

Long-term phase stabilization for metropolitan-scale dark quantum channels

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Abstract: We employ a frequency comb to demonstrate a multiband wavelength-division-multiplexing (WDM)-based phase stabilization over a metropolitan-scale fiber link while maintaining a dark quantum channel. We achieve phase stability over 100 seconds, a four orders of magnitude improvement of the current state of the art.

Phase stabilization over long-distance quantum channels is crucial for realizing phase-sensitive quantum protocols. Because crosstalk significantly limits optical powers that can be used to probe phase in a quantum channel, conventional phase-locked loops cannot be used. Special techniques have been developed to stabilize quantum channels while minimizing photonic noise [1, 2]. Previously reported wavelength-division-multiplexing (WDM)-based approaches (e.g. [1]) exhibit residual phase noise in the quantum channel and thus rely partially on time-division multiplexing. Here, we introduce and demonstrate a WDM-based phase-stabilization scheme that employs two reference channels and keeps the target channel completely dark. The scheme achieves long-term stabilization over a metropolitan-scale fiber link. Furthermore, it enables simultaneous phase stabilization across multiple wavelength channels without launching additional references, providing a scalable platform for future quantum networks.

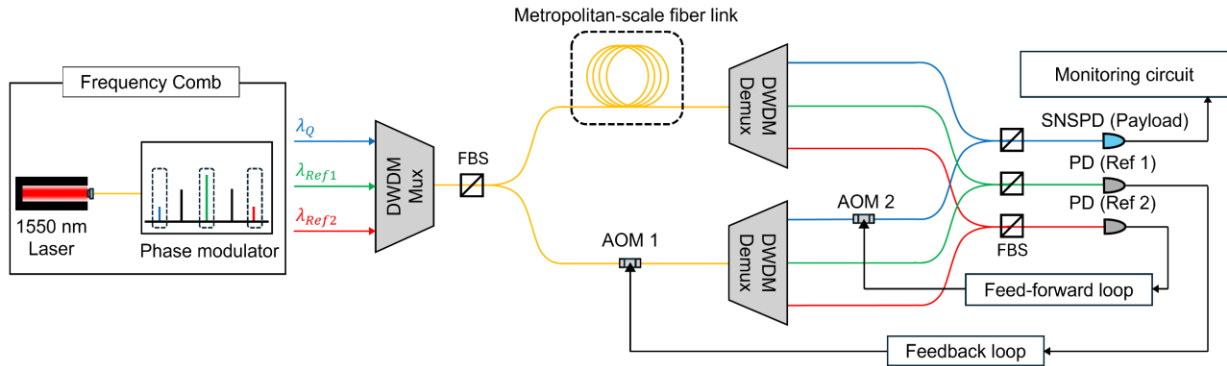


Figure 1. Experimental schematic of the triple-band wavelength-division-multiplexing (WDM) phase-stabilization system. A sub-Hz-linewidth 1550 nm laser combined with an electro-optic phase modulator generates a frequency comb. Three wavelengths ($\lambda_Q, \lambda_{Ref1}, \lambda_{Ref2}$) are selected using dense wavelength-division-multiplexing (DWDM) filters. After multiplexing, the combined signal is split into a long fiber link and a local oscillator (LO) arm, and each path is demultiplexed and recombined at beam splitters. Reference 1 is used for the common feedback loop, while Reference 2 provides a feed-forward correction for the payload (quantum) channel. Note that the payload channel is intended to be dark; here we use light at λ_Q to verify phase stability. AOM: Acousto-optic modulator, PD: Photo diodes, FBS: Fiber beam splitter, SNSPD: Superconducting nanowire single photon detector.

Figure 1 shows a schematic of the triple-band phase-stabilization experiment. A sub-Hz-linewidth 1550 nm laser combined with an electro-optic phase modulator generates a frequency comb. Three equally detuned wavelengths are selected using commercial dense wavelength-division-multiplexing (DWDM) filters. A fiber beam splitter (FBS) divides the optical signal, sending one part through a metropolitan-scale fiber link (100 km spool or 120 km field-deployed fiber) and the other to the local oscillator (LO) arm for phase referencing. At the output of both paths, 100 GHz DWDM filters separate the three wavelength channels, which are then recombined to form interferometers for phase measurement. Acousto-optic modulators (AOMs) placed in the LO path actively compensate fiber-induced phase noise with an 80 MHz offset frequency through feedback and feed-forward control signals.

The triple-band phase stabilization consists of two sequential stabilization steps. A common feedback signal derived from the reference 1 channel is applied to all three channels. Because the other two channels (reference 2 and payload)

are symmetrically detuned in frequency from reference 1, they exhibit residual phase fluctuations of nearly equal magnitude but with opposite drift directions under the linear approximation. In the experiment, the phase measured from reference 2 is inverted and applied to AOM 2 as a feed-forward correction, thereby stabilizing the payload channel without any time bin reference.

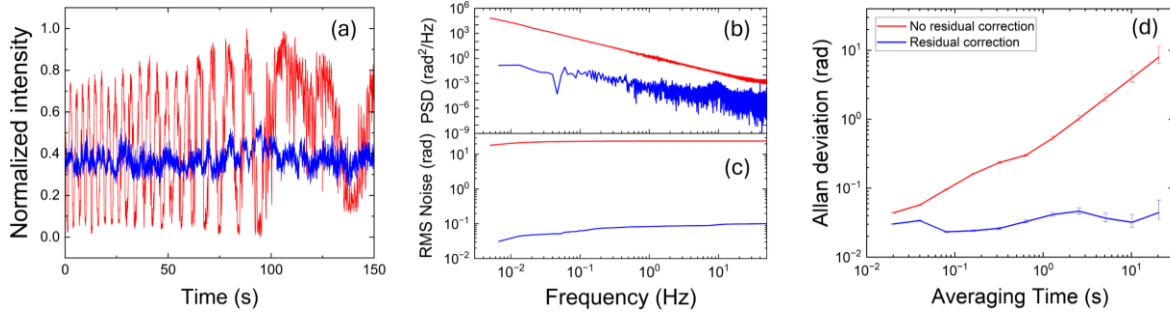


Figure 2. Phase-stabilization results over the 120 km deployed fiber link using the triple-band WDM scheme with feedback only (red) and with combined feedback and feed-forward correction (blue). (a) Normalized interference of the payload channel. (b) Power spectral density and (c) root-mean-square phase noise. (d) Allan deviation of the payload channel. Error bars indicate the 1- σ statistical uncertainty.

Figure 2 shows the measured interference in the payload channel for the 120 km field-deployed fiber with feedback only (red) and with combined feedback and feed-forward correction (blue). The 120 km deployed fiber link is partially stabilized with feedback alone but exhibits a unidirectional phase drift [Fig. 2(a)] mainly induced by environmental temperature fluctuations [3]. The interference under feedback-only operation appears cosine-like due to phase wrapping within $[0, \pi]$. In contrast, combining feedback and feed-forward correction effectively stabilizes the residual phase noise over 100 seconds. The power spectral density (PSD) shows that feed-forward correction suppresses residual phase noise by several orders of magnitude in the low-frequency band. The root-mean-square (RMS) phase jitter, obtained by integrating the PSD up to 50 Hz, was reduced to 0.10 rad, compared with 24 rad for feedback only. Figure 2(d) shows the Allan deviation (ADEV) of the payload channel. Without feed-forward correction, the ADEV increases monotonically with averaging time, whereas with residual feed-forward correction, it remains below 0.07 rad across the measured averaging times, reducing the long-term instability by more than two orders of magnitude. The major cause of instability at longer times is the polarization drift in the deployed fiber, not controlled in this experiment. Using a 100 km fiber spool in the laboratory environment, similar stabilization performance was achieved, and the long-term stability was improved by a factor of 40 (exceeding one hour).

The measured noise in the dark payload channel was approximately $500 \text{ photons s}^{-1}$, which is sufficiently low for quantum applications. This noise is consistent with estimation of inelastic scattering of the probe light into the quantum channel. The crosstalk can be reduced by increasing the detuning and/or lowering the power of the reference channel.

In summary, we demonstrated a triple-band WDM phase-stabilization scheme for metropolitan-scale fiber links that maintains a dark quantum channel without using any time-bin phase reference. By combining feedback and feed-forward compensation, the system achieves long-term phase stability over a 100 km fiber spool and a 120 km field-deployed fiber link, suppressing low-frequency phase noise by more than two orders of magnitude. Furthermore, under the linear-response approximation, additional WDM target channels can be phase-stabilized without introducing extra reference channels. This work demonstrates a scalable approach for multi-channel quantum communication, paving the way for the real-world deployment of wavelength-multiplexed quantum networks.

References

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