

Actively Phase-Stabilized Fiber-Based Mach-Zehnder Interferometer for Quantum Interference Measurements

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ABSTRACT

Fiber-based interferometers are attractive building blocks for quantum communication, quantum networking, and quantum metrology because they are compact, compatible with standard telecom components, and maintain stable spatial mode overlap without repeated free-space realignment. At the same time, their practical deployment is strongly limited by phase noise arising from thermal drift, acoustic perturbations, vibrations, and polarization fluctuations, all of which rapidly reduce interference visibility in single- and multi-photon experiments. This contribution reports the design and experimental characterization of an actively stabilized fiber-based Mach-Zehnder interferometric platform developed for operation from the classical regime down to the single-photon level, with direct applicability to correlated-photon interference.

Keywords: Quantum Interferometry, Optical Fiber, Fiber-based Mach-Zehnder Interferometry, Active Phase Stabilization, PID Control, Single-Photon Detection, Wavelength-Division Multiplexing

Introduction

Fiber-based interferometers are central to many emerging quantum-optical architectures because they combine compactness, direct compatibility with telecom-wavelength components, and stable spatial mode overlap with the possibility of straightforward integration into communication links. These advantages are particularly relevant for experiments in quantum communication, time-bin and energy-time encoding, quantum-enhanced sensing, and the interferometric characterization of nonclassical light [1-3].

However, the same fiber platform is intrinsically sensitive to environmental perturbations. Thermal drifts, acoustic noise, mechanical vibrations, and polarization fluctuations change the effective optical path length and thereby reduce the interference visibility, which is especially detrimental in experiments performed at the singlephoton level or with entangled photon pairs, where long integration times demand interferometric stability over extended periods [1-4]. Passive approaches

based on thermal insulation and mechanical isolation reduce environmental sensitivity but are generally insufficient for long-term operation. For this reason, active phase stabilization should not be regarded as a mere auxiliary technical aspect, but rather as a fundamental enabling mechanism for fiber-based quantum interferometry.

The approach adopted here is to separate phase stabilization from the measurement channel by wavelength multiplexing, so that a classical reference field and the measured field share the same physical paths while remaining spectrally distinct [2,4,5]. This paper reports the development and characterization of such an actively stabilized fiber Mach-Zehnder (MZ) platform, intended as a common experimental basis for classical, singlephoton, and, in the longer term, correlated-photon measurements. The contributions are threefold: a systematic optimization of the feedback loop based on a gain scan, a time- and frequency-domain characterization of the residual phase noise, and a demonstration of high-visibility interference in both the classical and the singlephoton-level regime on an identical interferometric core.

Phase Stabilization: Principle And Control Loop

Interference in a Mach-Zehnder interferometer arises from the superposition of two mutually coherent fields that are separated

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on the first coupler, propagate through the two arms, and are recombined on the second one. For an ideal device built from two 50:50 couplers, time averaging of the recombined field yields the intensities at the two output ports

$$I_{1,2} = \frac{I_0}{2} (1 \pm \cos \Delta\phi) \quad (1)$$

where I_0 is the input intensity and $\Delta\phi$ the relative phase accumulated along the two paths. The complete measurement outcome can therefore be represented by a scalar quantity, with the fringe contrast characterized by the visibility

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \quad (2)$$

Since $\Delta\phi$ is the sole free parameter in Eq. (1), any uncontrolled phase fluctuations occurring over the acquisition time effectively average out the cosine term, thereby manifesting directly as a reduction of the visibility defined in Eq. (2). The resulting contrast thus provides a quantitative measure of the phase stability and the overall performance of the interferometric system.

In a fiber implementation the relative phase $\Delta\phi$ follows from the optical path difference ΔL between the arms,

$$\Delta\phi = \frac{2\pi n_{\text{eff}} \Delta L}{\lambda} \quad (3)$$

with n_{eff} the effective refractive index and λ the vacuum wavelength. Three factors govern its stability: temperature, which changes both n_{eff} and, through thermal expansion, ΔL ; mechanical stress and acoustic vibration; and polarization drift, which leaves ϕ unchanged but reduces the fringe contrast. Passive isolation mitigates but cannot eliminate these effects, so active stabilization is required over the long integration times of single-photon measurements.

Active stabilization compensates residual fluctuations in real time using feedback control. The phase is not directly sensed on the signal channel but instead on an auxiliary classical field at a nearby wavelength propagating through the same fiber paths. Because both fields experience the same path length difference, residual tracking errors associated with the auxiliary phase lock are transferred to the signal channel essentially one to one. Consequently, the auxiliary channel serves as an accurate proxy for the signal phase while remaining spectrally distinct and separable from it.

The correction is applied by a phase actuator inside the interferometer. Several types are in common use: piezoelectric fiber stretchers, which mechanically strain the fiber; electro-optic modulators, which change the refractive index electrically; and thermal phase shifters, which tune it through temperature. The actuator investigated in this work is the piezoelectric fiber stretcher. The drive signal is generated by a feedback controller, in our case a PID regulator, as sketched in Figure 1.

The detected auxiliary signal is compared with a user-defined setpoint corresponding to the desired position on the fringe, and the deviation defines the error signal

$$e(t) = \text{in} - \text{setpoint}, \quad (4)$$

which the controller converts into the correction signal

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt} \quad (5)$$

where the proportional term (K_p) acts instantaneously but drives the loop into oscillation at excessive gain; the integral term (K_i) compensates slow drift and removes the steady-state error; the derivative term (K_d) adds predictive damping but amplifies high-frequency noise.

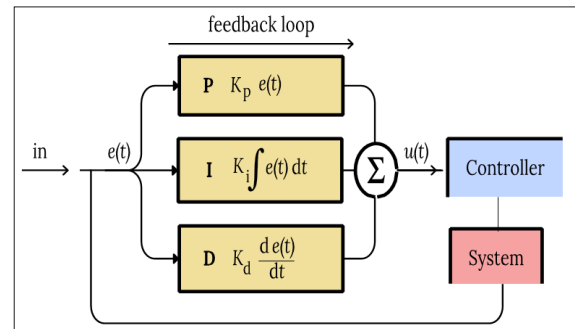


Figure 1: Principle of proportional–integral–derivative (PID) control in a closed-loop interferometric stabilization system. The error signal $e(t)$, the difference between the detected auxiliary signal and the setpoint, is processed by the P, I and D gain, whose outputs are summed into the control signal $u(t)$ applied to the phase actuator

Experimental Setup and Methods

The Mach–Zehnder interferometer, see Figure 2, is built from standard single-mode telecom fiber and formed by two 50:50 beam splitters (BS). One arm contains the fiber stretcher (FS) acting as phase actuator, the other an optical delay line (ODL) with 25 mm of mechanical tuning, which allows for a balanced configuration. Polarization controllers (PC) maximize the polarization overlap at recombination. Component insertion losses are approximately 1 dB (BS), 0.5 dB (FS), 1.5 dB (ODL) and 0.25 dB (PC), giving about 8.5 dB from the input to either output port.

Two signals propagate through this common path: the signal channel at $\lambda_{\text{signal}} = 1552.52$ nm carries the measurement, the auxiliary channel at $\lambda_{\text{aux}} = 1550$ nm serves as the phase reference. Both come from tunable Cband sources with a linewidth below 100 kHz and are combined and separated by DWDM filters with 100 GHz spacing (channel C31, insertion losses 1.13 dB in TX and 0.34 dB in RX). The auxiliary output is sent to a balanced photodetector (PDB) whose differential output forms the error signal of Eq. (4). The error signal is processed by a Red Pitaya STEMLab 125–14 running the open PID and lock-in firmware of Luda et al [5]. The ± 1 V control output is amplified $\times 20$ before reaching the fiber stretcher (0–150 V, nominal stroke 13π at full scale, resonance 80 kHz). The setpoint is expressed in dimensionless digital units, $\text{sp}[V] = \text{sp}[-]/8192$.

With the auxiliary laser at its optimum output power of about 11 dBm (Figure 2 top), the fixed 20 dB attenuator and the input DWDM filter leave roughly -10 dBm at the interferometer input, and the 8.5 dB of insertion loss to either output port gives approximately -18.5 dBm at each input port of the PDB. The attenuator was dimensioned so that this level stays within the ± 1 V input range of the Red Pitaya.

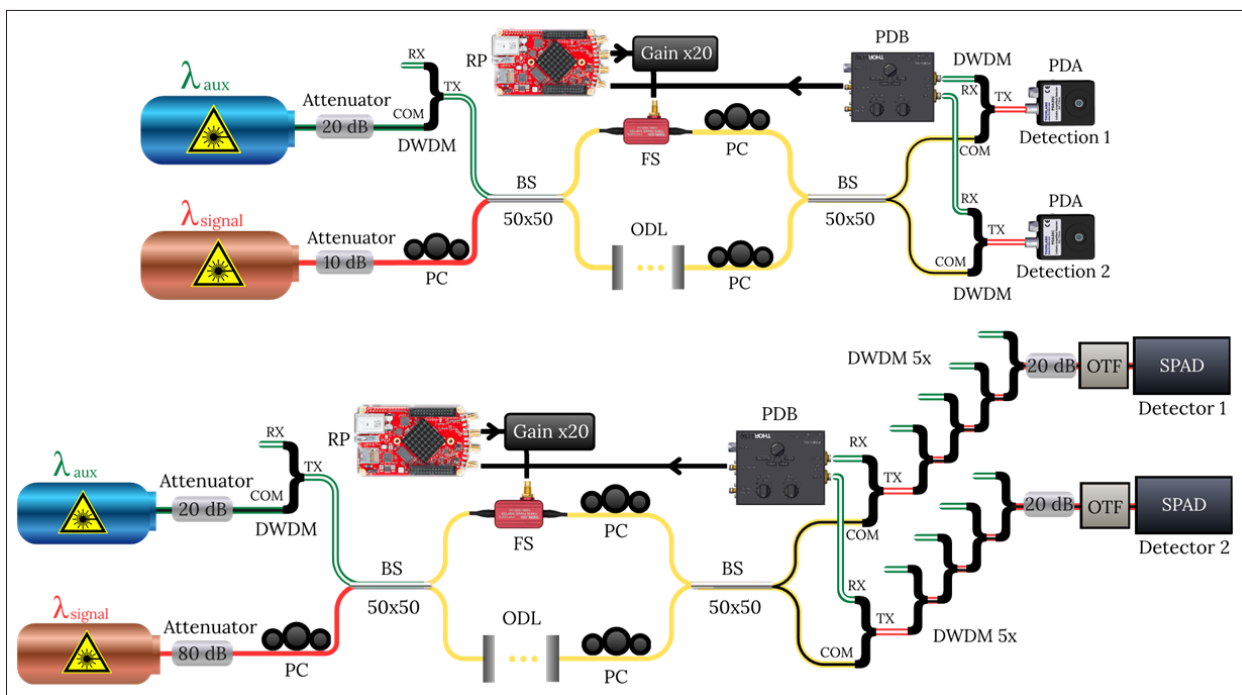


Figure 2: Actively stabilized fiber Mach-Zehnder interferometer in the classical (top) and single-photon-level (bottom) configuration. The signal laser (λ_{signal} , red) is used for interference measurements, while the auxiliary laser (λ_{aux} , green) provides a reference for phase stabilization. DWDM = Dense Wavelength Division Multiplexing (COM (black) – common, RX (white) – reflection, TX (white) – transmission), PC = Polarization Controller, BS = Beam Splitter, FS = Fiber Stretcher, ODL = Optical Delay Line, OTF = Optical Tunable Filter, SPAD = Single-photon Avalanche Detector (Detector 1 and 2), PDB = Balanced Photodetector, RP = Red Pitaya

The topology and the stabilization channel are identical in both regimes below; only the detection branch of the signal channel is exchanged. In the classical configuration, Figure 2 (top), the signal is attenuated by 10 dB, filtered by a single DWDM stage and measured on two amplified photodetectors (PDA) at the complementary output ports. In the single-photon-level configuration, Figure 2 (bottom), the same core is reused and only the signal path is modified. A cascade of five DWDM filters and an optical tunable filter (OTF) centred at 1552.52 nm separates the signal channel and suppresses the light reaching the SPAD modules so that these do not saturate. In total the signal is attenuated by about 110 dB of out-of-band suppression. An additional DWDM filter between the attenuator and the interferometer input narrows the auxiliary channel and further reduces its leakage.

Results and Discussion

Optimization of the Feedback Loop

The quality of the stabilization is quantified by the root-mean-square (RMS) value of the detected signal. RMS was used as the cost function for gain selection: a grid of the digital coefficients pidA_{kp} and pidA_{ki} was scanned over the range 0–100 in steps of 10 ($11 \times 11 = 121$ points). The gain graph is shown in Figure 3. Without phase stabilization (PID OFF, $\text{pidA}_{kp} = \text{pidA}_{ki} = 0$) the residual fluctuation amounts to $\text{RMS} = 0.104$, whereas the optimum (BEST, $\text{pidA}_{kp} = 60$, $\text{pidA}_{ki} = 100$) reduces it to $\text{RMS} = 0.015$. The derivative gain (pidA_{kd}) was set to zero, as it amplified high-frequency noise. Gains beyond the scanned range drove the loop into audible high-frequency oscillation, and poorly chosen gains can be worse than no feedback at all.

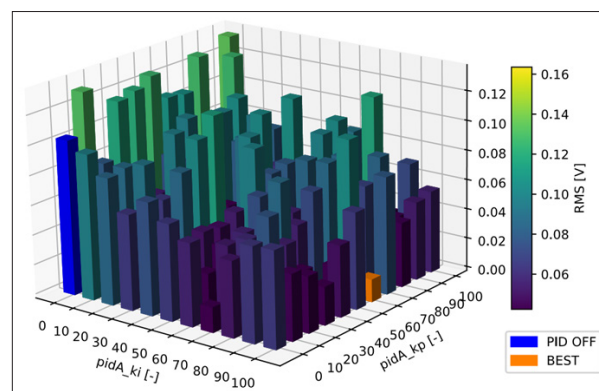


Figure 3: Dependence of the RMS value of the detected auxiliary signal on the digital gain coefficients pidA_{kp} and pidA_{ki} . The unstabilized regime (PID OFF) is shown in blue, the optimum (BEST, $\text{pidA}_{kp} = 60$, $\text{pidA}_{ki} = 100$) in orange.

The auxiliary optical power must also be selected with particular care; raising it initially improves the signal-to-noise ratio of the error signal, but beyond an optimum near 11 dBm of laser output the fiber stretcher develops an oscillatory response. The optimum set (11 dBm) was fixed for all subsequent measurements.

Subsequently, the signal laser of the Mach-Zehnder interferometer in classical and single-photon-level regimes is characterized independently by both detectors PDA and SPAD under two operating conditions, namely without and with active stabilization (PID OFF and ON), as shown in Figure 4. In the classical regime, Figure 4(a), the two detectors span 0–0.41 V and 0.03–0.67 V; they drift over these full ranges within about 2 ms ($\text{RMS} = 0.127$ V), whereas under lock the residual fluctuation

drops to 0.006–0.016 V. The π shift between the complementary ports is directly visible in the time domain; stable operation was obtained for $sp \in \langle -2160, 700 \rangle$ and $\langle -1800, 240 \rangle$, the intervals differing as the channels were recorded independently.

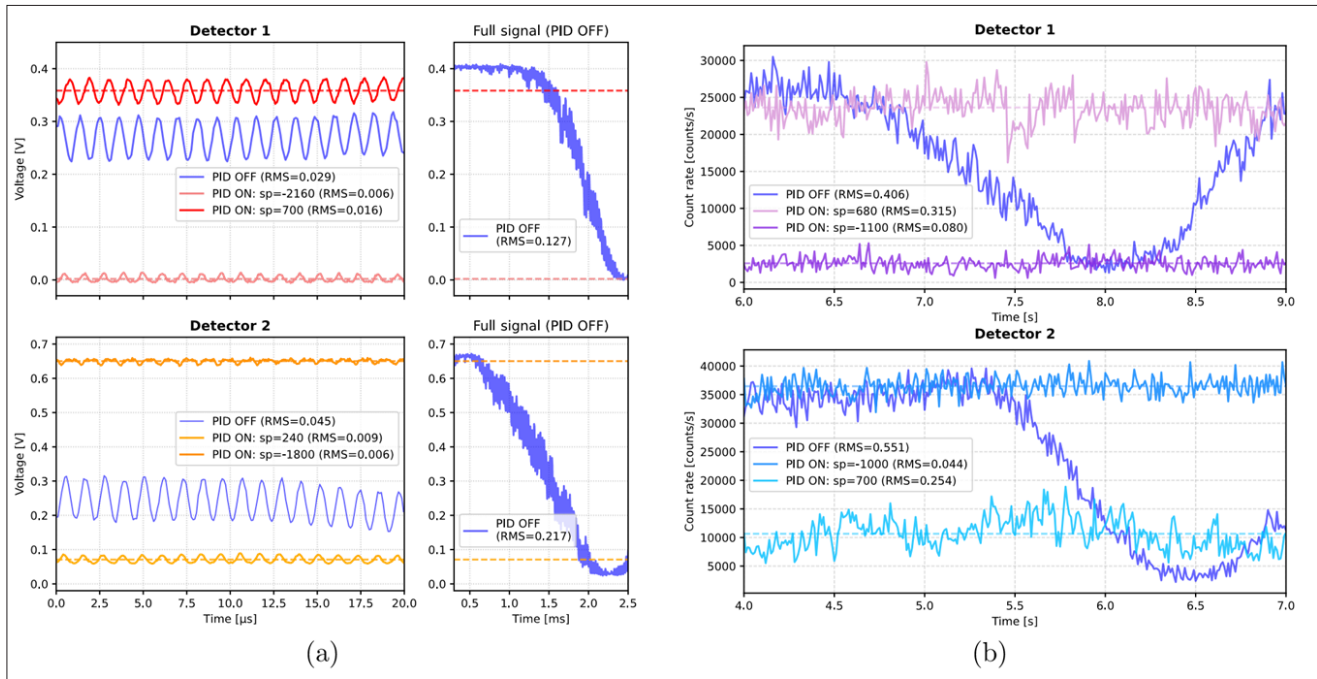


Figure 4: Signals of the unstabilized (PID OFF, blue) and stabilized (PID ON) interferometer on the measurement channel, including root-mean-square (RMS) values. RMS values are evaluated over the time window displayed in each panel. The setpoint represents the reference value of the control loop and defines the phase operating point at which the interferometer is locked (e.g., near minimum, quadrature, or maximum of the interference fringe). (a) Classical regime, recorded on the two amplified photodetectors PDA; the right-hand panels show PID OFF signal over an extended time range, illustrating pronounced phase drift. (b) Single-photon-level regime, recorded on the two SPAD detectors.

In the single-photon-level regime, Figure 4(b), the comparison is made on count rates and on a timescale of seconds. In the unstabilized case, the rates sweep over the full fringe within a few seconds (RMS = 0.406 and 0.551); under lock they stay constant throughout the acquisition, with the normalized RMS falling to 0.080 and 0.044. The suppression is weaker for the outermost setpoints ($sp = 680$ and 700 , RMS = 0.315 and 0.254), which lie at the edge of the accessible locking interval where the slope of the auxiliary fringe, and hence the phase discrimination of the error signal, is smallest. This behaviour is a consequence of the characteristics of the fiber stretcher, whose limited accessible phase excursion is discussed in Sec. 4.3, and it is the origin of the larger uncertainties near the fringe extrema in Figure 5(b); a similar behaviour is observed in Figure 5(a).

A Fourier analysis of the same traces confirms this behaviour in the frequency domain. On the measurement channel the power spectral density is reduced globally by about 5 dB, with the clearest suppression below ≈ 400 Hz; the interval over which suppression is observed gives an effective stabilization bandwidth of ≈ 1.5 kHz, consistent with the finite response of the actuator.

Classical and Single-Photon-Level Interference

In the classical regime the reconstructed curves, Figure 5(a), follow the expected cosine dependence

$$I = I_0 [1 + V \cos\phi(x)], \quad \phi(x) = \alpha x + \phi_0, \quad (6)$$

where x is the applied setpoint (or sp) of the feedback loop, α an effective phase-tuning coefficient and ϕ_0 a constant phase. Because the optical power is not distributed perfectly evenly between the output arms the traces are shown normalized; a fit after background subtraction gives $V_{\text{classical}} = (96 \pm 3) \%$. This high visibility indicates low phase noise and proper polarization alignment within the interferometer.

The same interferometer was then transferred into the single-photon-level regime, the interference being expressed in terms of count rates,

$$C = C_0 [1 + V \cos\phi(x)]. \quad (7)$$

A fit after background subtraction gives $V_{\text{single}} = (88 \pm 2) \%$, in reasonable agreement with values reported for comparable fiber Mach–Zehnder interferometers [2]. Although slightly lower, the obtained value remains reasonable given the experimental constraints. Interferometric visibility could be further enhanced by reducing the length of the interferometer arms (e.g., via fusion splicing of the fibers), which would concurrently decrease their susceptibility to phase noise. The implementation of polarization-maintaining fiber (PMF) would improve polarization stability and spatial mode matching, thereby yielding a higher interference contrast.

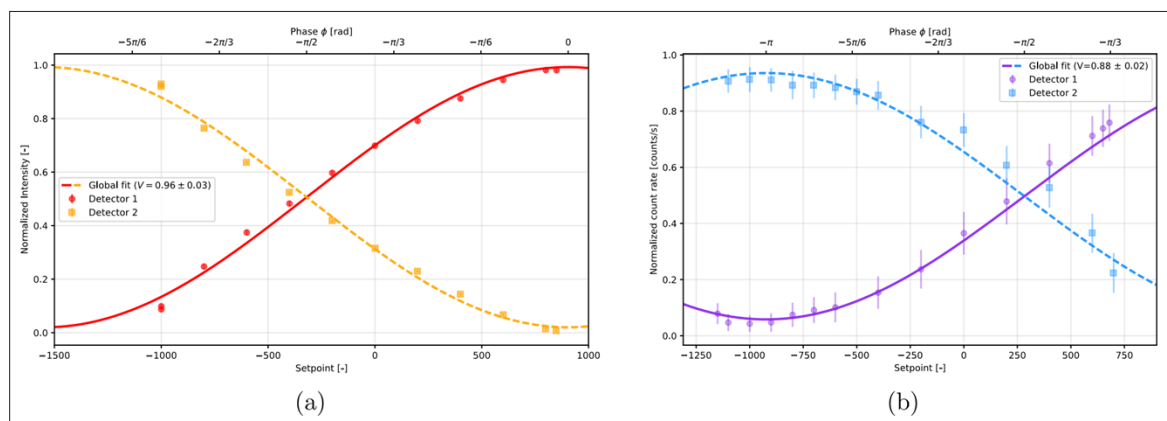


Figure 5: Interference signals, showing a relative phase shift of approximately $\Delta\phi = \pi$ between the two outputs. The setpoint represents the reference value of the control loop and determines the phase operating point at which the interferometer is locked. (a) Classical regime, measured with amplified photodetectors PDA; the fit to Eq. (6) gives $V = (96 \pm 3) \%$. (b) Single-photon-level regime, measured with SPAD detectors; the fit to Eq. (7) gives $V = (88 \pm 2) \%$.

The dominant limitation of the present implementation is the accessible phase excursion. Although the fiber stretcher is nominally capable of $\approx 13\pi$ at its full drive voltage, the ± 1 V control output amplified by $\times 20$ covers only a fraction of that range, restricting the realizable modulation to $\approx 5\pi/6$. Both reconstructions therefore sample somewhat less than half a period, which suffices for a reliable visibility estimate from the fitted amplitude but prevents a complete scan; outside the usable setpoint interval the loop loses lock. The constraint is set by the drive electronics rather than by the actuator and can be lifted by increasing the amplifier gain.

Conclusions and Outlook

We have designed, implemented and characterized an actively phase-stabilized fiber-based Mach–Zehnder interferometer operating on a single common platform from the classical regime down to the single-photon level. Stabilization is realized by wavelength multiplexing: an auxiliary reference at 1550 nm co-propagates with the signal channel at 1552.52 nm, is separated by 100 GHz DWDM components, and drives a Red Pitaya feedback loop acting on a piezoelectric fiber stretcher.

The feedback loop was optimized by a scan ($11 \times 11 = 121$ points) of the proportional and integral gains, using the RMS fluctuation of the locked signal as cost function. On this basis the platform delivers complementary fringes with a visibility of $(96 \pm 3) \%$ classically and $(88 \pm 2) \%$ at the single-photon level, the transition between regimes requiring only the addition of a filter cascade providing more than 110 dB of out-of-band suppression.

Because the stabilized core is independent of the nature of the input field, the same architecture is a natural starting point for two-photon experiments. Replacing the attenuated classical source by a source of correlated photon pairs turns the two couplers into a two-photon interference stage, making the platform directly relevant to Hong–Ou–Mandel interference, two-photon NOON-state phase measurements and Franson interferometry [6,3,7,8]. Wavelength-multiplexed active phase

stabilization thus provides a practical route towards robust, reconfigurable fiber interferometers for future advanced quantum-optical experiments.

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