Scalable end-to-end path length stabilization

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An approach for cascading conventional path length stabilization sections without the introduction of uncompensated paths is presented. The detection of the beat notes within each stage in the cascade is independent of the next stage, enabling to serve a large number of endpoints in complex network topologies. Furthermore, the concept[1] allows non-reciprocal elements such as unidirectional fiber amplifiers or phase-locked lasers for amplification and signal regeneration. These are the ingredients required for a scalable ultra-stable optical time and frequency distribution network.

Path length stabilization is crucial for precision metrology applications both via hundreds of kilometers long fiber links on a continental scale and for in-campus distribution (10 m - 1 km), e.g. of ultra-stable optical reference signals. A time and frequency distribution network should be scalable. In practice, scalability requires that the topology allows an addition or removal of end points without disturbing the other endpoints, which is the case in star topology networks, but not, e.g., in ring topology networks. Scaling requires cascading smaller sections, which can be conventional length stabilized path segments[2]. An end-to-end stabilization without uncompensated sections over the entire cascade is advantageous. The cascaded segments should be isolated in the backward direction, because otherwise the light reflected from all endpoints would ultimately reach the detector in the previous stage(s), disturbing there the detection of the individual beat notes. Addressing a scalable number of endpoints also requires signal amplification and regeneration. Conventional approaches require highly specialized reciprocal amplifiers, often introducing other problems such as parasitic lasing. Hence, unidirectional amplifiers would be advantageous.

The basic idea for end-to-end stabilized cascading is shown in Figure 1: The end mirror T1 of the first stabilized path segment equals the reference mirror S2 for the next segment in the cascade. The topology suppresses light travelling back to the preceding segment, with further suppression possible using polarization techniques. The source light field for the second segment can be derived from the signal in the first stage either by phase-locking a laser to it or by amplification in a unidirectional amplifier and phase-locking the amplification path to the reciprocal path. The beat note for this phase-lock is detected at a position (PD3 in Fig. 1) that enables phase-coherent unidirectional signal amplification or regeneration.

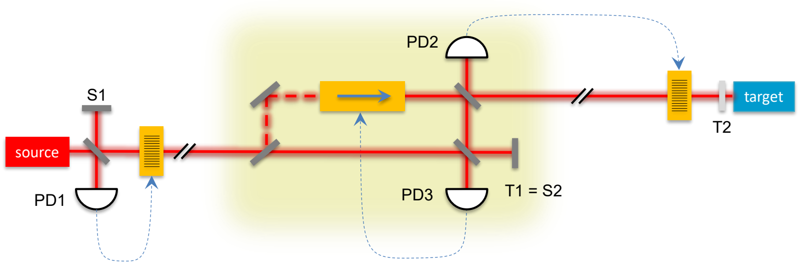

Fig. 1: Cascaded path length stabilization. The first segment stabilizes the phase between source mirror S1 and target mirror T1, the second segment between S2 and T2. A non-reciprocal element generates a light field for signal amplification or regeneration.

I will present this approach and discuss possible application scenarios, such as end-to-end stabilization between an ultra-stable cavity and an optical frequency comb.

[1] E. Benkler, German patent DE102022104332.

[2] P. A. Williams, W. C. Swann, and N. R. Newbury, "High-stability transfer of an optical frequency over long fiber-optic links," J. Opt. Soc. Am. B 25(8), 1284–1293 (2008).