# Periodically Poled Lithium Niobate (PPLN) - Tutorial

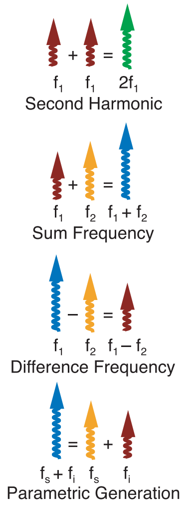
Periodically poled lithium niobate (PPLN) is a highly efficient medium for nonlinear wavelength conversion processes. PPLN is used for frequency doubling, difference frequency generation, sum frequency generation, optical parametric oscillation, and other nonlinear processes.

**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 $\lambda_1$ 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 $\lambda_1$ and $\lambda_2$ 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 $\lambda_1$ and $\lambda_2$ 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.

Nonlinear Effects

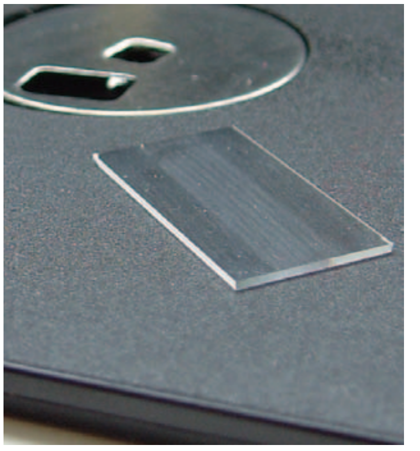



PPLN is an engineered, quasi-phase-matched material. The term engineered refers to the fact that the orientation of the Lithium Niobate crystal is periodically inverted (poled). The inverted portions of the crystal yield generated photons that are 180° out of phase with the generated photon that would 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



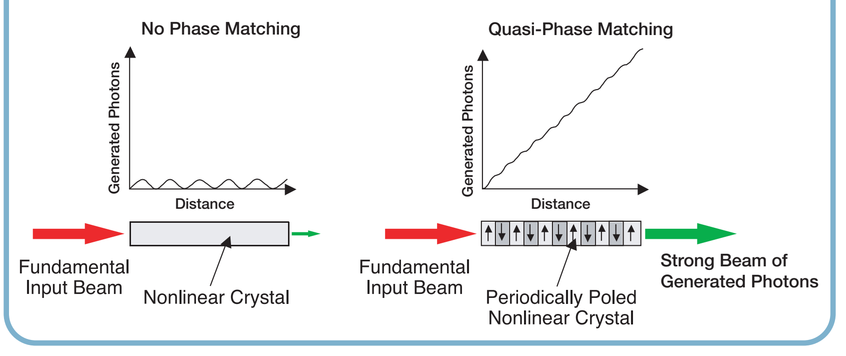
dipole moment. The orientation of the electric dipole in a unit cell is dependent on the positions of the niobium and lithium ions in that unit cell. The application of an intense electric field can invert the crystal structure within a unit cell and as a result flip the orientation of the electric dipole. 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 perioficity 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**

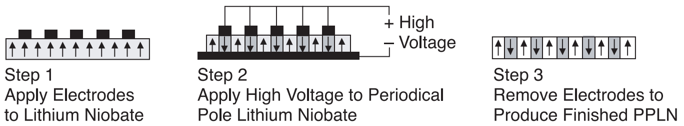
*Optical Parametric Oscillator:*

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:

Effects on Conversion Efficiency



**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:*

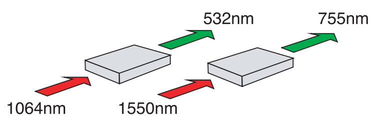
PPLN is one of the most efficient crystals for frequency doubling. It has been used to frequency double pulsed 1064nm beams with up to 80% conversion efficiency in a single pass, thus eliminating the need for difficult laser designs with intra-cavity doubling crystals or matched external cavities, which 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:*

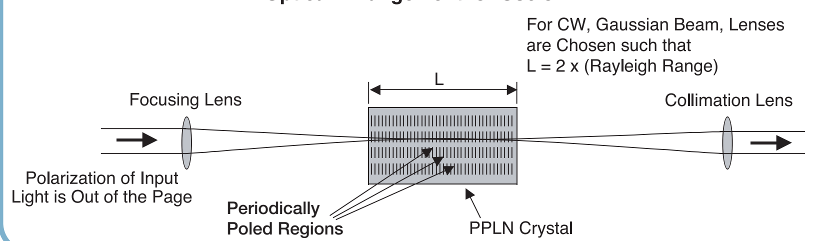
The polarization of the input light must be aligned with the dipole moment of the crystal in order to utilize the nonlinear properties of lithium niobate. This is accomplished by aligning the polarization axis of the light with the thickness of the crystal. Light polarized orthogonal to the thickness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

*Temperature and Period:*

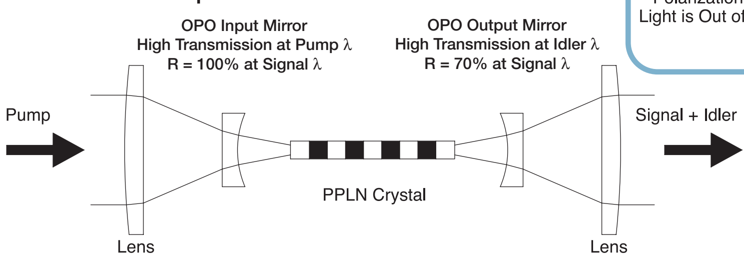
The poling period (PP) in the crystal is determined by the wavelength of light being used. The quasi-phase-matched wavelength can be tuned slightly by varying the temperature of the crystal, which changes the poling period. The Thorlabs/Stratophase PPLN crystals all have multiple PP sections in each 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**

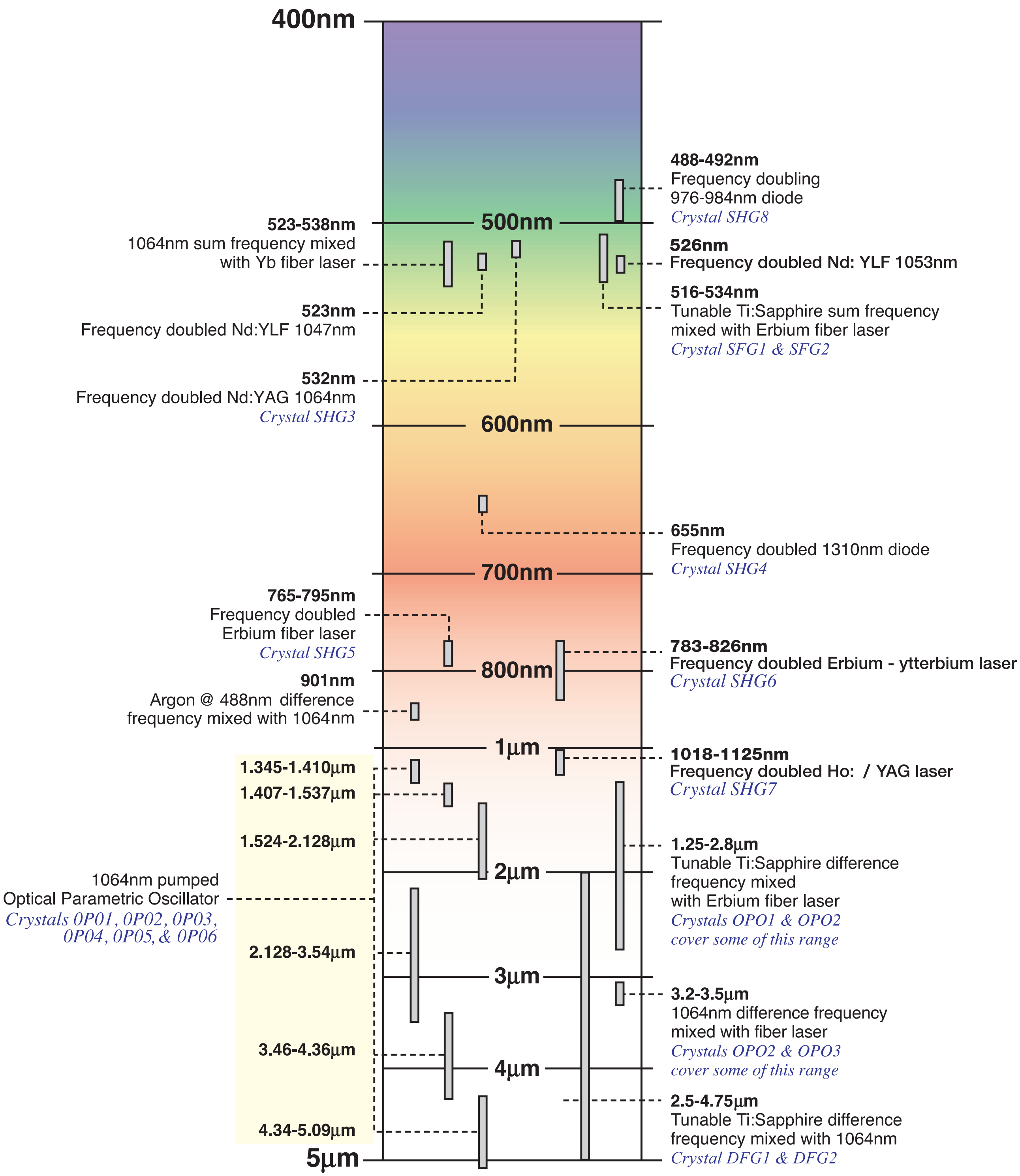



**Optical Parametric Oscillator Schematic**



# 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.



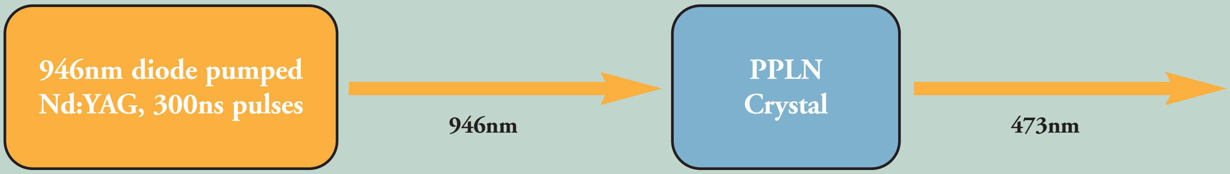
# Example Applications

## 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).

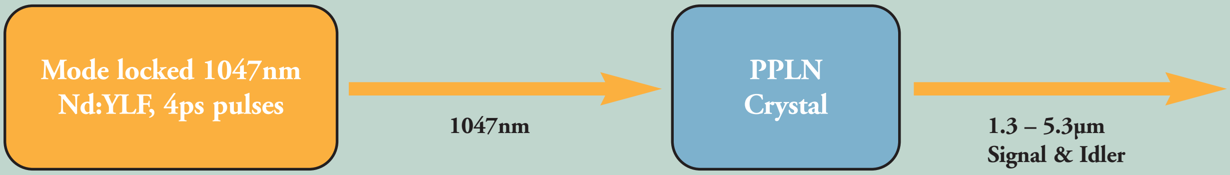
## High Power 473nm generation




- 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 LiNbO3", G.W.Ross et al. Optics Letters **23**, (3) 171-173 (1998).

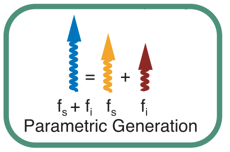
## Generation of picosecond, tunable, infrared light




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

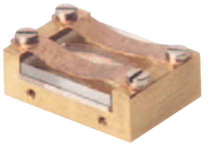
Reference – "Efficient, low-threshold synchronously-pumped parametric oscillation in periodically-poled lithium niobate over the 1.3µm to 5.3µm range" L.Lefort *et al.* Optics Communications **152,** (1-3), 55-58 (1998).

# PPLN Optical Parametric Oscillator Crystals
## For Wide Tuning Ranges

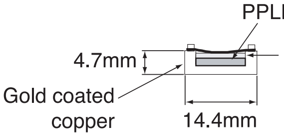



Periodically Poled Lithium Niobate (PPLN) is a nonlinear crystal that is commonly used as the active medium in highly efficient optical parametric oscillators (OPOs). Thorlabs' PPLN crystals are fabricated from high-quality congruent lithium niobate. Each crystal has nine periodically poled optical paths with each path having a different poling periodicity. As a result, only three separate temperature tuned crystals are required to cover the entire wavelength range from 1.3-5µm. The pre-mounted crystals are relatively safe to handle, and the mount eliminates the need to align the crystal when placing it in the Thorlabs PPLN oven.

Thorlabs has partnered with Stratophase to offer the most popular PPLN crystals as stock items. In addition, the mounted PPLN crystals are compatible with the ovens used to control the operating temperatures, thus leading to a complete and easy to assemble set of components.



- Components are Available From Stock
- High Efficiency Wavelength Conversion
- Converted Wavelengths From 1.3-5µm
- AR Coated Crystal Endfaces
- Mounted Crystals for Alignment-Free Insertion Into Temperature Controlled Oven
- Other Crystals Available From Stratophase Upon Request (e.g. 50mm Long, 1mm Thick, and Additional Poling Periods)



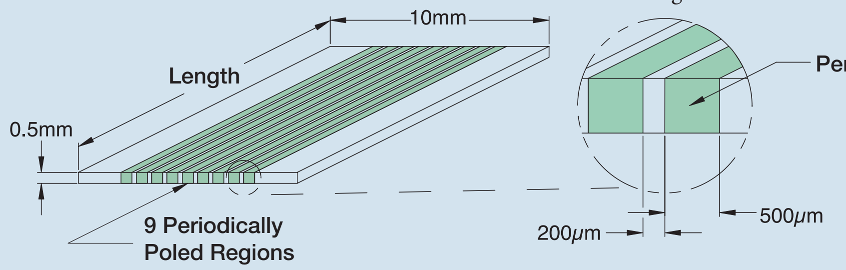

### Specifications

- AR Coated: R< 1% @1064nm; R <1% at Signal and Idler Wavelengths
- Polished to 20-10 Scratch-Dig
- **Flatness:** <λ/8 at 633nm
- Fewer Than 2 Edge Chips Larger Than 100µm per Face
- Faces Parallel to Within ±5 Minutes

**PPLN Crystals for Optical Parametric Oscillators (OPO)**
Six crystals are available from stock covering a range of OPO applications. These crystals may be suitable for generation of other wavelengths if used with different pump wavelengths. Custom crystals are available if these crystals do not meet your needs.

The PPLN crystals are sold pre-mounted so that when placed in a Thorlabs/Stratophase oven they will be automatically aligned with the optical axis of the oven, thereby allowing seemless crystal interchangeability. The stocked crystals are 0.5mm thick, 10mm wide, and either 20 or 40mm long. Each crystal contains nine periodically poled regions, each having a width of 500µm. There is a 200µm section of unpoled lithium niobate between each poled region. In addition, all crystals have anti-reflection coatings on the endfaces.

### SCHEMATIC OF PPLN CRYSTAL FOR OPOs




| ITEM | PPLN PERIODS (µm) | LENGTH (mm) | TEMPERATURE RANGE (°C) | PUMP (nm) | SIGNAL (µm) | IDLER (µm) |
|---|---|---|---|---|---|---|
| OPO1-20 | 25.00, 25.25, 25.50, 25.75, 26.00, 26.25, 26.50, 26.75, and 27.00 | 20 | 100 - 200 | 1064 | 1.345 – 1.410 | 5.09 – 4.34 |
| OPO1-40 | | 40 | | | | |
| OPO2-20 | 27.25, 27.50, 27.75, 28.00, 28.25, 28.50, 28.75, 29.00, and 29.25 | 20 | 100 - 200 | 1064 | 1.407 – 1.537 | 4.36 – 3.46 |
| OPO2-40 | | 40 | | | | |
| OPO3-20 | 29.50, 30.00, 30.25, 30.50, 30.75, 31.00, 31.25, 31.50, and 31.75 | 20 | 100 - 200 | 1064 | 1.524 – 2.128 | 3.54 – 2.128 |
| OPO3-40 | | 40 | | | | |

| ITEM # | $ | £ | € | RMB | DESCRIPTION |
|---|---|---|---|---|---|
| OPO1-20 | $ 1,950.00 | £ 1,228.50 | € 1.813,50 | ¥ 18,622.50 | OPO PPLN Crystals, 1.345-1.410µm Signal Wavelength Range, 20mm Long |
| OPO1-40 | $ 2,450.00 | £ 1,543.50 | € 2.278,50 | ¥ 23,397.50 | OPO PPLN Crystals, 1.345-1.410µm Signal Wavelength Range, 40mm Long |
| OPO2-20 | $ 1,950.00 | £ 1,228.50 | € 1.813,50 | ¥ 18,622.50 | OPO PPLN Crystals, 1.407-1.537µm Signal Wavelength Range, 20mm Long |
| OPO2-40 | $ 2,450.00 | £ 1,543.50 | € 2.278,50 | ¥ 23,397.50 | OPO PPLN Crystals, 1.407-1.537µm Signal Wavelength Range, 40mm Long |
| OPO3-20 | $ 1,950.00 | £ 1,228.50 | € 1.813,50 | ¥ 18,622.50 | OPO PPLN Crystals, 1.524-2.128µm Signal Wavelength Range, 20mm Long |
| OPO3-40 | $ 2,450.00 | £ 1,543.50 | € 2.278,50 | ¥ 23,397.50 | OPO PPLN Crystals, 1.524-2.128µm Signal Wavelength Range, 40mm Long |

# Optical Parameter Oscillator System – StratoLase SSOPO Series

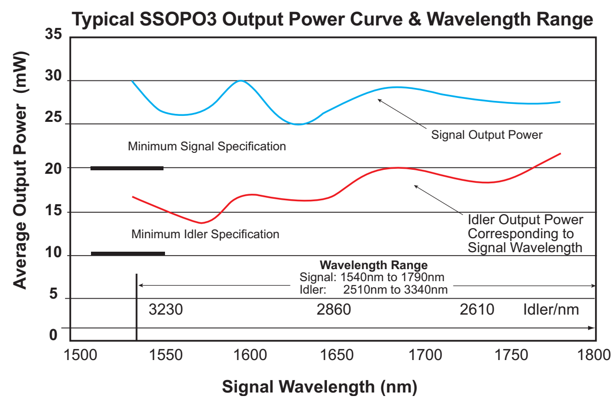
See Page 548

## Features

- Turnkey, Wavelength-Selectable IR Lasers
- Three Models With Wavelengths of 1330-5000nm
- Simple User Interface
- Power: Signal ~20mW, Idler ~3-5mW
- Pulse Length ~10ns
- Repetition Rate ~2kHz

## Applications

- "IR-HeNe" for Optical Component Alignment and Testing
- Low-Cost Test and Measurement
  - IR Optical Element Characterization
  - Waveguide Characterization
  - CCD Array Testing
- Low-Cost Access From 750-2170cm$^{-1}$
  - Hydrocarbons
  - Carbon Dioxide
  - Water


# Other Wavelength Conversion Components Available from Stratophase Ltd.

## OPO Mirrors

- **OPO Input Mirror:** BK7, Plano (S1)/ Concave (S2) with ROC = 200mm
  S1: AR @ 1.064µm (pump) <0.3% R
  S2: HT @ 1.064µm, HR @ 1.3 - 1.9µm (signal)
- **OPO Output Mirror:** $CaF_2$, Plano (S1) Concave (S2) with ROC = 200mm or (0.5° wedge)
  S1: Uncoated
  S2: HT @ 1.064µm (pump), 60-70% R @ 1.3 – 1.9µm (Signal); HT @ 2.2 – 5.1µm (idler)
- Other Curvatures Available Upon Request

## Customizable PPLN

- Range of Standard Periods, Available in a Variety of Semi-Standard Lengths
- Custom Cut & Polish Service; Crystal Lengths of 0.2-40mm Possible
- Custom PPLN Crystals: Design and Fabrication Service Available
- Wide Range of AR Coatings Available Upon Request

| STANDARD PERIODS (STEPS) |
|---|
| 5.00-5.08µm (0.04) |
| 6.81-6.38µm (0.04) |
| 6.30-6.38µm (0.04) |
| 6.50-6.58µm (0.04) |
| 6.60-6.70µm (0.05) |
| 7.05-7.15µm (0.05) |
| 8.96-9.04µm (0.04) |
| 10.90-11.00µm (0.05) |
| 12.10-12.30µm (0.10) |
| 12.70-13.10µm (0.10) |
| 18.20-19.00µm (0.20) |
| 18.00-21.00µm (0.25) |
| 19.00-21.00µm (0.25) |
| 20.00-23.00µm (0.25) |
| 21.00-23.00µm (0.25) |
| 23.00-25.00µm (0.25) |
| 25.00-27.00µm (0.25) |
| 27.25-29.25µm (0.25) |
| 29.50-31.50µm (0.25) |
| 29.50-32.50µm (0.50) |

**Please contact Thorlabs Technical Support or Stratophase Ltd. directly to discuss your requirements.**