

Toward integrated sensors for optimized optical coherence tomography with undetected photons

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The development of practical sensors for optical coherence tomography (OCT) with undetected photons requires miniaturization via integration. To be practical, these sensors must exhibit a large spectral bandwidth and a high brightness, which are linked to a high axial resolution and a sufficient signal-to-noise ratio, respectively. Here, we combine these requirements in a scheme for OCT measurements with undetected photons based on nonlinear Ti:LiNbO₃ waveguides. We investigate the performance benchmarks of the commonly used SU(1,1) scheme in comparison to an induced-coherence scheme and find that the latter is actually better suited when implementing measurements with undetected photons in integrated systems. In both schemes, we perform pump-gain optimization and OCT measurements with undetected photons with an axial resolution as low as 28 μm .

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I. INTRODUCTION

Classical ultrafast spectroscopy employs spectrally broadband light to measure spectral and spatial features of an object under test with high resolution. Typical systems rely on interferometric schemes in which the pulse is split into a probe and a reference path. After interaction of the probe pulse with the sample, spectral or temporal interference of the probe and reference is recorded. This allows one to obtain spatial depth information (via optical coherence tomography, OCT [1]) or spectral information (via Fourier-transform spectroscopy [2]) of a sample under test. Naturally, probing and detection occur at the same wavelength in these systems. This leads to challenges for detection when moving to wavelengths in the mid-infrared (MIR) spectral range and prohibits applications in the low-light regime.

Recently, the use of quantum nonlinear interferometers based on nondegenerate photon-pair sources has opened up previously inaccessible pathways to circumventing this problem, allowing for techniques that are referred to as “measurements with undetected photons.” In these

schemes, a photon at a long wavelength that is in a spectral region that is technically hard to access—e.g., the MIR—probes the object. Meanwhile, a second photon at a short wavelength serves as a reference and can be detected by broadly available detectors, e.g., in the near infrared. Due to information transfer from the long-wavelength photon to the short-wavelength photon, properties of the object under test can be extracted at this shorter wavelength. Consequently, many techniques from the field of ultrafast spectroscopy have been realized in this scheme; examples include spectroscopy [3–5], imaging [6–9], and OCT [10,11] with undetected photons.

OCT is generally implemented in two operational modes: time domain (TD) and Fourier domain (FD). In classical OCT devices, FD-OCT is often favored as it allows one to record a single-shot spectral interferogram and does not require moving parts; however, when operating with single photons, expensive spectrometers and long integration times are required. Therefore, TD-OCT becomes appealing at low light levels. Here, spectrally unresolved measurements can be carried out using a scanning approach with affordable single-photon detectors.

Quantum nonlinear interferometers generally come in two configurations, which differ in how the interference is realized. These are referred to as the induced-coherence (IC) [12] and SU(1,1) [13] schemes, and these will be discussed in more detail later. One of the first realizations of measurements with undetected photons, published in 1991, was performed in a setup based on IC [12].

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The first practical application demonstrated imaging with undetected photons of different colors [6]. Since then, the SU(1,1) configuration has gained more prominence due to the ease in alignment for experiments employing bulk nonlinear crystals. Recently, both setups have also been combined to design hybrid arrangements that allow for changes in the sensing modes [14,15] or have even been investigated in terms of the quantum optical properties in OCT [10,11,15,16].

So far, most experimental realizations have been based on bulk nonlinear crystals. For practical applications with widespread industrial use, however, integration is required. This comes with its own challenges: waveguides offer a long interaction length, which increases source brightness but generally limits the spectral bandwidth unless careful dispersion engineering is employed [17–19]; furthermore, due to the different wavelengths involved in measurements with undetected photons, waveguides can support multiple spatial modes, which limits interference in a specific mode.

In this work, we establish a detailed framework for the design and realization of integrated sensors for OCT with undetected photons. To this end, we demonstrate—in theory and experiment—how dispersion-engineered, broadband integrated photon-pair sources can be optimally used for the development of a practical quantum sensor comparing both the SU(1,1) and IC schemes. This comparison for an integrated platform adds to current developments toward interferometers operating in hybrid setups [14,15], highlighting that different geometries can have benefits for specific applications.

In our investigation, we first identify the optimal operation points of the pump-gain ratio of both schemes. Subsequently, we find that the IC scheme not only offers improved axial resolution when compared to the

SU(1,1) scheme but also simplifies system design and simultaneously improves robustness thanks to inherent single-spatial-mode operation for the probe and reference photon. Furthermore, we benchmark the performance of both systems against each other in terms of the axial resolution, pump power consumption, and axial scanning range of our system in the FD-OCT and TD-OCT operation modes. As a result, we identify TD-OCT in the IC scheme as the best candidate for the construction of an integrated quantum sensor.

II. THEORETICAL DESCRIPTION

Figure 1 shows a schematic realization of a nonlinear interferometer in the SU(1,1) and IC configurations. The interferometer is constructed from two identical, consecutive waveguide-based parametric down-conversion processes (PDC 1 and PDC 2) that are pumped with a common pump laser to ensure coherence. The generated long-wavelength photon (idler) from PDC 1 probes an optional target, in our case a bilayer sample with partially reflective surfaces, before it is coupled into PDC 2. The two processes are made indistinguishable by carefully aligning the paths of the idler photons from PDC 1 and PDC 2 on top of each other, which leads to quantum interference between the photon-pair-generation probability amplitudes of processes PDC 1 and PDC 2. Thereby, information is transferred from the long-wavelength photon of PDC 1 onto the short-wavelength photon (signal) of PDC 2. This information can then be uncovered upon interference of the signal photons from both processes.

In the IC configuration, the signal photons from PDC 1 and PDC 2 must be combined to interfere on an external beam splitter. In the experiment, the two signal fields are

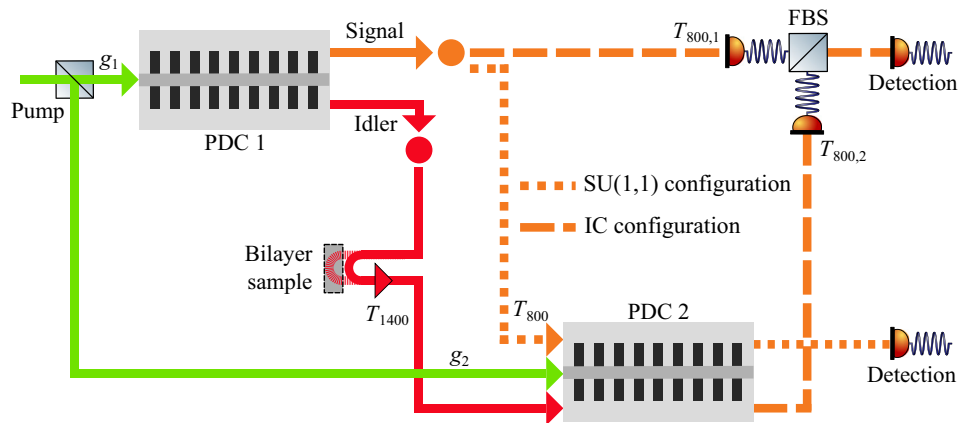


FIG. 1. Concept of a nonlinear interferometer in the SU(1,1) geometry (dotted) and in the IC geometry (dashed). In both cases, the idler photon from the first parametric down-conversion (PDC) process interacts with a bilayer sample. The signal photon from the first process overlaps with that from the second process either in the second PDC source in the SU(1,1) case or on a fiber beam splitter (FBS) in the IC case.

coupled into single-mode fibers and made to interfere on an integrated fiber beam splitter. The resulting interference is detected at one output port of the beam splitter.

In the SU(1,1) configuration, the signal from PDC 1 is sent through PDC 2 together with the idler. Here, interference is detected directly at the output of PDC 2.

For our OCT measurements, we place the aforementioned bilayer sample—which we define to have a layer separation d and layer reflectivities r_1 and r_2 —in the idler arm, as depicted in Fig. 1. Here, r_1 and r_2 are real numbers chosen such that the incoming light is reflected by either one layer or the other. The sample imprints a complex reflection coefficient $r(\Delta\omega)$ onto an incoming idler light field as

$$r(\Delta\omega) = r_1 + r_2 \exp\left(i \frac{2n_g d \Delta\omega}{c}\right), \quad (1)$$

assuming a constant group refractive index n_g over the spectral range of the incident PDC light. This is justified, as the difference in the group indices amounts to 0.5% over the spectral bandwidth covered in the experiment. Furthermore, we consider a frequency detuning $\Delta\omega = \omega_s - \bar{\omega}_s = -(\omega_i - \bar{\omega}_i)$ around the signal and idler central frequencies $\bar{\omega}_{s,i}$, assuming a continuous-wave pump laser.

With this object under test, the spectral interferogram at the signal wavelength can be written as

$$S(\Delta\omega) \propto |f_{\text{PDC}}(\Delta\omega)|^2 [1 + r_1^2 \times \cos(\Phi_{\text{int}}(\Delta\omega) + \tau \Delta\omega) + r_2^2 \times \cos(\Phi_{\text{int}}(\Delta\omega) + \tau \Delta\omega + 2n_g d/c \Delta\omega)]. \quad (2)$$

This interferogram is determined by the joint spectral amplitude (JSA) of a single PDC process $f_{\text{PDC}}(\Delta\omega)$, which describes the spectral distribution of the generated PDC light around the central frequencies, an optical path delay between the two processes τ , and an internal phase within the interferometer Φ_{int} . Both of these terms, as well as the underlying theoretical model, are discussed further in the [Appendix](#).

The resulting spectral interference pattern exhibits a beating between two distinct frequencies. Upon Fourier transformation, we observe two distinct peaks with a width that is determined by the spectral width of the biphotons contained in f_{PDC} via the Wiener-Khinchin theorem [1,20] (see [Appendix](#)). These peaks can be shifted by adjusting the optical path delay τ in the idler arm. This enables the avoidance of an overlap with the zero component and reduces low-frequency noise contributions. The distance of the sample layers, with separation $2n_g d/c$ as the round-trip optical path delay, is given by the peak separation in this Fourier transform.

Similarly, the temporal interferogram can be obtained by photon counting at the signal output while varying the temporal delay τ . This measurement is spectrally unresolved

and therefore equivalent to an integration over all spectral components. Thus, the observed signal count rate is given by

$$C_s(\tau) = \int_{-\infty}^{\infty} d\Delta\omega S(\Delta\omega, \tau). \quad (3)$$

An interference pattern in the signal photon count rate can be observed every time the time delay τ in the argument of the cosine terms in Eq. (2) matches the delay introduced by the separation between the sample layers. Thus, while scanning the reference delay, interference patterns are observed at delays that are separated by $2n_g d/c$. The achievable axial resolution is again given by the bandwidth of the biphoton source.

Nonetheless, in practical systems with integrated PDC sources, internal phases such as second-order dispersion lead to the generation of chirped biphotons in the PDC state. This results in longer actual correlation times and an increased width of the temporal interferograms, as discussed in Ref. [21]. Ultimately, this intrinsic dispersion during the generation of broadband photon pairs leads to a decreased axial resolution of the directly measured signals. The broadening of the signal can be numerically compensated for in postprocessing, as we discuss in the Supplemental Material [22] (see also Refs. [20,23,24] and references therein).

In addition to the shape of the interference signal, which defines the resolution and layer separation, a high signal-to-noise ratio (SNR) is necessary for a practical quantum sensor. When performing measurements with undetected photons, the interference visibility serves as an equivalent indicator of this SNR [25]. We achieve the highest visibility if the number of interfering photons from both processes is equal [26]; therefore, we consider different pump gains for the two PDC processes $g_{1,2}$ to maximize the visibility of the spectral interference. The gain parameter is proportional to the measured pump power, $g \propto \sqrt{P}$. From this follows the mean photon number of each PDC process as $\langle n \rangle = \sinh^2 g \approx g^2$ [26], which we use to calculate the expected interference visibility from the pump power in the experiment. Here, we consider operation in the single-photon-pair regime, where the gains $g_{1,2} \ll 1$. This coincides with our assumption of generating at most one photon pair per joint spectral mode in either of the two PDC processes.

In the following, we adapt the calculation in Ref. [26], which describes an SU(1,1) interferometer with losses between the two nonlinear processes and demonstrates how a high interference visibility can be restored by adjusting the pump-gain ratios. Although this theory assumes a single spectral mode, we can still apply it to our spectrally multimode system by detecting the frequency-resolved

interferograms. Thereby, we evaluate the system in distinct, effective spectral bins. In the time-resolved measurements, we expect a lower visibility due to second-order dispersion; however, this visibility is still maximal for the extracted optimal pump-gain ratios.

Differential pumping has been shown before in setups based on bulk nonlinear crystals [27] and for pump-gain regimes exceeding the low-gain limit [28]; however, when working with hybrid integrated setups, which combine waveguides and free-space beam propagation, differential pumping becomes even more relevant for counteracting losses from coupling out of and into the waveguide.

Specifically, the visibility at the signal wavelength around 800 nm in our measurements with undetected photons in the SU(1,1) scheme is given by [26]

$$V_{800,\text{SU}(1,1)} = \frac{2\sqrt{T_{800}T_{1400}g_1g_2}}{T_{800}g_1^2 + g_2^2}. \quad (4)$$

The relevant transmission and gain values are indicated in Fig. 1. We can observe that the maximum visibility is bound by the transmission in the idler arm T_{1400} and is reached at a pump-gain ratio of $g_1^2/g_2^2 = 1/T_{800}$ which is given by the transmission in the signal arm T_{800} . For a guided-wave PDC source, these transmission values are reduced due to coupling to the second source. Thus, the second waveguide source typically requires weaker pumping than the first.

So far, differential pumping has only been investigated in the SU(1,1) configuration; however, we also want to study these effects in the IC configuration. We therefore expand on the above treatment and now derive an expression for the visibility in the IC case (see Supplemental Material [22]). In this configuration, the two signal fields from both PDC processes are now coupled into two single-mode fibers for interference on a fiber beam splitter. Such a beam splitter ensures perfect spatial overlap and high-quality interference. Thus, two transmission parameters representing the fiber coupling efficiencies, $T_{800,1}$ and $T_{800,2}$, for the signal fields from the first and second processes must be considered in the calculation of the interference visibility:

$$V_{800,\text{IC}} = \frac{2\sqrt{T_{800,1}T_{800,2}T_{1400}g_1g_2}}{T_{800,1}g_1^2 + T_{800,2}g_2^2}. \quad (5)$$

It can be seen that the visibility is still limited by the idler transmission T_{1400} . Meanwhile, the optimal pump-gain ratio $g_1^2/g_2^2 = T_{800,2}/T_{800,1}$ is now determined by the ratio of the fiber coupling efficiencies from the first and second sources. These efficiencies can be optimized—without interacting with the waveguide source at the core of the interferometer—via mode matching for the fiber couplings and can reach values close to 1. Furthermore, the optimal pump gain is now determined solely by the ratio of

the fiber coupling efficiencies. This allows one to optimize the pump-gain ratio, e.g., by attenuating one signal beam, without having to adjust the pump powers. Such a procedure may be beneficial when working with a source that is equipped with a high-reflectivity coating for the pump light, eliminating the need for a second pump-coupling stage as in Ref. [21].

An additional technical advantage of the IC configuration is the elimination of the back-coupling of the signal field from the first process into a spatially multimode waveguide.

III. EXPERIMENTAL SETUP

The central element of the interferometer as shown in Fig. 2 is a 40-nm-long, periodically poled Ti:LiNbO₃ guided-wave PDC source with matching signal and idler group velocities, thus reaching spectral bandwidths of more than 6 THz. The shape and bandwidth of the PDC spectrum emitted from this source can be tuned by adjusting the waveguide temperature [18].

In the experimental setup, we pump our waveguide with a 514-nm continuous-wave laser, generating PDC light at 830 and 1360 nm in the signal and idler fields, respectively. The pump-gain ratio between the two PDC processes is adjusted by introducing a half-wave plate and polarizing beam splitter in front of the waveguide to split the pump power and achieve gains g_1 in the forward direction and g_2 in the backward direction. The pump polarization is adjusted in both arms to match the requirement for the type-II phase matching.

The signal and idler photons, which are generated in the first pass of the pump light through the waveguide, are collimated by an off-axis parabolic mirror. We separate the signal and idler photons using a dichroic mirror.

As illustrated in Fig. 2, we realize two different schemes for our nonlinear interferometer: the SU(1,1) scheme and the IC scheme, which are marked by the blue and yellow boxes, respectively. In both cases, the longer-wavelength idler interacts with a layered object under test before it is coupled back into the waveguide. The end mirror in the idler arm is moved with a motorized stage to introduce a delay between signal and idler, resulting in a linear spectral phase. The signal photons are either reflected back and coupled to the waveguide in the SU(1,1) scheme or directly coupled to a single-mode fiber in the IC scheme. We note here that the signal field is spatially multimode and therefore critically sensitive to misalignment when coupled back to the waveguide in the SU(1,1) configuration. This technical challenge is overcome in the IC configuration by directly coupling to single-mode fibers, which avoids the possibility of coupling to higher-order spatial modes.

After the second PDC process, the interference at the signal wavelength is observed by separating the interfering

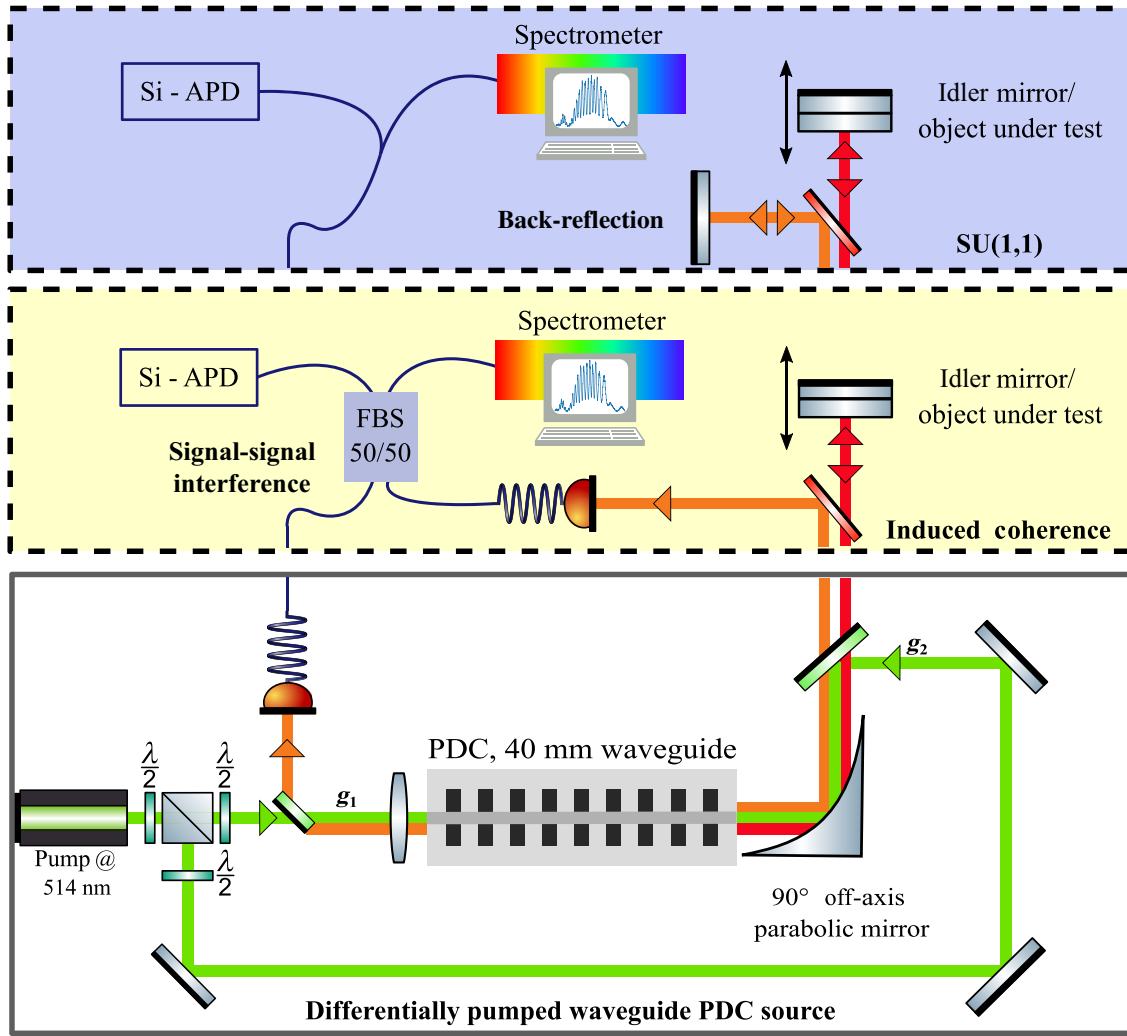


FIG. 2. The experimental setup consists of a differentially pumped 40-mm-long Ti:LiNbO₃ waveguide as a PDC source. The photons generated from the first process are collimated by an off-axis parabolic mirror. Subsequently, either both photons are coupled back into the waveguide [SU(1,1) scheme] or the signal is routed around the waveguide to a fiber beam splitter to interfere with the signal from the second process, while only the idler is coupled back to the waveguide (IC scheme). In both cases, the idler field interacts with a bilayer object under test, and the relative delay between signal and idler can be tuned by a motorized stage in the idler arm. The temporal and spectral interferograms are detected on a silicon avalanche photodiode (APD) or spectrometer, respectively.

signal photons from the pump and idler and coupling them to a single-mode fiber. In the SU(1,1) scheme, the interference occurs during the second pass through the nonlinear waveguide and can be observed directly in the signal field exiting the waveguide. For the IC scheme, the interference at the signal wavelength can be observed by coupling the photons from the first and second pass to a 50:50 fiber beam splitter. Both spectral and temporal interference can then be observed in both configurations.

IV. RESULTS

In this section, we provide the most important benchmarks of our system in the two different configurations. With that, we determine their suitability for the

implementation of a practical quantum sensor. We concentrate on optimizing the interference visibility for a high SNR via pump-gain optimization and discuss the axial resolution achieved in FD-OCT and TD-OCT.

We do not compare the SNR achieved by the two measurement techniques and experimental schemes, since the measurements were carried out at different pump powers and under different experimental conditions. As such, we are more interested in the general behavior of the system. Furthermore, the impact of other parameters, such as the signal losses, the system's sensitivity to low layer reflectivities, and the effects of averaging data, can be found in the Supplemental Material [22].

We start by optimizing the pump-gain ratio to achieve the highest interference visibility in both experimental

setups. Here, we measure the visibility of the spectral interferogram for different pump-gain ratios and compare the values obtained to the theoretical expectations.

We present the results for the SU(1,1) scheme in Fig. 3(a). The visibility is first measured using a plain silver idler end mirror, followed by a measurement using the reflection from a partially reflective ND03 filter that was attached to the silver mirror. This leads to idler transmission values of $T_{1400} = 0.4$ and $T_{1400} = 0.2$, respectively, which include losses due to coupling to the waveguide and the partial reflectivity of the filter.

In both cases, we observe a maximum in the visibility for a pump-gain ratio of $g_1^2/g_2^2 = 1/T_{800} \approx 3$, as expected from Eq. (4). This sets the optimal operation point of the SU(1,1) interferometer. It is important to note that this condition is independent of the idler transmission; hence, every test object is probed with the optimal SNR.

Furthermore, we can determine the reflectivity of the object in the idler arm by comparing the two transmission values. These transmission values are the only parameters used to match the experiment to the simulations, and they agree well with the expected coupling losses to the waveguide. We observe that, without further optimization of data acquisition, our setup can correctly retrieve transmissions in the idler arm as low as 5%, as shown in Fig. S2 in the Supplemental Material [22]. This highlights the capability to detect layers with low reflectivities in an object under test. Losses in the signal field, e.g., due to environmental impacts, can be mitigated by optimizing the pump-gain ratio, as investigated in Fig. S3 in the Supplemental Material [22].

In the IC scheme, the optimal pump-gain ratio is not determined by the coupling of the signal field to the waveguide but by the ratio of the fiber coupling efficiencies

$T_{800,1}$ and $T_{800,2}$. This behavior can be nicely observed in the data shown in Fig. 3(b). Here, the theory curve reaches its maximum at $g_1^2/g_2^2 = T_{800,2}/T_{800,1}$ and is based on the experimentally determined fiber coupling efficiencies of $T_{800,1} = 32\%$ for the signal from the first pass and $T_{800,2} = 28\%$ for the signal from the second pass.

The relevant fiber coupling efficiencies can be optimized without changing the alignment within the interferometer and can therefore reach values close to unity with adequate mode matching. Here, the realized fiber coupling efficiencies of 32% and 28% lead to an optimal gain ratio of 0.875, which is close to equal powers in both stages. Such a condition with equal pump powers is particularly useful, as it allows for the realization of practical integrated sensors with a simplified pumping scheme: As we have demonstrated in earlier work [21], highly reflective coatings at the waveguide end facets can replace a second pump light beam path. The ability to pump the waveguide from only one side, while still obtaining the optimal pump-gain ratio, makes this approach suitable for further integration of the setup into a practical sensor.

We note that, in both schemes, a high coupling efficiency of the idler field is required for high interference visibility and therefore high SNR. The coupling efficiency of the signal field determines the necessary pump-gain ratio to reach that visibility. At the same time, a high signal coupling efficiency enables higher count rates and shorter integration times.

To demonstrate the capabilities of our experimental setup for a practical sensor, we perform OCT measurements of a bilayer object under test consisting of a neutral-density filter (ND03) attached to a plain silver mirror. This configuration results in two surfaces that reflect the incoming light in equal portions and provides a single-trip optical path difference (OPD) of $\Delta L_{\text{theo}} = (1.50 \pm$

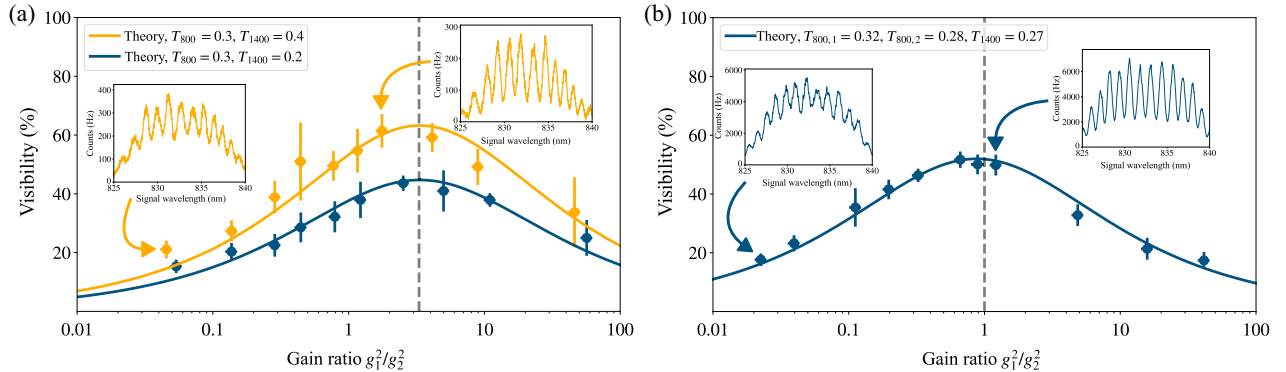


FIG. 3. (a) Gain optimization in the SU(1,1) geometry for two different transmission values in the idler arm at 1400 nm, using the reflection off a plain mirror or the front surface of a partially reflective ND03 filter. The optimal pump-gain ratio remains around 3 for both cases and is highlighted by the dotted gray line. (b) Gain optimization in the IC geometry with a plain mirror in the idler arm. The optimal gain ratio of $g_1^2/g_2^2 = 0.875$ is close to the highlighted value of $g_1^2/g_2^2 = 1$ and is given by the ratio of the fiber coupling efficiencies for the signal fields. The insets show recorded spectral interferograms at different pump-gain ratios, illustrating the increase in interference visibility.

0.15) mm. Here, the ND filter's thickness and its variation are provided by the manufacturer.

We record the FD-OCT and TD-OCT measurements of this sample for the IC and SU(1,1) experimental setups at their respective optimal pump-gain ratios. In these measurements, our focus is on determining the axial resolution of the setup rather than the true OPD introduced by the sample, which can be affected by alignment and potential air gaps.

First, we perform FD-OCT in the SU(1,1) and IC setups with a total pump power of 5 mW. After Fourier transformation of the measured spectral interferograms, the layer separation can be extracted from the distance between the peaks in Fig. 4(a), which shows the amplitude of the Fourier transform on the y axis while the x axis displays the single-trip OPD. The measured raw spectral interferograms, which were used to extract the FD-OCT signal, are shown in Fig. S4 in the Supplemental Material [22].

The measurements in both experimental schemes were performed with different delays introduced by the idler mirror. This leads to different shifts of the peak positions in the two setups, but it does not change their distance. We extract a layer separation of $\Delta L_{\text{SU}(1,1)} = (1.79 \pm 0.03)$ mm and $\Delta L_{\text{IC}} = (1.79 \pm 0.03)$ mm. These OPD values agree with each other and are larger than the expected OPD, which can be attributed to slight misalignment and air gaps. The layer separation of the sample is not homogeneous, introducing inaccuracies in the measured separation between subsequent realizations of the experiment. Therefore, we round the layer separation to the second decimal point. In contrast, the axial resolution is defined via the reflection from a single layer and does not suffer from the same inaccuracies. This allows us to determine the axial resolution with higher accuracy than the layer separation.

The measurements in the SU(1,1) and IC configurations show a similar axial resolution of $\Delta z_{\text{FD},\text{SU}(1,1)} = 29 \mu\text{m}$ for the SU(1,1) geometry and $\Delta z_{\text{FD},\text{IC}} = 28 \mu\text{m}$ for the IC geometry, which we retrieve from the FWHM peak width in the Fourier domain. The peaks from the sample's front layer, which have been used to extract these values, are depicted in an enlarged view of the Fourier transform in Fig. 4(b). Numerical dispersion compensation has been applied to the shown OCT peaks to account for quadratic and third-order phase in the experimental setup (see Appendix). The difference in peak widths can be attributed to slightly different spectral widths of the PDC source due to changes in waveguide temperature between measurements; however, the achieved resolution is close to the theoretically estimated resolution of $29.2 \mu\text{m}$ for the given PDC spectrum.

Finally, we measure the same object in TD-OCT at a total pump power of $50 \mu\text{W}$ by translating the idler mirror while recording the signal photon counts. Here, we can also extract an OPD of $\Delta L_{\text{IC}} = (1.80 \pm 0.03)$ mm and $\Delta L_{\text{SU}(1,1)} = (1.80 \pm 0.05)$ mm in the IC and SU(1,1) schemes, respectively, as shown in Fig. 5(a); however, we observe a better axial resolution of $\Delta z_{\text{TD},\text{IC}} = 34 \mu\text{m}$ in the IC scheme in comparison to $\Delta z_{\text{TD},\text{SU}(1,1)} = 46 \mu\text{m}$ in the SU(1,1) scheme when inspecting the enlarged view of the interference from one surface in Fig. 5(b). Similar to FD-OCT, dispersion compensation can be applied to the TD-OCT measurements, which allows us to reach an axial resolution of $25 \mu\text{m}$, as shown in the Supplemental Material [22].

The IC scheme exhibits a higher axial resolution in TD-OCT compared to the SU(1,1) configuration because only the idler, but not the signal, from the first process experiences the dispersion of the waveguide. This increased resolution reduces the need for phase compensation in

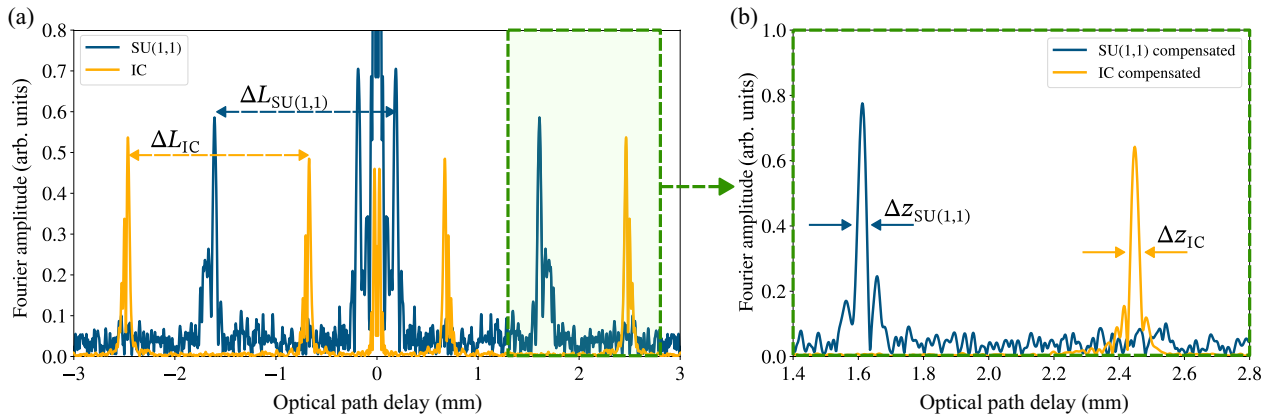


FIG. 4. (a) Fourier amplitude of the FD-OCT signal from the SU(1,1) and IC scheme used to obtain layer separations of $\Delta L_{\text{SU}(1,1)} = (1.79 \pm 0.03)$ mm and $\Delta L_{\text{IC}} = (1.79 \pm 0.03)$ mm. (b) Enlarged view of two peaks in the Fourier-transformed signal of the FD-OCT for the SU(1,1) and IC schemes, revealing axial resolutions of 29 and $28 \mu\text{m}$ from the FWHM after dispersion compensation.

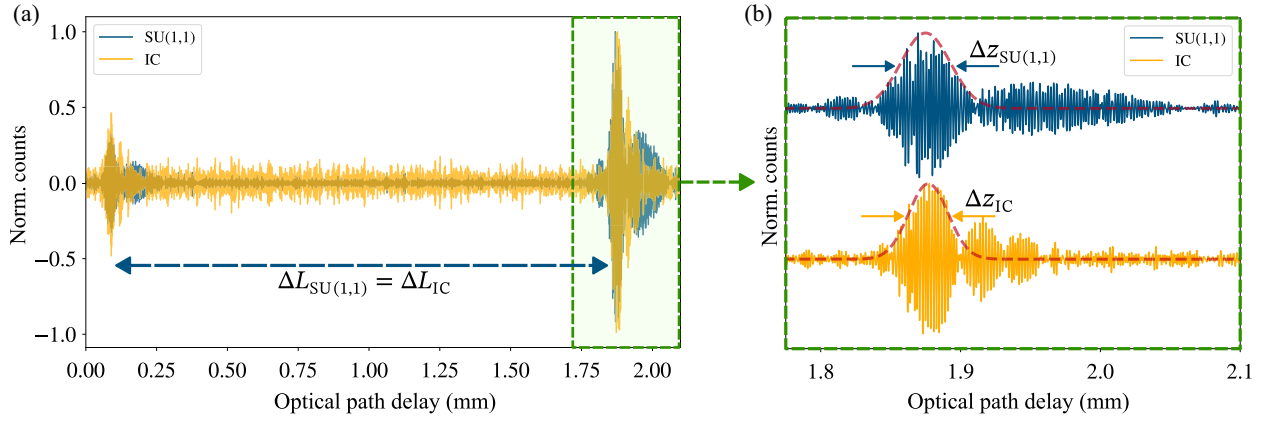


FIG. 5. (a) TD-OCT signals from the SU(1,1) and IC schemes used to obtain the layer separation $\Delta L_{IC} = (1.80 \pm 0.03)$ mm and $\Delta L_{SU(1,1)} = (1.80 \pm 0.05)$ mm, which is identical for both schemes. (b) An enlarged view of two peaks in the colored area reveals axial resolutions of $\Delta z_{SU(1,1)} = 46 \mu\text{m}$ and $\Delta z_{IC} = 34 \mu\text{m}$ for the SU(1,1) and IC configurations, respectively. The count rates in each interferogram are normalized to their maximum. The traces in (b) are offset for better visualization and comparison. A Gaussian envelope has been added for the estimation of the axial resolution.

postprocessing. Thus, the IC scheme is better suited to direct measurements of quantum TD-OCT traces.

Comparing the two methods, FD-OCT and TD-OCT, we find that they require a similar amount of resources. Meanwhile, TD-OCT can be carried out with less expensive equipment as it only requires a single-photon click detector instead of a single-photon-sensitive spectrograph as in FD-OCT, which makes TD-OCT suitable for inexpensive, miniaturized quantum sensors.

To move further toward practical applications, the SNR values of around 300 and 20 in TD-OCT and FD-OCT, respectively, in our proof-of-principle measurements can be increased via longer exposure times or averaging over multiple short measurements. We demonstrate such an increase in SNR due to averaging in the TD-OCT and FD-OCT measurements with undetected photons within our setup in part VII of the Supplemental Material [22]. Although further optimization of the sensor would be required to achieve a higher SNR, our experiments show that high SNR values can be reached at lower pump powers compared to bulk implementations of such a sensor, which typically operate at a few hundred milliwatts of pump power [20].

V. DISCUSSION

In this work, we provide a first comparison between two experimental configurations for nonlinear interferometers—IC and SU(1,1)—with respect to their suitability for the implementation of practical, integrated quantum sensors for OCT measurements with undetected photons. We have seen that integration comes with new challenges, requiring different experimental setups than current realizations of nonlinear interferometers based on bulk nonlinear crystals.

As a first step, we therefore theoretically described both systems, performed pump-gain optimization in both schemes to achieve an optimal gain ratio for a high SNR in the later measurements, and compared the underlying mechanisms in both schemes.

The SU(1,1) scheme, although popular for proof-of-concept demonstrations based on bulk PDC sources, requires coupling of both photons at the long and short wavelengths back into the waveguide. Due to the spatial multimode nature at the short wavelength, this configuration is sensitive to minute alignment errors. Furthermore, due to unavoidable losses while coupling back to the waveguide, it is necessary to pump the two PDC sources with different gains, further complicating the experiment. Lastly, in direct TD-OCT measurements, the SU(1,1) system shows worse performance due to the additional optical path through the dispersive waveguide material.

In contrast, in the IC configuration, the short-wavelength light can be directly coupled to single-mode fibers and interfering on an integrated beam splitter, which ensures perfect spatial overlap and high-quality interference. Moreover, light from both PDC processes can be coupled to the fiber with the same efficiency. Therefore, the optimal operation point is reached when both PDC processes are driven with the same pump power. This can easily be achieved with a reflective end-facet coating for the pump field, which reduces the need for a second pump coupling. Slight mismatches in the two gains can be externally compensated for by adjusting the fiber coupling efficiencies. Finally, the resolution in TD-OCT is improved in this scheme compared to the SU(1,1) configuration.

Considering resource requirements, FD-OCT is the preferred choice if spectrometers are available at the detection wavelength, thanks to its potential single-shot performance. For quantum OCT applications, however,

we find that the reduced pump power requirements of TD-OCT (2 orders of magnitude less than for FD-OCT; see Appendix), combined with the wide availability of cheap single-photon detectors for visible and NIR wavelengths and the (in principle) unlimited axial scanning range, render TD-OCT a better overall choice.

Meanwhile, we see that the achieved axial resolution of 28 μm agrees with the theoretical limit given by the bandwidth of our source and is comparable to the axial resolution achieved by bulk systems around 10 μm [20]. In the future, integrated PDC sources with even larger bandwidths [19] hold the potential to achieve even higher resolutions.

Furthermore, we have seen that our first demonstration of a quantum sensor based on an integrated waveguide source provides a similar SNR compared to already optimized bulk implementations. At the same time, our measurements can be performed at lower pump powers due to the higher brightness of our source. In the future, further optimization and integration of the presented quantum sensor therefore holds the potential for use in practical applications.

In summary, this work lays the foundation for the development of an integrated quantum sensor. We demonstrate that the induced-coherence scheme and TD-OCT may be beneficial in terms of resource requirements when working with integrated systems. Thus, we provide a different perspective on the advantages and challenges connected to using integrated waveguides as photon-pair sources for measurements with undetected photons.

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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.

APPENDIX

1. OCT system benchmarks

The main benchmark of an OCT system is the axial resolution Δz . In OCT with undetected photons, this

resolution is limited by the spectral bandwidth $\Delta\lambda$ of each of the generated PDC photons from our group-velocity matched, integrated source (c.f. Ref. [18]). The maximally achievable axial resolution Δz is then given by the coherence length of the source l_c via

$$\Delta z = l_c = \frac{f}{2} \frac{\lambda_0^2}{\Delta\lambda}. \quad (\text{A1})$$

In this formula, c is the speed of light in vacuum and f is a factor that changes for different shapes of the spectral envelope of the source and can be derived via the Wiener-Khinchin theorem. For our source, which exhibits a rectangular spectrum, this factor is $f = 1.2$ [20]. With a spectral bandwidth in the experiment of $\Delta\lambda = 14.2$ nm and a central wavelength of $\lambda_0 = 832$ nm, this formula predicts an axial resolution of $\Delta z = 29.2$ μm .

We investigate OCT measurements in two modes of operation: TD-OCT and FD-OCT. For TD-OCT, the reference arm needs to be scanned while signal photon counts are recorded to form an interferogram in the temporal domain. Meanwhile, in FD-OCT, the spectral interference is observed on a spectrometer for a fixed detuned position of the reference arm and therefore a fixed time delay. Thus, FD-OCT is mostly used in classical implementations due to higher data-acquisition rates and no need for moving parts in the setup; however, these setups are limited in their axial scanning range ΔL_z due to the limited number of pixels N of the spectrometer used to observe the spectral interference [1,23], resulting in a maximal axial scanning range of $\Delta L_z = \frac{1}{4}(\lambda_0^2/\Delta\lambda)N$. For the system at hand, which has $N = 670$ illuminated pixels, this scanning range for the round-trip optical path delay is $\Delta L_z = 8.2$ mm, which is larger than the tested optical path differences of the object under test used in this work.

2. Theoretical model

Here, we describe the model on which we base our OCT measurements with undetected photons for TD-OCT and FD-OCT. We provide a derivation of the expressions for the spectral and temporal interferograms in both experimental setups in a comprehensive way that is adjusted to our experimental conditions. We describe the IC and SU(1,1) configurations in one expression since the difference in the description of the SU(1,1) and IC geometry reduces to a different phase factor, as we will see later. To describe OCT measurements with undetected photons in the two schemes, we start with the two-photon component of the PDC state at signal and idler frequencies ω_s and ω_i at the output of one source, which can be written as [29]

$$|\Psi\rangle = C \int d\Delta\omega f_{\text{PDC}}(\Delta\omega) |\bar{\omega}_s - \Delta\omega\rangle \otimes |\bar{\omega}_i + \Delta\omega\rangle, \quad (\text{A2})$$

where C is a constant that is related to the conversion efficiency of the process. The JSA of a single PDC process is then given by

$$f_{\text{PDC}}(\Delta\omega) = \text{sinc}\left(\frac{\Delta\beta(\Delta\omega)L}{2}\right) \exp\left(i\frac{\Delta\beta(\Delta\omega)L}{2}\right). \quad (\text{A3})$$

Due to the structure of the bilayer sample, only a part of the idler generation probability amplitude is directly reflected back to the nonlinear crystal from the first sample layer, while the remainder acquires a linear phase shift and is reflected back by the second layer. After the interaction with this bilayer object, our two-photon state can be

written as

$$|\Psi\rangle_{\text{OCT}} = C \int d\Delta\omega f_{\text{PDC}}(\Delta\omega) |\omega_s\rangle \otimes \left(r_1 |\omega_i\rangle + r_2 \exp\left(i\frac{2n_g d \Delta\omega}{c}\right) |\omega_i\rangle \right). \quad (\text{A4})$$

We assume that a maximum of one photon pair per spectral mode is generated at the output of the interferometer. In this low-gain regime, we can describe the system in the framework of induced coherence without induced emission [6,12]. We can write the state after the interaction based on the JSA of the two single-PDC processes as

$$\begin{aligned} |\Psi\rangle_{\text{OCT}} &= C \int d\Delta\omega \left(f_{\text{PDC}}(\Delta\omega) r_1 |\omega_s\rangle |\omega_i\rangle + f_{\text{PDC}}(\Delta\omega) r_2 \exp\left(i\frac{2n_g d \Delta\omega}{c}\right) |\omega_s\rangle |\omega_i\rangle \right) \\ &= C \int d\Delta\omega \left(f_{\text{PDC}}(\Delta\omega) r_1 + f_{\text{PDC}}(\Delta\omega) r_2 \exp\left(i\frac{2n_g d \Delta\omega}{c}\right) \right) |\omega_s\rangle |\omega_i\rangle. \end{aligned} \quad (\text{A5})$$

Finally, the second source contributes to the output state of the interferometer $|\Psi\rangle_{\text{int}}$ as an added term in the form of a single PDC source. Thus, this state can be written as $|\Psi\rangle_{\text{int}} = |\Psi\rangle_{\text{OCT}} + |\Psi\rangle_{\text{PDC},2}$. We can identify the JSA of this state as a new JSA of the whole interferometer f_{int} and add an adjustable time delay on the idler arm τ . Thus, we end up with

$$\begin{aligned} f_{\text{int}}(\Delta\omega) &= f_{\text{PDC}}(\Delta\omega) [r_1 \exp(i\tau \Delta\omega + \Phi_{\text{int}}(\Delta\omega)) \\ &\quad + r_2 \exp(i\tau \Delta\omega + \Phi_{\text{int}}(\Delta\omega) + i2n_g d/c \Delta\omega)]. \end{aligned} \quad (\text{A6})$$

Here, the phase terms include internal phases Φ_{int} from the interferometer itself, e.g., dispersion from the waveguide material. We refer to earlier work for more details on the influence of phases in the SU(1,1) setup [21]. Meanwhile, this expression can also be applied to the IC configuration, where only the internal phase Φ_{int} is different due to changes in the signal path, as depicted in Fig. 1. From this joint spectral amplitude at the output of the interferometer, we arrive at the expressions for the spectral and temporal interferograms stated above. This is done by directly taking the square of the JSA or by further integrating over the frequency detuning $\Delta\omega$, respectively.

While this intuitive description is sufficient for our demonstration of OCT measurements with undetected photons based on integrated waveguides, the extraction of information about layered objects under test in nonlinear interferometers based on the IC or SU(1,1) geometries has

been described in earlier works using more general yet more complex frameworks [10,11,16].

3. Experimental details

Both facets of the waveguide are coated with antireflection coatings for the pump wavelength, as well as for the signal and idler wavelengths. We use a folded setup with a single waveguide source to ensure high spectral interference visibility, as the two PDC sources are identical by design. Furthermore, the use of a waveguide as a PDC source generally leads to strong frequency correlations in the JSA, while spatial correlations between photons do not arise due to their generation in single spatial modes. Thus, all fields in the setup are collinear. For the IC configuration, a 50:50 fiber beam splitter (Thorlabs TW805R5F2) was used to overlap the signal fields from both processes.

4. Spectral interferograms and visibility extraction

In the experiment, the spectral interference is recorded at a fixed idler mirror position and for integration times of 1 s on the spectrograph, if not stated otherwise. The measurements were performed at pump power levels of around 5 mW, which are required for a significant signal on the single-photon-sensitive spectrograph (Andor Shamrock SR-500i spectrograph with Newton 970P EMCCD camera) with a spectral resolution of 30 GHz.

The value for the interference visibility is obtained by evaluating fringes over the entire signal spectral range. The period of the oscillations is controlled by setting a fixed

delay between the signal and idler paths. Two examples of the raw spectral interferogram data are presented in Fig. S1 in the Supplemental Material [22]. The error bars on the visibility are obtained from the standard deviation of the extracted visibility across the spectral bandwidth, while the error bars of the gain ratio are based on the power meter used, which has a tolerance of 5%.

5. Temporal interferograms

We record temporal interferograms by moving the idler mirror in steps of 200 nm with a motorized stage (PI M111.1DG) and integrating the counts on a Si avalanche photodiode (Perkin Elmer Photon Counting Module SPCM-AQR-14FC) and time tagger (Swabian Instruments Time Tagger 20) for 0.05 s per step. For these measurements, lower pump powers of the order of 50 μ W are required. Drifts and fluctuations in the recorded count rates are eliminated by applying a Fourier filter to the data. This filters out the low-frequency noise while keeping the information at the frequency of the interference. This frequency is given by half of the central wavelength of the arm in which the stage is moved. In our case, this is the wavelength of the idler, around 1400 nm.

6. Resource comparison

In our current setup, we find that FD-OCT requires pump powers of 5 mW for sufficient SNR at integration times of 1 s. Meanwhile, the pump power of the TD-OCT measurements is set to 50 μ W with integration times of 0.05 s and a total of 10 000 steps per scan, resulting in a total measurement time of 500 s. The two methods become comparable in measurement time at the same pump-power level if we consider the factor of 100 in the pump powers and assume a linear connection between the pump power and mean photon number, which is directly linked to the required integration time.

7. Numerical dispersion compensation

The dispersion from the setup was compensated numerically in the FD-OCT measurements. To this end, a Hilbert transform was applied to the spectral interferogram. The resulting signal was multiplied by a quadratic and cubic spectral phase to compensate for spectral phases from the setup. To obtain the peaks presented in Fig. 4, phase factors of 11 500 fs² and −45 000 fs³ were applied in the case of SU(1,1). In the case of IC, spectral phases of 600 fs² and −45 000 fs³ were applied.

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