

50-km Fiber Interferometer for Testing Gravitational Signatures in Quantum Interference

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Quantum mechanics and general relativity are the foundational pillars of modern physics, yet experimental tests that combine the two frameworks remain rare. Measuring optical phase shifts of massless photons in a gravitational potential provides a unique quantum platform to probe gravity beyond Newtonian descriptions, but laboratory-based interferometers have not yet reached the sensitivity needed to access this regime. Here, we report the realization of a 50-km table-top Mach-Zehnder fiber interferometer operating at the single-photon level, achieving a phase sensitivity of 4.42×10^{-6} rad rms within the frequency range of 0.01–5 Hz. We demonstrate that this sensitivity is sufficient to resolve a phase-shift signal of $6.18(44) \times 10^{-5}$ rad rms at 0.1 Hz, associated with a modulated gravity-induced signal. Our results establish a milestone for quantum sensing with large-scale optical interferometry, demonstrating the capability to detect gravitational redshifts in a local laboratory, thereby paving the way for testing quantum phenomena within general relativistic frameworks.

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Introduction—Quantum mechanics revolutionized our understanding of the microscopic world, while Einstein’s theory of general relativity provides the most accurate description of gravity at macroscopic, even cosmological, scales. However, a unified framework connecting these two pillars of modern physics remains elusive, hindered by the lack of experimental insight. Although both theories have been tested with high precision [1–7], no experiment has yet accessed a regime where their concepts must be applied simultaneously.

In recent decades, numerous proposals and experiments have sought to test gravitational effects on quantum systems. These efforts fall broadly into two categories: investigations of the emergence of entanglement arising solely from gravitational coupling between particles [8–11] and studies of how quantum states are influenced by classical gravitational fields [12–19]. Since the first observation of gravitationally induced phase shifts in neutrons [12], the latter approach has seen significant progress with matter wave interferometers [13–19]. However, all experiments conducted to date remain consistent with Newtonian gravity and therefore do not necessitate a general relativistic explanation. Photons, as massless quantum particles, provide an ideal platform to probe the influence of gravity on quantum systems in regimes that elude a Newtonian description, thereby necessitating the simultaneous inclusion of quantum mechanics and general relativity [20,21].

Since general relativistic effects are extremely small in Earth’s weak gravitational field, experiments involving both general relativity and quantum mechanics are necessarily at the cutting edge of precision measurement. Theoretical schemes across various platforms have been pursued to explore this interface, including atom

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interferometers [22–24], trapped electrons [25], clock networks [26–28], and quantum memories [29,30]. A promising approach is to employ long-path photonic interferometers, in which the extended photon propagation time at different heights allows weak gravitational effects to build up to measurable levels. Several satellite-based proposals and initial proof-of-principle experiments have been put forward to realize this vision [31–38]. In practice, space-based experiments are technically demanding—fragile, costly, and often constrained by local weather and atmospheric conditions.

Fiber-based interferometers, on the other hand, provide a practical means to obtaining long photon propagation times—and therefore measurable optical phase shifts—within compact and controllable laboratory environments [20,39–42]. However, despite significant advances in optical platforms for quantum information processing [43–45] and quantum networks [46–48], laboratory-scale optical interferometry experiments have not yet achieved the sensitivity required to probe gravitational signatures. Recent experimental endeavors [49] toward this goal remain limited by pervasive environmental noise sources [50]. We aim to access the regime of measurable gravitational effects on photonic states in the context of general relativity by performing precision measurements using a large-scale, tabletop fiber interferometer whose arms are positioned at different heights to experience a gravitational potential difference [51].

In a Mach-Zehnder interferometer consisting of two fiber spools of equal length l separated vertically by a height h ,

the expected gravitational phase shift for a single photon of vacuum wavelength λ is

$$\Delta\phi_g = 2\pi n g h l / (\lambda c^2) \approx 10^{-6} \text{ rad} \times \left(\frac{h}{\text{m}}\right) \left(\frac{l}{\text{km}}\right) \left(\frac{\lambda}{\mu\text{m}}\right)^{-1}, \quad (1)$$

where $n \approx 1.46$ is the effective refractive index of the silica optical fiber, g is the local gravitational acceleration, and c is the speed of light in vacuum [21,52]. In this work, we report our first realization of a laboratory-based fiber interferometer with two arms of length $l = 50$ km located at the same height ($h = 0$), utilizing single-photon interference to achieve a phase sensitivity of 4.42×10^{-6} rad rms within the frequency range of 0.01–5 Hz. We demonstrate that the achieved sensitivity is sufficient to clearly resolve a simulated signal with a known magnitude of 6.48×10^{-5} rad rms, comparable to the gravitational phase shift accessible with a 2-m height tabletop apparatus. This surpasses the sensitivity of previous single-photon fiber interferometers by 2 orders of magnitude [49] and paves the way for testing quantum phenomena in the context of general relativity in a local laboratory.

Experimental setup—A sketch of our experimental setup is shown in Fig. 1. The apparatus consists of a bright single-photon source, a Mach-Zehnder interferometer with 50 km-long arms built entirely from fiber-based components, SNSPDs, and an auxiliary system employing

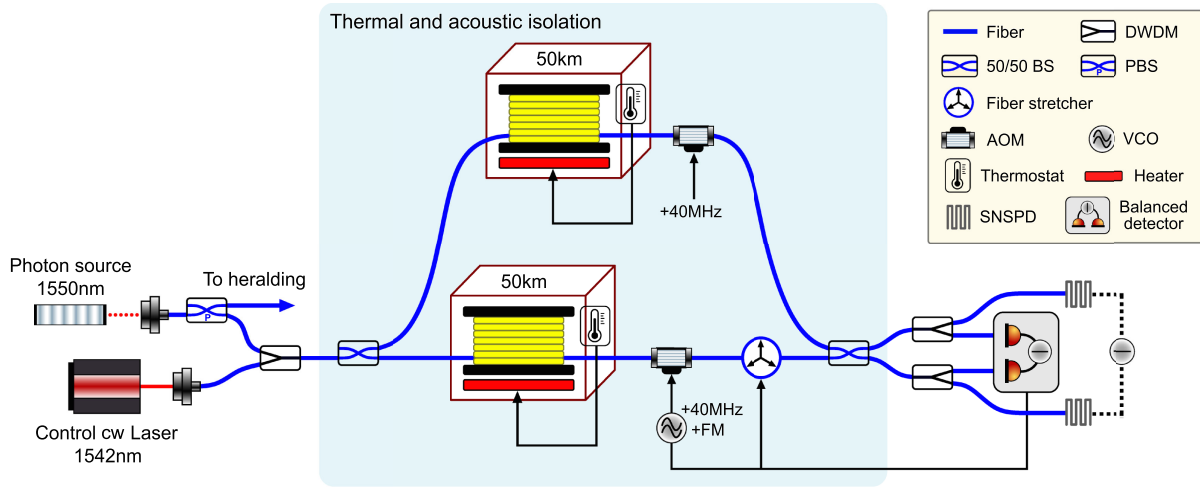


FIG. 1. Layout of the Mach-Zehnder fiber interferometer, with both interferometer arms maintained at the same height. The interferometer is composed of two 50/50 fiber beam splitters (BSs) and two 50-km low-loss fiber spools (yellow), each maintained under active temperature control. Single photons centered at 1550 nm, generated from a type-0 photon source, are used to probe the interferometer phase sensitivity. A weak continuous-wave (cw) laser field at 1542 nm is used to lock the interferometer phase. This classical field copropagates with the single photons through the interferometer before being separated by dense wavelength division multiplexers (DWDMs) and directed to a balanced photodetector. To stabilize phase fluctuations, the error signal from the balanced detector is sent to an acousto-optic modulator (AOM) driven by a voltage-controlled oscillator (VCO) for fast feedback, and to a fiber stretcher for slow feedback. The interferometer phase is extracted from the heralded photon number counts detected by superconducting nanowire single-photon detectors (SNSPDs). The core interferometer elements are placed in a thermally and acoustically isolated enclosure (blue shaded region).

cw control laser light with balanced detection to stabilize the interferometer. Broadband single photons centered at 1550.12 nm are generated via a type-0 spontaneous parametric down-conversion process in a periodically poled lithium niobate nonlinear crystal [53,54]. A polarizing beam splitter (PBS) separates the generated photon pairs, sending one photon through the interferometer while the other serves as a herald and is sent directly to the detector. (For details of the photon source, see Supplemental Material [55].) To strike a balance between a feasible coherence length and an adequate count rate for a reasonable integration time, the photons are filtered to a bandwidth of 100 GHz using DWDMs, resulting in detected photon pair rates exceeding 40 MHz.

The interferometer arms are composed of two compact fiber spools, each housed in a thermally insulated cylindrical enclosure with active temperature feedback control, providing stability at the 0.1-mK level to minimize phase noise from thermal fluctuations. We use a separate prestabilized laser with a 1-Hz linewidth at a wavelength of 1542.14 nm as a control field to actively stabilize the interferometer phase. The laser power is minimized to prevent spontaneous Raman-scattered photons from contaminating the single-photon channel and saturating the SNSPDs [57,58]. This control light field is combined with single photons using a DWDM, copropagates through the interferometer, and is then separated and directed to a balanced detector upon exiting. Error signals from the balanced detection are fed back to an AOM and a piezo-electrically actuated fiber stretcher for phase correction. This control field is also used to characterize the noise performance of the interferometer in the classical regime. To passively mitigate environmental noise, the majority of the interferometer components are enclosed within a thermally and acoustically insulated housing (blue shaded region in Fig. 1).

After interfering at the second beam splitter, the single photons leaving the interferometer are measured with single pixel SNSPDs, while the heralding photons are monitored with multipixel SNSPDs. In this current setup, we inject weak sinusoidal modulations into the control signal to introduce S_g , a signal associated with the gravitationally induced phase shift $\Delta\phi_g$. The total interferometer phase $\phi_0 + S_g$ is then extracted from the heralded photon counts at each output port, given by $N_{1,2} = \frac{1}{2}N[1 \pm V \cos(\phi_0 + S_g)]$, where N denotes the total photon counts out of the interferometer, V the fringe visibility, and ϕ_0 the initial locking offset phase of the interferometer [20,21].

Experimental results—This experiment aims to demonstrate the highest phase sensitivity achieved in a laboratory-based large-scale fiber interferometer and to showcase its capability to resolve the minute signal S_g . Our measurements comprise two long data runs of 68.8 and 91.2 h. The experimental conditions across the two runs were sufficiently stable and consistent to justify stitching the

data into a single dataset with total measurement duration $T_{\text{meas}} = 160$ h, referred to as the “main measurement,” shown in Figs. 2 and 3(b). To support our analyses we also carry out a series of auxiliary measurements, shown in Fig. 3(a).

Figure 2 presents the single-photon phase noise amplitude spectra after 160 h, revealing the emergence of the simulated signal S_g from the background noise. The interferometer is locked near $\phi_0 = \pi/2$ with photon interference visibility $V = 98\%$. Two sinusoidal dithers are injected into the feedback control loop to characterize the noise performance more accurately—a reference tone with a known rms amplitude of 2.10×10^{-3} rad at 0.25 Hz used to refine the calibration and the signal tone S_g at 0.1 Hz. In the main measurement, the rms amplitude of S_g was set to 6.48×10^{-5} rad.

The time series data of heralded photon counts from the two interferometer outputs are acquired at a sampling rate of 10 Hz using a time tagger. The measured photon counts are calibrated to rms phase noise in radians based on the fringe visibility of the interferometer determined from a full phase scan. To reject common-mode phase noise, we calculate the half-difference between the phase signals extracted from the two interferometer output ports, as shown by the red trace. The spectra are computed with the Fourier limited frequency resolution ($1/T_{\text{meas}} \approx 1.74 \mu\text{Hz}$) to maximize the contrast between the signal and background noise.

The achieved level of sensitivity allows the injected signal to emerge distinctly above the background phase noise. The interferometer noise above 0.01 Hz is limited by photon shot noise, reaching a level of $4.42 \times 10^{-3} \text{ rad}/\sqrt{\text{Hz}}$. This corresponds to a fractional displacement sensitivity, or a travel time dilation for 1550 nm photons, of $1.52 \times 10^{-14}/\sqrt{\text{Hz}}$. At lower frequencies, classical noise dominates due to residual thermal fluctuations, seismic vibrations, and acoustic disturbances coupling into fiber phase noise. A full characterization of the interferometer using classical light, including the photon noise spectral density and its comparison to the classical noise measurement can be found in Supplemental Material and Fig. S2 [55].

A postprocessing lock-in analysis is applied to eliminate ϕ_0 while extracting the amplitude and uncertainty of S_g more precisely. The in-phase components of the electrical signal, demodulated at 0.25 and 0.1 Hz, are extracted after low-pass filtering. During the extended measurement period, the visibility of the interferometer degrades due to polarization and temperature drifts. To compensate for this, we divide each of the two data series into ten segments and rescale the calibration factor in each segment by matching the 0.25-Hz dither amplitude to the known level of the calibration signal. With the calibration applied, we compute the mean of the demodulated time series and quantify its uncertainty using the standard error of the mean, yielding the measured signal of

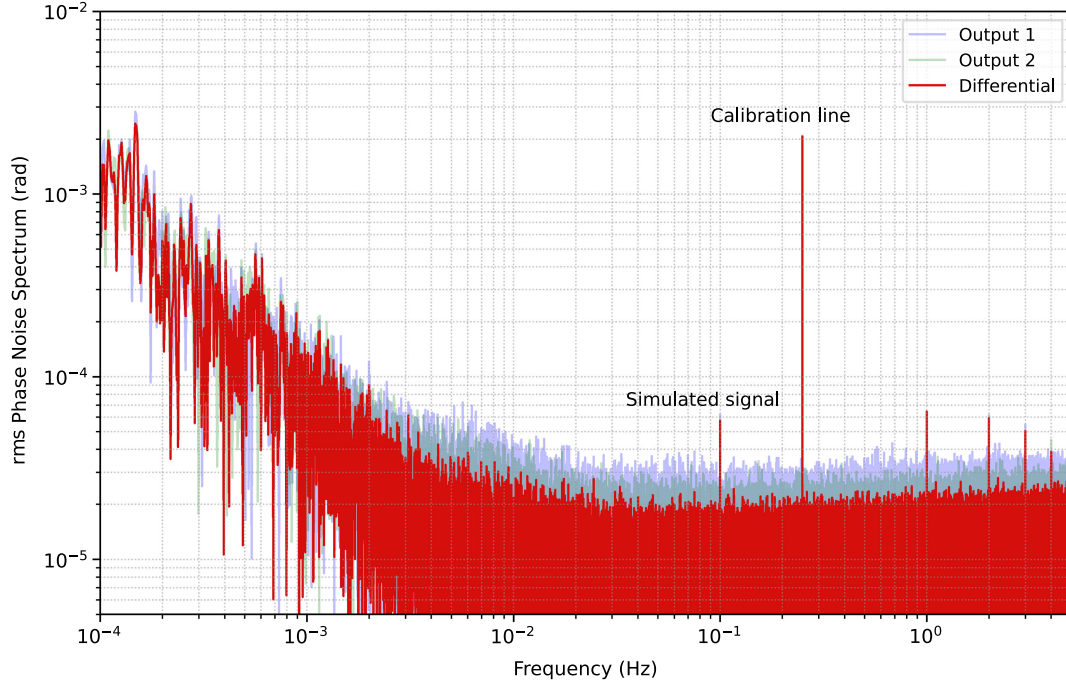


FIG. 2. Phase noise spectra of the single-photon interferometer from a 160-h measurement, spanning the frequency band from 10^{-4} –5 Hz. The dim blue and green traces show the phase noise sensitivity calibrated from heralded single-photon counts at each interferometer output. The red trace shows the half-difference between the phase noises measured at the two interferometer outputs, rejecting common-mode noise of the interferometer. The peak at 0.25 Hz corresponds to the injected dither tone for calibration; the peak observed at 0.1 Hz corresponds to the simulated gravitationally induced phase-shift signal, with an expected rms amplitude of 6.48×10^{-5} rad, in agreement with the measured value of $6.18(44) \times 10^{-5}$ rad. The signal is clearly resolved above the noise floor, which is primarily limited by photon shot noise. Additional peaks at 1 Hz and its harmonics arise from cryostat compressor noise.

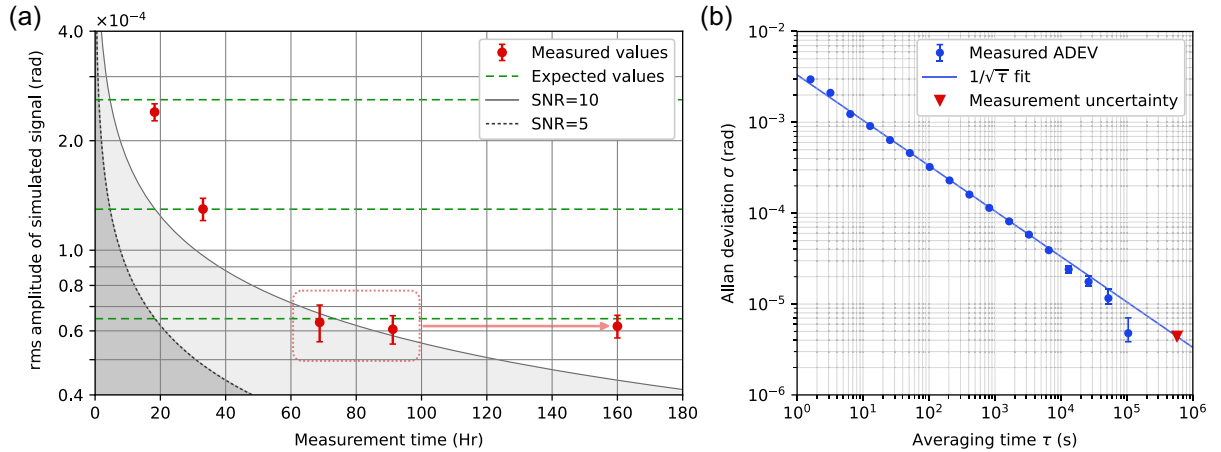


FIG. 3. (a) Measurements of injected signal amplitudes at 0.1 Hz. We use three different dithers with calibrated rms amplitudes of 2.59×10^{-4} , 1.30×10^{-4} , and 6.48×10^{-5} rad (green dashed lines). The measurement durations are 18.2, 33.1, and 160 h, respectively. The measured signal values are $2.40(13) \times 10^{-4}$, $1.30(09) \times 10^{-4}$, $6.18(44) \times 10^{-5}$ rad (red dots with error bars). The data for the smallest dither were combined from two separate runs (68.8 and 91.2 h), yielding independent estimates of $6.33(73) \times 10^{-5}$ and $6.06(54) \times 10^{-5}$ rad (red dotted box). This demonstrates the repeatability of the measurement and the stability of the apparatus. The thresholds for SNRs of 5 and 10 are shown in the plot to indicate the required measurement times for different signal levels. (b) Allan deviation (ADEV) of the in-phase component obtained from lock-in analysis of the simulated signal, showing the phase stability σ versus the averaging time τ . The blue dots with error bars show overlapping ADEV values calculated from the 160-h measurement. The blue line represents a $1/\sqrt{\tau}$ fit to the data for $\tau < 820$ s, extended to the full measurement duration. The data follow this $1/\sqrt{\tau}$ trend and are consistent with a white noise process, indicating that the measured signal is stationary. The red triangle shows an estimated statistical uncertainty of the measurement from the demodulated time series, which is consistent with the extrapolation of the ADEV trend.

TABLE I. Measured loss budget from various sources and the total optical loss of the entire fiber interferometer setup, from the photon source output to the detection stage. Measurements were performed using cw laser light at a wavelength of 1550 nm.

Loss source	Loss (dB)
Fiber spool	9.75(01)
Optical components	
AOM	2.35(02)
DWDMs	1.60(02)
BSs	0.09(01)
Fiber connections	1.00(02)
SNSPD efficiency	0.20(02)
Total	14.99(10)

$S_g = 6.18(44) \times 10^{-5}$ rad, which encompasses the expected value within its uncertainty. Figure 3(b) shows the overlapping ADEV plot, which characterizes the stability of the measured phase shift over an averaging period τ . The ADEV trend (fitted blue line) is consistent with a stationary noise process, indicating that the interferometer's mean phase shift remains constant throughout the measurement. By extrapolating this trend to the full measurement duration ($\tau = 160$ h), we see that it is consistent with our estimate of the statistical uncertainty (red triangle). The time series data plot from the lock-in analysis can be found in Supplemental Material Fig. S4 [55].

To assess the repeatability and consistency of the results, we performed S_g injections and measurements over a range of amplitudes with varying integration times. The measurement results for the three different signal levels are summarized and presented in Fig. 3(a). For each injection, we extracted the signal amplitude and uncertainty following the same procedure used for the main measurement. Figure 3(a) also indicates the measurement integration time necessary to reach a sufficiently high signal-to-noise ratio (SNR) for signals of different amplitudes.

Conclusions—We have demonstrated a 50-km fiber interferometer that, for the first time, achieves the sensitivity needed to observe gravitational redshifts with a photonic quantum state under laboratory conditions. This achievement establishes a milestone for quantum sensing with optical fiber interferometry, highlighting the potential to explore gravitational effects on single and entangled photons within the framework of general relativity.

Currently, the sensitivity performance is primarily limited by the optical loss of the whole fiber system. A loss budget from various sources of the setup is summarized in Table I. The total loss of each interferometer path is 14.99(10) dB, corresponding to a transmission efficiency of 3.17(7)%. This substantial loss reduces the photon count at the outputs, imposing a photon shot-noise limitation at frequencies above 0.01 Hz. To reduce optical loss, the current fibers can be replaced with ultra-low-loss fibers with spliced connections, minimizing insertion losses.

Regarding classical noise, seismic disturbances can be further suppressed with vibration-minimizing fiber spools, while long-term phase drift arising from polarization and temperature fluctuations can be mitigated through active polarization control and enhanced thermal insulation.

Based on the results presented here and supported by extensive theoretical studies [52,59,60], the authors have initiated the design and construction of a next-generation setup incorporating a modulated vertical height difference between two interferometer arms. The primary challenges lie in simultaneously mitigating environmental perturbations across two vertically separated fiber spools and preserving polarization stability during dynamic height adjustments. The technical upgrades outlined above are expected to address these issues. This differential measurement scheme (see Supplemental Material [55] for additional details) will be capable of comparing gravitational redshift-induced effects on classical and quantum light, probing potential new effects of gravity on entangled quantum fields, and taking an important step toward experimentally accessing the interface between quantum mechanics and general relativity.

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Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council Executive Agency.

Data availability—The data that support the findings of this article are openly available at [61], embargo periods may apply.

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