PPLN Tutorial

Sintec Optronics specialises in the manufacture of periodically poled lithium niobate (PPLN) devices, such as, MgO-doped periodically poled lithium niobate (MgO:PPLN or PPMgO:LN) and undoped PPLN. These PPLN devices are highly efficient mediums for nonlinear wavelength conversion processes, such as: second harmonic generation; difference frequency generation; sum frequency generation; optical parametric oscillation; and other second order nonlinear processes.

Principles:

Second order nonlinear processes (Fig. 1) involve the mixing of three electromagnetic waves, where the magnitude of the nonlinear response of the crystal is characterized by the $\chi(2)$ coefficient. Second harmonic generation (SHG), or frequency doubling, is the most common application that utilizes the $\chi(2)$ properties of a nonlinear crystal. In SHG, two input pump photons with the same wavelength λp are combined through a nonlinear process to generate a third photon at λSHG= λp/2. Similar to SHG, sum frequency generation (SFG) combines two input photons at λp and λs to generate an output photon at λSFG with λSFG = (1/λp + 1/λs)-1. Alternatively, in difference frequency generation (DFG) when two input photons at λp and λs are incident on the crystal, the presence of the lower frequency signal photon, λs, stimulates the pump photon, λp, to emit a signal photon λs and idler photon at λi with λi = (1/λp - 1/λs)-1. In this process, two signal photons and one idler photon exit the crystal resulting in an amplified signal field. This is known as optical parametric amplification. Furthermore, by placing the nonlinear crystal within an optical resonator, also known as an optical parametric oscillator (OPO), the efficiency can be significantly enhanced.

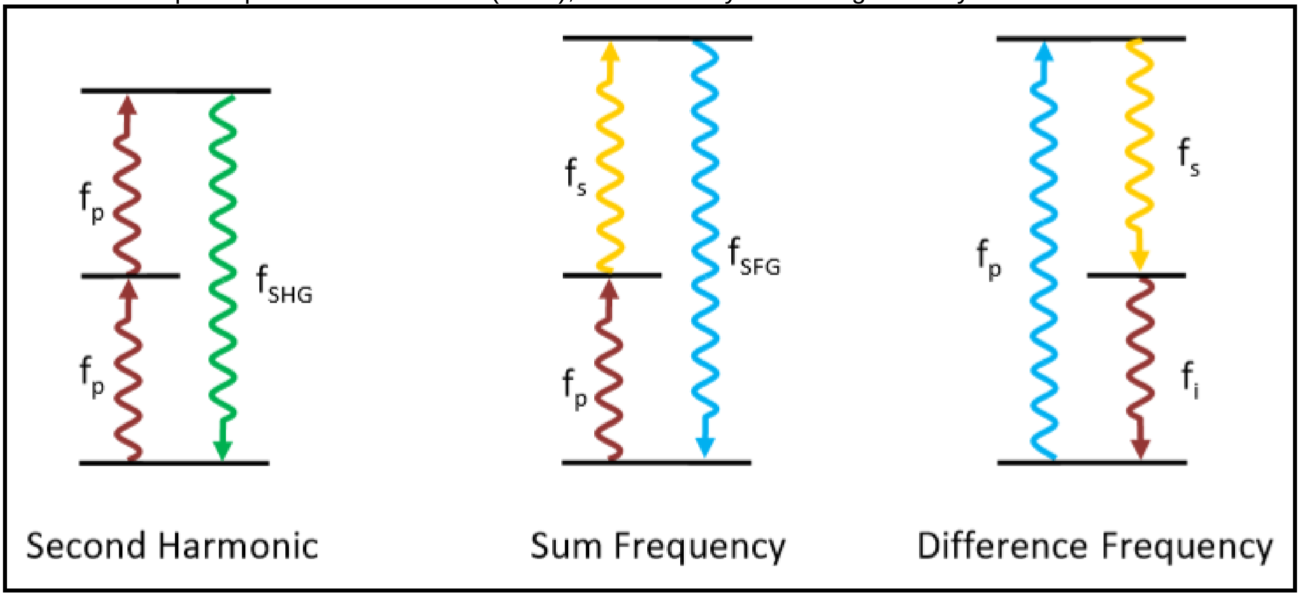

Fig. 1 Second-Order Nonlinear Interactions

Phase matching refers to fixing the relative phase between two or more frequencies of light as they propagate through the crystal. The refractive index is dependent on the frequency of light. Thus, the phase relation between two photons of different frequencies will vary as the photons propagate through the material, unless the crystal is phase matched for those frequencies. It is necessary for the phase relation between the input and generated photons to be maintained throughout the crystal for efficient nonlinear conversion of input photons. If this is not the case, the generated photons will move in and out put phase with each other in a sinusoidal manner, limiting the number of generated photons that exit the crystal. This is shown in Fig. 2. Traditional phase matching requires that the light is propagated through the crystal in a direction where the natural birefringence of the crystal matches the refractive index of the generated light. Despite providing perfect phase matching, this technique is limited to a small 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). By inverting the crystal orientation at every peak of the sinusoidal generation, one can avoid the photons slipping out of phase with each other. 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 (Fig. 2).

The period with which the crystal needs to be inverted (the poling period) depends on the interacting wavelengths and the temperature of the PPLN. For example, a PPLN crystal with a poling period of 6.6µm 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 the same PPLN crystal will efficiently

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generate frequency doubled photons from 1068.6nm wavelength photons. Thus, changing the temperature of the crystal therefore varies the phase matching conditions, allowing some tuning of the wavelength interaction.

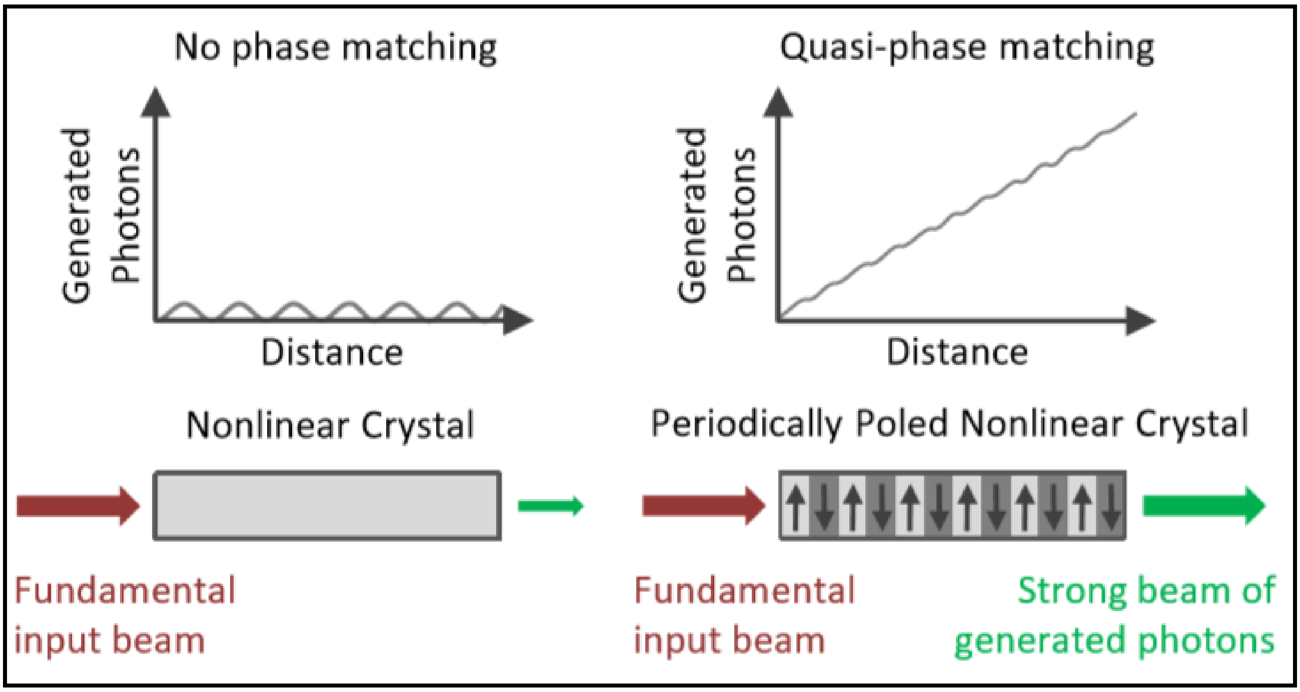

Fig. 2 Quasi-Phase Matching

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 in Fig. 3. 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: 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.

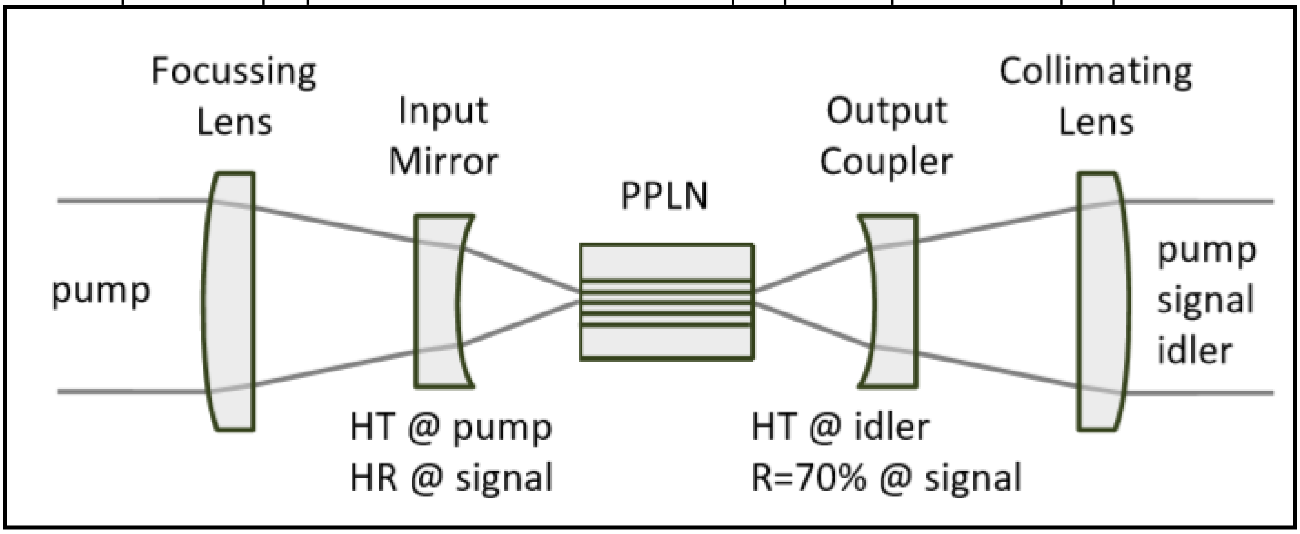

Fig. 3 Typical schematic of an OPO

Second Harmonic Generation:

PPLN is one of the most efficient crystals for frequency doubling and is well known for highly efficient green and red generation. It has been used to frequency double pulsed 1064nm beams with up to 80% conversion efficiency in a single pass pulsed system1. In CW systems, conversion efficiencies in excess of 50% have been demonstrated in an intracavity arrangement.

How to use PPLN:

Crystal length:

The crystal length is an important factor when choosing a crystal. For narrowband CW sources our longer crystal lengths, at 20 to 40mm, should give best efficiency. However, for pulsed sources, a long crystal can have a negative effect due to increased sensitivity to laser bandwidth and pulse duration. For nanosecond pulses, we typically recommend 10mm lengths and our shortest lengths at 0.5to 1mm are ideal for femtosecond pulse systems.

Polarization:

In order to access the highest nonlinear coefficient of lithium niobate, the input light must e-polarized, i.e. the polarization must be aligned with the dipole moment of the crystal. This is accomplished by aligning the polarization axis of the light parallel to the thickness of the crystal. This applies to all nonlinear interactions.

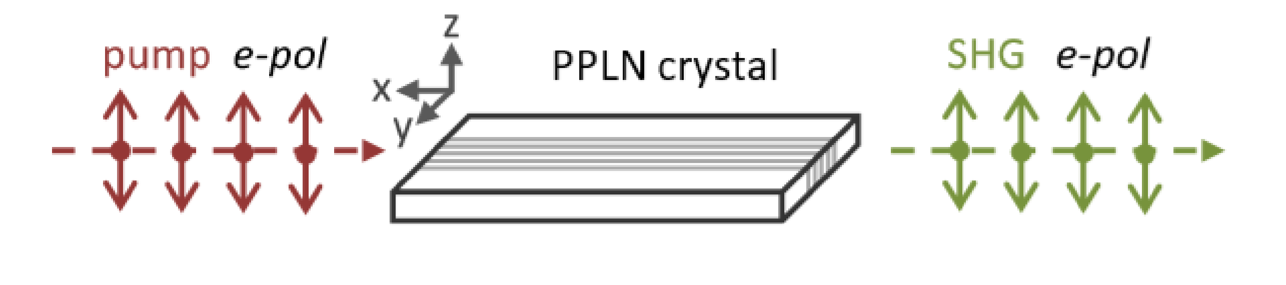

Fig. 4 SHG requires polarization parallel to the z-axis

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. PPLN has a high index of refraction that results in a 14% Fresnel loss per uncoated surface. To increase transmission through our crystals, the crystal input and output facets are AR coated, thus reducing the reflections at each surface to less than 1%.

Temperature and Period:

The poling period of a PPLN crystal is determined by the wavelengths of light being used. The quasi-phase-matched wavelength can be tuned slightly by varying the temperature of the crystal.

The range of off-the-shelf PPLN crystals each include multiple different poling periods, which allow different wavelengths to be used at a given crystal temperature. Our calculated tuning curves give a good indication of the required temperature for phase-matching. The temperature dependence of conversion efficiency follows a sinc2 function, describing a crystal temperature acceptance bandwidth (Fig. 5). The longer the crystal, the narrower and more sensitive the acceptance bandwidth. In many cases the efficiency of the nonlinear interaction is very sensitive to within a few degrees Celsius.

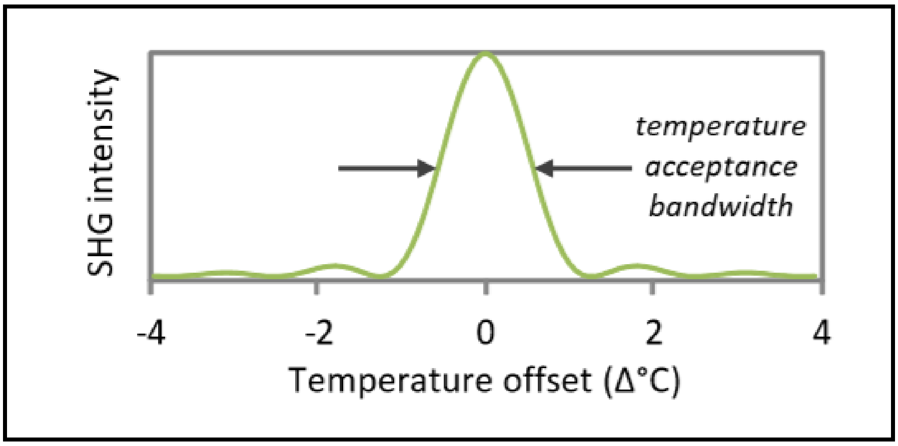

Fig. 5 SHG intensity temperature dependence for 1064nm pump in a 20mm long MgO:PPLN crystal

The optimum temperature can be determined by heating the crystal to e.g. 10°C higher than the calculated temperature and then allowing the crystal to cool whilst monitoring the output power at the generated wavelength.

Our PPLN oven is easy to incorporate into an optical setup. It can be paired with the OC2 temperature controller to maintain the crystal temperature to within ±0.01°C, providing highly stable output power.

MgO:PPLN vs undoped PPLN

Undoped PPLN is usually operated at temperatures between 100°C and 200°C, to minimize the photorefractive effect that can damage the crystal and cause the output beam to become distorted. Since the photorefractive effect is more severe in PPLN when higher energy photons in the visible part of the spectrum are present, it is especially important to use the crystal only in the recommended temperature range.

The addition of 5% MgO to lithium niobate significantly increases the optical and photorefractive resistance of the crystal while preserving its high nonlinear coefficient. With a higher damage threshold, MgO:PPLN is suitable for high power applications. It can also be operated from room temperature up to 200°C, significantly increasing the wavelength tunability of the device. Moreover, in some special cases, the MgO:PPLN can be operated at room temperature and without the need for temperature control.