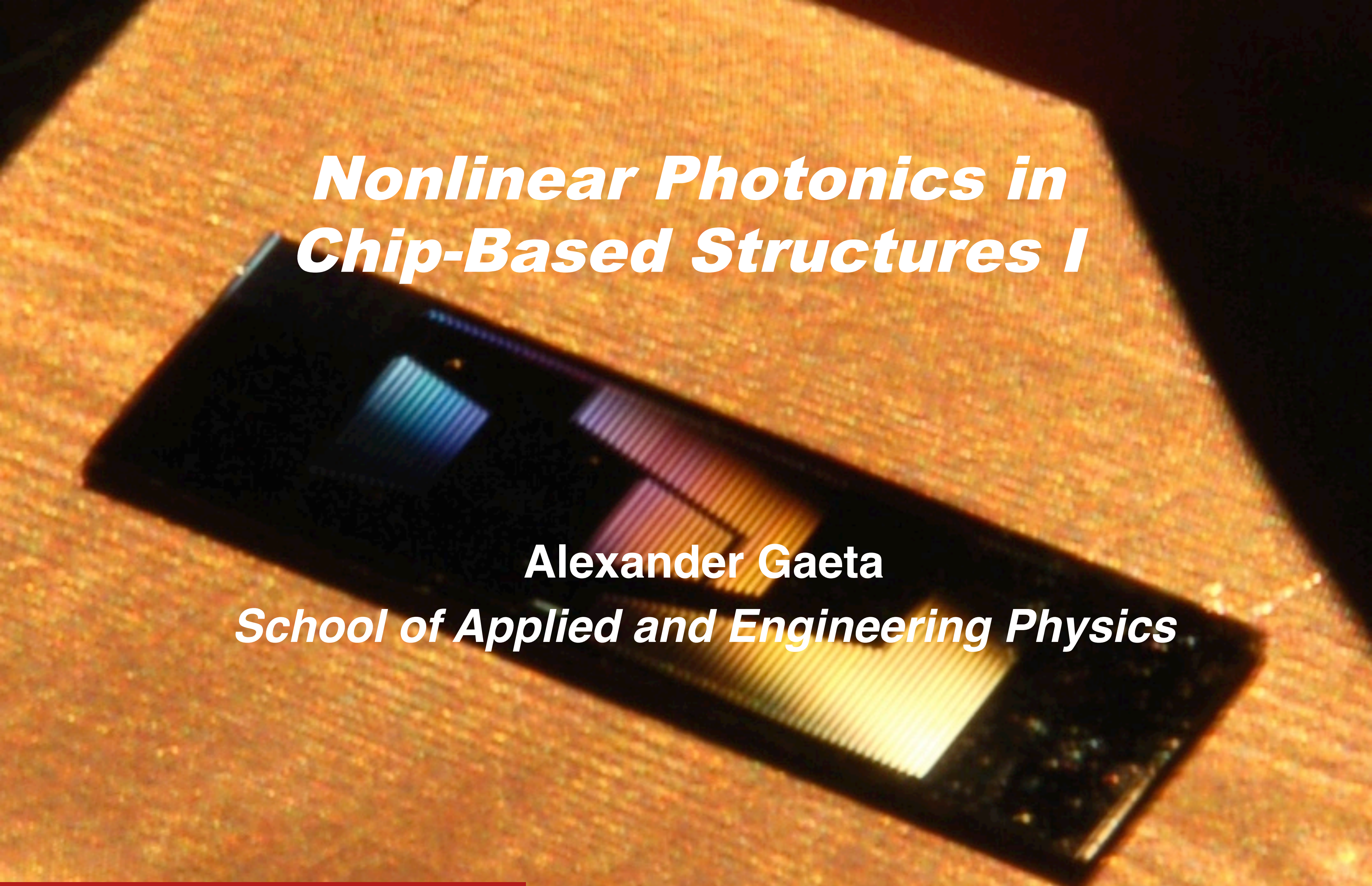


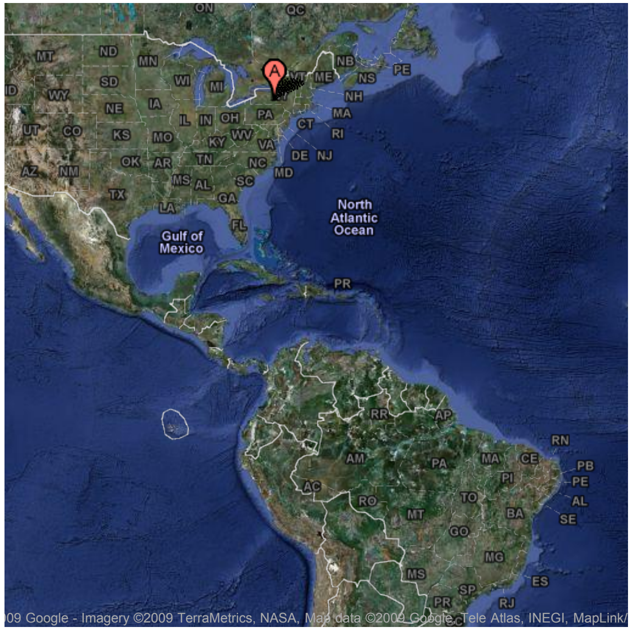
Nonlinear Photonics in Chip-Based Structures I

Alexander Gaeta

School of Applied and Engineering Physics

Cornell University

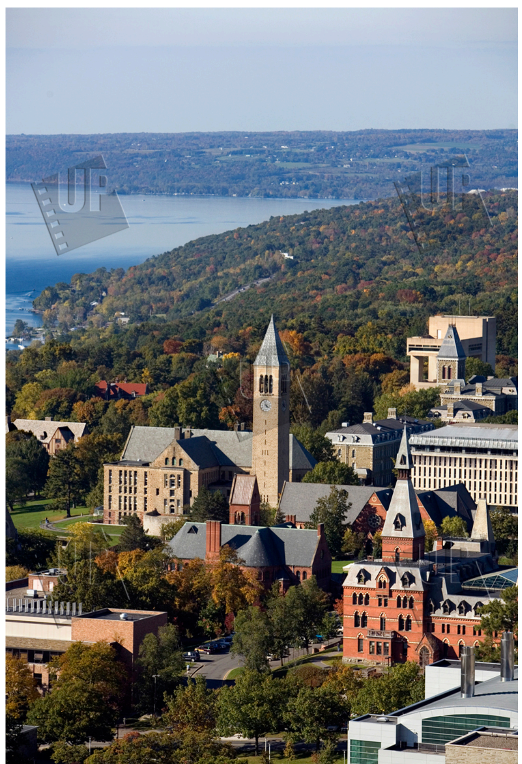
ICTP Summer School on Nonlinear Optics and Nanophotonics
Sao Paulo, December 2013



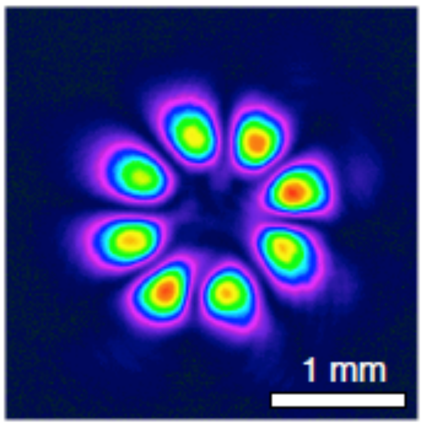
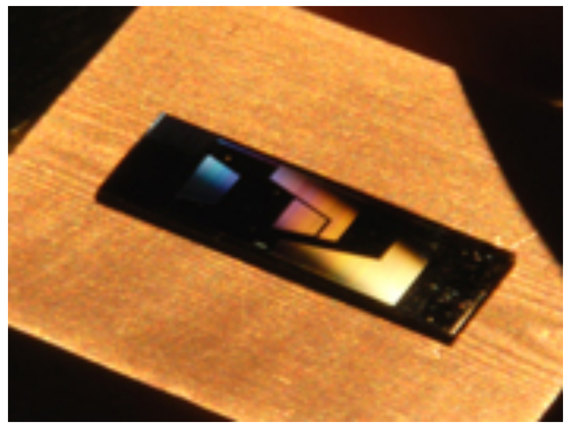
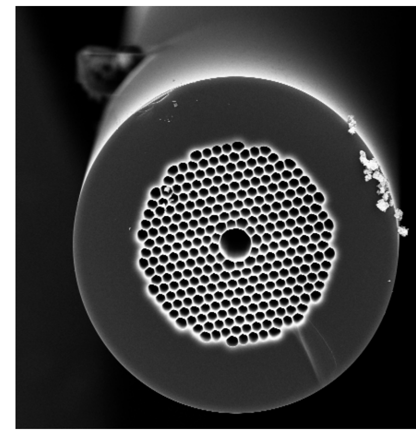
Cornell University

Undergraduate: 14,000

Graduate: 6,000



Light-Matter Interactions over 23-Orders of Magnitude

Ultrafast Propagation Dynamics	Chip-Based Nanophotonics	Photonic Crystal Fibers
		
10 MW – 1 TW	100 μW – 1 W	10 pW – 1 μW

Outline: Nonlinear Photonics in Chip-Based Structures

Lecture I

- Brief review of nonlinear optics
- Nonlinear processes in nanowaveguides
- Four-wave mixing (FWM) in Si nanowaveguides
    - ✧ Dispersion engineering
    - ✧ Ultra-broadband wavelength conversion
    - ✧ Applications: correlated photons, signal regeneration

Lecture II

- Optical parametric oscillators
- Broad-band frequency combs, ultrashort-pulse generation, WDM source

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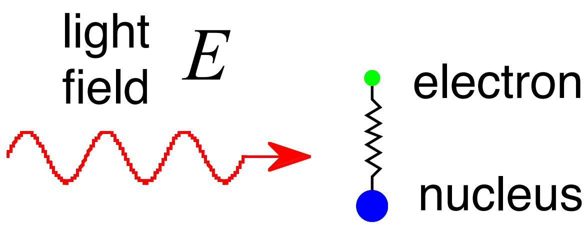
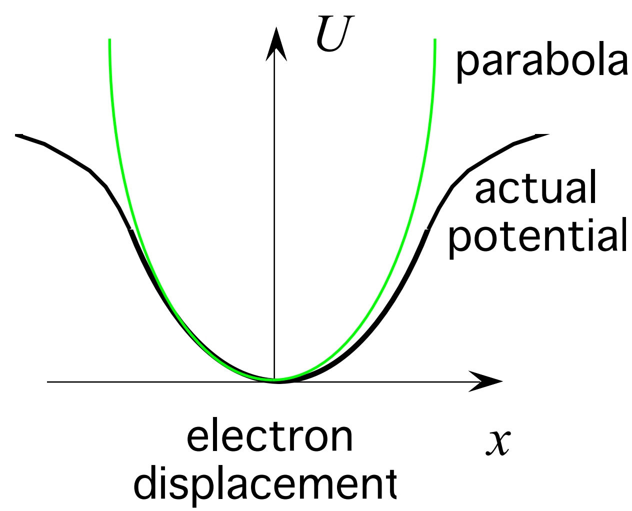
Nonlinear Optics: Interaction of Laser Light with Matter

- Microscopic picture: Lorentz-atom model.





restoring force: $F_{res} = -kx + ax^2 + bx^3 + \ldots$

- Macroscopic picture: nonlinear dependence on applied field.

polarization of the medium

$$P = \chi^{(1)} E + \cancel{\chi^{(2)}} E^2 + \chi^{(3)} E^3 + \ldots$$

linear susceptibility

nonlinear susceptibilities

2nd-Order Nonlinear Processes

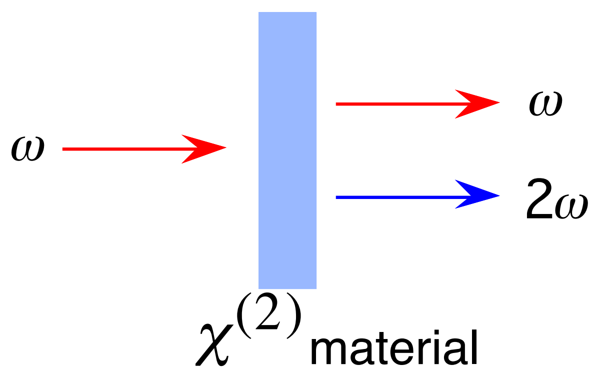
- Consider oscillating electric field: $E(t) = A\cos\omega t$

- $\chi^{(2)}$ effects: second-harmonic generation:

$$P^{(2)}(t) = \chi^{(2)} E^2(t) = \chi^{(2)} \frac{A^2}{2}(1 + \cos 2\omega t)$$

dc   second-harmonic

frequency doubling



- Other processes:
  - terahertz generation
  - sum- and difference-frequency generation
  - optical parametric amplification

- Only occurs in non-centrosymmetric crystals.
  - requires phase-matching (e.g., $n_\omega = n_{2\omega}$)

3rd-Order Nonlinear Processes

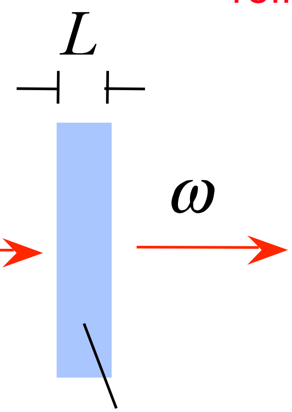
- $\chi^{(3)}$ effects: intensity-dependent refractive index

$$P^{(3)}(t) = \chi^{(3)} E^3(t) = \chi^{(3)} \frac{A^3}{4}\left(3\cos\omega t + \cos 3\omega t\right)$$

intensity-dependent refractive index

3rd-harmonic (usually not phase matched)

<u>All materials exhibit a nonlinear refractive index (usually $n_2 > 0$)</u>



$$A_{in} \xrightarrow{\ \omega\ } \qquad \xrightarrow{\ \omega\ } A_{out} = A_{in} e^{i\phi_{nl}}$$

$$n_2^{glass} \sim 10^{-16}\ \mathrm{cm}^2/\mathrm{W}$$

$$n_2^{Si} \sim 10^{-14}\ \mathrm{cm}^2/\mathrm{W}$$

$$n_2^{air} \sim 10^{-20}\ \mathrm{cm}^2/\mathrm{W}$$

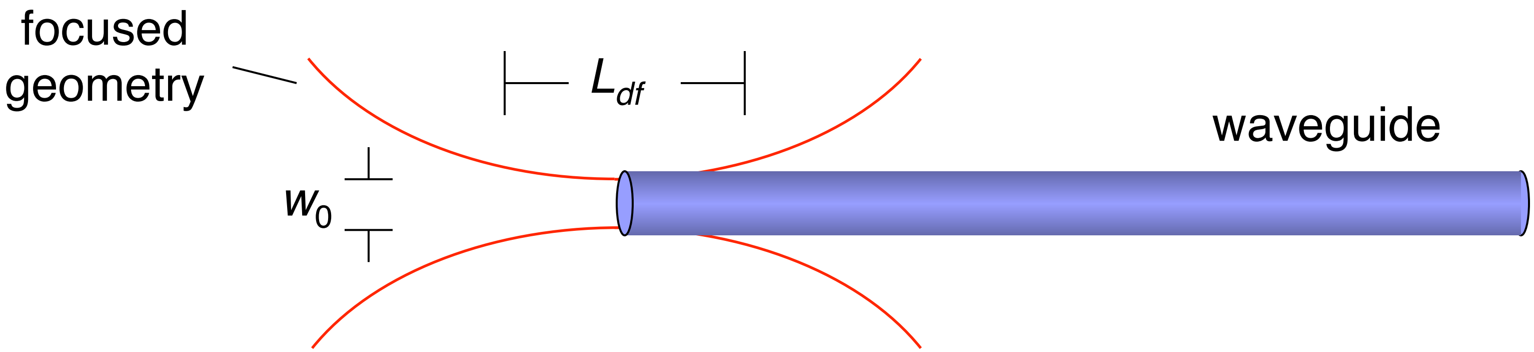
$$n_2 \propto \mathrm{Re}\left\{\chi^{(3)}\right\}$$

$$n = n_0 + n_2 I$$

intensity

- Nonlinear phase shift is important when: $\phi_{nl} = \frac{2\pi}{\lambda} n_2 I L \geq \pi$

Nonlinear Interactions: Why Waveguides?



power

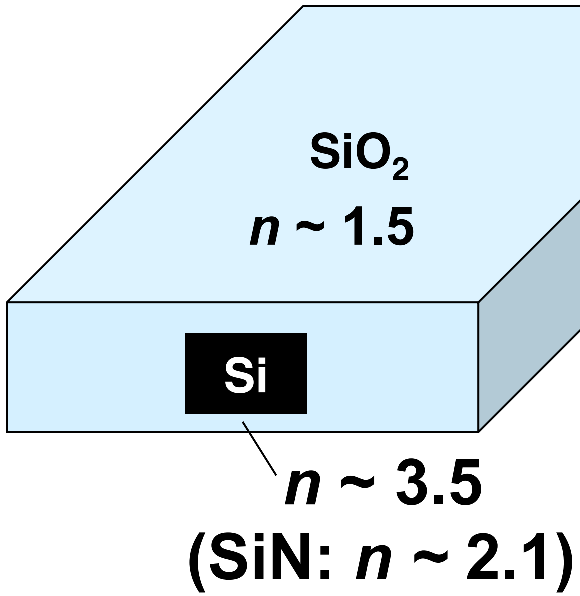
nonlinear parameter $\phi_{NL} = \kappa_{NL} \dfrac{P}{w_0^{\,2}} L$

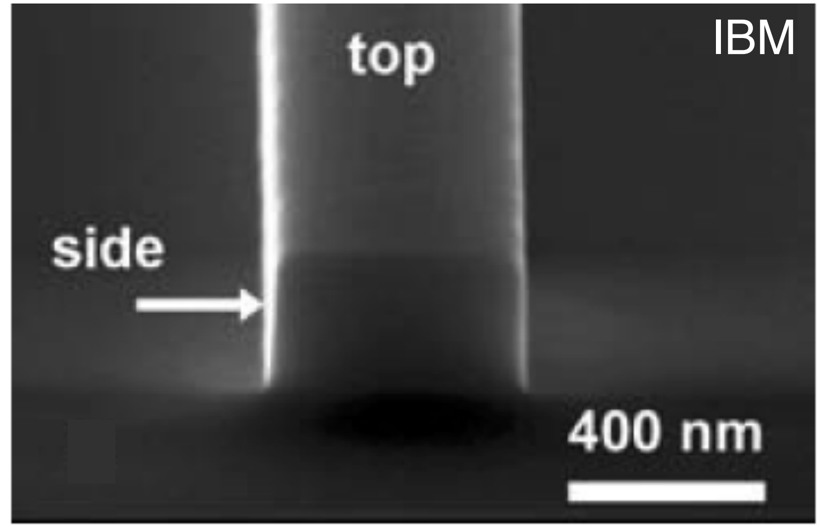
area

interaction length

- **Interaction length can be >> the diffraction length.**
- **Dispersion can be engineered.**

Nonlinear Optics in Silicon-Based Nanowaveguides

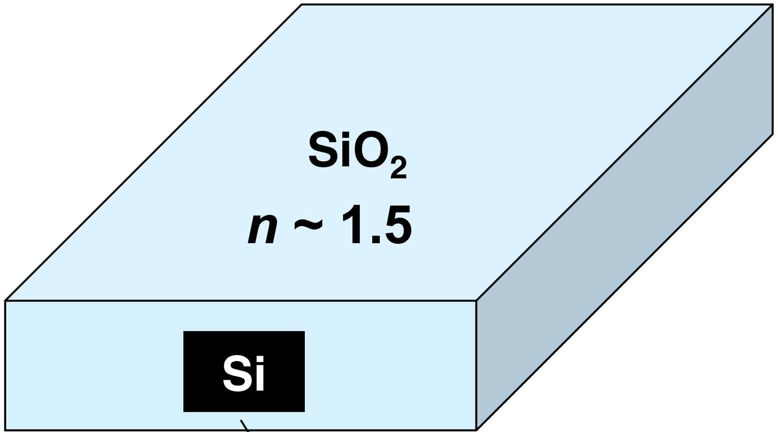




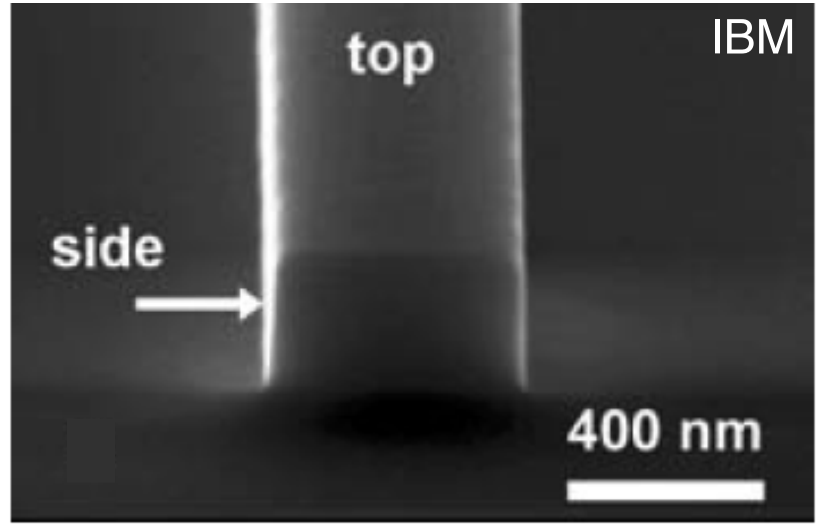
Absorption edge: Silicon => ~ 1.1 μm Si_3N_4 => ~ 400 nm

- Nonlinearity of Silicon 100X (Si_3N_4: 10X) silica
- Losses: Silicon – 2 dB/cm (Si_3N_4 – 0.2 dB/cm)
- Light confined to a region < than a wavelength.

Nonlinear Optics in Silicon-Based Nanowaveguides



$n \sim 3.5$
(SiN: $n \sim 2.1$)



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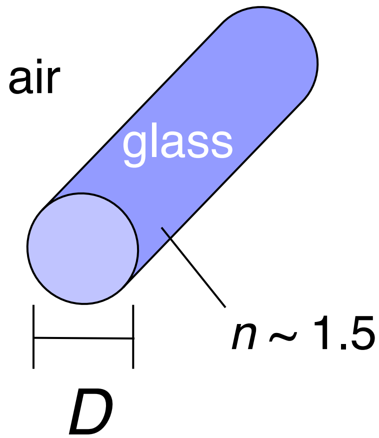
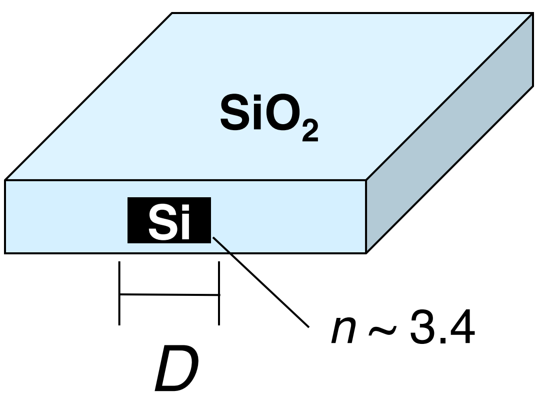
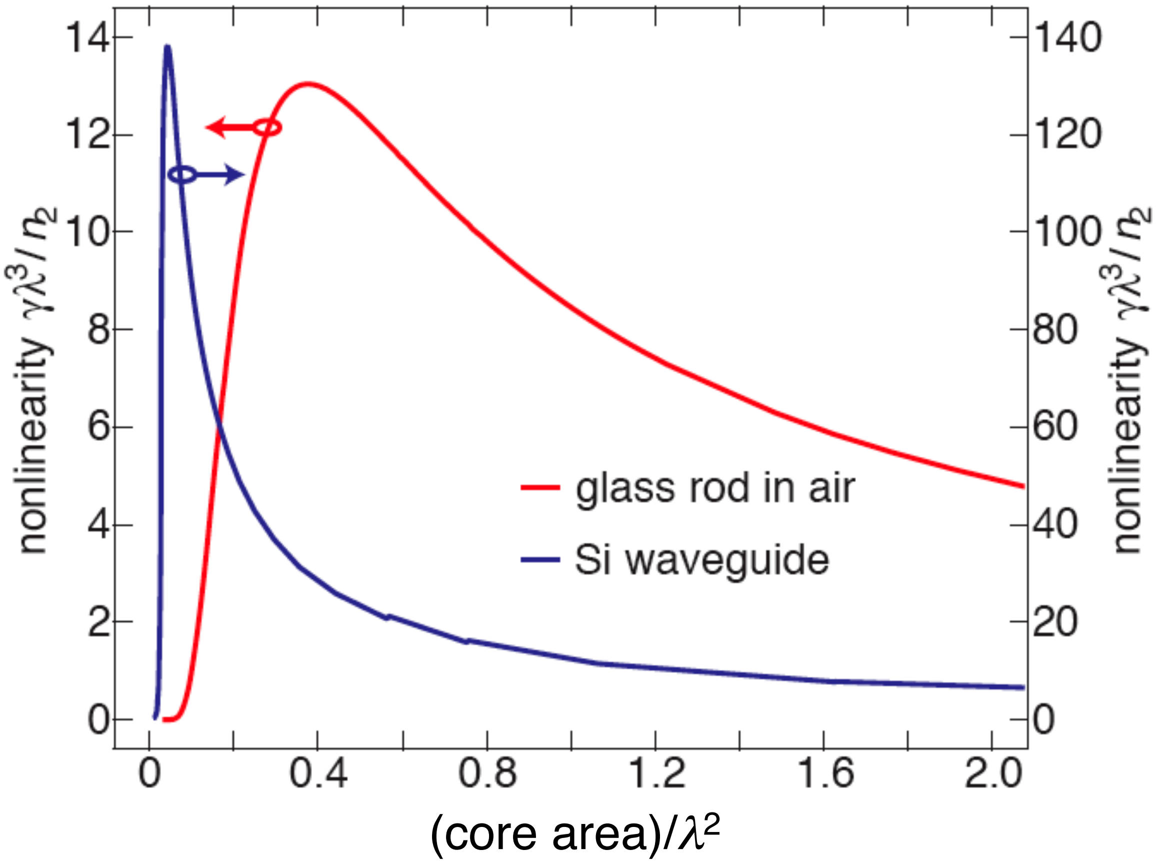
- **Dispersion can be engineered.**

Confinement Properties of Ultra-Small-Core Waveguides





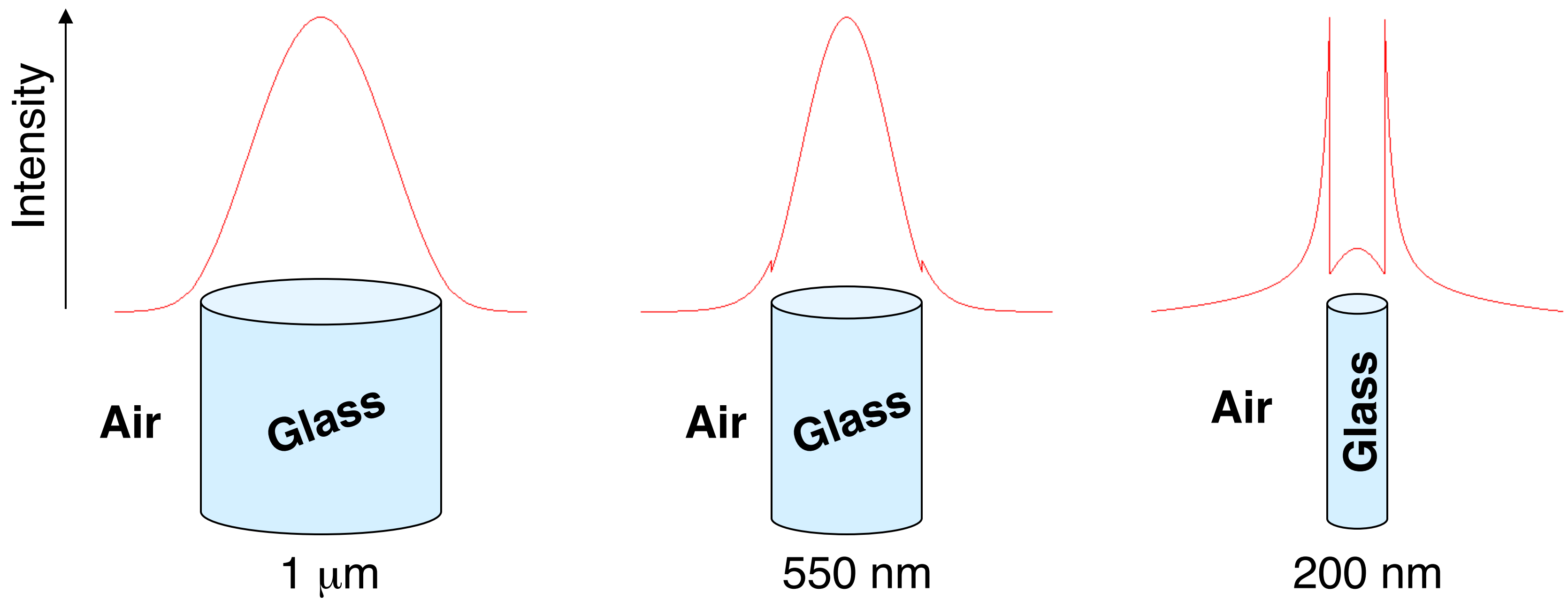


$$D_{optimal} < \lambda$$

Foster, Moll, and Gaeta, *Opt. Express* **12**, 2880 (2004)

Confinement Properties

λ = 800 nm



NLO in Silicon-Based Waveguides

- Raman scattering
  - ✧ Raman gain & oscillation [Claps et al 2003; Rong et al 2004; Espinola et al 2004; Xu, et al. 2005; Rong et al 2004; Boyraz et al 2004]
  - ✧ Raman-induced slow light [Okawachi et al 2006]
  - ✧ Zeno-switching [Wen et al 2011]
- Instantaneous Kerr nonlinearity
  - ✧ phase modulation & continuum generation [Tsang et al 2002; Boyraz et al 2004; Dulkeith et al, 2006; Hsieh et al, 2006; Hsieh, et al 2007; Koonath, et al 2007; Kuyken, et al. 2011; Halir, et al 2012]
  - ✧ harmonic generation [Corcoran et al. 2009; Levy et al. 2011]
- Four-wave mixing [Dimitropoulos et al 2004; Fukuda et al 2005; Espinola et al 2005; Yamada et al 2006; Rong et al 2006; Foster et al. 2006; Koos et al 2009); McMillan et al 2010; Zlatanovic et al. 2010; Xiaoping et al. 2010; Kuyken et al. 2011; Hu, et al. 2011]
  - ✧ generation of correlated photons [Sharping, et al. 2006; Harada et al 2007; Clemmen et al 2008]
  - ✧ signal regeneration [Salem, et al 2007, 2008]
  - ✧ parametric oscillation & comb generation (Levy, et al 2010; Foster et al 2011; Okawachi et al 2011; Ferdous et al. 2011); Herr, et al 2012]
  - ✧ ultrafast processing [Foster, et al 2008; Salem et al 2008; Corcoran et al 2010; Christian, et al. 2011]

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Reviews: Foster, et al. *Opt. Express* **16**, 1300 (2008)

Osgood, et al., *Adv. Opt. Phot.* **1**, 162 (2009)

Leuthold, et al., *Nat. Phot.* **4** 535 (2010).

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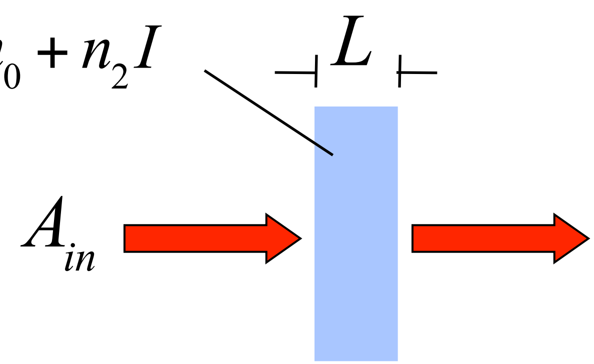
Self- and Cross-Phase Modulation

- Self-phase modulation (SPM)

$n = n_0 + n_2 I$

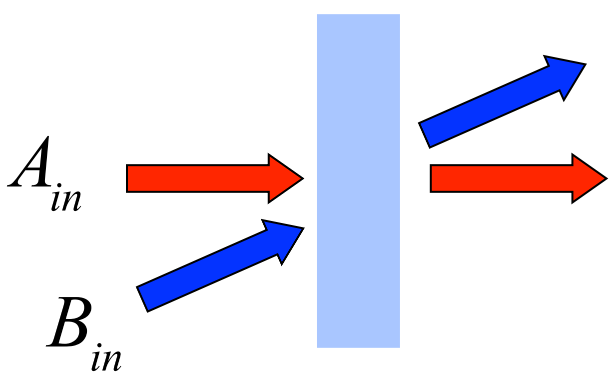


$A_{out} = A_{in} e^{i\phi_{nl}}$

SPM

$$\phi_{nl} = \gamma I L$$

- Cross-phase modulation (XPM)



$A_{out} = A_{in} e^{i\phi_{nl}}$

XPM

$$\phi_{nl} = \gamma (I_A + 2 I_B) L$$

Self-Phase Modulation w/ Pulses

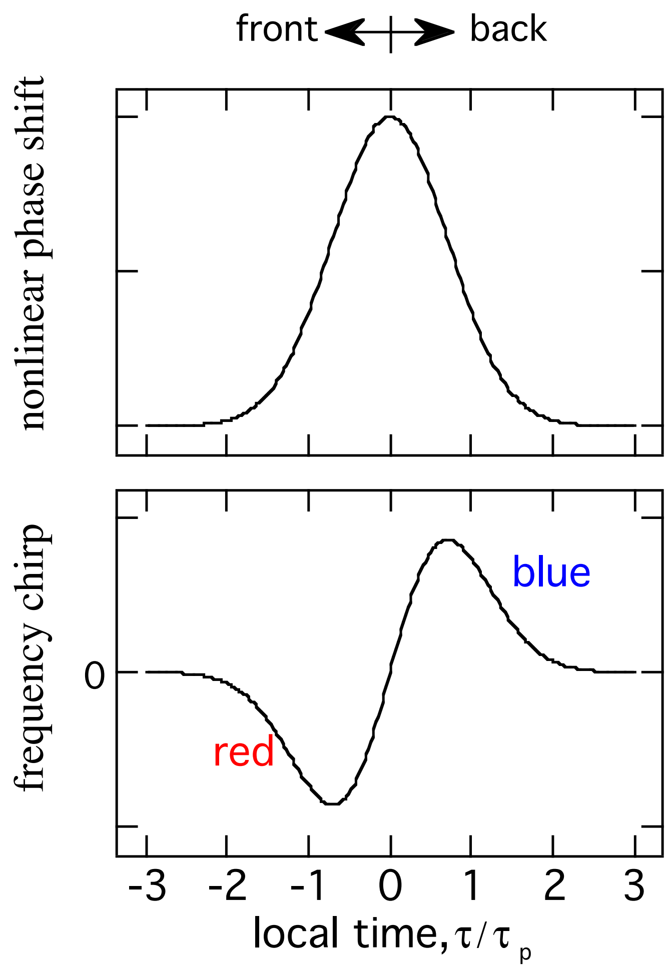
- Neglect dispersion:

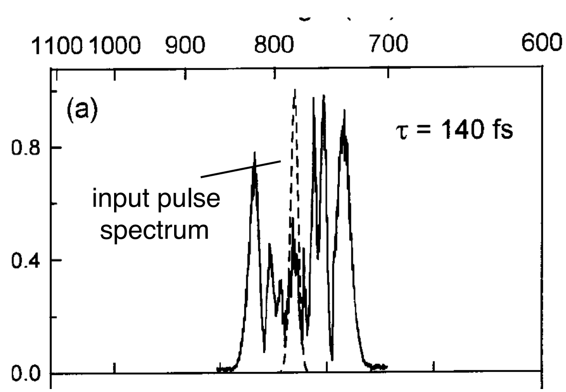
output field $$A_{out}(\tau) = A_{in}(\tau)e^{i\phi_{nl}(\tau)}$$

nonlinear phase shift $$\phi_{nl}(\tau) = \frac{2\pi}{\lambda} n_2 I_{in}(\tau) L$$

frequency chirp $$\delta\omega(\tau) = -\frac{\partial\phi_{nl}}{\partial\tau} \propto \frac{\phi_{nl}^{\max}}{\tau_p}$$

- Pulse duration is unchanged, but spectrum is broadened.

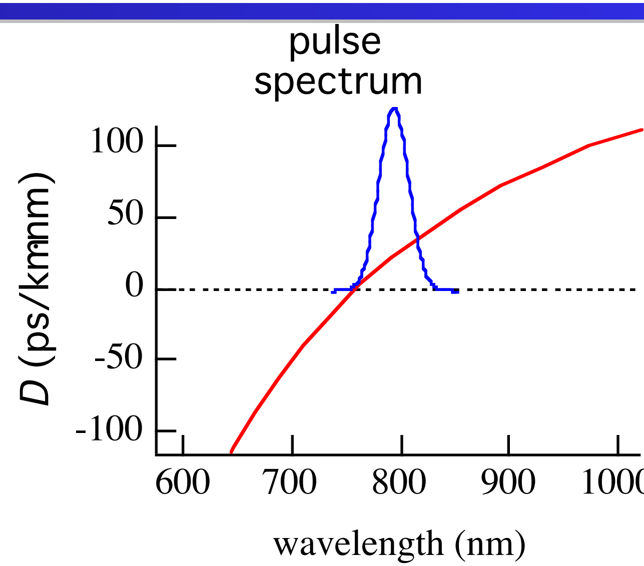


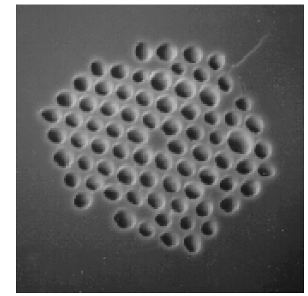


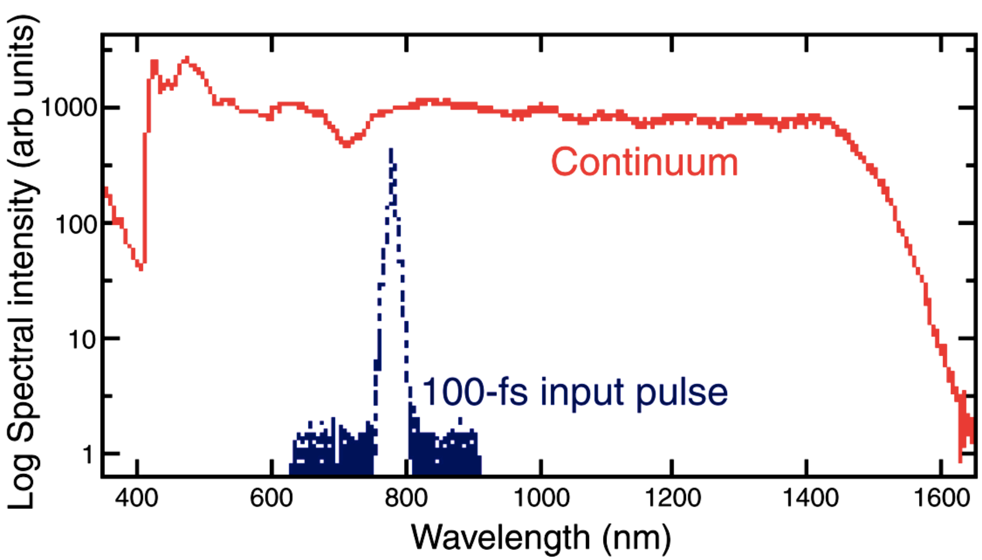
Nisoli, et al. Appl. Phys. B (1997)

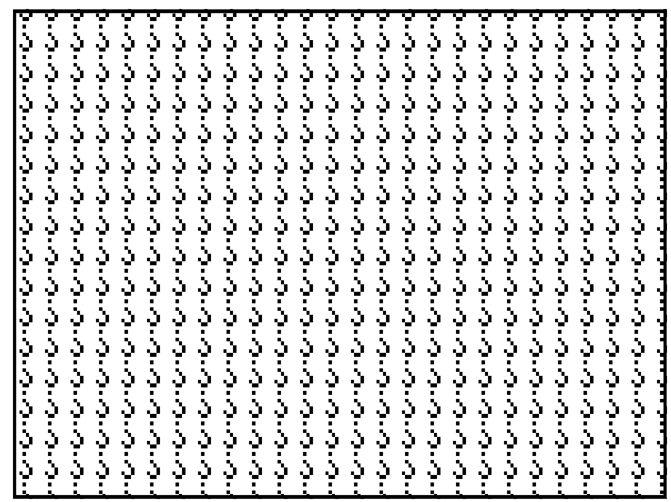
Supercontinuum Generation in Optical Waveguides

- Initial observation: Inject < 100 fs pulses directly from Ti:sapphire modelocked oscillator.
- Combination of small core and zero group-velocity dispersion allow for broad supercontinuum spanning > octave.





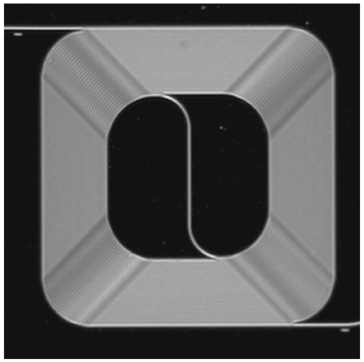


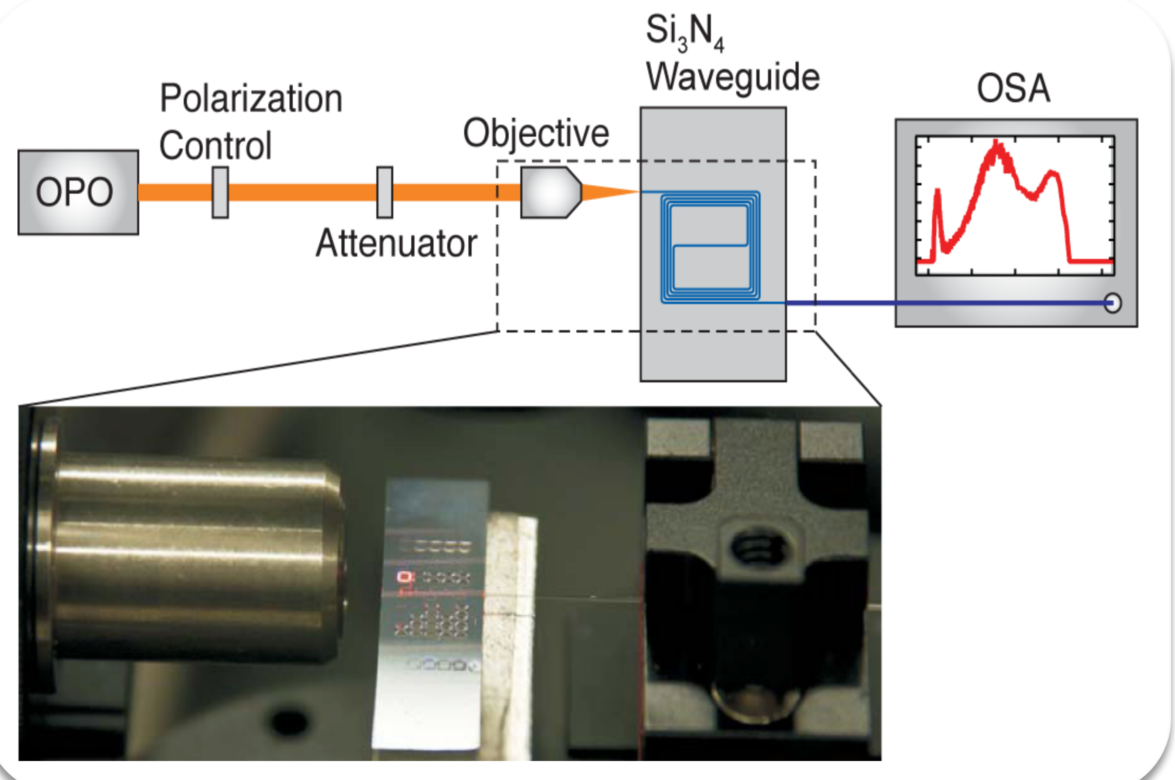


Ranka et al. 2001

Experimental Setup for Supercontinuum Generation

- Si_3N_4 spiral waveguide with 4.3 cm length, 715 x 1100 nm cross section
- 0.8 dB/cm propagation loss
- 80-MHz repetition rate, 200-fs pulsewidth OPO centered at 1335 nm
- Quasi-TE polarization





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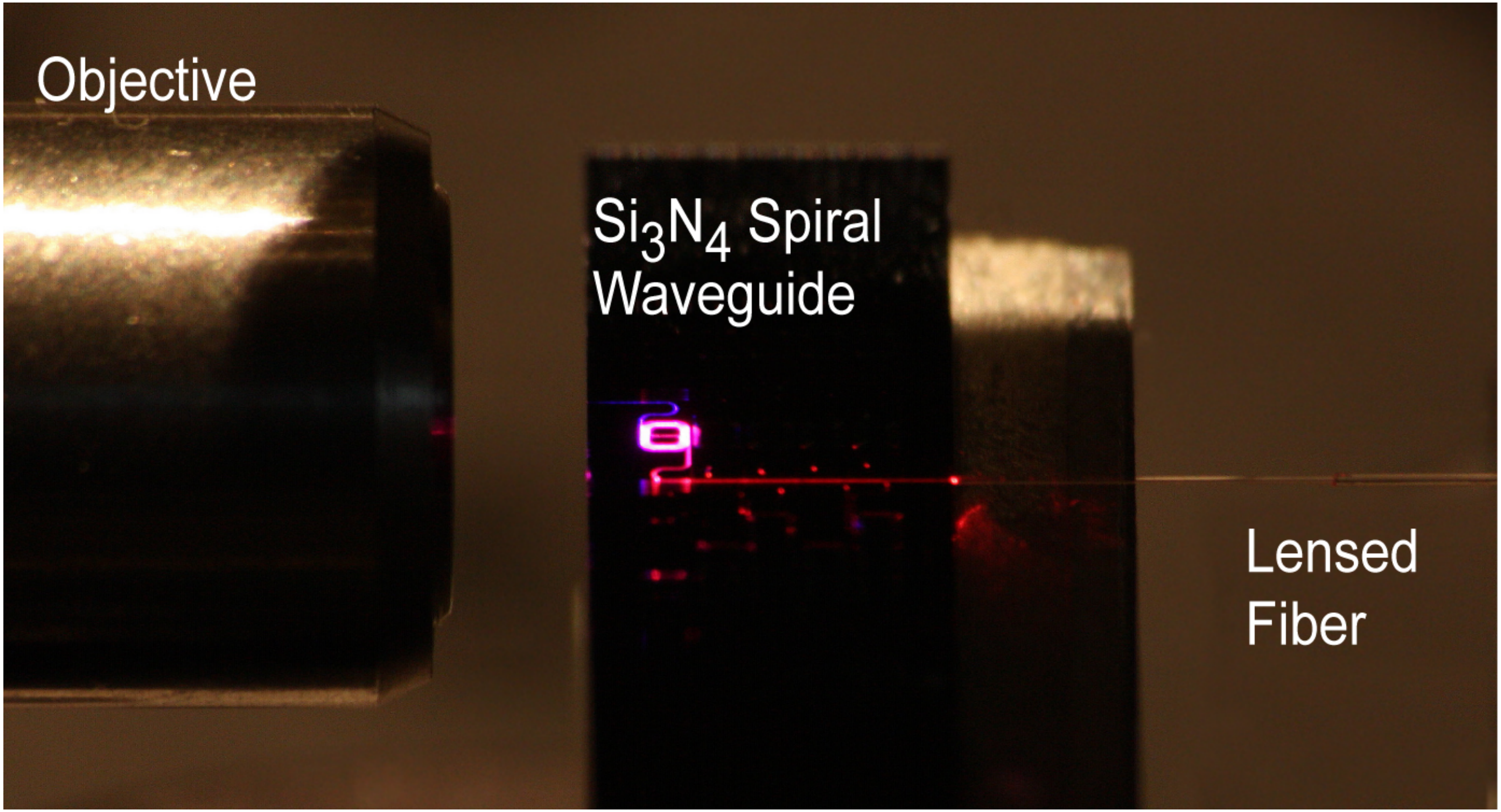
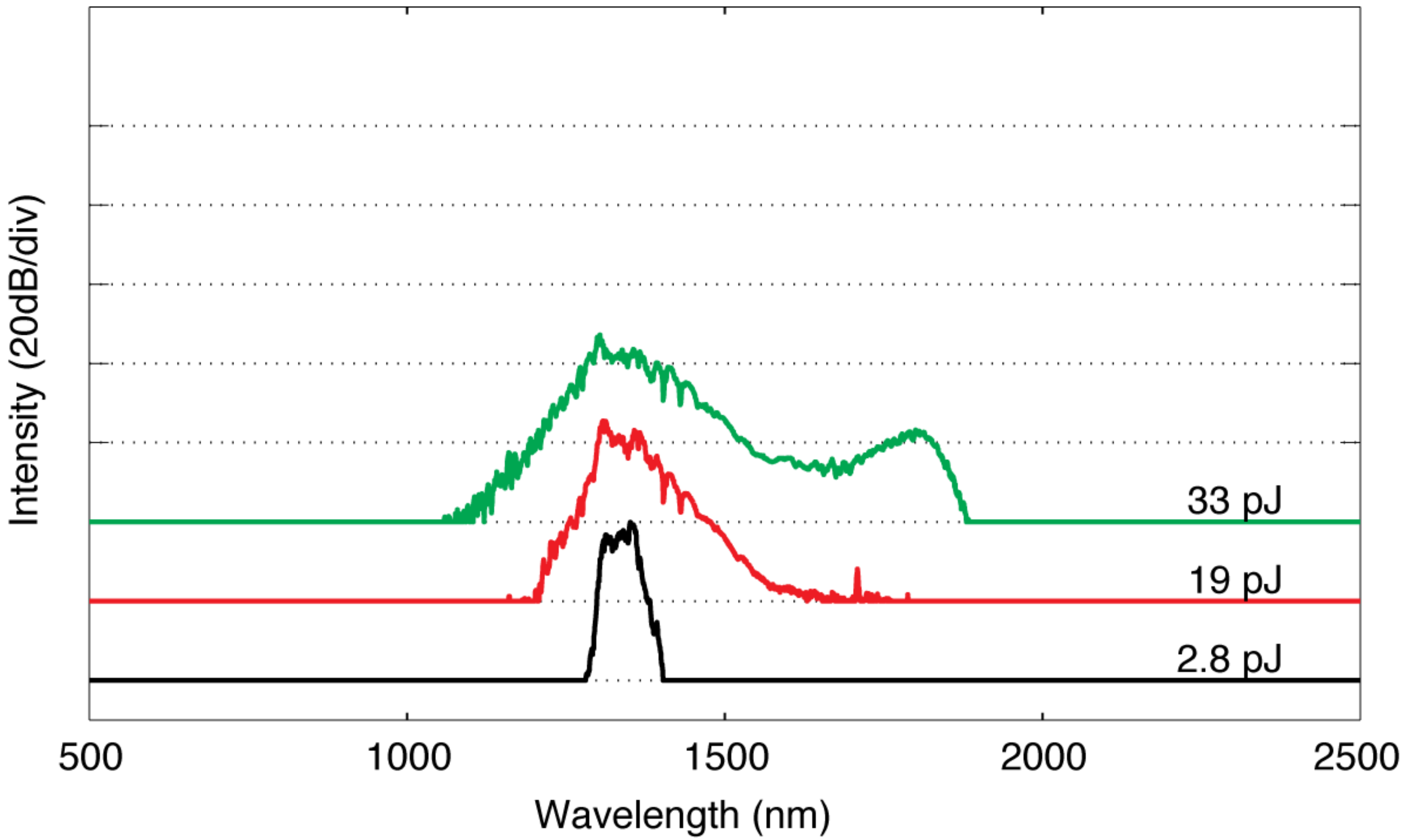


Supercontinuum Generation in Si_3N_4 Waveguide

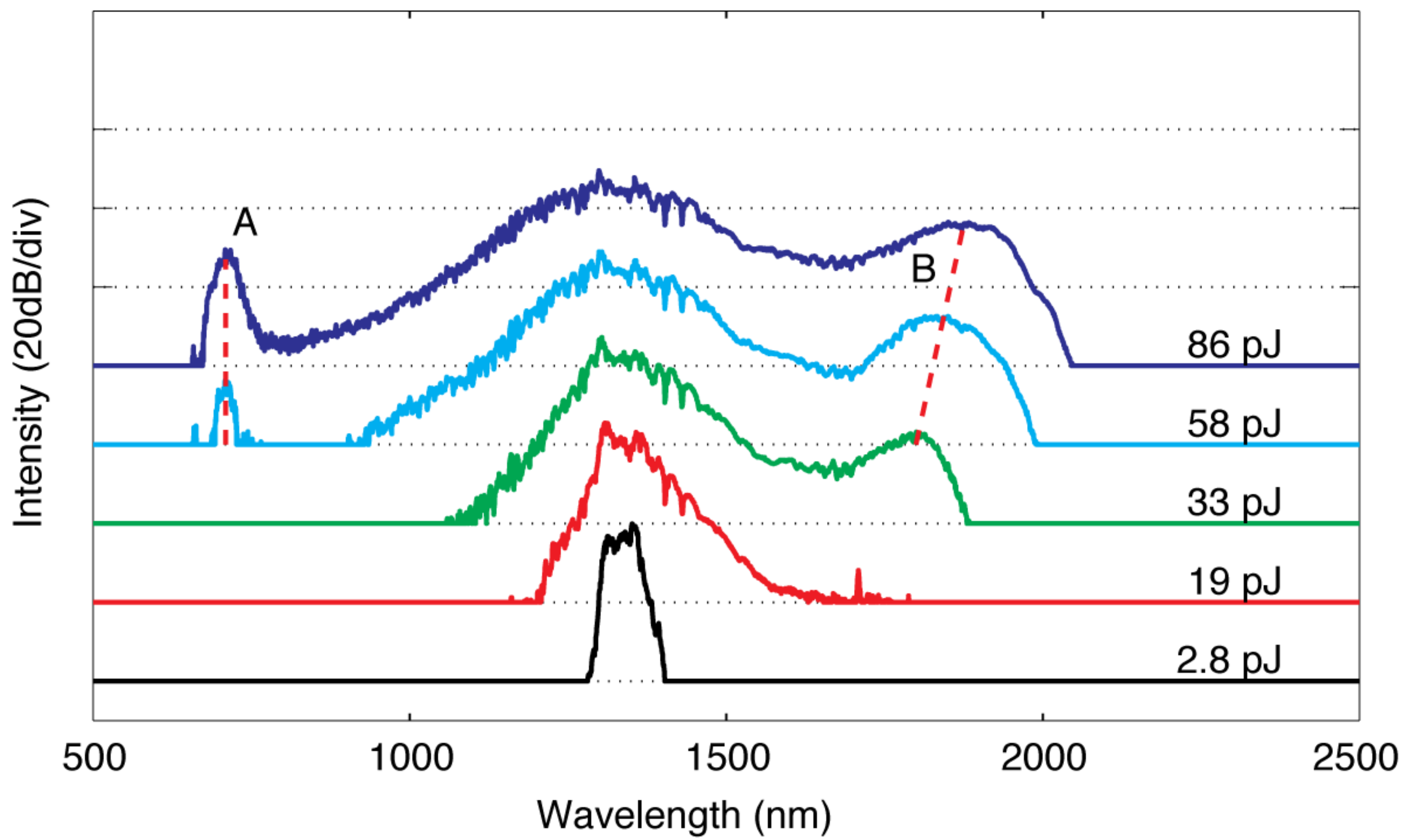


- Peak appears at 1800 nm

→ onset of soliton fission

Halir, Okawachi, Levy, Foster, Lipson, and Gaeta , *Opt. Lett.* (2012).

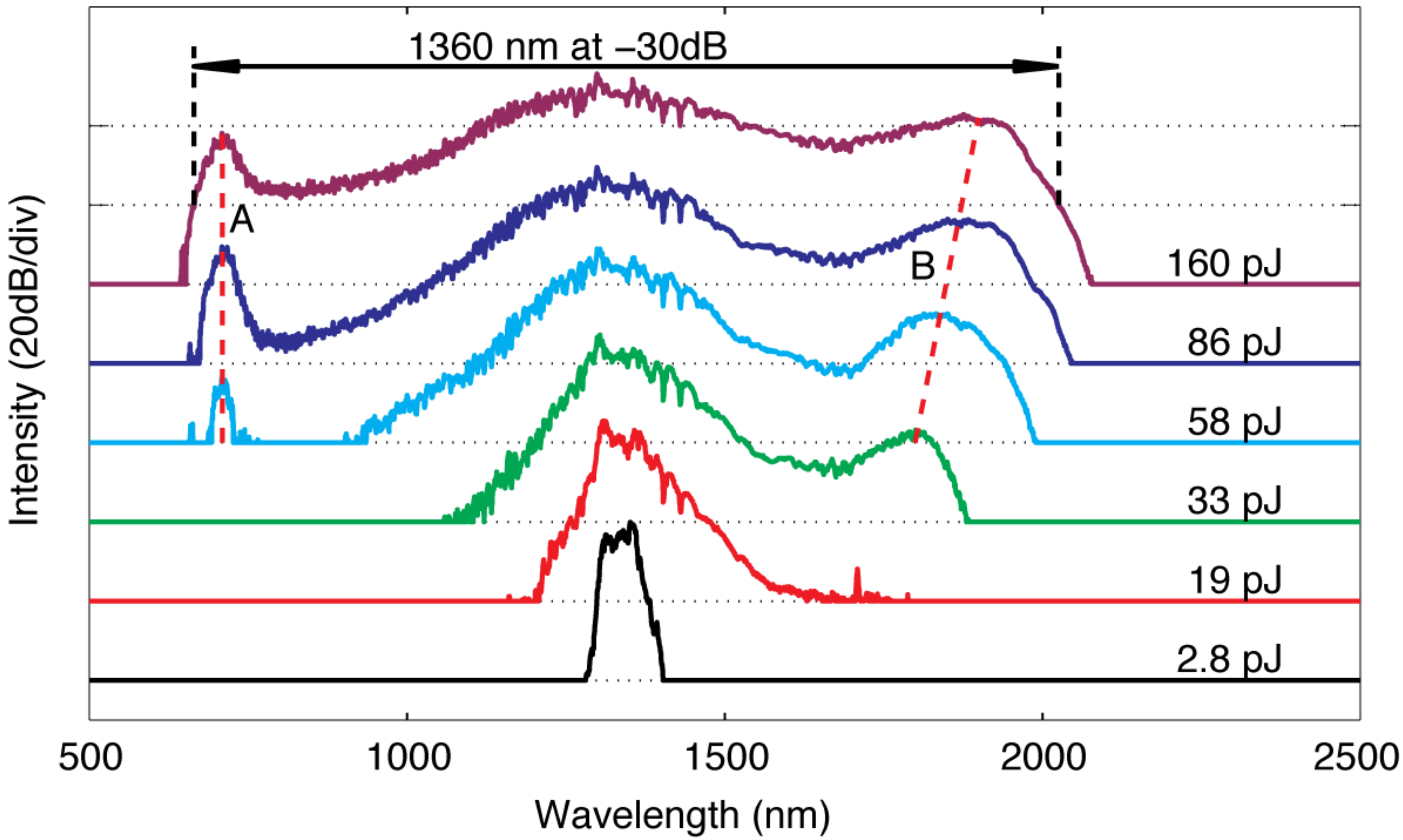
Supercontinuum Generation in Si_3N_4 Waveguide



- Self-frequency shift → 1800 nm peak to higher wavelengths
- Dispersive wave generation at 710 nm seeded by soliton fission

Halir, Okawachi, Levy, Foster, Lipson, and Gaeta , *Opt. Lett.* (2012).

Supercontinuum Generation in Si_3N_4 Waveguide



- Supercontinuum generation spans from 665 nm to 2025 nm

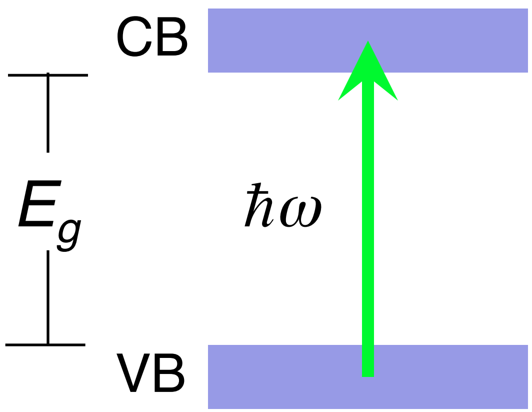
  → 1.6 octave span

Halir, Okawachi, Levy, Foster, Lipson, and Gaeta, *Opt. Lett.* (2012).

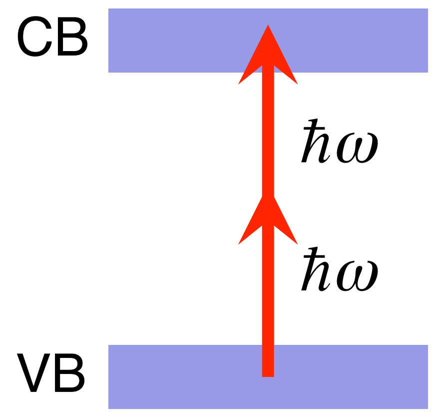
Im{ $\chi^{(3)}$ } – Nonlinear Absorption

- 1- and 2-photon resonances lead to absorption

Saturated Absorption



Two-Photon Absorption



intensity

$$\frac{dI}{dz} = -\alpha_0 \left(1 - \frac{I}{I_s}\right) I$$

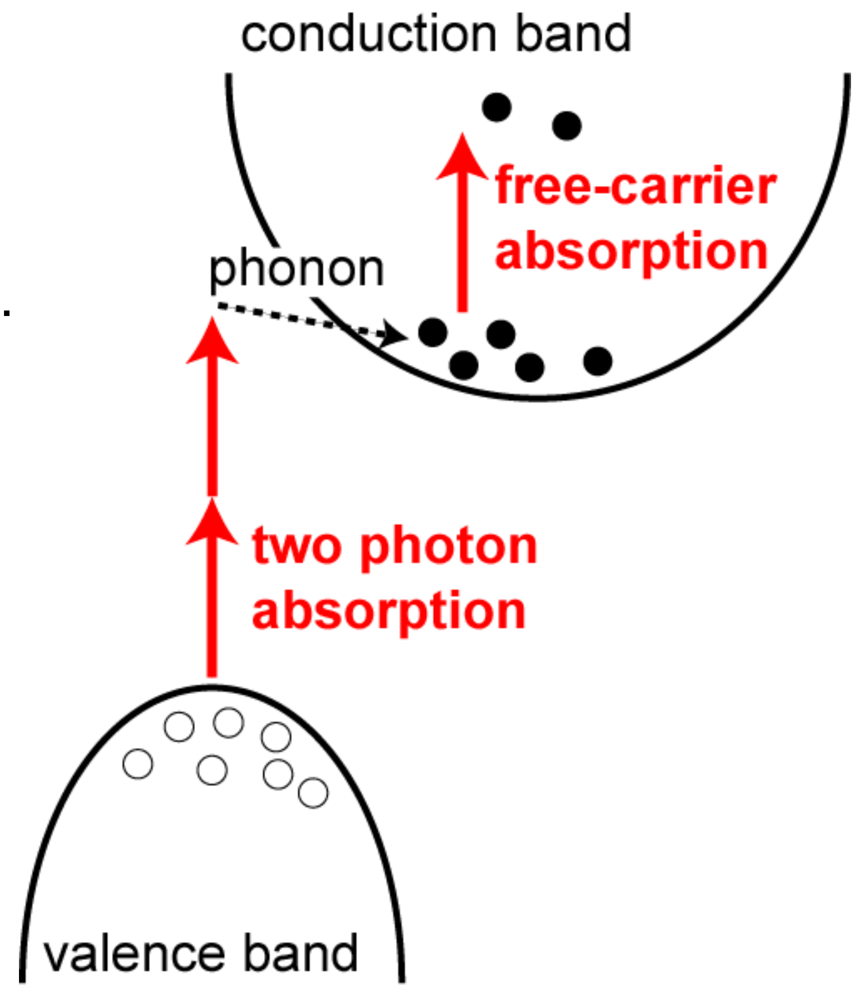
I_s: saturation intensity

$$\frac{dI}{dz} = -\beta I^2$$

β: TPA coefficient

Issue for High-Power Operation: Nonlinear Absorption

- Two-photon absorption generates free carriers.
- Free carriers absorb incoming photons.
- Reduction of free-carrier lifetime can reduce loss.

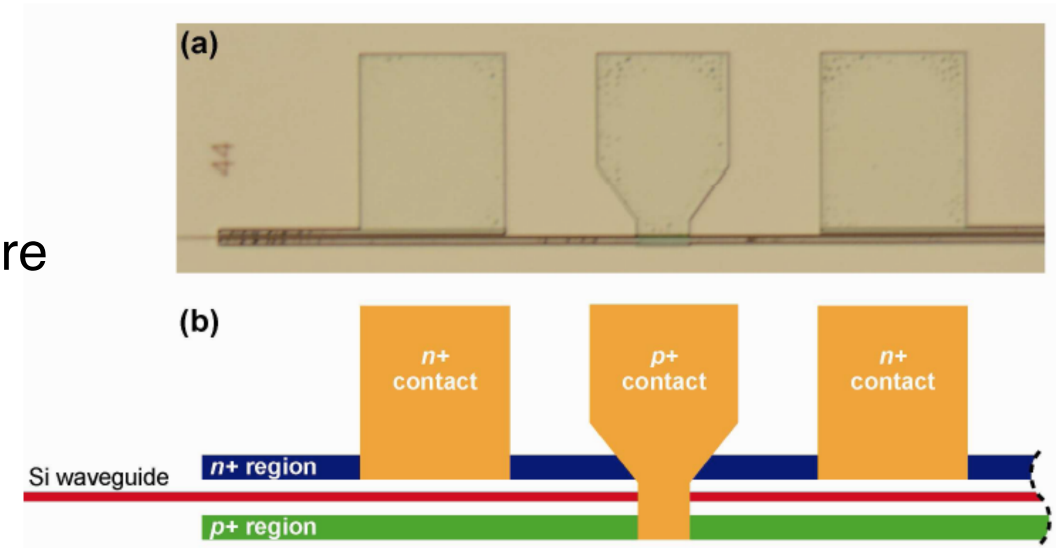


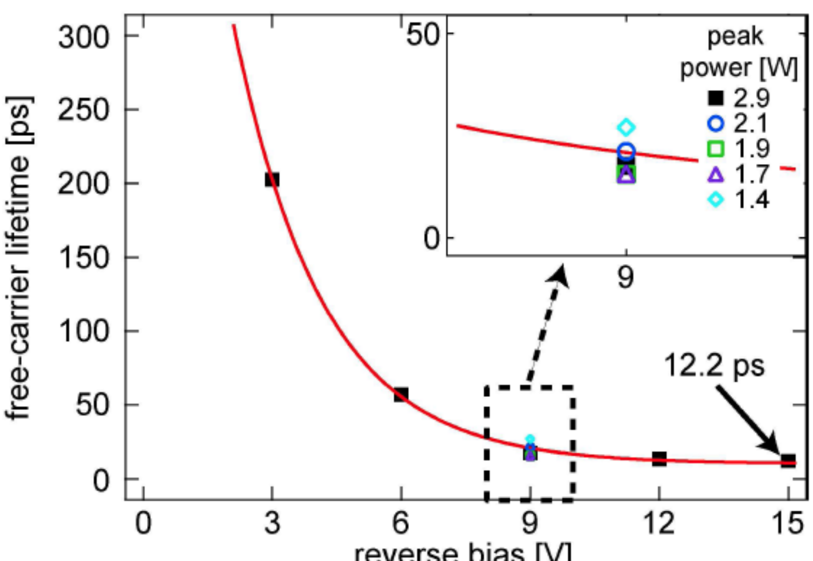
Solution:

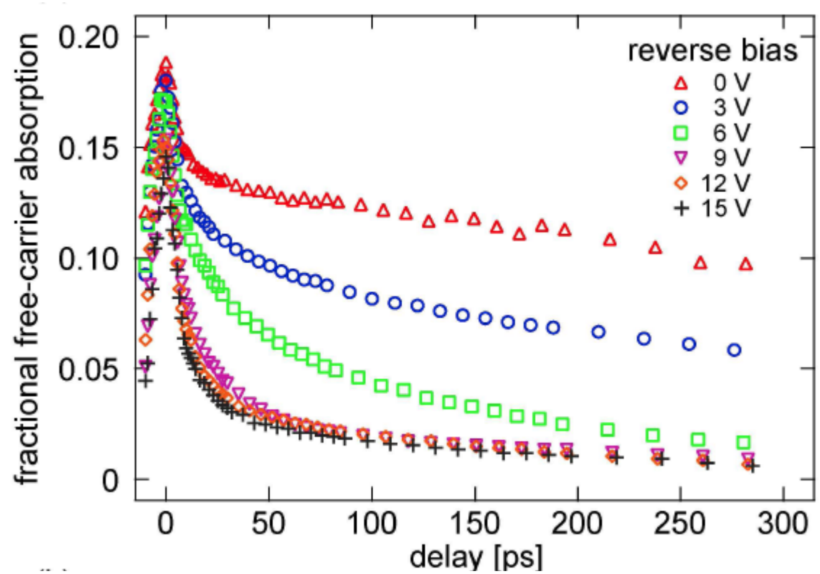
- Integrate PIN-diode structure into waveguides.
- Operate w/ pump > 2 μm
- Use SiN (broader band-gap).

Reduction of Free-Carrier Lifetime

- Incorporate *p-i-n* structure

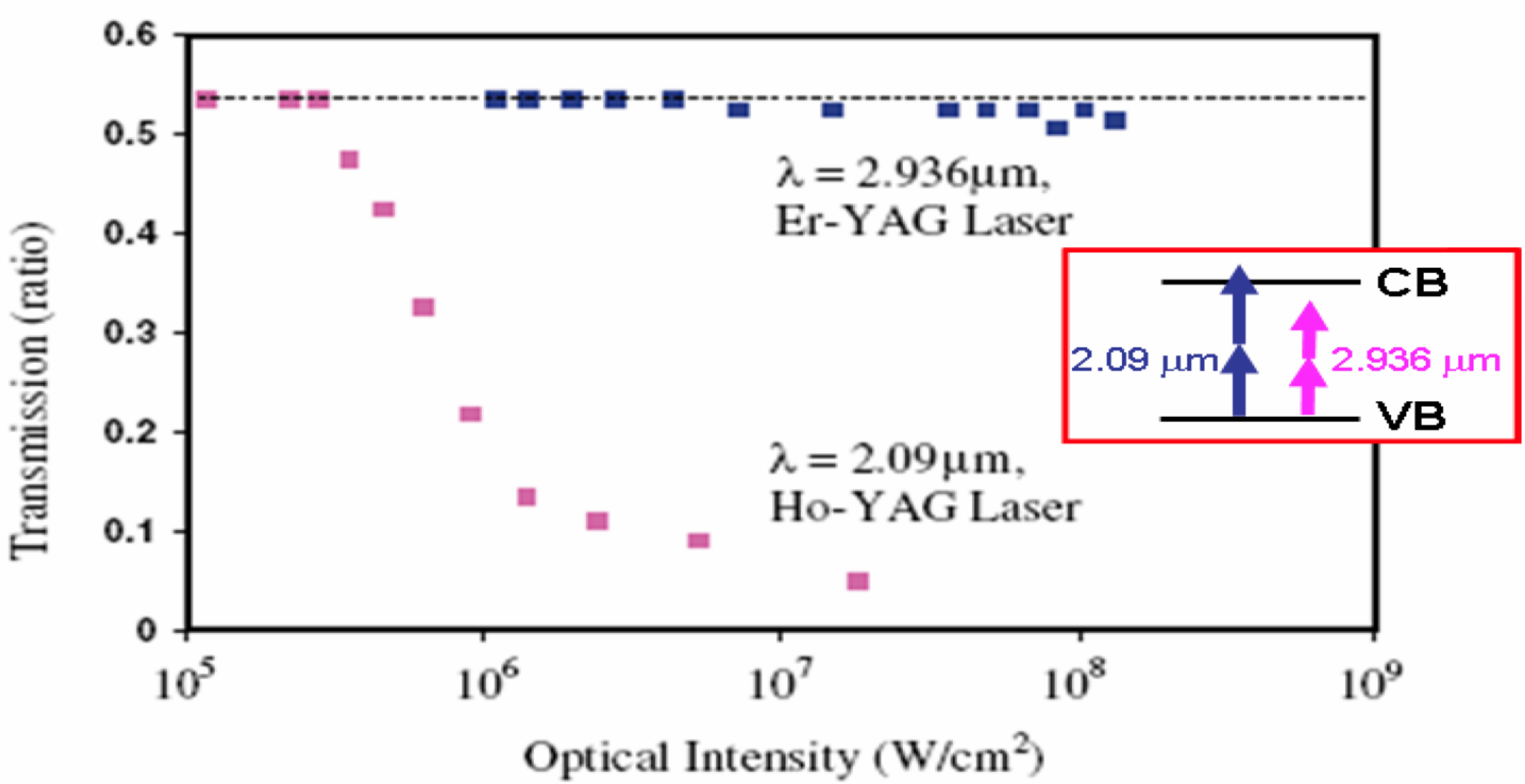






Effects of Two-Photon Absorption

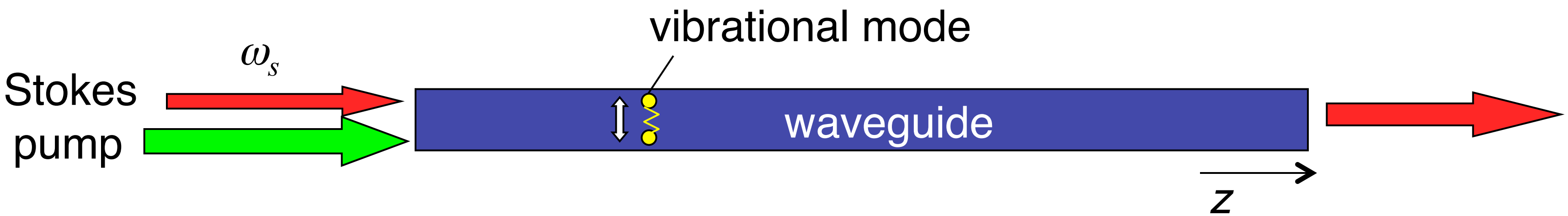
- 1- and 2-photon resonances lead to absorption



Raghunathan, et al. (2010).

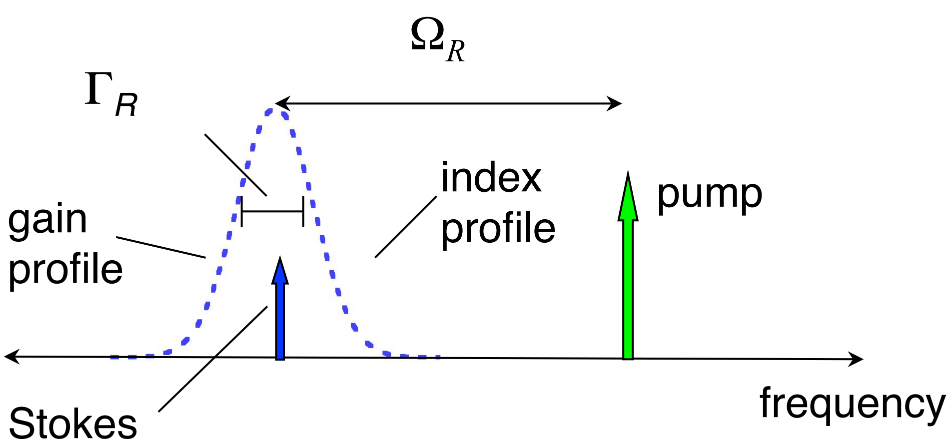
Im{ $\chi^{(3)}$ } – Raman Amplification

- Stimulated Raman scattering produces gain for Stokes wave.



Stokes intensity

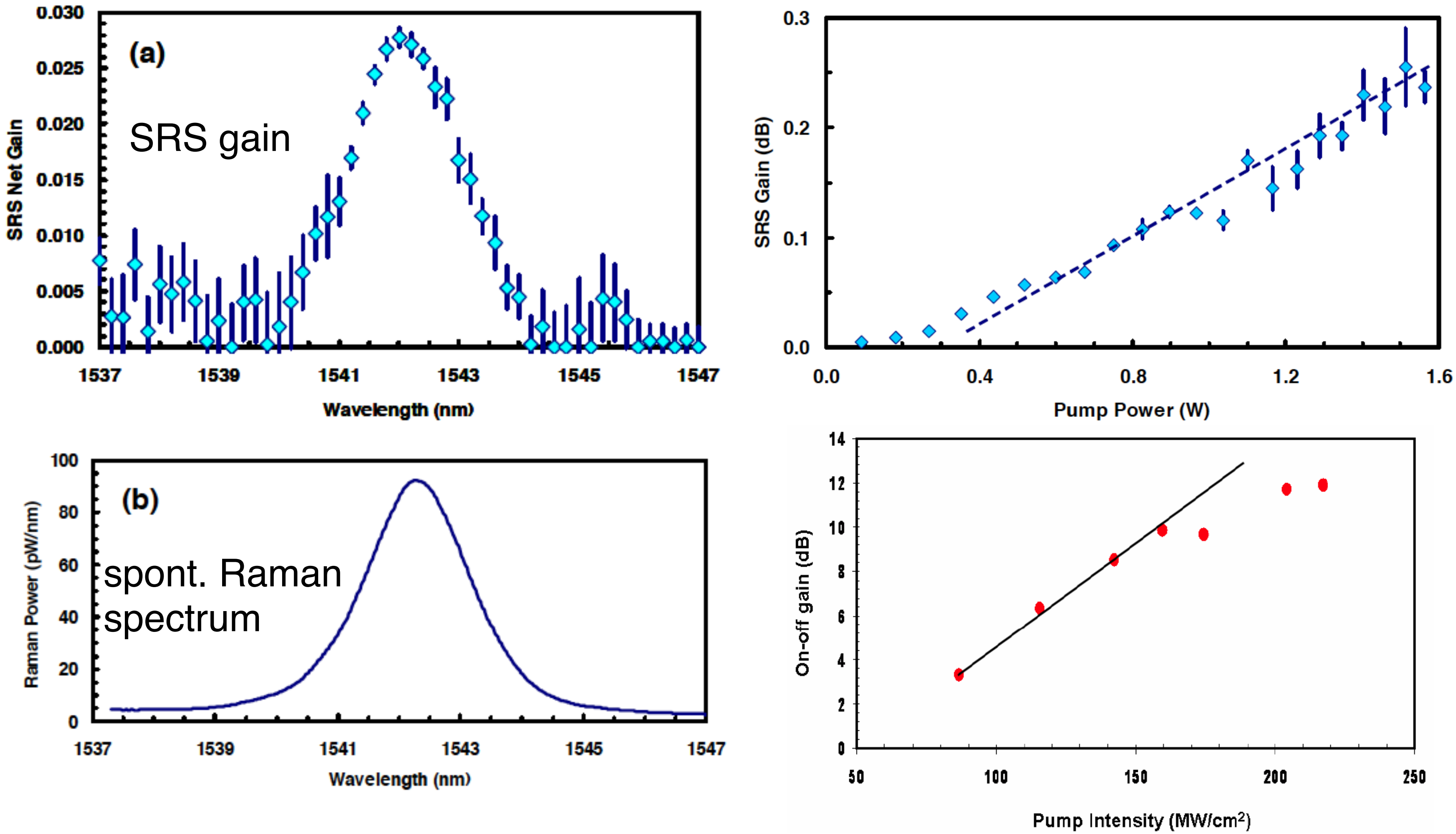
$$\frac{dI_s}{dz} = (g_R I_R) I_s \qquad g_R \propto \mathrm{Im}\left\{\chi_R^{(3)}\right\}$$



Typical Raman values

Silicon	**SiO_2**
Γ_R ~ 100 GHz	Γ_R ~ 3 THz
Ω_R ~ 13 THz	Ω_R ~ 12 THz

Raman Gain in Silicon-Based Nanowaveguides



Claps, Dimitropoulos, Raghunathan, Han and Jalali, Opt. Express **11,** 1731 (2003).

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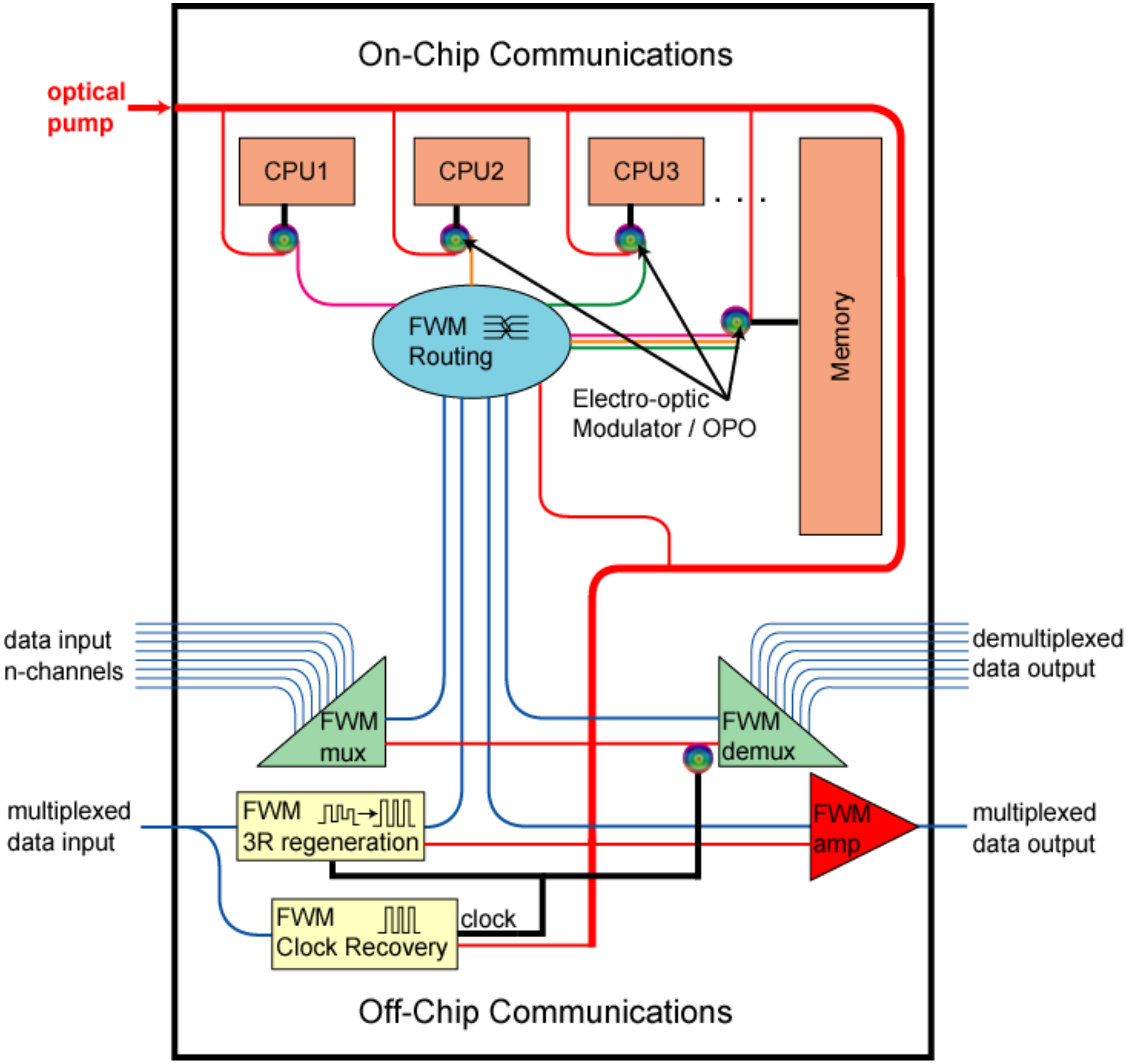
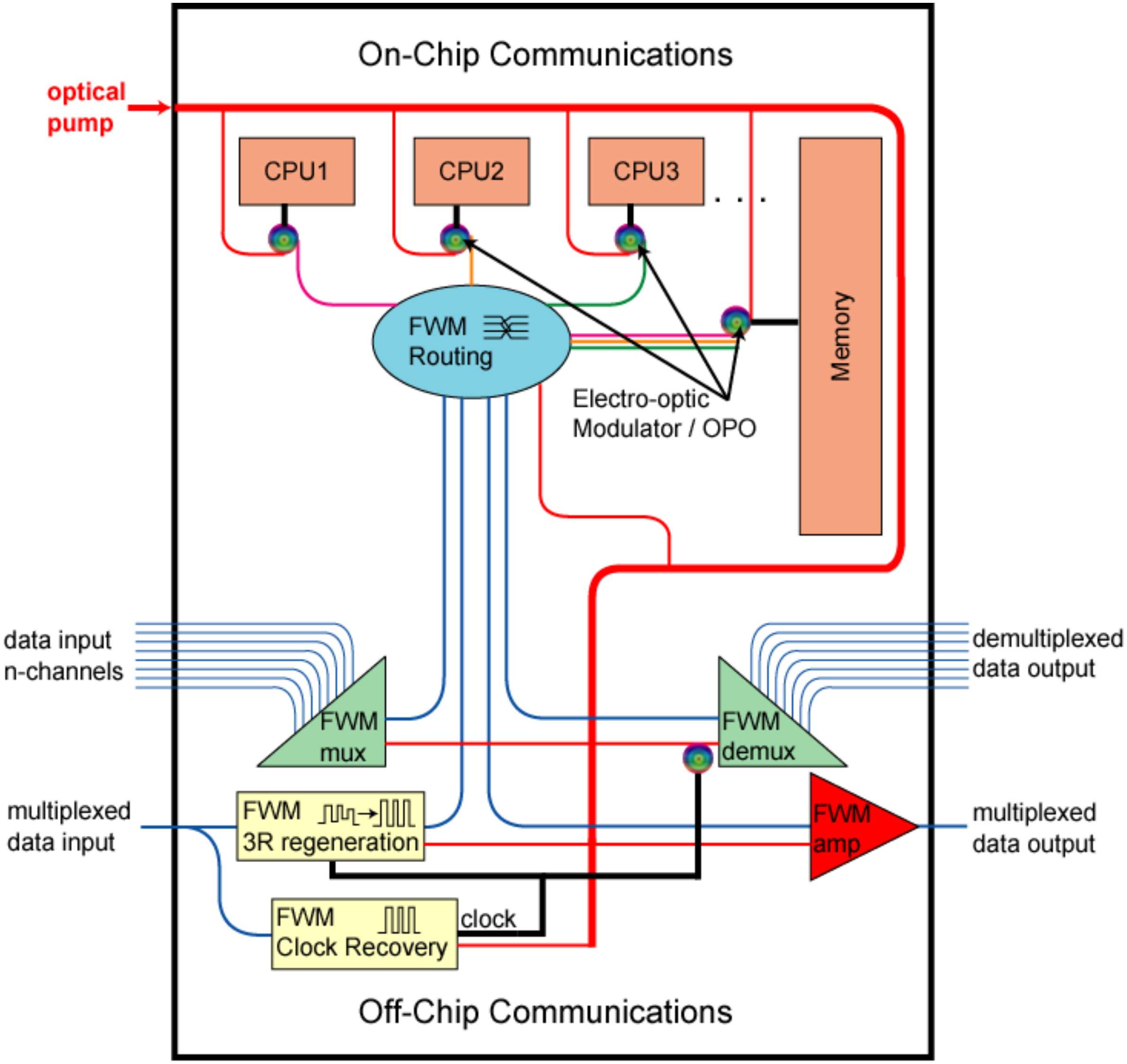
Nonlinear Photonics on Silicon Chip



On-Chip Processing

- Multiplexing/demux
- Regeneration
- Optical buffers
- Routing (switching / logic)
- Multicasting
- A-D conversion
- Wavelength conversion
- Amplification
- Oscillator/comb source

Nonlinear Photonics on Silicon Chip

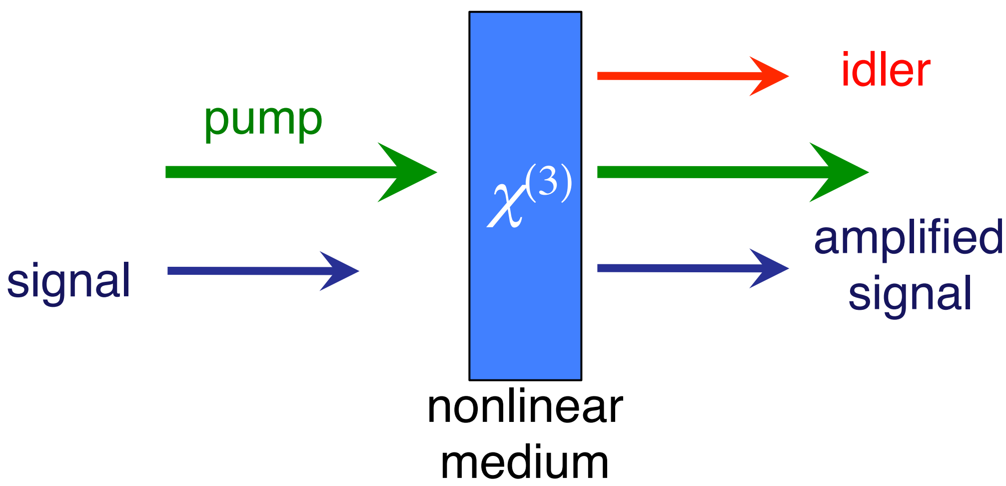


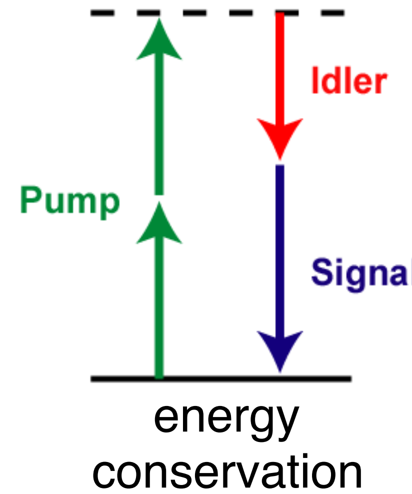
On-Chip Processing

- Multiplexing/demux
- Regeneration
- Optical buffers
- Routing (switching / logic)
- Multicasting
- A-D conversion
- Wavelength conversion
- Amplification
- Oscillator/comb source

All performed via four-wave mixing.

Four-Wave Mixing





<u>input field</u>

$$E_{input} = E_p + E_s = A_p e^{-i\omega_p t} + A_s e^{-i\omega_s t} + c.c.$$

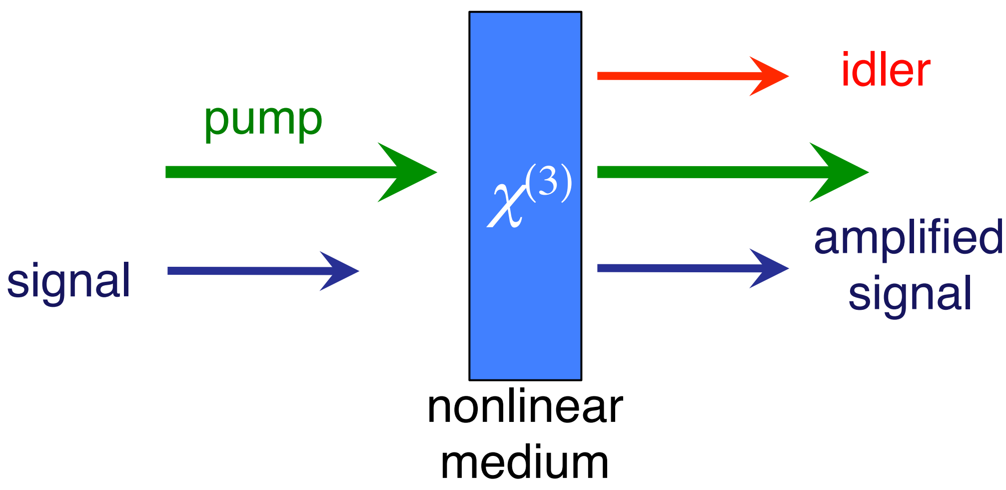
<u>nonlinear polarization</u>

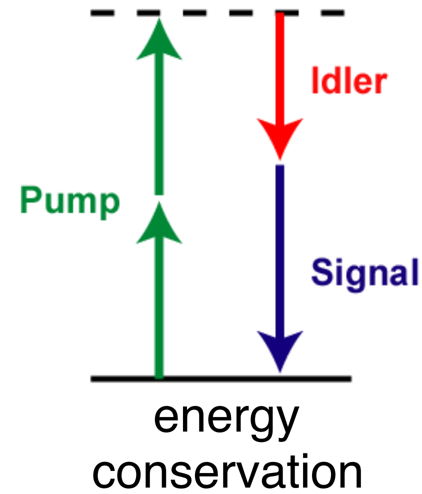
$$P^{(3)} = \chi^{(3)} E^3 = \underbrace{\chi^{(3)} A_p^2 A_s^* e^{-i(2\omega_p - \omega_s)t}}_{\text{idler driving term}} + \text{other terms}$$

idler driving term

$$\omega_i = 2\omega_p - \omega_s$$

Four-Wave Mixing





<u>input field</u>

$$E_{input} = E_p + E_s = A_p e^{-i\omega_p t} + A_s e^{-i\omega_s t} + c.c.$$

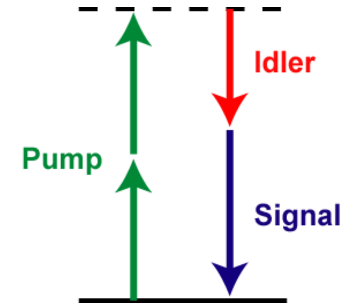
<u>nonlinear polarization</u>

$$P^{(3)} = \chi^{(3)} E^3 = \underbrace{\chi^{(3)} \left[A_p^2 A_s^*}_{\text{idler driving term}} + \underbrace{2 | A_p |^2 A_i \right]}_{\text{cross-phase modulation}} e^{-i(2\omega_p - \omega_s)t}$$

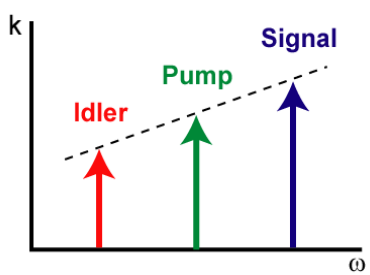
- Efficient generation requires momentum conservation (i.e., phase matching)

Phase Matching in Four-Wave Mixing

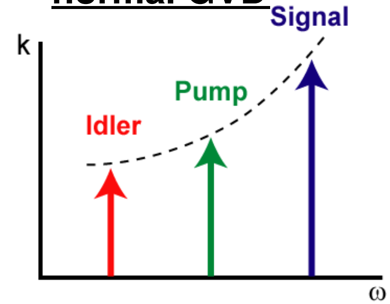
- Energy conservation: $2\omega_p - (\omega_s + \omega_i) = 0$
- Momentum conservation: $\Delta k = 2k_p - (k_s + k_i) + \Delta k_{nl}$
  - Balance of GVD and effects of self-phase modulation & cross-phase modulation
  - Want $\Delta k_L \, L < 1$



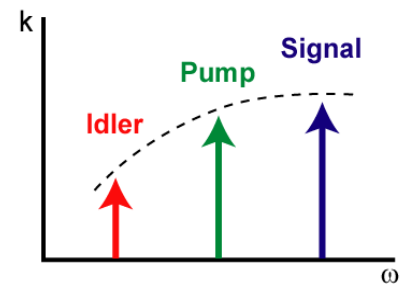
No dispersion, no SPM/XPM



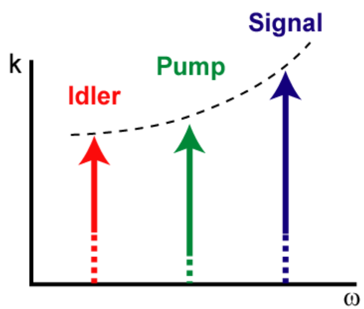
normal GVD



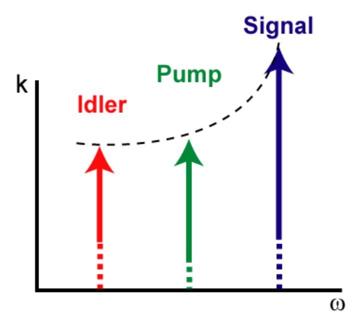
anomalous GVD



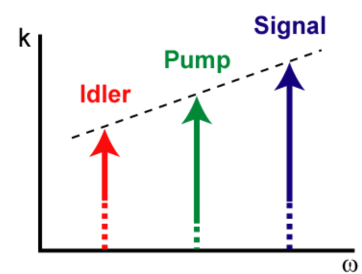
SPM/XPM



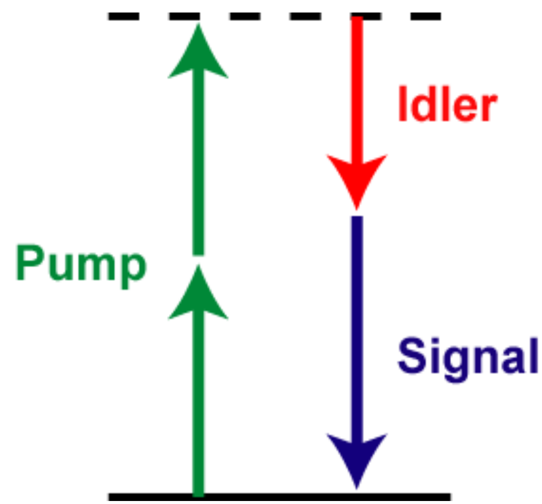
normal GVD + SPM/XPM



anomalous GVD + SPM/XPM



Requirements for Efficient Four-Wave Mixing



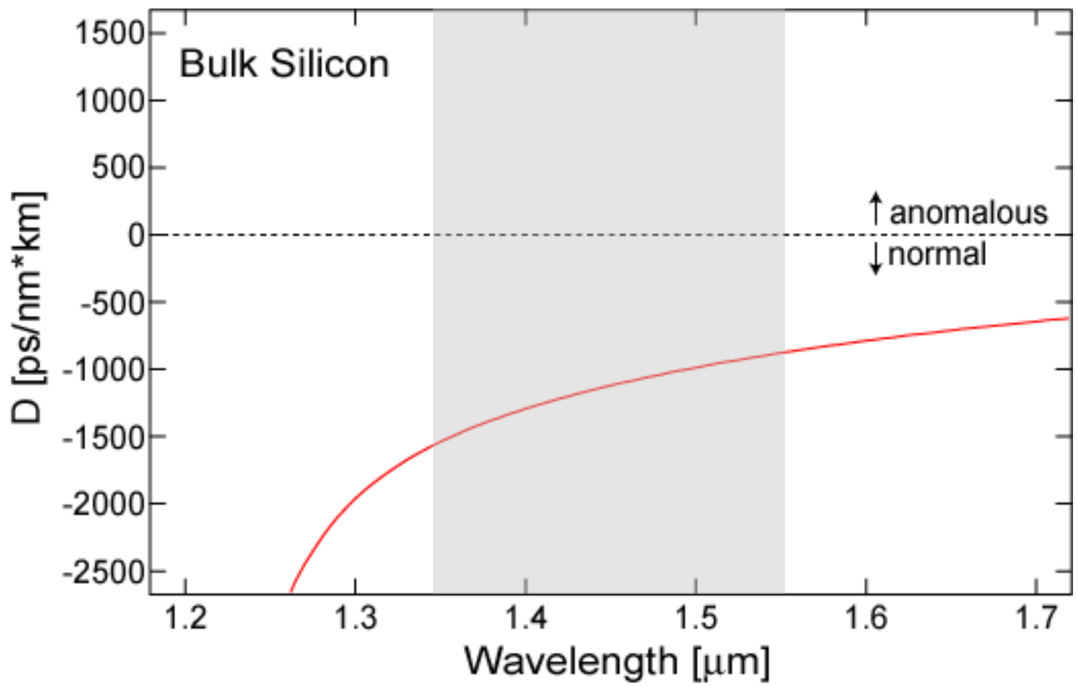
- Energy conservation: $2\omega_p - (\omega_s + \omega_i) = 0$
- Momentum conservation: $\Delta k = 2k_p - (k_s + k_i) + \Delta k_{nl}$
  - Balance of GVD and effects of self-phase modulation & cross-phase modulation

group-velocity dispersion: $$\mathrm{GVD} \propto -\frac{d^2 n}{d\lambda^2} \geq 0$$

Challenge: Large Normal GVD of Si

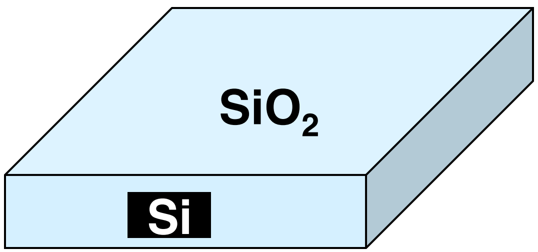
- Bulk Silicon
  - absorption band edge @ 1.1 μm
  - Si @ 1.55 μm: ***D* ~ − 1000 ps/(nm*km)**
    [silica glass @ 1.5 μm: ***D* ~ 20 ps/(nm*km)**]

GVD

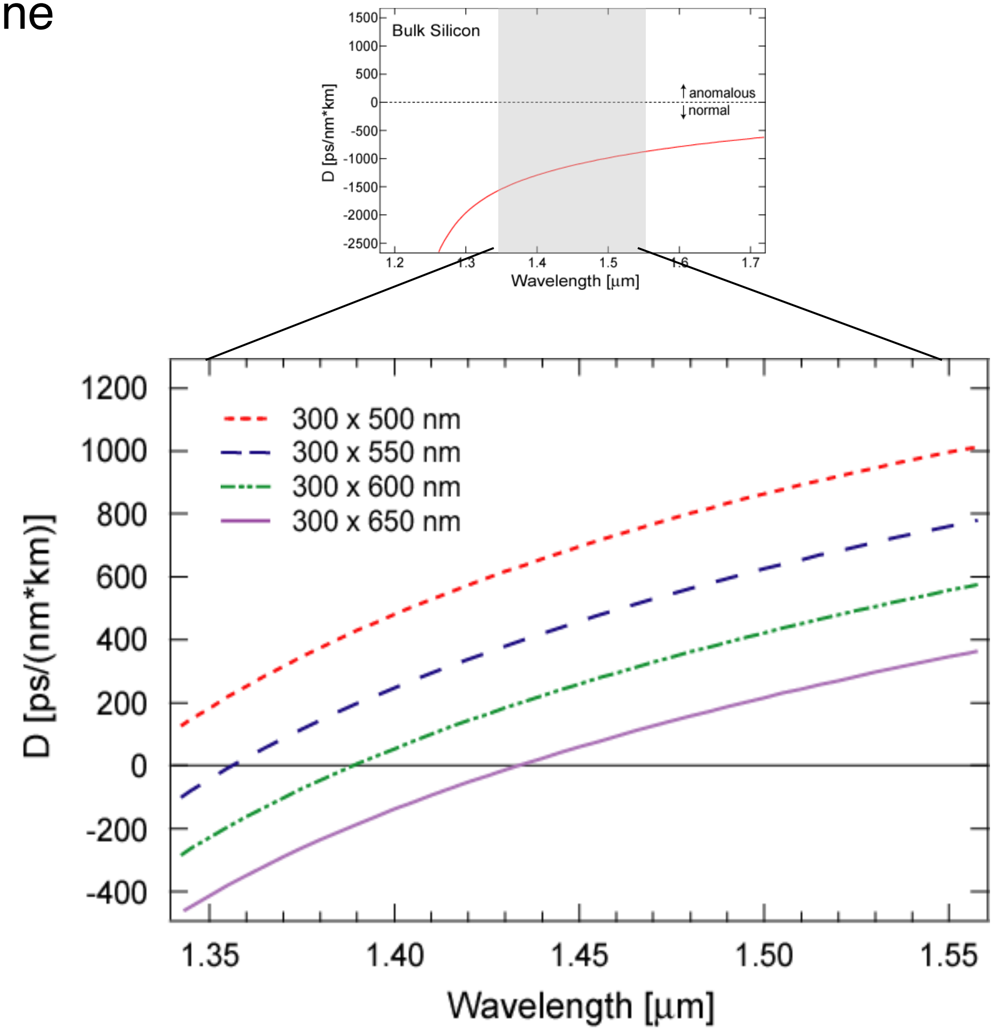


Tailoring of GVD in Si Waveguides

- Utilize waveguide dispersion to tune GVD.



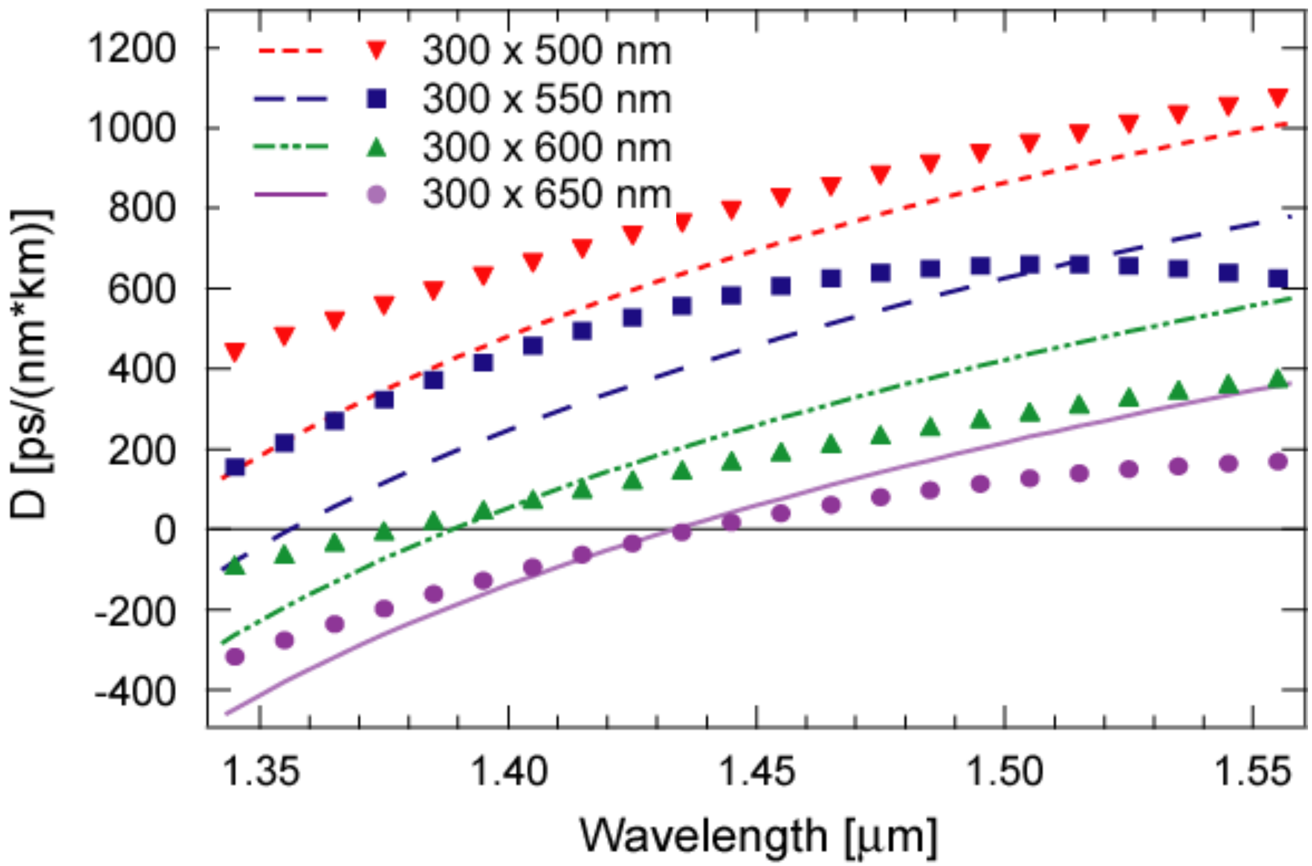
- GVD can be tuned by varying waveguide shape and size.



Turner et al. (2006)
Lin et al. (2006)

Predicted anomalous-GVD ~50X SMF-28 fiber [20 ps/(nm·km)].

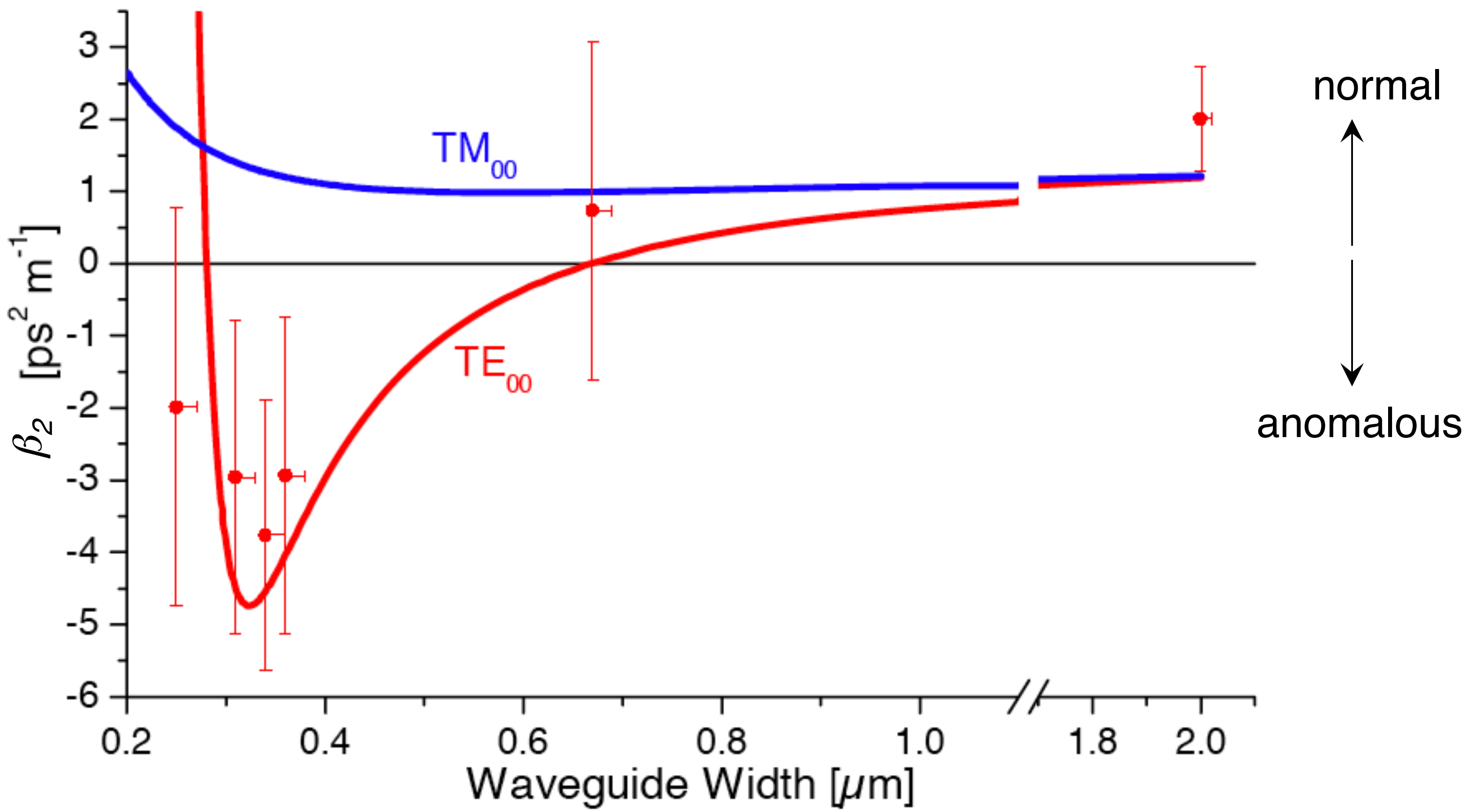
Measurement of Anomalous-GVD in Si Waveguides



Turner, Manolatou, Schmidt, Lipson, Foster, Sharping, and Gaeta, *Opt. Express* **14**, 4357 (2006).

Dulkeith, Xia, Schares, Green, and Vlasov, *Opt. Express* **14**, 3853 (2006).

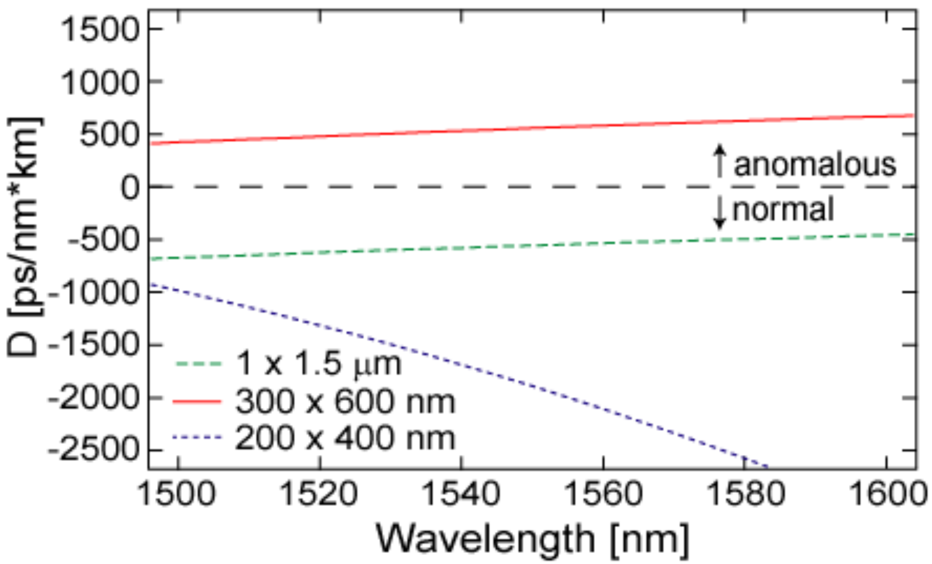
Dispersion Control in AlGaAs Waveguides

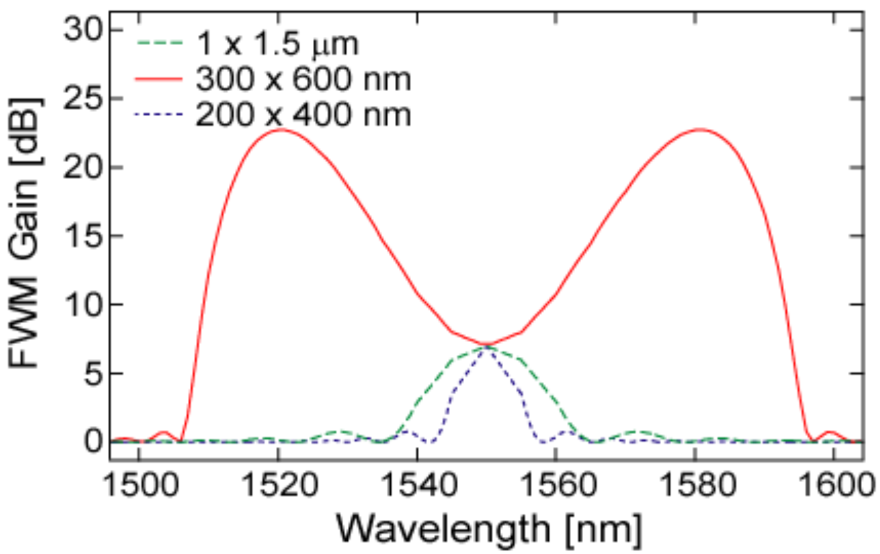


Meier, Mohammed, Jugessur, Qian, Mojahedi, and Aitchison, *Opt. Express* **15**, 12755 (2007).

Phase-Matched Four-Wave Mixing in Si

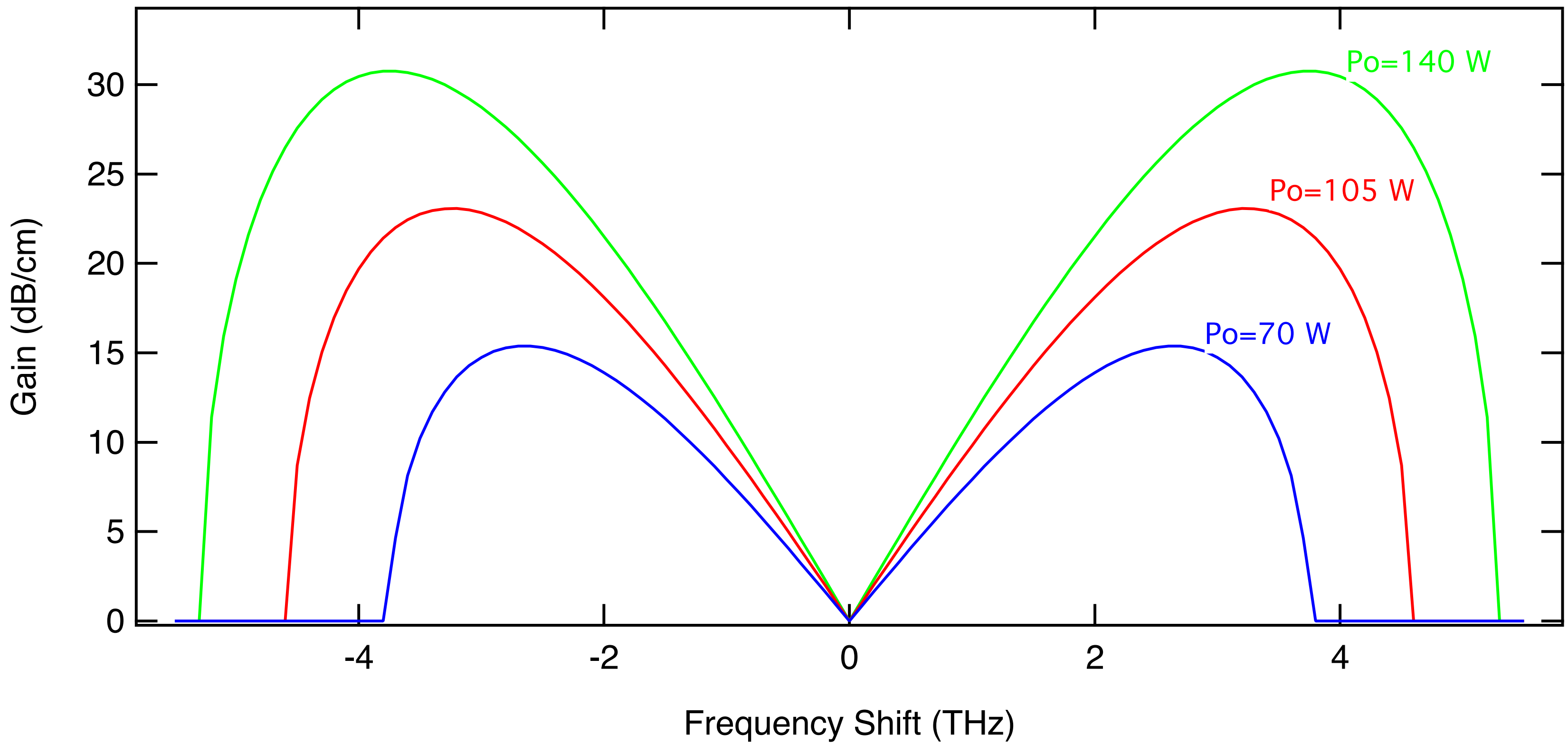
- Broad regions of FWM gain predicted.



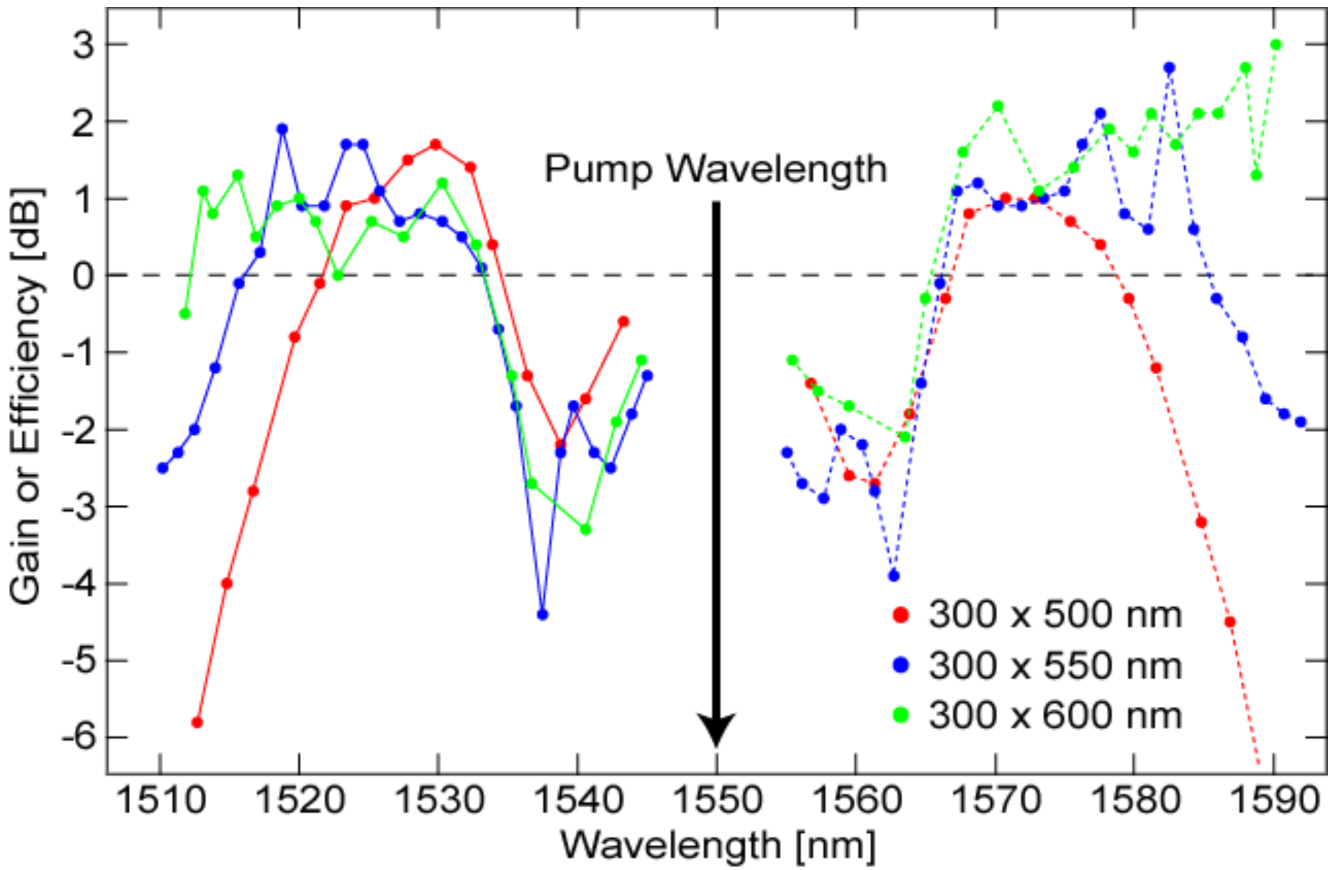


Phase-Matched Four-Wave Mixing

- Peak gain occurs where $\Delta k = 0$



Four-Wave Mixing Amplification

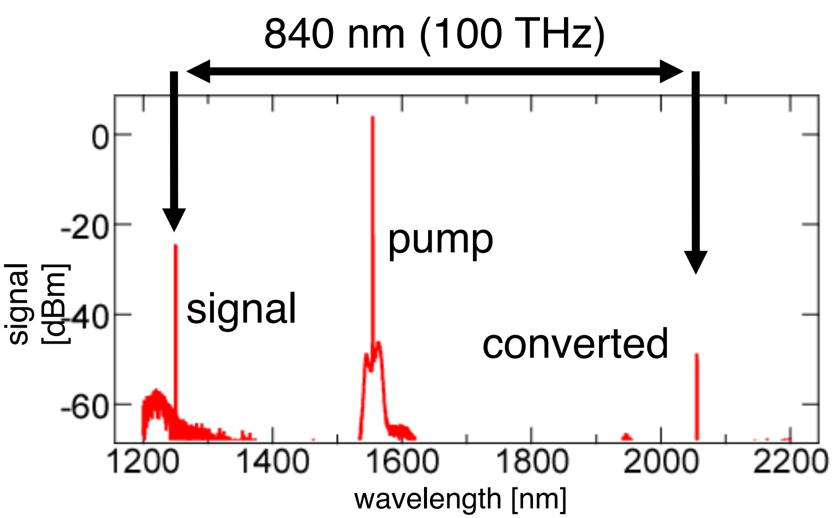


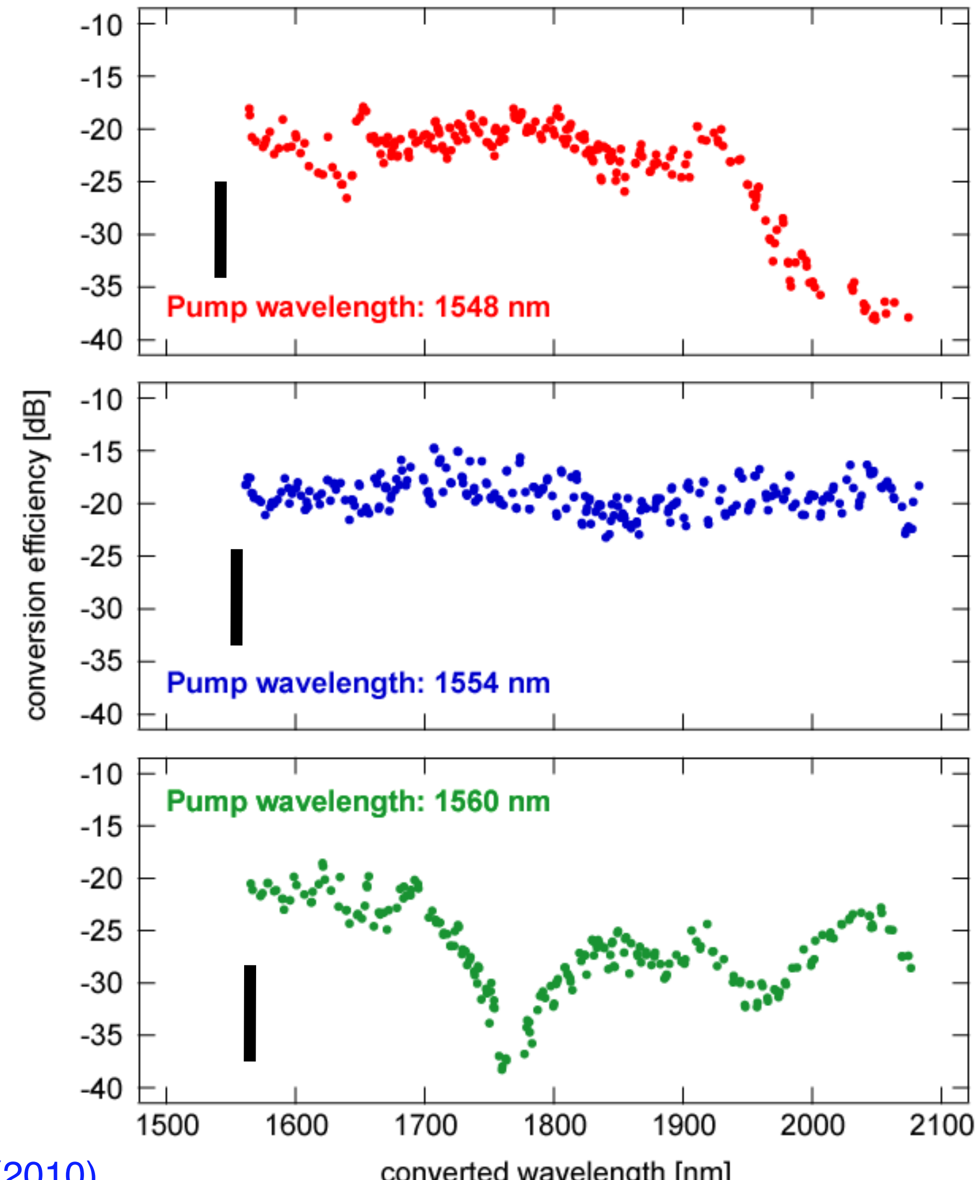
- First observation of broadband gain in Si. (Raman gain bandwidth ~ 1 nm)

Foster, Turner, Sharping, Schmidt, Lipson, and Gaeta, *Nature* **441**, 960 (2006).

CW Wavelength Conversion over 900-nm Bandwidth

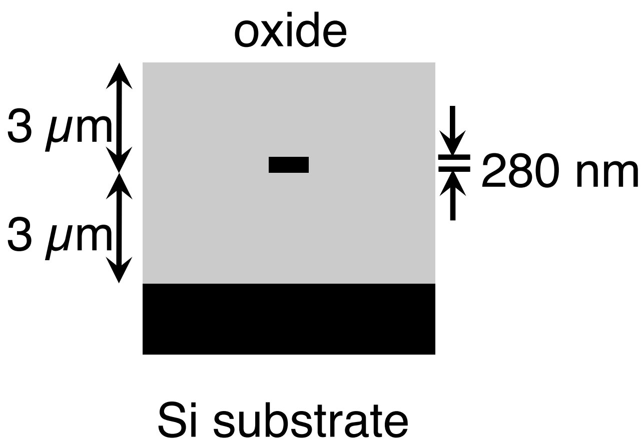
- Pump: 50 mW
- **Conversion bandwidth > 2/3 of an octave!**



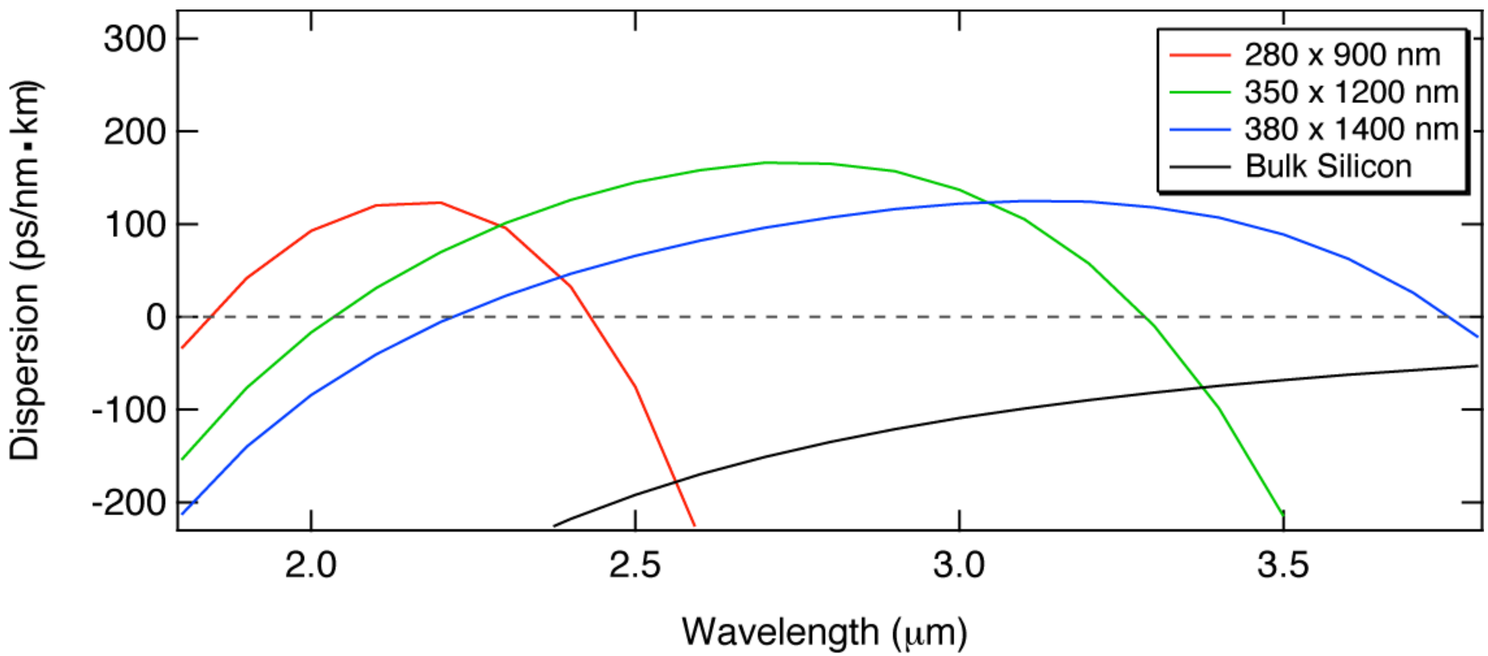


Turner, Lipson, Foster, and Gaeta, *Opt. Express* (2010).

Dispersion Engineering into Mid-IR

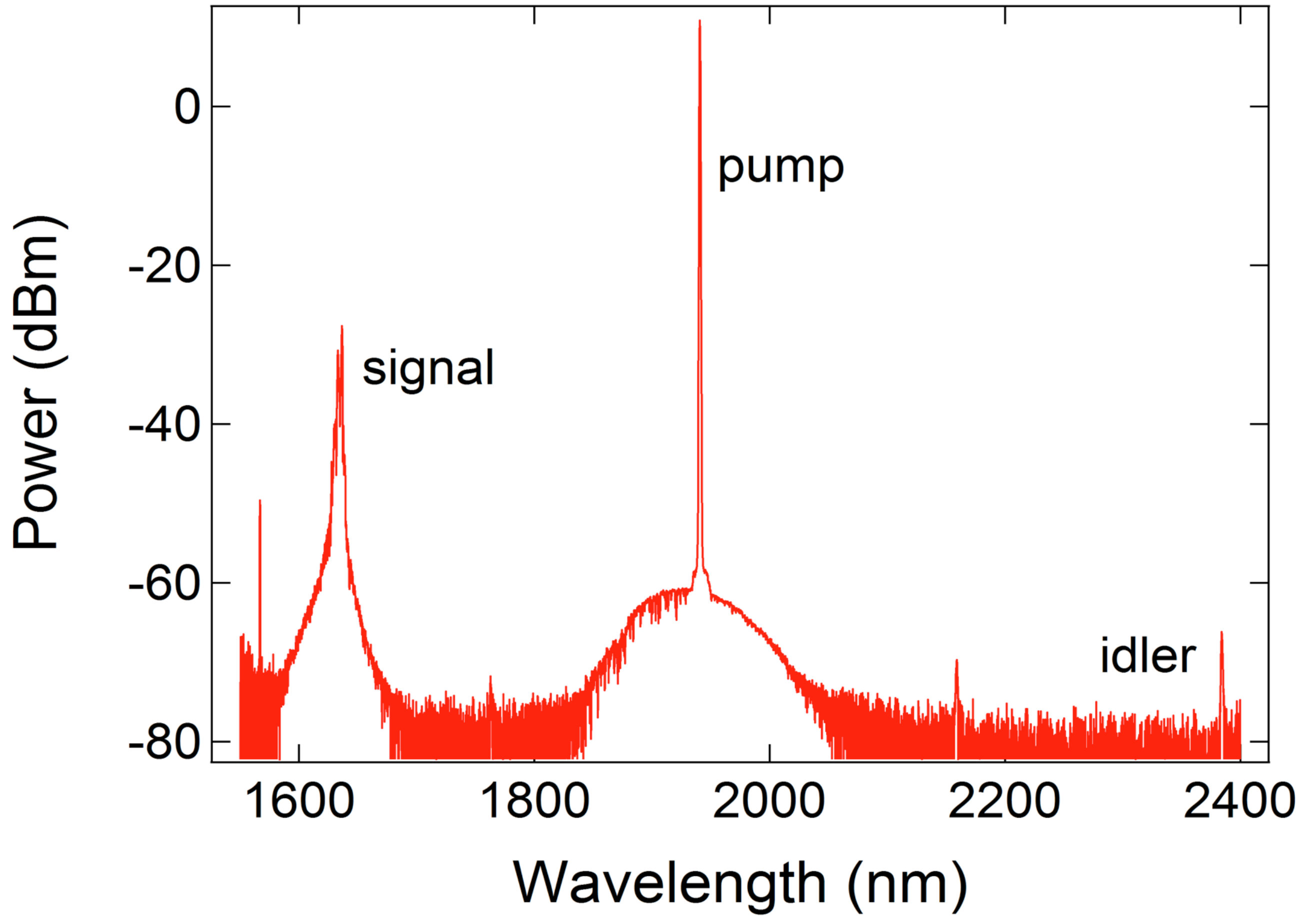


- Broadband anomalous GVD in MIR.



Mid-IR Frequency Conversion

Lau, et al., Lipson, and Gaeta, *Opt. Lett.* (2011).



- Pulsed conversion (w/ gain) [Zlatanovic et al. (2010); Kuyken et al. (2010, 2011).]
- Need other cladding materials (e.g., sapphire, SiN) for longer MIR wavelengths [Baehr-Jones et al. (2010)]

Four-Wave Mixing Amplification in Mid-IR

November 15, 2011 / Vol. 36, No. 22 / OPTICS LETTERS 4401

50 dB parametric on-chip gain in silicon photonic wires

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Richard M. Osgood, Jr.,[2] and William M. J. Green[3,*]
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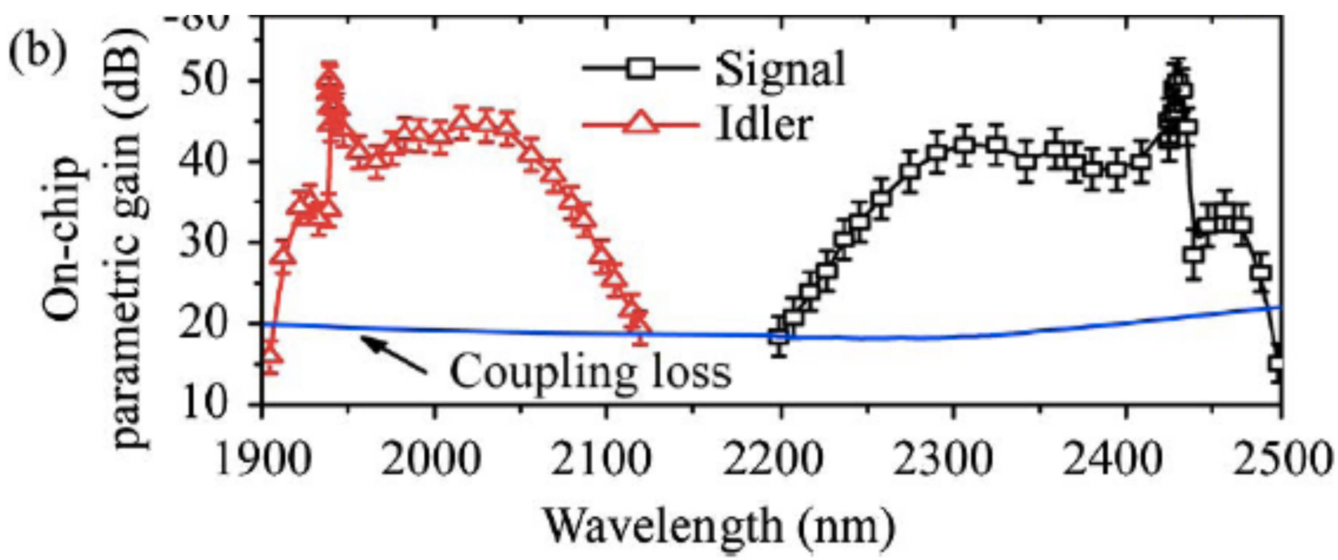
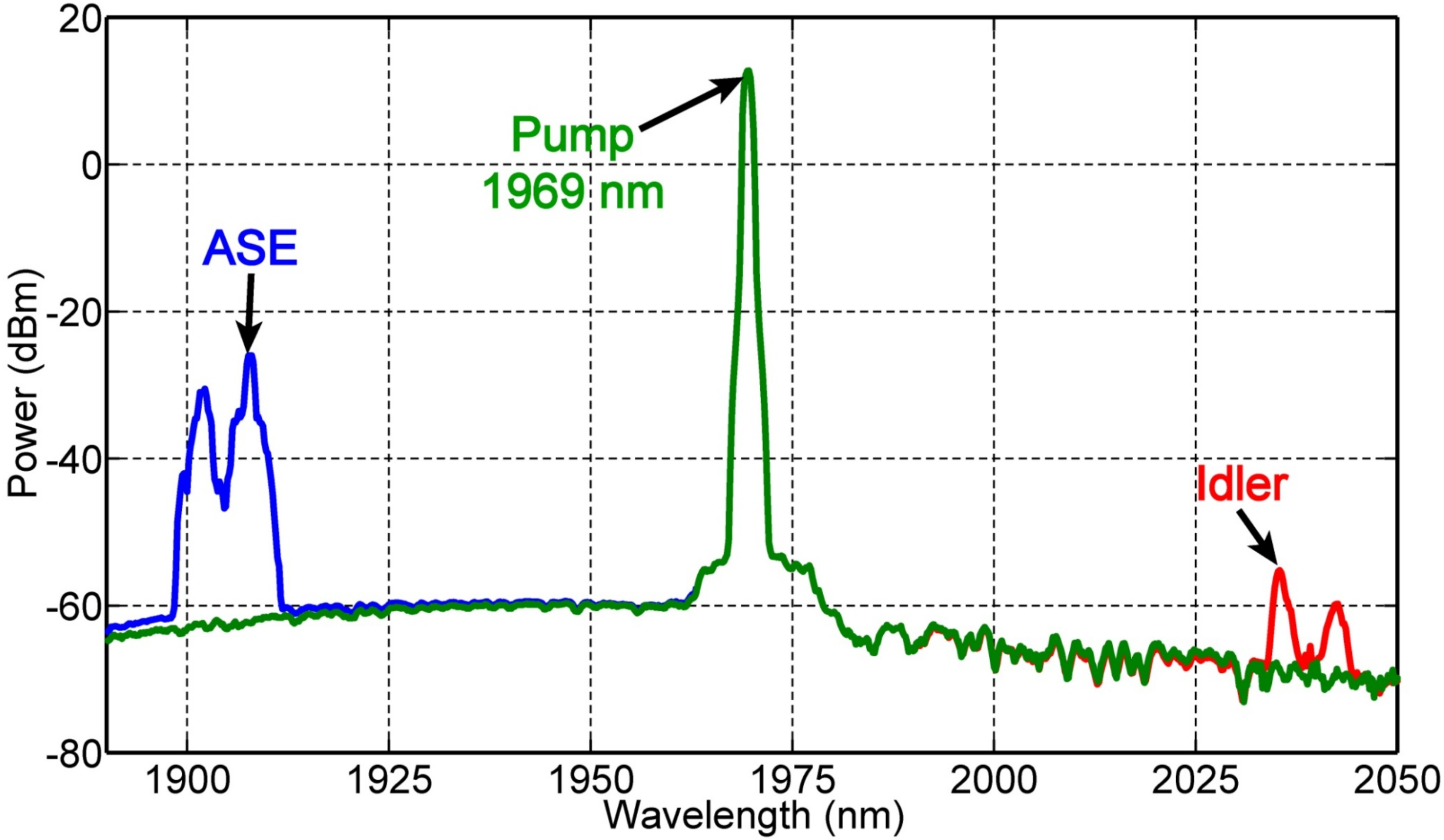
[2]Department of Electrical Engineering, Columbia University, 1300 S. W. Mudd Building, 500 W. 120th Street, New York, New York 10027, USA
[3]IBM Thomas J. Watson Research Center, 1101 Kitchawan Road, Yorktown Heights, New York 10598, USA
[4]Current address: OFS Labs, 19 Schoolhouse Road, Somerset, New Jersey 08873, USA
*Corresponding author: wgreen@us.ibm.com



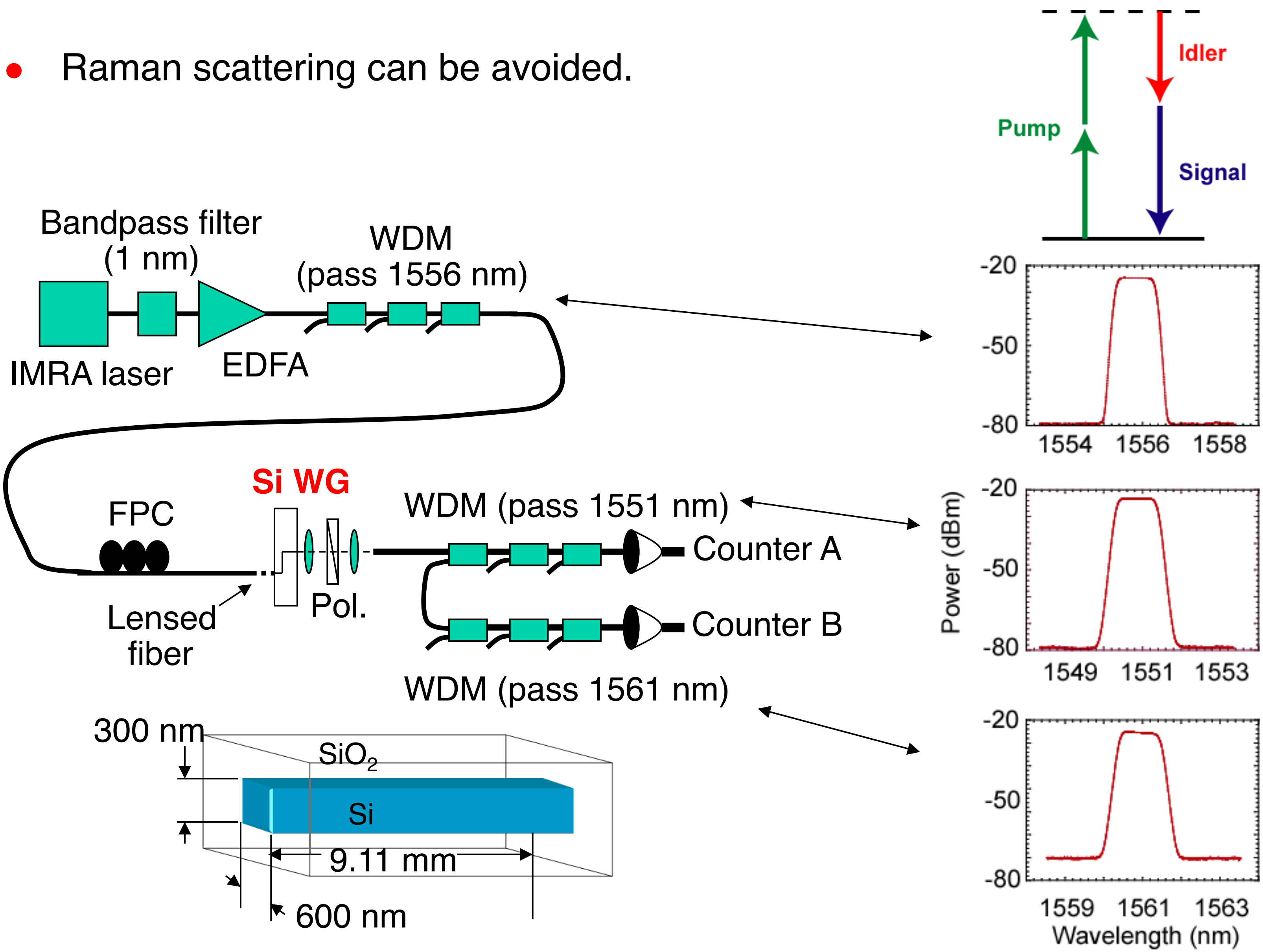
Frequency Conversion of Incoherent Source



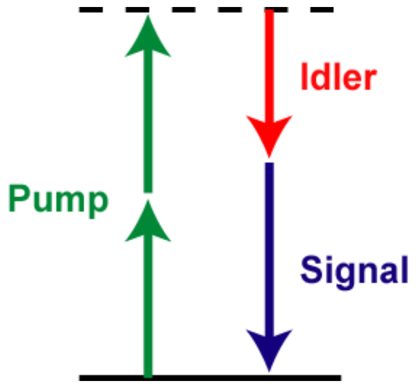
- 50-mW pump at 1969 nm, ASE from thulium fiber amplifier

Application: Chip-Based Source for Correlated Photons

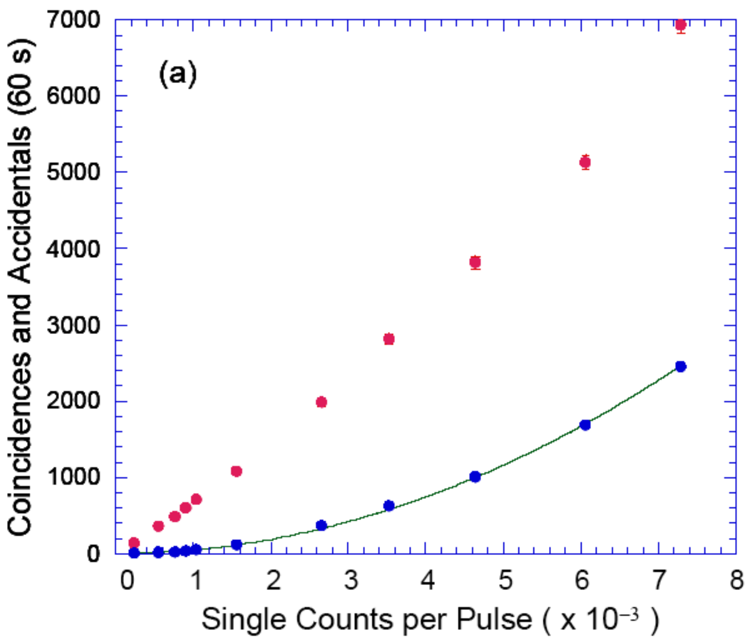
- Raman scattering can be avoided.

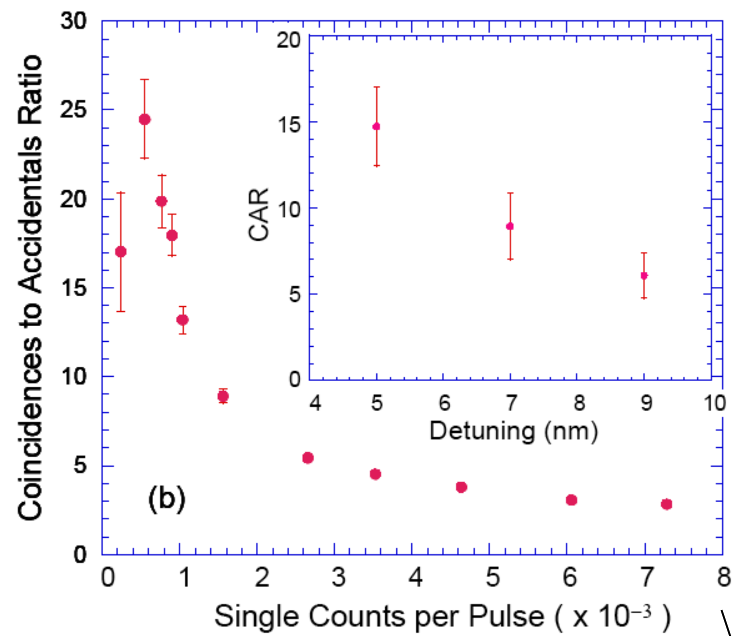


Generation of Correlated Photons in Si



- Results show good quantum characteristics.
- Raman scattering can be avoided.



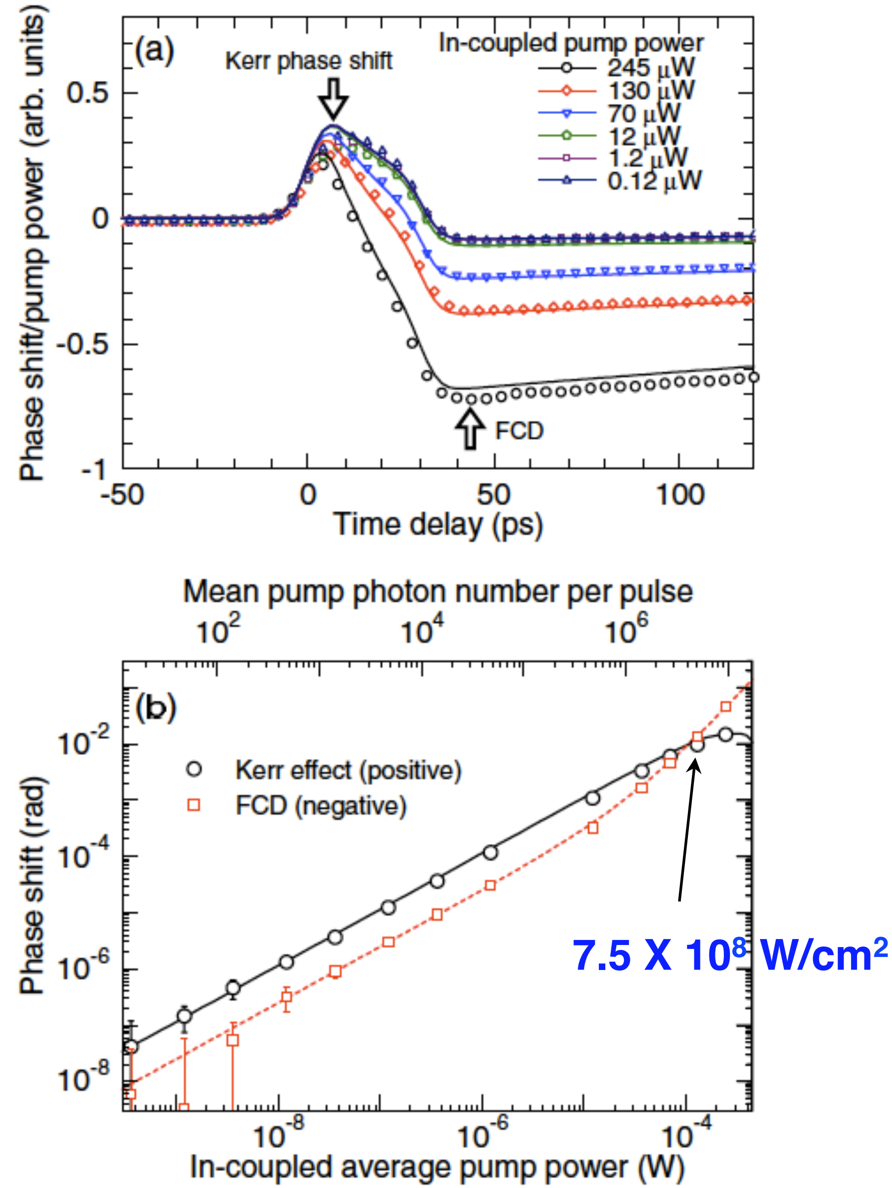


10^9 W/cm^2

Sharping, Lee, Foster, Turner, Lipson, Gaeta, and Kumar, *Opt. Express* **14**, 12388 (2007),

Contribution of Free-Carriers Spoils Correlations

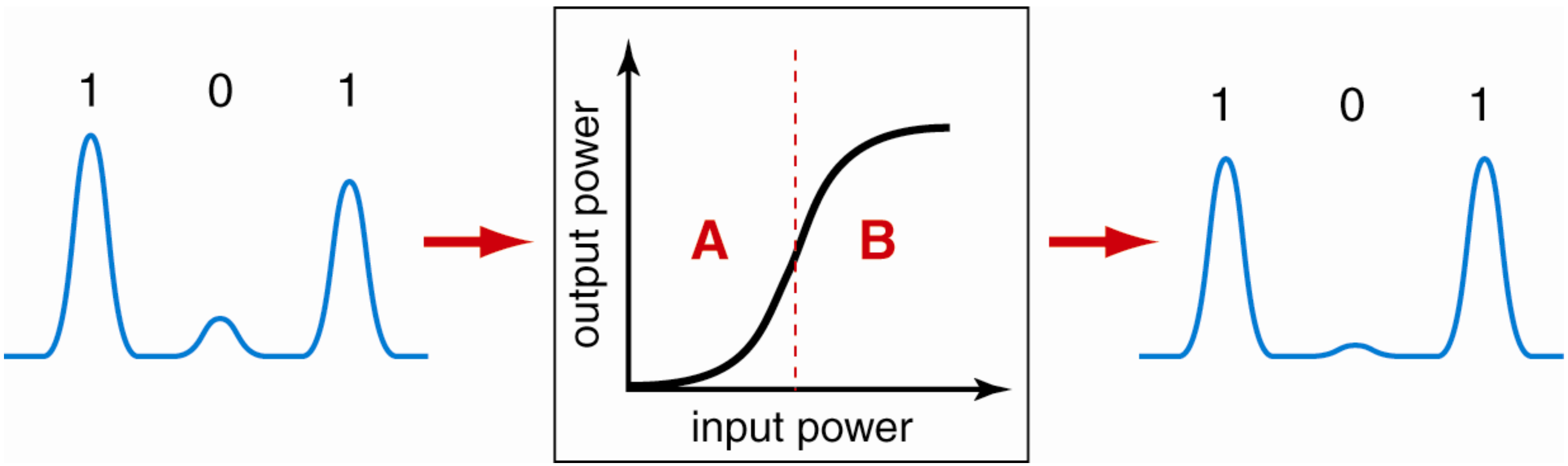
- Plasma dispersion effect leads to generation of blue photons.
- $\chi^{(3)}$ due to free-carriers comparable to electronic for peak intensities ~ 7.5 X 10^8 W/cm^2



Matsuda, *et al.*, Appl. Phys. Lett. **95**, 171110 (2009).

Application: Signal Regeneration & Reshaping

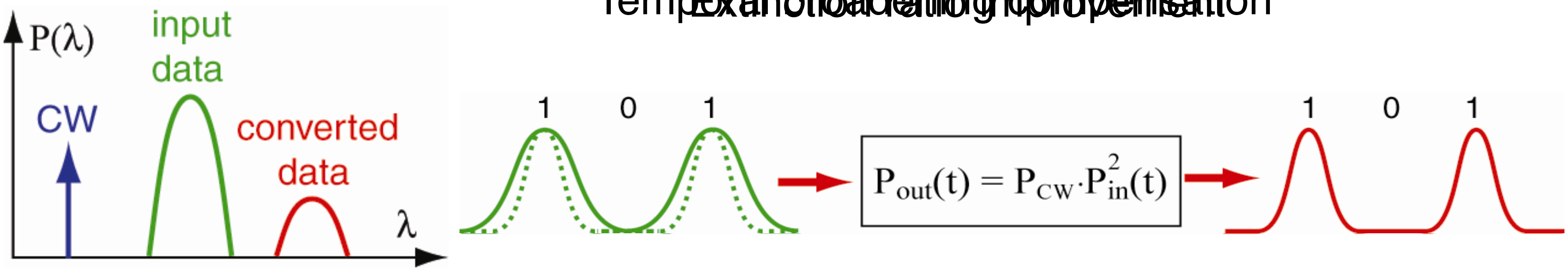
S-shaped power transfer function



- **Region A**
  - Reduces fluctuations on the logical 0’s.
  - Improves the extinction ratio.
- **Region B**
  - Reduces fluctuations on the logical 1’s.

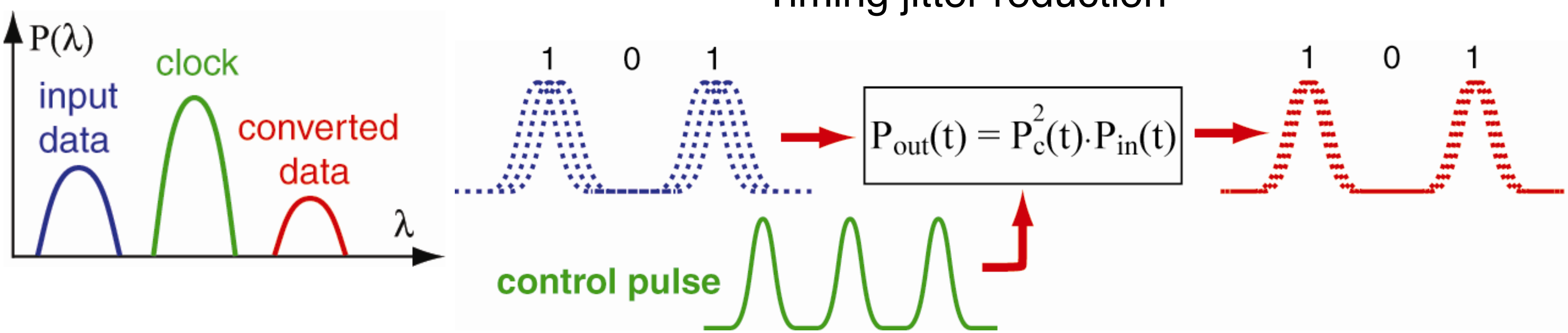
Application: FWM-Based Signal Regeneration for Optical Communications

Temporal broadening compensation
Extinction ratio improvement



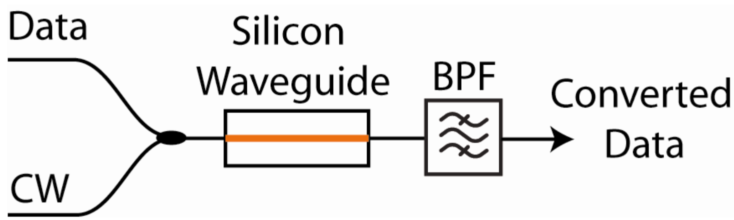
- ER improvement by FWM in fiber, Ciaramella et. al. (2001) & Bogris et al. (2003)
- ER improvement by FWM in SOA, Gosset et al. (2001) & Simos et al. (2004)

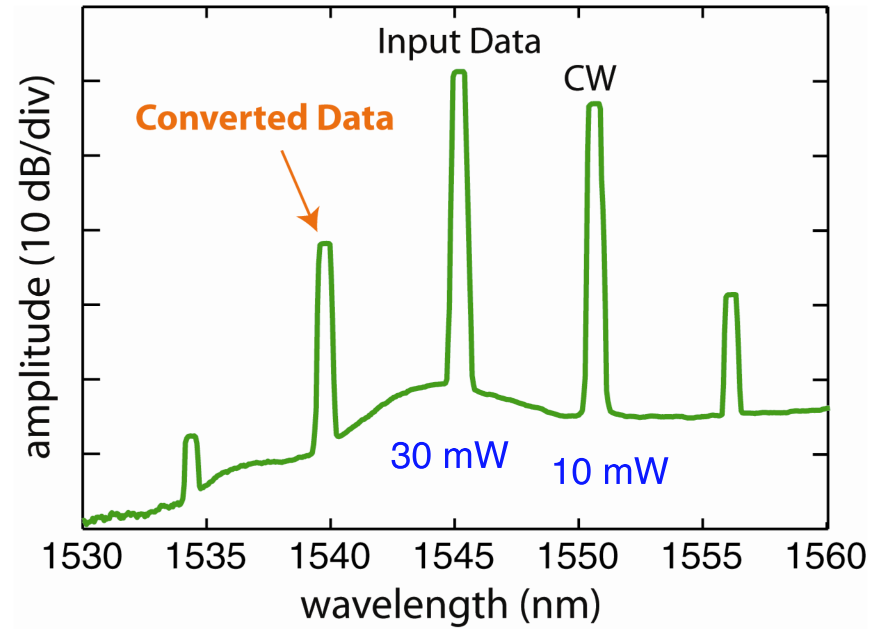
Timing jitter reduction



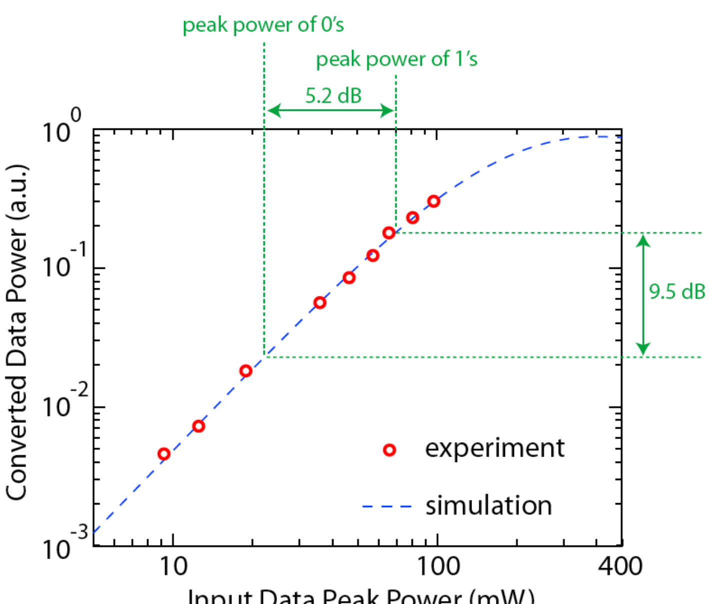
- 3R regeneration by FWM in fiber, Su et al. (2001)
- 3R regeneration by OPA in fiber, Yu et al. (2005)

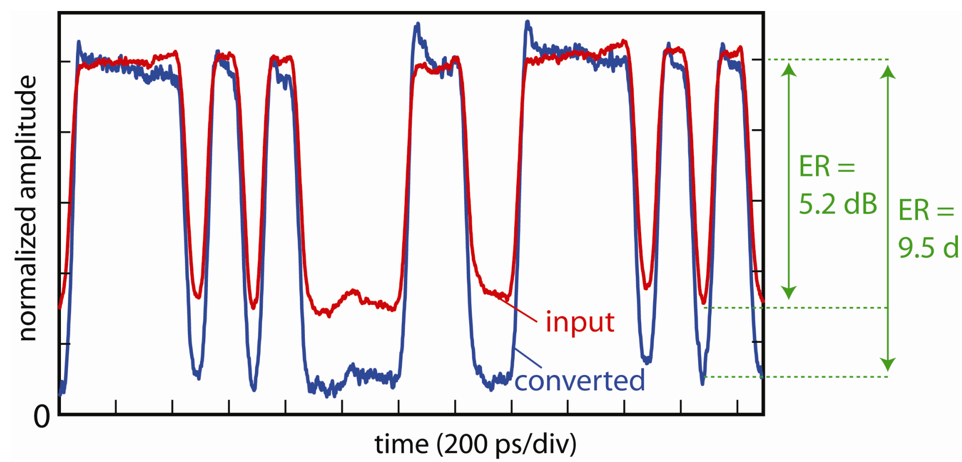
Signal Regeneration Using FWM in Si





- Data extinction ratio (ER) improved due to the quadratic input/output power transfer function.



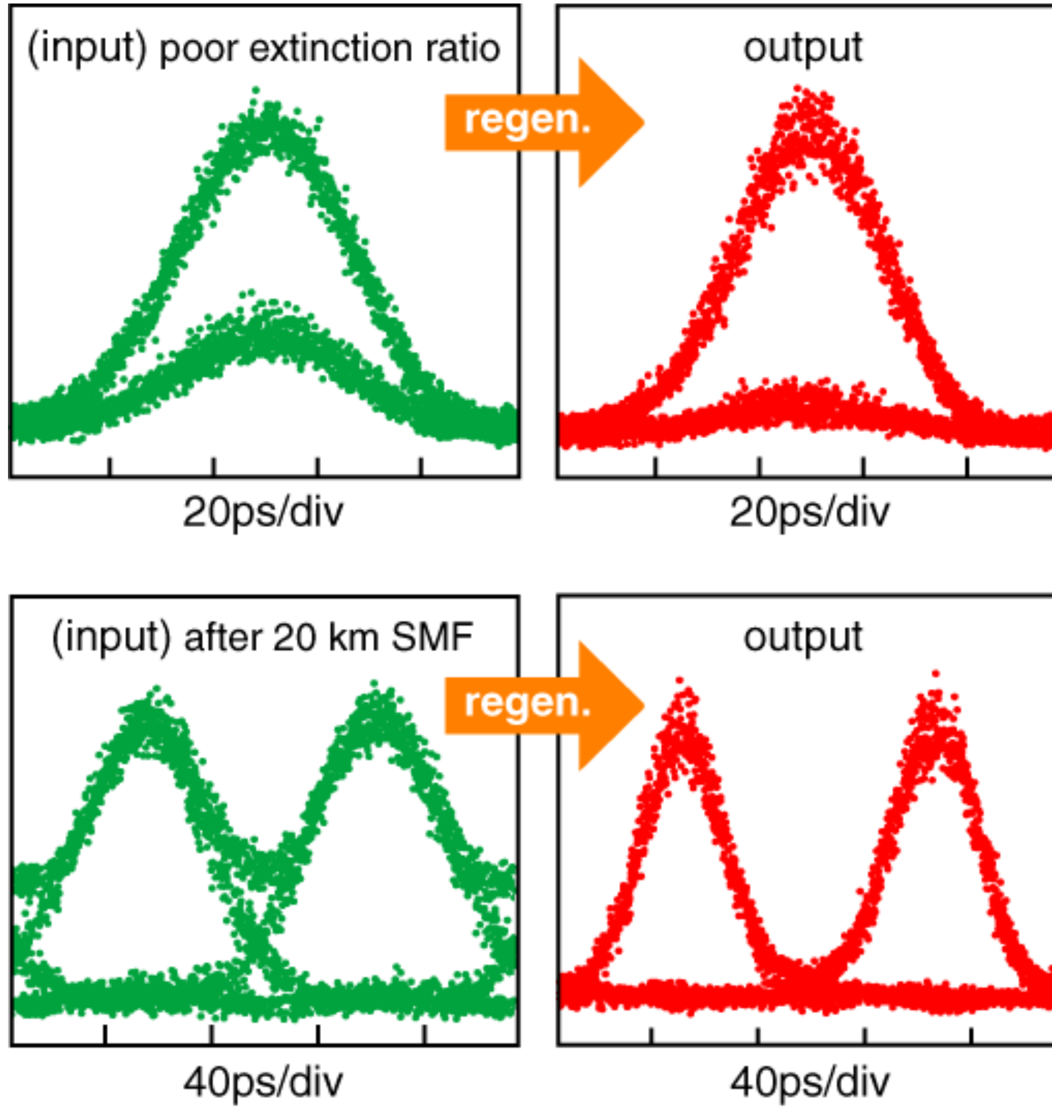


Salem, Foster, Turner, Geraghty, Lipson, and Gaeta, *Nature Phot.* **2, 35** (2007).

10 Gb/s RZ Data Regeneration

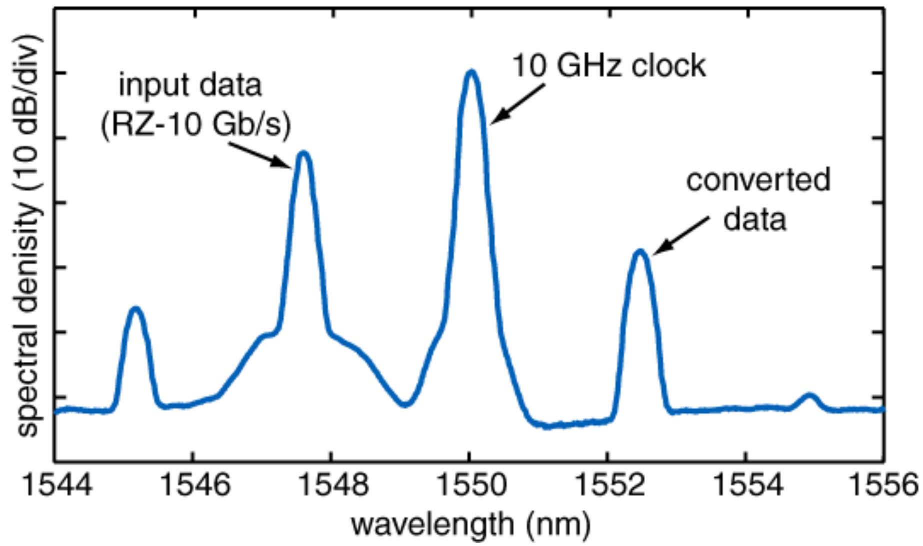
Extinction ratio improvement

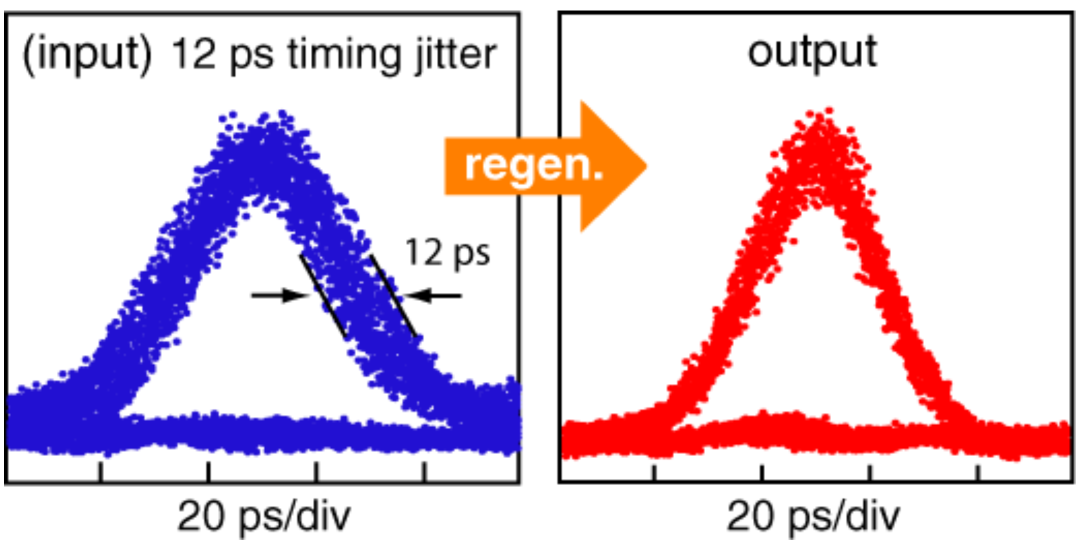
Pulse compression



10 Gb/s RZ Data Regeneration

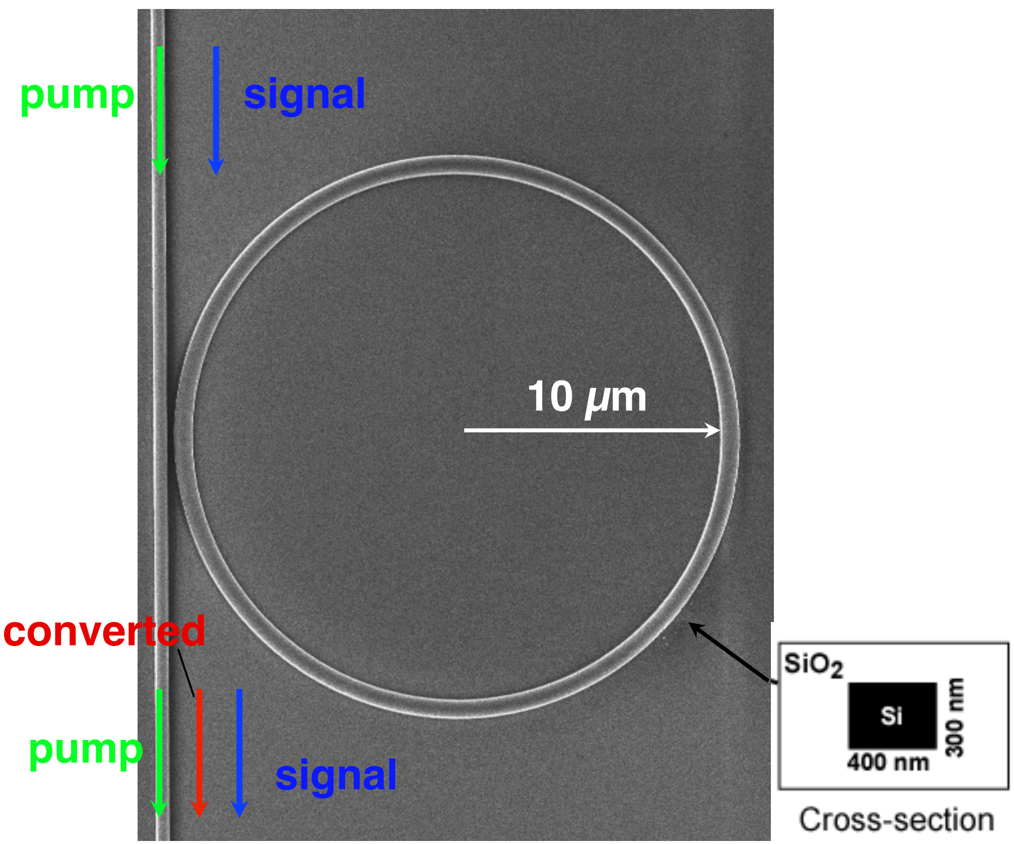
Timing jitter suppression using a clock (control) signal

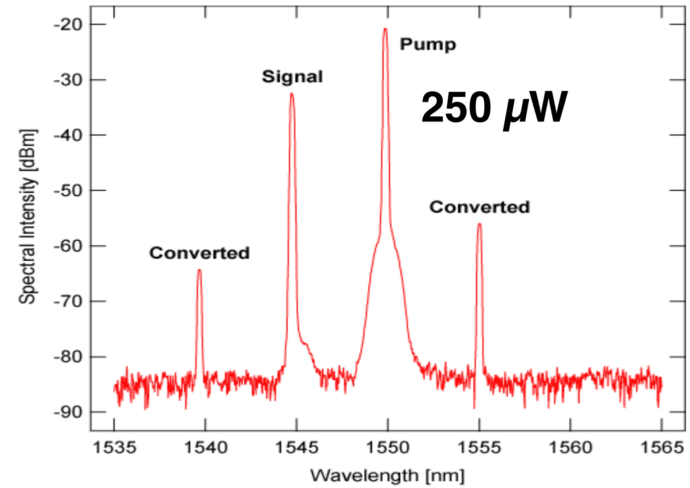


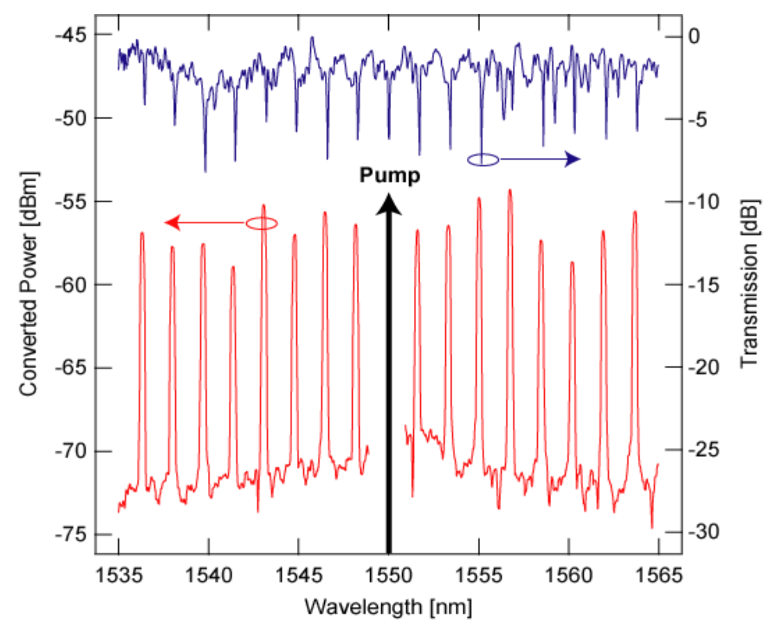


Ultralow Power Frequency Conversion

- Use ring resonator to enhance efficiency of FWM.
- Frequency conversion: < **mW** cw powers.







Turner, Foster, Gaeta, and Lipson, *Opt. Express* (2008).