channel crosstalk. To illustrate the effectiveness of the expanded beam concept, the sensitivity of the IL to the ferrule-to-ferrule lateral misalignment in the x direction is plotted in Fig. 2(b). As compared to the traditional SM PC connectors, which is known to have a loss increase of about 0.25 dB when the mating fibers have a lateral offset of 1 µm, the EBO connectors are much more tolerant of the lateral misalignment.

By studying the IL sensitivities of the major alignment variables, including the fiber-to-ferrule and ferrule-to-ferrule lateral and angular misalignments and considering molding and tooling tolerances, it is predicted that a single mode IL specification of less than 0.7 dB can be achieved with a yield of 99%.

3. Optical characterizations

The SM EBO ferrules have been massively and repeatably molded and terminated at the internal pilot production lines. Fig. 3 (a) and (b) show the histograms with accumulative frequency of recently manufactured SM samples.

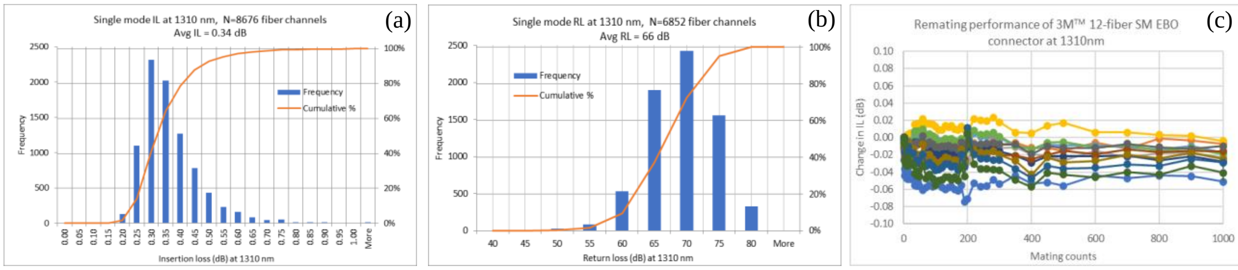

Fig. 3. Histograms with accumulative frequency of 12-fiber SM EBO samples: (a) IL of 723 samples; (b) RL of 571 samples. (c) IL change in a durability and repeatability test of a pair of SM EBO connector. The 12 colors stand for the 12 fiber channels.

From the data, it is shown that about 99% of the channels have IL< 0.7 dB, and RL > 55 dB at 1310 nm. The average IL and RL at 1310 nm is about 0.34 dB and 66 dB, respectively.

The mating durability and repeatability of a SM connector pair is tested and demonstrated in Fig. 3(c). During 1,000 mating cycles and without cleaning during the test, the IL variation is less than 0.1 dB across all 12 fibers channels. The mating durability and repeatability test demonstrates that the ferrule pin and socket features provide robust ferrule-to-ferrule alignment without the needs for external guide pins. This high durability and repeatability without the need for cleaning gives rise to significant benefits for cabling, maintenance and operations for DC operators.

High performance multimode (MM) connectors can also be manufactured with the new EBO ferrule design. MM samples manufactured for 850 nm operation can achieve IL < 0.3 dB with an average of about 0.14 dB, and RL > 40 dB, which is of great importance for the signal integrity at high data rate.

4. Conclusions and outlooks

In summary, a new 12-fiber, injection molded, EBO ferrule suitable for use in high performance SM and MM fiber applications has been demonstrated. The SM EBO connectors with 1310 nm optimized AR-coating have repeatably achieved IL < 0.7 dB with a typical value of 0.34 dB, and RL > 55 dB. Using the same ferrules with 850 nm optimized AR-coating, the MM EBO connectors can constantly achieve IL < 0.3 dB with a typical value of 0.14 dB, and RL > 40 dB.

These new EBO ferrules with low IL and high RL provide several advantages including reduced dust sensitivity, high mating repeatability and durability, low mating force, and allow for automated fiber to ferrule termination. The new EBO ferrule can be deployed in a number of connector designs including single ferrule latched connectors, MPO adapter compatible single ferrule connectors, and multi-ferrule high fiber count connectors. The development of a family of other EBO ferrules and connectors, for example EBO ferrules with different fiber counts, is under way.

5. References

[1] D. Childers, M. Hughes, T. Satake, “New single-mode, multi-fiber, expanded-beam, passive optical interconnect,” Proceedings of the SPIE, Optical Interconnects XIV, Vol. 8991, March 2014, pp. 89910J.
[2] D. Childers, J. Graham, M. Hughes, S. Lutz and T. Satake, "Multi fiber connector technologies," *2015 Optical Fiber Communications Conference and Exhibition (OFC)*, Los Angeles, CA, USA, 2015, W4B.4, pp. 1-4.
[3] S. Yakabe, T. Hosokawa, H. Arao, D. Sasaki and T. Shimazu, "Dust Insensitive Single Mode Multi Fiber Connector with Expanded Beam," *2019 Optical Fiber Communications Conference and Exhibition (OFC)*, San Diego, CA, USA, 2019, W2A.14, pp. 1-3.
[4] A. Tonini, V. Coggi, “Modular lensed-ferrule solution for single-mode fiber connectors,” Proc. SPIE 11286, Optical Interconnects XX, 112860G (28 February 2020).
[5] M. Kadar-Kallen, D. Jurtz, S. Lutz, D. Schoellner, K. Wang, D Fortusini, R. A. Modavis, "Single-Mode Expanded Beam MT Connector with Angled Lens Array for Improved Optical Performance," *2022 European Conference on Optical Communication (ECOC)*, Basel, Switzerland, 2022, pp. 1-4.
[6] D. Schoellner, S. Lutz, K. Wang, D. Kurtz, T. Kerr, M. Wang, “A Mechanical-Optical Interface for 25+ Gbps VCSEL/PD Fiber,” Photonics West Optical Interconnects XVII, SPIE, 10109 (2017).
[7] M. Hughes, J. Graham, D. Schoellner, D. Childers, E. Childers, and A. Ugolini, "Miniature Detachable Photonic Turn Connector for Parallel Optic Transceiver Interface," in Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2011, OSA Technical Digest (CD) (Optical Society of America, 2011), paper NTuA4.
[8] T. Kumagai, T. Nakanishi, T. Hayashi, K. Takahashi, M. Shiozaki, A. Kataoka, T. Murakami and T. Sano, "Low-Loss and Highly Reliable Low-Profile Coupler for Silicon Photonics," *2019 Optical Fiber Communications Conference and Exhibition (OFC)*, San Diego, CA, USA, 2019, W2A.2, pp. 1-3.