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*WINTER COLLEGE ON OPTICS ON OPTICS AND PHOTONICS
IN NANOSCIENCE AND NANOTECHNOLOGY*

(7 - 18 February 2005)

"Nonlinear Optical Waveguides" - III

presented by:

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Nonlinear Waveguides in Microstructured Media: Materials, Devices, and Applications

Fixing Some Problems
&
Pushing the Envelope

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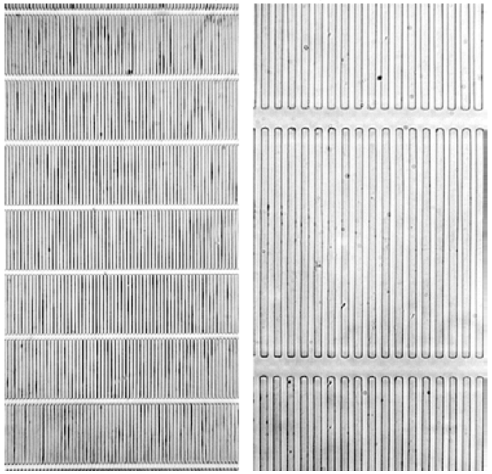
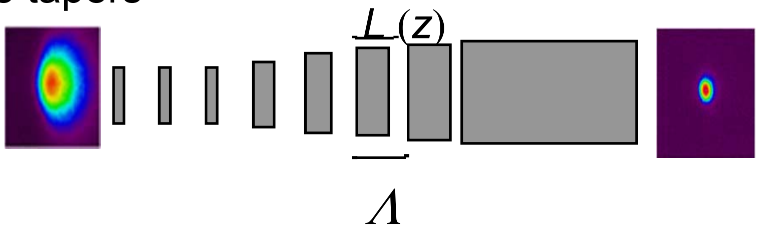
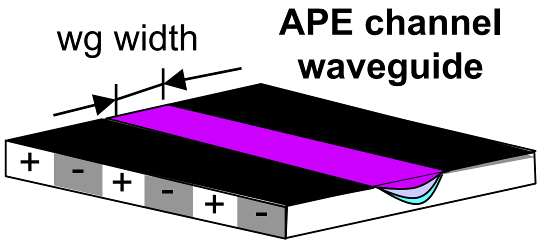
Fabrication tools for extremely efficient NLO devices

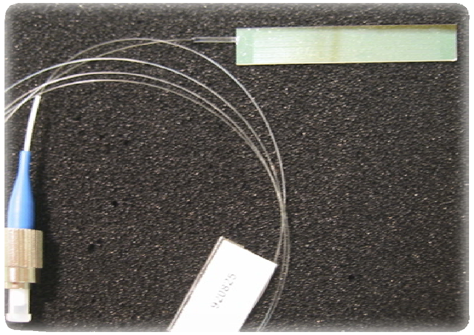
Ferroelectric gratings for QPM

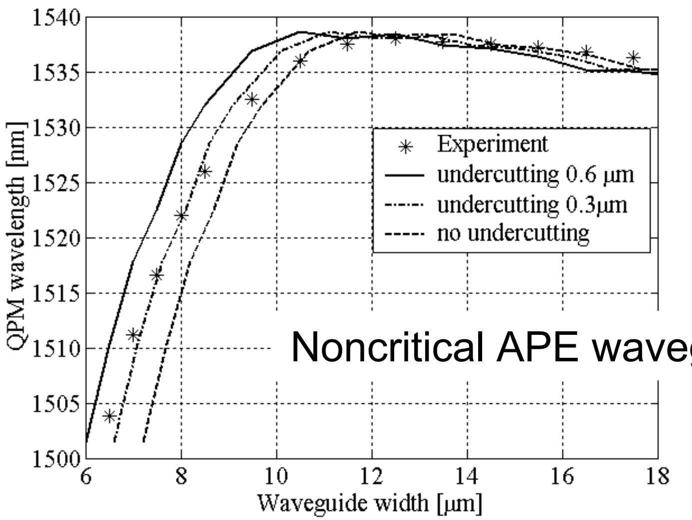


Adiabatic waveguide tapers



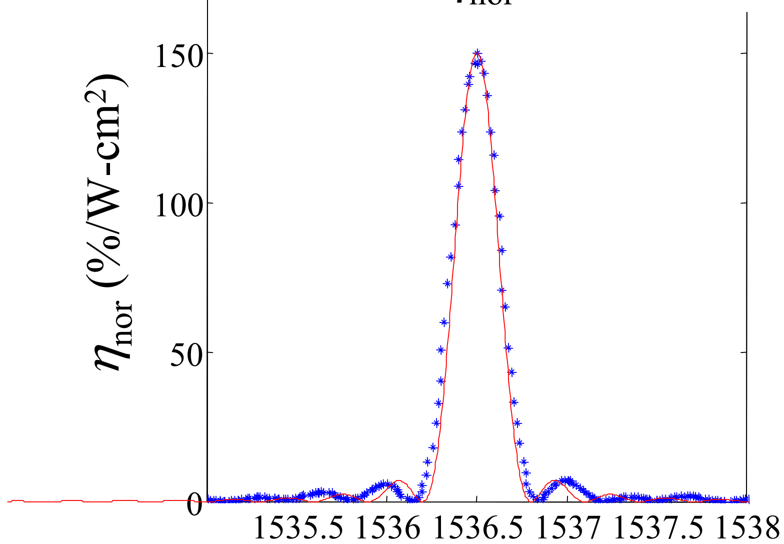






Noncritical APE waveguide designs

$\eta_{nor}L^2$=3000%/W

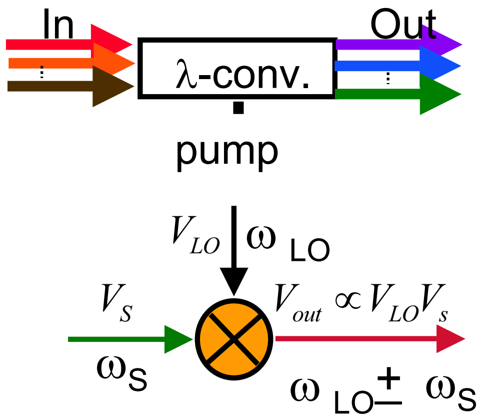


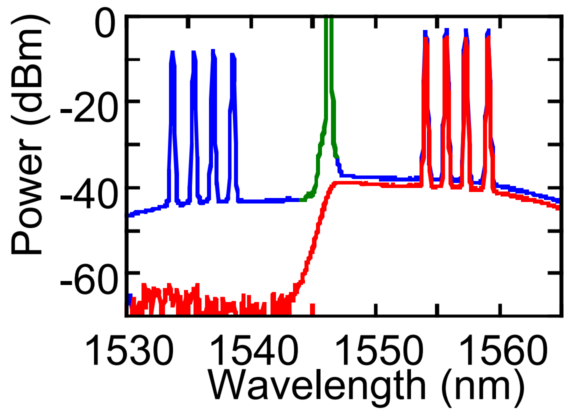
Examples of Applications of Highly Nonlinear Waveguides

Efficient waveguide mixers for telecom

various signal processing functions

wavelength domain

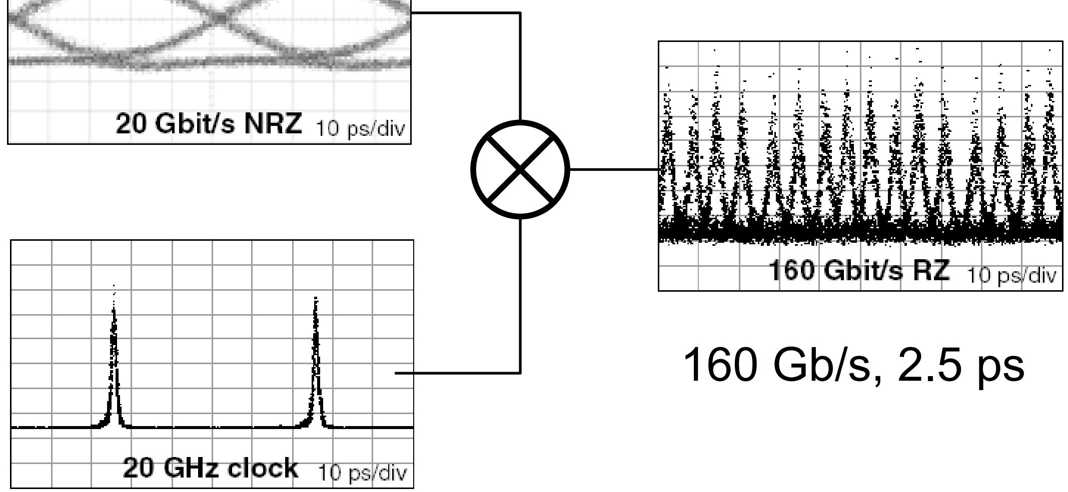




time domain

Waveguide mixers

in time domain

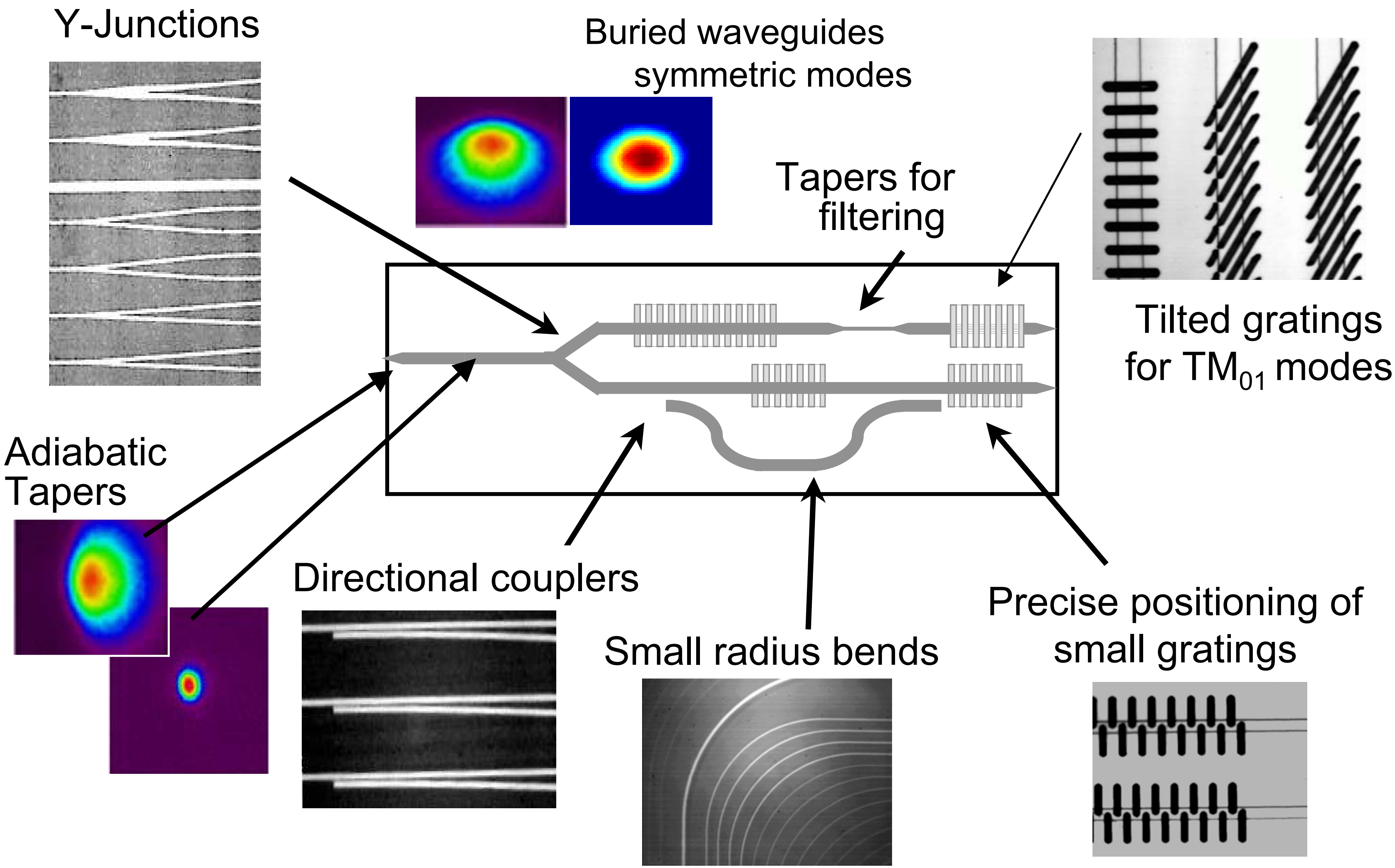


160 Gb/s, 2.5 ps

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

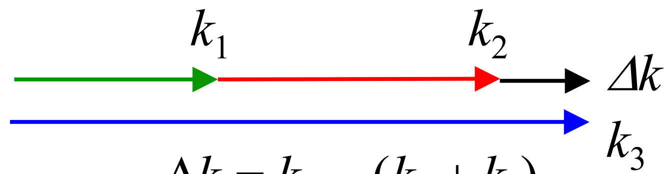
Integrated structures for advanced devices



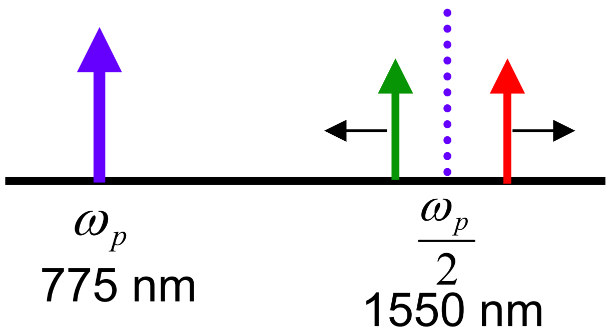
Combination of high gain, uniform devices + various integrable structures → Multi-function devices for classical and quantum comm.

Narrow vs wide tuning

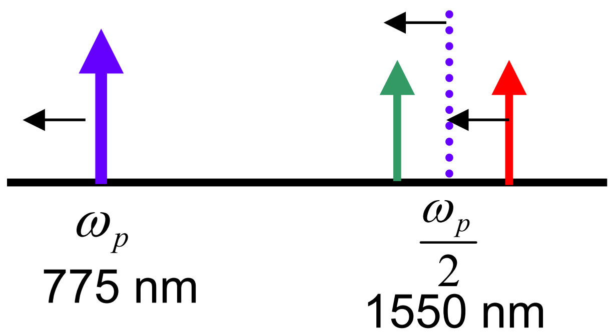
- Bandwidth depends on tuned parameter
  - very broad for tuning signal at fixed pump
  - narrow for tuning pump at fixed signal



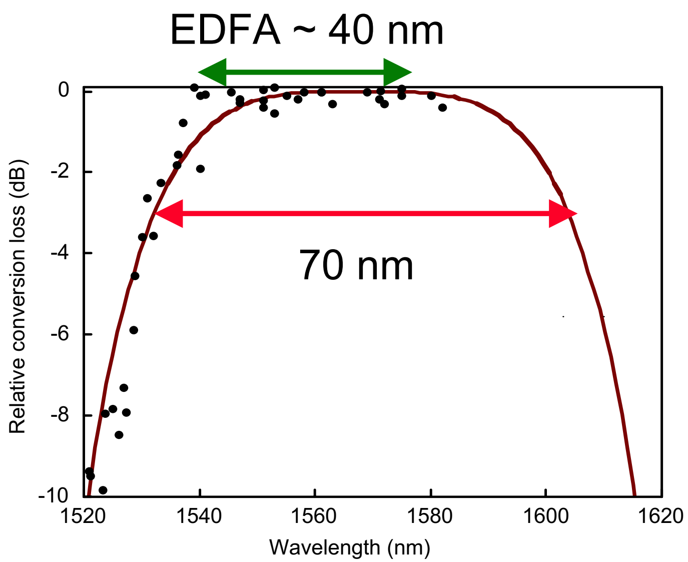
$$\Delta k = k_p - (k_s + k_i)$$

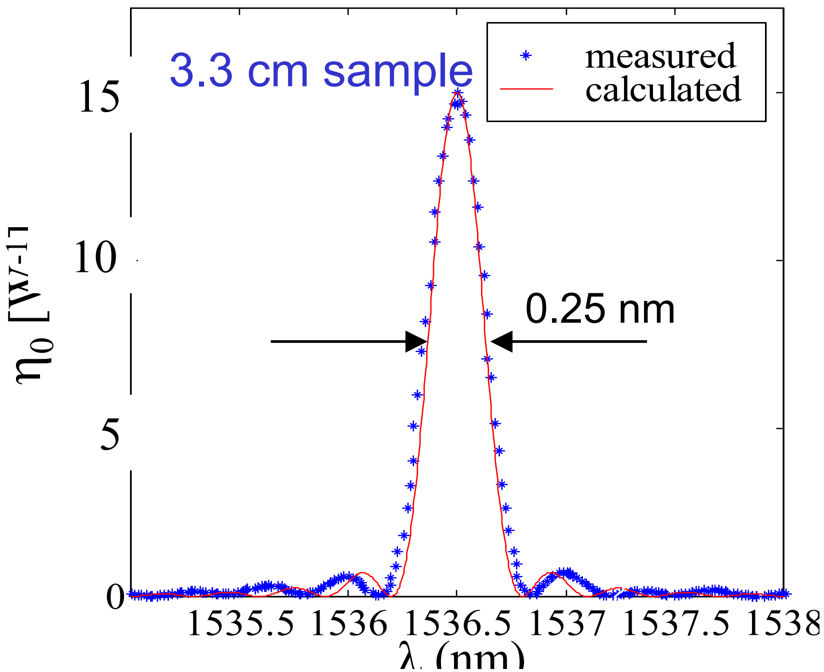


$$\Delta k = k_p - (k_s + k_i) \sim \text{constant}$$



$$\Delta k = k_p - (k_s + k_i) \text{ changes}$$





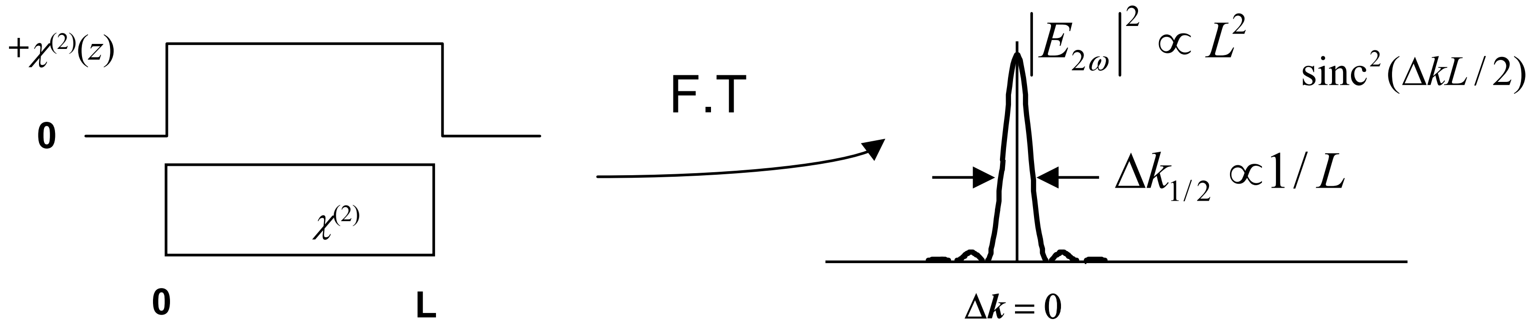
Tuning Curves Are Fourier Transforms

Solution to undepleted-pump SHG SVEA equation:

$$E_{2\omega} \propto E_{\omega}^{2} \int_{0}^{L} \chi^{(2)}(z)\, e^{i\Delta k(\omega) z}\, dz = E_{\omega}^{2}\, \hat{\chi}^{(2)}[\Delta k(\omega)]$$

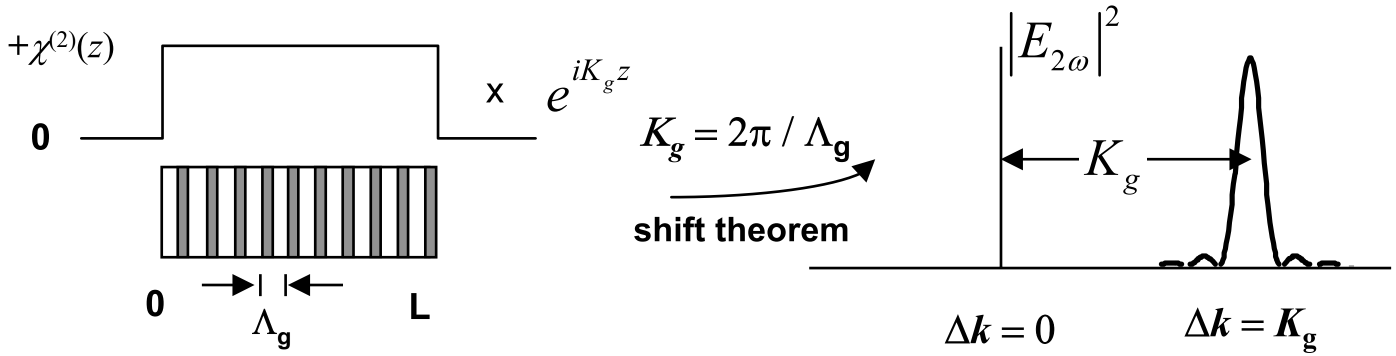
Generated second harmonic proportional to Fourier Transform of $\chi^{(2)}(z)$

PM:



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

QPM:

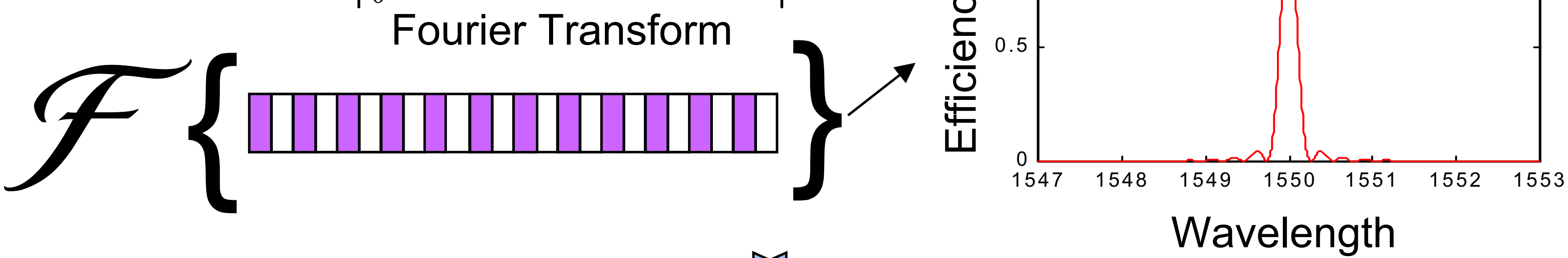


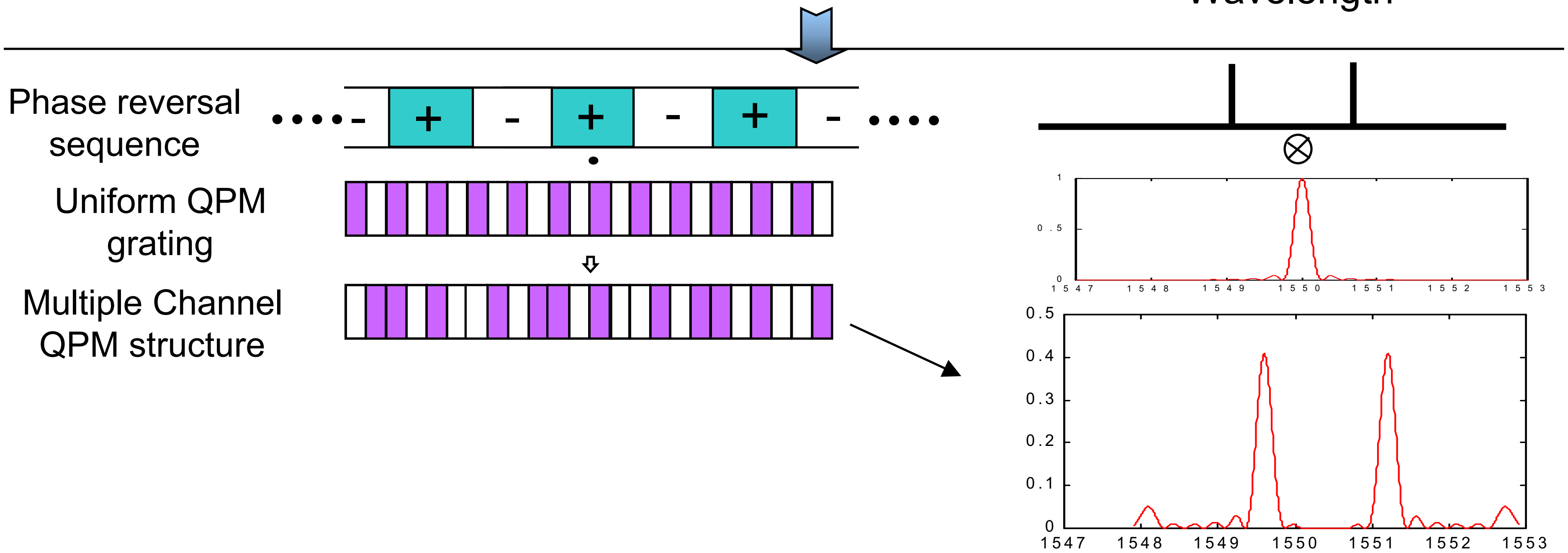
Generalize to Fourier synthesize "arbitrary" transfer function

Multiple Pump Channel Devices: Synthetic QPM Gratings

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

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

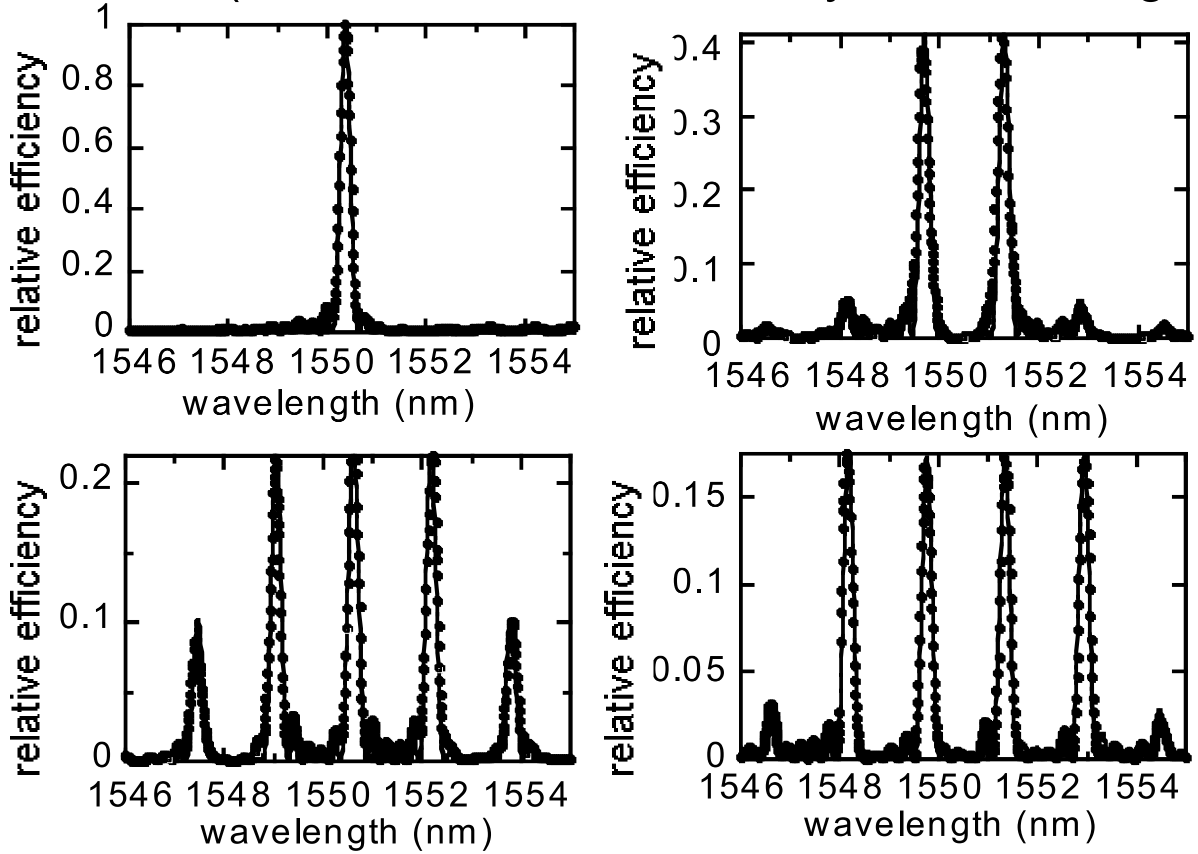


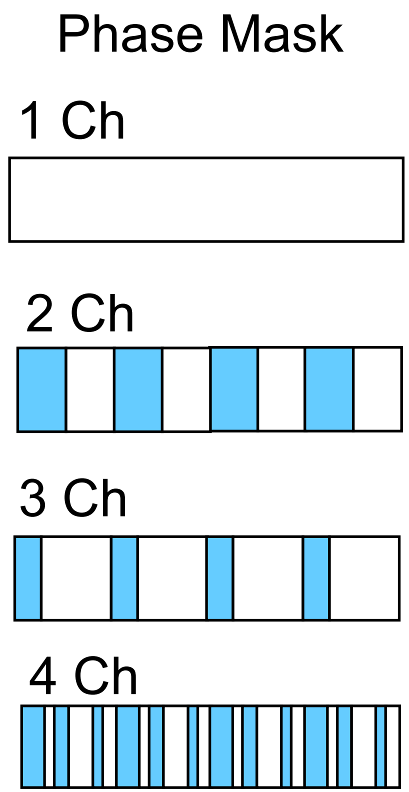


Multiple Channel Mixers

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

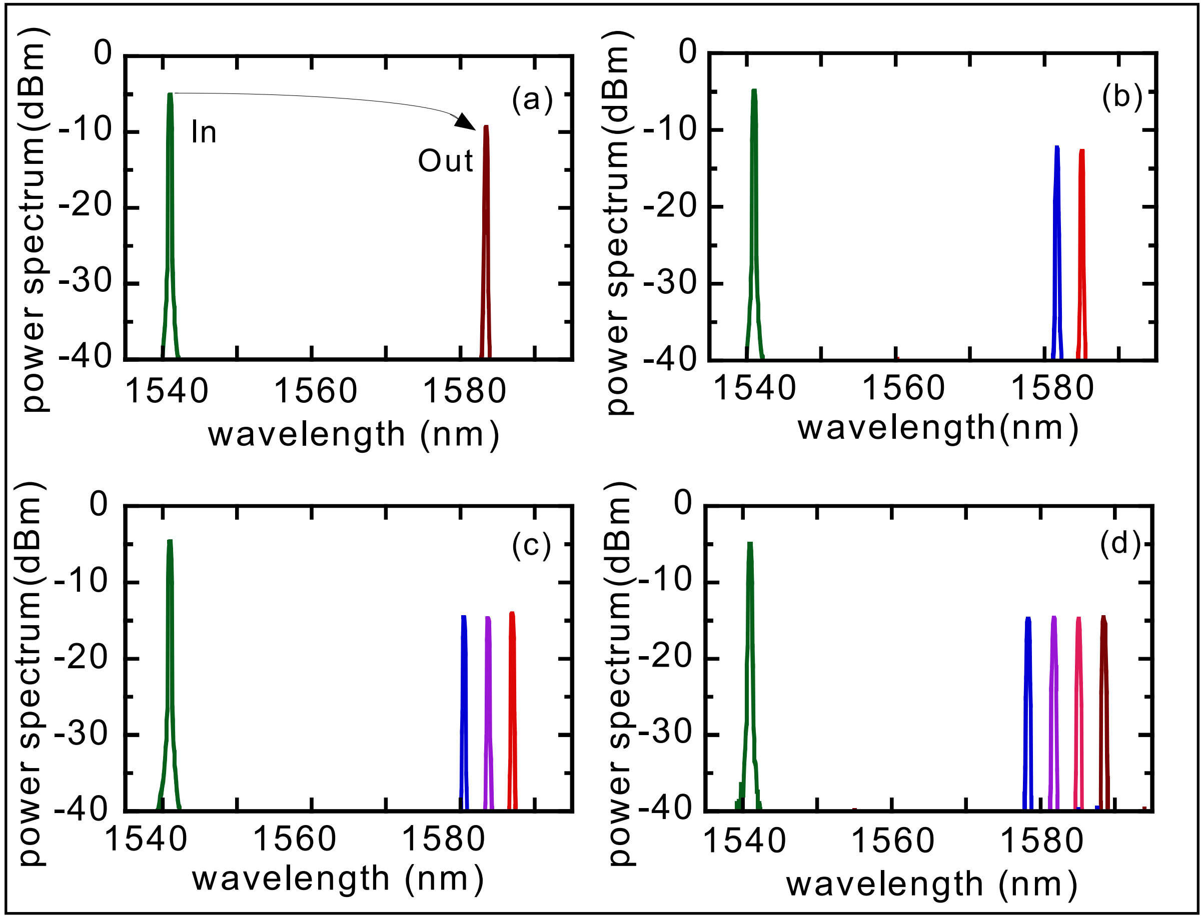
SHG (Measurement of efficiency vs. wavelength)



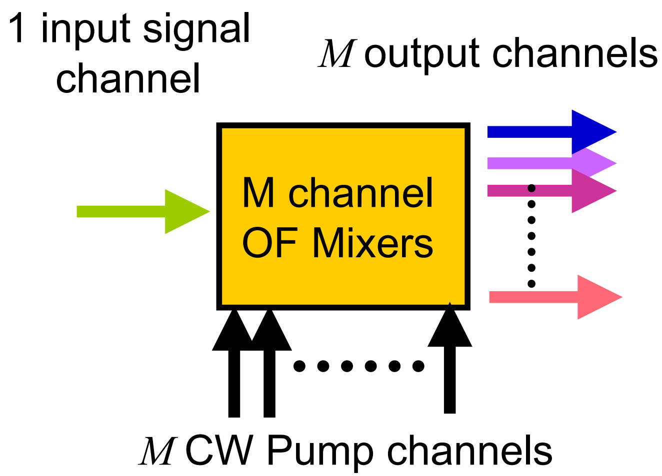


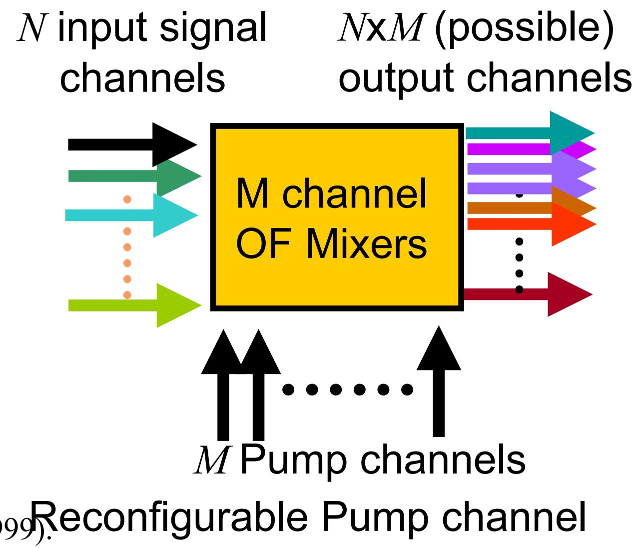
M. H. Chou, K. R. Parameswaran, M. M. Fejer, and I. Brener, *Opt. Lett.* **24**, 1157-59 (August 1999).

1.5 μm Band "Broadcast" λ-converter



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





One channel can be replicated onto *N* channels

M channels can be replicated onto *N*x*M* channels

- Dynamic reconfiguration
- Broadcasting: 1 in ---> *N* out

M. H. Chou, K. R. Parameswaran, M. M. Fejer, and I. Brener, *Opt. Lett.* **24**, 1157-59 (August 1999).

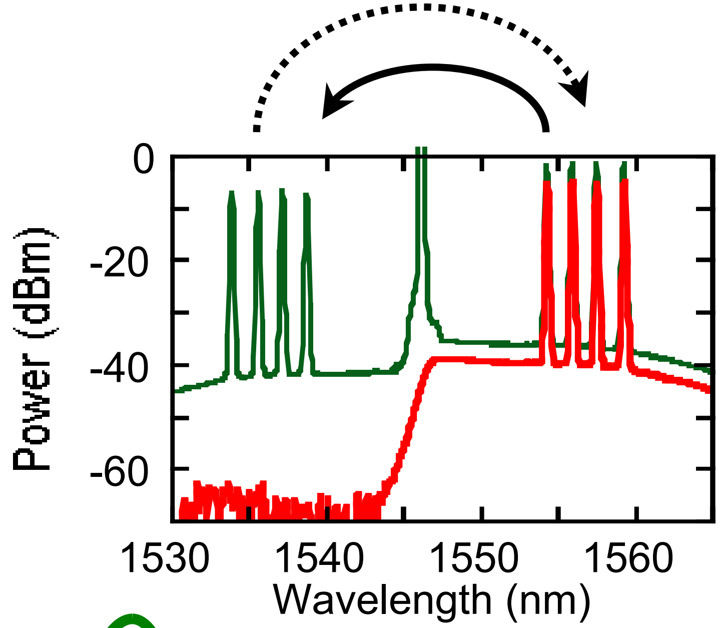
Distinguishability and spatial separation:

How to distinguish input from output?

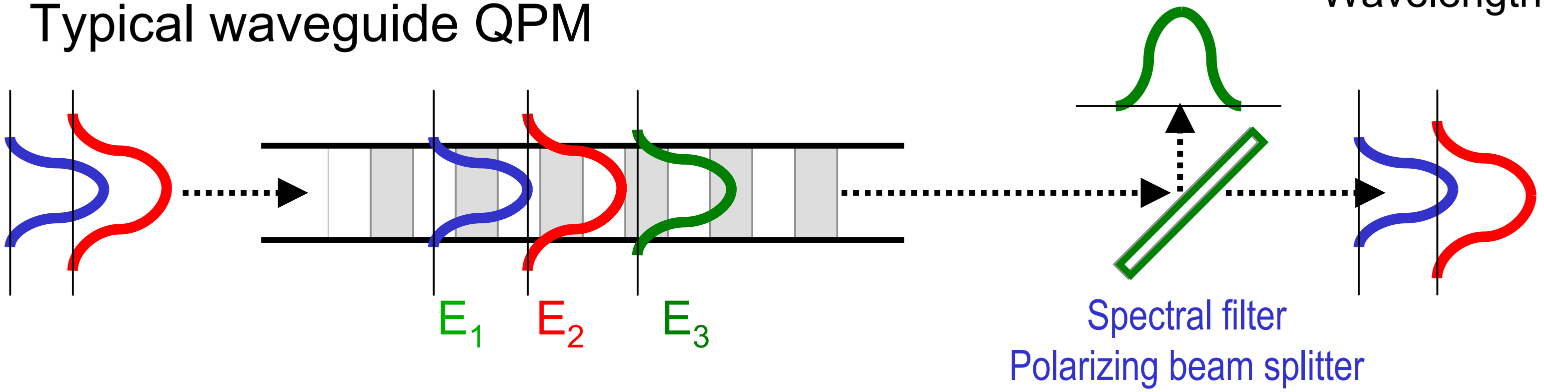
Spectral filtering required

Can’t work at degenerate point

No spectral inversion without shift



Typical waveguide QPM



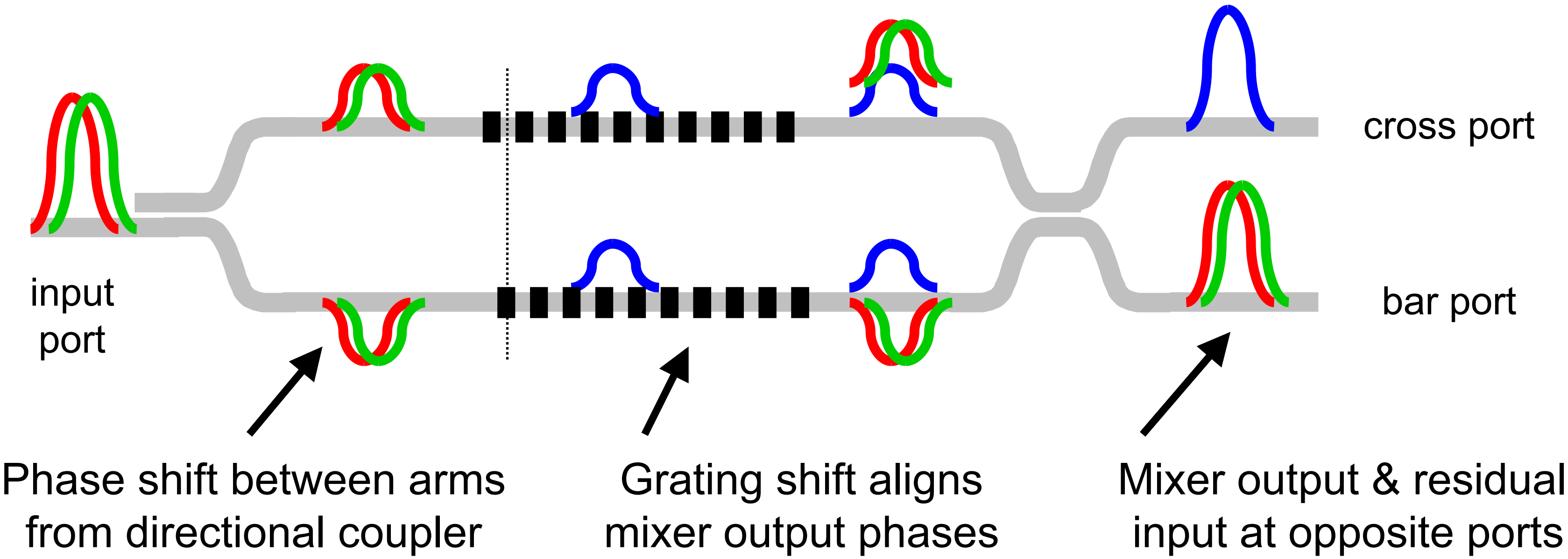
Two integrated optics solutions:

- Optical frequency balanced mixer
- Odd and even mode quasi-phase-matching

Optical Frequency Balanced Mixer

Mach Zender interferometer structure:

π-phase shifted QPM allows independent bias of mixer output

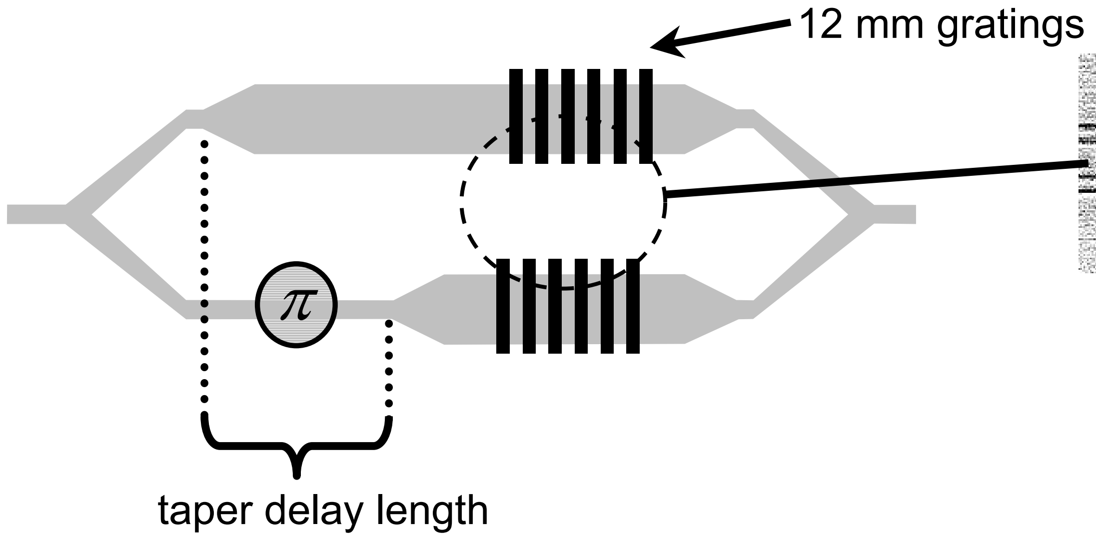


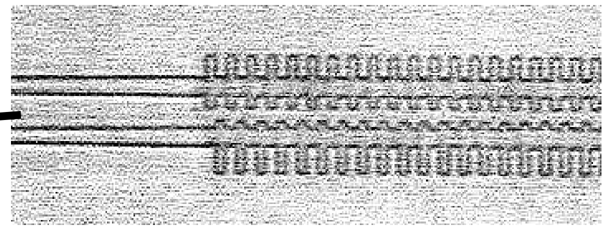
- Broadband separation of inputs and output
- Requires twice as much pump power as standard device

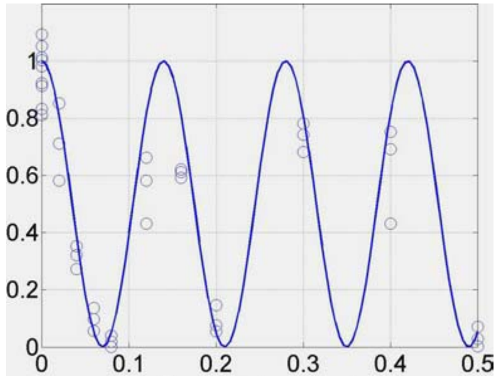
$$P_{out} = \tfrac{1}{4}\eta^2 L^4 P_p^2 P_s$$

Optical frequency balanced mixer: Implementation

Optical frequency balanced mixer





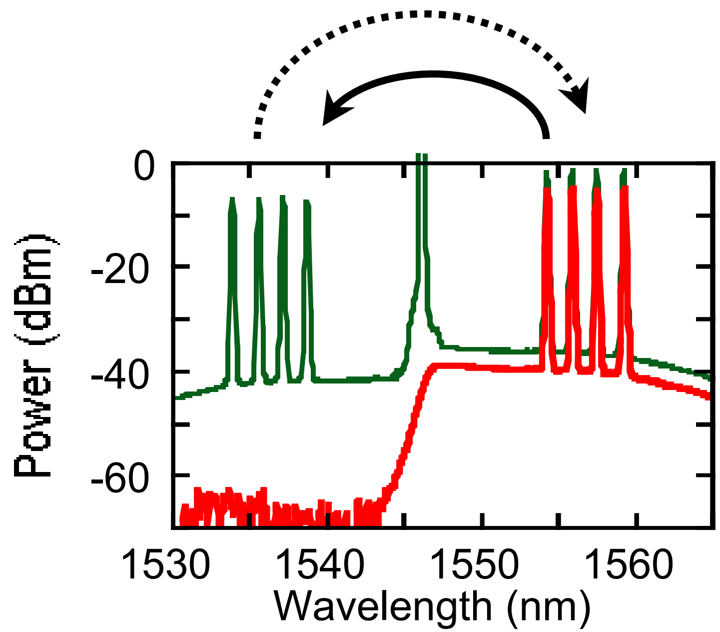


$$\pi = \frac{2\pi}{\lambda} L_{delay}\left[n_{eff}\left(12\mu m\ \text{width}\right) - n_{eff}\left(3\mu m\ \text{width}\right)\right]$$

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

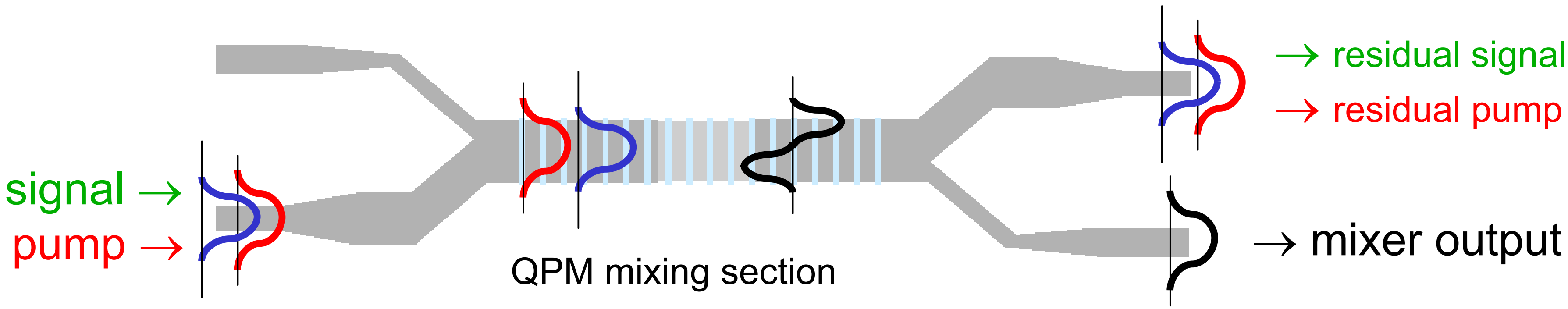
J. R. Kurz, K. R. Parameswaran, R. V. Roussev, and M. M. Fejer, Optics Letters, vol. 26, no. 16, pp. 1283-1285 (August 2001).

Alternative for distinguishability and spatial separation:



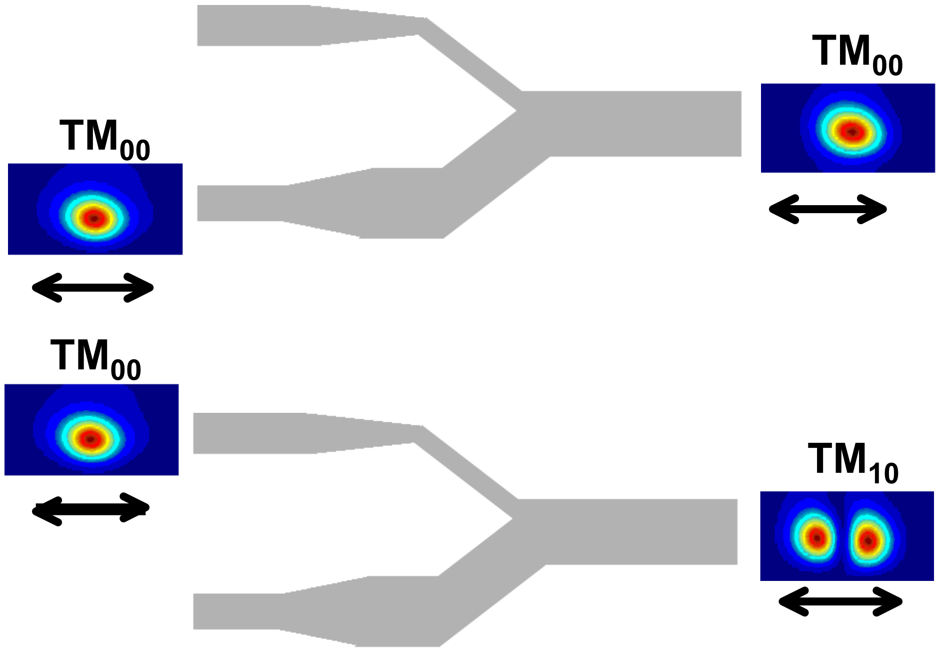
Can use *spatial modes* to distinguish:
gives more design flexibility

Larger fabrication tolerances

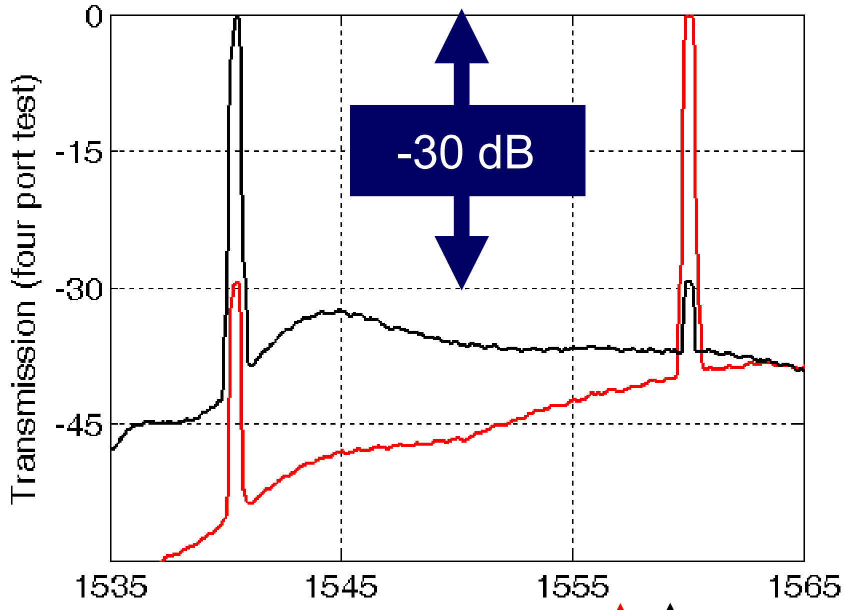


Separating modes: asymmetric Y-junction
Even-odd mode interactions: asymmetric QPM gratings

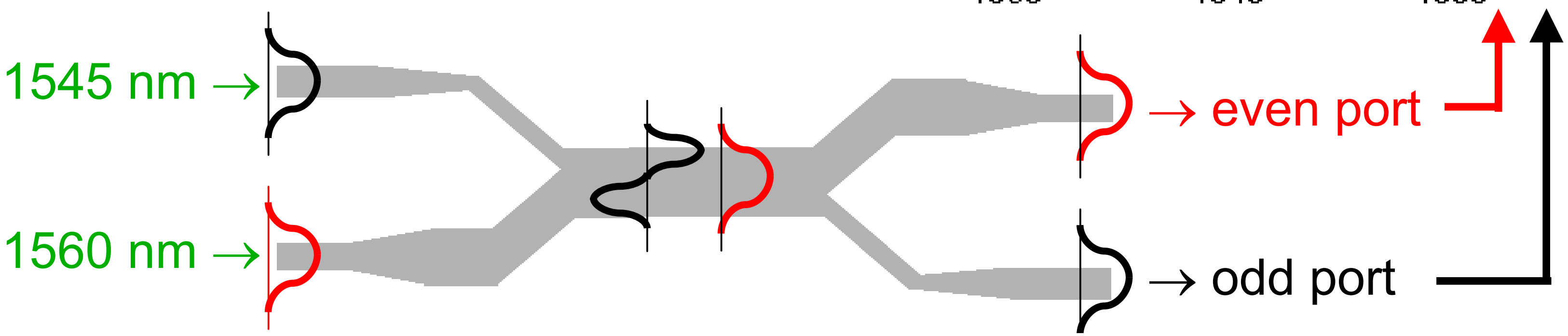
Asymmetric Y-junctions: Mode filtering and Launching



Adiabatic mode evolution
TEM_{00} and TEM_{01} different ports

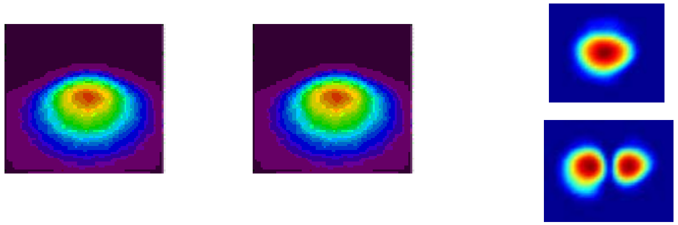


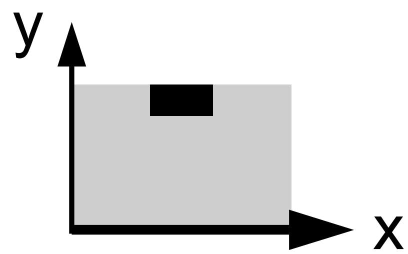
can launch/filter TM_{00} and TM_{10} modes with > 30 dB contrast

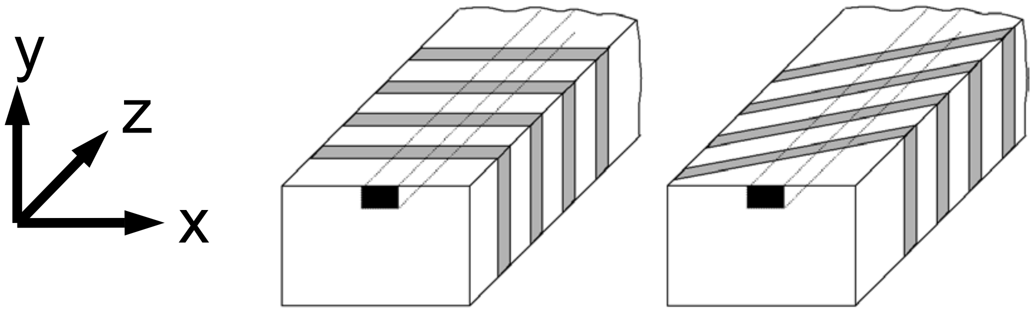


Asymmetric QPM gratings: Even & Odd Modes

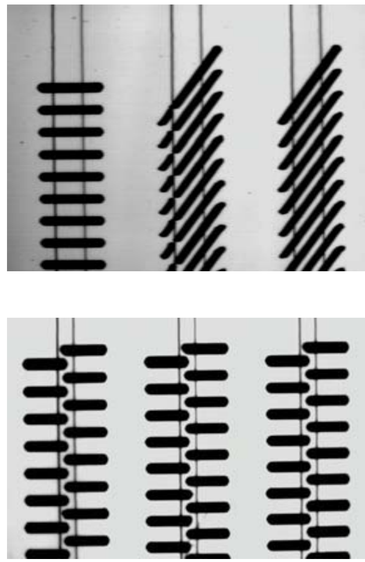
$$\eta \propto \left| \int_{\infty}^{-\infty} \int \bar{d}(x,y) E_{1,jk}(x,y) E_{2,lm}(x,y) E^{*}_{3,np}(x,y)\, dx\, dy \right|^2$$





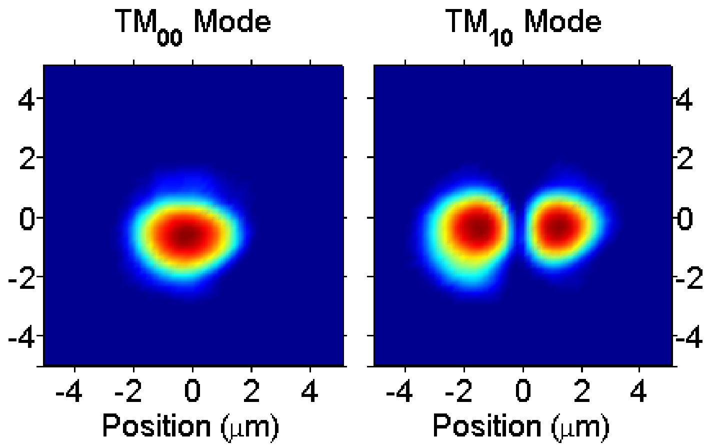


Standard Poling Angled Poling



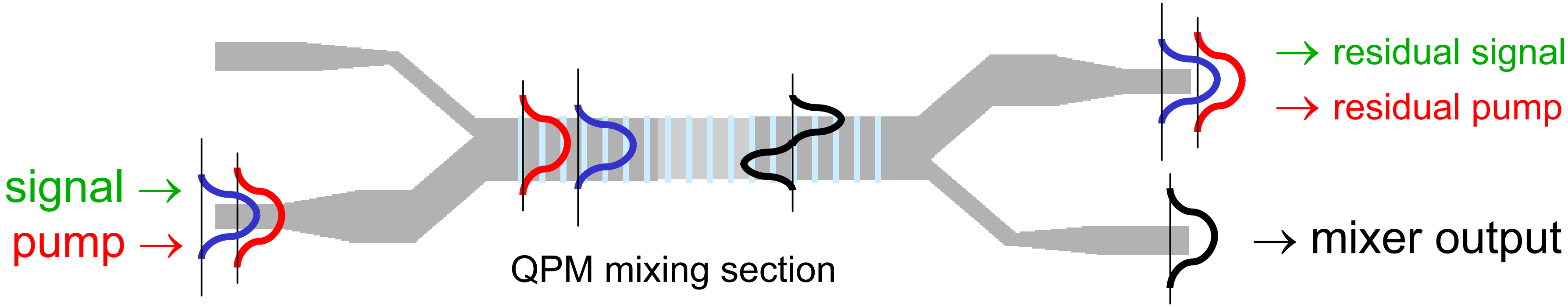
Waveguides and gratings, etched for visibility

Measured SHG output modes



J. R. Kurz, X. P. Xie, M. M. Fejer, Optics Letters, 27, 1445-47 (August 2002).

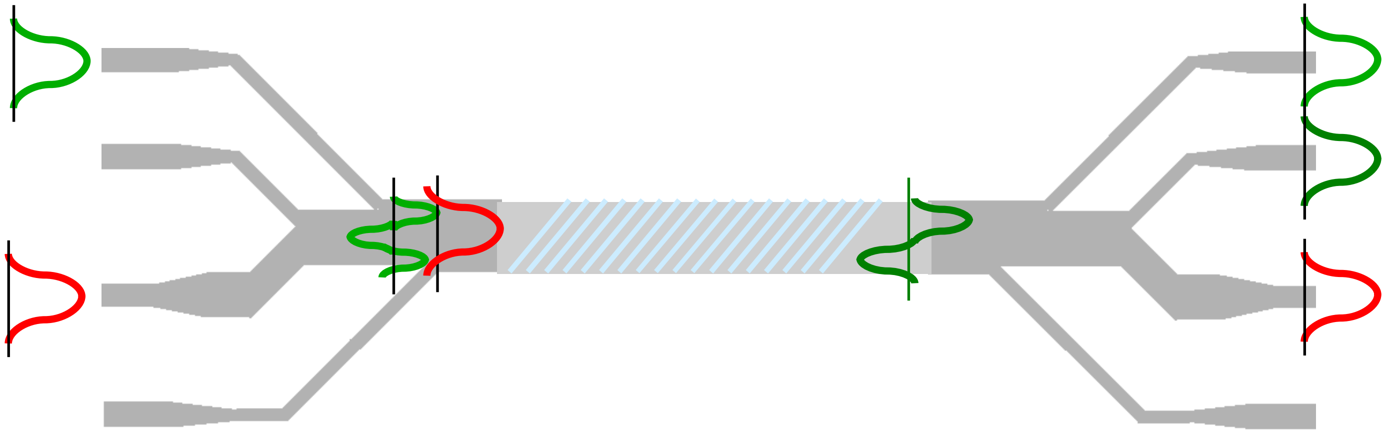
Odd/Even Mode QPM Mixer



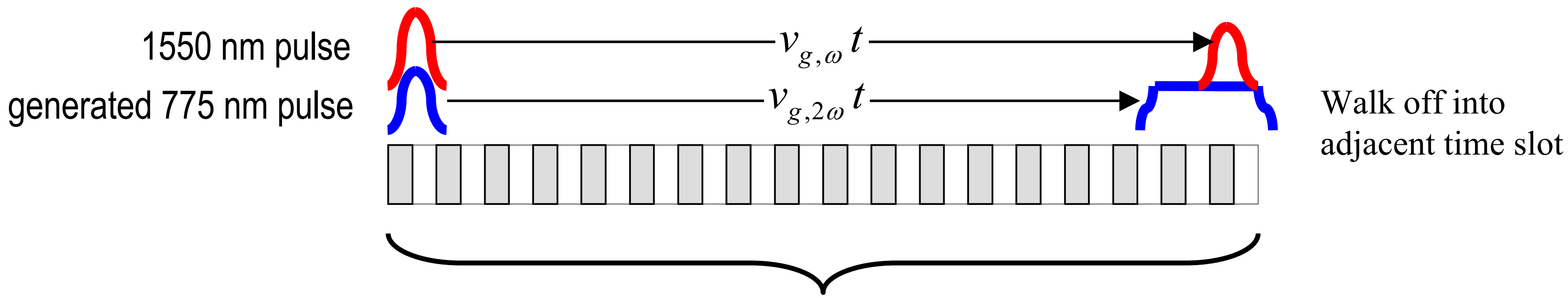
Can solve problems of distinguishability and spatial separation, enabling:

- 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

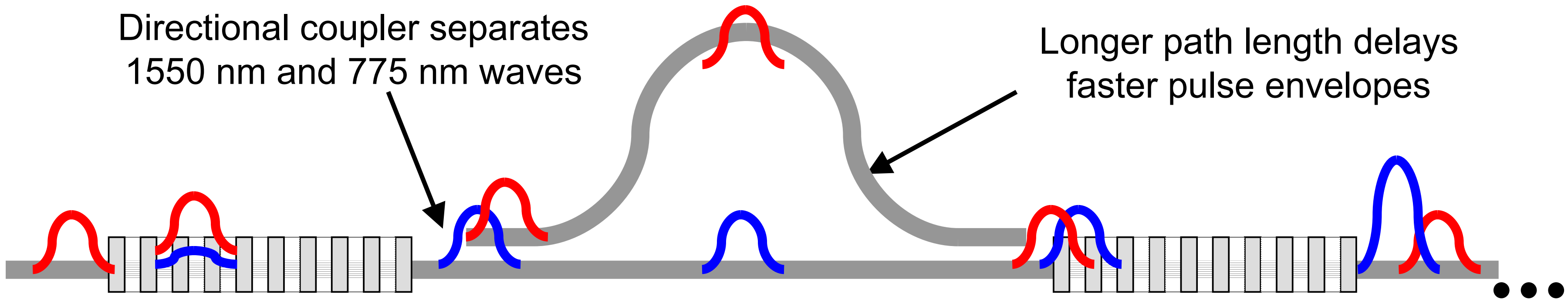


interaction length limited to one walk-off length, but efficiency scales with L^2

$$L_{\max}(\tau) = \tau / \delta v_g^{-1}$$

can equally view as bandwidth limit of long device

Quasi GVM compensation

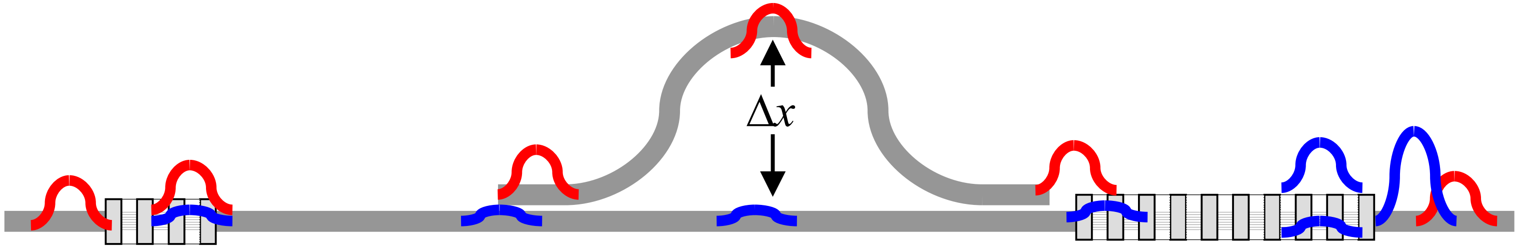


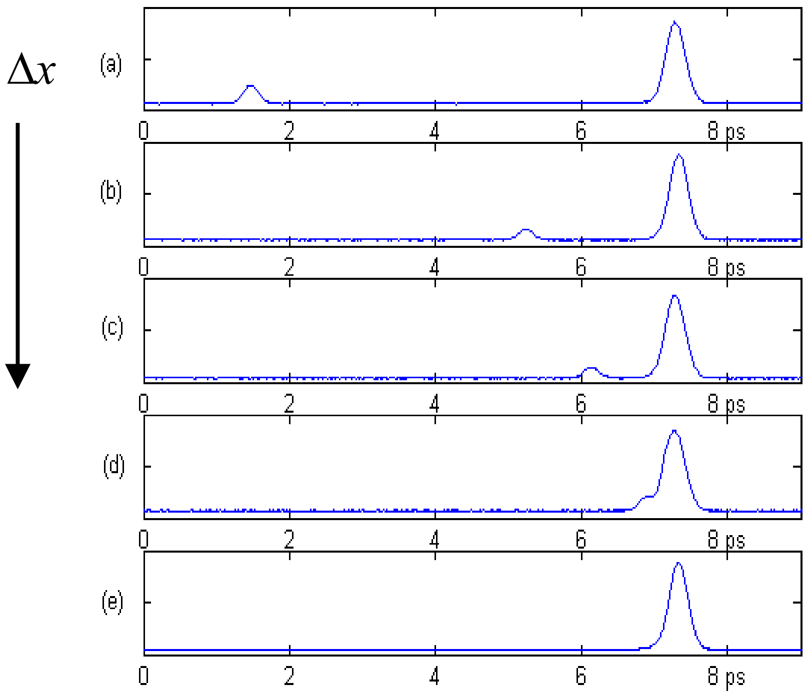
Doubles interaction length, obviating speed/efficiency trade-off

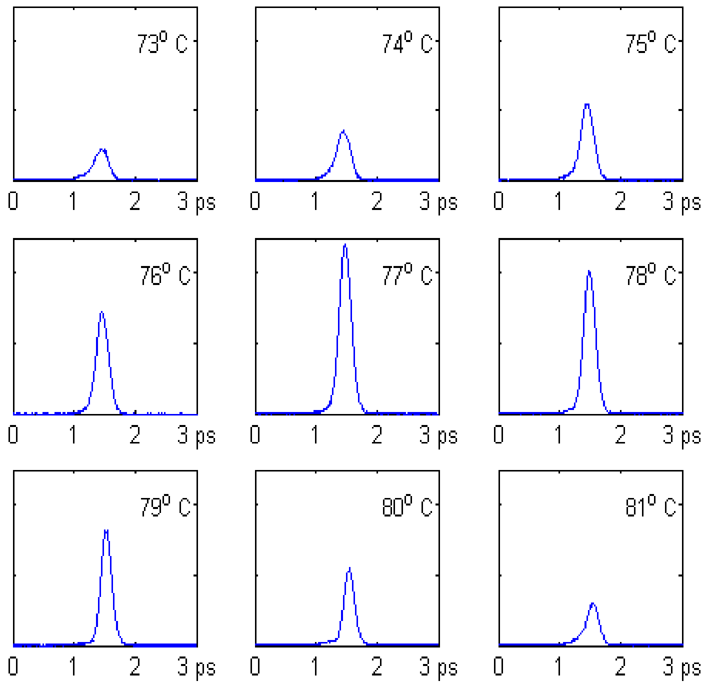
Iterate for discrete compensation for quasi-GVM

akin to QPM compensation for phase velocity mismatch

Demonstration of quasi-GVM compensation devices







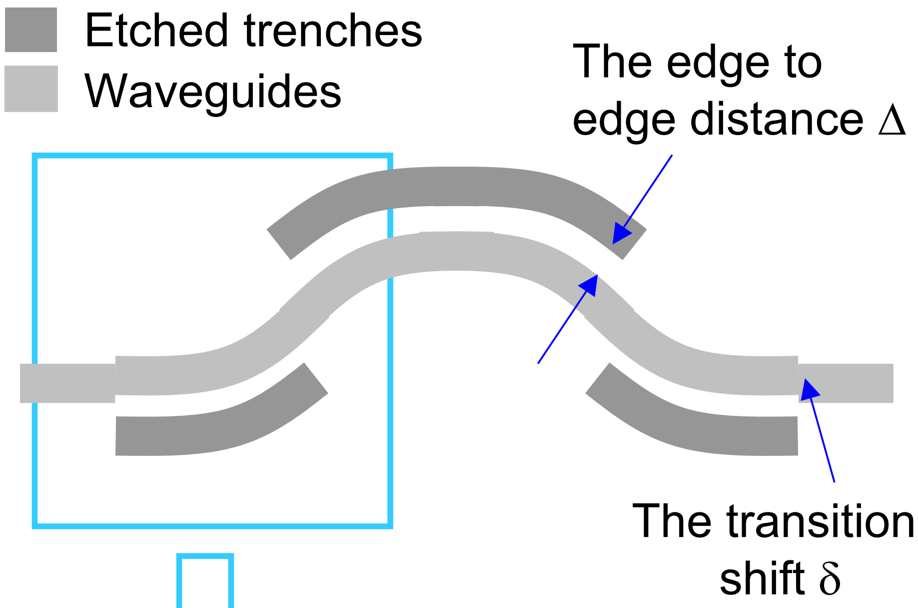
(a): two pulses generated 6 ps apart
(b)-(d): pulses move closer as delay increases
(e): pulse envelopes overlap

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



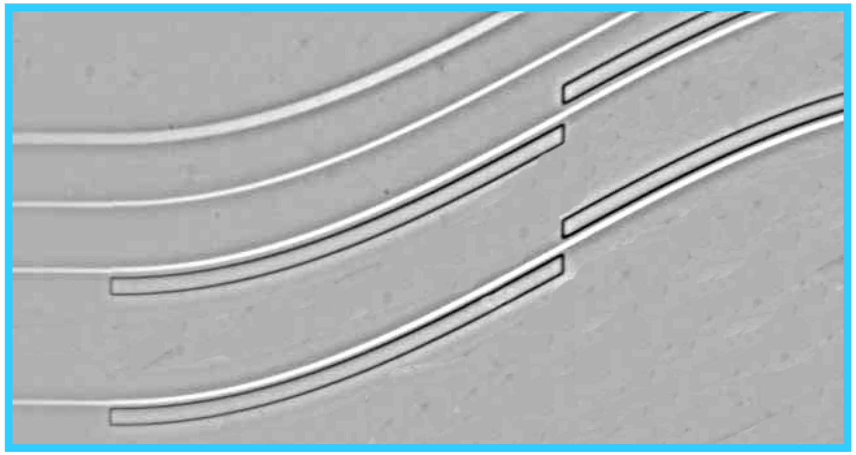
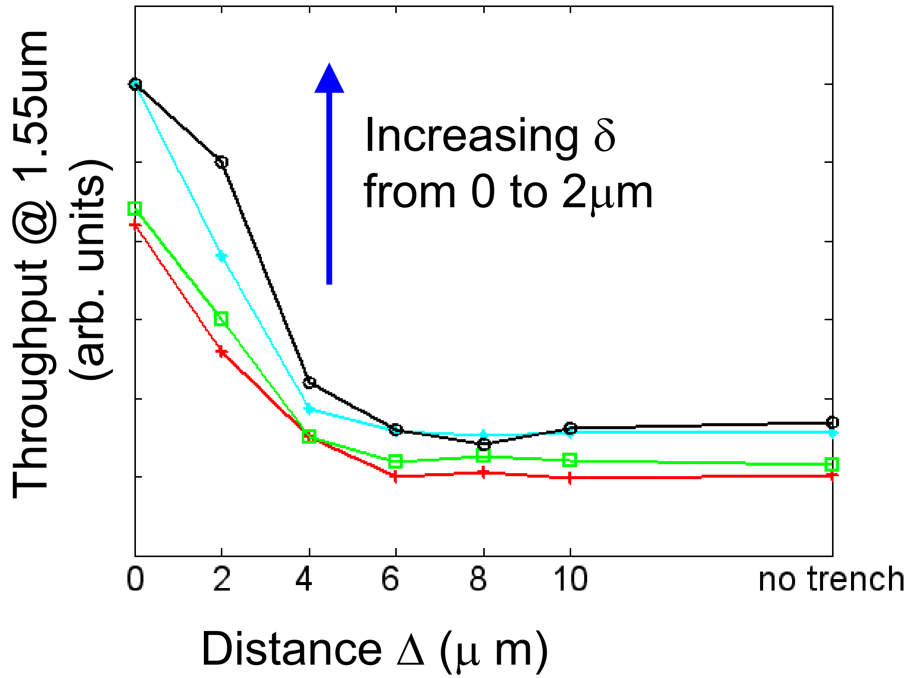


Photo of the S-bends on the chip

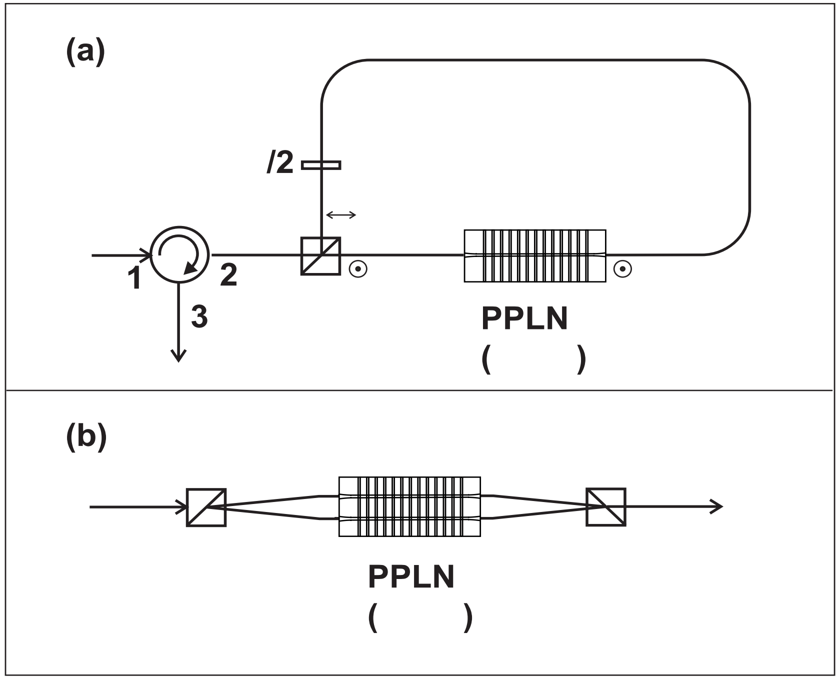
S-Bends with 1.5mm minimum radius and 2.7um-deep etched trenches



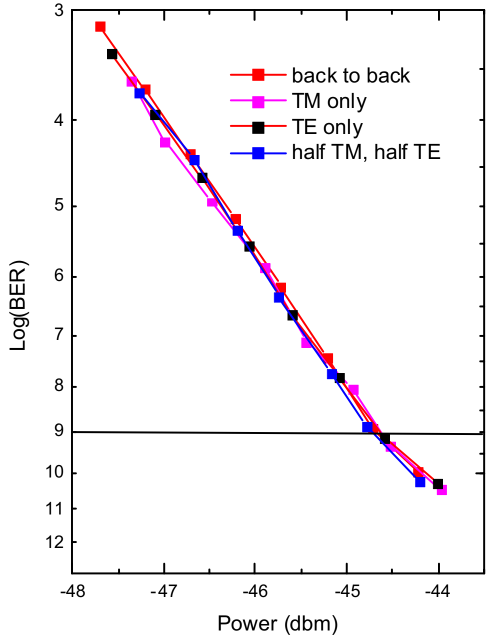
- Loss comparable to S-bends of 4mm-minimum radius without trenches
- By increasing the trench depth and δ, <1mm bend radius is possible

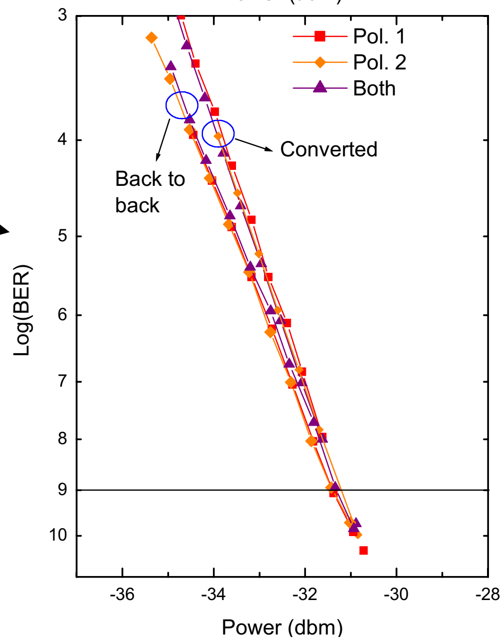
Polarization Insensitive Converter

- $\chi^{(2)}$ 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

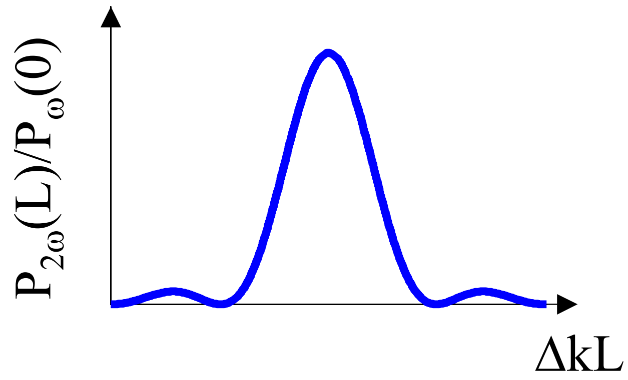
- Quadratic nonlinear interactions often in low-conversion limit

$$\eta \equiv P_{2\omega}(L)/P_{\omega}(0) = \kappa L^2 P_{\omega}(0)\,\mathrm{sinc}^2(\Delta k\, L/2)$$

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

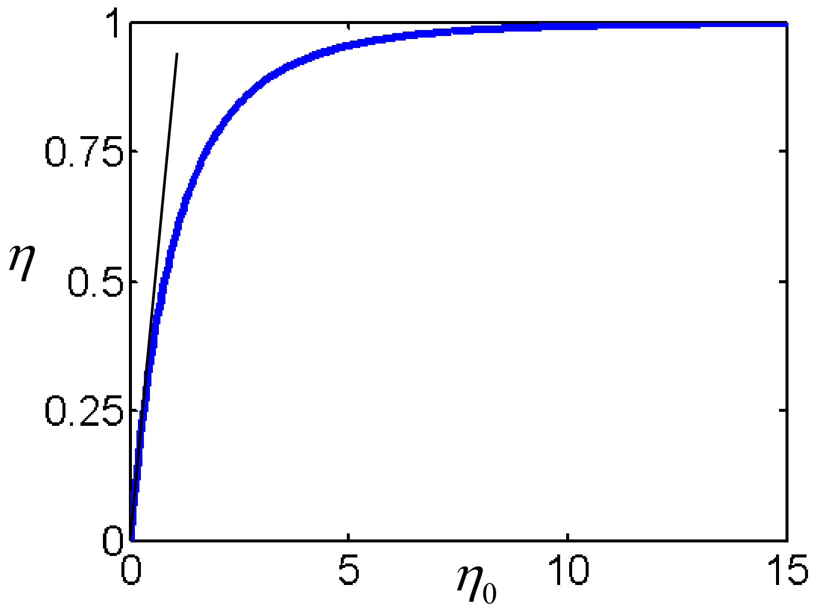
$$\Gamma[\mathrm{W}^{-1}] = \kappa L^2$$

$$\eta_0 = \Gamma P_{\omega}(0)$$

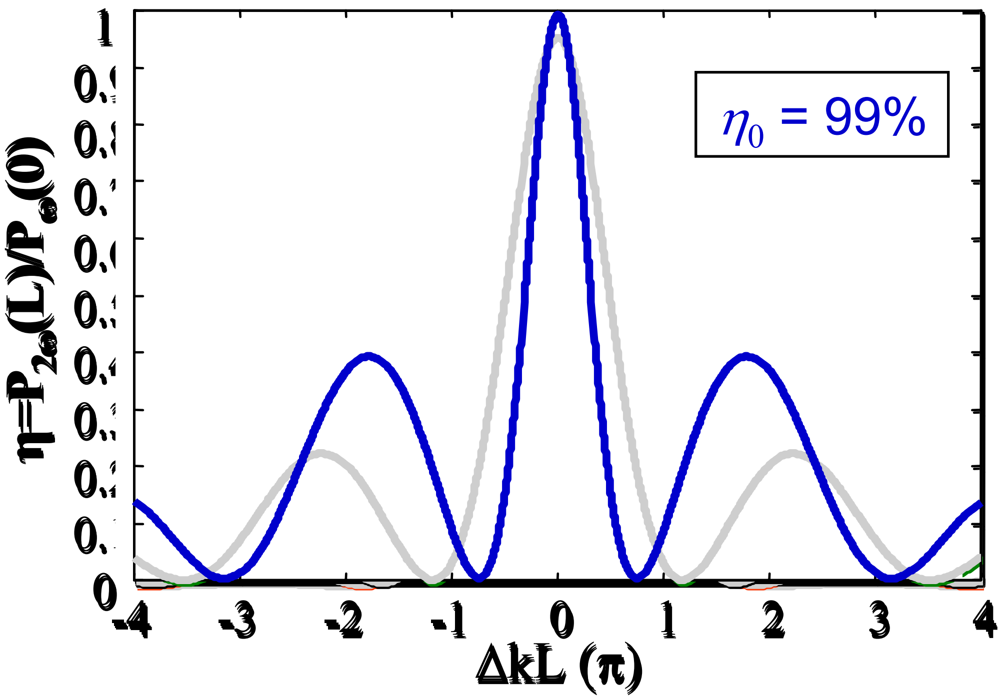


- Different in high conversion limit

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

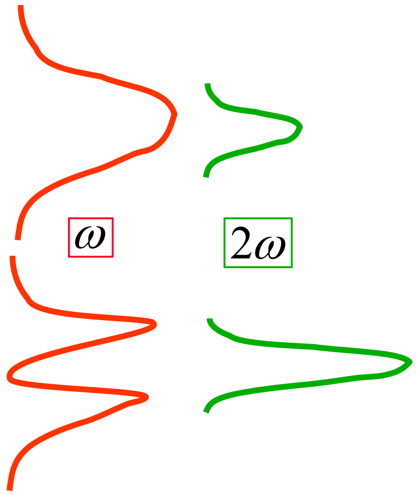


$$\eta = f(\eta_0, \Delta k\, L)$$

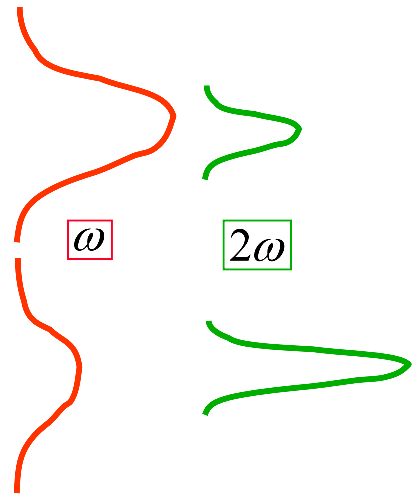


High Efficiency NLO Is Challenging (but Useful)

- 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

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":
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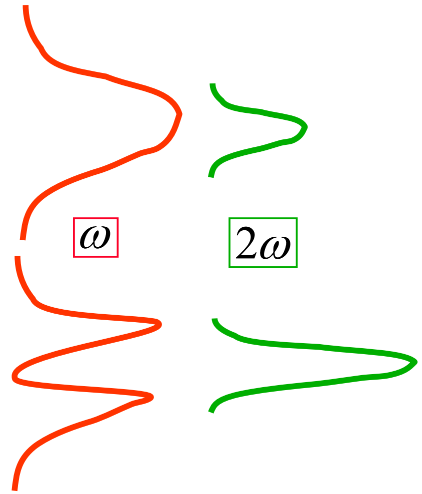

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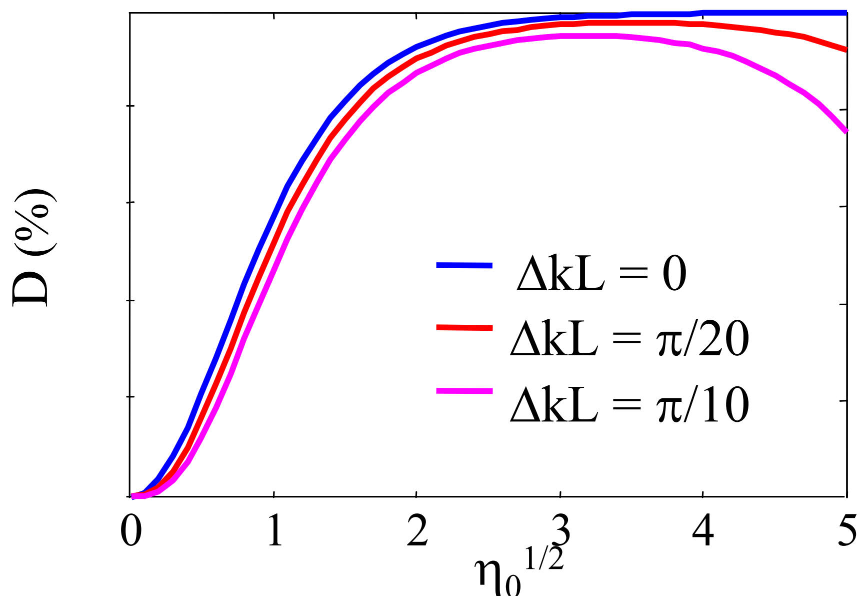
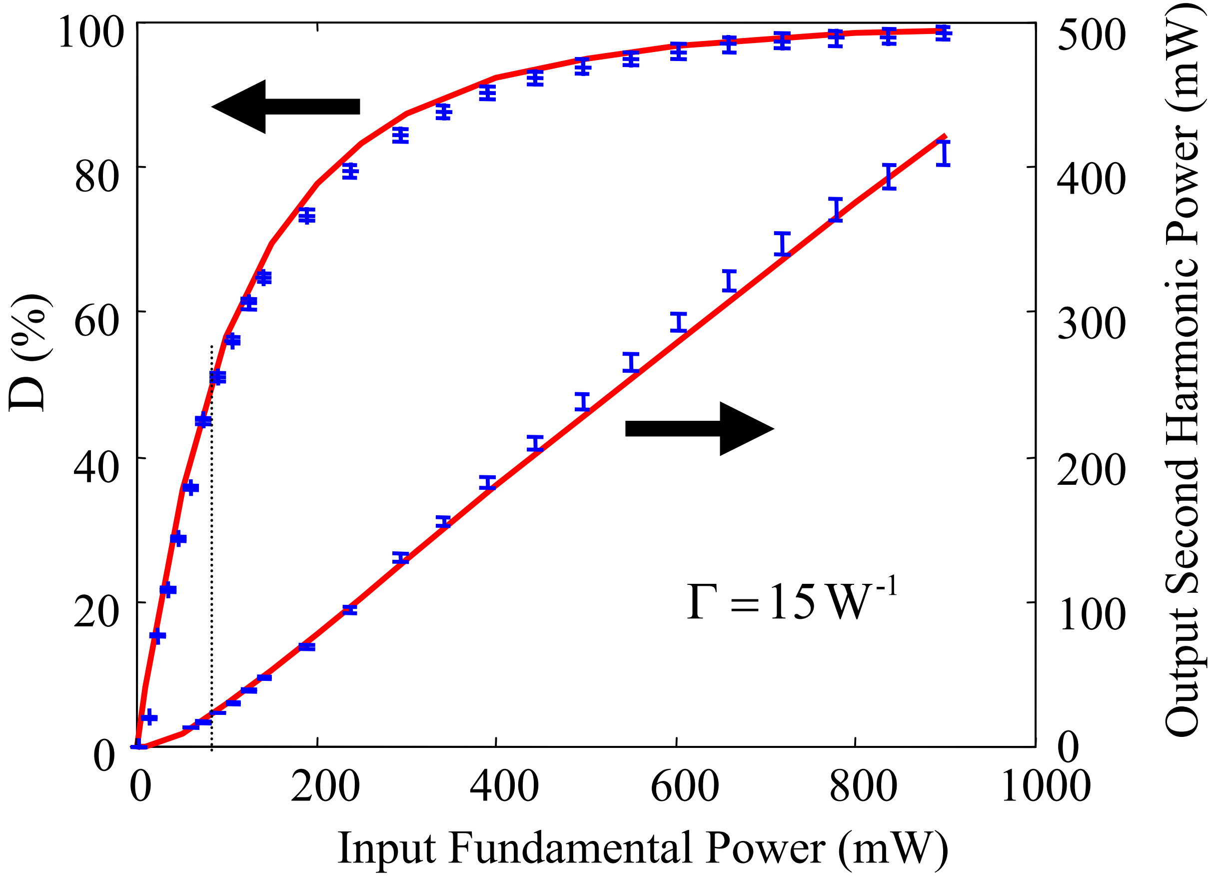
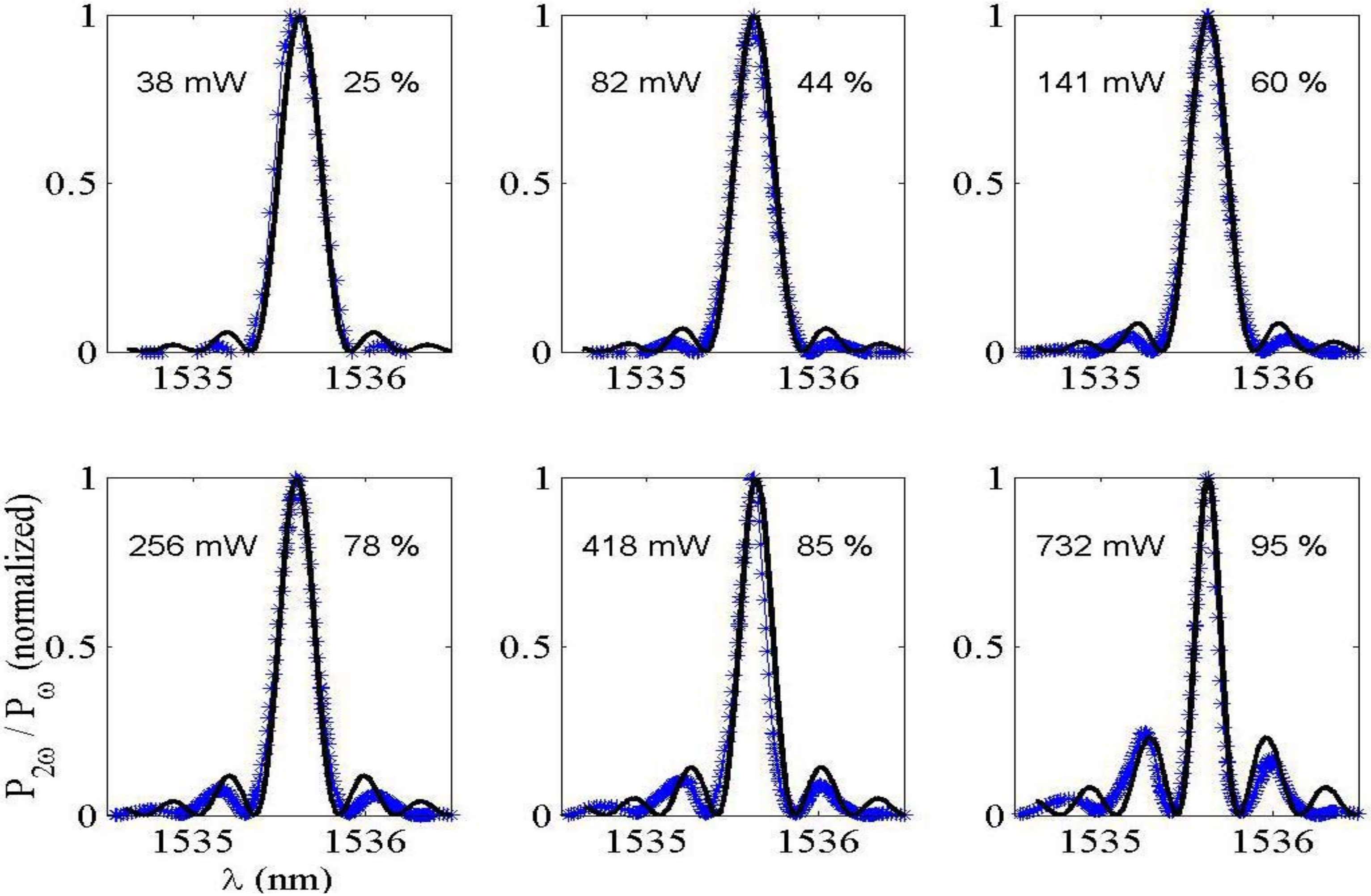


Pump Depletion Results

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

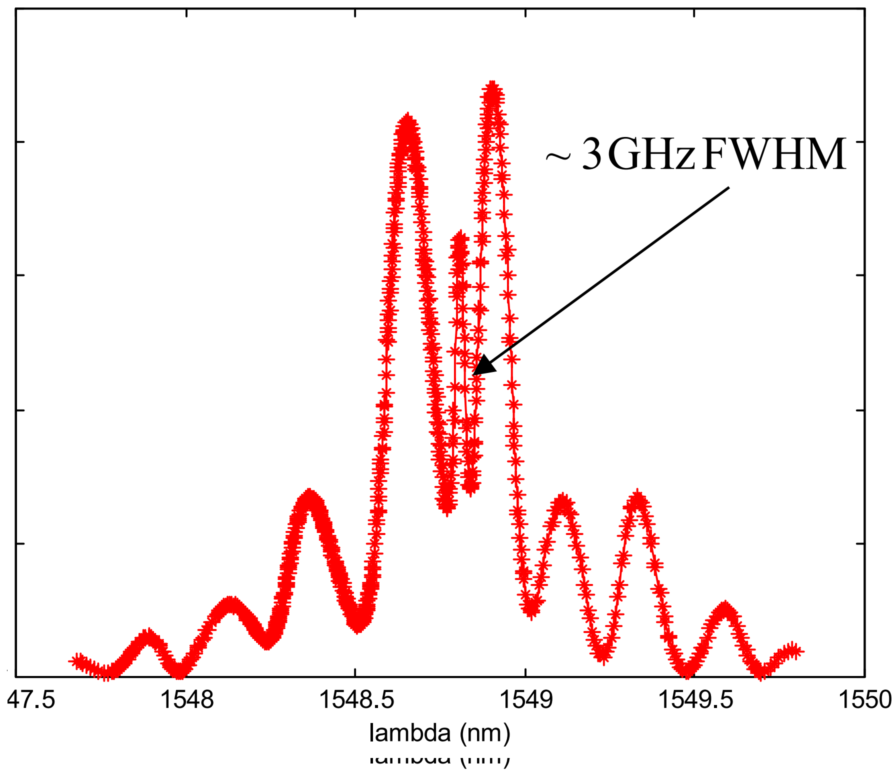


Measured Tuning Curves



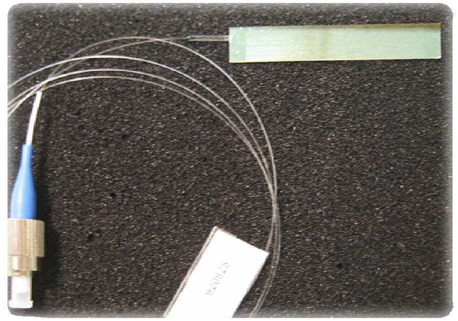
Into High-Gain Regime

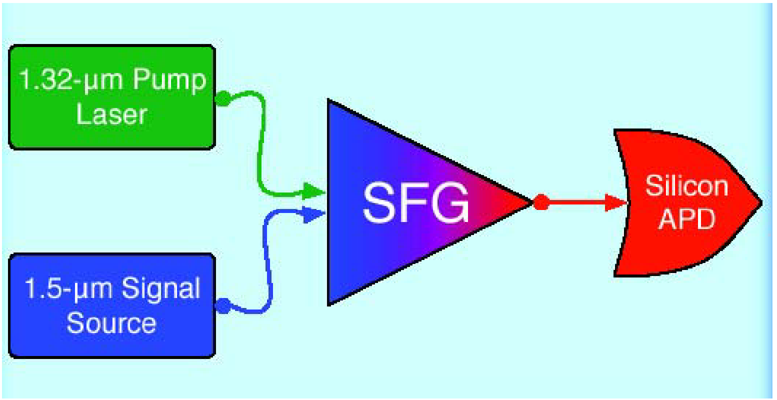
- Experiment done with longer sample
- Parametric amplification of ASE from pump laser induces back conversion
  - precludes quantitative analysis

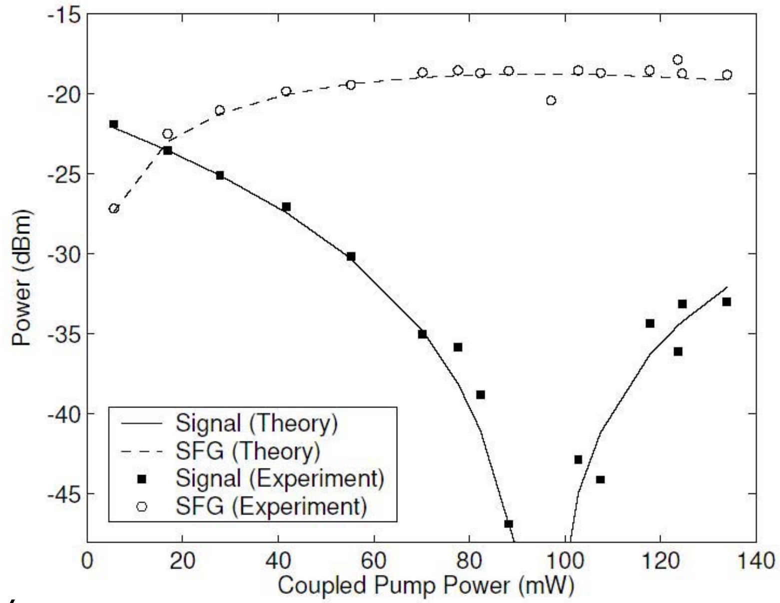


Photon Counting at 1.5 μm

- 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

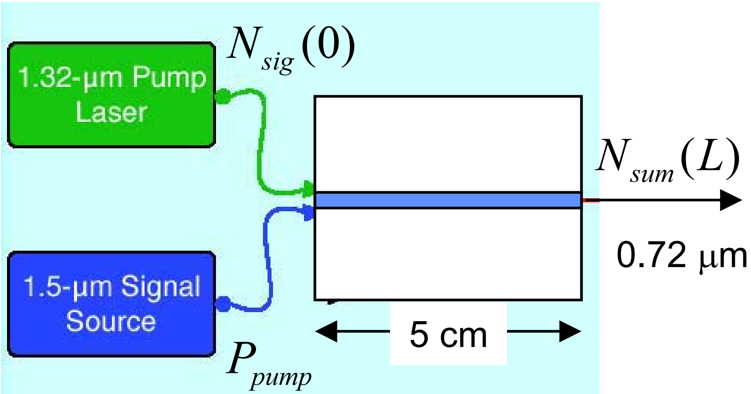
- Easier (and more useful) to deplete SFG

$$\frac{N_{sum}(L)}{N_{sig}(0)} = \cos^2\left(\sqrt{4\Gamma P_{pump}}\right)$$

$$\frac{N_{sig}(L)}{N_{sig}(0)} = \sin^2\left(\sqrt{4\Gamma P_{pump}}\right)$$

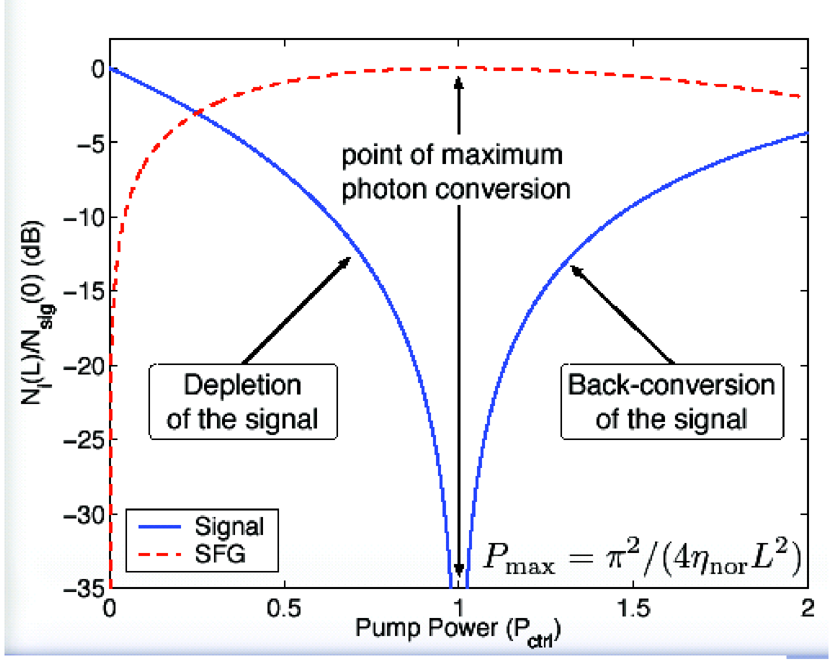
  – predict total conversion for 50 - 100 mW pump

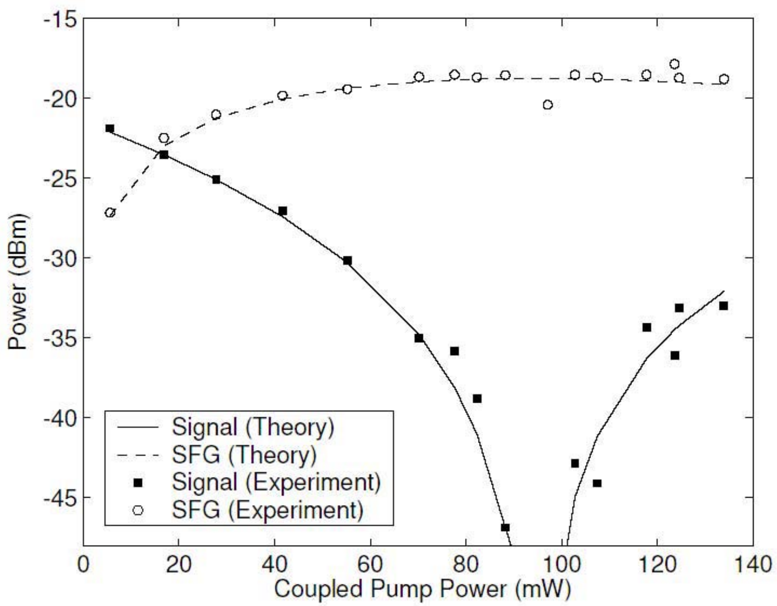
- Experiment: 5 cm PPLN waveguide



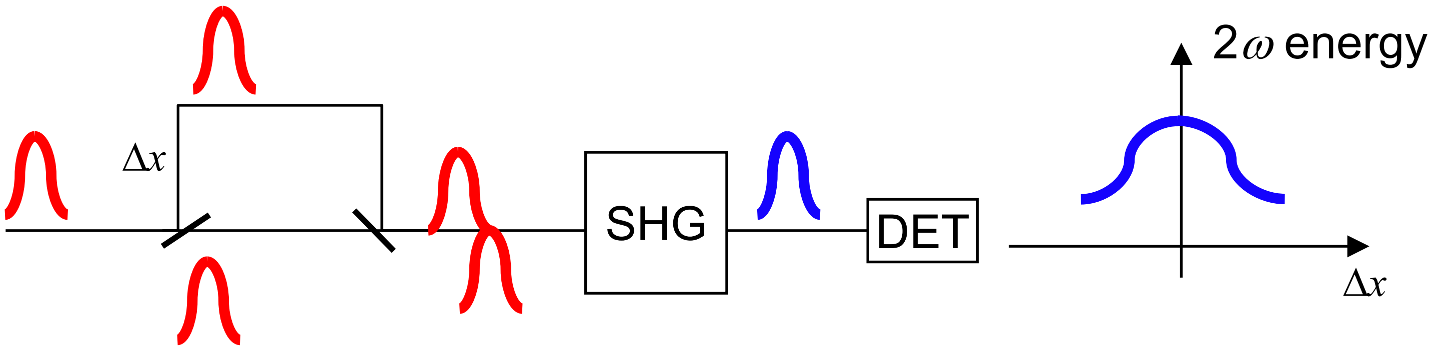
> 99% conversion at P_{pump} = 88 mW

[C. Langrock, R. Roussev]

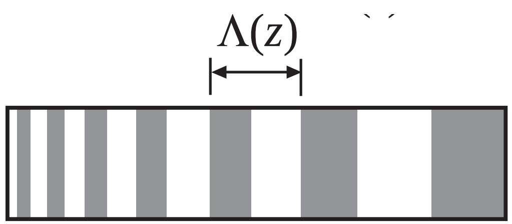




Low Power Autocorrelator for Ultrafast Pulse Measurements

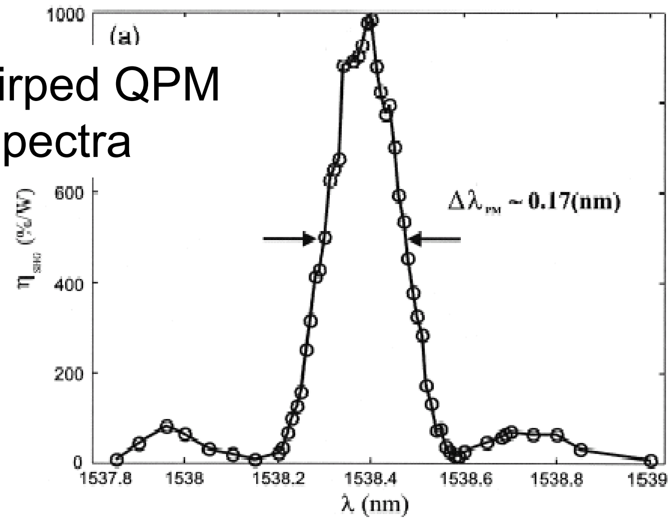


- Autocorrelation is a common pulse measurement tool
  - measure 2ω energy vs time delay
  - infer pulse duration
- Requires a nonlinear process like SHG
  - makes measurement at low energies challenging
  - needs adequate spectral bandwidth to accommodate pulse spectrum
- Combine two ideas
  - waveguide for high efficiency
  - chirped QPM grating to obtain bandwidth

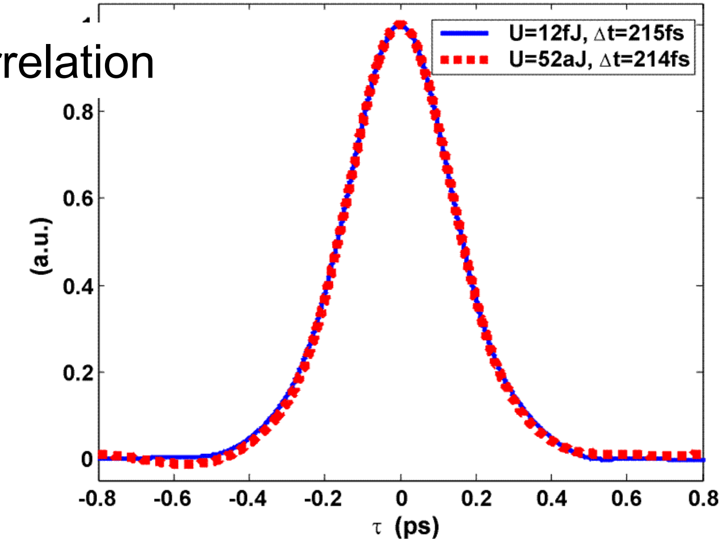


Autocorrelation with 400 Photons

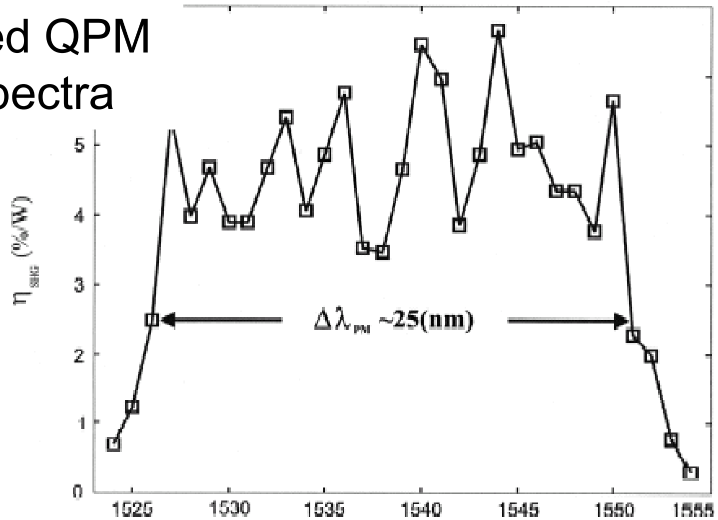
unchirped QPM
PM spectra



autocorrelation



chirped QPM
PM spectra



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

52 attoJoules
400 photons (!)
1000x more sensitive

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

A. Weiner, Purdue

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