

Nonlinear frequency conversion in quasi-phase-matched materials

David Hanna

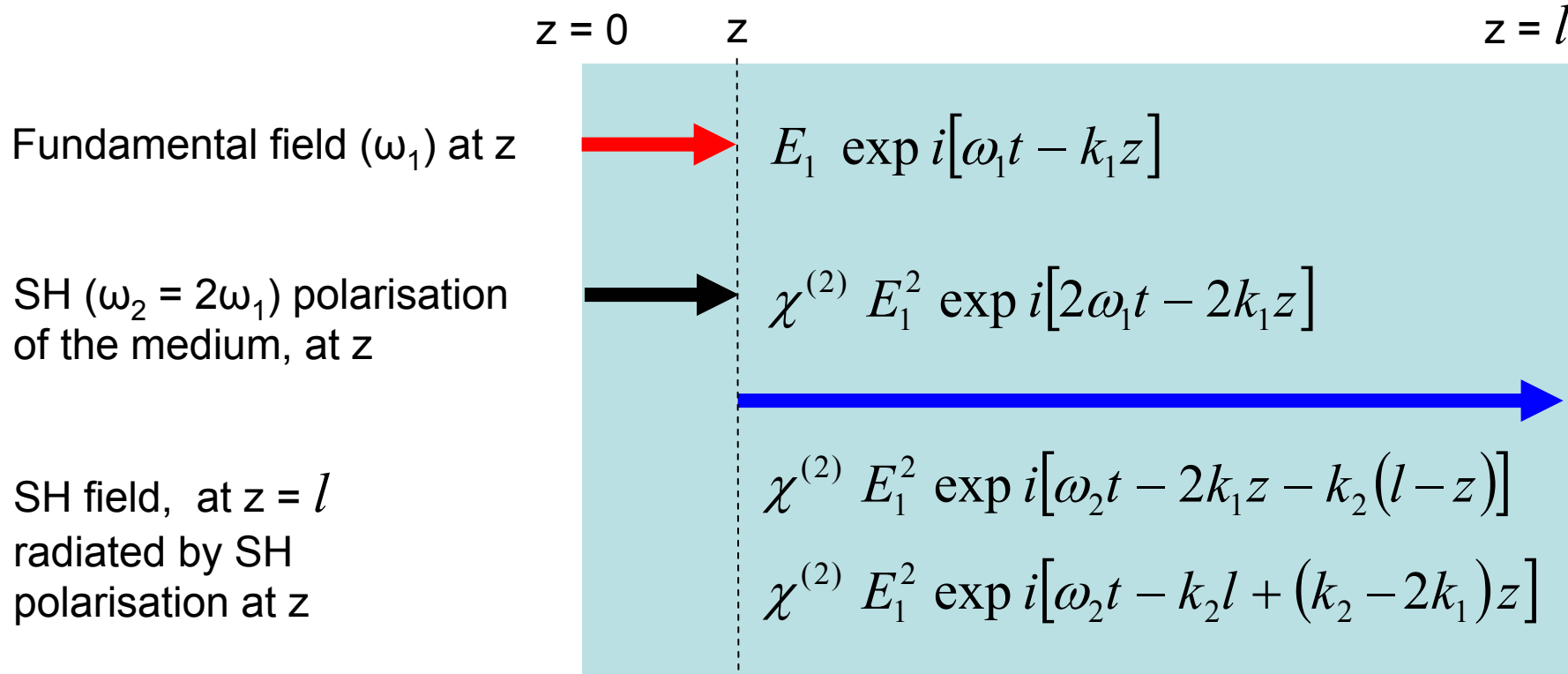
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Outline of tutorial

- **Introduction to QPM:**
A pictorial representation
- **Simple analytical description:**
In the language of wavevectors
- **Practical matters:**
how to achieve QPM,
material fabrication
benefits and constraints of QPM,
typical magnitudes
- **Examples of performance from QPM media**
- **Some thoughts on OPOs vs lasers**

Phase matching for second harmonic (SH) generation



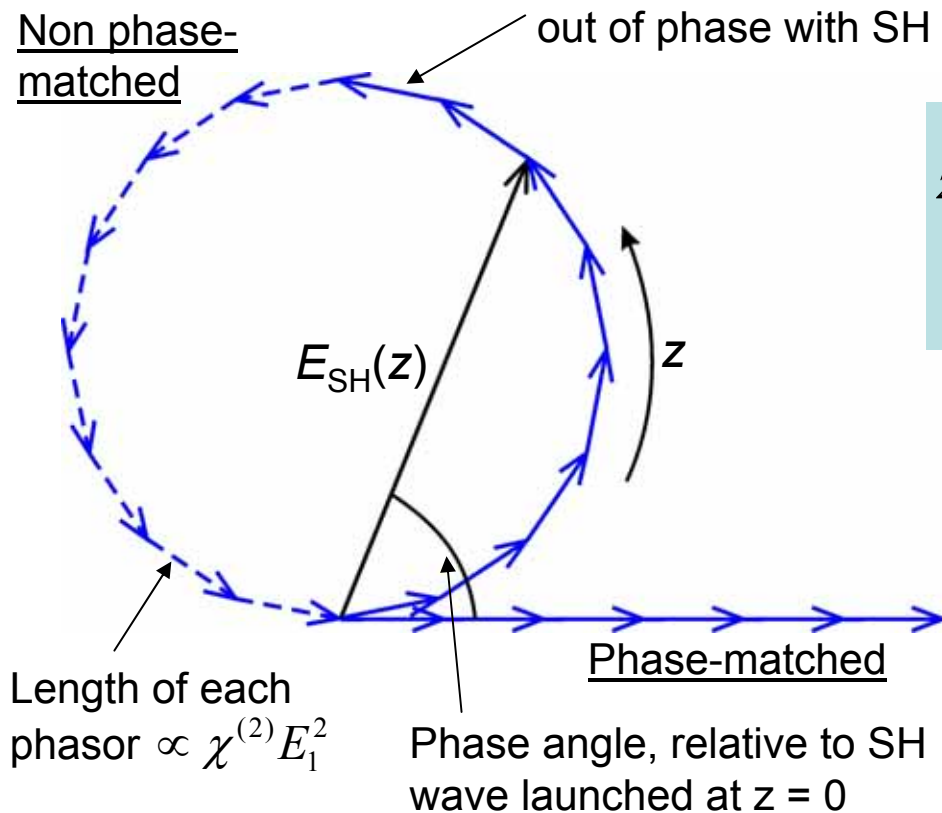
If all SH field contributions, for z from 0 to l , are to add in phase, one needs $\Delta k \equiv k_2 - 2k_1 = 0$ (phase-matching)
ie $n_1 = n_2$

Calculation of total field, E_{SH} , at exit ($z = l$) from nonlinear medium

$$E_{SH}(l) \propto \exp(\omega_2 t - k_2 l) \int_0^l \chi^{(2)} E_1^2 \exp(i\Delta k z) dz$$

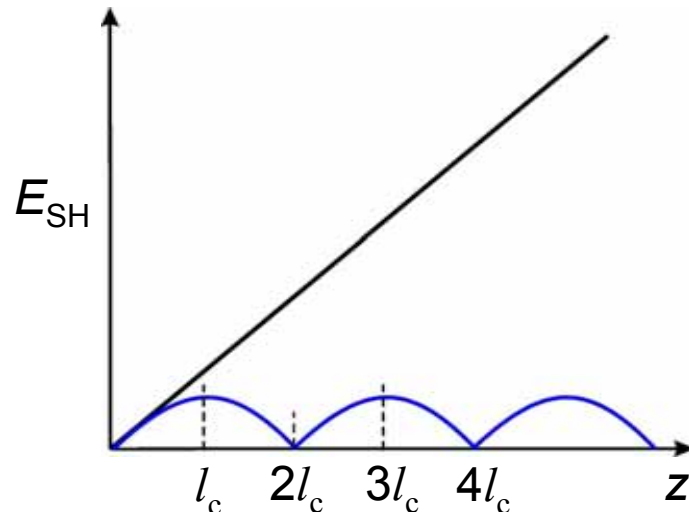
Here $\Delta k z = \pi$, so SH field generated at z is π out of phase with SH field generated at $z = 0$:

Non phase-matched



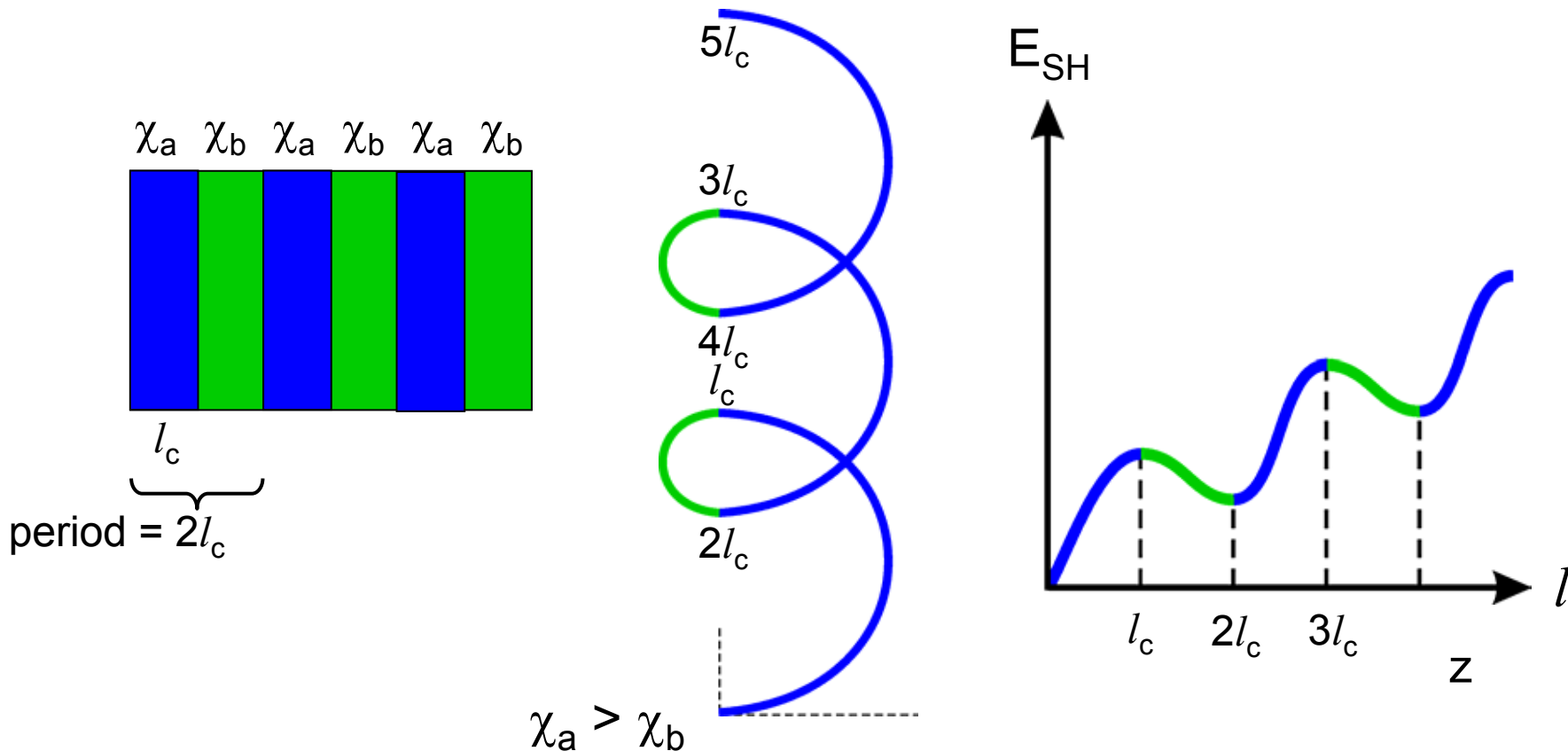
$$z = l_c \equiv \frac{\pi}{\Delta k} \quad (\text{coherence length})$$

$$= \lambda_1 / 4(n_2 - n_1) \text{ for SHG}$$



Principle of quasi-phase-matching

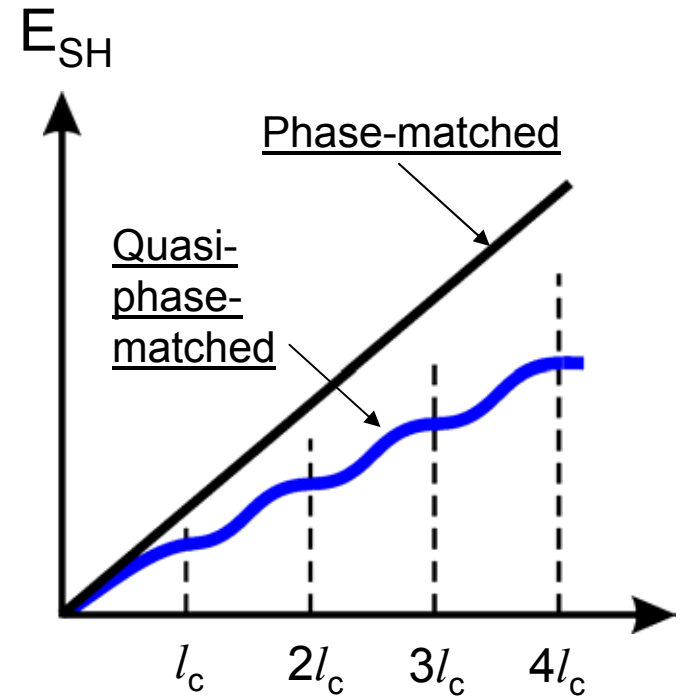
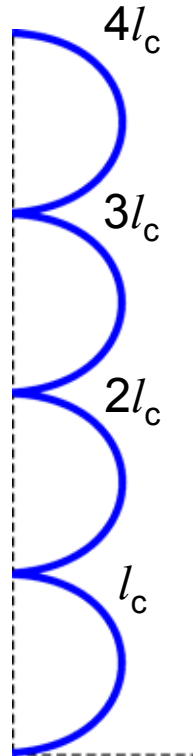
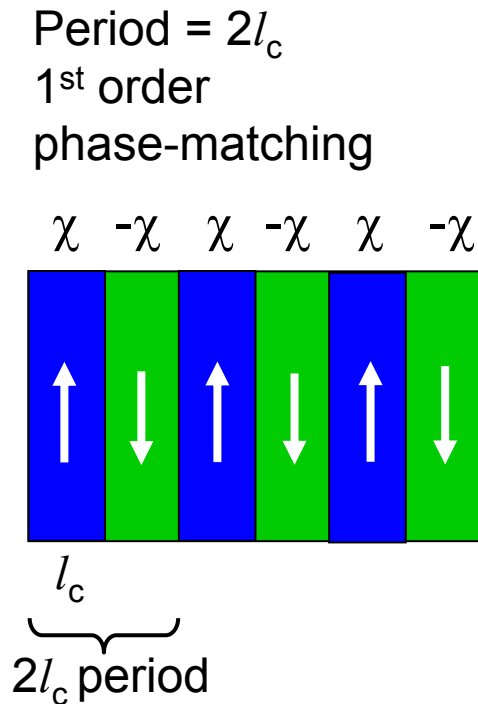
Ensure that the contribution to generated field from each coherence length does not cancel with that from preceding l_c
e.g. modulate $\chi^{(2)}$ between adjacent coherence lengths



Some quasi-phase-matching schemes

- Periodic E field (via segmented electrode) + field-induced $\chi^{(2)}$
- 'Frozen-in' field-induced $\chi^{(2)}$, in optical fibres
- Periodic destruction/reduction of nonlinearity, eg via ion-implantation through a mask
- Overgrowth on a template having periodic modulation of substrate orientation (orientation-patterning, eg OPGaAs)
- Periodic modulation of pump intensity (eg use corrugated capillary waveguide for High Harmonic Generation)
- Fresnel 'birefringence' via periodic TIR in a thin plate
- Periodic-poling of ferroelectrics, switching $\chi^{(2)} \rightarrow -\chi^{(2)}$

Periodic-poling scheme (e.g. as in PPLN)

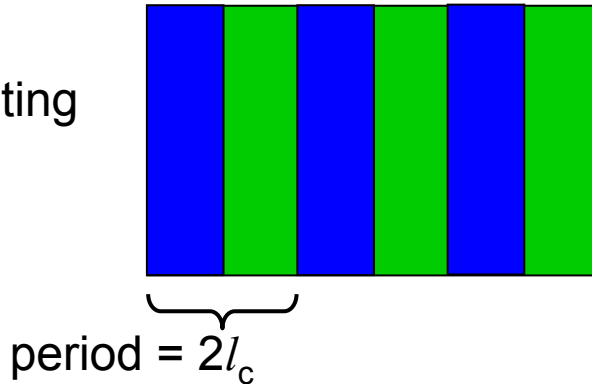


E_{SH} after each l_c is $\pi/2$ smaller than for perfect phase-matching over the same length of medium.

So, effective nonlinear coefficient reduced by $\pi/2$.

Quasi-phase-matching condition

Nonlinear grating
of period $2l_c$



Grating period is Δ , hence
grating wave-vector, Δk_G , is

$$\Delta k_G \equiv \frac{2\pi}{\Lambda} = \frac{2\pi}{2l_c} = \Delta k$$

(Phase-mismatch)

ie. Quasi-phase-matching requires $\Delta \mathbf{k} = \Delta \mathbf{k}_G$

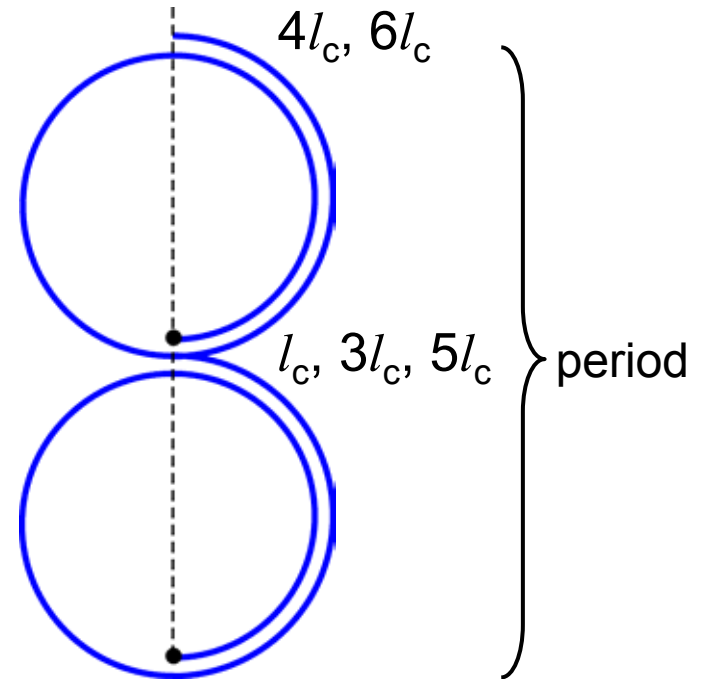
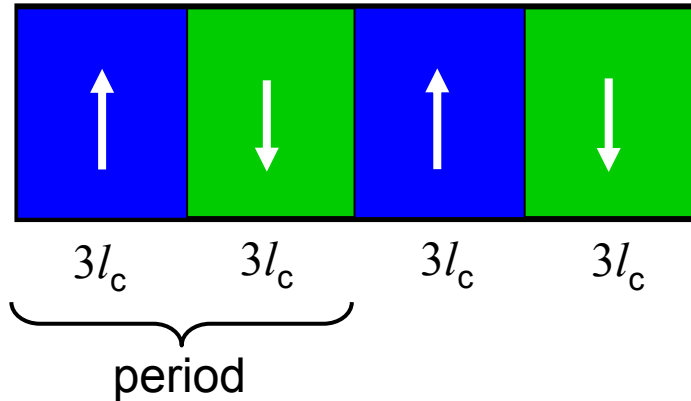
So, instead of making $\Delta \mathbf{k}$ zero, we make $\Delta \mathbf{k}' \equiv \Delta \mathbf{k} - \Delta \mathbf{k}_G = 0$

Generalisation

If any nonlinear parametric process has a phase-mismatch $\Delta \mathbf{k}$, impose (somehow) a periodic modulation on the nonlinearity, with wavevector, $\Delta \mathbf{k}_G$ such that $N\Delta \mathbf{k}_G = \Delta \mathbf{k}$ where N is the QPM order

Higher order QPM

3rd order:



One period ($6l_c$) produces the net effect of $2l_c$; 3x smaller χ_{eff}

Advantage: larger scale pattern, easier to fabricate

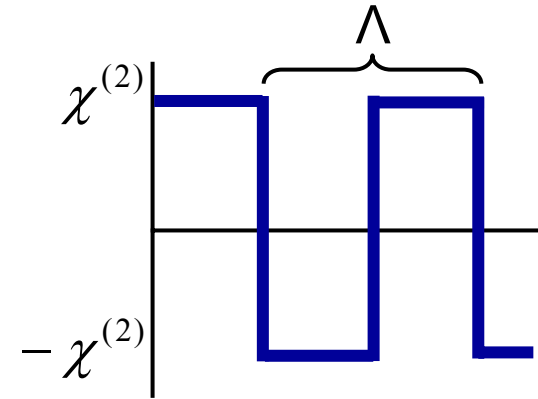
Disadvantage: effective nonlinear coefficient for N^{th} order QPM is reduced by N

Quasi-phase-matching condition

$$E_{SH} \propto E_1^2 \int_0^l \chi^{(2)}(z) \exp(i\Delta k z) dz$$

If $\chi^{(2)}(z)$ has 50/50 duty cycle \longrightarrow

then $\chi^{(2)}(z) = \chi^{(2)} \sum_{\text{odd } N=-\infty}^{+\infty} (-i) \left(\frac{2}{\pi N} \right) \exp(iK_N z)$



$$K_N = \frac{2N\pi}{\Lambda} = N\Delta k_G$$

If $\Delta k \sim K_N$ $E_{SH}(l) \propto E_1^2 l \chi^{(2)} \left(\frac{2}{\pi N} \right) \text{sinc} \left(\frac{\Delta k' l}{2} \right)$

where $\Delta k' = \Delta k - N\Delta k_G$

i.e. $\Delta \mathbf{k}' = 0$, QPM condition

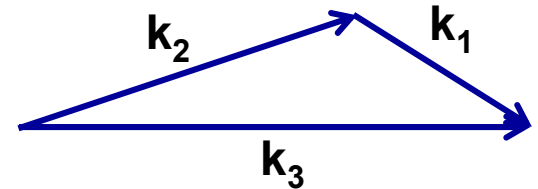
Quasi-phase-matching condition

Nonlinear process

$$\omega_3 = \omega_2 + \omega_1$$

Conventional phase-match condition

$$\mathbf{k}_3 = \mathbf{k}_2 + \mathbf{k}_1$$



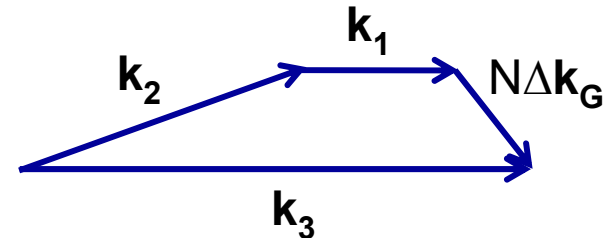
Phase-mismatch

$$\Delta \mathbf{k} = \mathbf{k}_3 - \mathbf{k}_2 - \mathbf{k}_1$$

QPM condition
(Nth order QPM)

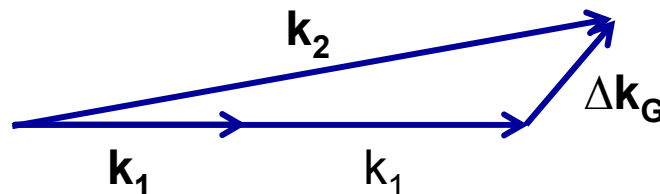
$$\Delta \mathbf{k} = N \Delta \mathbf{k}_G$$

$$\mathbf{k}_3 = \mathbf{k}_2 + \mathbf{k}_1 + N \Delta \mathbf{k}_G$$



Note: if QPM grating is tilted, eg to 'tune' its effective period, the interaction is necessarily non-collinear

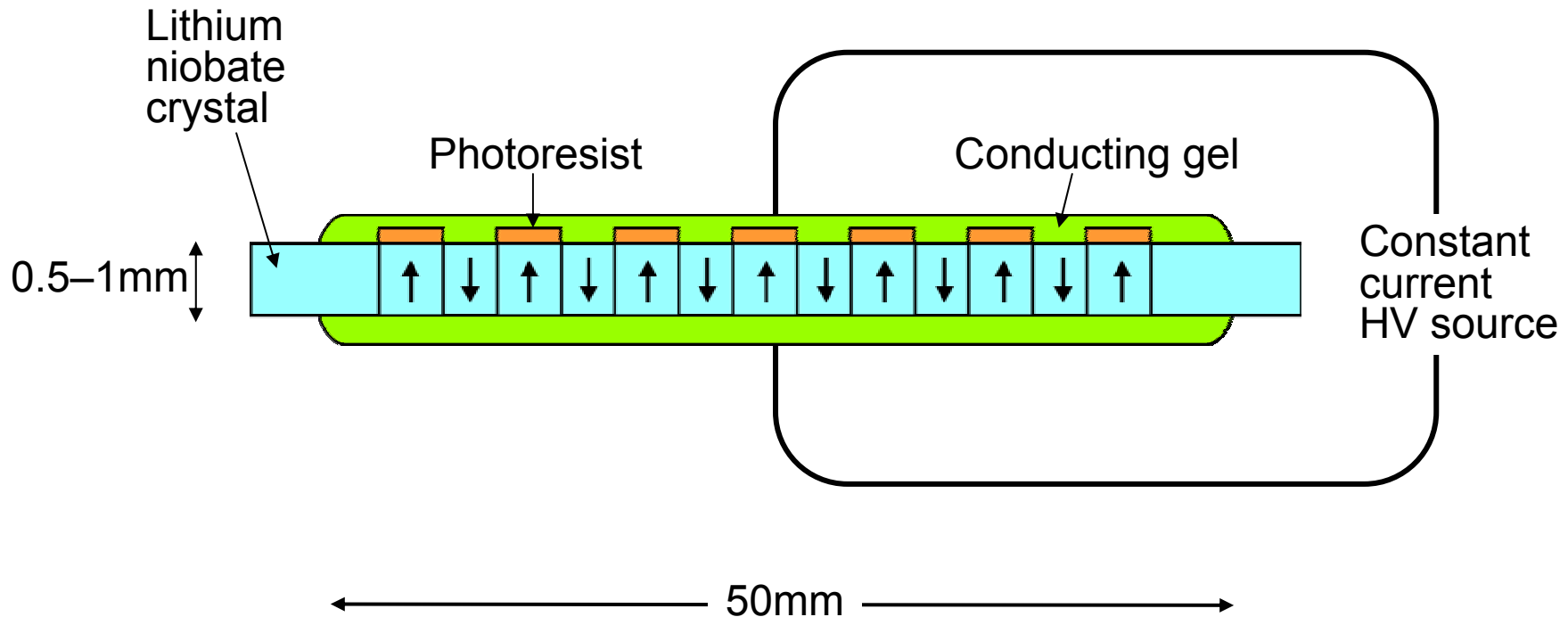
e.g. SHG 1st order:



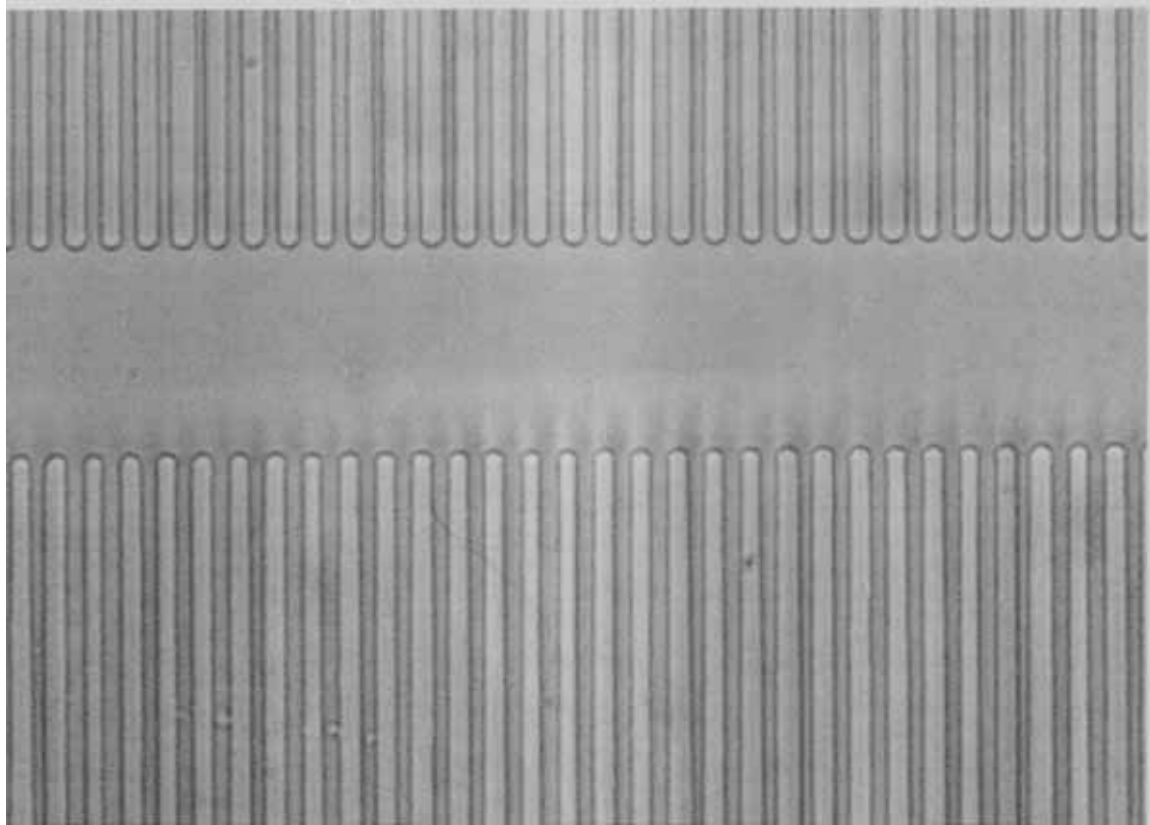
Some benefits of QPM

- Access materials having too low a birefringence for phase-matching, e.g. LiTaO_3 , GaAs
- Ability to phase-match any frequencies in the transparency range, freedom to choose ideal pump for an OPO
- Non-critical (90°) phase-matching, allows tight (confocal) focussing
- Access to largest nonlinear coefficient, e.g. d_{33} in LiNbO_3

Fabrication of Periodically Poled Lithium Niobate



Periodically Poled Lithium Niobate Crystal



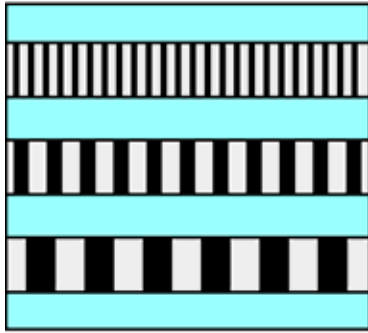
Acknowledgements to Peter Smith, Corin Gawith and Lu Ming
ORC, University of Southampton

Attractions of photolithography for QPM grating fabrication

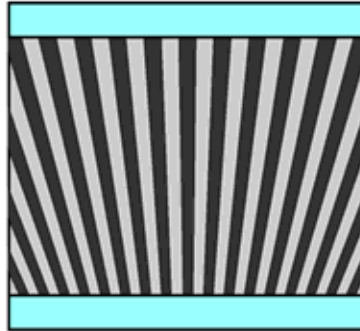
- Precise control over grating period
- Fast processing over whole wafer
- Allows complex grating patterns
 - fan-out gratings
 - different gratings on same wafer
 - tandem gratings
 - controlled distribution of d_{eff}
 - aperiodic, e.g. chirped gratings
 - 2-D gratings

Various grating designs

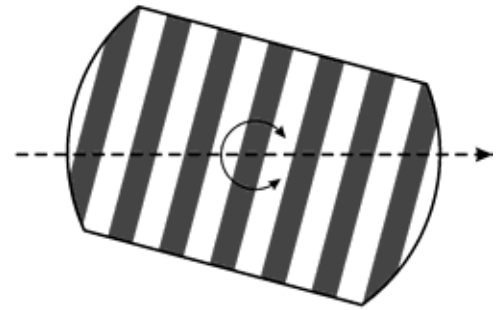
Multiple grating



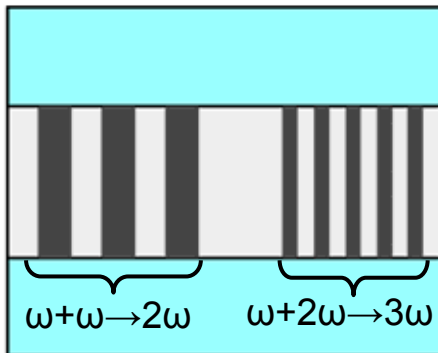
Fan-out grating



Angle-tuned cylindrically polished crystal



Tandem gratings, sequential processes

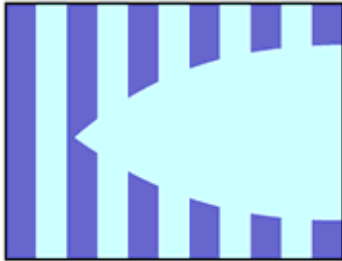


GQPS (Generalised Quasi-Periodic-Structure)
APOSL (Aperiodic Optical Superlattice)

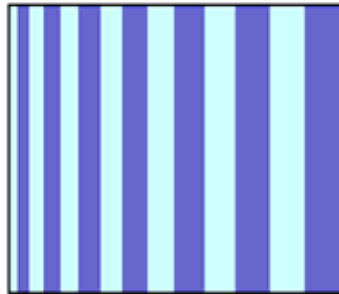


Various grating designs

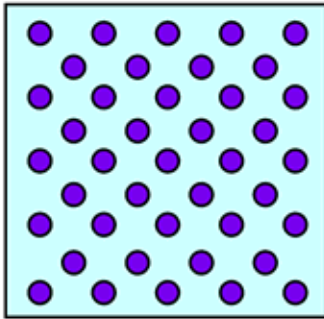
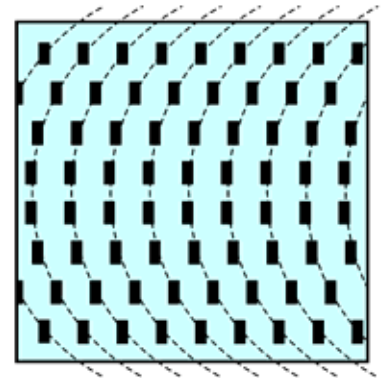
Transverse
modulation of d_{eff}



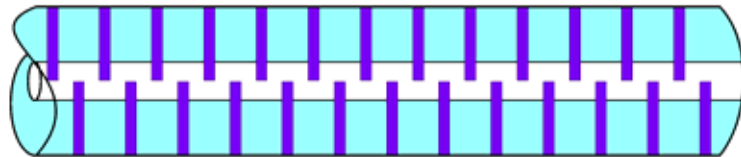
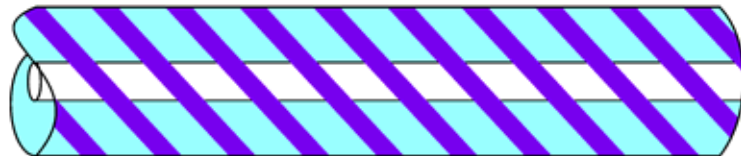
Chirped
grating



Nonlinear physical optics
with transverse-patterned
QPM gratings

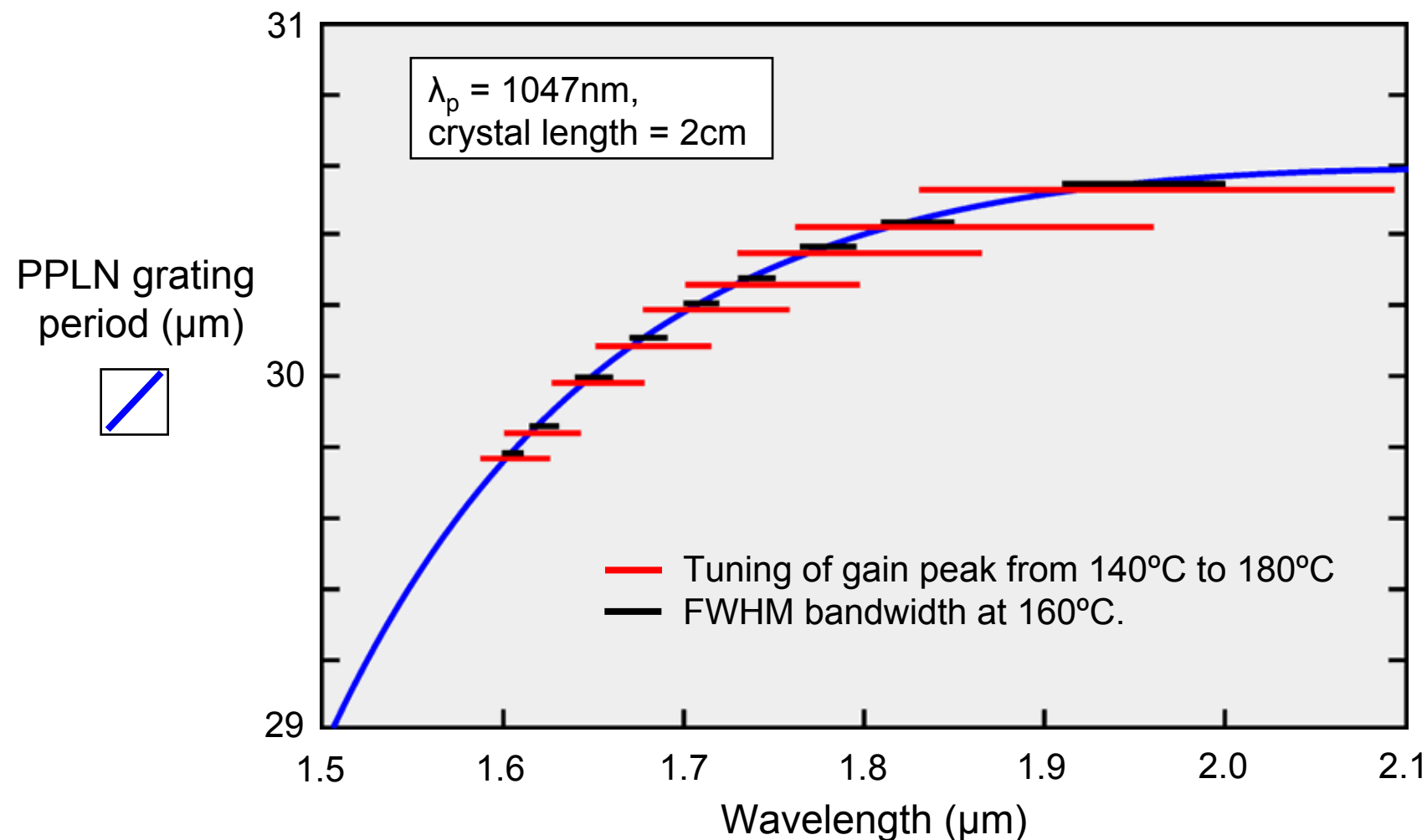


2-D nonlinear 'photonic'
crystal, e.g. HXLN



Odd waveguide mode QPM
with angled & staggered gratings


PPLN tuning via grating period and temperature



Frequency-conversion efficiency and parametric gain in PPLN

SHG conversion efficiency, confocal focus ($l = b = 2\pi w_0^2 n_1 / \lambda$)
($\omega_1 \rightarrow 2\omega_1$)

$$\sim 16\pi^2 P(\omega_1) d_{\text{eff}}^2 l / c \epsilon_0 n_1 n_2 \lambda_1^3$$

SHG,	1064nm \rightarrow 532nm	} 	~2%/ Wcm ($d_{\text{eff}} = 17\text{pm/V}$)
or			
Parametric gain	532nm \rightarrow 1064nm		

(Waveguide enhancement by $\lambda/w^2 \sim 10^3$; $>1000\%$ / Wcm²)

Parametric gain, $1\mu\text{m} \rightarrow 2\mu\text{m}$, $\sim 0.25\%$ / Wcm (PPLN)
 $2\mu\text{m} \rightarrow 4\mu\text{m}$, $\sim 0.5\%$ / Wcm (GaAs)

Minimum pump energy for $1\mu\text{m}$ – pumped PPLN parametric devices

CW SRO	$\sim 1\text{-}3\text{W}$	
Nanosecond-pumped OPO	$\sim 5\ \mu\text{J}$	
Synchronously-pumped OPO	$\sim 100\text{pJ}$ $(\sim 10\ \text{mW @ } 100\ \text{MHz})$	
Optical parametric generator	$\sim 100\text{nJ (fs/ps)}$ $\sim 100\mu\text{J (1 nsec)}$	$\left. \begin{array}{l} 130\ \text{dB} \\ \text{gain} \end{array} \right\}$

All values scale as $d^2/n^2\lambda^3$

cw singly-resonant OPOs in PPLN

- **First cw SRO:** *Bosenberg et al. Opt.Lett., 21, 713 (1996)*
13W Nd:YAG pumped 50mm Xtal, ~3W threshold, >1.2W @ 3.3 μ m
- **cw single-frequency:** *van Herpen et al. Opt.Lett., 28, 2497 (2003)*
Single-frequency idler, 3.7 \rightarrow 4.7 μ m, ~1W \rightarrow 0.1W
- **Direct diode-pumped:** *Klein et al. Opt.Lett., 24, 1142 (1999)*
925nm MOPA diode, 1.5W threshold, 0.5W @ 2.1 μ m (2.5W pump)
- **Fibre-laser-pumped:** *Gross et al. Opt.Lett., 27, 418 (2002)*
1.9W idler @ 3.2 μ m for 8.3W pump

Some results from PPLN ps/fs parametric devices

- Low threshold SPOPO;
7.5 mW (av), 1047nm pump, 4ps, @120 MHz
21mW, pumped by Yb fibre laser
- High gain devices (at mode-locked rep. rate)
Widely-tuned SPOPO, idler $>7\mu\text{m}$
OPCPA, 40 dB gain, mJ output
OPG operated at 35 MHz, $\sim 0.5\text{W}$ signal
- High average power femtosecond SPOPO
19W (av) signal @ $1.45\mu\text{m}$, 7.8w @ $3.57\mu\text{m}$

Nanosecond QPM OPOs

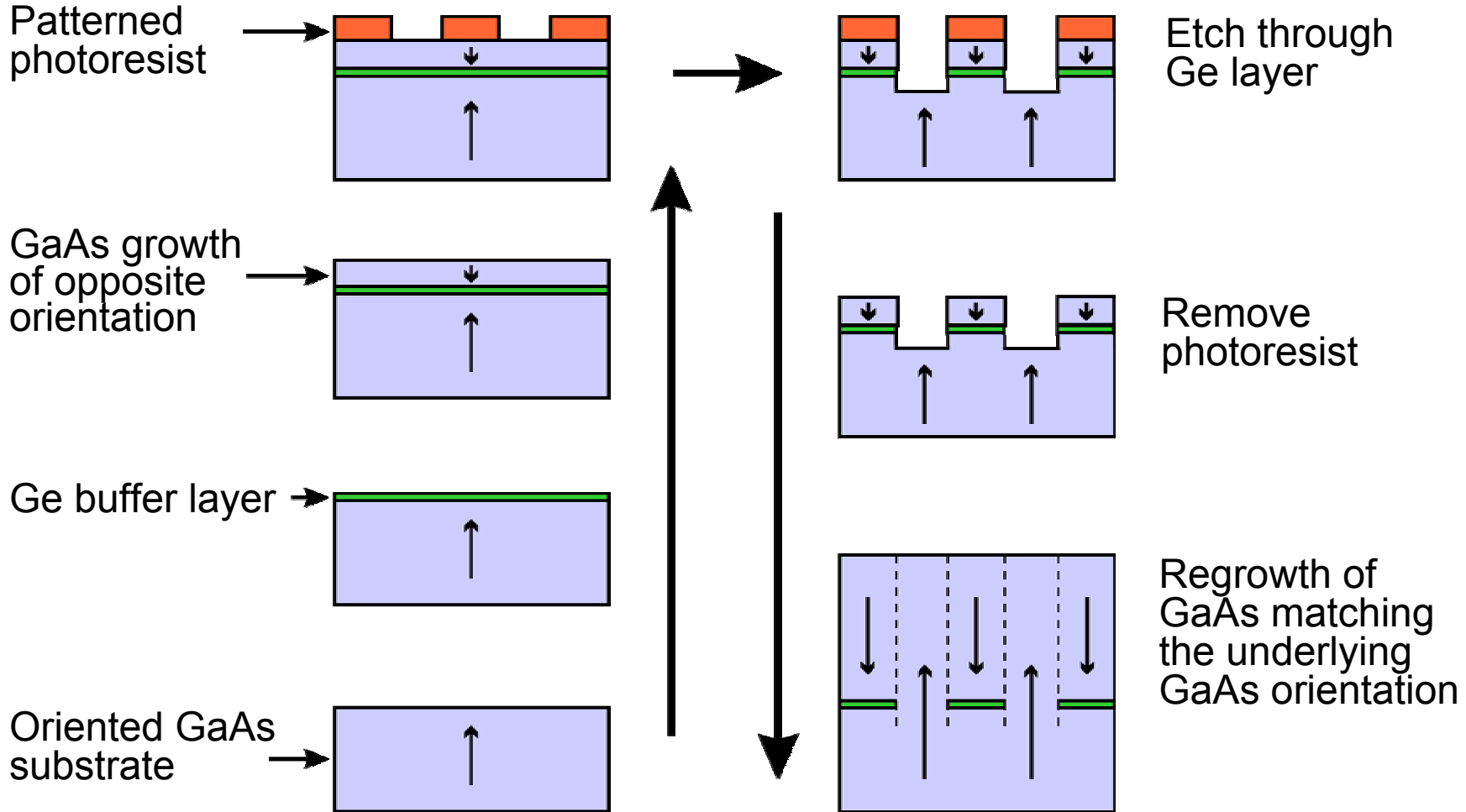
- Threshold of few micro joules
- Wide tunability, idler $>5.5 \mu\text{m}$ in PPLN
- Few hundred μJ output typical
(30 mJ demonstrated with PPLN stack)
- QPM GaAs; 2-10 μm covered so far
Paper CTuA1, CLEO 2004

Why GaAs?

- Large nonlinearity, $d_{14} \sim 100\text{pm/V}$
- Extensive transparency, $0.9\ \mu\text{m} - 17\ \mu\text{m}$
- Mature technology

But, how to make a QPM structure ?

Orientation-patterned GaAs : OPGaAs



Difference-frequency generation of 8 μm radiation in orientation-patterned GaAs

O.Levi et al Optics Letts, 27 2091, (2002)

QPM GaAs: 20x5x0.5 mm

period 26.3 μm , for first-order QPM

estimated loss $\sim 0.05 \text{ cm}^{-1}$

Experiment: mix cw 1.3 μm and 1.55 μm ,
to generate $\sim 8 \mu\text{m}$

Result: agreement within factor of 3 between measured
output power and calculation based on $d_{14} = 105 \text{ pm/V}$

QPM waveguide devices

Blue SHG at high conversion efficiency in $\text{MgO}:\text{LiNbO}_3$
852nm \rightarrow 426nm, 1500%/Wcm² in 10mm guide
55mW \rightarrow 17.3mW
Sugita et al Optics Letts. 24, 1590 (1999)

High Efficiency SHG in 1550nm communication band
1536nm \rightarrow 768nm, in 3.3cm PPLN guide
150%/Wcm², 1600%/W
Parameswaran et al Optics Letts. 27, 179 (2002)

Predict: 10dB signal gain at 1550nm, for
115mW of pump at 775nm in 6cm guide

**Can OPOs dethrone
Ti:sapphire and other lasers?**

Parametric gain contrasted with stimulated emission

- No heat input to the gain medium
- Bandwidth and gain are not related
- Gain-peak can be tuned; wide spectral coverage
- Phase-matching constrains relative directions of pump signal & idler
- Gain determined by instantaneous pump intensity

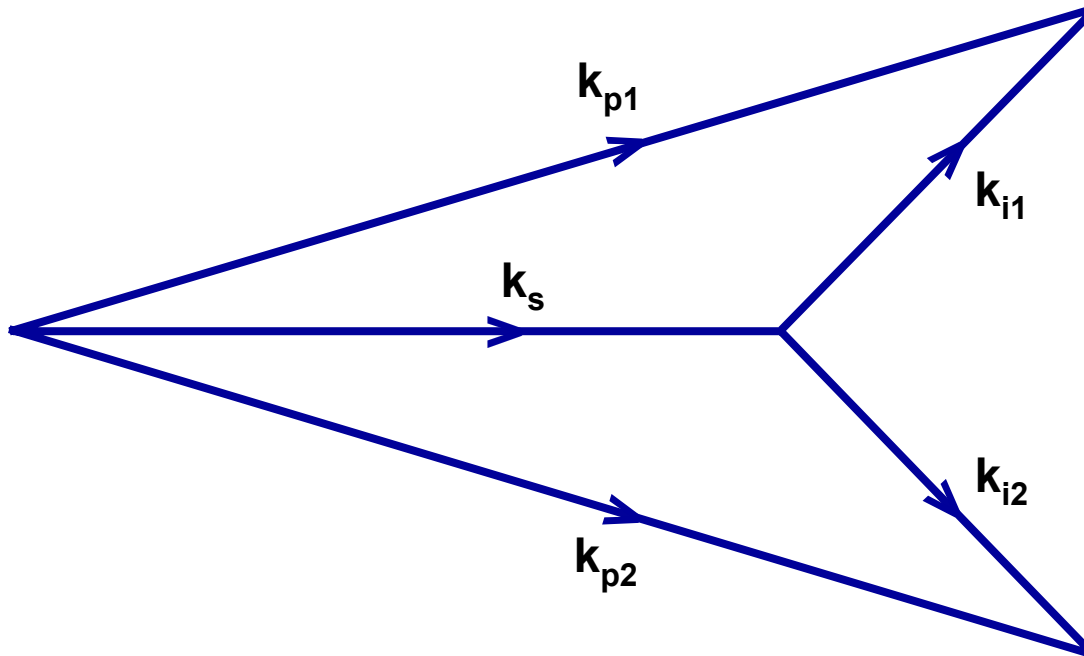
ps/fs OPO vs LASER

- ~ 10 fs signal pulses have been generated
- Very low threshold, few mW average
- Very high gain, > 80dB; OPG
- High average o/p power, ~20W signal, 7W idler
- OPCPA demonstrated
- Carrier-envelope phase stabilised in OPA

Multimode-pumping of a single-mode signal

$$\omega_p = \omega_s + \omega_i$$

$$\mathbf{k}_{p1,2} = \mathbf{k}_s + \mathbf{k}_{i1,2}$$

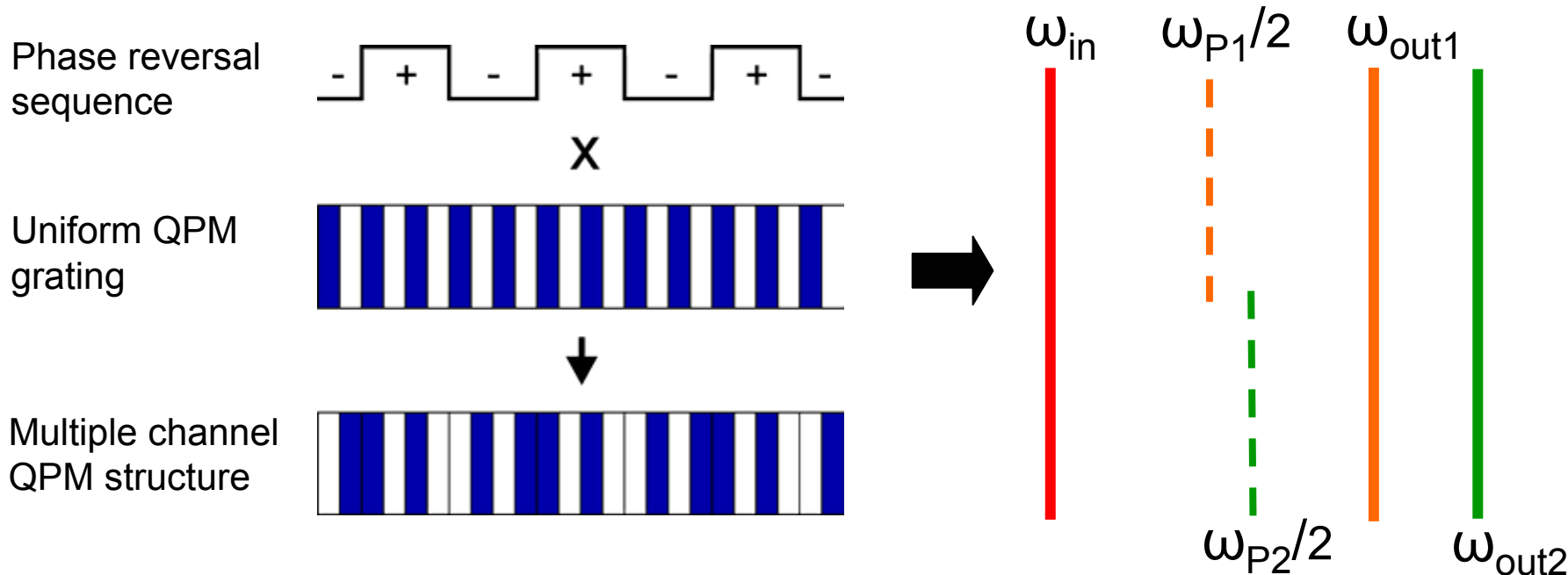


SPOPO: Obstacles/challenges/unknowns

- Absence of detailed stability/noise characterisation
- Lack of straightforward master-equation
- SPOPO community is sub-critical

Multiple-channel wavelength-conversion via engineered QPM structures in LiNbO₃ waveguides

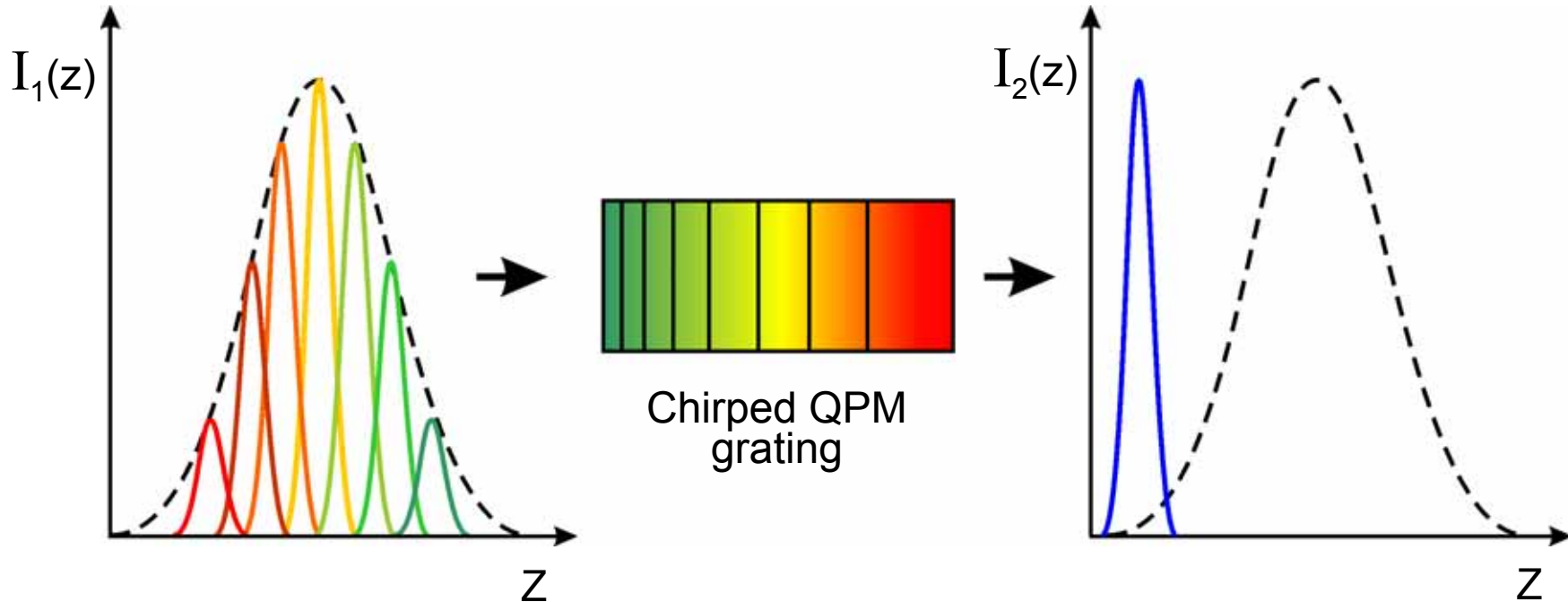
Chou *et al*, Optics Letts 24, 1157 (1999)



More channels via extra phase-reversal sequences and tailored duty cycle

Pulse compression during second harmonic generation in aperiodic quasi-phase-matched grating

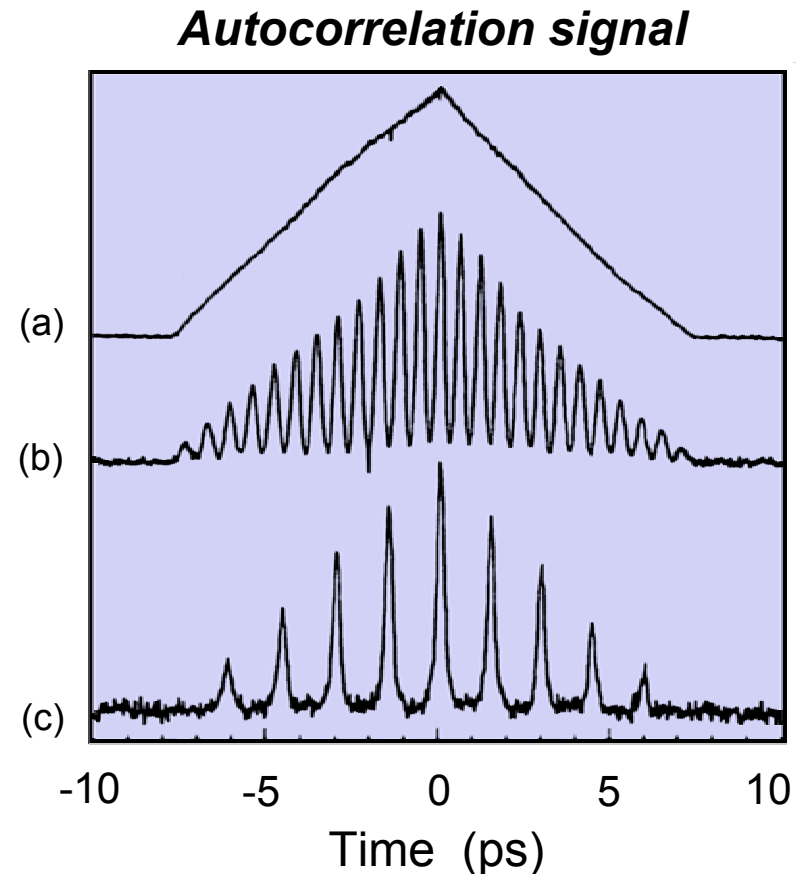
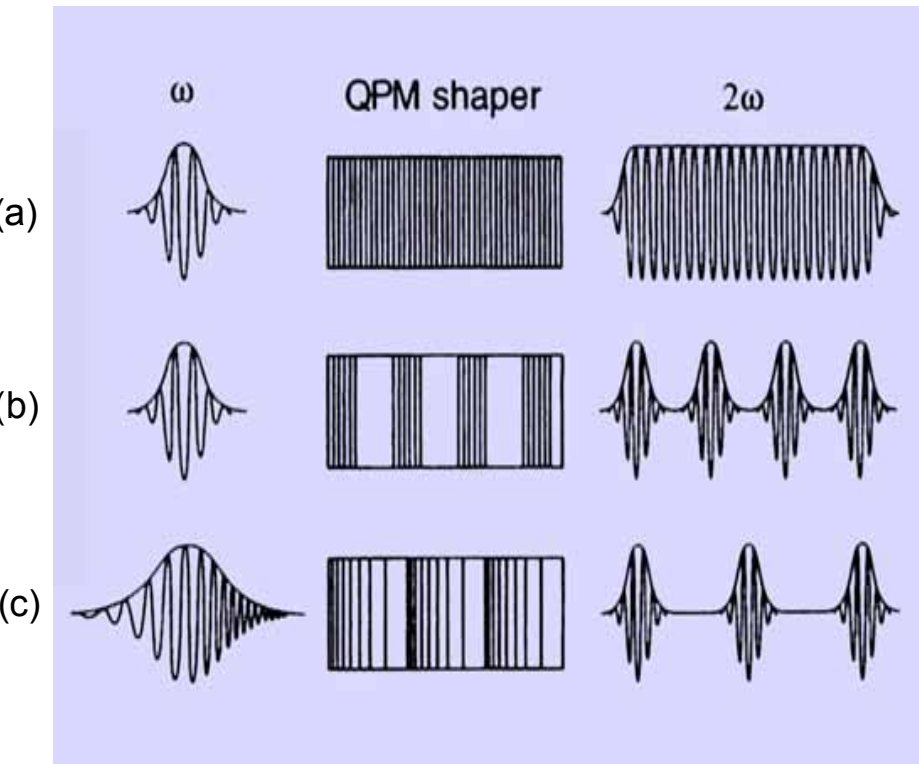
Arbore, Marco & Fejer, Optics Letts. 22, 865 (1997)



- Leading edge converts to SH at grating entrance, and so travels more slowly than trailing edge which converts near exit.

Engineerable fs pulse-shaping by SHG with Fourier synthetic QPM gratings

Imeshev *et al* Opt. Letts. 23, 864 (1995)

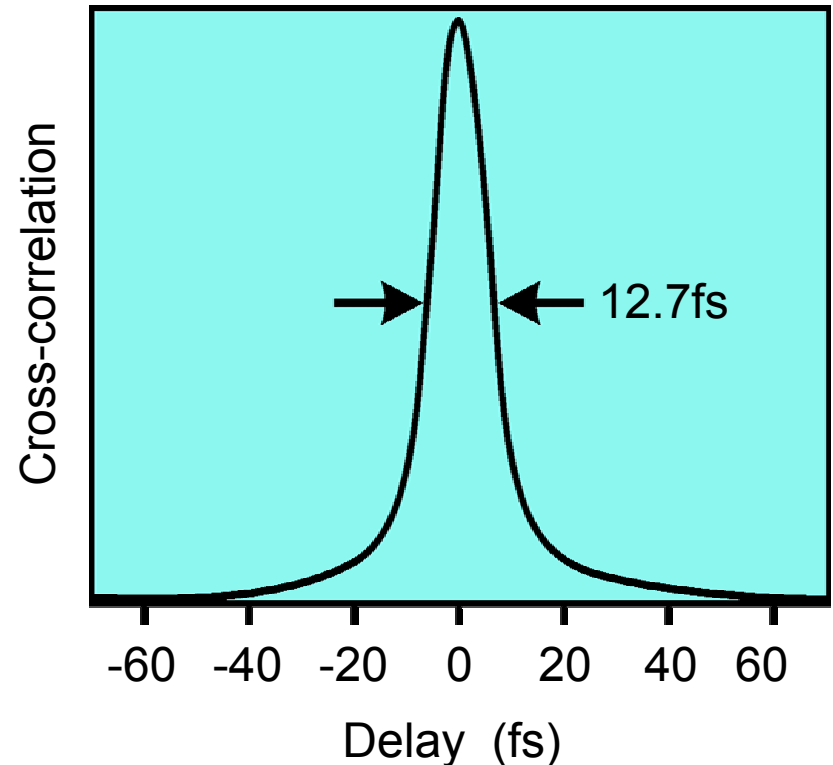


Generation of sub-6-fs blue pulses by frequency doubling with QPM gratings

310 μm PPLT crystal

Nonlinearly-chirped grating,
Periods from 6.5 μm to 1.8 μm
405nm SH pulse, 5.3fs

Conversion, $\sim 0.5\%$ /nJ



Some topics not covered

Quantum optics; correlated photons etc

Multiple-wavelength QPM interactions

2D, 'photonic' QPM structures

Backward wave OPO

UV materials, polymers

Nonlinear physical optics

THz sources

Future agenda

GaAs, GaN etc.....

Power scaling, eg with fibre laser pumps

Larger transverse dimensions

UV materials

More sophisticated uses, eg
telecom
aperiodic gratings
2-D QPM

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