Optical frequency transfer over deployed multi-core fiber with 10^{-18} stability at 1000 seconds

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Stabilized bi-directional optical fiber links allow comparisons of state-of-the-art optical clocks over 100s of kilometers. One hurdle in stabilizing deployed fiber links is the uni-directional nature of data traffic of telecommunications networks prevent using a back-reflection signal to stabilize the link, requiring circumvention of telecom hardware or the use dark fiber. A potential solution is the utilization of multi-core fiber (MCF)[1]. MCFs increase the data transmission capacity of long-haul fibers, and plans are currently underway for its sub-sea deployment [2]. Importantly for time and frequency transfer, different cores can be used in different directions for both data traffic and stabilized light, and environmental noise is highly correlated among the cores. Here we demonstrate stabilization of a deployed MCF at a level capable of supporting the best optical atomic clocks. Two cores are used to achieve forward and backward propagation without requiring bi-directional propagation along a single core.

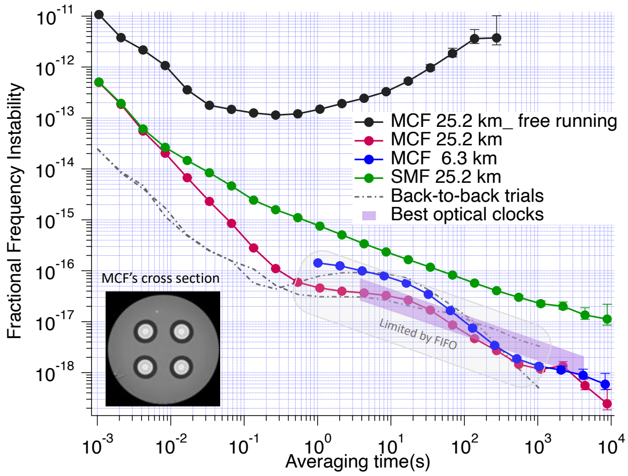

Fig. 1: MDEV plot of the deployed 4-core MCF and SMF28 duplex, showing the capability of MCF for transferring optical clock signals.

We performed a series of experiments over a deployed MCF test bed located under the city of L'Aquila, Italy. The link consists of 4 segments of uncoupled 4-core MCF, each 6.3 km long, with 25.2 km maximum link length, starting and ending in the same location. We performed optical frequency transfer by launching cavity-stabilized light at 1550 nm over the link. The light at the "local" end is shifted with an AOM by 100 MHz and sent over core1. At the "remote" end of 25.2 km link, some of the light is sent back through a different core for stabilization (core2). A beat is generated between the returned shifted light and the source laser and used for stabilizing the fiber link. To evaluate the performance of the link, we measured the beat between the light at the remote end and the direct output of the source light. By tracking this beat-note phase, we calculated the modified Allan deviation (MDEV) of 25.2 km MCF link as shown in Fig. 1. The MCF clearly supports the transfer of the best optical clocks. Back-to-back data, where the MCF is removed, shows that the performance of MCF link between 10-1000 second is limited by the noise from fiber pigtails, predominately those of the fan-in fan-out (FIFO) devices used to interface with MCF, and could be further improved. The large noise correlation between cores is shown by comparing to a 25.2 km link using SMF-28 fibers deployed along the same path as the MCF, where the return light for stabilization is sent over a separate fiber strand.

1. T. Hayashi, T. Taru, O. Shimakawa, T. Sasaki, and E. Sasaoka, "Design and fabrication of ultra-low crosstalk and low-loss multi-core fiber", *Optics Express*, vol. 19, no. 17, pp. 16 576–16 592, Aug. 2011
2. B. Quigley, M, Cantono, Google, September 12, 2023. https://cloud.google.com/blog/products/infrastructure/delivering-multi-core-fiber-technology-in-subsea-cables