

Practical Single Photon Source for Quantum Communications.

Anton Zavriyev and Alexei Trifonov.
MagiQ Technologies, Inc., 11 Ward Street, Somerville, MA 02143.
ATrifonov@magiqtech.com.

P. Battle, D. Mohatt, E. Noonan, and T. Roberts.
AdvR, Inc., 2311 S 7th, Bldg #1, Bozeman, MT 59715.
Battle@advr-inc.com.

Abstract: We describe a robust heralded single photon source based on parametric down conversion of CW 532-nm light in a periodically polled KTP waveguide. Low required pump power (sub-mW), reasonable operational temperature (43°C), high heralding efficiency (60%), and narrow spectral width of the heralded photons (sub-nm) make it an ideal light source for long-distance quantum communications.

Recent advances in quantum informatics and its subfield, quantum cryptography (also known as quantum key distribution, or QKD), have highlighted a need for a reliable single photon source. A number of different approaches for building such a source have been proposed [1-7]. A reader can be referred to the reference [7] for a comparison analysis of the pros and cons of these approaches. While the final verdict is yet to be made, it appears that at the current state of the technological development, parametric down conversion of pump light into time and energy entangled photon pairs is the most practical way to generate single photons on demand [8]. While there had been a number of publications describing this approach [7,9-12], no practical device has been built to this date. In this paper we describe a prototype of a compact robust source that is cheap and simple to build, yet has the level of performance required for the real world QKD systems.

Contradictory to its name, a typical heralded single photon source (HSPS) produces photon pairs, not single photons. These pairs are generated in a nonlinear medium (bulk or waveguide) illuminated by a pump light. A detector preceded by a bandpass filter is typically used to register a photon pair creation: Detection of one of the photons of the pair (a so-called heralding photon) signifies presence of the other one (the heralded photon). A few parameters are of the key importance if such a source is to be used for practical fiber-based QKD: First of all, the heralded photons must be able to travel a significant distance in the optical fibers (i.e. their wavelength must be within one of the so-called telecom windows). This limits the choice of the pump laser and the nonlinear medium used for parametric process. Secondly, since the maximum a communication link distance is usually limited by the signal-to-noise ratio (SNR) at the receiving side (called Bob); the transmitting side (called Alice) must be able to maximize the collection efficiency of the heralding photons. In another words, when Alice detects a heralding photon and sends the signal to Bob, advertising the transmission of the heralded photon, she needs to be sure that a heralded photon has indeed been sent to Bob. (If Alice mistakenly informs Bob that a photon had been sent, and he still triggers his receivers, he can detect a dark count, increasing the noise level. A dark count event takes place when the detector registers an event that did not take place – i.e. non-existing photon.) The same line of reasoning can be used to argue that Alice's detector should have the minimal dark count probability. This effectively governs the choice of Alice's detectors, which in turn limits the possible wavelength range of the heralding photons. Additional limitations are put on the source by the requirement that the Bob's detectors' erroneous count rate is minimized. First of all, this means that no other photons (except for the heralded ones) are sent from Alice. Also, since Bob's detectors are typically ran in the gated mode and their dark count probability is proportional to the duration of the gate, the heralded photons arrival time should be very well known in order to minimize the detector active time and their dark count rate. As the heralded photons travel through the fiber from Alice to Bob, they experience chromatic dispersion effects that increase the uncertainty in the photon arrival time and result in the longer required gate durations. The time spreading of the photon wave packet is proportional to its optical bandwidth; hence the latter must be limited in order to decrease Bob's detectors gate duration and their noise level. Finally, to be practical, a heralded single photon source should be pumped by a low power (i.e. – expensive) pump laser and must operate reasonably close to the room temperature.

A number of groups throughout the world had made experimental advances towards building a practical heralded single photon source. Both, bulk medium, as well as waveguide approach had been tried; the recent results (and their comparison this work) are summarized in the table I below:

Non-linear process	Heralding efficiency	Signal bandwidth (nm)	Comments	Reference
532 nm → 810 nm + 1550 nm in PPKTP waveguide	60%	0.44 nm	Asynchronous. $P_{\text{pump}} < 1 \text{ mW}$ Room temperature	This publication
710 nm → 1310 nm + 1550 nm in PPLN waveguide	38%	Not reported	Asynchronous. $P_{\text{pump}} < 1 \text{ mW}$ Room temperature	[7]
532 nm → 810 nm + 1550 nm in bulk KnbO_3	60%	6.9 nm	Asynchronous. $P_{\text{pump}} \sim \text{tens of mW}$ Room temperature	[9]
532 nm → 808 nm + 1559 nm in bulk PPLN	12.8%	1.26 nm	Asynchronous. $P_{\text{pump}} \sim 1 - 2 \text{ mW}$ 142°C	[10]
400 nm → 800 nm + 800 nm in PPKTP waveguide	85%	50 nm	Pulsed. $P_{\text{pump}} < 1 \text{ mW}$	[11]
390 nm → 780 nm + 780 nm in bulk BBO	83%	9 nm	Pulsed. $P_{\text{pump}} \sim 80 \text{ mW}$	[12]

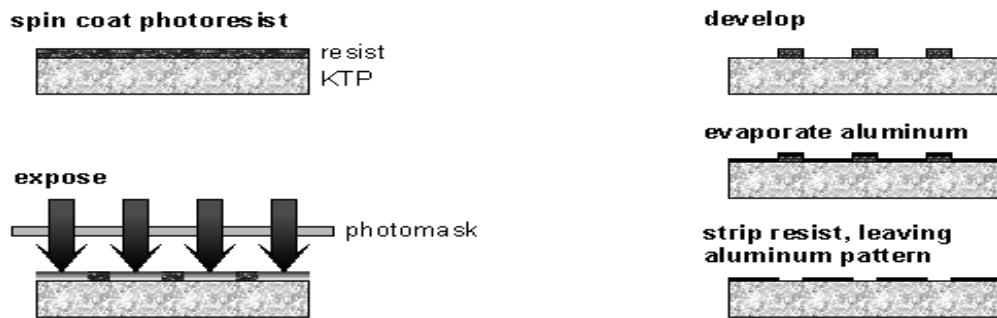
Table I: Comparison of our results with the recent work published by other groups.

Our approach involved pumping a periodically polled KTP (PPKTP) waveguide (polling period, $\Lambda = 9.1 \mu\text{m}$) by a CW 532-nm pump. In a QPM nonlinear optical process, the waveguide is segmented into regions with alternating anti-parallel ferroelectric domains. The period of the domain grating for first order QPM is determined by the quasi-phase matching condition:

$$\frac{n_p}{\lambda_p} = \frac{n_s}{\lambda_s} + \frac{n_i}{\lambda_i} + \frac{1}{\Lambda}$$

where Λ is the period of the domain grating, $\lambda_{p,s,i}$ and $n_{p,s,i}$ are the wavelength and index of refraction of the pump, signal and idler fields. For waveguides the index of refraction terms in the equation above incorporate both the bulk properties of the crystal (as determined from the Sellmeier equations) and the additional dispersion due to modal confinement in the waveguide. In contrast to the usual birefringent phase matching, quasi-phase matched mixing processes can be done over the entire transparency range of the crystal.

The waveguides were fabricated using photolithography to transfer a mask containing the waveguide patterns to a KTP wafer and then using an ion-exchange process to embed the waveguides. The exact steps to fabricate the waveguides in a KTP wafer are outlined in Figure 1 and are described in detail below.



To the left is a wafer consisting of 16 individual chips. Details of the actual aluminum patterned KTP substrate are shown to the right as seen under a microscope.

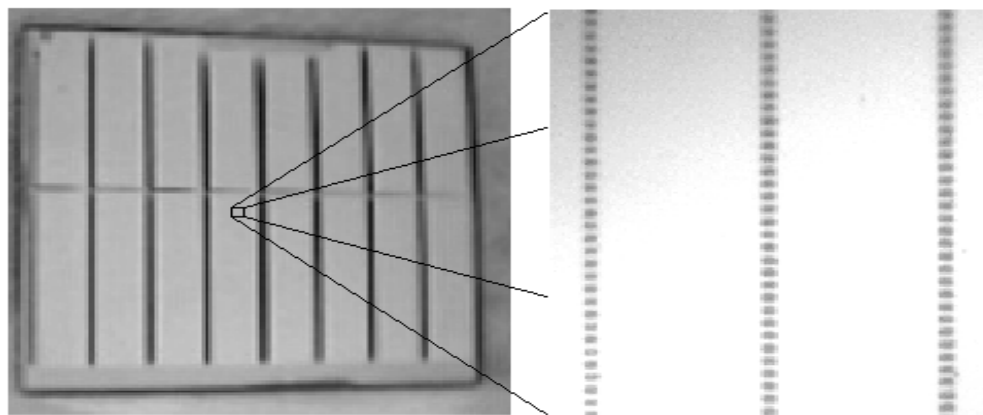


Figure 1. Top: the five steps required to transfer the waveguide pattern to the KTP substrate. Bottom left: The patterned KTP wafer has two rows of 8 KTP chips. Each chip is identical and has approximately 50 waveguides patterned on the surface. The photolithography was done at the use facilities that are part of the National Nanofabrication User Network (NNUN)

The initial step is to layout the waveguide pattern using AutoCAD software. The waveguide pattern is segmented, with the period of the segmentation equal to the required QPM period for generation of down converted photon pairs using a 532nm pump. AutoCAD files of the waveguide mask design is converted into a photomask. The waveguide pattern is transferred from the photomask to the KTP substrates using photolithography as shown in the first four steps in Figure x at a National Nanofabrication User Network (NNUN) facility. The first step in the photolithography process is to spin on a thin layer of photoresist that evenly covers the surface of a z-cut KTP substrate. The photomask, with waveguide design, is imaged onto the photoresist using a 5x projection lithography system. A developing process removes the exposed photoresist so only the unexposed regions of the KTP are covered. Next, a thin aluminum or SiO₂ coating is deposited onto the wafer. Submerging the wafer in acetone removes the remaining resist along with any aluminum (but not the SiO₂) in the exposed area creating a waveguide pattern.

For a standard KTP wafer measuring 25 x 25 mm, a single photolithography run will typically produce two rows of KTP chips, with each chip hosting as many as 50 waveguides, thereby providing several samples for testing, confirming reproducibility, and building in redundancy. The rows of the patterned KTP wafer are separated using a Disco 321 semi-automated dicing saw shown in Figure x. Each row is mounted between glass slides so the input and output ends can be polished to provide a clean, smooth surface for coupling light into and out of the waveguides. After polishing, the dicing saw separates each row into 8 KTP chips ~3 mm wide.

□

After the dicing and polishing is complete, the KTP chips are individually immersed in a molten bath of RbNO₃ and Ba(NO₃). Within this bath, the **Rb** and **Ba** ions diffuse into the unmasked portions of the KTP chip, while the **K** ions diffuse out of the substrate and into the bath, shown in the illustration in Figure 1. In the diffused regions, the rubidium

ions increase the index of refraction relative to the undiffused KTP and thus form the optical waveguide. Note that when barium is included in the ion exchange process, in addition to the increased index of refraction, the ferroelectric domain in the diffused region is also reversed and hence the term chemical poling is used for this process.

Figure 2 below depicts our experimental setup. The pump light was focused using an aspheric 15-mm focal length lens in order to mode match the waveguide mode ($\sim 4 \mu\text{m} \times 4 \mu\text{m}$). A 6-mm long segmented waveguide was fabricated on the z-face of a bulk KTP crystal by a process of ion exchange (the chip was manufactured by AdvR, Inc.) The crystal temperature was stabilized by a thermo-electrical cooler at 43 degrees C to achieve the optimal conditions for phase matching of the pump, signal (810 nm) and idler (1550 nm) waves. This choice of wavelengths for a heralded single photon source was initially suggested by the Geneva group [13]. All the waves were z-polarized and propagated in the direction of the y-axis. The wavelength choice has a double advantage of having a heralded photon (idler) with the lowest possible absorption in the optical fibers; In addition, very good detectors with quantum efficiencies of over 70% and very low dark count rates (tens of Hz) are available for heralding photons. A short focal length aspheric lens ($f = 15 \text{ mm}$) was placed next to the waveguide to collect the emitted light. It followed by a dichroic beam splitter that reflected 1550-nm photons while letting 810-nm photons to pass through. A narrow-band ($\text{FWHM} = 0.12 \text{ nm}$) interference filter was placed in the 810-nm beam path to cut down its spectral width and minimize the chromatic dispersion effects for the corresponding idler light in the transmission fiber. An aspheric 15-mm focal length lens was used to focus the heralding 810-nm photons into a short (5 m) piece of fiber designed for single mode operation at 830 nm. This fiber was connected to the silicon APD that was used to detect the 810-nm photons. Another aspheric 15-mm lens was put into the 1550-nm beam pass to focus the light into a 80-m spool of the SMF-28 fiber connected to a thermo electrically cooled InP/InGaAs APD used to detect the incoming 1550-nm photons ($\text{QE} \sim 10\%$, $\text{DCR} \sim 2 \times 10^{-6}/\text{ns}$). Upon a detection event, the Si APD would trigger a delay generator that sent a short 2-ns pulse to gate the InP/InGaAs APD. By changing the delay generator settings we were able to differentiate between the heralded and unheralded (background) photons.

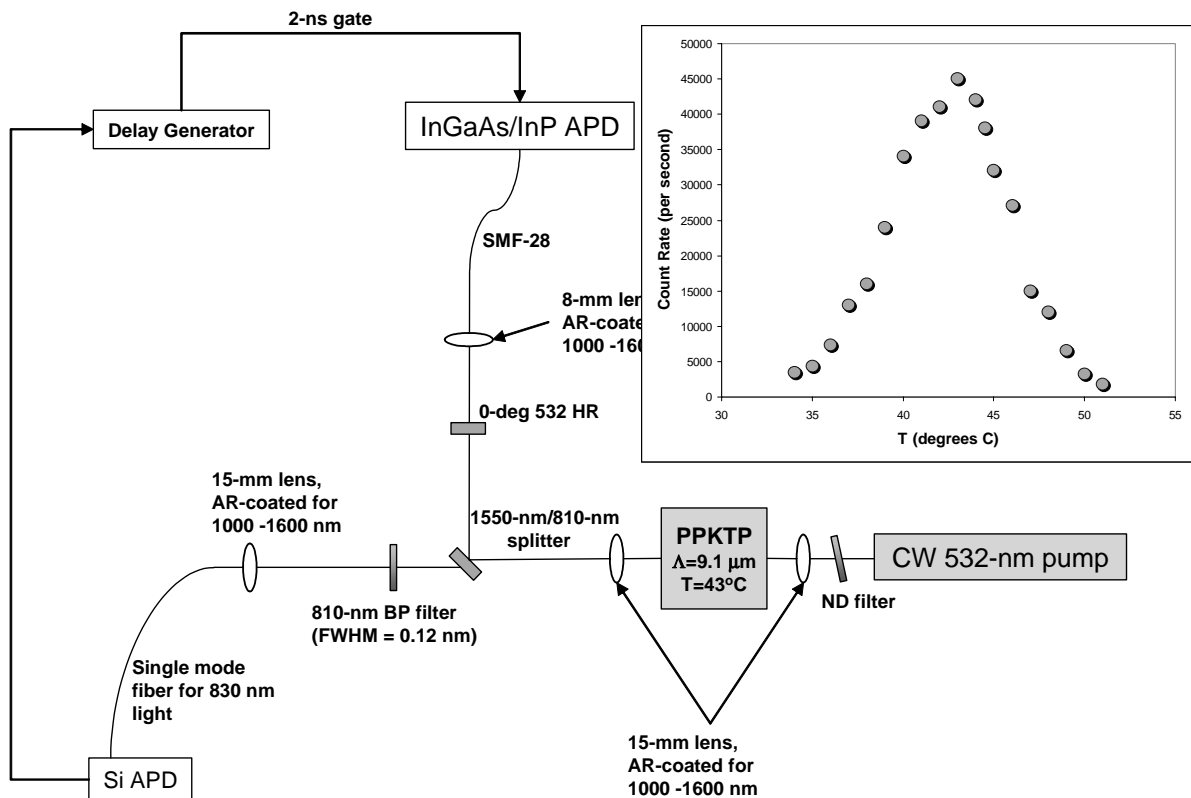


Figure 2: The experimental setup. Insert: Temperature dependence of the signal.

While the pair production is a function of the phase mismatch between the waves, which, in turn, is a function of the crystal temperature, we observed a relatively broad (FWHM = 5°C) temperature dependence of the signal. This relaxes the requirements on the temperature control, which is a nice feature for a practical photon source. Moreover, while the KTP has a relatively weak nonlinear coefficient ($d_{\text{eff}} = 5.3 \text{ pm/V}$), we were able to observe up to 50,000 photon pairs per second while pumping with only 400 μW of 532-nm light. (In reality, the pair production rate was much higher: Our count rate was limited by the low transmission of the interference filter ($\sim 35\%$) as well as the losses on the optics and fiber coupling.) The signal was linearly proportional to the incident pump power. We also tried to measure the heralded photons spectrum. Unfortunately, the bandwidth of our tunable filter was roughly three times as wide as the calculated bandwidth of the 1550-nm light. (Using the energy conservation law, we calculated FWHM $\sim 0.44 \text{ nm}$ for the idler wave; our filter had the FWHM $\sim 1.25 \text{ nm}$.) We plan to conduct a more precise measurement in the near future.

The measured heralding efficiency of the source (i.e. – a conditional probability of finding a heralded photon in the fiber if a herald was detected) was 48% (independent of the crystal temperature). The ratio of the background (non-heralded) photons to the heralded ones was 6%. If the source were to be used for QKD over any significant fiber distance, it would not have needed the 0-degree 532-nm HR mirror, placed in the 1550-nm light beam pass to remove the remaining pump photons. This would have increased the heralding efficiency to 54%. Additionally, placing a layer of AR-coating on the KTP crystal should bring the heralding efficiency up to 60%. In the real practical source, the output fiber would be index-matched to the crystal, increasing the heralding efficiency even higher.

In conclusion, the modest pump power and temperature requirements of the PPKTP waveguide-based heralded photon source, combined with its excellent performance make it an ideal approach for building a compact and robust single photon source for practical applications.

References:

1. F. Treussart, R. Alleaume, V.L. Floch, L. Xiao, J.-M. Courty, and J.-F. Roch, Phys. Rev. Lett. **89**, 093601(2002).
2. B. Lounis and W. Moerner, Nature **407**, 491 (2000).
3. A. Beveratos, S. Kuhn, R. Gacoin, J.-P. Poizat, and P. Grangier, Eur. Phys. J. D **18**, 191 (2002).
4. C. Kurtsiefer, S. Mayer, P. Zarda, and H. Weinfurter, Phys. Rev. Lett. **85**, 290 (2000).
5. M. Pelton, C. Santori, J. Vuckovic, B. Zhang, G.S. Solomon, J. Plant, and Y. Yamamoto, Phys. Rev. Lett. **89**, 233602 (2002).
6. E. Moreau, I. Robert, J.M. Gerard, I. Abram, L. Manin, and V. Thierry-Mieg, Appl. Phys. Lett. **79**, 2865 (2001).
7. O. Alibart, *et al.*, arXiv:quant-ph/0405075 v2 (2004).
8. Hong, C. K. and L. Mandel, Phys. Rev. Lett. **56**, 58-60 (1986).
9. S. Fasel, *et al.*, New Journal of Physics **6** (2004) 163.
10. E.J. Mason, *et al.*, arXiv:quant-ph/0207156 v1 (2002).
11. A.B U'Ren, *et al.*, arXiv:quant-ph/0312118 v1 (2003).
12. T.B. Pittman, *et al.*, arXiv:quant-ph/0408093 v1 (2004).
13. G. Ribordy, J. Brendel, J.D. Gautier, N. Gisin, , and H. Zbinden, Phys. Rev. A, **63**, 012309/1-12 (2001).