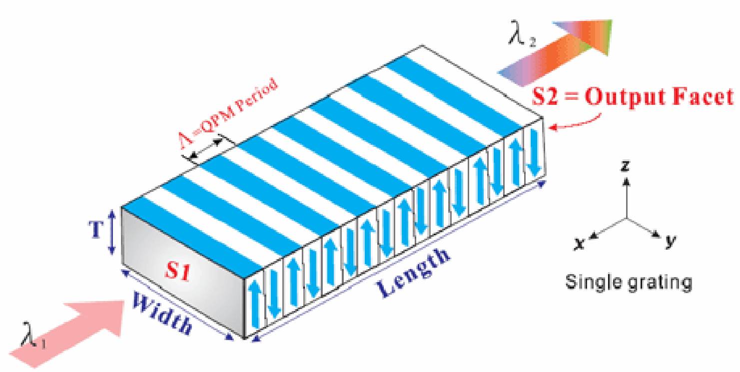
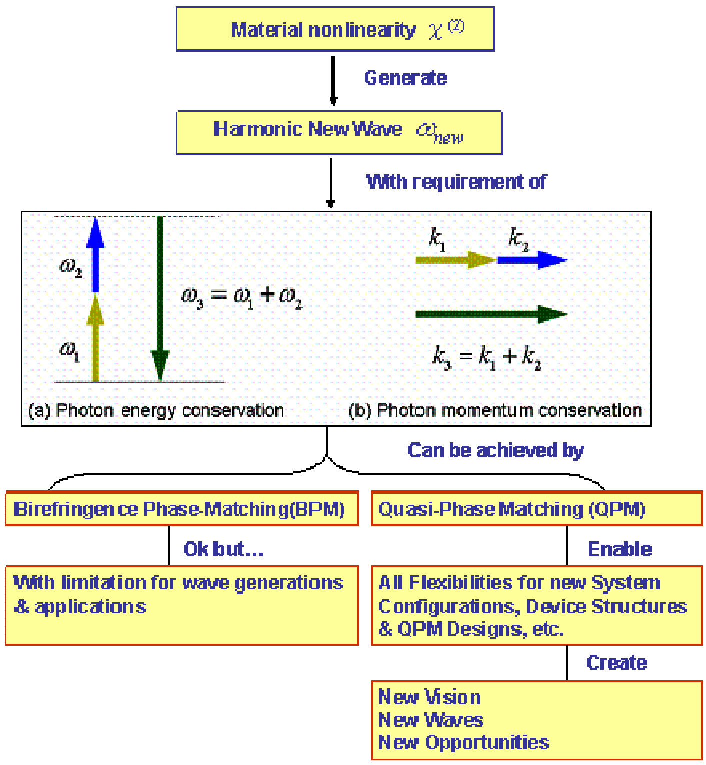
PPXX Technology

PPXX technology is an efficient laser wavelength conversion technology, which enables the generation and conversion of new laser wavelengths via material's nonlinearity $\chi^{(2)}$. Based on engineered microstructures within ferroelectric nonlinear materials, PPXX technology provides a powerful tool — quasi-phase-matching (QPM) to compensate the phase-velocity mismatching between interaction waves for efficient wave-mixings.

PPXX technology has enabled photonics applications, ranging from laser-based RGB display, biomedicine, high-speed optical signal processing, gas sensing and many other innovative photonics applications. The fundamental and technology opportunities of PPXX technologies are described below.





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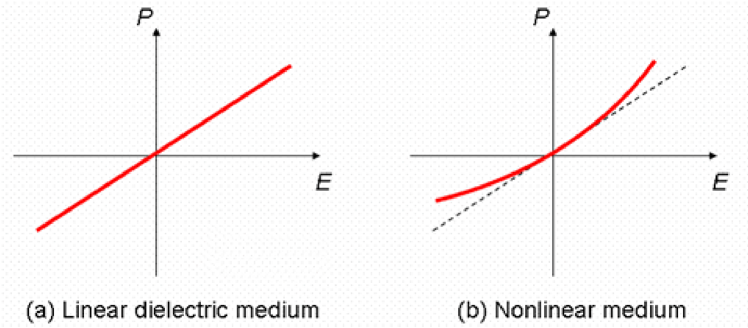
Frequency Mixing, Nonlinear Polarization and Phase-matching:

The interaction between electro-magnetic field and dielectric material results in an induced polarization field within the material. Normally, the response of the material is linear, as shown in figure below. In the nonlinear medium, polarization vector is not proportional to optical electric field and can be expressed as Taylor series expansion:



◆The relation between the polarization vector and optical electric field

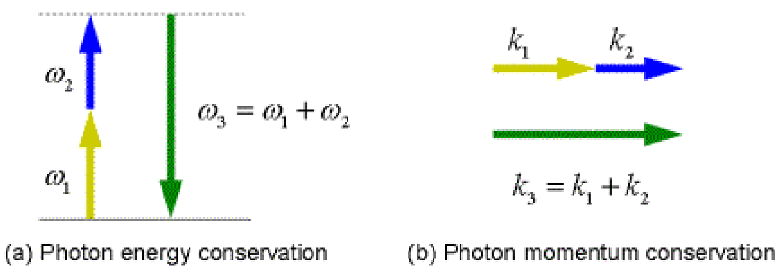
where P_i is the ith component of polarization vector. E_i is the ith component of input electric field. $\chi_{ij}^{(1)}$ is linear susceptibility, while $\chi_{ijk}^{(2)}$ and $\chi_{ijkl}^{(3)}$ are the second-order and third-order nonlinear susceptibility. In other words, the susceptibility can be expressed as

$$\chi(\omega) = \chi_{ij}^{(1)} + \chi_{ijk}^{(2)} E_k + \chi_{ijkl}^{(3)} E_k E_l + \cdots$$

The linear term $\chi^{(1)}$ determines the linear propagation of optical waves (including refraction, reflection, diffraction and dispersion.), while the higher order terms (such as $\chi^{(2)}$ and $\chi^{(3)}$) correspond to nonlinear effects under strong electrical fields. The second order term $\chi^{(2)}$ vanishes in materials with inversion symmetry structures but could be large in several nonlinear materials such as Lithium Niobate ($LiNbO_3$). In nonlinear materials with $\chi^{(2)}$, a light with frequency ω will generate a nonlinear polarization vector:

$$P_i(2\omega) = d_{ijk} E_j(\omega) E_k(\omega)$$

where $d_{ijk}(=\chi_{ijk}^{(2)})$ is the nonlinear coefficient. This polarization vector will induce a double-frequency electric field. Such process is called $\chi^{(2)}$ frequency conversion or mixing process. To enable efficient conversion, both the photon energy conservation and photon momentum conservation are to be achieved simultaneously, as shown in figure below. The requirement on the photon momentum conservation is also called *"phase-matching"* constraint.

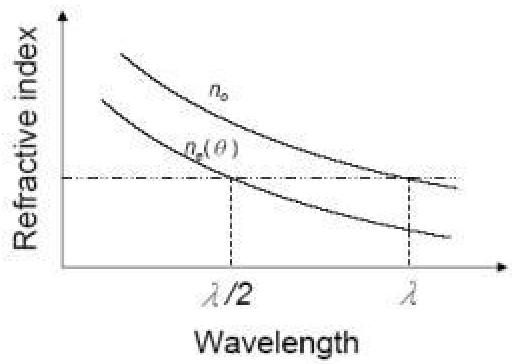


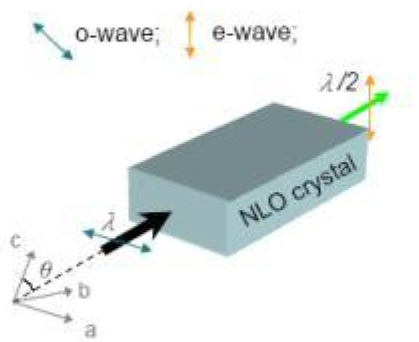
Birefringence-Phase-Matching (BPM)

In order to achieve efficient wavelength conversion, phase matching between interaction waves are required. Traditionally, this has been done in nonlinear materials through birefringence phase matching techniques, which orient crystal axis to a specific angle to achieve phase matching condition for specific interaction wavelengths.

However, such techniques can not enable efficient use of material's full transparency wavelength ranges at optimized conversion efficiency. In addition, Birefringence phase-matched frequency conversion processes occur in the presence of both ordinary and extraordinary polarized radiations. While propagating along non-optic axis direction of a NLO crystal, the extraordinary waves suffer birefringence walk-off; whereas ordinary rays do not. Thus this walk-off issue (the converted wave diverges from the fundamental wave) will limit the effective interaction length and distort the beam quality, and hence limits the conversion efficiency of birefringence phase-matched NLO processes.

Take SHG as an example, the refractive index of the fundamental wave must be equal to that of SHG wave to achieve birefringence phase matching under specific wavelength condition. Therefore, the fundamental wave will be oblique an angle θ to the optical axis (c-axis) of the nonlinear optical crystal.





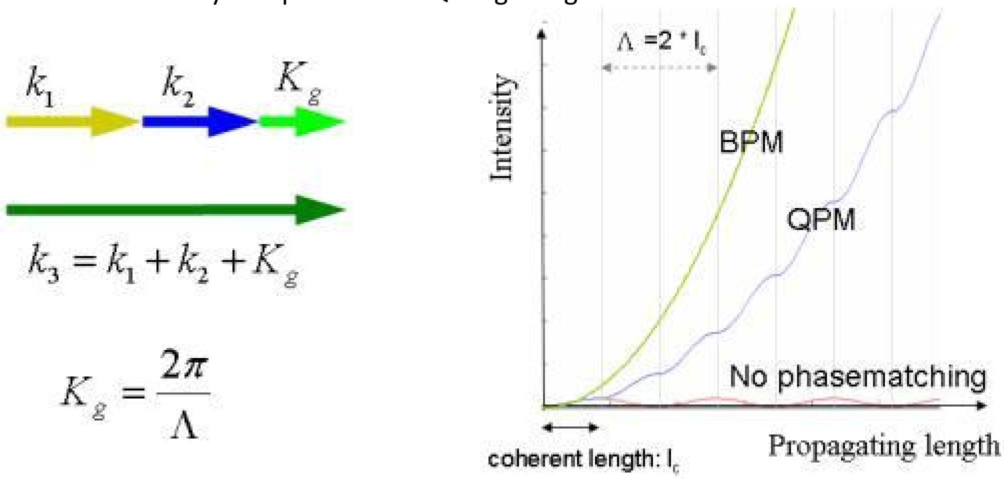
Quasi-Phase-Matching (QPM)

Quasi-phase matching is a technique for phase matching nonlinear optical interactions in which the relative phase is corrected at regular intervals using a structural periodicity built into the nonlinear medium. The phase velocity difference is compensated by shifting the phase relative to one another over a coherent distance through inverting the sign of the nonlinear coefficient. And therefore, the unidirectional power flow can be produced for any mixing interaction for which the material is transparent.

The principle and effects of quasi-phase matching on nonlinear frequency conversion are illustrated in the following figure. It shows the phase matching condition for a quasi-phase matching scheme, where the wave vector associated with a periodic modulation of the properties of the nonlinear medium compensates for the wavevector mismatch of the interacting waves.

The figure also shows the effect of quasi-phase matching on second-harmonic generation using periodically reversed domains as an example. In the nonlinear medium, the distance over which the accumulated phase difference of the interacted waves reaches π is the "coherence length" l_c. Without phase matching, the generated second harmonic grows and decays as the fundamental and second harmonic waves go in and out of phase over each coherence length l_c.

In the perfectly phase-matched case (as is obtained using birefringence phase matching), the generated power grows quadratically with crystal length. The QPM method involves reversal of the sign of the nonlinear coefficient at each multiple of l_c, also results in a net quadratic increase with crystal length, where the discrete nature of the reversals results in a lower second derivative than that obtained with perfect phase matching. Instead of perfect phase-matching everywhere like in the phase-matched case, phase mismatch is discretely compensated in QPM gratings.



QPM structures are most commonly obtained by periodic poling of ferroelectric crystals like lithium niobate (LiNbO3) and lithium tantalate (LiTaO3). The most widely used method for periodic poling makes use of electric fields. The principle is that the spontaneous polarization in a ferroelectric material such as lithium niobate can be reversed periodically under the influence of a sufficiently large electric field (In general, it is meant to be "periodically poled").

Such periodically domain-inverted structures are used to compensate the phase velocity mismatching between interaction waves based on QPM techniques. Thus, the periodically poled devices are engineered to maintain proper phase relationship between the propagating waves, so as to maximize the efficiency of non-linear frequency conversion.

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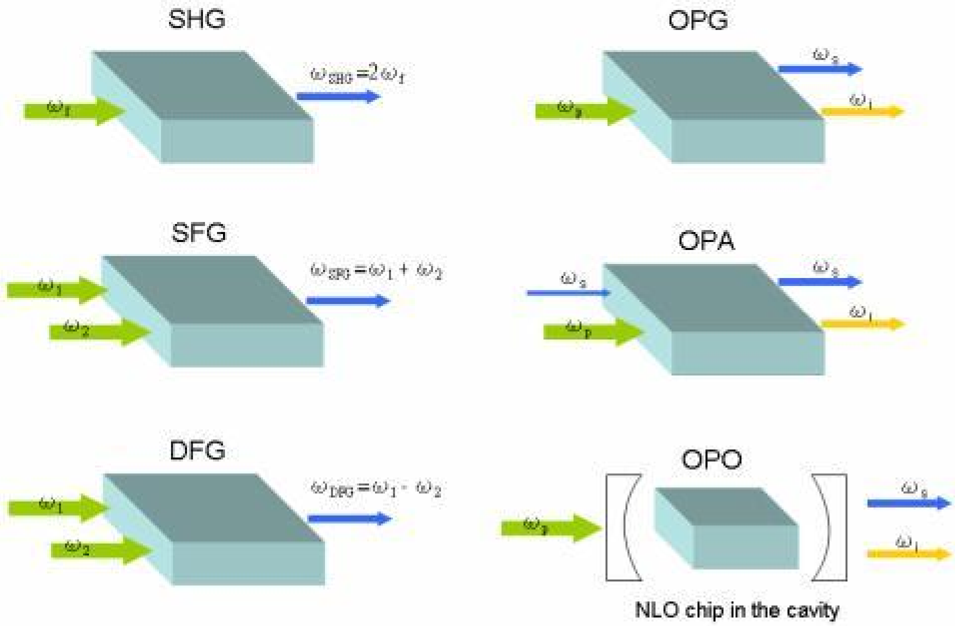
Material / Properties	$LiNbO_3$	$LiTaO_3$	BBO	LBO	KTP	KN
Transparency Range (nm)	330-5500	280-5500	185-2600	160-2600	350-4500	400-4500
Refractive Index	2,2	2,2	1,6	1,6	1,86	2,2
Nonlinearity	d21=-2,6pm/V d31=-4,6pm/V d33= 25pm/V	d31= 0,85pm/V d33= 13,8pm/V	d21= 2,2pm/V d31= 0,08pm/V	d21=-0,67pm/V d23= 0,85pm/V	d31= 1,95pm/V d32= 3,9pm/V d33= 15,3pm/V	d11= 21,9pm/V d12= 8,9pm/V d13= 12,4pm/V
Surface Damage Threshold for 10ns (J/cm²)	10	>> $LiNbO_3$	13	25	15	1,7
Phasematching Schemes	QPM, BPM	QPM, BPM	BPM	BPM	QPM, BPM	QPM, BPM
Note: The comparisons are under the wavelength 1064nm Reference: Data from the software "SNLO"						

MgO:LN and MgO:SLT have been regarded as the attractive nonlinear materials for the QPM devices because of their large nonlinear coefficient, short-wavelength transparency, and high resistance to photorefractive damage. They have attracted much attention for use in high-density optical storage, and in biomedical applications, because of its shorter wavelength and higher photon energy. Recent development of higher-power infrared and visible-red laser diodes makes it more realistic to achieve compact UV source based on QPM MgO:SLT chip.

Convert or Amplify Pump Laser by Using Specific Frequency Mixing Configuration

As a difference from birefringence phase matching, QPM technique utilizes full transparency ranges (350 nm ~ 5000 nm in the case of lithium niobate) of the non-linear materials and their highest non-linear coefficient to achieve efficient optical frequency conversion. This enables efficient wavelength conversions via different wave-mixing schemes. Examples of frequency mixing configurations are illustrated below:

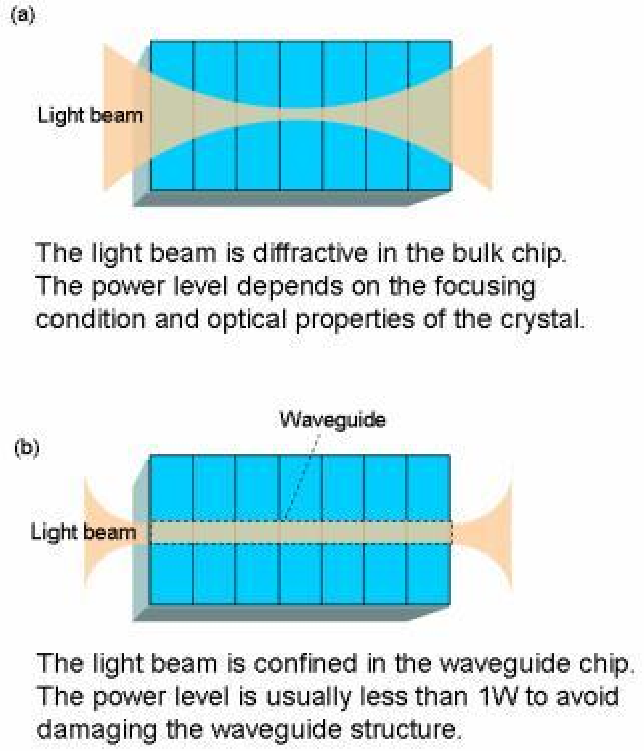


Choose PPXX Bulk or Waveguide ?

While PPXX bulk device offers advantages of higher power and larger apertures applications, PPXX waveguides (WG) can be used to further enhance nonlinear efficiency mixing as compared to PPXX bulk devices, by tightly confining the laser over long distances.

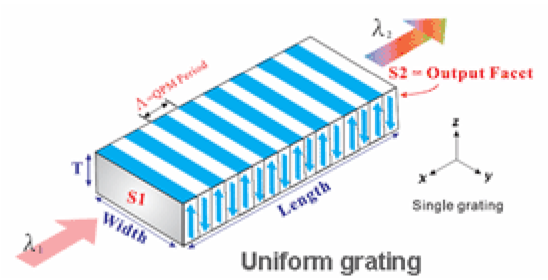
The tightly focused optical wave will often diffract when it propagates in a bulk device, so single-pass high conversion efficiency cannot be achieved. In waveguides, the mode profile is confined to a transverse dimension in the order of the wavelength, and hence high optical intensities can be maintained over considerable distance to improve the conversion efficiency by two to three orders of magnitude as compared to bulk devices.

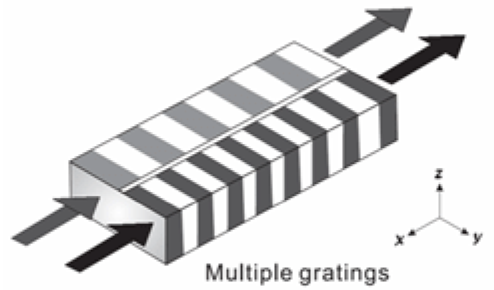
Also, the nonlinear mixing efficiency is quadratically proportional to the interaction length of the waveguide device (linear proportional for bulk devices), thus the fabrication of long, uniform and low-loss waveguide is essential for highly efficient optical frequency mixer.

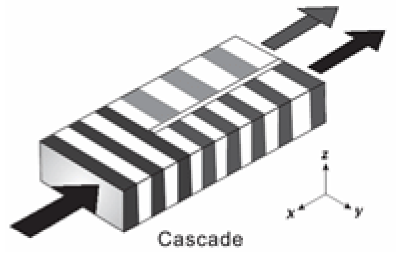


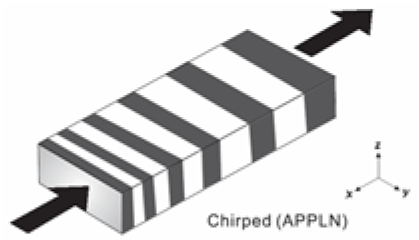
Different QPM Patterns Allow Diverse Applications

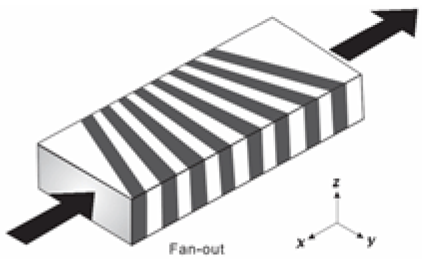
Other advantages of PPXX technology are its domain structures defined by the mask patterning process, which provides additional application dimensions unavailable by traditional nonlinear bulk materials. Several others specific periodic pattern designs such as cascaded, fan-out, and customized configuration are also available for specific applications using the CW, pulsed and ultra-short pulsed laser pumps.











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