Phase Matching using Bragg Reflector Waveguides

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# 2nd Order Nonlinearities; III-Vs vs. PPLN

<table>
<thead>
<tr>
<th>Point of Comparison</th>
<th>LiNbO$_3$</th>
<th>GaAs/AlGaAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^{(2)}$ Coefficient</td>
<td>$d_{33} \cong 30$ pm.V$^{-1}$</td>
<td>$\chi_{xyz} \cong 100$ s pm.V$^{-1}$</td>
</tr>
<tr>
<td>Transparency Window</td>
<td>0.4 – 4.8 $\mu$m</td>
<td>0.8 -17 $\mu$m</td>
</tr>
<tr>
<td>Phase-Matching Technologies</td>
<td>- Cerenkov PM</td>
<td>- Birefringent Waveguides</td>
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<td></td>
<td>- Natural Birefringence</td>
<td>- QPM-Domain Amorphisation</td>
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<td></td>
<td>- <strong>QPM-Periodic Poling</strong></td>
<td>- <strong>QPM-Domain Reversal</strong></td>
</tr>
<tr>
<td>Associated Losses</td>
<td>$\ll 1$ dB.cm$^{-1}$</td>
<td>$\sim 10$ s dB.cm$^{-1}$</td>
</tr>
<tr>
<td>Phase-Matching Performance</td>
<td><strong>Frequency Conversion</strong> $1000 % . W^1$</td>
<td><strong>Frequency Conversion</strong> $&lt; 100 % . W^1$</td>
</tr>
<tr>
<td></td>
<td>Optical Parametric Oscillator</td>
<td>Optical Parametric Oscillator</td>
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<td></td>
<td>$P_{th} (\text{CW}) &lt; 5$ mW</td>
<td>Demonstrated using DR</td>
</tr>
</tbody>
</table>
III-Vs for 2\textsuperscript{nd} Order Nonlinearities

- $\chi^{(2)}$ in Zinc-Blende compounds is much larger than that of PPLN
- Advanced semiconductor processing can be used to fabricate complex structures such as high Q cavities, waveguides .. etc
- Gain can be provided by electronic pumping
- Pump lasers can be monolithically integrated with the non-linear devices
Phase matching in III-V Semiconductors

- Waveguides with embedded AlO\textsubscript{x}
  - Scattering losses $\sim 10$ cm\textsuperscript{-1}
  - Current pumping is not possible

- Domain reversal by growth on patterned substrates:
  - Scattering losses $\sim 10$ s dB.cm\textsuperscript{-1}
  - Overgrowth
  - Device integration
Phase matching in III-V Semiconductors

- Periodic domain destruction through amorphisation:
  - Scattering losses $\sim 30 \, \text{dB.cm}^{-1}$
- Periodic domain modulation intermixing
  - Scattering loss $\sim 6 \, \text{dB.cm}^{-1}$
  - Low effective $\chi^{(2)}$

Crystal
SiO$_2$ SiO$_2$:P SiO$_2$ SiO$_2$:P SiO$_2$

Non-Crystal

GaAs
Phase matching in III-V Semiconductors

- For high $\chi^{(2)}$ one operates near the band gap resonance
  - High material dispersion

- For phase matching between fundamental & a higher order mode
  - Overlap integral is compromised

![Graph showing refractive index vs. wavelength](image)
Phase matching in III-V Semiconductors

- For high $\chi^{(2)}$ one operates near the band gap resonance
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![Graph showing refractive index versus wavelength](image)
Phase matching in III-V Semiconductors

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Bragg Reflection Waveguides

We propose to use vertical Bragg reflectors as the cladding layers.

Vertical structure can be analyzed using any multi-layer scheme.
- Transfer matrix
- Bloch wave representation
- ..
Bragg Reflection Waveguides

@775 nm

@1550 nm

Distance from Waveguide Core (μm)

Refractive Index

Refraction Index

Wavelength (nm)

TIR

BR
Bragg Reflection Waveguides

\[ E(x) = \begin{cases} 
C_1 \cos(k_c x) + C_2 \sin(k_c x), & |x| \leq \frac{t_c}{2} \\
C_3 E_K(|x| - \frac{t_c}{2}) e^{iK(|x| - \frac{t_c}{2})}, & |x| > \frac{t_c}{2}
\end{cases} \text{ (core)}, \]

Dispersion Relation (TE): 
\[ \kappa^2 \tan \left( \frac{k_c t_c}{2} \right) = i k_1 \frac{e^{i K \Lambda} - A - B}{e^{i K \Lambda} - A + B} , \]

\[ \Lambda = a + b \]

\[ A = e^{i k_1 a} \left[ \cos k_2 b + i \frac{k_2}{2} \left( \frac{k_1}{k_2} \right) \sin k_2 b \right] , \]

\[ B = e^{-i k_1 a} \left[ i \frac{k_2}{2} \left( \frac{k_1}{k_2} \right) \sin k_2 b \right] , \]

\[ C = B^* , \quad D = A^* , \]
\(\lambda/4\) Bragg Reflection Waveguides

\[k_1 a = k_2 b = \pi/2\]

\[k_c \tan\left(\frac{k_c t_c}{2}\right) = i k_1 \frac{e^{i K \Lambda} + k_1 / k_2}{e^{i K \Lambda} + k_2 / k_1} .\]

\[K \Lambda = m \pi - i \ln \left(\frac{k_2}{k_1}\right),\]

\[k_c = \frac{\pi}{t_c} = \frac{2\pi}{\lambda} \sqrt{n_c^2 - n_{\text{eff}}^2},\]
$\lambda/4$ Bragg Reflection Waveguides

The modal index of both TIR and BRW

Phase matched modes for an arbitrary structure
\( \lambda/4 \) BRWs; Optimization

- Conversion efficiency will chiefly benefit from the spatial overlap in the core.
- Conversion efficiency depends on
  - \( P^{2\omega}(x) = \varepsilon_0 d(x) [E^\omega(x)]^2 \)
  - \( E^{2\omega}(x) \)
- Maximizing the power in core region is key.
\( \lambda/4 \) BRWs; Losses

- Waveguiding losses as a function of the number of Bragg pairs
- Losses depend on the number of cladding periods
  - Practically lossless structures can be achieved

![Graph showing propagation loss in QW-BRW as a function of the number of periods in each cladding. The graph includes data points for Clading = 0.3 (red), 0.4 (blue), 0.5 (green), indicating circles for TE and squares for TM.](image)

Circles = TE, Squares = TM
\( \Delta(\text{Al}_x\text{Ga}_{1-x}\text{As})_{\text{Clading}} = 0.3 \) (red), 0.4 (blue), 0.5 (green),
\( \lambda/4 \) BRWs; Tunability

- Thermal, electro-optic & carrier tuning
- BRWs are resonance based
  - carrier and electro-optic effects for continuous tuning
- The figure shows phase-matching using carrier tuning
  - The core is the intrinsic region in a p-i-n junction

![Graph showing Phase Matching Wavelength vs. Carrier Density in Core]
Iterative process needed to design 2D Waveguides

- The $\lambda/4$ condition changes as the 1D & 2D to propagation constants are different

- Transverse single mode condition restrict the 2D design
  - This will govern the etch depth and ridge width
Summary

- We proposed Bragg reflection waveguides as a promising phase matching alternative.
- We presented calculations showing practical structures are possible using the GaAs/AlGaAs system.
  - Propagation losses due to leakage can be in the $10^{-5}$ dB.cm$^{-1}$ with < 10 Bragg reflector pairs.
  - Carrier tuning in $p$-$i$-$n$ structures over 10s of eVs.
  - Excellent spatial overlap, with conversion efficiency that can be maximized through mode confinement in the core.
- Device growth and fabrication is underway.