RAICOL

Leading The Way To A Quantum Future

Quantum photon sources for every application

About Raicol Quantum

Raicol Quantum is part of Raicol innovation labs, pioneering novel products at cutting edge technologies. Raicol utilizes its state of the art production line and world leading ppKTP and RTP crystals for new products for the emerging quantum industry. Our quantum products consist from unique crystals such as the ppKTP, apKTP and SppKTP crystals which give superior performance for SPDC, through components such as waveguides all the way to full entangled photon source systems. Each product specific for the exact quantum needs, e.g. QKD, single photon source, heralded photon sources, narrow band and broadband sources and squeezed light sources.
With these world leading products, Raicol is leading the world to new quantum capabilities.

ppKTP

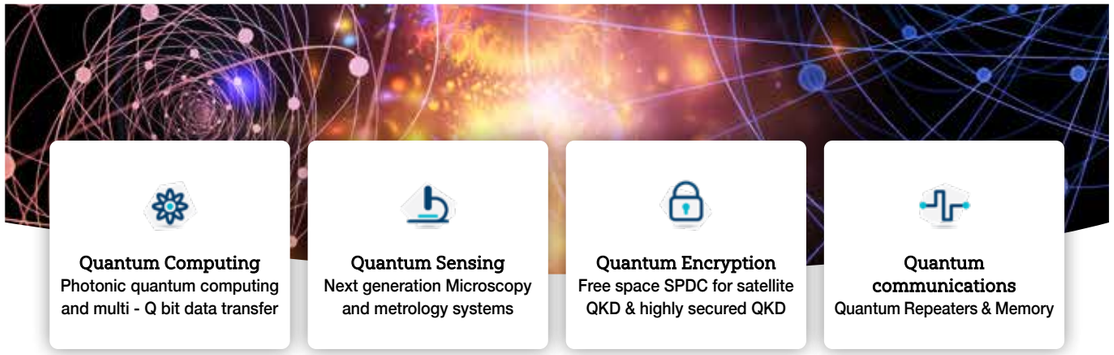
The leading crystal for quantum applications

Periodically poled potassium titanyl phosphate (ppKTP) is a quasi phase-matched, nonlinear crystal that was first introduced to the industry by Raicol over 20 years ago. Today, ppKTP is mostly commonly used as an SPDC source in the quantum industry.

In recent years, Raicol-Quantum, the Raicol Crystals Quantum Division, has been deepening its unparalleled expertise in the manufacture of quasi-phase-matched ppKTP crystals. By controlling the complete manufacturing process, from the initial growth of the crystal to its periodic poling, Raicol has been able to fine-tune the final product to accommodate the challenging requirements of the quantum industry, and create unique custom crystals for specific applications.

Serving the world's leading quantum research labs, Raicol QPM crystals are the building block for the future of quantum applications:

- Quantum computing
- Quantum sensing
- Quantum encryption
- Quantum communications



Raicol-Quantum, together with our academic partners, are working to optimize ppKTP crystals as industrial sources of entangled photon pairs for EPS (entangled photon sources), SLS squeezed light sources and HSPS (heralded single-photons sources).

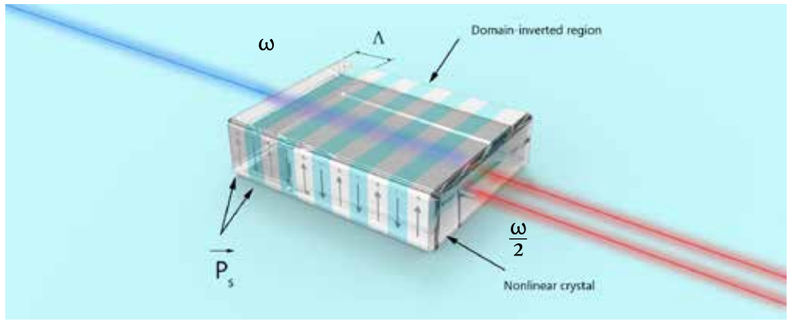
Raicol's ppKTP crystals are prominent SPDC sources for:

- Polarization entanglement
- High purity heralded single photons
- Squeezed light
- Quantum frequency conversion

Our ppKTP crystals are highly customizable, offering:

- Type-0 or Type-II phase matching
- Broad pumping range, including 405, 532 and 775nm
- Narrowband or broadband SPDC spectrum
- Aperiodic polling for high spectral purity
- Single or multi-period KTP

Raicol-Quantum's typical ppKTP crystal scheme



Raicol-Quantum utilizes its advanced knowledge in QPM to help companies design and manufacture poled KTP with advanced poling schemes for specific quantum applications.

apKTP

Aperiodically Poled KTP (apKTP)

apKTP represents a breakthrough in nonlinear crystal technology through precise engineering of its domain structure, offering unprecedented control over quantum light properties. While standard ppKTP uses uniform periodic poling, apKTP implements sophisticated non-uniform poling patterns, including chirped designs, to shape the joint spectrum of down-converted photons.
These advanced structures enable unique capabilities not achievable with periodic poling, such as the generation of highly pure single photons without external filtering, creation of specific entangled states, production of ultrabroad-spectrum SPDC light, generation of multiple modes, and achievement of exceptionally narrow Hong-Ou-Mandel dips.

When precise control over quantum state properties is fundamental to system performance, apKTP has become essential for cutting-edge quantum applications including:

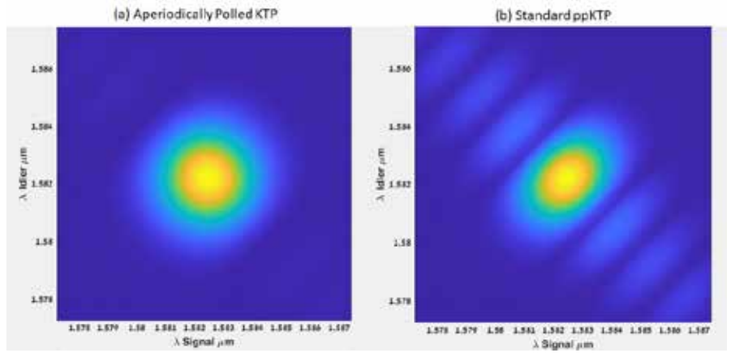
- Entangled photon sources
- Quantum Computing
- Quantum Communications
- Quantum Sensing

HP-apKTP

High Purity aperiodically polled KTP

Shaping the joint spectrum of down-converted photons

Customizing the poling structure of KTP crystals via aperiodic-polling[1] enables the shaping of the joint spectrum of the SPDC process. Based on this method, Raicol now offers high-purity apKTP crystals that increase the spectral purity and indistinguishability of the emitted photon pairs, yielding improved performance of entangled photon sources and higher Hong-Ou-Mandel visibility compared to standard ppKTP and ppLN crystals.



Raicol's High Purity apKTP is a uniquely designed KTP crystal that maximizes spectral purity at telecom wavelengths. It is a type-2 crystal, suitable for pumping with Ti-Sapphire lasers (775-795nm) with a degenerate SPDC output. Using the HP-apKTP enables quantum researchers to achieve higher spectral purity without any external narrowband filters, therefore reducing the losses in the system and increasing the quantum properties of the entangled state.

[1] A. Dosseva et al. "Shaping the joint spectrum of down-converted photons through optimized custom poling", Phys. Rev. A 93, 013801 (2016).

SppKTP

Raicol SppKTP is a specialized nonlinear crystal designed for high-power applications.

Key Features:

- Power Handling: support up to 6 times the power levels of standard PPKTP
- Low Absorption: x 5 times less GRIIRA

Applications:

- Squeezed Light
- QKD

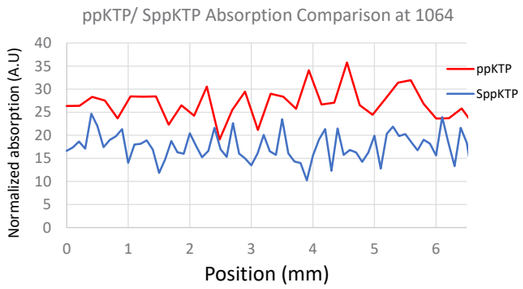
SppKTP characterization

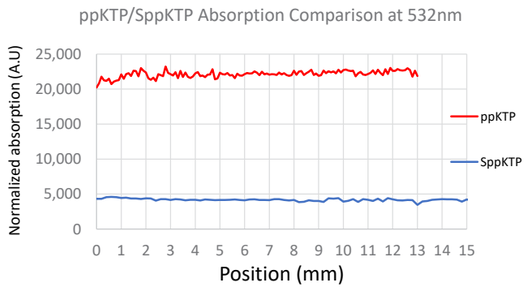
Absorption measurements scan across the crystal width and GRIIRA (Green Induced Infrared Absorption) test using Common Path Interferometer showed the following results:

	Absorption ppm / cm		
Type	**Scan (A.U)**		**GRIIRA**
	1064 nm	**532 nm**	
KTP	27	22,000	25
SKTP	17	4200	5

Absorption measurements

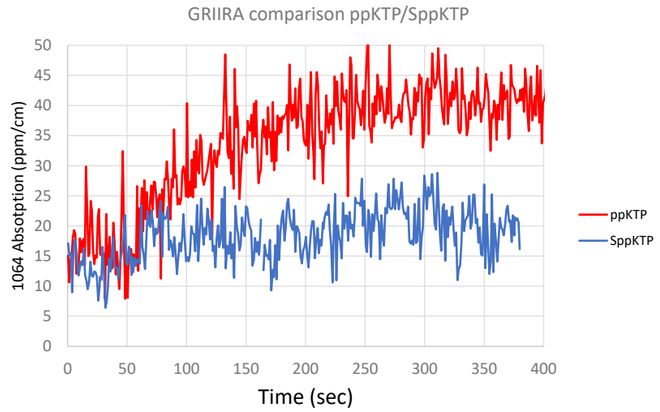
Scan to the Length of the crystal (at 1064 nm and 532 nm).





GRIIRA measurements

The test measurements absorption at 1064nm over time with induced 532nm as the following profile: Starting with 60 sec of the 1064nm at 15KW/cm^2 and then adding the 532nm at 8KW/cm^2 with the 1064nm at 15KW/cm^2.



With its remarkable power handling capabilities and low optical absorption, Raicol SppKTP opens up new possibilities for cutting-edge research and industrial applications in the realm of high-power nonlinear optics.

MgO:PPLN

Periodically poled Lithium Niobate (PPLN)

PPLN is created by periodically inverting the ferroelectric domains in a lithium niobate (LiNbO3) crystal, resulting in a higher efficiency of nonlinear optical processes.

Quasi-phase matching (QPM): PPLN enables efficient second-order nonlinear optical processes, such as second harmonic generation (SHG), sum-frequency generation (SFG), optical parametric oscillation (OPO), and spontaneous parametric down-conversion (SPDC), through quasi-phase matching. This technique compensates for the phase mismatch between the interacting waves, allowing for efficient energy conversion over longer interaction lengths. The QPM in PPLN can be engineered during the fabrication process, allowing for phase matching at tailored wavelengths. This tunability enables the generation of coherent radiation over a wide range of wavelengths.

Features of PPLN

- Broad transparency range: 420 nm - 5200 nm
- High nonlinear coefficient: PPLN has a large nonlinear optical coefficient (d_{33}~27pm/V), which is essential for efficient nonlinear optical processes.
- Compact design: PPLN devices can be designed in compact and integrated configurations, making them suitable for applications where size and portability are important considerations.
- PPLN exhibits a relatively high resistance to photorefractive damage enabling high-power operation and improved device lifetime. Absorption coefficient of ~0.1/cm @ 1064nm and Laser damage threshold of 100MW/cm^2 @1064, 10ns.

Applications

- Frequency conversion for laser systems
- Nonlinear spectroscopy
- Optical communications
- Integrated photonics
- Perfectly suited for compact low power solid state laser systems
- Quantum light sources

PPLN Specifications

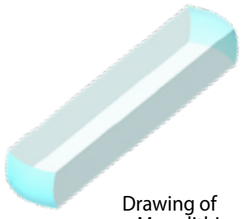
Aperture	Up to 1x5 mm^2
Length	Up to 40 mm
Transparency range	420-5200nm
Flatness	Up to λ/10 @633nm
Scratch/Dig	10/5
Perpendicularity	<10 arc min.
Parallelism	20 arc sec.
Wavefront distortion control	λ/8 @633 nm
AR Coating	AR, DBAR, HR
Absorption Coefficient	<0.1/cm@1064nm
Laser-Induced Damage Threshold	100 MW/ cm^2, @1064 nm. 10 ns

ppKTP Innovations

Raicol's development team continues to improve and bring novel capabilities to the market. We have developed new PPKTP-based features and applications for initial prototype testing.

Monolithic crystals

In recent years, Raicol has started manufacturing monolithic ppKTP crystals with reflective mirror coating on the facets.
These crystals are designed to create a cavity within the crystal itself and serve as compact generators of squeezed light, to be used in quantum sensing and narrowband entanglement. The mirror coating on the facets of the crystal is specifically designed to form a cavity that enhances the efficiency of the nonlinear optical processes taking place within the crystal. This advancement has the potential to expand the range of applications for ppKTP crystals and further push their performance for new quantum technologies.



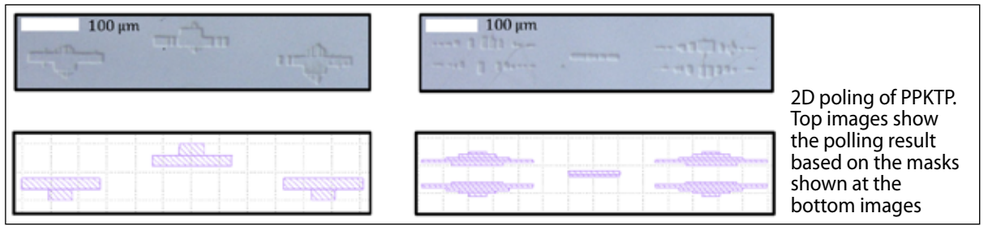
Drawing of a Monolithic PPKTP crystal

Applications

- Squeezed light generation- ppKTP has been a prominent crystal for a squeezed light application, best demonstrated in the interferometric measurements of gravitational waves in LIGO, in which a semi-monolithic ppKTP crystal was utilized.
- Narrowband entanglement for quantum memories
- High-efficiency frequency conversion

2D poling

Recent developments in the field of nonlinear optics have led to the fabrication of two-dimensional (2D) poling in KTP crystals by Raicol. While typical periodically poled KTP is poled in one dimension of the wavefront propagation (the KTP X-Axis), 2D poling enables new and complex schemes of periodic poling. A notable example of this advancement is the work by Prof. Ady Arie at Tel-Aviv University, in which they used a crystal with this unique poling design to generate spatially entangled qudits.
This advancement has the potential to offer new and exciting applications and utilizations of PPKTP crystals.



2D poling of PPKTP. Top images show the polling result based on the masks shown at the bottom images

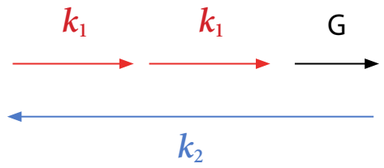
Applications

- Direct generation of spatially entangled qudits using quantum nonlinear optical holography | Arie et al. Science Advances

Short Poling Period ppKTP

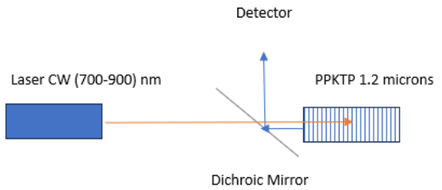
Raicol has experienced a surge in demand for ppKTP crystals with extremely short poling periods, as low as 1.2 microns, driven by applications in narrow-band "Counter Propagation SPDC" for quantum memory integration and sensing. This technique can achieve remarkably narrow SPDC bandwidths of 0.06 nm [1] in a single pass. To meet this demand, Raicol now offers ppKTP crystals up to 35 mm in length, as longer crystals produce narrower bandwidths. Raicol has also developed specialized measuring systems, based on backward propagation to quantify and verify the performance of these short poling periods, ensuring high-quality crystals for cutting-edge quantum applications.

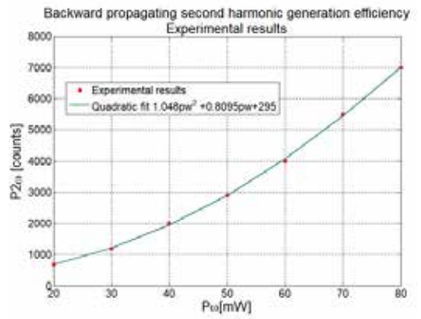
Backward second harmonic generation:



[1] Liu, YC., Guo, DJ., Ren, KQ. *et al*. Observation of frequency-uncorrelated photon pairs generated by counter-propagating spontaneous parametric down-conversion. *Sci Rep* **11**, 12628 (2021).

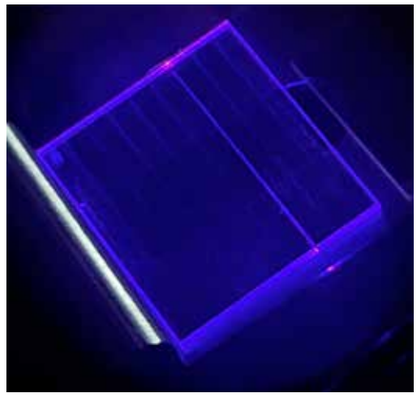
Backward second harmonic measuring system and results:





ppKTP Waveguides

Laser-written ppKTP waveguides are high-efficiency nonlinear devices that enable superior quantum light generation compared to bulk crystals. Their fiber compatibility and enhanced nonlinear interaction make them a cornerstone of modern quantum technologies.



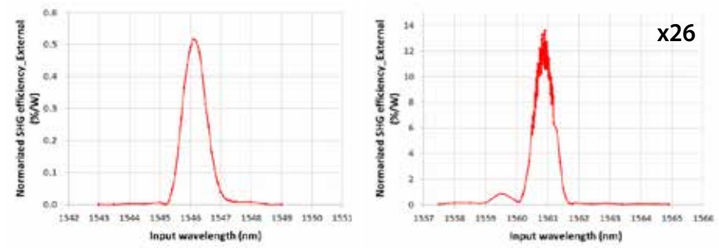
Available WG:

Wavelengths	Type	Length	Fiber Coupled
405 → 810 nm	0, II	5, 10, 20	Contact us
532 → 1064 nm	0, II	5, 10, 20	Contact us
775 → 1550 nm	0, II	5, 10, 20	Yes

*Custom wavelengths and aperiodic poling upon request.

Advantages Compared to Bulk

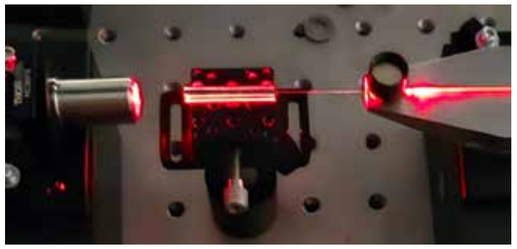
- Increased Efficiency of Nonlinear Interactions
- Low-loss Connectivity to Single-mode Fibers via Mode Matching
- Increased Detected Photon Pair Rate



Bulk Waveguide

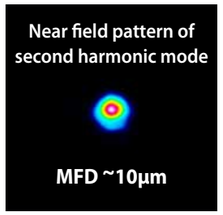
Functionality

- SPDC
- SHG
- Squeezed Light



Applications

- High Resolution Microscopy
- Entangled Photon Generation
- Quantum Computing and Communication
- Quantum Sensing and Imaging

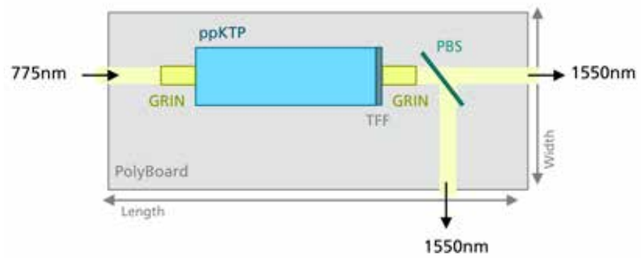


Specifications

Available Wavelengths	405 → 810 nm; 532 → 1064 nm; 775 → 1550 nm; Custom wavelengths and aperiodic polling on request
Mode Field Diameter	~10 µm
Length	Up to 30 mm
Transparency Range	350-4000 nm
Laser Induced Damage Threshold	600MW/cm^2 @ 1064 nm, 10 ns pulses
SPDC Type	Type I, Type 0, Type II
Aperture / # of Waveguides	1 mm x 2 mm / 2 per element
AR Coatings	AR, DBAR, HR, Triple band

Heralded Single Photon Module (Beta)

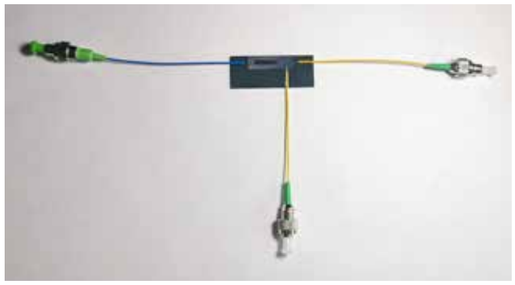
Raicol has integrated its ppKTP crystals into an innovative fiber-coupled platform, suitable for generation of correlated photon pairs and heralded single photons at telecom wavelengths.
Designed for the SPDC process using Raicol's Type II PPKTP crystals, you can implement a modular, fiber-coupled heralded single-photon source for all your quantum applications.



- Non-committal estimate dimensions for PIC
  - Lengh 15 ... 25 mm (depends on crystal length
  - Width 5 ... 6 mm
  - Hight 1.5 ... 2 mm

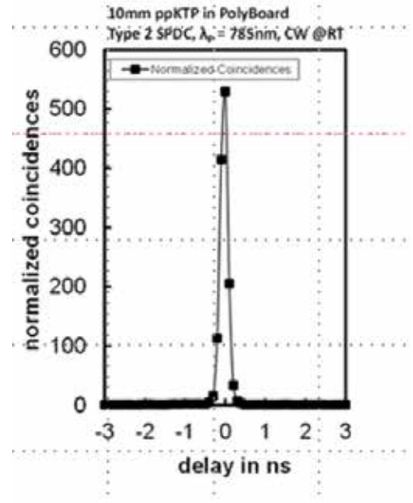
The HSPS module features

- 10/15mm Type II ppKTP or apKTP
- 775 PM pump input, 2x 1550 SM signal/idler outputs with orthogonal polarizations
- Pump suppression filters
- Integrated Peltier oven for thermal tuning of the SPDC spectrum

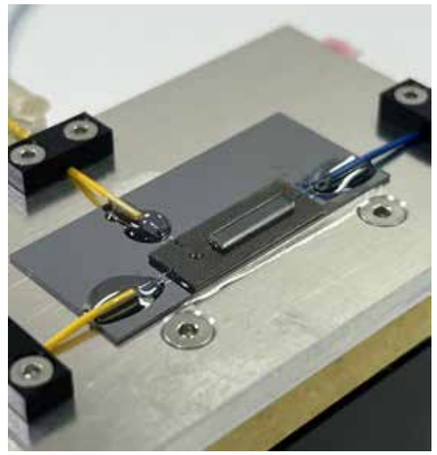


The HSPC module assembly on the Polyboard

Technical specifications



Normalized coincident counts based
At 785nm Pump

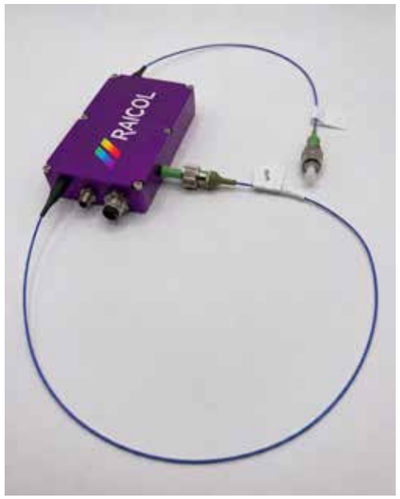


The HSPS module embbeded in the pltier oven

* The product is in the Beta stage, and all specifications are not final.

Fiber Coupled ppKTP Waveguide Module

Integration of our laser-written waveguides into fiber-coupled modules provides a compact and bright quantum light source. Coupled to polarization-maintaining fibers, our module can be effortlessly incorporated into space- and power-efficient nonlinear optical systems, fit for operation in satellite-based quantum communication and standard frequency conversion systems.



Available WG:

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532 → 1064 nm	0, II	5, 10, 20	Contact us
775 → 1550 nm	0, II	5, 10, 20	Yes

*Custom wavelengths and aperiodic poling upon request.

Expected Parameters:

Type-0 SPDC, 775->1550nm	Bulk	Module*
Heralding Efficiency	20%	19.6±0.8%
Spectral Bandwidth	---	125 nm
Collected Pair Rate	1 MHz/mW	~ 37 MHz/mW
WG Improvement	---	37X

* Waveguide parameters measured on several Beta modules.

Functionality

- SPDC
- SHG

Applications

- Entangled Photon Generation
- Correlated Photon-Pair Generation
- Entanglement-Based Quantum Communication
- Quantum Sensing and Imaging

Specifications

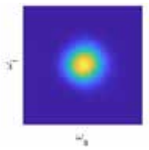
Available Wavelengths	405 → 810 nm; 532 → 1064 nm; 775 → 1550 nm; Custom processes and aperiodic poling available upon request
Crystal Length	20 mm
Operating Temperature Range	20-28 C
Temperature Control	TEC and Thermistor module connections
Fiber Connections	PM fibers at input and output frequencies, OD=900um, FC/APC connectors
Dimensions (LxWxH)	12 x 4 x 1.8 cm

Advanced SPDC-Based Solutions

Advanced Nonlinear Crystals

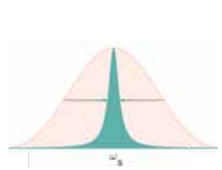
High-purity Telecom Heralded Single Photons

- Aperiodically poled KTP (apKTP) for maximized spectral purity
- Enhanced Hong-Ou-Mandel visibility without filtering
- Fiber-coupled module for plug-and-play integration



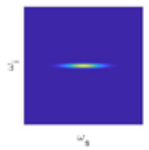
Cavity-enhanced SPDC

- Narrow bandwidth: 10-200 MHz
- Monolithic and semi-monolithic designs
- Large Free Spectral Range for easy single-mode spectral filtering
- Direct single-mode generation option
- Wavelengths, matched to atomic transitions



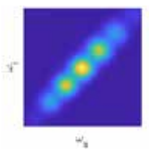
Counter-propagating SPDC

- Narrow bandwidth (GHz)
- High spectral purity at wavelengths, not limited to the GVM wavelength



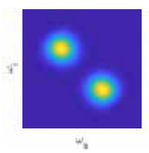
Multidimensional Entangled States

- 2D poling structures for spatial qudit generation
- Custom domain engineering for tailored joint spectral intensity
- Frequency-encoded qudits
- Time-bin entanglement



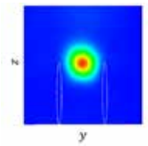
Direct Polarization-Entangled Photon Pair Generation

- Novel dual-lobe phase-matching design for simplified setups
- Compact and stable entanglement



Nonlinear-Optical Waveguides

- 23x higher nonlinear efficiency compared to bulk
- Precision-engineered laser-written waveguides
- Fiber-compatible mode profiles
- Miniaturized, efficient quantum light sources

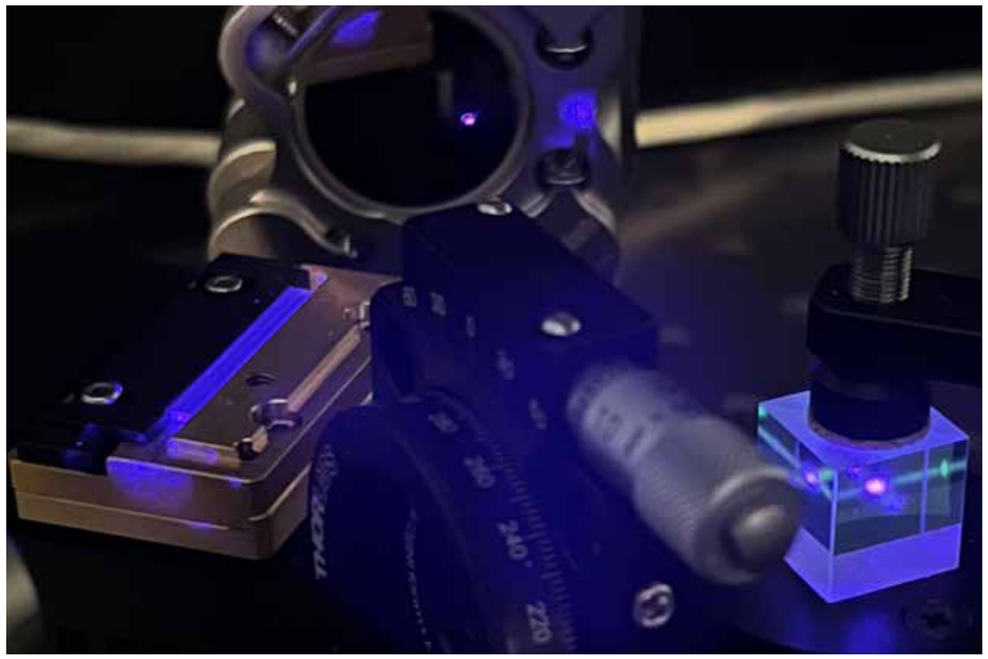


High Damage Threshold Crystals

- SPPKTP crystals with 6x higher power handling
- 50% lower absorption at 532 nm compared to standard PPKTP
- Minimal Green-Induced Infrared Absorption
- Pulsed QKD and squeezed light generation

Robust SPDC

- Adiabatic frequency conversion
- Reduced sensitivity to crystal temperature
- Reduced sensitivity to pump wavelength



Complete Quantum Systems

Customized Sagnac-Loop Polarization-Entangled Photon Pair Source

- Type II, 405 → 810 nm, SM fiber output
  - Output brightness: >70,000 pairs/s/mW
  - Bell-state fidelity: >0.98
  - Collection efficiency: >0.35
  - Max pump power: 20 mW / 50 mW
  - Degenerate and non-degenerate regimes

Correlated Photon Pair Source

- Type II, 405 → 810 nm, SM fiber output
  - Output brightness: >500,000 pairs/s/mW
  - Collection efficiency: >0.65
  - Max pump power: 20 mW / 50 mW

Integrated Heralded Single-Photon Module

- Fiber-coupled 775 nm pump input
- Dual 1550 nm SM outputs with orthogonal polarizations
- Integrated filtering and temperature control
- Compact footprint for equipment integration

For inquiries about other wavelengths or type-0 configurations, please contact us at **www.raicol.com**

Custom Solutions for your Research

Looking for specialized SPDC-based solutions? Our team can develop tailored systems optimized for your specific research needs.

Collaboration opportunities

We actively seek partnerships with research institutions, quantum technology companies, and industry innovators. We view our innovations as starting points for deeper collaboration, where we can jointly develop customized solutions that address global challenges of the second quantum revolution. We believe in co-developing advanced quantum solutions that push the boundaries of what's possible in quantum information processing, sensing, and communications.

Waveguide-based RTP modulator
Thin film RTP modulator

- **Designed for integrated photons**
- **Ultra-low Vπ**
- **Compact design**
- **Thermally stable**

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