

Accurate and precise optical phase sensor based on a nonlinear quantum Sagnac interferometer

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Optical phase measurements play a key role in the detection of macroscopic parameters such as position, velocity, and displacement. They also permit to qualify the microscopic properties of photonic waveguides such as polarization mode dispersion, refractive index difference, and chromatic dispersion. In the quest for ever-better measurement performance and relevance, we report a quantum nonlinear interferometer based on a Sagnac configuration allowing precise, accurate, self-stabilized, and reproducible optical phase measurement. The potential of this system is demonstrated through the measurement of second-order dispersion, namely, chromatic dispersion of a commercial dispersion-shifted fiber at telecommunication wavelength. We demonstrate a precision of 0.007%, surpassing state-of-the-art measurements by more than one order of magnitude. Additionally, the accuracy of the second-order dispersion value is determined through the measurement of the third-order dispersion, showing a quadratic error as low as 5%. Our system promises the development of photonic-based sensors enabling the measurements of optical-material properties in a user-friendly manner.

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I. INTRODUCTION

Precise measurement is at the heart of science and technology [1]. A fundamental concern lies in achieving the best precision in measuring optical phase, which impacts a large variety of domains encompassing gravitational wave detection, microscopy, and optical coherence tomography [2–4]. Quantum physics allows, in principle, ultimate precision achievable by exploiting correlated quantum resources, such as entangled states, offering significant advantages over even the most optimized iterations of classical counterparts [5,6]. Quantum-enhanced optical phase estimation holds the promise of substantial improvements in all interferometry-based measurements [7]. The central challenge, however, remains the stability of the interferometer itself. Environmental factors, such as temperature fluctuations and vibrations, introduce phase drifts that must be smaller than the variations being measured. Most of the interferometric phase measurements are based on Mach-Zehnder or Michelson interferometer architectures that require the use of sophisticated stabilization systems. The associated experimental complexity merely shifts the underlying challenge without fully resolving it [8].

In contrast, Sagnac interferometers are immune to phase drifts, as reciprocal phase shifts cancel out when the drift rate is slower than the light propagation time, resulting in zero relative phase. This characteristic has greatly benefited the measurement of nonreciprocal phenomena, such as Faraday rotation and the gyroscopic effect, in both classical [9] and

quantum [10] regimes. Conversely, this configuration also finds limitations as Sagnac interferometers are inherently insensitive to chromatic dispersion (CD), a critical parameter for numerous photonics applications where both high precision and stability are essential [11,12].

In this paper, we introduce an interferometric architecture that integrates a different type of nonreciprocity by embedding a nonlinear element within the Sagnac loop. This original approach grants access to previously unattainable parameters, such as the optical phase in the frequency domain, enabling precise CD measurements of the sample under test. We demonstrate several significant advantages: (i) the inherent system self-stabilization facilitated by a common path for all beams; (ii) a deterministic output for photons exiting the interferometer, unlike the typical 50% output [13], thereby reducing the overall loss budget of the system; and (iii) a straightforward alignment achieved through a fully fibered configuration operating at telecom wavelengths. Furthermore, energy-time entanglement plays a crucial role in parameter estimation by mitigating systematic errors. When applied to chromatic dispersion measurement, it effectively reduces the impact of higher-order dispersion effects, which are a major source of systematic errors in classical white-light interferometry [14]. While quantum interferometry is indeed a well-established field, our methodology provides a new paradigm for phase estimation in metrology by demonstrating a level of precision that surpasses state-of-the-art classical and quantum techniques [12,14,15].

II. THEORY

The schematic of the quantum nonlinear Sagnac interferometer is shown in Fig. 1. It comprises a common-path bulk configuration using a polarization beam splitter (PBS). The loop itself consists of a half-wave plate (HWP), a second-order nonlinear medium, and a dispersive medium acting as a

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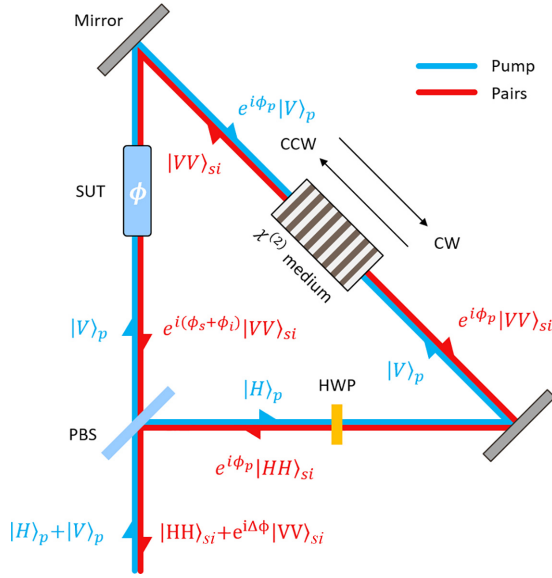


FIG. 1. Principle of a nonlinear Sagnac interferometer in free space configuration using a type-0 phase-matched medium. The blue (red) path represents the propagation of the pump (pairs). HWP: half-wave plate; PBS: polarizing beam splitter; CWi: clockwise; CCWi: counter-clockwise.

sample under test (SUT). We assume that the path-difference between the nonlinear medium and the PBS in both clockwise (CW) and counterclockwise (CCW) only comes from the dispersive medium. For the sake of clarity, we first consider the pump at frequency ω_p to be vertically polarized. The latter propagates in the CWi path through the dispersive medium and accumulates a phase denoted by ϕ_p . Subsequently, within the nonlinear medium, it undergoes spontaneous parametric down-conversion (SPDC) to generate photon pairs at the degenerate frequency $\omega_0 = \omega_p/2$. A type-0 phase matching condition is achieved, ensuring polarization conservation between the pump and the generated paired photons. The latter then pass through the HWP to rotate their polarization to the horizontal state. Finally, they exit through the pump arm in the opposite direction. As SPDC preserves the phase, the final state in the CWi path reads

$$|\psi_{\text{cwi}}\rangle_{si} = e^{i\phi_p} |HH\rangle_{si}, \quad (1)$$

where the subscripts s and i denote down-converted signal and idler photons. Conversely, if the pump is horizontally polarized, it propagates through the CCWi path. The pump light first travels through the HWP to rotate its polarization and then undergoes down-conversion into the crystal. The paired photons pass through a dispersive medium and exit the PBS through the pump arm. Thus, the final state in the CCWi path is given by

$$|\psi_{\text{ccwi}}\rangle_{si} = e^{i\phi_s + \phi_i} |VV\rangle_{si}. \quad (2)$$

Finally, we consider the pump to be diagonally polarized:

$$|\psi_{\text{in}}\rangle_p = |D\rangle_p \equiv \frac{1}{\sqrt{2}}(|H\rangle_p + |V\rangle_p), \quad (3)$$

where the subscript p denotes the pump. No relative phase between the horizontal and vertical polarization components

is considered. Assuming that the SPDC efficiency is equal in both directions, the final state after propagation is the coherent superposition of Eqs. (1) and (2):

$$|\psi_{\text{out}}\rangle_{si} = \frac{1}{\sqrt{2}}[|HH\rangle_{si} + e^{i\Delta\phi} |VV\rangle_{si}], \quad (4)$$

$$\Delta\phi = \phi_s + \phi_i - \phi_p = (k_s + k_i - k_p)L. \quad (5)$$

Here, k and L denote the wave vector of the interacting photons and the length of the dispersive medium, respectively. Therefore, the photons are prepared in a maximally polarized entangled state, and the relative phase between the contributions to the state solely depends on the dispersive properties of the SUT. The phase imparted by the dispersive medium can be expressed as a Taylor expansion of the wave vector of the signal and idler photons around the degenerate frequency:

$$\frac{\Delta\phi}{L} = -k_p + \sum_{k=i,s} \sum_{n=0}^{\infty} \beta^{(n)} \frac{\Delta\omega_k^n}{n!}, \quad (6)$$

where $\beta^{(n)} = \frac{\partial^n k}{\partial \omega^n}|_{\omega_0}$ and $\Delta\omega$ stands for the detuning from ω_0 . The energy conservation of the nonlinear process implies $\Delta\omega_s = -\Delta\omega_i$. Consequently, every odd-order term of the dispersion vanishes, a phenomenon called nonlocal dispersion cancellation [16]. By limiting the Taylor expansion to the second order, i.e., neglecting fourth-order dispersion, the relative phase carried by the entangled state reads

$$\Delta\phi = (\beta^{(2)} \Delta\omega^2 + 2\beta^{(0)} - k_p)L = \beta^{(2)} \Delta\omega^2 L + \phi_{\text{off}}, \quad (7)$$

where $\beta^{(2)}$ represents the CD. Therefore, two-photon interference pattern measured from the entangled state in the spectral domain will lead to quadratic fringes, allowing the direct extraction of the CD. This striking feature of quantum white-light interferometry (QWLI) stands as a unique and precise method for CD measurement. Here, it is the only free parameter of the relative phase, in opposition to classical white-light interferometry, where odd-order dispersion terms are still present [17]. Furthermore, the polarized Sagnac configuration offers two main advantages. On one hand, as the system is self-stabilized, it is extremely immune to environmental drifts (i.e., temperature, vibration) and does not require any passive or active stabilization. It therefore enables the development of an easy-to-use, compact, and robust experimental setup. On the other hand, it relies on polarization entanglement, avoiding the inherent 3 dB loss attributed to time-energy entanglement in the case of a nondeterministic splitting [18,19]. While classical CD measurement, such as phase modulation [20] and time of flight [21], needs dozens of meters to kilometric sample lengths, QWLI based on nonlinear Sagnac interferometer provides the capability to measure CD in samples as short as a few centimeters. This distinctive feature opens up avenues for precisely characterizing the dispersion of various materials, including optical chips (such as microrings and silicon waveguides), bulk glasses, or nonlinear media [22].

III. EXPERIMENTAL REALIZATION

From theory to experiment. To ensure compliance with telecom standards, an experimental setup based on cascaded up- and down-conversion is used [23], as depicted in Fig. 2, where the interferometric setup lies in the gray dotted line. In

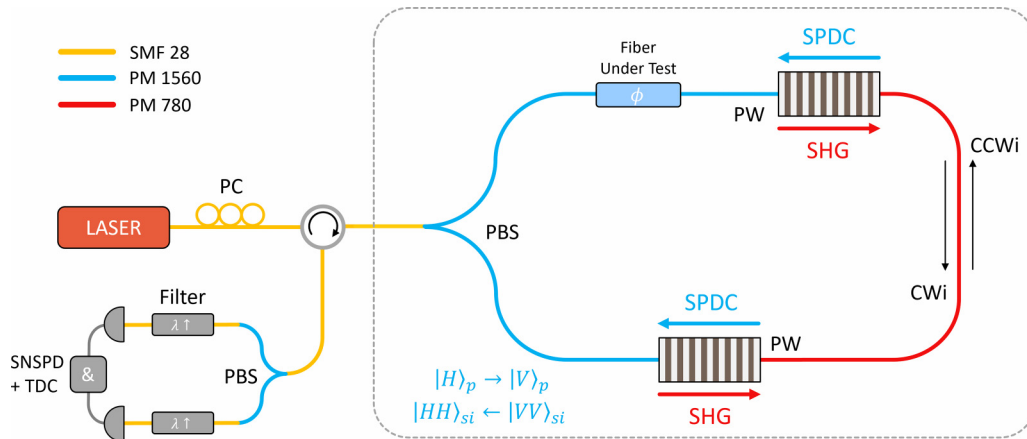


FIG. 2. Experimental setup for CD measurement using the nonlinear Sagnac interferometer. An amplified and filtered telecom laser is injected into the Sagnac loop, which consists of the FUT and two type-0 PPLN waveguides. The blue (red) path represents polarization-maintaining telecom (visible) fiber. The two output arms of the PBS are aligned to the same polarization axis such that only one polarization state propagates inside the interferometer. At the loop's output, a circulator directs the photons to the detection apparatus, comprising a PBS, two tunable bandpass filters, and single-photon detectors for recording coincidence measurements. PW: pigtailed waveguide. SNSPD: superconducting nanowire single-photon detector; TDC: time-to-digital converter.

addition to being fully fibered, this configuration does not involve the use of expensive and cumbersome dual-wavelength components mandatory in free space experiments. It comprises a PBS, a fiber under test (FUT), and two cascaded type-0 pigtailed nonlinear waveguides. Here, the initial pump state is that of Eq. (3), but the pump wavelength is adjusted to match the degenerate wavelength of the paired photons ($\omega_p = \omega_0$). Upon passing through the PBS, the pump beam is once again split into the CWi and CCWi paths, which corresponds to the decomposition of the diagonal state $|D\rangle$ in the $\{|H\rangle, |V\rangle\}$ basis. Note that the two outputs of the PBS are precisely aligned to the same axis, ensuring that only vertically polarized light propagates within the loop. Within the CWi path, the pump first propagates through the FUT, undergoes up-conversion in the first waveguide through second harmonic generation (SHG), and then is down-converted into photon pairs in the second waveguide. At the output, the quantum state associated with the CWi path reads

$$|\psi_{\text{CWi}}\rangle_{si} = e^{i2\phi_0} |HH\rangle_{si}, \quad (8)$$

where the factor 2 comes from the SHG process. Conversely, in the CCWi path, the pump first undergoes up-conversion and then down-conversion, with the photon pairs passing through the FUT. In this case, the contribution to the quantum state of the CCWi path is given by Eq. (2). Finally, assuming that the nonlinear processes are identical in both directions, the output state carried by the photons pairs is a maximally polarization entangled state, as described in Eq. (4). Here, the relative phase difference contains the dispersion cancellation property:

$$\Delta\phi = (\beta^{(2)}\Delta\omega^2 + 2\beta^{(0)} - 2k_0)L. \quad (9)$$

Note that the only difference from Eq. (7) is the value of the phase offset.

Description of the experimental apparatus. A tunable telecom laser is first amplified and propagates in a sequence of filters, commonly referred to as dense wavelength division multiplexers (DWDMs), to eliminate amplified spontaneous

emission. The polarization controller (PC) associated with the PBS allows the precise control of the infrared pump power to precompensate any discrepancies in brightness between the two directions, e.g., losses of the FUT and coupling in the waveguides. The laser light then enters the Sagnac loop, which consists of two nonlinear waveguides in periodically poled lithium niobate (PPLN). The use of polarization-maintaining fibers within the loop eliminates the need for active polarization control and optimizes the SHG and SPDC processes. To ensure high-visibility interference patterns, it is imperative that both the SPDC spectra and coincidence counts from each path are identical to prevent distinguishability. Figure 3 displays the measured spectra from the CWi

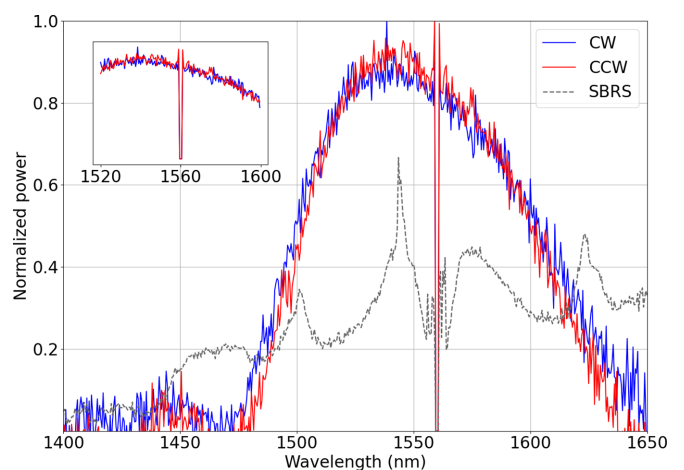


FIG. 3. Spectrum of the photon pairs measured by inserting an optical spectrum analyzer inside the Sagnac loop. The blue curve represents the spectrum in the CWi path, while the red curve represents the spectrum in the CCWi path. The inset provides a closer view of the measurement area. The gray dotted line corresponds to the SBRs spectrum. The dip around 1560 nm corresponds to the DWDMs used to filter out the residual pump.

and CCWi paths. Carefully controlling the temperature of both PPLN waveguides, a nearly perfect spectral overlap is achieved. The FUT is a commercially available polarization-maintaining dispersion-shifted fiber (PM DSF) of length $L = 0.9$ m. At the output of the circulator, additional WDMs are used to prevent any residual pump light from entering the detection stage. This stage comprises a PC and a PBS to project the entangled state into a specific polarization basis. Each arm of the PBS is followed by a tunable bandpass filter, allowing for coincidence measurements in the spectral domain.

Finally, the measurements are performed using superconducting nanowire single-photon detectors (SNSPDs) and a time-to-digital converter (TDC) to record coincidence events. Given the assumption of identical spectra for the photon pairs in both CWi and CCWi paths, the coincidence rate is determined by

$$P_c(\Delta\omega) \propto \frac{1}{2} \text{sinc}\left(\frac{\Delta k_c L_c}{2}\right) [1 + V \cos(\Delta\phi)], \quad (10)$$

where Δk_c and L_c are the phase matching and length of the waveguides, respectively, V stands for the visibility of the two-photon interferences, and $\Delta\phi$ is given by Eq. (9). It is worth mentioning that spontaneous backward Raman scattering (SBRS) occurs within the Sagnac loop, as shown by the spectrum in Fig. 3. The dotted gray line was obtained with the crystals at room temperature to suppress SHG and SPDC processes during the SBRS measurement. The initial set of peaks around the central frequency is a result of SBRS within the fiber, while the subsequent set, located away from the central frequency, corresponds to SBRS within the crystals [24]. This phenomenon exhibits a linear dependence on both input power and material length [25]. However, photons generated via SBRS induce uncorrelated events and do not contribute directly to coincidence detection. A large number of SBRS photons can lead to accidental coincidences, thereby reducing the coincidence-to-accidental ratio. In our specific case, the proportion of accidental SBRS coincidences is less than 1% of the measured SPDC coincidence peak, and is therefore negligible.

IV. RESULTS

Measurement results. The precision is estimated through the measurements of the normalized coincidence spectrum, as a function of the signal photon wavelength (corresponding to the first filter spectral position). We emphasize that prior to any measurement, the polarization of the pump is carefully adjusted to optimize the contribution of the CWi and CCWi paths, thus maximizing the visibility of the interference pattern. An example is presented in Fig. 4(a) in blue. For each measurement point, filters with a spectral bandwidth of $\Delta\lambda \approx 500$ pm are adjusted in accordance with the energy conservation of the SPDC process around the pump wavelength, and a coincidence histogram is registered. In our case, the maximum coincidence rate is approximately 2 kcts/s to prevent statistical errors arising from the Poissonian emission statistic of photon pairs [15]. The interferogram is normalized by the single-photon rate, removing the cardinal sine term found in Eq. (10), and the noise extracted from the coincidence histogram is subtracted. Then, this interferogram

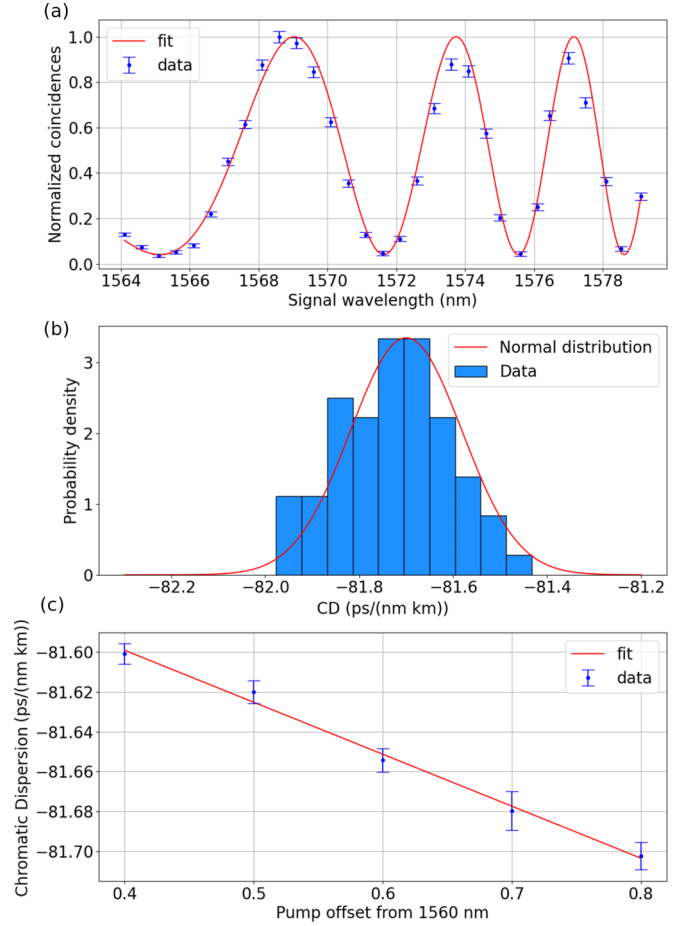


FIG. 4. (a) Normalized coincidence measurement as a function of the signal wavelength; the blue dots are fitted using Eq. (10). (b) Histogram of extracted CD for 100 measurements at $\lambda_p = 1560.800$ nm. The red line is calculated assuming a normal distribution. (c) Extracted CD for different pump wavelengths. The red curve represents a linear fit used to extract the TOD. The error bars are the statistical errors extracted after 100 measurements.

is used to fit the experimental values (red curve) in order to extract the CD of the FUT. Since the statistics of N distinct measurements follows a normal distribution, the experiment is replicated 100 times to ascertain the central value of the CD and its statistical precision, shown in Fig. 4(b). For a pump wavelength of $\lambda_p = 1560.600$ nm, we obtain a CD value of $-81.654(6)$ ps/(km nm), with a statistical error of $7 \times 10^{-3}\%$. To the best of our knowledge, this represents a state-of-the-art measurement for chromatic dispersion at a telecom wavelength, being one order of magnitude higher than classical and quantum measurements [14,15]. Moreover, by normalizing the statistical error by the number of detected photons $N \approx 1.2 \times 10^9$, we find a precision of 208 ps/(km nm)/ $N^{1/2}$, which is reached using 3 times less photons compared to the same precision of the aforementioned QWLI measurement for the same value. We emphasize that the calibration of the CD of the system itself (without the FUT) is essential to exclusively extract the CD of the FUT. While in our case this measurement leads to an apparent negligible value (no visible fringes in the spectrum), measuring the CD subtraction of 2

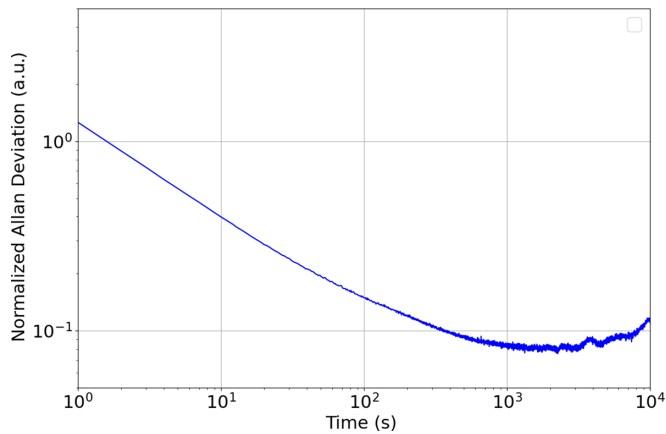


FIG. 5. Normalized Allan deviation. The measurement is performed at fixed filter positions around the steepest point of the first interference fringe.

FUTs with different lengths would lead to a calibration-free approach.

Then, we proceed with evaluating the accuracy by measuring the derivative of the CD, known as the third-order dispersion (TOD). The derivative allows us to infer the variation in CD, thus enabling us to compare the slopes of the estimated and target parameters, the latter being provided by the manufacturer. The measurement procedure, involving the recording of a coincidence spectrum, was repeated for various pump wavelengths ranging from $\lambda_p = 1560.400$ nm to $\lambda_p = 1560.800$ nm, which correspond to the phase matching bandwidth of the crystals, with a step of $\Delta\lambda_p = 100$ pm. For each pump wavelength, the experiment is repeated 100 times. The results are illustrated in Fig. 4(c).

Result analysis. Assuming that the second-order derivative of the CD, i.e., the fourth-order dispersion, is negligible, the TOD is easily extracted through a simple linear fit of the experimental CD values. We obtain a TOD value of $-0.26(1)$ ps/(nm² km), corresponding to a fit uncertainty of less than 5%, which stands as a state-of-the-art measurement for TOD [17]. We emphasize that both the CD and TOD values fall within the range of the manufacturer's specifications [26], $-85(9)$ ps/(km nm) for the CD and $-0.28(2)$ ps/(nm² km) for the TOD. While the statistical error of the CD measurement is related to the precision of the protocol, the quadratic error of the extracted TOD indicates the accuracy of the measurement. Both values, directly accessible from the experimental parameters of the setup, attest to the quality of the results related to the chosen architecture and its implementation, ensuring the stability and reliability of the measurement procedure.

Uncertainty analysis. Assessing the accuracy of the interferometer requires a careful analysis of stability and systematic errors. A static measurement is first performed, i.e., without moving the spectral filters, to extract the Allan deviation of the setup, as shown in Fig. 5. The bias instability, corresponding to the minimum of the Allan deviation, occurs at a characteristic time $t \approx 2250$ s, primarily induced by long-term polarization and power drifts of the pump laser. In this case, the measurement time of a single interferogram is ≈ 50 s,

which remains significantly lower than the bias instability, demonstrating the stability of the Sagnac interferometer.

The Sagnac phase induced by the rotation of the interferometer, or by vibration noise translated into rotational noise, is given by

$$\phi = 2 \frac{2\omega RL}{2c_0^2} \Omega, \quad (11)$$

where ω , R , L , c_0 , and Ω denote the frequency of the telecom pump, the radius of the Sagnac loop, the length of the FUT, the speed of light, and the angular velocity of the loop, respectively. The first factor of 2 results from the use of entangled photon pairs. By applying this equation with the dimensions of the experiment, the required loop rotation to achieve a π phase shift is found to be $\approx 7748^\circ/\text{s}$. The experiment was conducted using a standard laboratory optical table, actively isolated from vibrations and not subjected to rotation. Consequently, the Sagnac phase, as well as vibration and rotation noise, can be considered negligible.

Regarding calibration, the pump wavelength, which determines the measurement wavelength, is known within 8 MHz, corresponding to the accuracy of a commercial wavemeter. We measured a long-term drift of ≈ 50 MHz/h, which corresponds to a statistical uncertainty in the CD measurement of $\approx 10^{-4}\%$. Additionally, the spectral filters are calibrated with sub-GHz precision. Any calibration discrepancy between the two filters, relative to the energy conservation of the photon pairs, would solely result in a loss of the overall coincidence count.

Polarization mode dispersion and its effect on the uncertainty are negligible since the entire interferometer and the FUT maintain polarization and only vertical polarization propagates within the loop. Moreover, the loop itself acts as a horizontal polarization filter as the phase matching condition of the crystals for both SHG and SPDC implies a vertical polarization.

Although the precise refractive index law of the FUT is not known, the impact of temperature fluctuations on the CD of fused silica is theoretically analyzed [27]. A CD variation of $\approx 2 \times 10^{-2} \%$ /K at room temperature is obtained. By measuring the temperature of the experimental room, we find a variation of ≈ 0.2 K/h, which gives a statistical uncertainty on the CD measurement of $4 \times 10^{-3}\%$. Therefore, precise temperature stabilization of the FUT could enhance both the statistical precision and accuracy of the measurement.

It is worth noting that measuring the spectrum of the system for different pump wavelengths corresponds to measuring its joint spectral intensity (JSI), which encodes the spectral correlations of the paired photons as a function of the pump wavelength. Thus, by acquiring the JSI with a spectrally broadened pump laser, the CD and therefore TOD could be extracted by a single-shot measurement. By assuming the pump bandwidth to match the phase matching bandwidth of the crystals, the limitation of this measurement would be determined by the latter; i.e., using shorter crystals or aperiodic poled crystals would provide access to more CD values from which higher-order dispersion terms could be inferred. Moreover, as the Sagnac configuration relaxes constraints on the pump coherence since the optical paths are identical in both

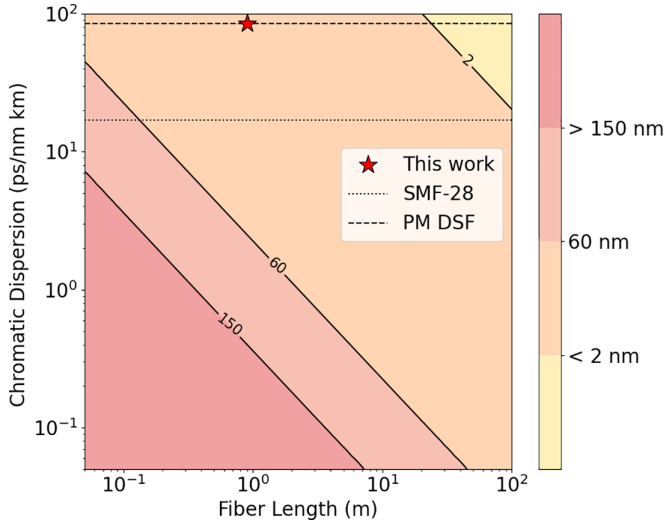


FIG. 6. Spectral width of the first quadratic two-photon fringe as a function of the sample length and its CD value. The dotted lines represent the dispersion value of the FUT and a standard SMF-28 telecom fiber. PM DSF: polarization maintaining dispersion-shifted fiber.

CWi and CCWi directions, a standard wide-spectrum light source such as a superluminescent diode could be employed. This is in contrast to both Mach-Zehnder and Michelson configurations, which necessitate the use of a pulsed coherent laser.

In a broader context, the working range of the nonlinear Sagnac loop for CD measurement can be calculated by deducing the spectral width of the first quadratic fringe of the two-photon interference:

$$\Delta\lambda = \left(\frac{\lambda_p^4}{2\pi c^2 |\beta^{(2)}| L} \right)^{1/2}. \quad (12)$$

In this equation, we assume $\phi_{\text{off}} = 0$. The spectral width is presented in Fig. 6 as a function of the SUT length and its CD. This synthetic figure can be divided into four zones:

(1) The yellow zone corresponds to scenarios where both dispersion and SUT length play the most significant role (resulting in narrow fringes), requiring extremely narrow filters.

(2) The orange zone represents the CD measurements accessible with our system, including the interferometer and filters.

(3) The salmon and red-colored zones depict cases where either the length of the SUT is short and/or its CD value is low (resulting in wide fringes). To measure the CD in these scenarios, filters with a broader bandwidth are required, and the waveguides should be shorter to achieve a wider single-photon spectrum.

While our system is mainly limited by the bandwidth and operating range of the filters used for coincidence measurements, the orange zone remains fully accessible even for longer samples, given the self-stabilizing nature of the Sagnac loop. Consequently, CD can be extracted from relatively small samples, ranging from a few centimeters of optical materials to kilometer-long fibers, even when the latter approach

zero-dispersion values, demonstrating the versatility of the method, which, to the best of our knowledge, is not currently available. In contrast, traditional methods such as time-of-flight and phase modulation require long fiber lengths to accumulate a measurable signal for achieving high precision [15].

V. CONCLUSION

In this work, we have introduced a quantum nonlinear interferometric configuration for CD measurements based on a Sagnac loop. This approach enables precise, accurate, and self-stabilized optical phase measurements, showcased by the measurement of CD. By exploiting the polarization entanglement of photon pairs within this nonlinear Sagnac architecture, our method significantly surpasses conventional techniques in both accuracy and experimental simplicity. The system's intrinsic self-stabilizing nature, which eliminates the need for intricate active stabilization mechanisms, combined with the advantages of utilizing entangled photon pairs, constitutes one of its key strengths.

Beyond its robustness, the versatility of this interferometer—capable of characterizing a broad spectrum of optical samples, ranging from kilometers of fiber to materials only a few centimeters in length—underscores the maturity and practical potential of quantum technologies. Furthermore, this work paves the way for future miniaturization efforts, particularly with the integration of $\chi^{(3)}$ nonlinearities into compact, micrometer-scale devices, reinforcing the transformative potential of quantum metrology based on photon entanglement. Our results demonstrate a clear path forward for the development of photon-based sensors that marry high performance with user-friendly operation, ensuring that quantum-enhanced measurement systems will continue to push the frontiers of experimental science and technology.

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All the authors contributed equally to the entire process, from the first draft to the final version of the manuscript before submission. We all read, discussed, and contributed to the writing, reviewing, and editing. S.T. and L.L. coordinated and managed the project, ensuring its successful completion.

The authors declare that there are no competing interests.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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