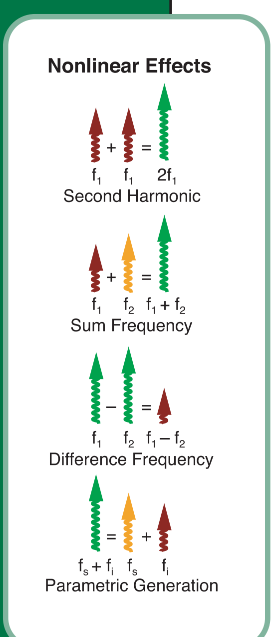
Periodically Poled Lithium Niobate (PPLN) - Tutorial

Periodically poled lithium niobate (PPLN) is a nonlinear crystal that enables very high efficiency wavelength conversion. It is used for frequency doubling, difference frequency generation, sum frequency generation, optical parametric oscillation and optical parametric amplification, in addition to other nonlinear processes.

PPLN is a robust, transparent crystal that must be temperature controlled when in use. PPLN has been available as a custom device for a number of years; now Thorlabs has teamed up with Stratophase to bring this material to market as standard catalog items.

Principles

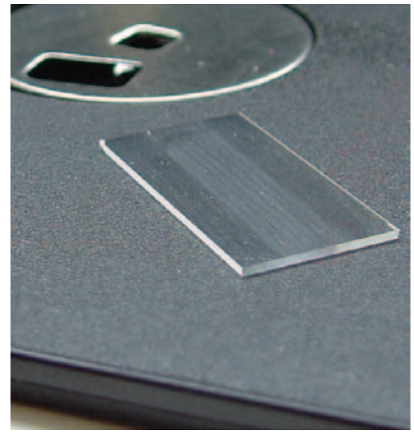
Nonlinear crystals use the second order nonlinearity (known as $\chi^{(2)}$) properties of the crystal to mix together three optical waves; the most common example of this is frequency doubling (second harmonic generation, SHG). This is a special case where two input photons having the same wavelength, λ_1, generate a third photon at $\lambda_{1/2}$. Other nonlinear effects include difference frequency generation where two input photons at λ_1 and λ_2 generate an output photon at $\lambda_{generated}$ ($1/\lambda_{generated} = 1/\lambda_1 - 1/\lambda_2$). Additionally, sum frequency generation is where the input photons at λ_1 and λ_2 generate an output photon at $\lambda_{generated}$ ($1/\lambda_{generated} = 1/\lambda_1 + 1/\lambda_2$). Other processes are possible where one photon is split into two photons of longer wavelength such that energy is conserved. These parametric processes are different from the first type of nonlinear process because the wavelength of the output is not determined by the input wavelength. In this case the wavelength of the output is selected according to which wavelengths are phase matched.



Most materials have slightly different refractive indices at the fundamental and second harmonic wavelengths. This means that as the light travels through the crystal for SHG, light at the fundamental and second harmonic wavelengths become out of phase; such that, second harmonic photons generated at one point in the crystal are out of phase with those generated a few microns further down the crystal. The result is that very little frequency doubled output is obtained. In fact, the intensity of the second harmonic oscillates to zero as the light propagates along the crystal. The conventional way to get around this problem is to phase match the fundamental and second harmonic by carefully picking the direction of light through the crystal so that the natural birefringence of the crystal gives the same refractive index for the fundamental and second harmonic. This is why most conventional crystals have to be carefully angle tuned to achieve optimal conversion efficiency. The drawback of this approach is that not all crystals have suitable birefringence for this method to work at all wavelengths.

The solution to phase matching Lithium Niobate is periodic poling. This technique relies on the fact that if the crystal structure is inverted there is a 180° phase shift in the generated second harmonic light. So, if as the light travels through the crystal the crystal structure is inverted when the generated second harmonic is at a maximum, then second harmonic generated past this point adds constructively to the existing second harmonic. If this is done periodically along the crystal, the intensity of the second harmonic light builds all the way along the crystal, giving very efficient frequency conversion.

The period with which the crystal needs to be inverted (the poling period) depends on the wavelengths of the light and temperature. For instance a PPLN crystal with a period of 6.6µm will frequency double 1060nm when the crystal temperature is held at 100°C or 1068.6nm when the temperature is 200°C. So adjusting the temperature allows some tuning of the operation wavelength.



How are PPLN crystals made?

The key to producing PPLN is the poling process. This is the process that inverts the crystal structure. Lithium Niobate is a ferroelectric crystal which means that each unit cell in the crystal has a small electric dipole moment. This dipole is caused by slight offsets in the position of niobium and lithium ions in the unit cell. The application of an intense electric field can invert the crystal structure, rearranging the crystal at an atomic level. The electric field needed to invert the crystal is very large (~22kV/mm), and is applied for only a few milliseconds, after which the periodically reversed structure is 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 also key to producing small period PPLN used for frequency doubling in to the visible. Once poled, the crystals are permanently set into the new pattern.