"Nonlinear Optical Waveguides" - III

presented by:

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These are preliminary lecture notes, intended only for distribution to participants.
Nonlinear Waveguides in Microstructured Media: Materials, Devices, and Applications

Fixing Some Problems
&
Pushing the Envelope

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Fabrication tools for extremely efficient NLO devices

Ferroelectric gratings for QPM

Adiabatic waveguide tapers

APE channel waveguide

Noncritical APE waveguide designs

\[ \eta_{\text{nor}} L^2 = 3000\%/W \]
Examples of Applications of Highly Nonlinear Waveguides

*Efficient waveguide mixers for telecom*
various signal processing functions

wavelength domain

\[ V_{LO} \rightarrow \omega_{LO} \]
\[ V_s \rightarrow \omega_s \]
\[ \omega_{LO} + \omega_s \]

Power (dBm)

Wavelength (nm)

1530 1540 1550 1560

Waveguide mixers
in time domain

20 Gbit/s NRZ 10 ps/div

160 Gbit/s RZ 10 ps/div

20 GHz clock 10 ps/div

160 Gb/s, 2.5 ps
Issues and Approaches

• Limited allowed pump tuning range
  – engineered QPM gratings

• Separation of output from input without spectral filtering
  – for operation near degeneracy
  – balanced optical mixer

• Limit on allowed pump modulation bandwidth
  – quasi-group velocity matching
**Integrated structures for advanced devices**

- **Y-Junctions**
- **Buried waveguides**
  - Symmetric modes
- **Tapers for filtering**
- **Tilted gratings**
  - For TM$_{01}$ modes
- **Adiabatic Tapers**
- **Directional couplers**
- **Small radius bends**
- **Precise positioning of small gratings**

**Combination of high gain, uniform devices**
+ Various integrable structures

**Multi-function devices for classical and quantum comm.**
Narrow vs wide tuning

- Bandwidth depends on tuned parameter
  - very broad for tuning signal at fixed pump
  - narrow for tuning pump at fixed signal

\[ \Delta k = k_p - (k_s + k_i) \sim \text{constant} \]

EDFA \(\sim 40\) nm

\[ \text{Relative conversion loss (dB)} \]

\[ \text{Wavelength (nm)} \]

3.3 cm sample

\[ \eta_0 \text{ [W}^{-1}\text{]} \]

\[ \lambda \text{ (nm)} \]

measured

calculated
Tuning Curves Are Fourier Transforms

Solution to undepleted-pump SHG SVEA equation:

\[ E_{2\omega} \propto E_{\omega}^2 \int_0^L \chi^{(2)}(z) e^{i\Delta k(\omega)z} \, dz = E_{\omega}^2 \hat{\chi}^{(2)}[\Delta k(\omega)] \]

Generated second harmonic proportional to Fourier Transform of \( \chi^{(2)}(z) \)

PM:

\[ +\chi^{(2)}(z) \]

\[ \begin{array}{c}
0 \\
\chi^{(2)} \\
0 \\
L 
\end{array} \]

F.T

\[ E_{2\omega} \bigg| \propto L^2 \text{sinc}^2(\Delta k L / 2) \]

\[ \Delta k = 0 \]

\[ \Delta k_{1/2} \propto 1 / L \]

QPM just shifts peak from \( \Delta k = 0 \) to \( \Delta k = K_g \):

QPM:

\[ +\chi^{(2)}(z) \]

\[ \begin{array}{c}
0 \\
\chi^{(2)} \\
0 \\
\Lambda_g \\
L 
\end{array} \times e^{iK_g z} \]

\[ K_g = \frac{2\pi}{\Lambda_g} \text{ shift theorem} \]

\[ \begin{array}{c}
E_{2\omega} \bigg| ^2 \\
\Delta k = 0 \\
\Delta k = K_g 
\end{array} \]

Generalize to Fourier synthesize “arbitrary” transfer function
Multiple Pump Channel Devices: Synthetic QPM Gratings

- TWM devices are broadband for signal, narrowband for pump
  - multiple pump wavelengths accommodated by engineering QPM grating

\[ P_{out} \propto P_{LO} P_s \left| \int_0^L \chi^{(2)}(z) e^{-i\Delta kz} \, dz \right|^2 \]

**Fourier Transform**

\[ \mathcal{F} \left\{ \right\} \]

- Phase reversal sequence
- Uniform QPM grating
- Multiple Channel QPM structure

**Efficiency**

**Wavelength**
Multiple Channel Mixers

Different phase masks on uniform QPM structures:
1,2,3,4 channel devices

1.5 μm Band “Broadcast” λ-converter

One channel can be replicated onto $N$ channels

$M$ channels can be replicated onto $N \times M$ channels
- Dynamic reconfiguration
- Broadcasting: 1 in --- $N$ out

$\omega_{\text{out}} = \omega_{p,m} - \omega_{s,n}$

$M$ output channels

1 input signal channel

$M$ channel OF Mixers

$N$ input signal channels

$N \times M$ (possible) output channels

$M$ Pump channels

Reconfigurable Pump channel

Distinguishability and spatial separation:

How to distinguish input from output?

Spectral filtering required

Can’t work at degenerate point

No spectral inversion without shift

Typical waveguide QPM

Two integrated optics solutions:
- Optical frequency balanced mixer
- Odd and even mode quasi-phase-matching
Mach Zender interferometer structure:

\( \pi \)-phase shifted QPM allows independent bias of mixer output

- Broadband separation of inputs and output
- Requires twice as much pump power as standard device

\[ P_{out} = \frac{1}{4} \eta^2 L^4 P_p^2 P_s \]
Optical frequency balanced mixer

Optical frequency balanced mixer

\[ \pi = \frac{2\pi}{\lambda} L_{\text{delay}} \left[ n_{\text{eff}} (12\mu \text{m width}) - n_{\text{eff}} (3\mu \text{m width}) \right] \]

- Proof of principle demonstration using 12 mm gratings
- Achieved >13dB of isolation from pump and signal
- Current devices: contrast >20dB

Alternative for distinguishability and spatial separation:

Can use spatial modes to distinguish:
  gives more design flexibility
  Larger fabrication tolerances

Separating modes: asymmetric Y-junction
Even-odd mode interactions: asymmetric QPM gratings

\[
\begin{align*}
\text{signal} & \rightarrow \text{pump} \\
\text{QPM mixing section} & \rightarrow \text{residual signal} \\
& \rightarrow \text{residual pump} \\
& \rightarrow \text{mixer output}
\end{align*}
\]
Asymmetric Y-junctions: Mode filtering and Launching

Adiabatic mode evolution
TEM\(_{00}\) and TEM\(_{01}\) different ports

can launch/filter TM\(_{00}\) and TM\(_{10}\) modes with > 30 dB contrast

1545 nm → even port
1560 nm → odd port
Asymmetric QPM gratings: Even & Odd Modes

\[ \eta \propto \left| \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} d(x,y) E_{1,jk}(x,y) E_{2,lm}(x,y) E_{3,np}^*(x,y) \, dx \, dy \right|^2 \]

Standard Poling  Angled Poling

Measured SHG output modes

Waveguides and gratings, etched for visibility

Odd/Even Mode QPM Mixer

Can solve problems of distinguishability and spatial separation, enabling:
- spectral inversion without offset
- simultaneous bi-directional wavelength conversion
- degenerate difference-frequency mixing

Can be generalized to N-mode mixer:
Speed limits of PPLN devices due to GVM

1550 nm pulse generated 775 nm pulse

Walk off into adjacent time slot

*interaction length limited to one walk-off length, but efficiency scales with $L^2$*

*can equally view as bandwidth limit of long device*

Quasi GVM compensation

Directional coupler separates 1550 nm and 775 nm waves

Longer path length delays faster pulse envelopes

Doubles interaction length, obviating speed/efficiency trade-off

Iterate for discrete compensation for quasi-GVM akin to QPM compensation for phase velocity mismatch
Demonstration of quasi-GVM compensation devices

(a): two pulses generated 6 ps apart
(b)-(d): pulses move closer as delay increases
(e): pulse envelopes overlap

Easy control of phase by temperature tuning:
two pulses go between in phase and out of phase alternately in an 8° C cycle

[Jie Huang, Xiu-Ping Xie]
Tight bends required to integrate multiple delay sections

Need to suppress radiation loss with more complex bend designs

- Loss comparable to S-bends of 4mm minimum radius without trenches
- By increasing the trench depth and $\delta$, <1mm bend radius is possible

Throughput @ 1.55um (arb. units)

Distance $\Delta$ (\(\mu\)m)

Increasing $\delta$ from 0 to 2\(\mu\)m

Photo of the S-bends on the chip
Polarization Insensitive Converter

- $\chi^{(2)}$ converters meet all requirements except polarization insensitivity
- Device PPLN designs can address this issue
  - two have been demonstrated with negligible penalty

I. Brener, M. Chou, K. Parameswaran, M. M. Fejer, OFC 2000

GaAs-based devices alternative
intrinsic insensitivity (Yoo et al)
Final topics: Pushing the Envelope

• We have uniquely efficient and engineerable nonlinear optical platform
  – are there applications beyond telecom?

• Quantum efficiencies > 99%

• Single photon manipulations for quantum optics

• Interactions with attojoule pulses
High Conversion Nonlinear Optics

• Quadratic nonlinear interactions often in low-conversion limit

\[ \eta = \frac{P_{2\omega}(L)}{P_{\omega}(0)} = \kappa L^2 P_{\omega}(0) \text{sinc}^2(\Delta k L / 2) \]

\[ \kappa [\text{W}^{-1} \text{cm}^{-2}] \propto \chi^{(2)} \alpha / A_{\text{eff}} \]

\[ \Gamma [\text{W}^{-1}] = \kappa L^2 \]

\[ \eta_0 = \Gamma P_{\omega}(0) \]

• Different in high conversion limit

\[ \eta = \tanh^2(\sqrt{\eta_0}) \]

\[ \eta = f(\eta_0, \Delta k L) \]

\[ \eta_0 = 99\% \]
High Efficiency NLO Is Challenging (but Useful)

- Difficult to push nonlinear interactions to high conversion
  - strong drive required by spatial/temporal averaging
    - 75% energy efficiency $\Rightarrow$ 99% peak efficiency
    - 99% energy efficiency $\Rightarrow$ >99.99% peak
  - exacerbates narrowing of tuning curves
    - small inhomogeneities cause backconversion
  - spatial distortions & "gain-induced diffraction": with extreme peak powers get quadratic solitons

- Waveguides have interesting properties
  - high efficiency: CW/quasi-CW operation
  - eigenmodes convert as entities: eliminates spatial variations

- Waveguides present some challenges
  - strict homogeneity requirements to avoid backconversion
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\[ D(\%) \]
\[ \Delta kL = 0 \]
\[ \Delta kL = \pi/20 \]
\[ \Delta kL = \pi/10 \]
Pump Depletion Results

- 99% depletion observed at input power of 900 mW
- Calculation agrees well with measurement

\( \Gamma = 15 \text{ W}^{-1} \)
Measured Tuning Curves

- 38 mW, 25%
- 82 mW, 44%
- 141 mW, 60%
- 256 mW, 78%
- 418 mW, 85%
- 732 mW, 95%

$P_{2\theta}/P_\theta$ (normalized) vs. $\lambda$ (nm)
Into High-Gain Regime

- Experiment done with longer sample
- Parametric amplification of ASE from pump laser induces back conversion
  - precludes quantitative analysis

![Graph showing spectral lines with a FWHM of ~3 GHz](image)
Photon Counting at 1.5 μm

- Photon counting at 1.5 μm important for quantum information
  - InGaAs APDs: high dark count, low Q.E.
  - Si APDs: no response at 1.5 μm

- Efficient SFG converts 1.5 μm photons to 720 nm
  - suitable for Si APD
  - photon statistics altered only if QE<100%

- Demonstrated w/fiber pigtail:
  - Internal QE: >99%, External QE: 60%

- Anticipate (AR coatings, etc):
  - Internal QE: >99%, External QE: >80%

- Dark counts: dominated by non-phasematched SHG of pump
  - ~100 dB filtering (LPF + prism) to get to ~200 cps

[C. Langrock, E. Diamanti]
Efficient Sum Generation

- Easier (and more useful) to deplete SFG
  \[ \frac{N_{\text{sum}}(L)}{N_{\text{sig}}(0)} = \cos^2 \left( \sqrt{4 \Gamma P_{\text{pump}}} \right) \]
  \[ \frac{N_{\text{sig}}(L)}{N_{\text{sig}}(0)} = \sin^2 \left( \sqrt{4 \Gamma P_{\text{pump}}} \right) \]
  - predict total conversion for 50 - 100 mW pump

- Experiment: 5 cm PPLN waveguide

> 99% conversion at \( P_{\text{pump}} = 88 \text{ mW} \)

[C. Langrock, R. Roussev]
• Autocorrelation is a common pulse measurement tool
  – measure $2\omega$ energy vs time delay
  – infer pulse duration

• Requires a nonlinear process like SHG
  – makes measurement at low energies challenging
  – needs adequate spectral bandwidth to accommodate pulse spectrum

• Combine two ideas
  – waveguide for high efficiency
  – chirped QPM grating to obtain bandwidth
Autocorrelation with 400 Photons

unchirped QPM PM spectra

chirped QPM PM spectra

A. Weiner, Purdue

52 attoJoules
400 photons (!)
1000x more sensitive

Measurement Technology | Sensitivity (mW)$^2$
-----------------------------|--------------------------
Bulk crystal, SHG | $\sim 1$
Silicon avalanche photodiode, TPA | $1.5 \times 10^{-3}$
InGaAsP laser diode, TPA | $1.5 \times 10^{-4}$
A-PPLN waveguide, SHG | $3.2 \times 10^{-7}$

[*] Sensitivity is defined as $P_{avg} * P_{peak}$ of minimal detectable signal, the lower the better.
Summary

• Materials essential for NLO devices
  – microstructured materials provide systematic solutions
  – best new material is often a better understood old material
    (like silicon in microelectronics)

• Many useful device concepts can be borrowed from microwave world

• Microstructured waveguides implementing QPM
  – careful design allows orders of magnitude improvement in performance
  – highly engineerable solutions for various signal processing functions
    classical and quantum optical

• Higher levels of integration coming for multifunction devices
  – new materials may offer further qualitative improvements (e.g. OP-GaAs)

• May be possible to use nanophotonic devices to implement similar functions