Phase stabilization for next-generation long-distance quantum networks

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Tracking and stabilizing the optical phase over long-distance fiber infrastructure is crucial for next-generation phase-sensitive networking protocols. An additional challenge for quantum and faint-light networking is keeping the payload channel dark at the same time. Indeed, phase stabilization enables the so-called single rail entanglement distribution, that not only can drastically improve the rate of entanglement distribution but also enable key quantum repeater protocols. Those protocols were out of reach for practical networks because quantum compatible phase control was considered impossible. Indeed, a strong classical optical phase reference was required until now. That in turn introduces classical-to-quantum crosstalk: bright and broadband noise in quantum channels. Such a noise is not compatible with quantum signals.

Here, we demonstrate two distinct approaches to phase-stabilize a long distance quantum link: time-division multiplexed (TDM) phase stabilization that takes advantage of the quantum phase estimation and thereby needs just 650,000 photons per second at the receiving detector [1] and wave-division multiplexed (WDM) phase stabilization with picowatt-level signals, which keep the quantum payload channel dark and stabilized [2].

We use faint coherent light from an ultra-narrowband laser at 1550 nm to stabilize the 120 km optical fiber loop deployed between NIST (Gaithersburg) and UMD (College Park). An attenuated ultra-stable reference laser is time multiplexed (TDM) or used to generate a frequency comb (WDM). One arm of the interferometer carries the signal through a long optical fiber spool or a deployed fiber loop, while the other arm is used as a local oscillator.

TDM takes advantage of a displacement quantum phase estimation, i.e. when the reference signal is set to distructively interfere with the single-photon level reference signal. The success of such displacement is verified with a single photon detector such that even one photon detection suggests the need to adjust the phase. This technique outperforms an idealized classical phase measurement by 1.4dB in deployed fiber. WDM takes advantage of two teeth of a frequency comb and keeps the quantum channel dark with a minimal background of just 500 photons s^{-1}. In both schemes, we obtain phase stabilization with RMS timing jitter of ≈0.1 fs. In other words, a 120 km link is stabilized to within approximately 4 nm, or to a fraction of approximately 3×10^{-13}!

[1] M.V. Jabir et. al., Optica 12, 570–576 (2025) https://doi.org/10.1364/OPTICA.540759

[2] D. Ahn et al., Optica, 13, 511-518 (2026) https://doi.org/10.1364/OPTICA.586649