

# Nonlinear frequency conversion in quasi-phase-matched materials

David Hanna

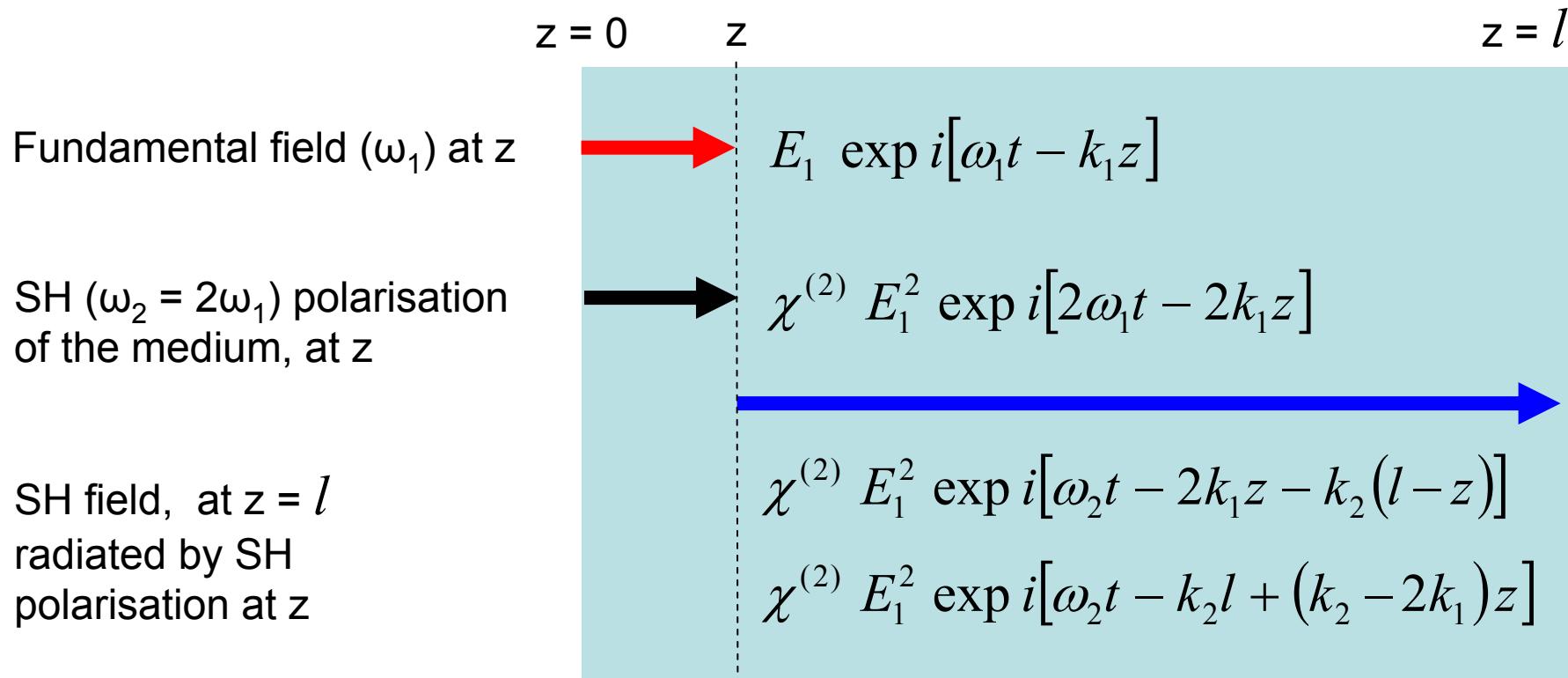
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# Outline of tutorial

- **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



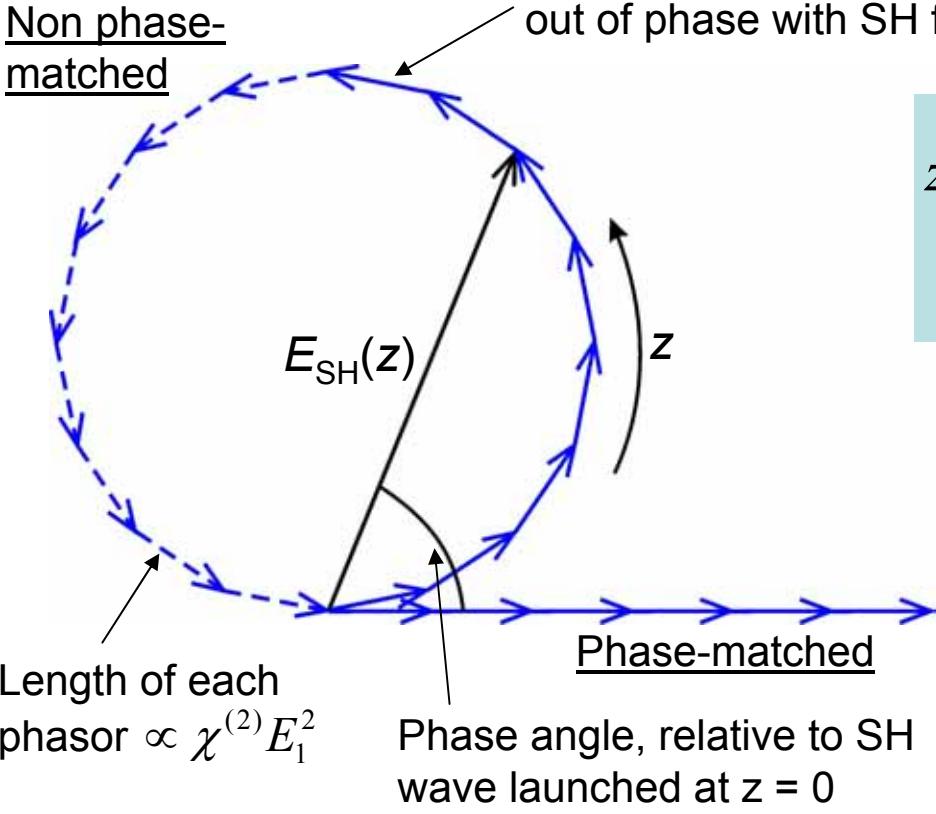
If all SH field contributions, for  $z$  from 0 to  $l$ , are to add in phase, one needs  $\Delta k \equiv k_2 - 2k_1 = 0$  (phase-matching)  
ie  $n_1 = n_2$

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

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

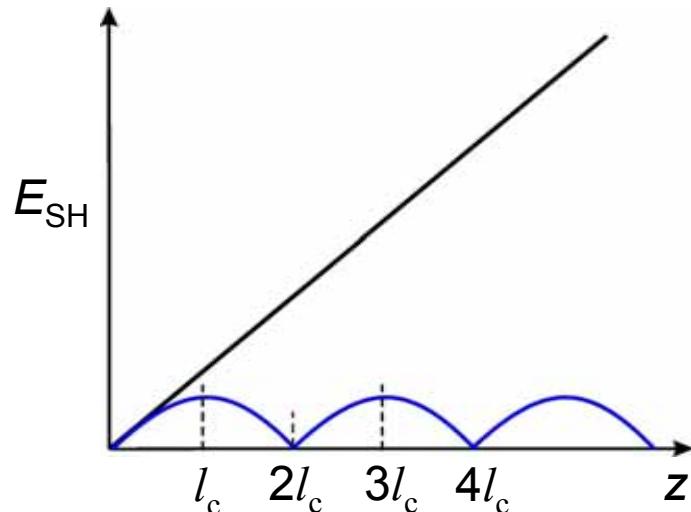
Here  $\Delta kz = \pi$ , so SH field generated at  $z$  is  $\pi$  out of phase with SH field generated at  $z = 0$  :

Non phase-matched



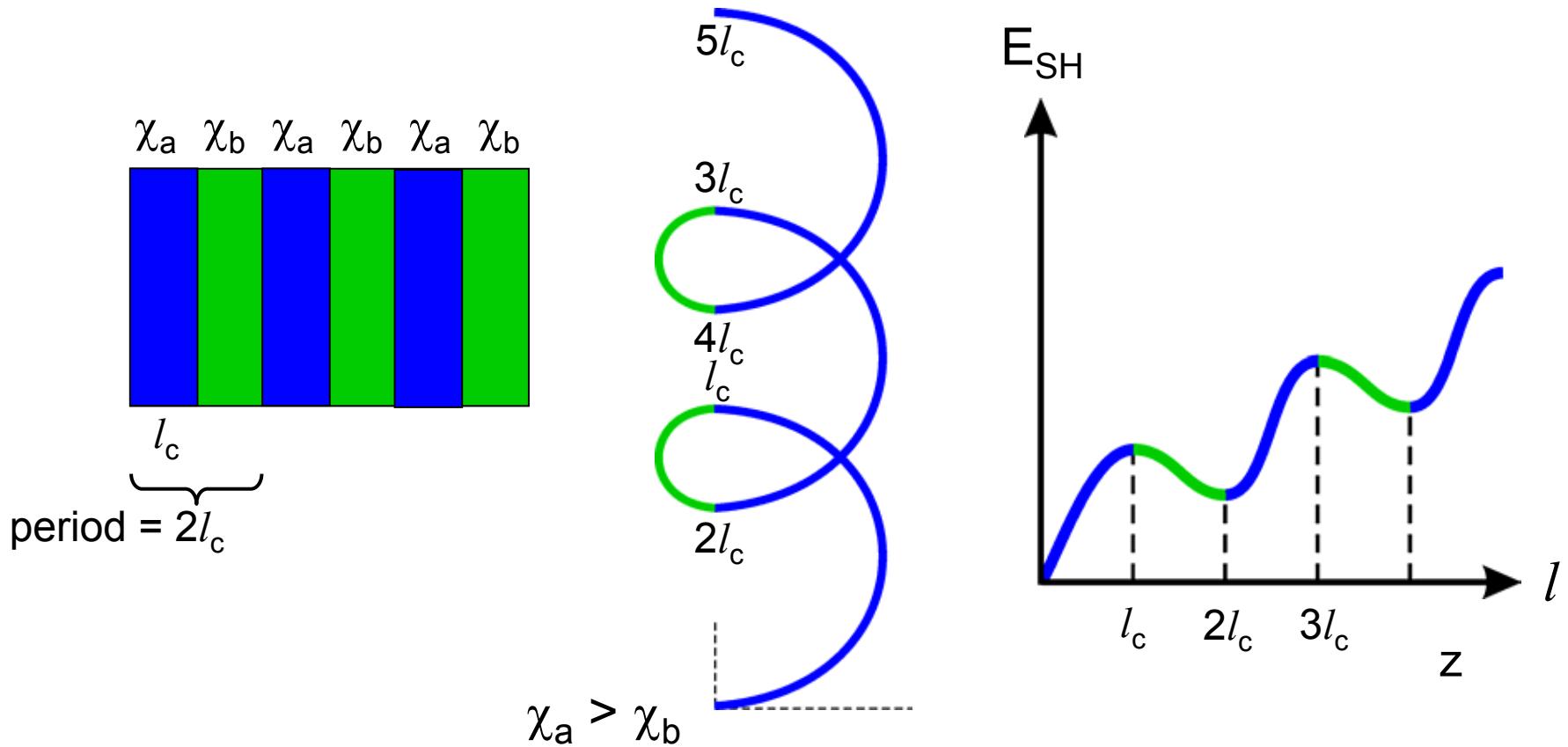
$$z = l_c \equiv \frac{\pi}{\Delta k} \quad (\text{coherence length})$$

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



# 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

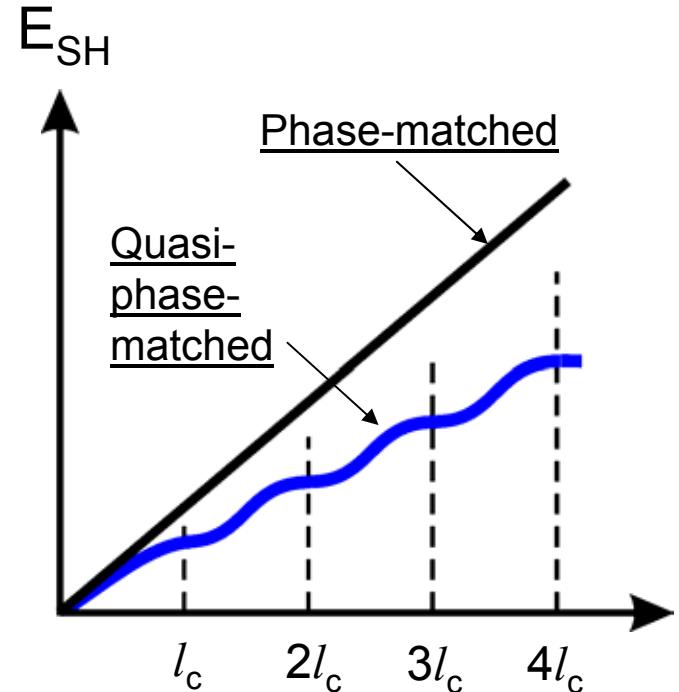
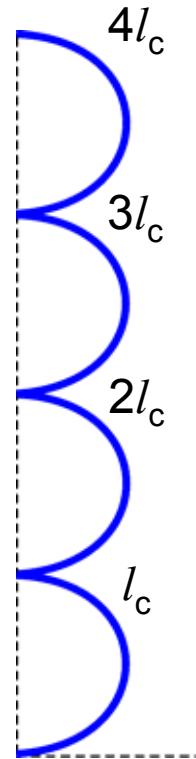
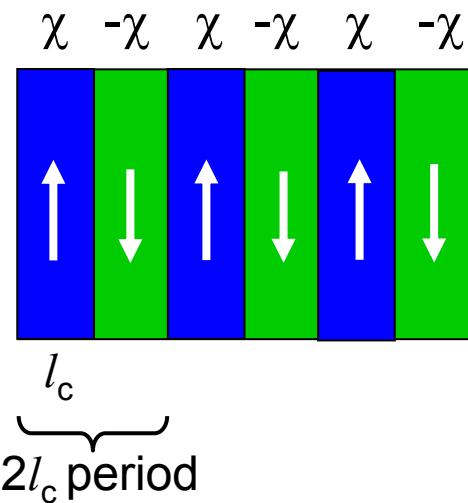
- Periodic E field (via segmented electrode) + field-induced  $\chi^{(2)}$
- ‘Frozen-in’ field-induced  $\chi^{(2)}$ , in optical fibres
- Periodic destruction/reduction of nonlinearity,  
eg via ion-implantation through a mask
- Overgrowth on a template having periodic modulation of  
substrate orientation (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)

Period =  $2l_c$

1<sup>st</sup> order

phase-matching

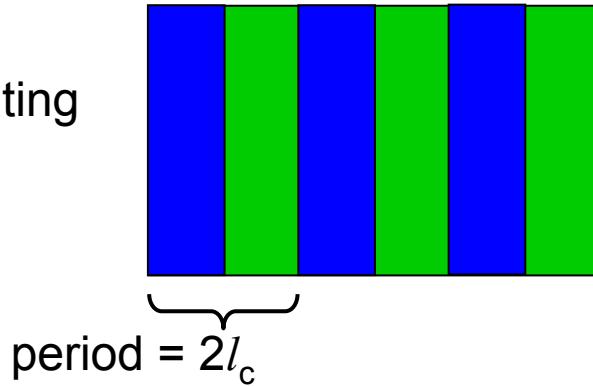


$E_{SH}$  after each  $l_c$  is  $\pi/2$  smaller than for perfect phase-matching over the same length of medium.

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

# Quasi-phase-matching condition

Nonlinear grating  
of period  $2l_c$



Grating period is  $\Delta$ , hence  
grating wave-vector,  $\Delta k_G$ , is

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

*(Phase-mismatch)*

ie. Quasi-phase-matching requires  $\Delta k = \Delta k_G$

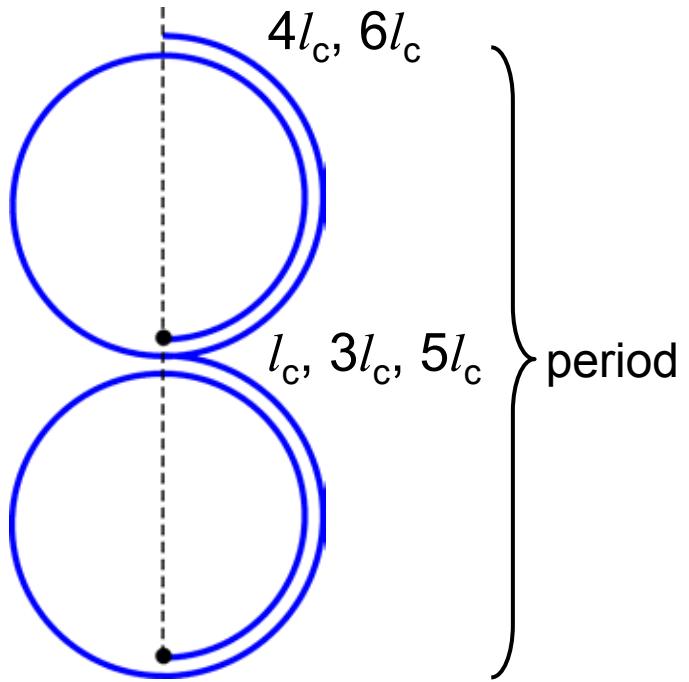
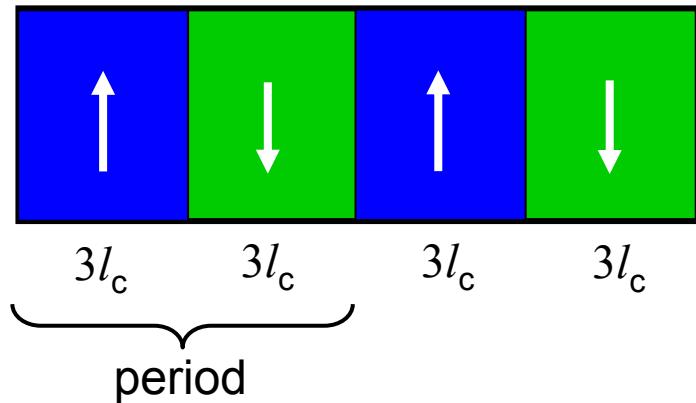
So, instead of making  $\Delta k$  zero, we make  $\Delta k' \equiv \Delta k - \Delta k_G = 0$

## Generalisation

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

# Higher order QPM

3<sup>rd</sup> order:



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

Advantage: larger scale pattern, easier to fabricate

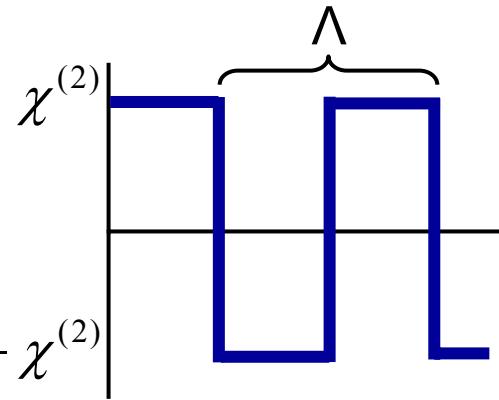
Disadvantage: effective nonlinear coefficient for N<sup>th</sup> order QPM is reduced by N

# Quasi-phase-matching condition

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

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

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



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

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.  $\Delta k' = 0$  , QPM condition

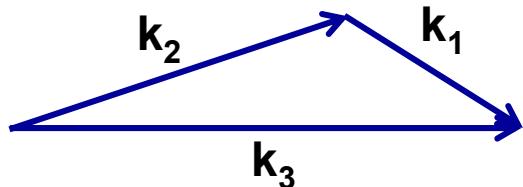
# Quasi-phase-matching condition

Nonlinear process

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

Conventional phase-match condition

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



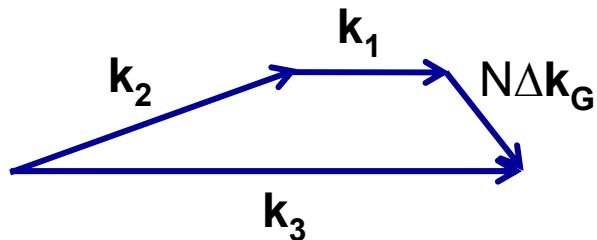
Phase-mismatch

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

QPM condition  
( $N^{\text{th}}$  order QPM)

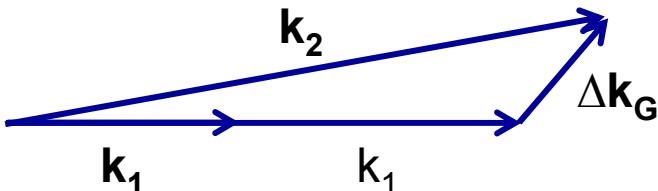
$$\Delta\mathbf{k} = N \Delta\mathbf{k}_G$$

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



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

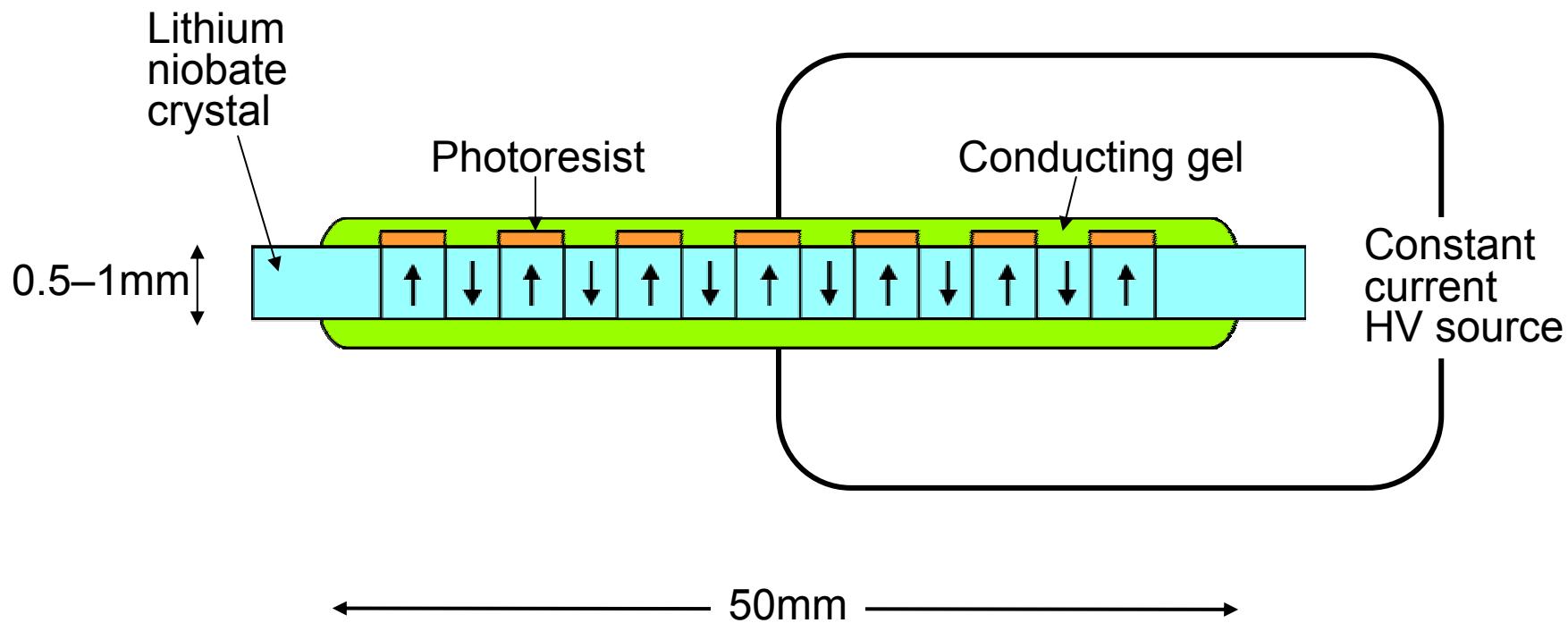
e.g. SHG 1<sup>st</sup> order:



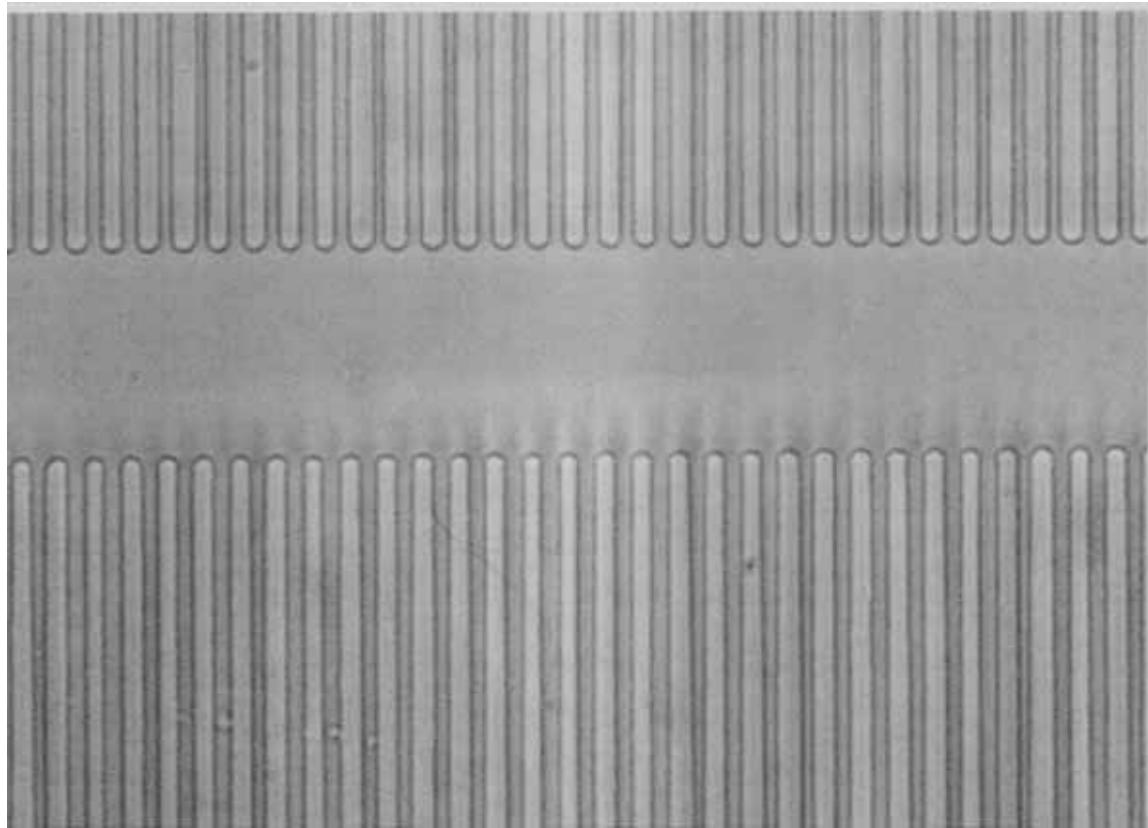
# Some benefits of QPM

- Access materials having too low a birefringence for phase-matching, e.g.  $\text{LiTaO}_3$ , GaAs
- Ability to phase-match any frequencies in the transparency range, freedom to choose ideal pump for an OPO
- Non-critical ( $90^\circ$ ) phase-matching, allows tight (confocal) focussing
- Access to largest nonlinear coefficient, e.g.  $d_{33}$  in  $\text{LiNbO}_3$

# Fabrication of Periodically Poled Lithium Niobate



# Periodically Poled Lithium Niobate Crystal



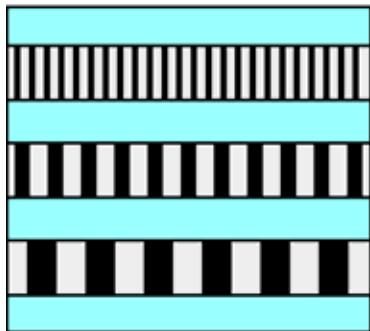
Acknowledgements to Peter Smith, Corin Gawith and Lu Ming  
ORC, University of Southampton

# Attractions of photolithography for QPM grating fabrication

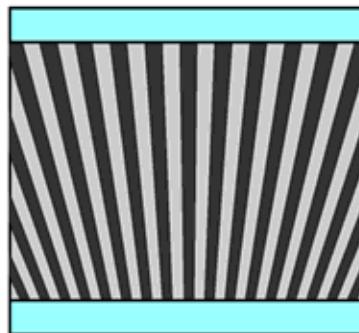
- Precise control over grating period
- Fast processing over whole wafer
- Allows complex grating patterns
  - fan-out gratings
  - different gratings on same wafer
  - tandem gratings
  - controlled distribution of  $d_{\text{eff}}$
  - aperiodic, e.g. chirped gratings
  - 2-D gratings

# Various grating designs

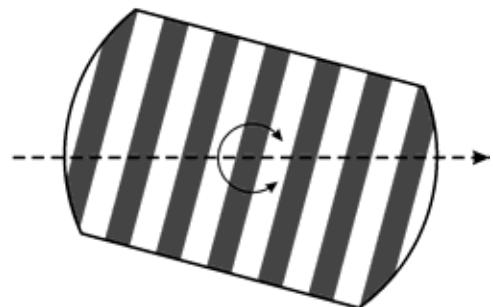
Multiple grating



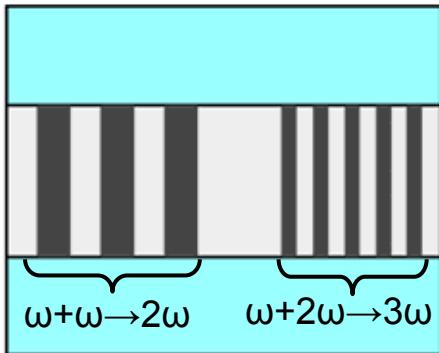
Fan-out grating



Angle-tuned cylindrically polished crystal



Tandem gratings,  
sequential processes

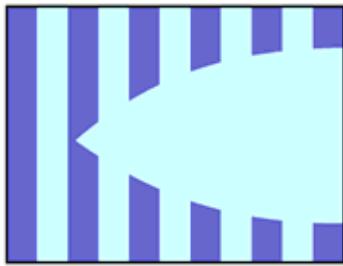


GQPS (Generalised Quasi-Periodic-Structure)  
APOS (Aperiodic Optical Superlattice)

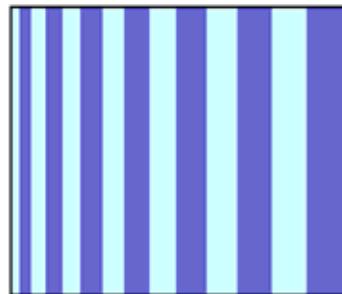


# Various grating designs

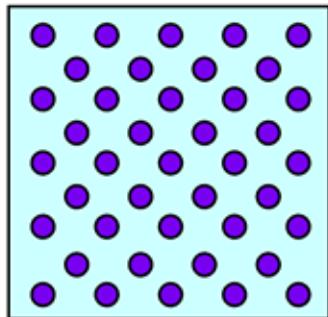
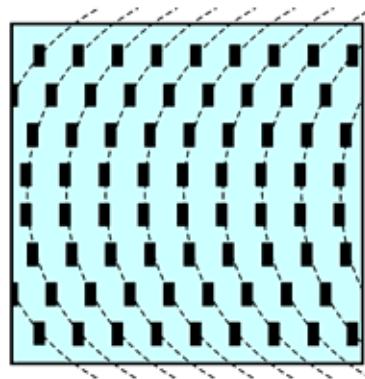
Transverse  
modulation of  $d_{\text{eff}}$



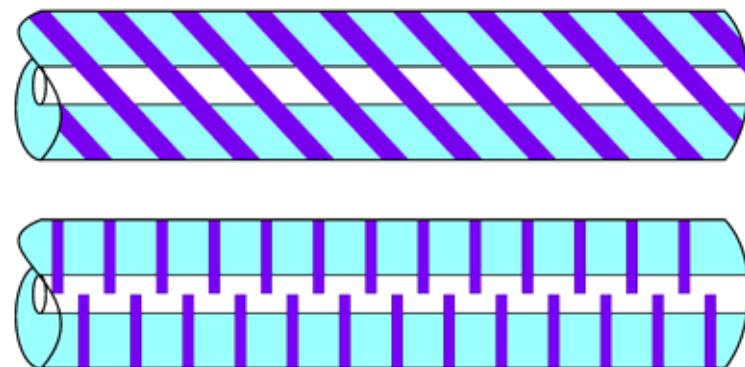
Chirped  
grating



Nonlinear physical optics  
with transverse-patterned  
QPM gratings

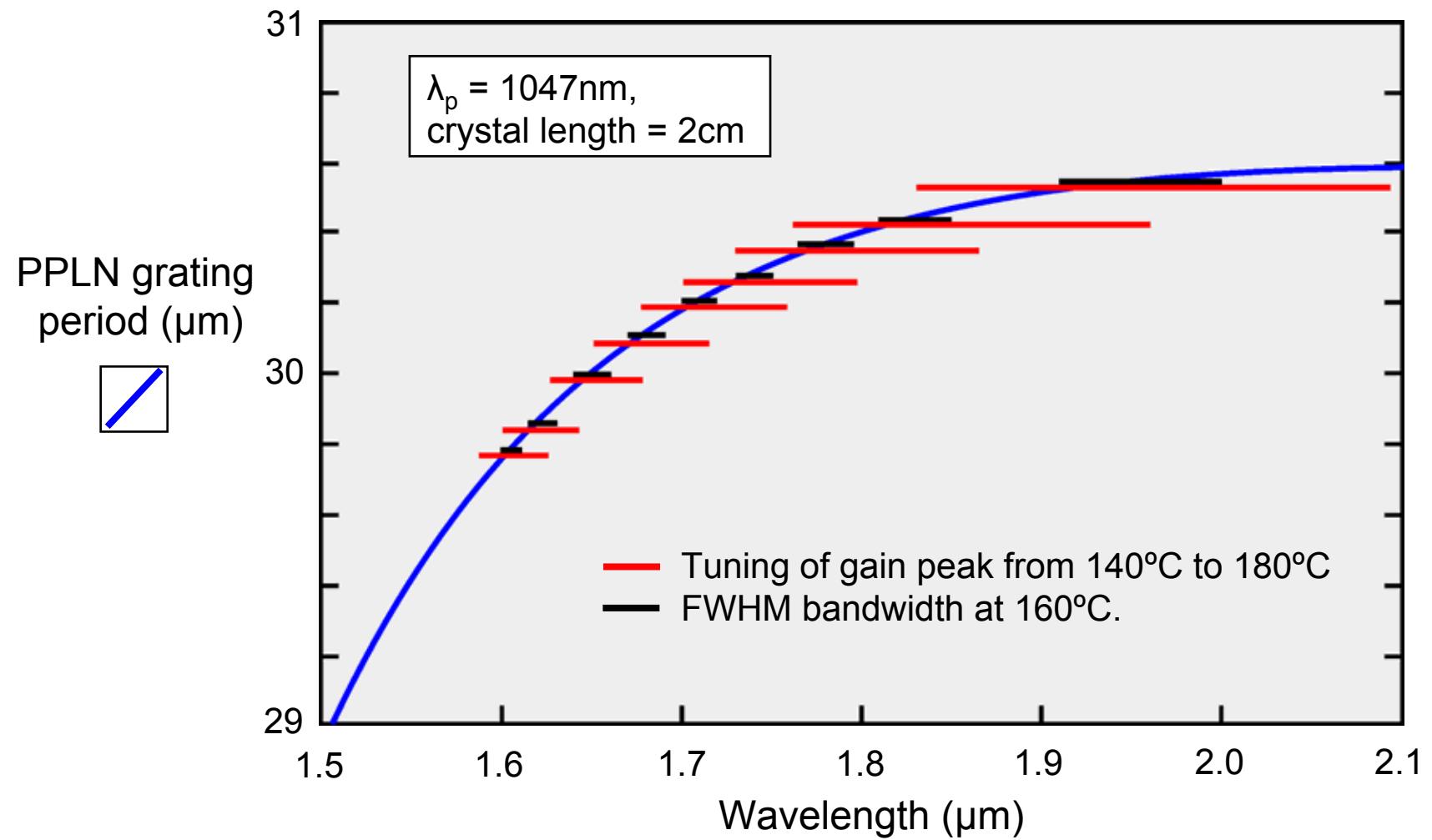


2-D nonlinear 'photonic'  
crystal, e.g. HXLN



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

(Waveguide enhancement by  $\lambda l / w^2 \sim 10^3$ ;  $> 1000\% / \text{Wcm}^2$ )

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

# Minimum pump energy for 1 $\mu$ m – pumped PPLN parametric devices

<b>CW SRO</b>	$\sim$ 1-3W
<b>Nanosecond-pumped OPO</b>	$\sim$ 5 $\mu$ J
<b>Synchronously-pumped OPO</b>	$\sim$ 100pJ ( $\sim$ 10 mW @ 100 MHz)
<b>Optical parametric generator</b>	$\sim$ 100nJ (fs/ps) $\sim$ 100 $\mu$ J (1 nsec) } 130 dB } gain

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 @  $3.3\mu\text{m}$
- **cw single-frequency**: *van Herpen et al. Opt.Lett., 28, 2497 (2003)*  
Single-frequency idler,  $3.7 \rightarrow 4.7 \mu\text{m}$ , ~1W  $\rightarrow$  0.1W
- **Direct diode-pumped**: *Klein et al. Opt.Lett., 24, 1142 (1999)*  
925nm MOPA diode, 1.5W threshold, 0.5W @  $2.1\mu\text{m}$  (2.5W pump)
- **Fibre-laser-pumped**: *Gross et al. Opt.Lett., 27, 418 (2002)*  
1.9W idler @  $3.2\mu\text{m}$  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

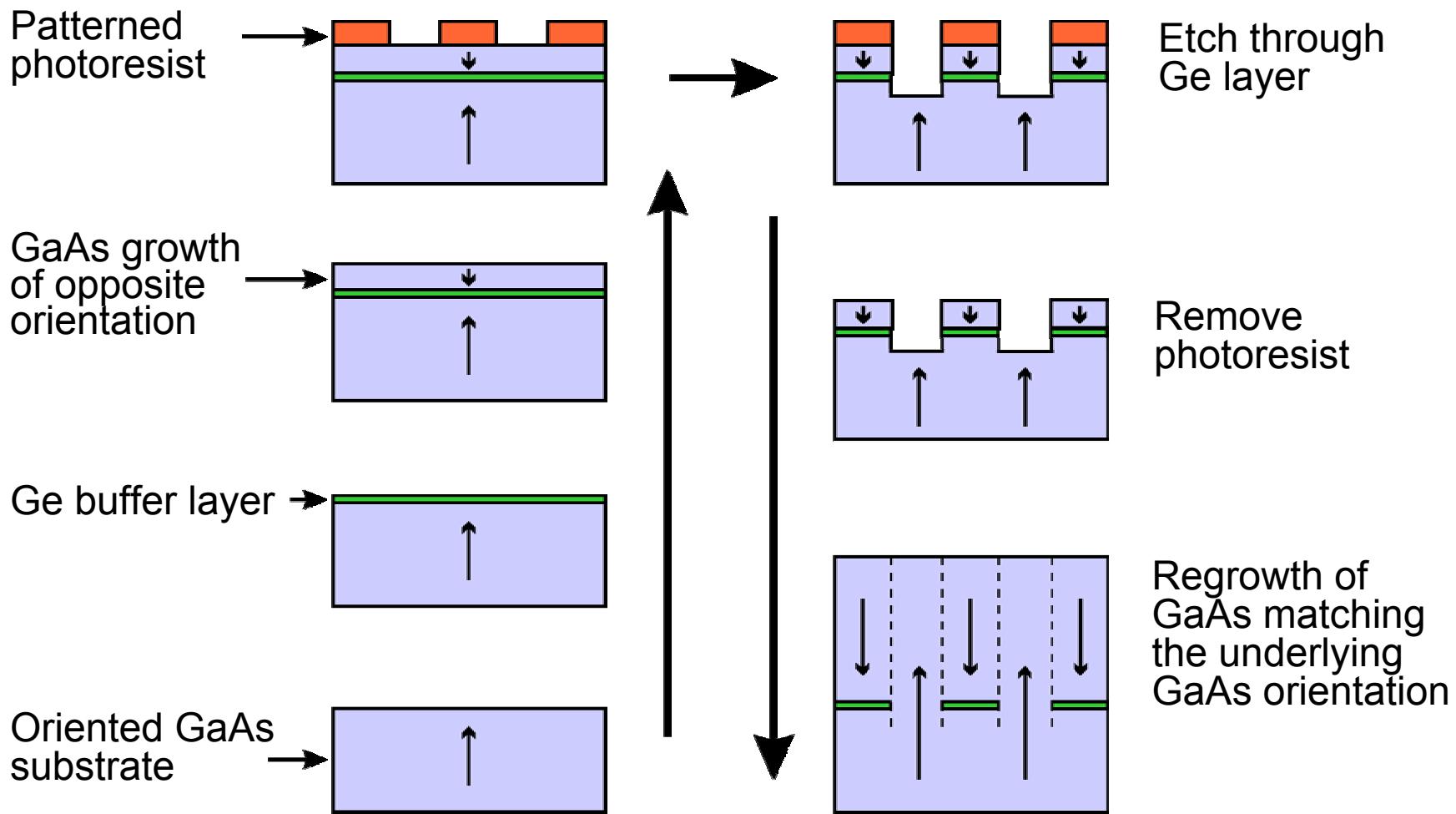
- Threshold of few micro joules
- Wide tunability, idler  $>5.5 \mu\text{m}$  in PPLN
- Few hundred  $\mu\text{J}$  output typical  
(30 mJ demonstrated with PPLN stack)
- QPM GaAs; 2-10  $\mu\text{m}$  covered so far  
*Paper CTuA1, CLEO 2004*

# 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 $8 \mu\text{m}$ radiation in orientation-patterned GaAs

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

**QPM GaAs:** 20x5x0.5 mm

period  $26.3 \mu\text{m}$ , for first-order QPM

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

**Experiment:** mix cw  $1.3 \mu\text{m}$  and  $1.55 \mu\text{m}$ ,  
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  $\text{MgO:LiNbO}_3$   
852nm → 426nm, 1500%/Wcm<sup>2</sup> in 10mm guide  
55mW → 17.3mW

*Sugita et al Optics Letts. 24, 1590 (1999)*

**High** Efficiency SHG in 1550nm communication band  
1536nm → 768nm, in 3.3cm PPLN guide  
150%/Wcm<sup>2</sup>, 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

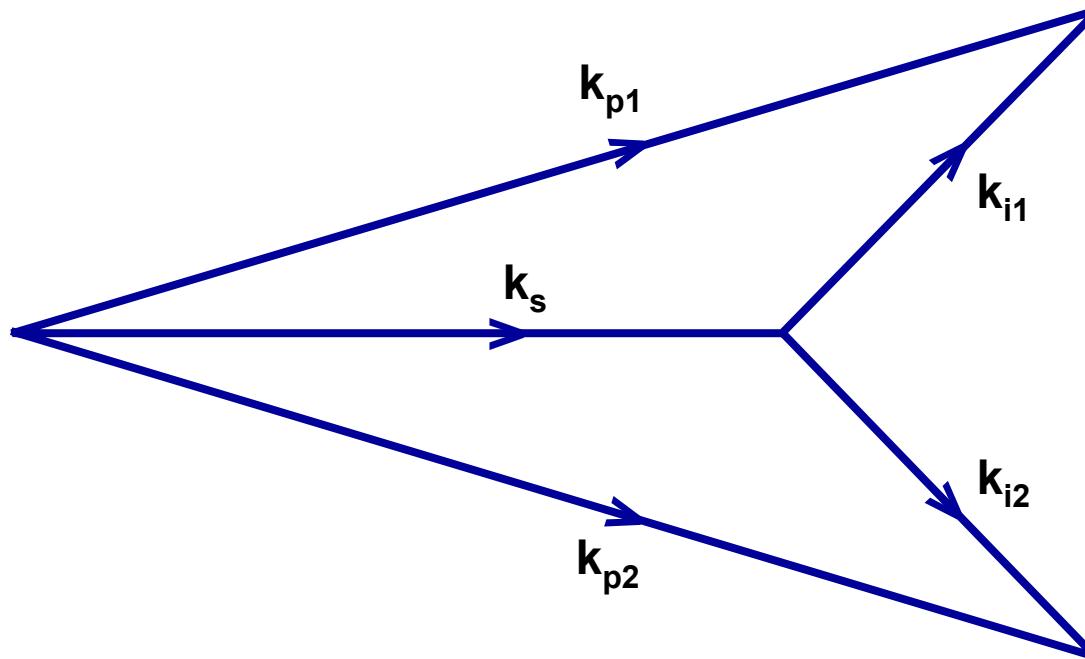
# ps/fs OPO vs LASER

- ~ 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

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

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

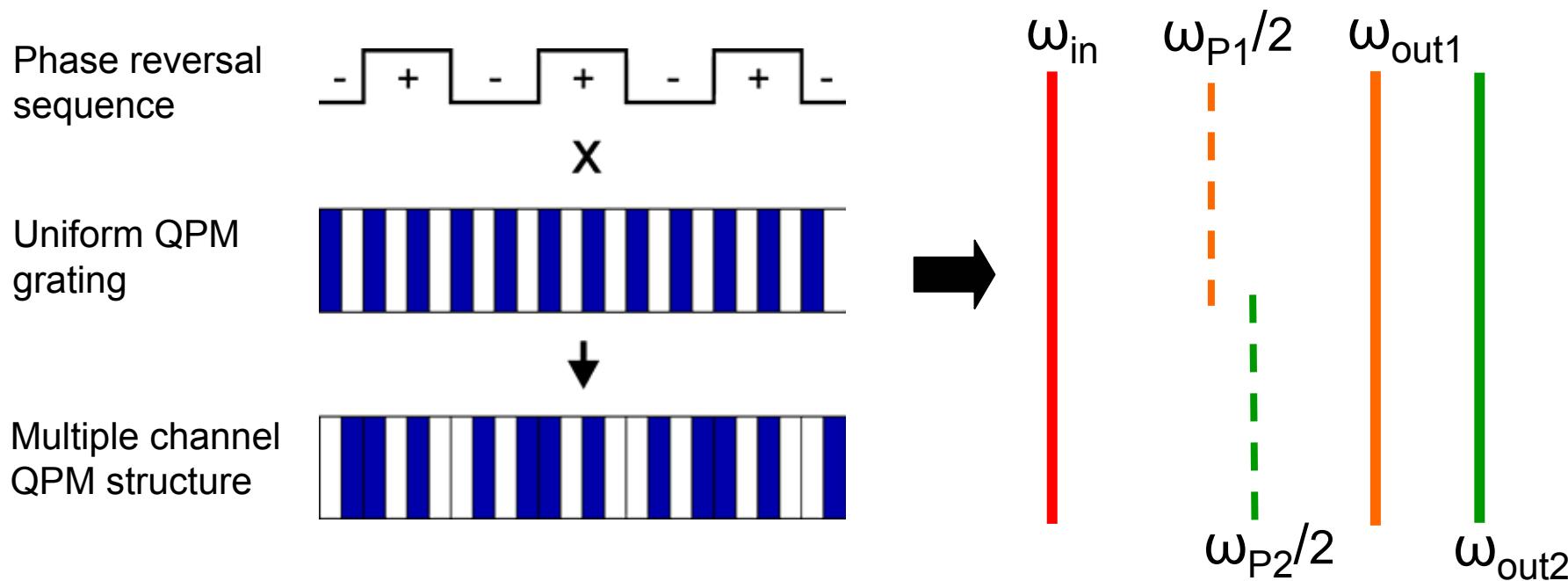


# SPOPO: Obstacles/challenges/unknowns

- 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 $\text{LiNbO}_3$ waveguides

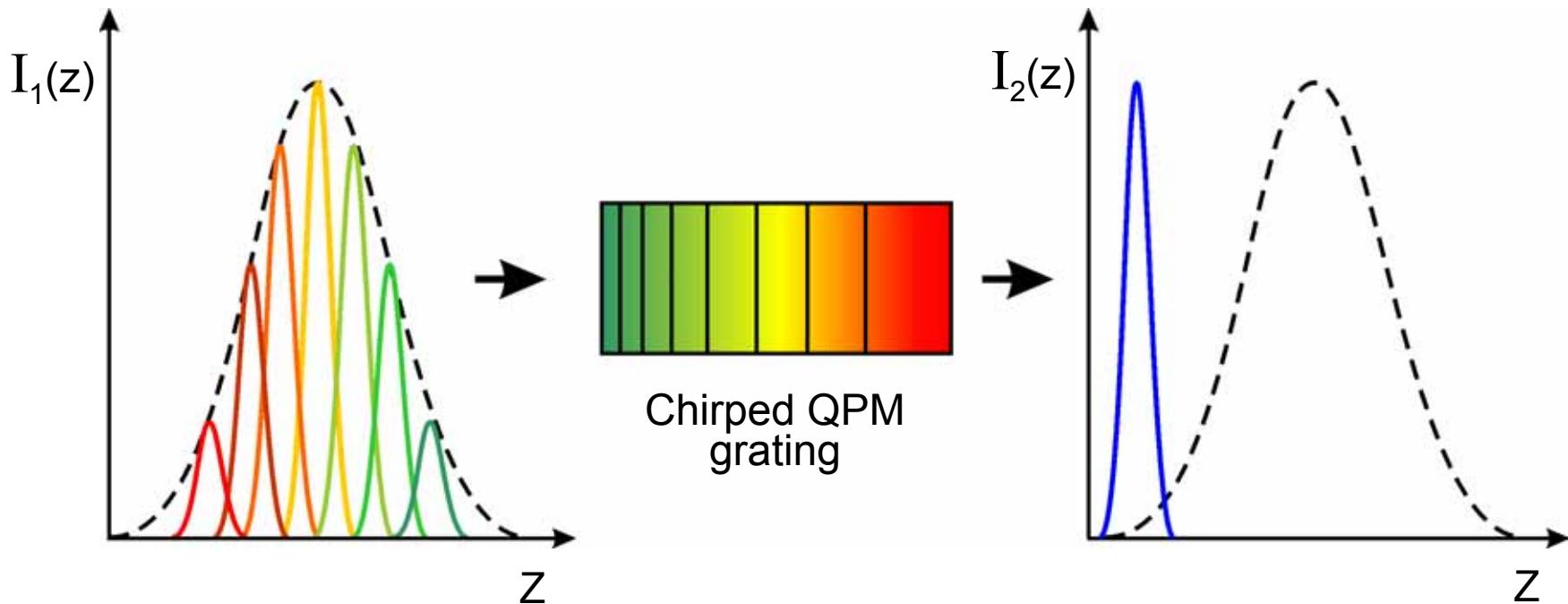
Chou *et al*, Optics Letts 24, 1157 (1999)



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

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

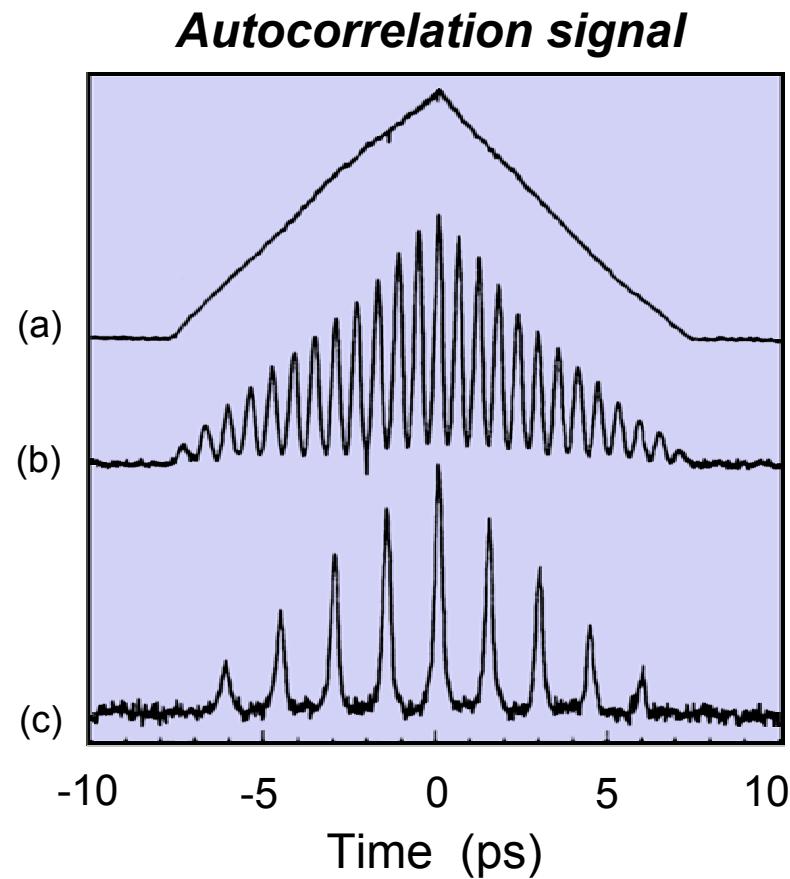
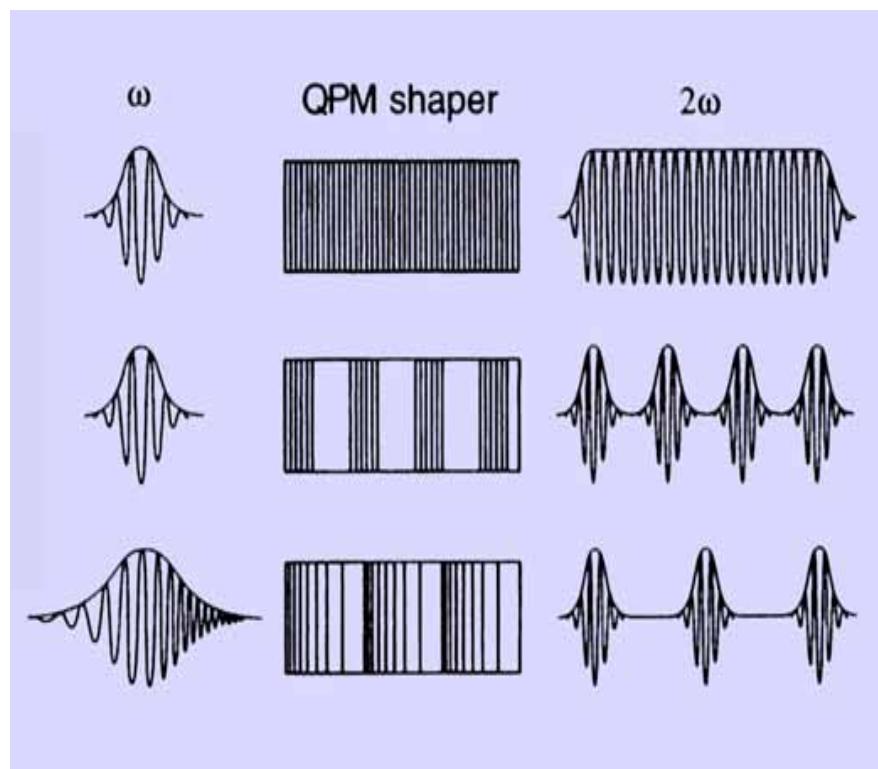
Arbore, Marco & Fejer, Optics Letts. 22, 865 (1997)



- 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)



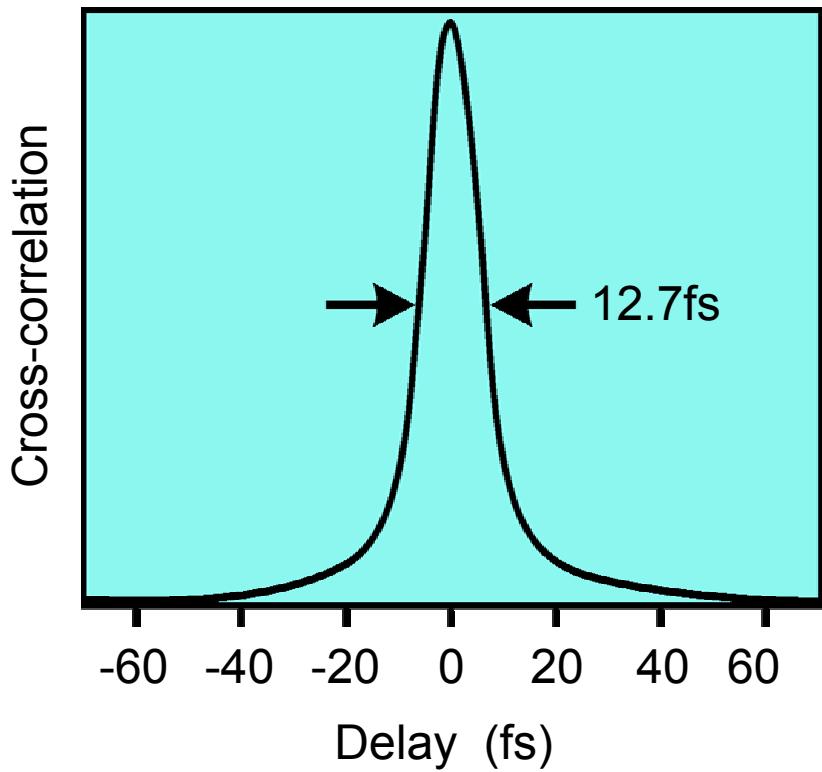
# Generation of sub-6-fs blue pulses by frequency doubling with QPM gratings

310 $\mu$ m PPLT crystal

Nonlinearly-chirped grating,  
Periods from 6.5 $\mu$ m to 1.8 $\mu$ m

405nm SH pulse, 5.3fs

Conversion, ~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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