

Closed-Loop Optimization of Entangled Photon Sources via Alignment, Polarization, and Dual-Crystal Phase-Matching Control

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ABSTRACT

Reliable operation of entangled photon sources (EPS) requires not only high brightness and entanglement fidelity, but also reproducible calibration of the experimental degrees of freedom that determine source performance. Here, we present a closed-loop calibration framework for a polarization-entangled photon source combining crossed-crystal ppKTP with a bidirectionally pumped Sagnac interferometer. Time-reversed Hong–Ou–Mandel (TR-HOM) interference enables deterministic separation of degenerate Type-0 SPDC photon pairs. The framework addresses three principal control domains: optical alignment, independent crystal temperatures T_1 and T_2 , and pump polarization. Independent temperature tuning reveals an operating point displaced from the common-temperature condition $T_1 = T_2$, while Powell optimization and coordinate descent reduce the search of the two-dimensional temperature space from several hours of exhaustive scanning to approximately 30–40 min. Pitch–yaw alignment measurements show that the singles and coincidence maxima are displaced by three motor half-steps in yaw, demonstrating that maximum single-photon coupling does not necessarily correspond to maximum photon-pair collection. M-LOOP is therefore used with coincidence-rate feedback for multi-parameter collection alignment. Following spatial and thermal calibration, automated pump-polarization optimization reaches an estimated fidelity of $F_{\text{est}} = 98.5\%$ in less than 10 min. These results demonstrate a subsystem-specific approach to closed-loop EPS calibration that reduces exhaustive parameter scanning and manual adjustment.

Keywords: Entangled photon sources, polarization entanglement, spontaneous parametric down-conversion, closed-loop optimization, Sagnac interferometer, automated alignment, phase matching, quantum communication

1. INTRODUCTION

Entangled photon sources (EPS) are a key enabling component for quantum communication and distributed quantum technologies, where source performance is determined not only by the achievable photon-pair generation rate and entanglement quality, but also by the ability to maintain these properties reproducibly over extended operation. High-brightness polarization-entangled sources based on spontaneous parametric down-conversion (SPDC) have been developed using several architectures, including crossed-crystal and Sagnac configurations. Crossed-crystal Type-0 sources provide access to high SPDC generation efficiencies,¹ whereas Sagnac interferometers are widely used because their common-path geometry provides intrinsically stable generation of polarization entanglement.²

The source investigated here combines these two approaches. Two orthogonally oriented ppKTP crystals are incorporated into a bidirectionally pumped Sagnac interferometer and operated close to wavelength degeneracy around 810 nm. Time-reversed Hong–Ou–Mandel (TR-HOM) interference allows frequency-degenerate photon pairs to be separated into distinct output modes while preserving the indistinguishability required for high-quality polarization entanglement.^{3,4} The resulting architecture provides a phase-stable platform with access to the high spectral brightness of degenerate Type-0 SPDC, but its operation depends on several experimentally adjustable degrees of freedom.

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Three control domains are particularly relevant. First, the two nonlinear crystals need not exhibit identical effective quasi-phase-matching conditions, motivating independent control of the crystal temperatures T_1 and T_2 . Second, the collection alignment determines both single-photon coupling and coincidence collection, but the alignment conditions maximizing these observables need not coincide. Third, the pump-polarization condition controls the relative amplitudes contributing to the generated entangled state and therefore requires accurate calibration.

These parameters can be adjusted manually, but manual calibration becomes increasingly inefficient as the number of controlled degrees of freedom increases or when recovery after drift is required. Closed-loop optimization provides an alternative by using measured source observables directly to guide subsequent actuator settings. Related approaches have demonstrated online optimization and autonomous calibration in other quantum experiments^{5,6}

In this work, we investigate closed-loop optimization of the source through independent dual-crystal temperature control, motorized collection alignment, and automated pump-polarization calibration. Rather than imposing a single global objective, each subsystem is evaluated using the experimentally relevant observable. The results show that independent T_1, T_2 control changes the accessible temperature optimum, that the alignment maxima obtained from singles and coincidences are spatially displaced, and that automated polarization optimization reaches a high-entanglement operating condition within a measurable calibration time. These observations motivate a structured approach in which the controlled variables, feedback metric, and optimization method are selected according to the physical subsystem being calibrated.

2. EXPERIMENTAL PLATFORM AND CONTROL ARCHITECTURE

2.1 Polarization-Entangled Photon Source

The experimental source combines a crossed-crystal ppKTP configuration with a bidirectionally pumped Sagnac interferometer, as illustrated in Fig. 1. The source is pumped at approximately 405 nm and operated in a Type-0 SPDC configuration close to wavelength degeneracy at 810 nm. The two ppKTP crystals have dimensions of $1 \times 2 \times 15 \text{ mm}^3$ and a nominal poling period of $\Lambda = 3.425 \mu\text{m}$.

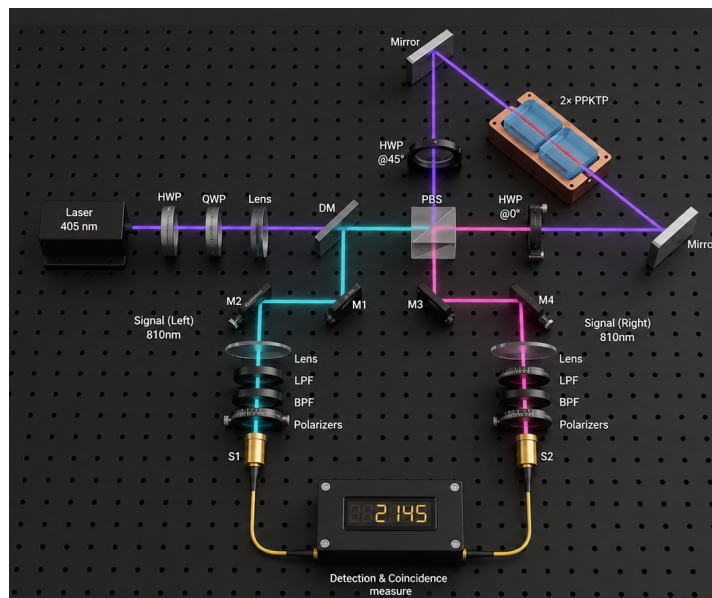


Figure 1: Schematic of the polarization-entangled photon source. A 405 nm pump is coupled into a Sagnac interferometer containing two PPKTP crystals, while the generated 810 nm photons are directed to two filtered polarization-analysis and detection arms for singles and coincidence measurements.

The crystals are oriented orthogonally and mounted in independently controlled temperature stages, defining the temperatures T_1 and T_2 . Independent temperature control allows the effective quasi-phase-matching condition of each crystal to be adjusted separately rather than enforcing a common temperature setpoint.

At wavelength degeneracy, signal and idler photons cannot be deterministically separated by wavelength. TR-HOM interference is therefore used to separate the degenerate photon pairs into distinct spatial output modes.^{3,4} Residual pump radiation is suppressed using a long-pass filter, followed by a 3 nm band-pass filter around the degenerate emission wavelength.

The output photons are coupled into single-mode fibers and detected using Excelitas SPCM-NIR single-photon counting modules with a nominal detection efficiency of approximately 65%. The reported count rates are not corrected for detector efficiency. Detection events are registered using a qutag time tagger. Coincidences are calculated using a 1 ns coincidence window and are corrected for accidental coincidences.

The measured observables include the singles rates R_1 and R_2 , the coincidence rate R_c , and the polarization-basis visibilities V_{HV} and V_{DA} . The entanglement quality is estimated from the two measured visibilities as $F_{\text{est}} = (V_{HV} + V_{DA})/2$.

2.2 Automated Control and Optimization

The source is integrated into a common software-based control and data-acquisition framework. The alignment system provides eight motorized degrees of freedom, corresponding to the pitch and yaw coordinates of four tip-tilt mirrors. The two nonlinear crystals are controlled independently through T_1 and T_2 . Polarization control provides four rotational degrees of freedom, comprising two motorized pump waveplates and two motorized polarizers. The complete actuator vector can therefore be written compactly as

$$\mathbf{x} = [\mathbf{x}_{\text{align}}^{(8)}, T_1, T_2, \boldsymbol{\theta}_{\text{pol}}^{(4)}], \quad (1)$$

where $\mathbf{x}_{\text{align}}^{(8)}$ contains the eight mirror pitch–yaw coordinates and $\boldsymbol{\theta}_{\text{pol}}^{(4)}$ contains the four motorized polarization angles. The closed-loop architecture is illustrated in Fig. 2. For each optimization step, the selected control parameters are applied to the source, photon-counting observables are measured, and the resulting performance metric is returned to the optimizer to determine the next actuator setting.

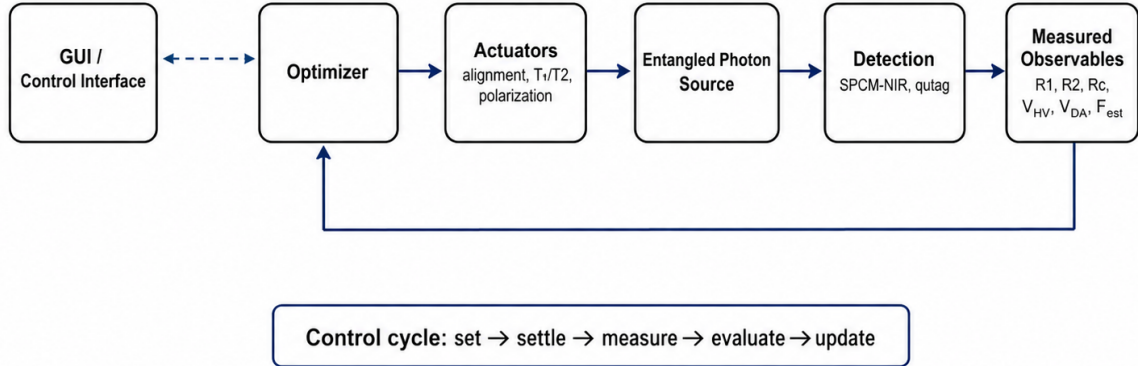


Figure 2: Closed-loop control architecture linking the optimizer, source actuators, photon detection, and measured feedback observables.

Photon events recorded by the qutag provide the singles rates R_1 , R_2 and coincidence rate R_c in real time. The coincidence rate is used as the primary optimization objective, while singles are retained for diagnostics and alignment analysis. Polarization visibilities V_{HV} and V_{DA} , and the corresponding F_{est} , are evaluated after optimization.

M-LOOP, a machine-learning-based framework for noisy online optimization,⁵ is used for the four-parameter collection-alignment task. The lower-dimensional temperature and polarization calibrations are performed using Powell optimization or coordinate descent.^{7,8}

Table 1: Controlled parameters, feedback observables, and optimization methods.

Domain	Variables	Objective	Method
Alignment	mirror pitch/yaw	R_c	M-LOOP
Temperature	T_1, T_2	R_c	Powell / coordinate descent
Polarization	rotation angles	R_c	Powell / coordinate descent

3. EXPERIMENTAL RESULTS

3.1 Dual-Crystal Temperature Control

Efficient TR-HOM separation requires a high degree of spectral indistinguishability between the photon pairs generated by the two ppKTP crystals. Small differences in the effective quasi-phase-matching conditions, for example from fabrication tolerances in the poling period, can therefore shift the temperature at which the two crystals produce spectrally matched output. Independent control of T_1 and T_2 is used to compensate for such differences.

To characterize the temperature dependence, T_1 and T_2 were independently scanned from 22 to 26 °C, as shown in Fig. 3. The measured singles maximum of $1.53 \times 10^5 \text{ s}^{-1}$ occurs at $(T_1, T_2) = (23.6, 23.8)^\circ\text{C}$, displaced from the common-temperature condition $T_1 = T_2$. This displacement is consistent with the two crystals requiring slightly different operating temperatures to reach their respective quasi-phase-matching conditions.

A full two-dimensional temperature scan is experimentally expensive because each temperature pair requires thermal stabilization and photon-count acquisition. For a temperature step ΔT_{step} , the number of measurement points is

$$N_T = \left(\frac{T_{\text{max}} - T_{\text{min}}}{\Delta T_{\text{step}}} + 1 \right)^2, \quad t_{\text{scan}} \simeq N_T (t_{\text{settle}} + t_{\text{int}}). \quad (2)$$

With $t_{\text{settle}} = 30 \text{ s}$ and $t_{\text{int}} = 30 \text{ s}$, a 22–26 °C scan with a 0.1 °C step contains 1681 points and requires approximately 28 h. Even a 0.2 °C step requires 441 measurements, corresponding to approximately 7.4 h. Closed-loop optimization therefore provides a practical alternative to exhaustive mapping. Both Powell optimization and coordinate descent reached the selected temperature operating region within approximately 30–40 min, with similar convergence behavior.

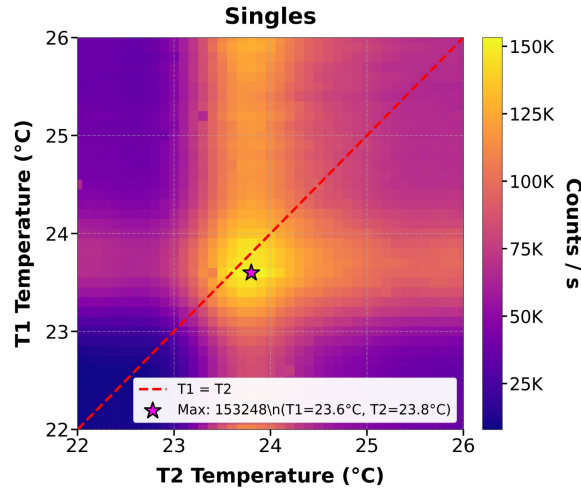


Figure 3: Measured singles-count landscape as a function of the independently controlled crystal temperatures T_1 and T_2 . The dashed line indicates the common-temperature condition $T_1 = T_2$; the measured maximum occurs at $(23.6, 23.8)^\circ\text{C}$.

3.2 Feedback-Metric Dependence of Optical Alignment

The alignment response was characterized by scanning the pitch and yaw of one collection mirror in a single output arm while simultaneously recording the singles and coincidence rates. As shown in Fig. 4, the singles maximum occurs at $(-3, -1)$ half-steps with a rate of $98\,820\text{ s}^{-1}$, whereas the coincidence maximum occurs at $(-3, 2)$ half-steps with $19\,488\text{ s}^{-1}$. The coincidence optimum is therefore displaced by three half-steps in yaw and exhibits a narrower alignment response.

The difference arises because the singles rate primarily reflects coupling into the measured output arm, whereas coincidences depend on the joint collection of both photons. Maximum singles coupling therefore does not necessarily correspond to maximum pair collection, making the coincidence rate the more relevant feedback quantity for source alignment.

The scan in Fig. 4 varies only one collection mirror to illustrate this effect. During automated operation, M-LOOP simultaneously optimizes the pitch and yaw of both collection mirrors, corresponding to four alignment degrees of freedom, with the coincidence rate used as the objective. The motor coordinates are expressed in half-steps and can be converted to physical mirror angles from the actuator angular resolution and subsequently to beam displacement at the fiber-coupling plane using the collection geometry and intermediate optics.

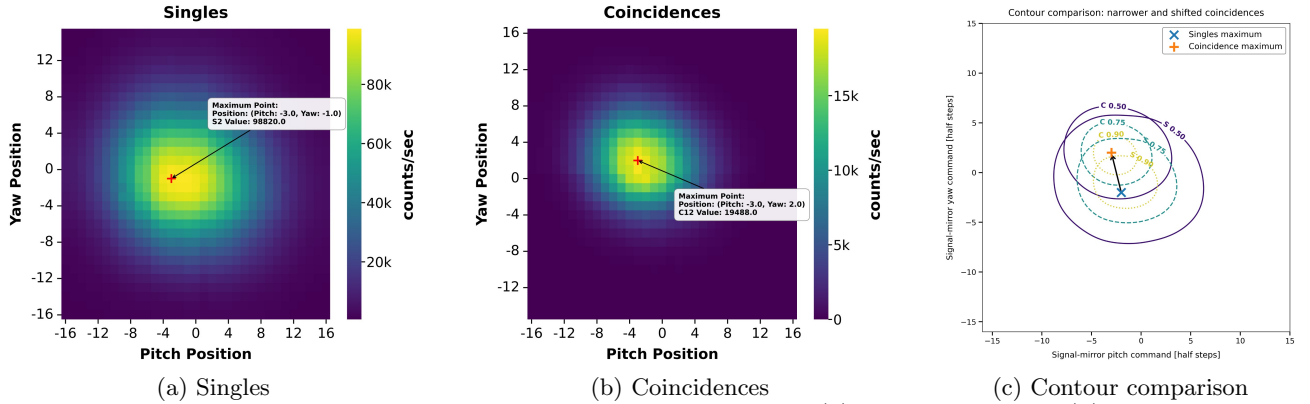


Figure 4: Pitch-yaw alignment response of one collection mirror. (a) Singles-rate and (b) coincidence-rate landscapes, with their respective maxima indicated. (c) Normalized contour comparison showing the narrower coincidence response and the displacement of the coincidence maximum relative to the singles maximum.

3.3 Automated Pump-Polarization Calibration

Following alignment and temperature optimization, the polarization state is analyzed using motorized polarizers to measure the visibilities in the H/V and D/A bases. The pump polarization is then adjusted using motorized waveplates, with Powell optimization and coordinate descent used to maximize the measured coincidence response.

The complete polarization calibration requires less than 10 min corresponding to an estimated fidelity of

$$F_{\text{est}} = 98.5\%.$$

This demonstrates rapid automated recovery of the polarization operating point after the spatial alignment and crystal-temperature conditions have been set.

4. DISCUSSION AND OPERATIONAL IMPLICATIONS

The measurements identify three practical requirements for automated EPS calibration. First, the two nonlinear crystals cannot necessarily be treated with a common temperature setpoint. Independent T_1 and T_2 control allows differences in their effective quasi-phase-matching conditions to be compensated while maintaining the spectral matching required for the source. This is particularly relevant experimentally because exhaustive two-dimensional temperature mapping requires approximately 7.4–28 h for the scan parameters considered here, whereas the closed-loop search reaches the selected operating region in approximately 30–40 min.

Second, the alignment measurements show that the feedback observable itself determines the selected operating point. For the measured mirror scan, the singles and coincidence maxima differ by three half-steps in yaw, and the coincidence landscape is narrower. Singles therefore provide useful single-channel diagnostics, while coincidence rate is the more appropriate objective for optimizing collected photon pairs. Extending the alignment to both collection mirrors results in a four-dimensional optimization problem, for which M-LOOP is used.

Finally, after spatial and temperature calibration, automated polarization control reaches an estimated fidelity of $F_{\text{est}} = 98.5\%$ in less than 10 min. Taken together, these results show that efficient automation is obtained by matching the controlled parameter space, feedback observable, and optimization method to the physical calibration task rather than applying a single optimization strategy to the complete source.

5. CONCLUSION

A closed-loop calibration framework was implemented for the temperature, alignment, and pump-polarization degrees of freedom of a polarization-entangled photon source. Independent dual-crystal temperature control addresses differences between the effective operating conditions of the two ppKTP crystals while reducing calibration from an exhaustive multi-hour scan to approximately 30–40 min. Alignment measurements show a three-half-step displacement between the singles and coincidence optima, demonstrating the importance of coincidence-based feedback for pair collection. Following spatial and thermal calibration, automated polarization control reaches $F_{\text{est}} = 98.5\%$ in less than 10 min. The combined approach provides a practical route from manual calibration toward automated operation of entangled photon sources.

APPENDIX A. EXPERIMENTAL CONTROL AND CALIBRATION DETAILS

A.1 Direction-Dependent Hysteresis of the Motorized Alignment

A representative yaw scan was performed in both forward and reverse directions while monitoring the coincidence rate R_c . The two scans show similar overall coupling profiles, but their maxima are displaced by approximately two commanded motor steps.

The shift indicates a direction-dependent response of the motorized alignment system. This is relevant for closed-loop optimization because the same commanded position may not reproduce the same optical operating point when approached from opposite directions. The effect may arise from backlash, mechanical play, or finite positioning repeatability in the motor–mount assembly.

For reproducible optimization and recovery, the alignment routine should therefore use a consistent direction of approach or explicitly compensate for the observed hysteresis. Since the measurement characterizes the response of the complete motorized alignment system, the displacement is not assigned to a single mechanical component.

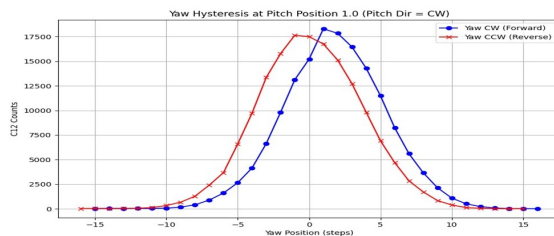


Figure 5: Representative direction-dependent alignment hysteresis measured during a yaw scan of the motorized collection mirror. The coincidence rate $C12$ is recorded while the yaw coordinate is scanned in the forward and reverse directions at fixed pitch. The displacement between the two response curves indicates that the achieved optical alignment depends on the direction from which a commanded position is approached.

A.2 Control and Monitoring Interface

A common graphical user interface integrates actuator control, real-time singles and coincidence monitoring, and execution of diagnostic scans and optimization routines, as shown in Fig. 6. The same software layer therefore supports both manual source characterization and closed-loop operation.

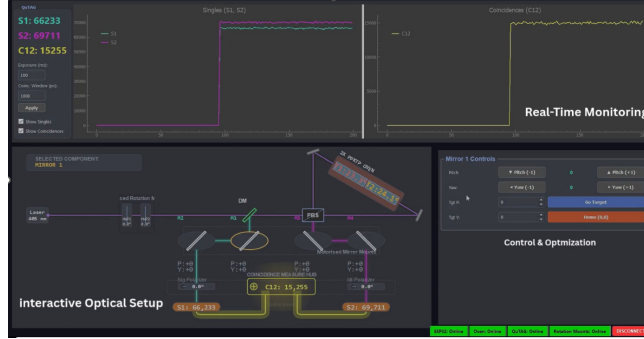


Figure 6: Graphical user interface used for source control and real-time monitoring. The interface displays the measured singles rates $S1$ and $S2$ and coincidence rate $C12$, provides an interactive representation of the optical setup, and enables direct control of the motorized mirror pitch and yaw coordinates. Device-status indicators provide simultaneous monitoring of the connected control and acquisition hardware.

A.3 Optimization and Data-Acquisition Parameters

Coincidences are evaluated using a 1 ns coincidence window and are corrected for accidental coincidences. No correction is applied for the nominal detector efficiency of approximately 65%. For the dual-crystal temperature measurements, each new temperature setpoint is followed by a 30 s stabilization period and a 30 s acquisition period.

ACKNOWLEDGMENTS

This work was carried out within the framework of the i-EPS project, supported by DLR and BMFTR. The authors thank Sara Lucia Montano Gamarra for her contribution to the development of the automated tip-tilt mirror system through her master’s thesis, Mohamed Hassan for support with the electronics and system operation, and Omar Sebak for support with GUI development and programming.

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