Single-Mode, Narrow Band Photon Source Using SPDC for Hybrid Quantum Systems

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ABSTRACT

Generating single-mode, narrow-band photons with high purity and brightness has proven to be difficult. Researchers at the University of Vienna have designed a photon source using Spontaneous Parametric Down-Conversion (SPDC) with a doubly resonant Optical Parametric Oscillator (OPO) utilizing an additional birefringent crystal to tune clusters independent of SPDC phase-matching. Achieving the doubly resonant condition in the OPO that enables a single mode is the challenge when creating a photon source with both single-mode and narrow-bandwidth. This is resolved here, as the resulting photon source has a bandwidth of 10.9 MHz to match the linewidths of atomic transitions. The source also produces single-mode photon pairs at a rate of 47.5 Hz without mode filters reducing loss in the system. This novel design enables research and applications in the quantum realm using hybrid light-matter interactions.

HYBRID QUANTUM SYSTEMS

Many quantum systems utilize single photons and their spectral properties. Hybrid quantum systems combine single photon-based and matter-based designs to implement two-qubit gates, the foundation for quantum computers and information processing.[1] Applications for this type of photon source range from observing quantum phenomena to quantum communication.

Spontaneous Parametric Down-Conversion (SPDC) is one hybrid photon-matter based system used to generate single photons at a high purity level. This method also allows some control of the wavelength and bandwidth of the output photons.

An Optical Parametric Oscillator (OPO) can be used to generate coherent light.[2] The novel use of a birefringent crystal in the OPO combined with SPDC achieves photon selection with minimal losses.

METHODS & PROBLEMS

To implement two-qubit gates for many quantum applications, hybrid quantum systems need to be created with photon-matter interactions. Several characteristics of the generated photon must be achieved to establish a quality photon source for quantum applications.

One challenge is obtaining high-purity single photons. Successful methods include: quantum dots, single nitrogen vacancy center in nanodiamonds, and SPDC.[1] The first two methods do not allow for photon heralding. That is, after a photon is down-converted to two lower energy photons, one of the signal or idler photons is detected or measured, ensuring the other will also be detected with accurate knowledge of its state.

What is SPDC & OPO?

SPDC is, essentially, a "down-conversion" of a single photon instantaneously. **Figure 1** shows how SPDC works.

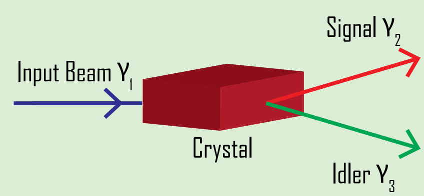

Figure 1. Spontaneous Parametric Down-Conversion Process

One photon (γ_1) enters the nonlinear crystal and is down-converted into two separate photons: signal and idler (γ_2 and γ_3). Down-converted means that the two output photons will have lower frequencies (and also energies) than the input photon. Because of the laws of conservation of energy and momentum, the two output photons must have lower energies and momenta than that of the initial photon such that:

$$E\gamma_1 = E\gamma_2 + E\gamma_3 \tag{1}$$

$$\vec{k}_1 = \vec{k}_2 + \vec{k}_3 \tag{2}$$

where E is the energy of the appropriate photon, $\gamma_{1,2,3}$ distinguishes each photon, and $\vec{k}$ is the momentum of the photon. The frequency of each photon can be related in the same way, as energy is related to frequency by either h or ħ (planck constant or reduced planck constant depending on using frequency or angular frequency).

The combination of Equation (1) and Equation (2) is called the "phase-matching conditions." This allows some control of the characteristics (wavelength and bandwidth) of the signal and idler photons to produce a desired result.

There are two types of OPO: Singly Resonant OPOs (SRO) and Doubly Resonant OPOs (DRO). An SRO provides feedback to only one of the signal or idler photons, while a DRO provides feedback at both the signal and the idler frequencies.

The DRO is designed such that both frequencies coincide with resonator modes to allow SPDC emission but exhibit different free spectral ranges (FSR).[1] This is the OPO that is used for single-mode photon sources.

DROs have lower threshold pump power, and the tuning behavior of the photons can be affected by changing crystal temperature.[3] DROs also can leverage cluster effects. When signal and idler modes overlap, the spectrum of the OPO is made of clusters of a few modes. This can be seen in **Figure 2**.

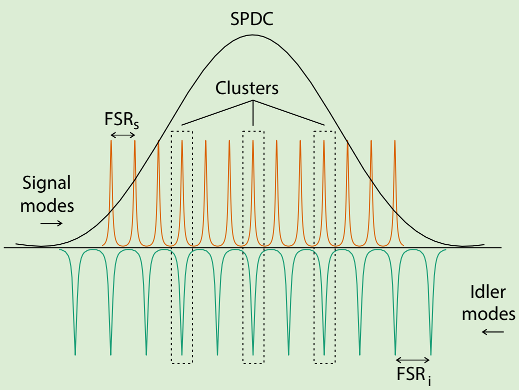

Figure 2. Cluster effect. The longitudinal modes for signal are shown in orange and the modes for idler are in green. The two arrows indicate the direction in which frequency increases. The overlap condition is periodical, but because of the difference in the FSRs for signal and idler, the modes that are next to the fully overlapping ones coincide only partially. This leads to a spectrum that is made of clusters of modes, separated by $\Delta\nu_C$.[1]

Designers change the properties of the SPDC crystal to reach this doubly resonant condition where both the signal and idler modes are resonant to the cavity at the same time.

If the SPDC method is used, it can be very difficult to obtain narrow photon bandwidth. Generally, SPDC creates photons with very broad bandwidth, orders of magnitude larger than atomic transitions. In order for these hybrid quantum systems to be successful, the bandwidth of the generated photons needs to be narrow enough to interact with and match the linewidths of the atomic transitions. A simple solution is to introduce passive spectral filtering into the system. However, this creates a large amount of loss in the design. An alternate solution is using an OPO to utilize the advantages of cluster effects.

An OPO, combined with SPDC, however, can generate multi-mode spectral characteristics which are not ideal for efficient interaction with the atomic transition. Two ways to suppress the unwanted modes are filter cavities and atomic line filters. These methods of mode-filtering work but at the cost of photon loss and increased complexity in the setup.[1]

Using doubly resonant OPOs, it can be difficult to reach the doubly resonant condition as the tuning behavior is heavily dependent on stable crystal temperature. Once attained, cluster effects can enable a narrow band photon source with fewer modes. However, the attempts at achieving this condition have been unsuccessful at highly non-degenerate (photon pair with different energies) SPDC.

UNIVERSITY OF VIENNA'S SOLUTION

Researchers at the University of Vienna, Austria have developed a single-mode, narrow-bandwidth photon source for quantum applications. They accomplish this through a novel design utilizing a doubly resonant Optical Parametric Oscillator (OPO) with Spontaneous Parametric Down-Conversion (SPDC). In order to achieve the doubly resonant condition, an additional birefringent crystal is inserted into the Type-II OPO. This allows for narrow band photons with fewer modes. A complete setup, including a pump laser, probe laser, OPO cavity with two crystals, and other components can be seen in **Figure 3**.

The two lasers shown are used as a pump laser (426 nm, 30 mW) and a probe laser (852 nm, 50 mW). The probe laser is tuned to the Cs D2 line by passing some of the light through Cs vapor, performing polarization spectroscopy on the Cs vapor and allowing frequency tuning. The pump laser is locked to the probe laser by combining a portion of the pump laser beam with the frequency-doubled probe laser. The probe laser is frequency-doubled using a single-pass Type-I PPKTP crystal to 426 nm. Another portion of the probe laser is sent to a double-pass Acousto-Optic Modulator (AOM) system.

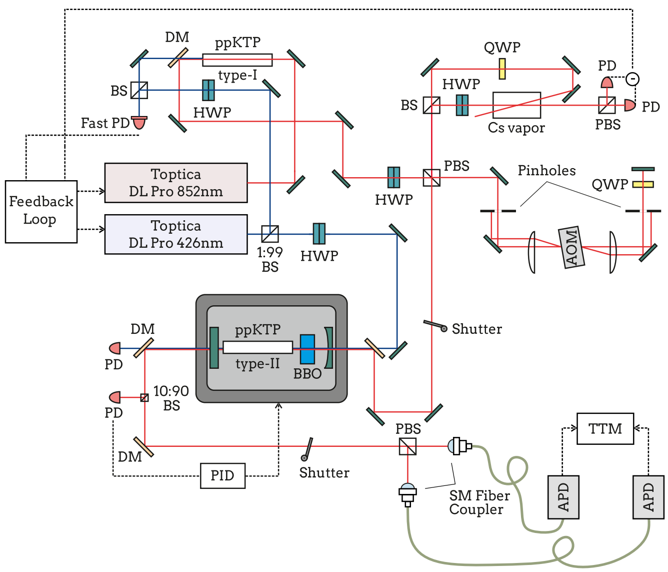

Figure 3. Narrow-band single photon source. Two tunable diode lasers operating at 852 nm—called probe, stabilized to Cs D2 line via polarization spectroscopy—and 426 nm—called pump—locked to the probe by frequency-offset lock constitute the laser system. The OPO cavity's geometry is semihemispherical, and it contains two crystals: A 30-mm-long PPKTP (periodically poled potassium titanyl phosphate) for collinear, type-II phase-matched SPDC of 426 nm–852 nm and a 15-mm-long BBO (barium borate) for tuning the cluster effect. Two optical shutters switch the probe beam and block the APDs to iterate between the cavity lock and the measurement mode with 60% duty cycle. The photons are coupled into single-mode fibers and routed to the APDs and the TTM for analyzing the temporal correlations.[1]

With this system, both lasers can be stabilized to the Cs D2 line and independently tuned to specific frequencies.

The OPO has been designed in a linear, semihemispherical configuration. This allows for non-degeneracy in transverse modes with asymmetric geometry. This simplifies alignment and coupling the light to the single-mode (SM) fibers. Inside the cavity there are two crystals. The first is a 30 mm-long Periodically Poled Potassium Titanyl Phosphate (PPKTP) Type-II crystal used for the SPDC. The second crystal is added specifically to tune the cluster separation independently of the SPDC phase matching, solving a critical issue with previous methods. It is 15 mm-long Barium Borate (BBO). Tuning the cluster effect allows a broad range of frequencies of photon generation. The temperature stability of these crystals is critical to the success of the photon source. The crystal temperature needs to be regulated to a high level of precision for control of the characteristics of the beam passing through it given the temperature-dependent birefringent properties of the crystal. Once the two beams (pump and probe) pass through the cavity, the residual pump beam is separated from the single photons using two dichroic mirrors (DM), two long pass filters, and one bandpass filter. This way, only the single photons are coupled into the single-mode fibers.

To couple the photons into the SM fibers, a Polarizing Beam Splitter (PBS) is used to separate the signal and idler photons. This is possible due to the SPDC crystal properties. The PPKTP is a Type-II crystal, meaning the output photons (signal and idler) have perpendicular polarizations. In this way, when separated using the PBS, one photon in the pair can be heralded by the detection of the other in the pair using Avalanche Photodiodes (APD). The photons are then counted for detection and analysis.

RESULTS

With this novel design, the researchers have accomplished the goal of a single-mode, narrow-band photon source using an OPO for SPDC. The cross-correlation function, $G^{(1,1)}(\tau)$ and the autocorrelation function, $G^{(2)}(\tau)$ characterize the spectral properties of this photon source. These functions are related to the bandwidth and number of modes of the photon source. The cross-correlation function is related to the probability of detecting a signal photon at time t and an idler photon at time t + τ.

The FWHM of the cross correlation temporal profile is defined as the cross correlation time, τ_c, and is inversely proportional to the bandwidth of emitted photons.[1] **Figure 4** shows the measured cross correlation.

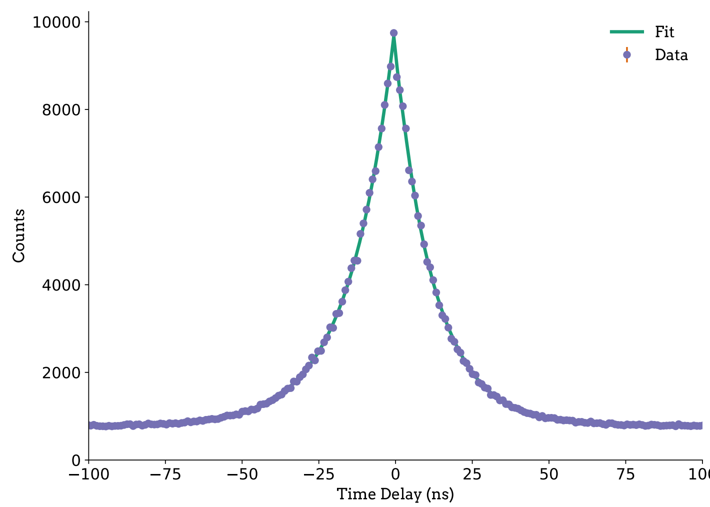

Figure 4. Experimental Cross Correlation with Curve Fit[1]

From the data, the effective bandwidth of the photons is found to be 10.9 ± 0.3 MHz for the photon pairs. This is close to the few megahertz linewidth of typical atomic transitions.

The autocorrelation function is related to the statistics of the single SPDC fields and the number of modes in the system.

The value at 0 decay can show the number of modes in the cavity, N:

$$G^{(2)}(0) = 1 + \frac{1}{N} \tag{3}$$

giving a single mode value (N=1) of $G^{(2)}(0) = 2$. **Figure 5** shows the delays calculated from the TTM recordings.

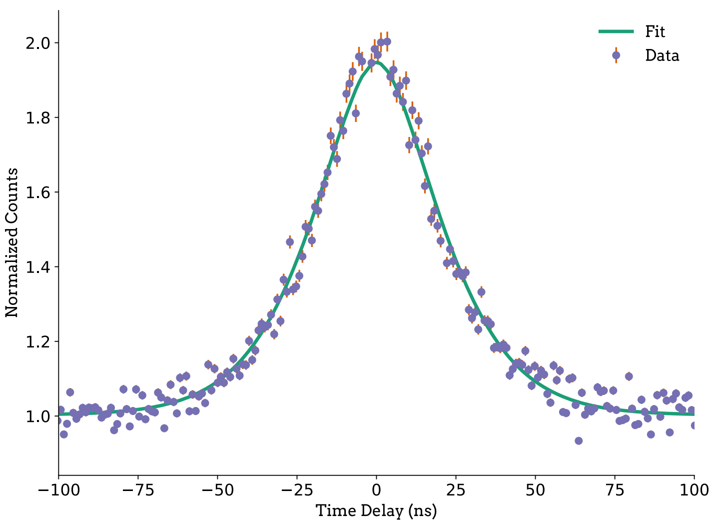

Figure 5. Experimental Autocorrelation with Fit Curve[1]

From this plot, the peak value at 0 decay is 1.942 ± 0.001, corresponding to single-frequency-mode operation.

Another parameter that is used to characterize photon sources is the heralded or conditional second-order correlation function, $g^{(2)}(\tau)$. Detection of the signal photon is heralded (or known to be detected) by the detection of a idler photon. An ideal single-photon source will have $g^{(2)}(0) = 0$. The data from this study recorded a value of $g^{(2)} = 0.04 \pm 0.01$ at 1 mW of pump power showing an almost perfect single-photon source without higher order emissions.[1]

At 10 mW of pump power, researchers recorded 2.5 kHz 2-fold coincidence counts. This translates to a photon-pair generation rate of 47.5 kHz leading to a spectral brightness of 436 s^{-1} mW^{-1} MHz^{-1}. This rate surpasses all previously known research of single-mode photon pair generation while maintaining the high level of purity. This method reduces losses known to previous systems and provides solutions for many quantum applications.

WAVELENGTH'S ROLE

The Optical Parametric Oscillator (OPO) is highly dependent on the temperature of the crystal. Changing temperature alters the index of refraction which changes the wavelength of the light. The crystal can also change length due to temperature, causing a shift in efficiency and cluster tuning capabilities. Temperature regulation of both crystals in the OPO cavity is essential.

Wavelength Electronics' PTC5K-CH (**Figure 6**) provides a current limit of 5 A with multiple features and benefits. In this application it controlled the temperature of the crystals in the OPO cavity with precision better than 2 mK, generating the necessary crystal stability.

The PTC5K-CH temperature controller operates from a single power supply between 5 V and 30 V. The linear bipolar controller can drive a Peltier thermoelectric cooler or a resistive heater, and integrates easily into the system. It can stabilize temperature to 0.0012ºC.

The compact chassis mount design simplifies heatsinking and requires minimal space. The PTC5K-CH can be found in systems in diverse applications such as particle and droplet measurement, biomolecular interaction analysis, manufacturing machine vision systems, and now single-mode narrow-bandwidth photon sources for hybrid quantum applications.

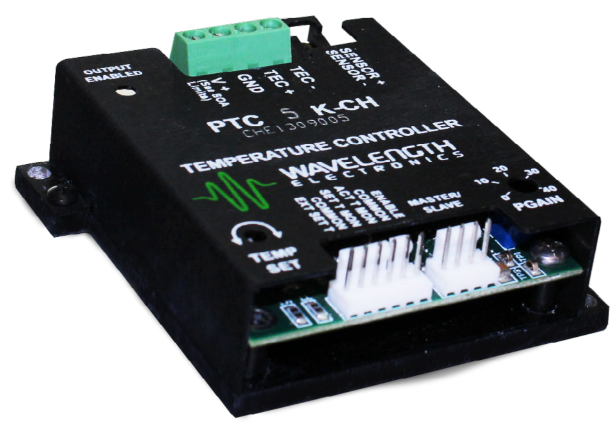

Figure 6. PTC5K-CH Temperature Controller

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2. B. E. Saleh, M. C. Teich, and B. E. Saleh, *Fundamentals of Photonics* (Wiley, New York, 2007).
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USEFUL LINK

- PTC5K-CH Product Page

OPEN ACCESS

No changes were made to the images. They are presented here in their original form.

The captions for Figures 2, 4, and 5 have been modified from their original form.

PRODUCT USED
PTC5K-CH

KEYWORDS
Hybrid Quantum Systems, Photon Source, Single-mode, Narrow-band, Spontaneous Parametric Down-Conversion, Optical Parametric Oscillator, Doubly Resonant Oscillator, High Brightness

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