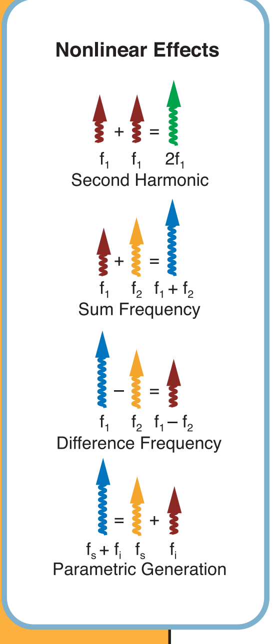
Periodically Poled Lithium Niobate (PPLN) - Tutorial

Periodically poled lithium niobate (PPLN) is a highly efficient medium for nonlinear wavelength conversion processes. PPLN is used for frequency doubling, difference frequency generation, sum frequency generation, optical parametric oscillation, and other nonlinear processes.

Principles

Second order nonlinear processes involve the mixing of three electromagnetic waves, where the magnitude of the nonlinear response of the crystal is characterized by the $\chi^{(2)}$ coefficient. Frequency doubling (Second Harmonic Generation, SHG) is the most common application that utilizes the $\chi^{(2)}$ properties of a nonlinear crystal. In SHG, two input photons with the same wavelength λ_1 are combined through a nonlinear process to generate a third photon at $\lambda_{1/2}$. Similar to SHG, Sum Frequency Generation (SHG) combines two input photons at λ_1 and λ_2 to generate an output photon at $\lambda_{generated}$ with $1/\lambda_{generated} = 1/\lambda_1 + 1/\lambda_2$. Alternatively, in Difference Frequency Generation (DFG) the two input photons at λ_1 and λ_2 are combined to generate an output photon at $\lambda_{generated}$ with $1/\lambda_{generated} = 1/\lambda_1 - 1/\lambda_2$. Nonlinear processes where the frequency of the generated photon is not determined by the frequency of the input photon are termed parametric processes. In a parametric process, a single input photon is split into two generated photons where the only restriction on the combination of frequencies of the generated photons is that it conserves energy. Only the combination of photon frequencies that is phase matched will be efficiently generated.

Phase matching refers to fixing the relative phase between two or more frequencies of light as the light propagates through the crystal. In materials, the refractive index is dependent on the frequency of light propagating through the material. In these materials, the phase relation between two photons of different frequencies will vary as the photons propagate through the crystal, unless the crystal is phase matched for those frequencies. It is necessary for the phase relation between the input and generated photons to be constant throughout the crystal for efficient nonlinear conversion of input photons. If this is not the case, the generated photons will destructively interfere with each other, limiting the number of generated photons that exit the crystal. This is shown in the plots. Traditional phase matching requires that the light is propagated through the crystal in a direction where the natural birefringence of the crystal has the same refractive index as the generated photons. The drawbacks to this technique include the limited number of available materials and the range of wavelengths in those materials that can be phase matched.

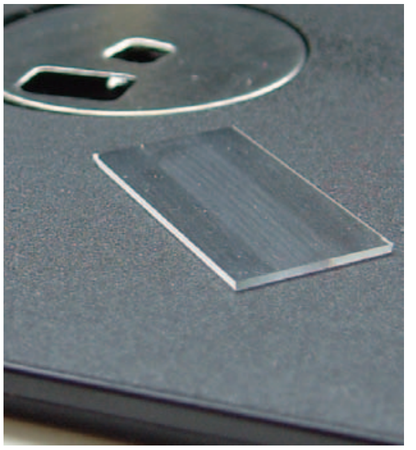


PPLN is an engineered, quasi-phase-matched material. The term engineered refers to the fact that the orientation of the Lithium Niobate crystal is periodically inverted (poled). The inverted portions of the crystal yield generated photons that are 180° out of phase with the generated photon that would have been created at that point in the crystal if it had not been poled. By choosing the correct periodicity with which to flip the orientation of the crystal, the newly generated photons will always (at least partially) interfere constructively with previously generated photons, and as a result, the number of generated photons will grow as the light propagates through the PPLN, yielding a high conversion efficiency of input to generated photons. The periodicity of the poling should be such that the crystal structure is inverted when the number of generated photons at a given point in the crystal is at a maximum as shown in the plot.

The period with which the crystal needs to be inverted (the poling period) depends on the wavelengths of the light (input and generated) and the temperature of the PPLN. For instance, consider a PPLN crystal that has a poling period of 6.6µm at room temperature. It will efficiently generate frequency doubled photons from 1060nm photons when the crystal temperature is held at 100°C. By increasing the temperature of the crystal to 200°C PPLN will efficiently generate frequency doubled photons from 1068.6nm photons. Changing the temperature of the crystal varies the phase matching conditions, which alters the periodicity of the poling in the crystal and thereby allows some tuning of the generated photon frequency. Thus adjusting the temperature allows some tuning of the generated photon wavelength.

How are PPLN crystals made?

The key to producing PPLN is the process by which the crystal structure of Lithium Niobate is inverted (poled). Lithium Niobate is a ferroelectric crystal, which means that each unit cell in the crystal has a small electric

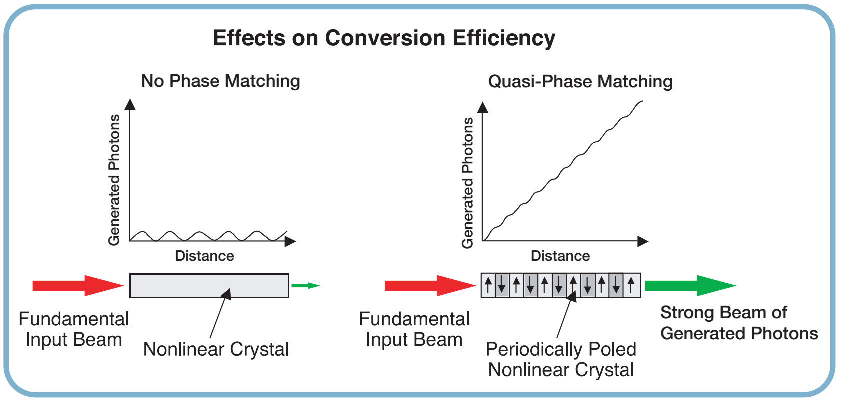


dipole moment. The orientation of the electric dipole in a unit cell is dependent on the positions of the niobium and lithium ions in that unit cell. The application of an intense electric field can invert the crystal structure within a unit cell and as a result flip the orientation of the electric dipole. The electric field needed to invert the crystal is very large (~22kV/mm) and is applied for only a few milliseconds, after which the inverted sections of the crystal are permanently imprinted into the crystal structure. To produce PPLN, a periodic electrode structure is deposited on the lithium niobate wafer, and a voltage is applied to invert the crystal underneath the electrodes. The voltage must be very carefully controlled so that the poled regions are created with the desired shape. The design of the electrodes is key to producing periofic ity a short PPLN crystal that can be used for an efficient SHG process, which produces photons in the visible portion of the electromagnetic spectrum.

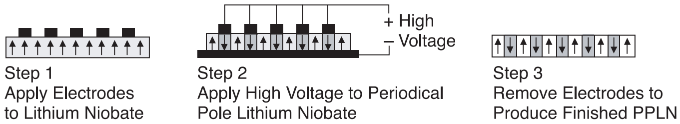
Example uses of PPLN

Optical Parametric Oscillator:

One of the most common uses of PPLN is in an Optical Parametric Oscillator (OPO). A schematic of an OPO is shown on the next page. The common arrangement uses a 1064nm pump laser and can produce signal and idler beams at any wavelength longer than the pump laser wavelength. The exact wavelengths are determined by two factors:



Fabrication of Periodically Poled Litium Niobate (PPLN)



energy conservation and phase matching. Energy conservation dictates that the sum of the energy of a signal photon and an idler photon must equal the energy of a pump photon. Therefore an infinite number of generated photon combinations are possible. However, the combination that will be efficiently produced is the one for which the periodicity of the poling in the lithium niobate creates a quasi-phase matched condition. The combination of wavelengths that is quasi-phase matched, and hence referred to as the operation wavelength, is altered by changing the PPLN temperature or by using PPLN with a different poling period. Nd:YAG pumped OPOs based on PPLN can efficiently produce tunable light at wavelengths between 1.3 and 5µm and can even produce light at longer wavelengths but with lower efficiency. The PPLN OPO can produce output powers of several watts and can be pumped with pulsed or CW pump lasers.

Second Harmonic Generation:

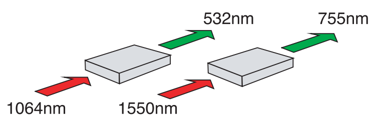
PPLN is one of the most efficient crystals for frequency doubling. It has been used to frequency double pulsed 1064nm beams with up to 80% conversion efficiency in a single pass, thus eliminating the need for difficult laser designs with intra-cavity doubling crystals or matched external cavities, which are needed with conventional doubling crystals. The power handling is excellent for infrared pump and output wavelengths (e.g. SHG of 1550nm → 775nm); however, when using PPLN to frequency double into the visible, the power handling ability of the crystal is more limited. It has been demonstrated that PPLN can handle up to 600mW at 532nm when frequency doubling 1064nm. The exact power handling limit and conversion efficiency depend on the properties of the laser beam used (e.g. pulse length, repetition rate, beam quality, and line width.)

How to use PPLN

Focusing and the Optical Arrangement:

Since PPLN is a nonlinear material, the highest conversion efficiency from input photons to generated photons will occur when the intensity of photons in the crystal is the greatest. This is normally accomplished by coupling focused light into the center of the PPLN crystal through the end face of the crystal at normal incidence. For a particular laser beam and crystal, there is an optimum spot size to achieve optimum conversion efficiency. If the spot size is too small, the intensity at the waist is high, but the Rayleigh range is much shorter than the crystal. Therefore, the size of the beam at the input face of the crystal is large, resulting in a lower average intensity over the whole crystal length, which reduces the conversion efficiency. A good rule of thumb is that for a CW laser beam with a Gaussian beam profile, the spot size should be chosen such that the Rayleigh range is half the length of the crystal. The spot size can then be reduced in small increments until the maximum efficiency is obtained. The PPLN material has a high index of refraction that results in a 14% Fresnel loss per uncoated surface. To increase the transmission through the crystals, the crystal input and output facets are AR coated, thus reducing the reflections at each surface to less than 1%.

Second Harmonic Generation



Polarization:

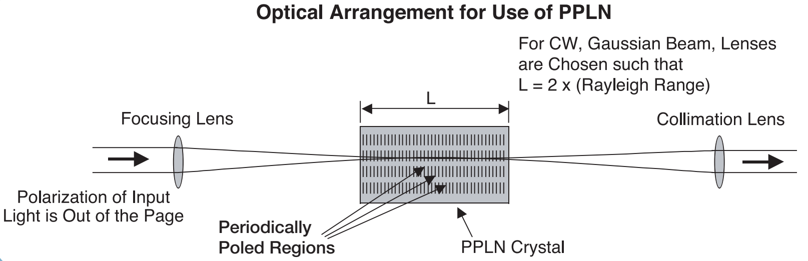
The polarization of the input light must be aligned with the dipole moment of the crystal in order to utilize the nonlinear properties of lithium niobate. This is accomplished by aligning the polarization axis of the light with the thickness of the crystal. Light polarized orthogonal to the thickness of the crystal will be transmitted through the crystal unaltered.

Temperature and Period:

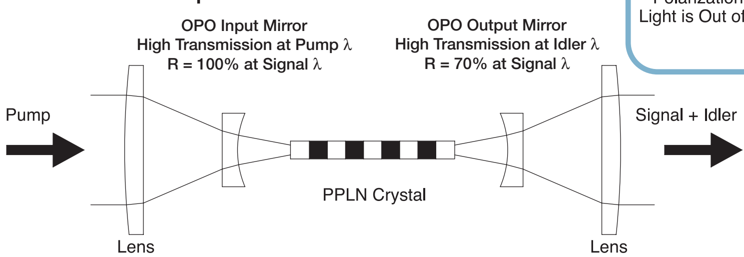
The poling period (PP) in the crystal is determined by the wavelength of light being used. The quasi-phase-matched wavelength can be tuned slightly by varying the temperature of the crystal, which changes the poling period. The Thorlabs/Stratophase PPLN crystals all have multiple PP sections in each crystal, each with a different poling period, which allows different wavelengths to be used at a given crystal temperature. The optimum temperature can be determined by adjusting the temperature while monitoring the output power at the generated wavelength. PPLN is usually used at temperatures between 100°C and 200°C.

The Thorlabs/Stratophase PPLN oven is easy to incorporate into an optical setup and can stably maintain the elevated temperature of the crystal. Temperatures in the 100°C-200°C range are used in order to minimize the photorefractive effect that can damage the crystal and causes the output beam to be distorted. Since the photorefractive effect is more severe in PPLN when higher energy photons in the visible part of the spectrum are present in the crystal, it is especially important to use the crystal only in the recommended temperature range. When using a PPLN crystal as an OPO that is pumped with and generates light in the infrared region of the spectrum, it may be possible to use temperatures lower than 100°C if necessary without damaging the crystal.

Optical Arrangement for Use of PPLN

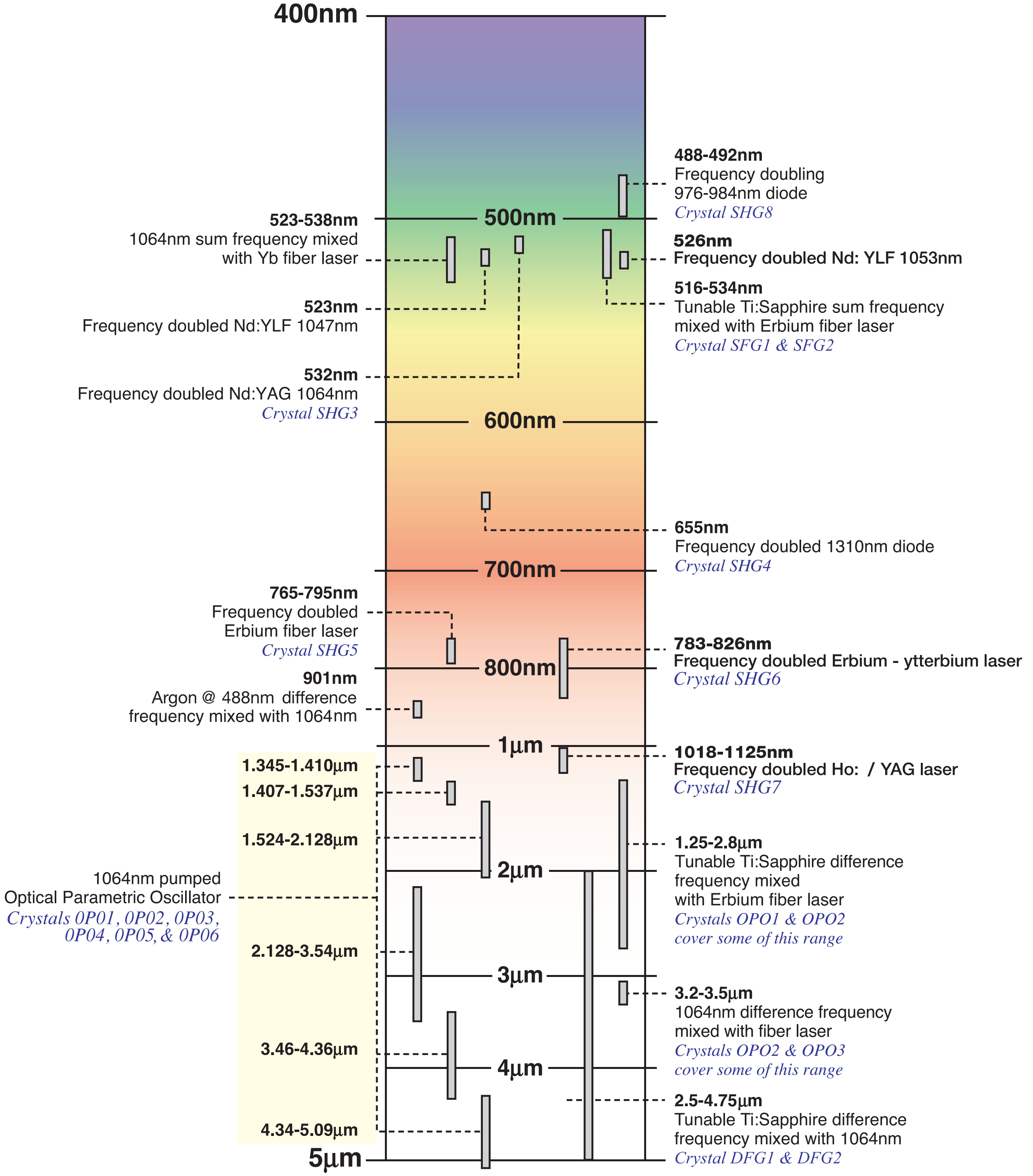


Optical Parametric Oscillator Schematic



Periodically Poled Lithium Niobate – Wavelength Selection Guide

By using PPLN in combination with common lasers, it is possible to access a wide range of wavelengths in the visible and infrared. These wavelengths are created by either frequency doubling a laser or mixing the output of two lasers together in a PPLN crystal. Where a standard catalog PPLN crystal is appropriate, the crystal type is shown. Crystals for other applications and advice are available from Stratophase.



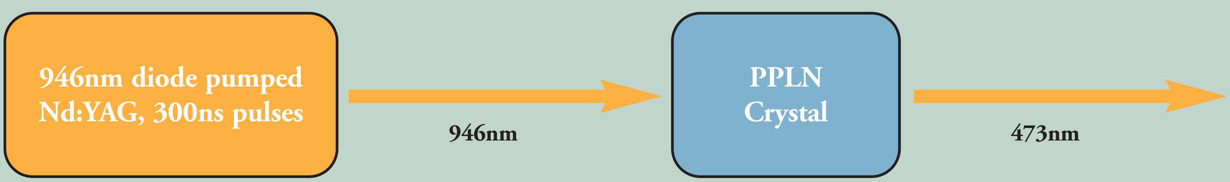
Example Applications

Frequency doubling and tripling an Erbium fiber laser

- 83% Conversion Efficiency (1536nm → 768nm)
- 34% Conversion Efficiency (768nm → 384nm)
- Excellent Beam Quality

Reference – "Highly efficient second-harmonic and sum-frequency generation of nanosecond pulses in a cascaded erbium-doped fiber: periodically poled lithium niobate source", D.Taverner, *et al.* Optics Letters Vol. **23**, (3), 162-164, (1998).

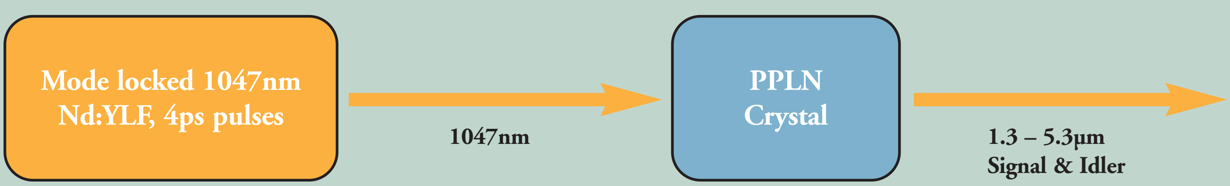
High Power 473nm generation



- 450mW Average Power at 473nm
- 40% Conversion Efficiency
- No Observed Photorefractive Effect
- Excellent Beam Quality

Reference – "Generation of high-power blue light in periodically poled $LiNbO_3$", G.W.Ross et al. Optics Letters **23**, (3) 171-173 (1998).

Generation of picosecond, tunable, infrared light



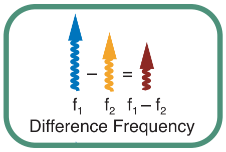
- 4ps Pulses Tunable IR Light, 1.3 – 5.3µm
- **Signal Power:** >400mW
- Slope Efficiency, Signal and Idler up to 160%
- **Threshold:** 7.5mW

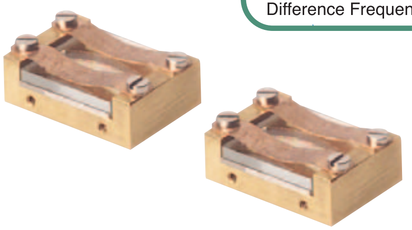
Reference – "Efficient, low-threshold synchronously-pumped parametric oscillation in periodically-poled lithium niobate over the 1.3µm to 5.3µm range" L.Lefort *et al.* Optics Communications **152,** (1-3), 55-58 (1998).

Optical Systems
Free Space Isolators
E-O Devices
Spherical Singlets
Multi-Element Lenses
Cylindrical Lenses
Aspheric Lenses
Mirrors
Diffusers & Lens Arrays
Windows
Prisms
Gratings
Polarization Optics
Beamsplitters
Filters & Attenuators
Gas Cells

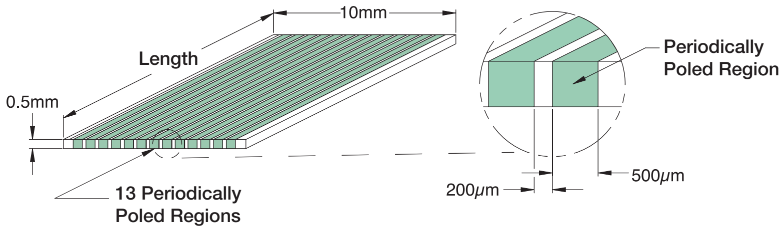
PPLN For Difference Frequency Generation

Difference Frequency Generation (DFG) allows tunable pump sources to be used to produce widely tunable outputs that are ideally suited to a variety of spectroscopic applications. The accessible range of frequencies that can be generated using our DFG PPLN crystals is further increased due to the inclusion of 13 optical paths, each with a different poling periodicity. Each optical path can be temperature tuned to provide a range of generated photon frequencies.





- Components are Available From Stock
- High Efficiency Wavelength Conversion
- Mounted Crystals for Alignment-Free Insertion Into Temperature Controlled PPLN Oven
- Other Crystals Available (e.g. Alternative Lengths, Periods, and AR Coating Specifications)



Specifications

- Input Face AR Coated, R<1% at Specified Pump Wavelengths
- Output Face AR Coated, R<1% at Specified DFG Wavelengths
- Polished to 20-10 Scratch-Dig
- **Flatness:** <λ/4 @633nm
- Fewer Than 2 Edge Chips Larger Than 100µm Per Face
- Faces Parallel to Within ±5 Minutes

PPLN Crystal used to Generate Tunable Light from 2.44-3.17µm

0.5mm thick PPLN crystal designed for DFG of wavelengths in the range of 2.4 – 3.2µm, using simultaneous pump wavelengths from both tunable Ti:Sapphire and Nd:YAG lasers.

- Suitable for Producing Wavelengths From 2.4 – 3.2µm

ITEM	APPLICATION	PERIODS	CRYSTAL LENGTH (mm)	OPERATING TEMPERATURE	$	£	€	RMB
DFG1-20	DFG of 2.44 – 3.17µm Using Simultaneous Pumps at 742 – 796nm and 1064nm.	18.00, 18.25, 18.50, 18.75, 19.00, 19.25, 19.50, 19.75, 20.00, 20.25, 20.50, 20.75, and 21.00µm	20	160 - 200°C	$2,350.00	£1,480.50	€2.185,50	¥22,442.50
DFG1-40	DFG of 2.44 – 3.17µm Using Simultaneous Pumps at 742 – 796nm and 1064nm.		40	160 - 200°C	$2,950.00	£1,858.50	€2.743,50	¥28,172.50

PPLN Crystal used to Generate Tunable Light from 2.85–4.74µm

0.5mm thick PPLN crystal designed for DFG of wavelengths in the range of 2.84 – 4.74µm, using simultaneous pump wavelengths from both tunable Ti:Sapphire and Nd:YAG lasers.

- Suitable for Producing Wavelengths From 2.85 – 4.74µm

ITEM	APPLICATION	PERIODS	CRYSTAL LENGTH (mm)	OPERATING TEMPERATURE	$	£	€	RMB
DFG2-20	DFG of 2.85 – 4.74µm Using Simultaneous Pumps at 775 - 869nm and 1064nm.	20.00, 20.25, 20.50, 20.75, 21.00, 21.25, 21.50, 21.75, 22.00, 22.25, 22.50, 22.75, and 23.00µm	20	160 - 200°C	$2,350.00	£1,480.50	€2.185,50	¥22,442.50
DFG2-40	DFG of 2.85 – 4.74µm Using Simultaneous Pumps at 775 - 869nm and 1064nm.		40	160 - 200°C	$2,950.00	£1,858.50	€2.743,50	¥28,172.50