Nonlinear frequency conversion in quasi-phase-matched materials

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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**
- **A peep at what has not been covered and at the future**

Phase matching for second harmonic (SH) generation

$z = 0$ $\quad$ z $\quad$ $z = l$

Fundamental field (ω_1) at z

$$E_1 \ \exp i\left[\omega_1 t - k_1 z\right]$$

SH ($\omega_2 = 2\omega_1$) polarisation of the medium, at z

$$\chi^{(2)} \ E_1^2 \ \exp i\left[2\omega_1 t - 2k_1 z\right]$$

SH field, at $z = l$ radiated by SH polarisation at z

$$\chi^{(2)} \ E_1^2 \ \exp i\left[\omega_2 t - 2k_1 z - k_2\left(l - z\right)\right]$$

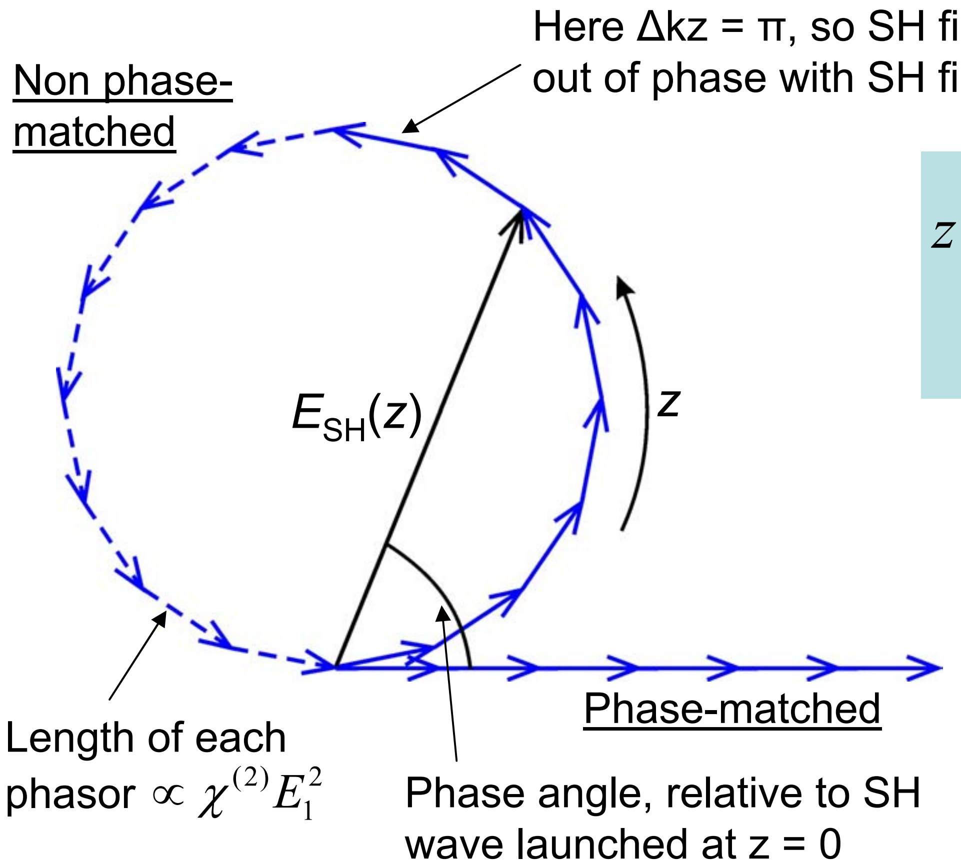
$$\chi^{(2)} \ E_1^2 \ \exp i\left[\omega_2 t - k_2 l + \left(k_2 - 2k_1\right) z\right]$$

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)

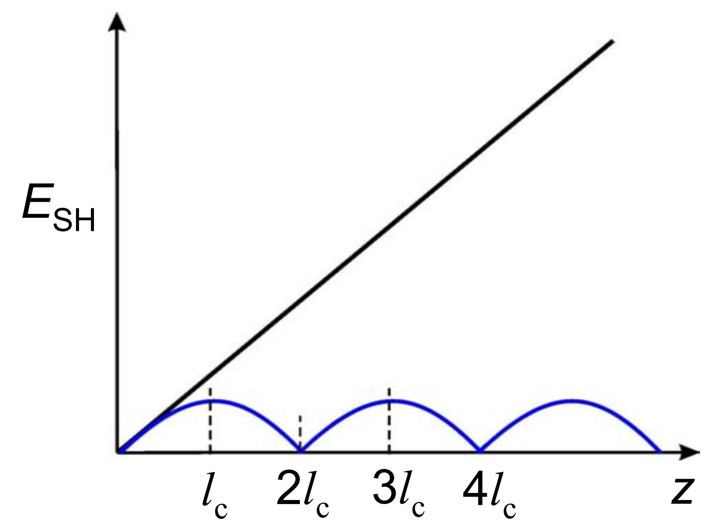
ie $n_1 = n_2$

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

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

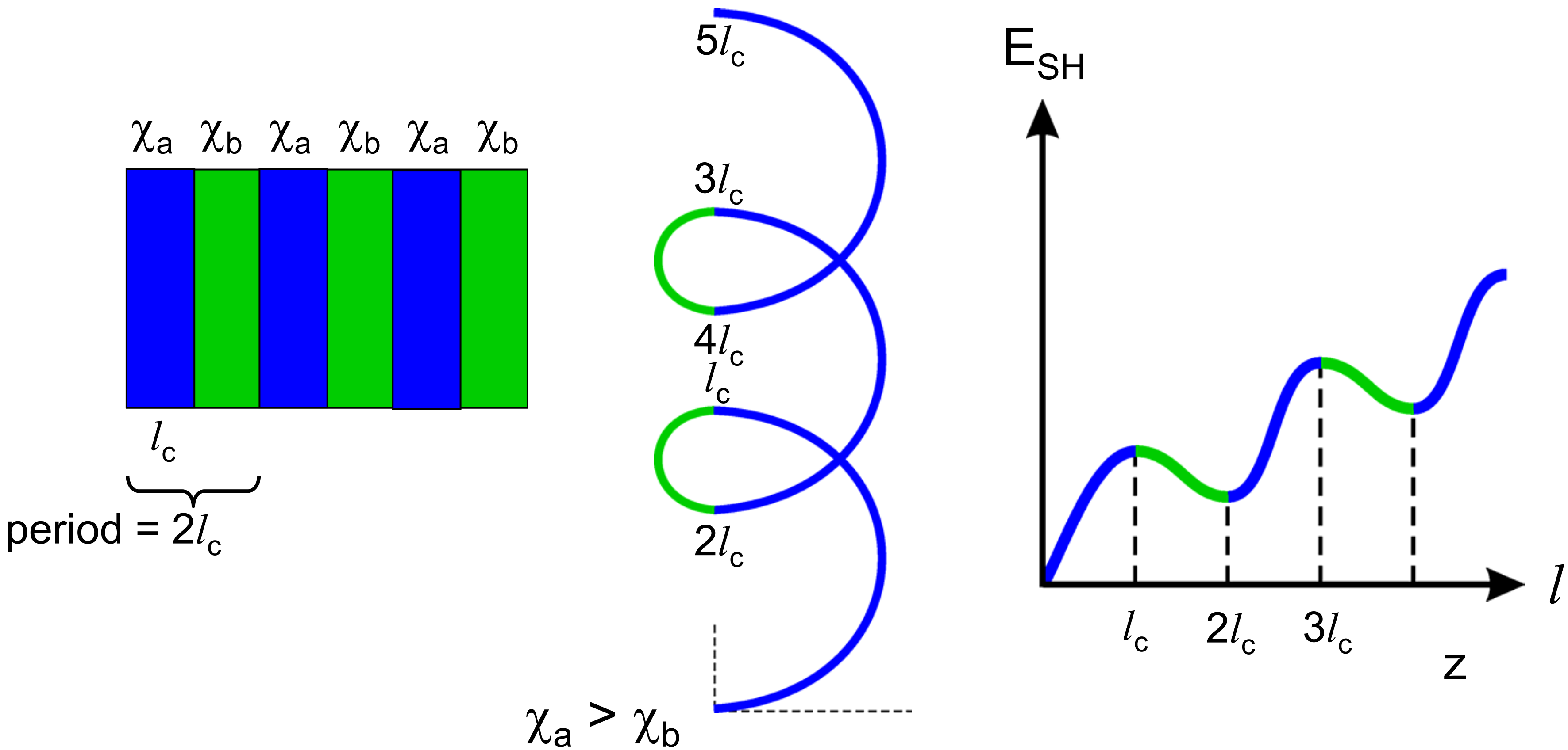


$$z = l_c \equiv \frac{\pi}{\Delta k} \quad (coherence\,length)$$
$$= \lambda_1 / 4(n_2 - n_1) \;\; for\ SHG$$



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

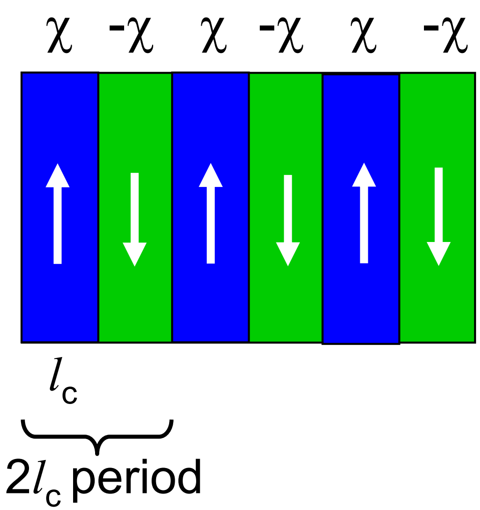


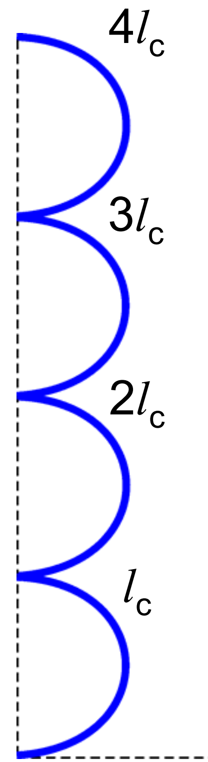
Some quasi-phase-matching schemes

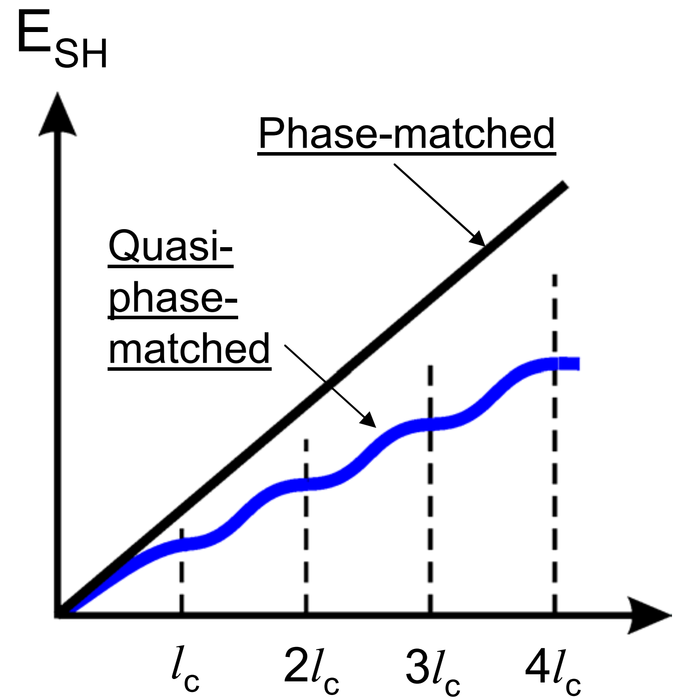
- Periodic E field (via segmented electrode) + field-induced $\chi^{(2)}$
- 'Frozen-in' field-induced $\chi^{(2)}$, in optical fibres
- Periodic destruction/reduction of nonlinearity,
  eg via ion-implantation through a mask
- Overgrowth on a template having periodic modulation of
  substrate orientation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





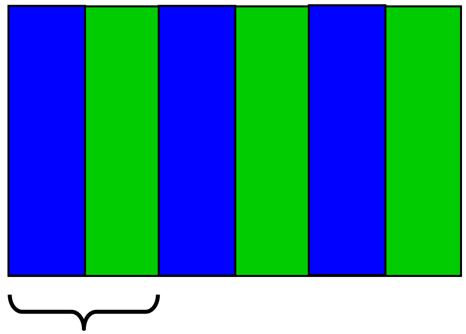


E_{SH} after each l_c is $\pi/2$ smaller than for perfect phase-matching over the same length of medium.

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

Quasi-phase-matching condition

Nonlinear grating of period $2l_c$



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 $\Delta \mathbf{k} = \Delta \mathbf{k}_\mathbf{G}$

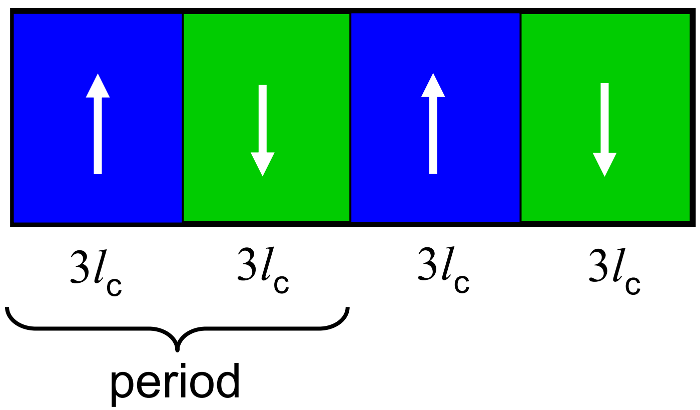
So, instead of making $\Delta \mathbf{k}$ zero, we make $\Delta \mathbf{k}' \equiv \Delta \mathbf{k} - \Delta \mathbf{k}_\mathbf{G} = 0$

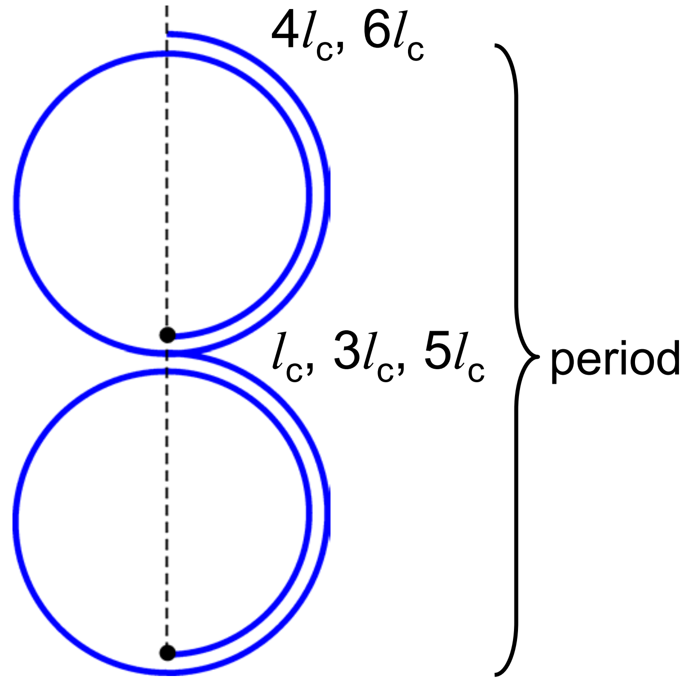
<u>Generalisation</u>

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

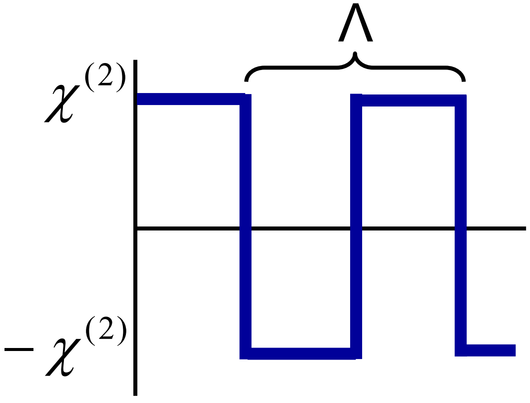
<u>Advantage</u>: larger scale pattern, easier to fabricate

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

Quasi-phase-matching condition

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

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



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

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

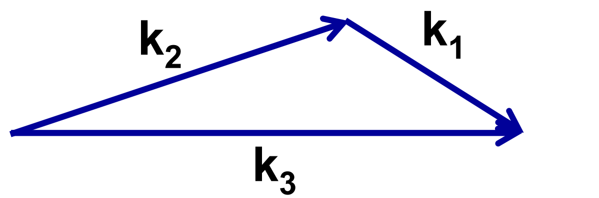
If $\Delta k \sim K_N$ $\quad E_{SH}(l) \propto E_1^2\, l\, \chi^{(2)}\left(\frac{2}{\pi N}\right) sinc\left(\frac{\Delta k' l}{2}\right)$

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

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

Quasi-phase-matching condition

Nonlinear process $\omega_3 = \omega_2 + \omega_1$

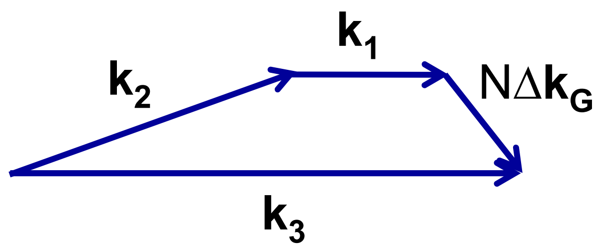


Conventional phase-match condition $\mathbf{k_3} = \mathbf{k_2} + \mathbf{k_1}$

Phase-mismatch $\Delta \mathbf{k} = \mathbf{k_3} - \mathbf{k_2} - \mathbf{k_1}$

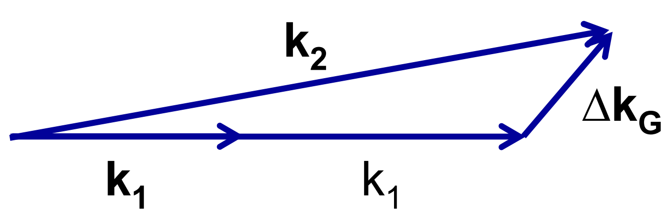
QPM condition (Nth order QPM) $\Delta \mathbf{k} = N\, \Delta \mathbf{k_G}$

$$\mathbf{k_3} = \mathbf{k_2} + \mathbf{k_1} + N\Delta \mathbf{k_G}$$



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

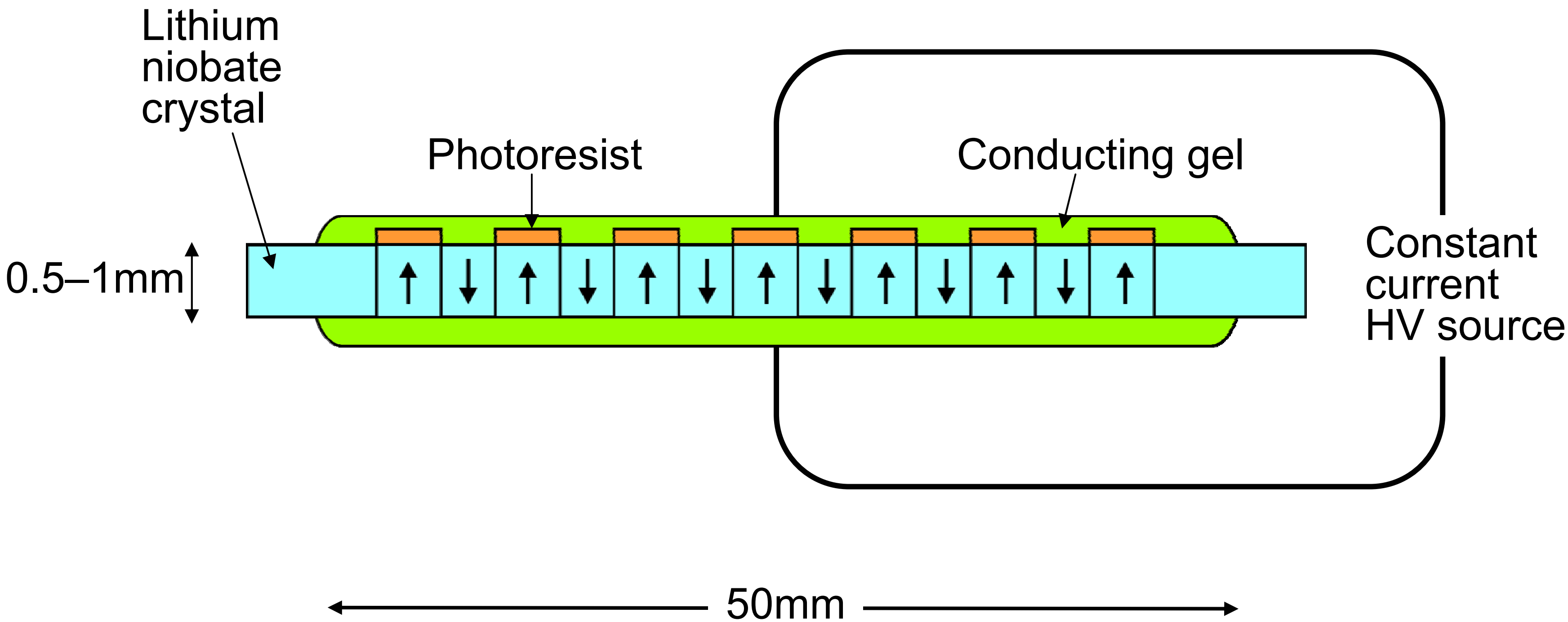
e.g. SHG 1st order:



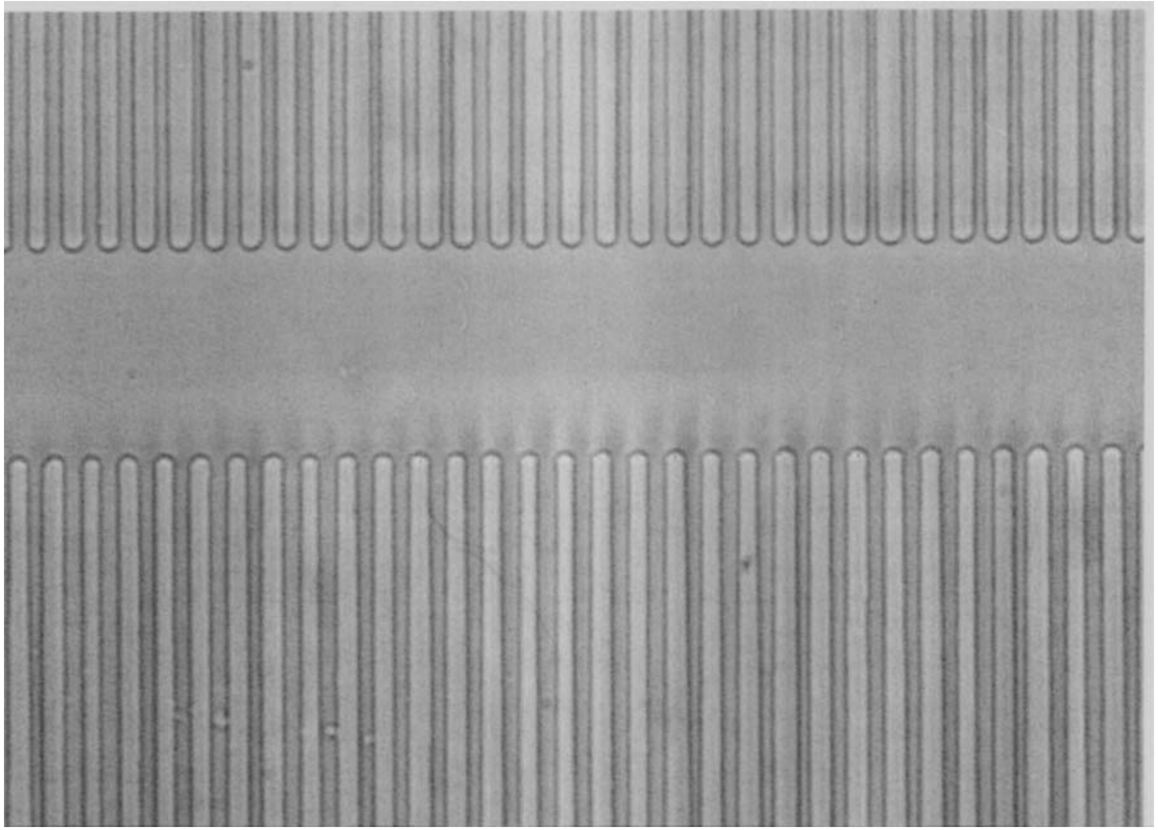
Some benefits of QPM

- 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
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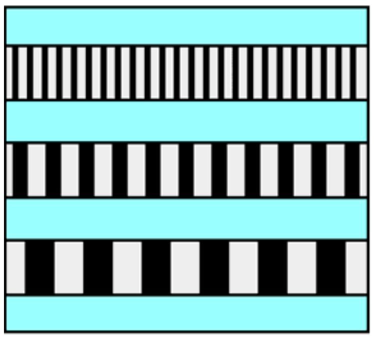
Attractions of photolithography for QPM grating fabrication

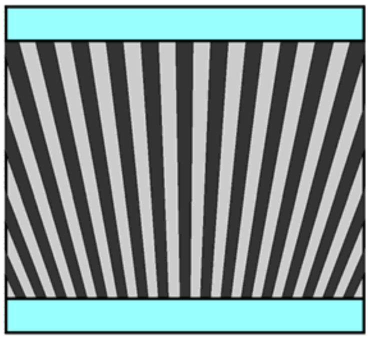
- Precise control over grating period
- Fast processing over whole wafer
- Allows complex grating patterns
  - fan-out gratings
  - different gratings on same wafer
  - tandem gratings
  - controlled distribution of d_{eff}
  - aperiodic, e.g. chirped gratings
  - 2-D gratings

Various grating designs

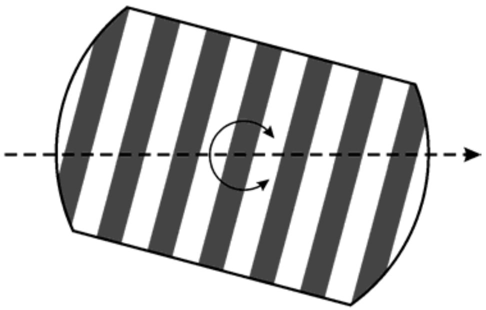
Multiple grating



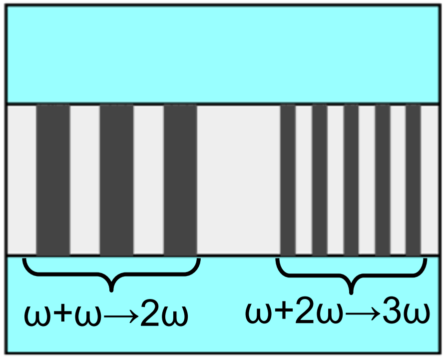
Fan-out grating



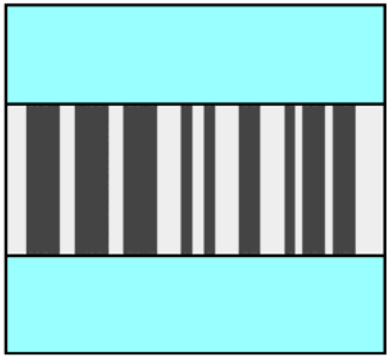
Angle-tuned cylindrically polished crystal



Tandem gratings, sequential processes

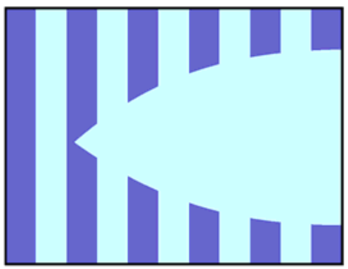


GQPS (Generalised Quasi-Periodic-Structure)
APOSL (Aperiodic Optical Superlattice)

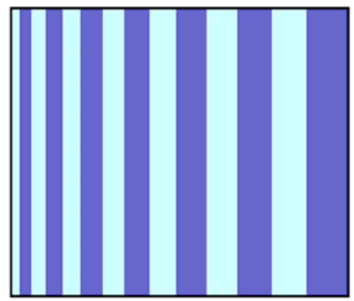


Various grating designs

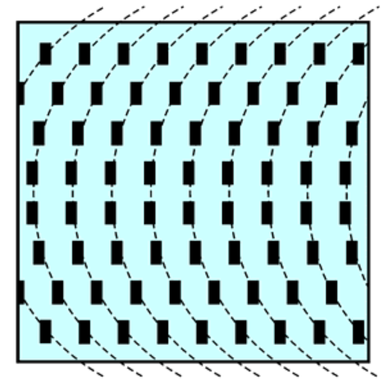
Transverse modulation of d_{eff}

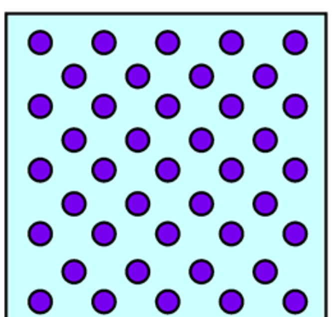


Chirped grating

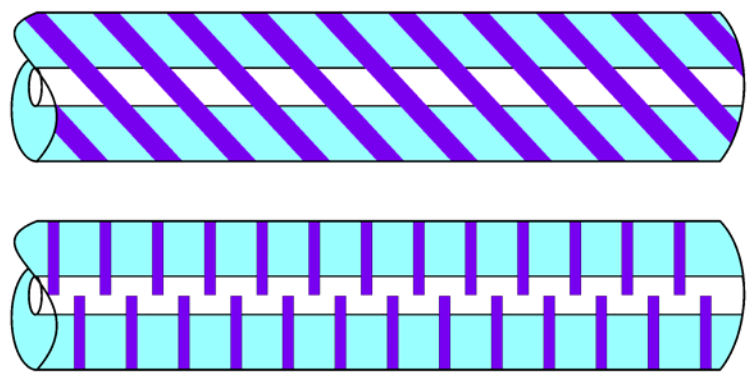


Nonlinear physical optics with transverse-patterned QPM gratings



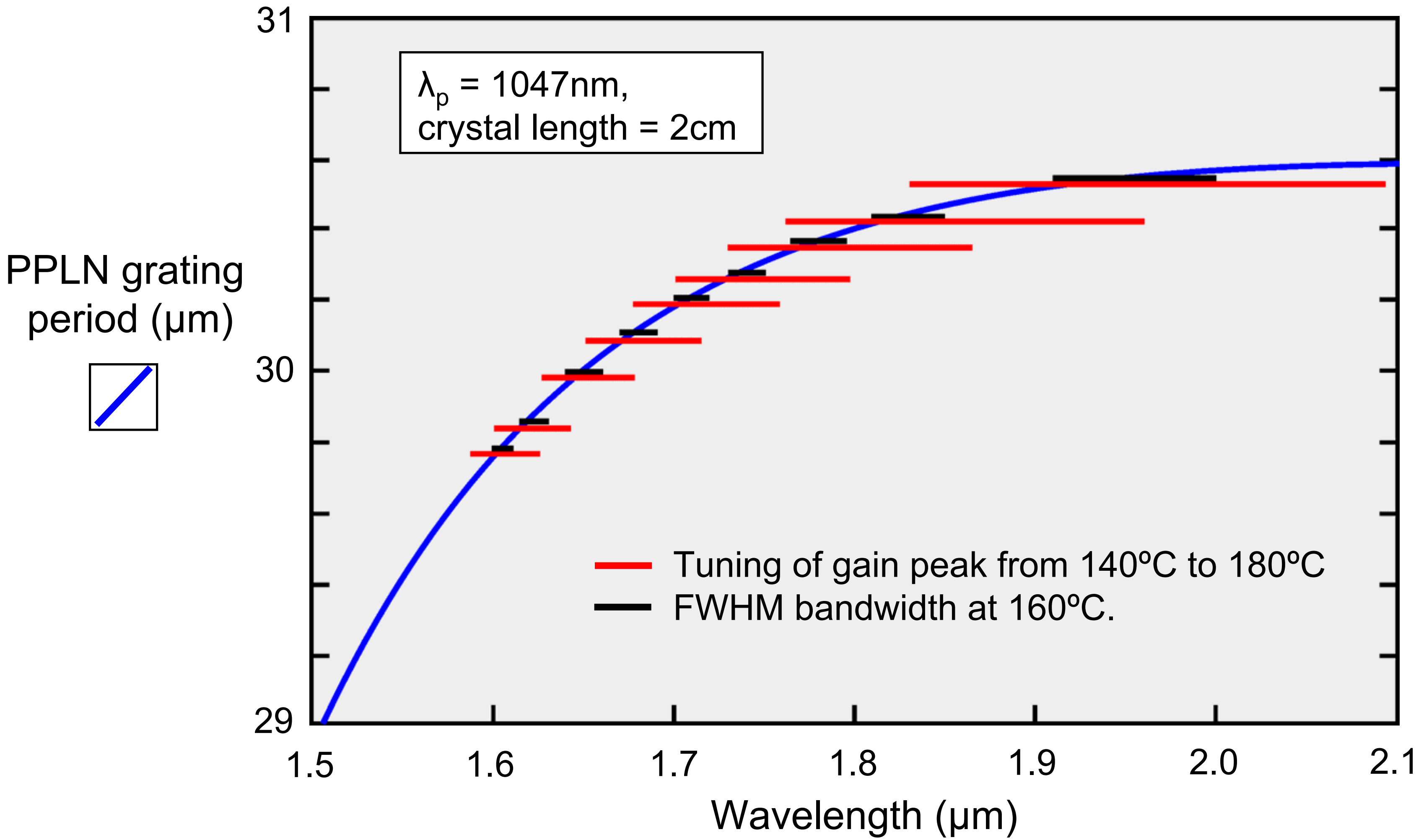


2-D nonlinear ‘photonic’ crystal, e.g. HXLN



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 ($l = b = 2\pi\, w_o^2 n_1/\lambda$)
($\omega_1 \rightarrow 2\omega_1$)

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

SHG, 1064nm → 532nm
or
Parametric gain 532nm → 1064nm

→ ~2%/ Wcm
(d_{eff} = 17pm/V)

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

Parametric gain, 1*μ*m → 2*μ*m, ~0.25%/ Wcm (PPLN)
2*μ*m → 4*μ*m, ~0.5%/ Wcm (GaAs)

Minimum pump energy for 1μm – pumped PPLN parametric devices

CW SRO	~1-3W
Nanosecond-pumped OPO	~5 μJ
Synchronously-pumped OPO	~100pJ (~10 mW @ 100 MHz)
Optical parametric generator	~100nJ (fs/ps) ~100μJ (1 nsec) } 130 dB gain

All values scale as $d^2/n^2\lambda^3$ (except OPG $\propto$ $(d^2/n^2\lambda^3)^{1/2}$)

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 @ 3.3μm

- **cw single-frequency**: *van Herpen et al. Opt.Lett., 28, 2497 (2003)*
  Single-frequency idler, 3.7 → 4.7 μm, ~1W → 0.1W

- **Direct diode-pumped**: *Klein et al. Opt.Lett., 24, 1142 (1999)*
  925nm MOPA diode, 1.5W threshold, 0.5W @ 2.1μm (2.5W pump)

- **Fibre-laser-pumped**: *Gross et al. Opt.Lett., 27, 418 (2002)*
  1.9W idler @ 3.2μm 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 >7μm
  OPCPA, 40 dB gain, mJ output
  OPG operated at 35 MHz, ~0.5W signal

- High average power femtosecond SPOPO
  19W (av) signal @ 1.45 μm, 7.8w @ 3.57 μm

Nanosecond QPM OPOs

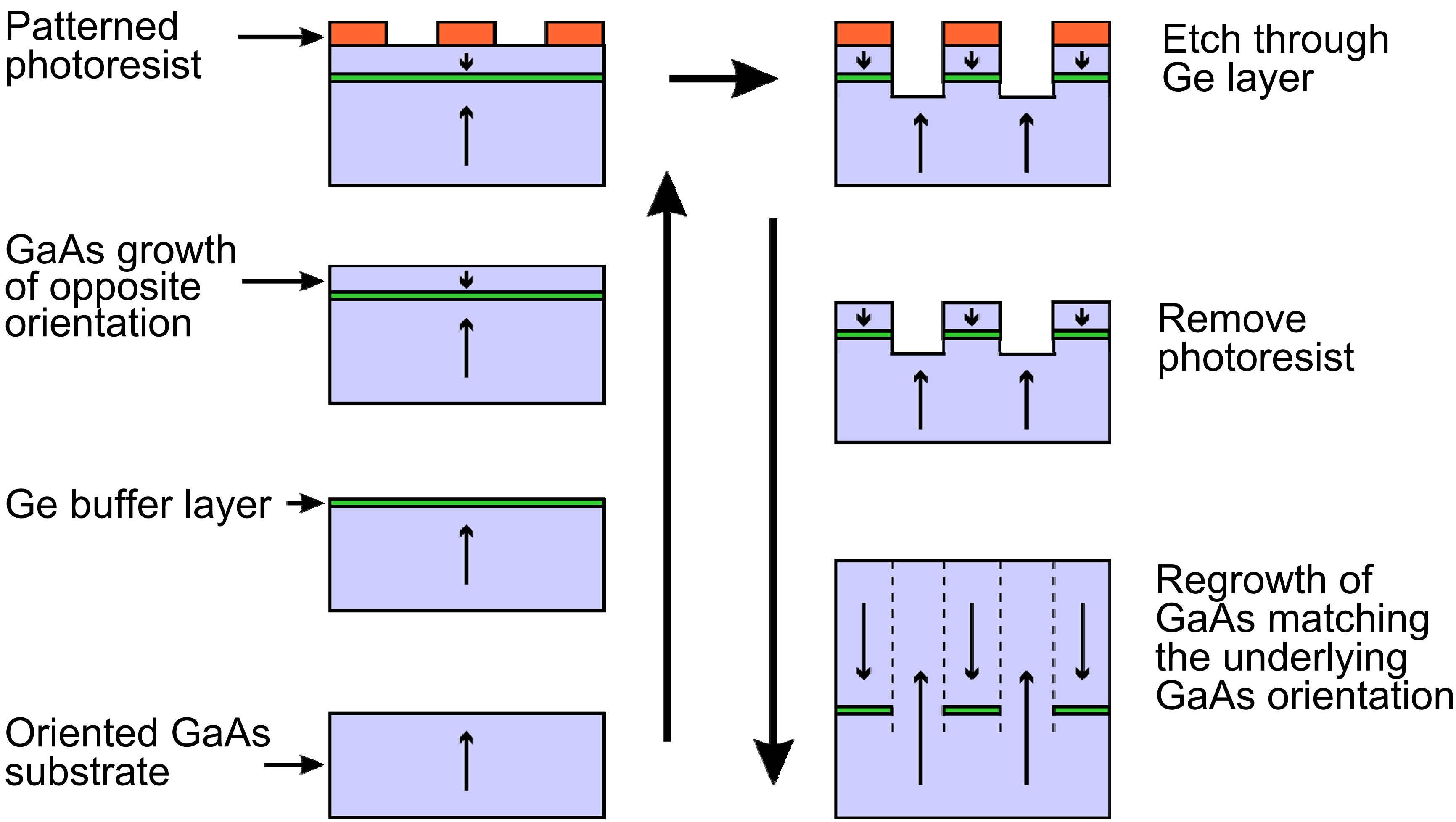
- Threshold of few micro joules
- Wide tunability, idler >5.5 μm in PPLN
- Few hundred μJ output typical
  (30 mJ demonstrated with PPLN stack)
- QPM GaAs; 2-10 μm covered so far
  Paper CTuA1, CLEO 2004

Why GaAs?

- Large nonlinearity, d_{14} ~ 100pm /V
- Extensive transparency, 0.9 μm - 17 μm
- 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 ~0.05 cm^{-1}

Experiment: mix cw 1.3 μm and 1.55 μm,

to generate ~8 μm

Result: agreement within factor of 3 between measured

output power and calculation based on d_{14} = 105pm/V

QPM waveguide devices

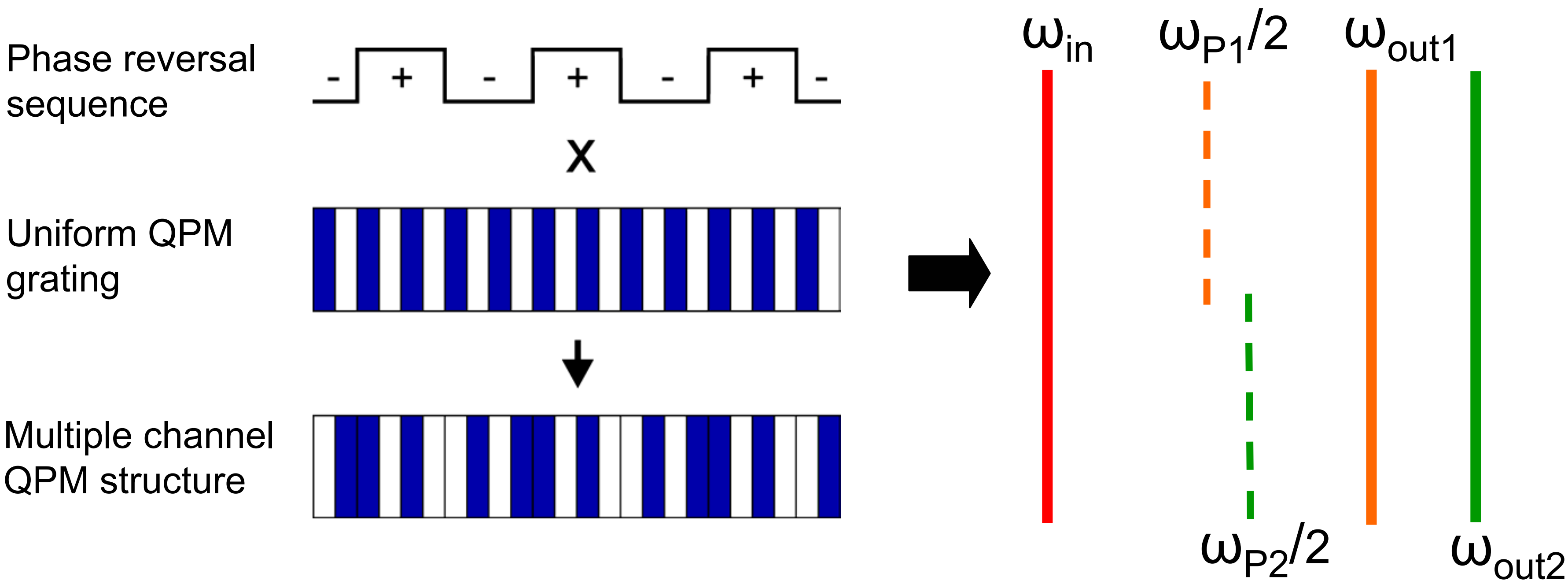
Blue SHG at high conversion efficiency in $MgO:LiNbO_3$
852nm → 426nm, 1500%/Wcm^2 in 10mm guide
55mW → 17.3mW
Sugita et al Optics Letts. 24, 1590 (1999)

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

Multiple-channel wavelength-conversion via engineered QPM structures in $LiNbO_3$ waveguides

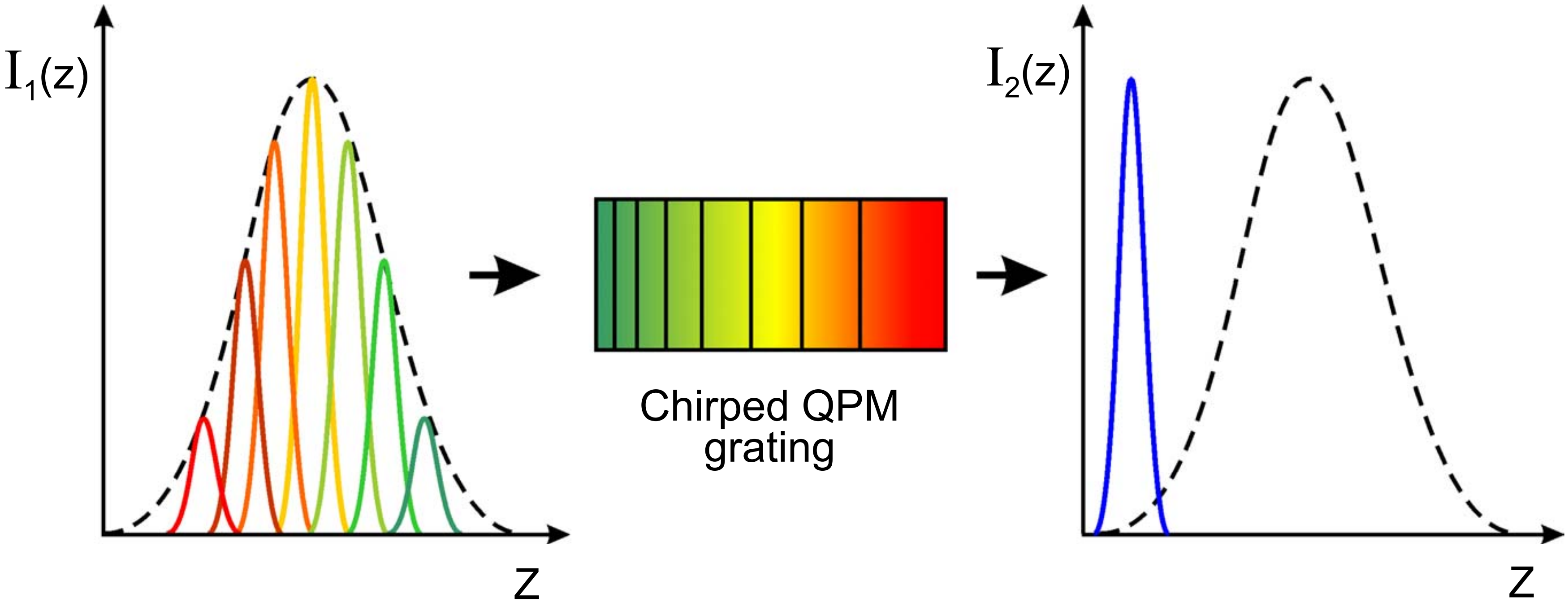
Chou *et al*, Optics Letts 24, 1157 (1999)



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

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

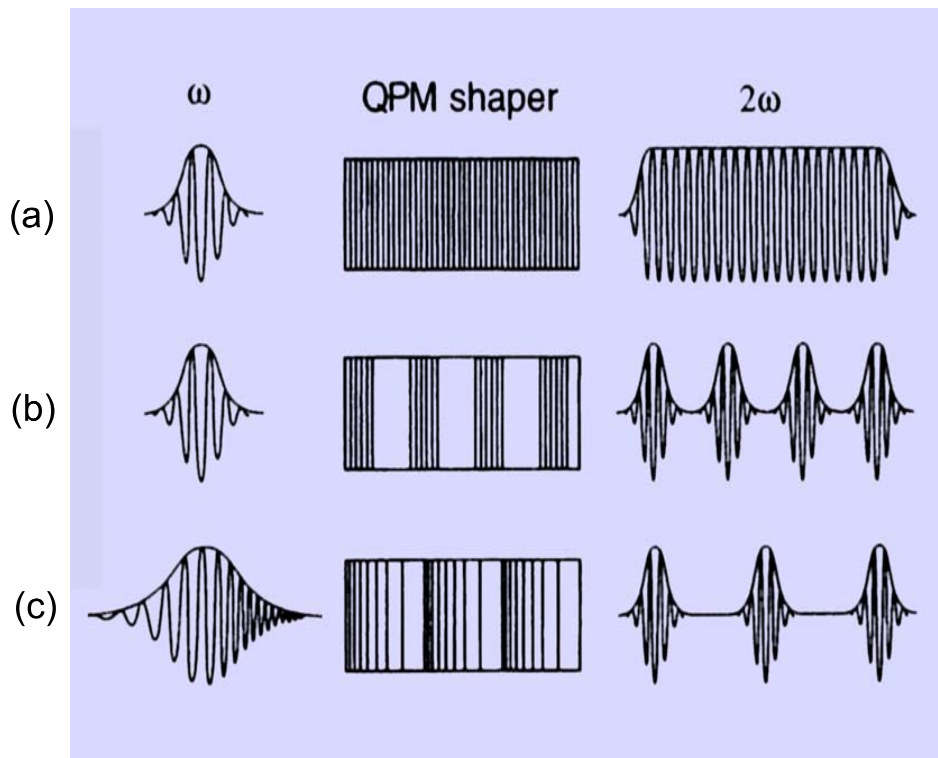
Arbore, Marco & Fejer, Optics Letts. 22, 865 (1997)



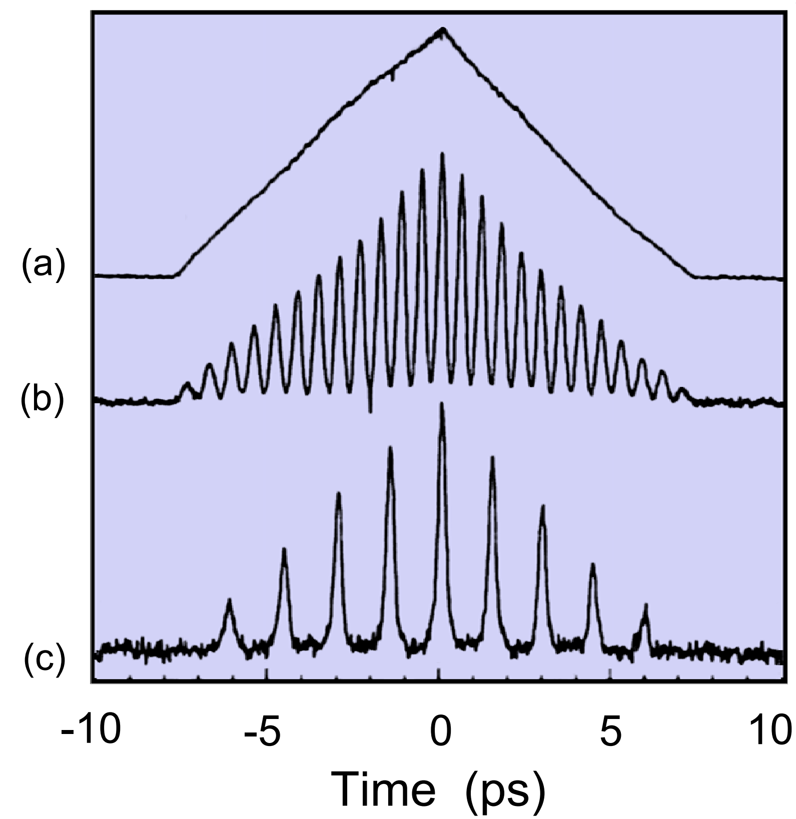
- Leading edge converts to SH at grating entrance, and so travels more slowly than trailing edge which converts near exit.

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

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



Autocorrelation signal



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

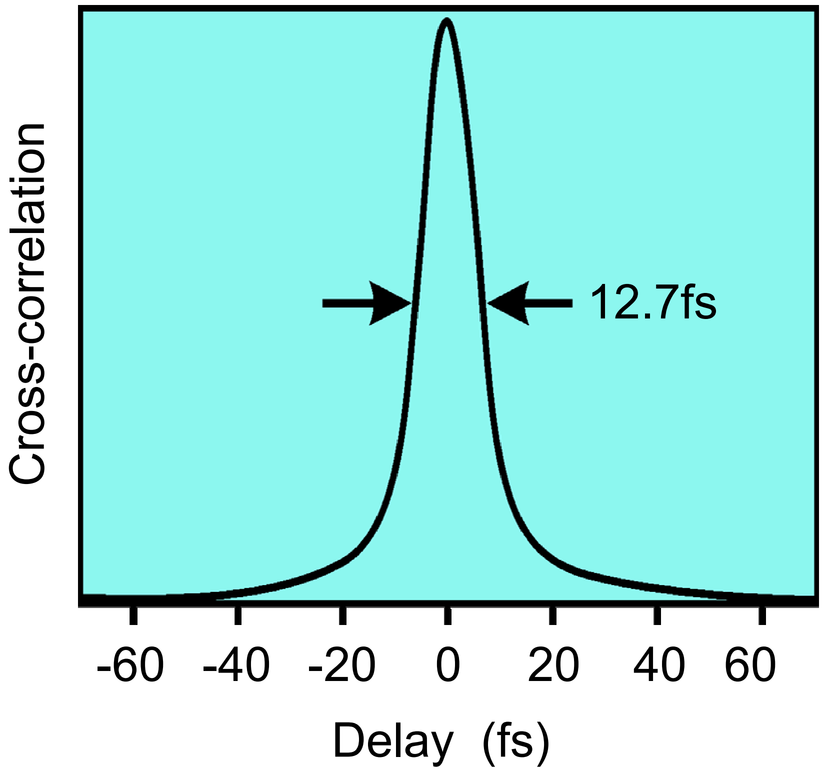
310μm PPLT crystal

Nonlinearly-chirped grating,

Periods from 6.5μm to 1.8μm

405nm SH pulse, 5.3fs

Conversion, ~0.5% /nJ



Gallman et al Opt. Letts. 26, 614, 2001

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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