SR QPM OPO
or
How many acronyms can you put in your title?

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• Motivation:
What are optical parametric oscillators? Why not use a laser instead?
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  Temperature & QPM-Period Tuning, Pump Depletion.
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- **Conclusion:** Where do we go from here?
What are optical parametric oscillators?

- Widely tunable source for coherent radiation.
- Efficient nonlinear conversion from “pump” to “signal” wavelength.
- Low threshold for onset of oscillation.
Motivation II

Why not use a laser instead?

- **LASER**
  - collect & store wideband uncollimated spectral energy.
  - center wavelength & linewidth determined by atomic transition.
  - pump does not influence output of laser to first order.

- **OPO**
  - No energy storage. Instantaneous nonlinear process.
  - center frequency & linewidth determined by phase mismatch.
  - phase coherence between signal, idler, and pump is essential.
Theory

Optical Parametric Oscillators (OPO)

- Maxwell’s equations in source-free media
- Slowly Varying Envelope Approximation (SVEA)
- Examine $\chi^{(2)}$ processes, i.e. $P(t) \sim E^2(t)$
- Three field interaction at $\omega_p, \omega_s$, and $\omega_i$

\[
\frac{dE_p}{dz} = -i\eta_p \omega_p d(z) E_s E_i e^{i\Delta k z} \quad \text{with} \quad \omega_p = \omega_s + \omega_i
\]
\[
\frac{dE_s}{dz} = -i\eta_s \omega_s d(z) E_p E_i^* e^{-i\Delta k z}
\]
\[
\frac{dE_i}{dz} = -i\eta_i \omega_i d(z) E_p E_s^* e^{-i\Delta k z}
\]
\[\Delta k = k_p - k_s - k_i\]
Coupled equations describe various nonlinear processes.

- **Sum Frequency Generation (SFG):**
  strong pump signal at $\omega_i$, weak signal at $\omega_s$
  $\leadsto$ up-converted signal at $\omega_p$

- **Difference Frequency Generation (DFG):**
  strong pump at $\omega_p$, signal at $\omega_s$ $\leadsto$ signal at $\omega_i$

- **Parametric Generation (OPA, OPG, OPO):**
  strong pump at $\omega_p$ $\leadsto$ generation of signals at $\omega_s$ and $\omega_i$
Simple cartoon for optical parametric amplification.

1. Electromagnetic waves at $\omega_p$ and $\omega_s$ generate polarization at $\omega_i$.

2. If polarization travels with same speed as free electromagnetic wave at $\omega_i$, signal at $\omega_i$ will grow.

3. $\omega_i$ mixes with $\omega_p$ and creates polarization current at $\omega_s \rightarrow$ signal at $\omega_s$ grows.

Same principle holds for OPG and OPO where input fields at $\omega_s$ and $\omega_i$ are created out of quantum vacuum fluctuations.
Phase Matching and Quasi Phase Matching (QPM).

Solutions to coupled equations predict efficient frequency conversion only if

\[ \Delta k = k_p - k_s - k_i = 0 \]

\textbf{Phase Mismatch}

Due to dispersion, this is not given, in general.

\textbf{Solution:}

- **Birefringence:**
  works, but we are stuck with material properties.

- **Quasi Phase Matching:**
  engineer appropriate phase mismatch for desired signal wavelength; take advantage of largest nonlinear coefficient.
Quasi Phase Matching (QPM).

Problem:

- $\Delta k \neq 0$
- Conversion only over crystal length $L_c = \pi / \Delta k$.
- Polarization and free wave slip out of phase.

Reset phase after $L_c$ by changing sign of nonlinear coefficient (QPM).

Equivalent to introducing a grating $k_g = 2L_c$ with $g = 2L_c$. 

Theory V
Quasi Phase Matching (QPM).

Solution:

- Reset phase after $L_c$ by changing sign of nonlinear coefficient (QPM)
- Equivalent to introducing a grating $k$-vector $K_g = 2\pi/\Lambda_g$ with $\Lambda_g = 2L_c$. 
Quasi Phase Matching (QPM).
Experimental Setup

Signal and idler wavelength are determined by phase mismatch:

$$\frac{1}{\Lambda_g} = \frac{n_p}{\lambda_p} - \frac{n_s}{\lambda_s} - \frac{n_i}{\lambda_i}$$

Tuning is achieved by varying either $\Lambda_g$, $n_p$, $n_s$, or $n_i$, i.e. change temperature or QPM period.
Experimental Results

Temperature Tuning.

Measured \( \omega_p + \omega_s \sim \omega_s \) and \( \omega_i \) via \( \omega_p = \omega_s + \omega_i \) and \( \omega_p = 1.06 \mu m. \)
15 QPM periods on chip starting at 31.5 μm, decreasing in 0.5 μm decrements.
Experimental Results III

Pump Depletion = Increased Conversion Efficiency.

As the pump energy is being increased, the conversion efficiency increases and the pump gets depleted.
In this talk we presented the theory behind OPA, OPG, OPO, and other $\chi^{(2)}$ processes. 

- need for phase matching to achieve efficient conversion.
- advantage of quasi phase matching as compared to birefringent phase matching.
- generation of 1.6 $\mu$m, 3 $\mu$m, and 636 nm radiation using an OPO.
- possibility of temperature and QPM-period tuning.
Future research will involve

- direct detection of signal wavelength at 1.6 µm.
- complete characterization of conversion efficiency.
- modification of setup to lower oscillation threshold (DRO instead of SRO).
- implementation of continuously tunable QPM-period by means of “fanned” grating structure.
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