Nonlinear Photonics in Guided-Wave Nanostructures

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Summer School on Quantum and Nonlinear Optics
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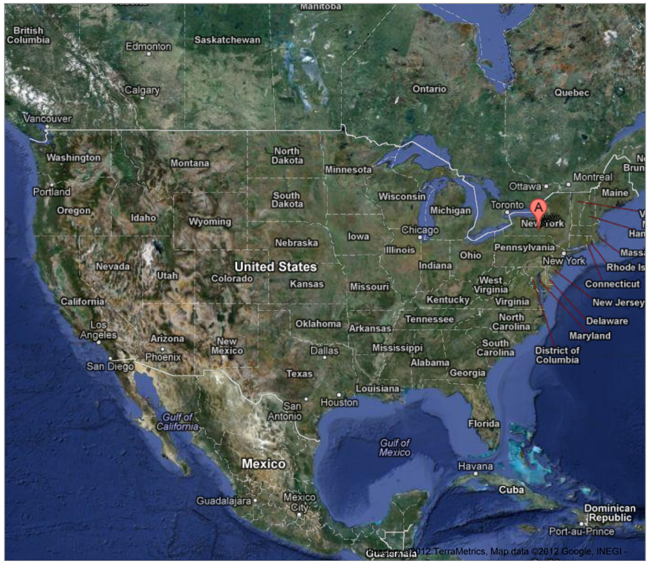
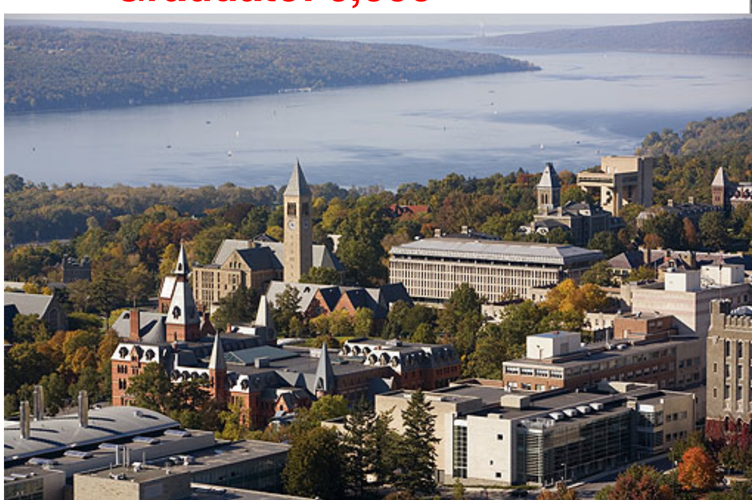


Cornell University

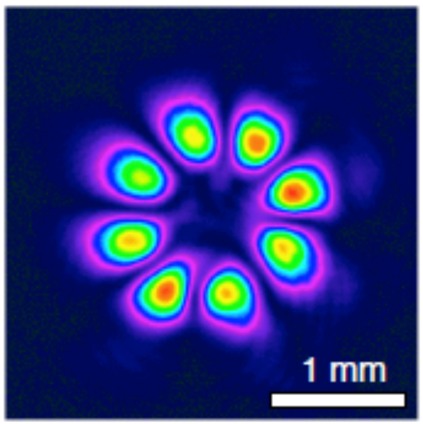
Undergraduate: 14,000

Graduate: 6,000



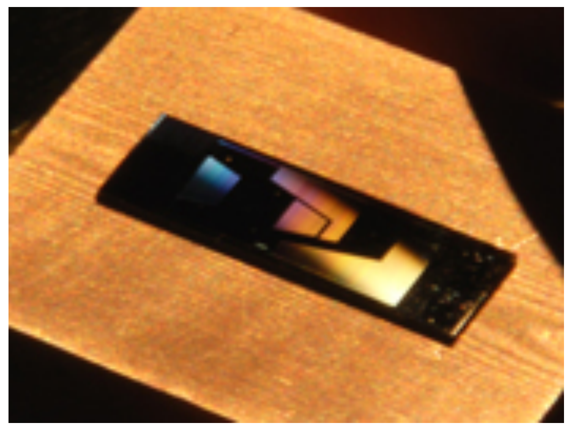
Light-Matter Interactions over 23-Orders of Magnitude

Ultrafast Propagation Dynamics



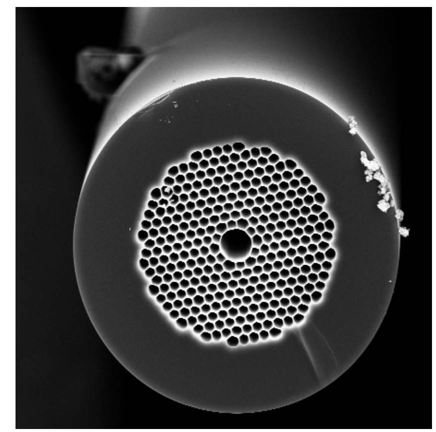
10 MW – 1 TW

Chip-Based Nanophotonics



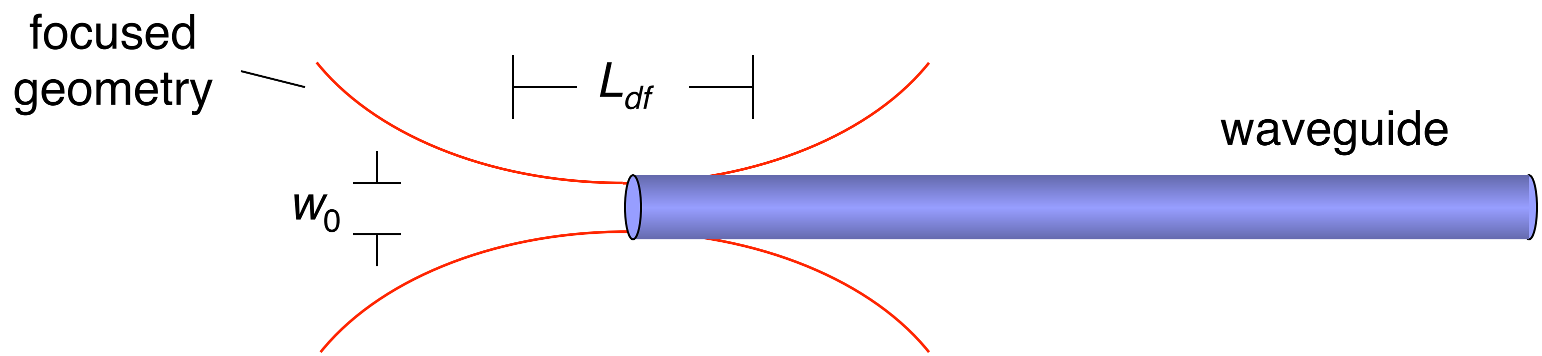
100 μW – 1 W

Photonic Crystal Fibers



10 pW – 1 μW

Nonlinear Interactions: Why Waveguides?



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

power

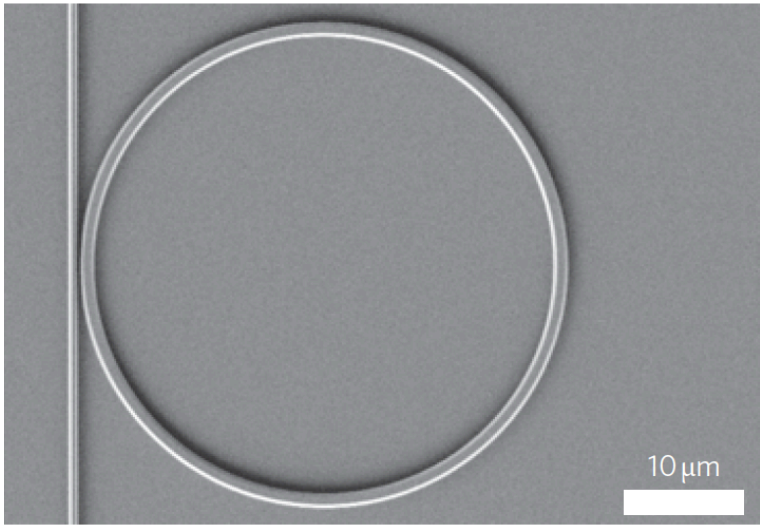
area

interaction length

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

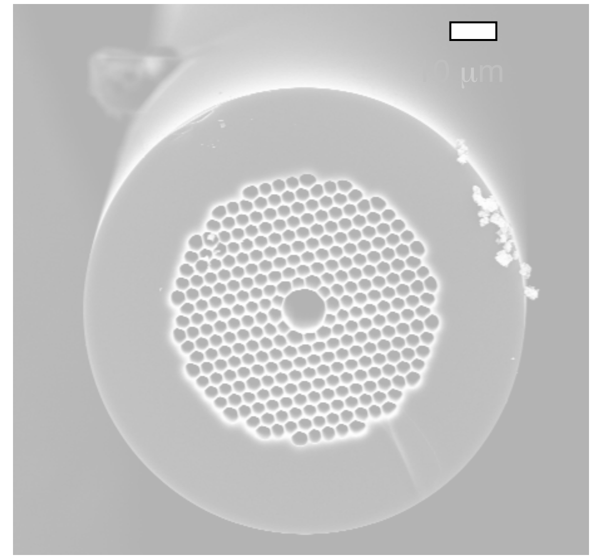
Outline: Nonlinear Optics in Nanostructured Materials

Silicon-Based Nonlinear Nanophotonics



- Four-wave mixing with mW's
- Optical parametric oscillation & frequency comb generation
- Ultrashort pulse generation

Gas-Filled Photonic Crystal Fibers



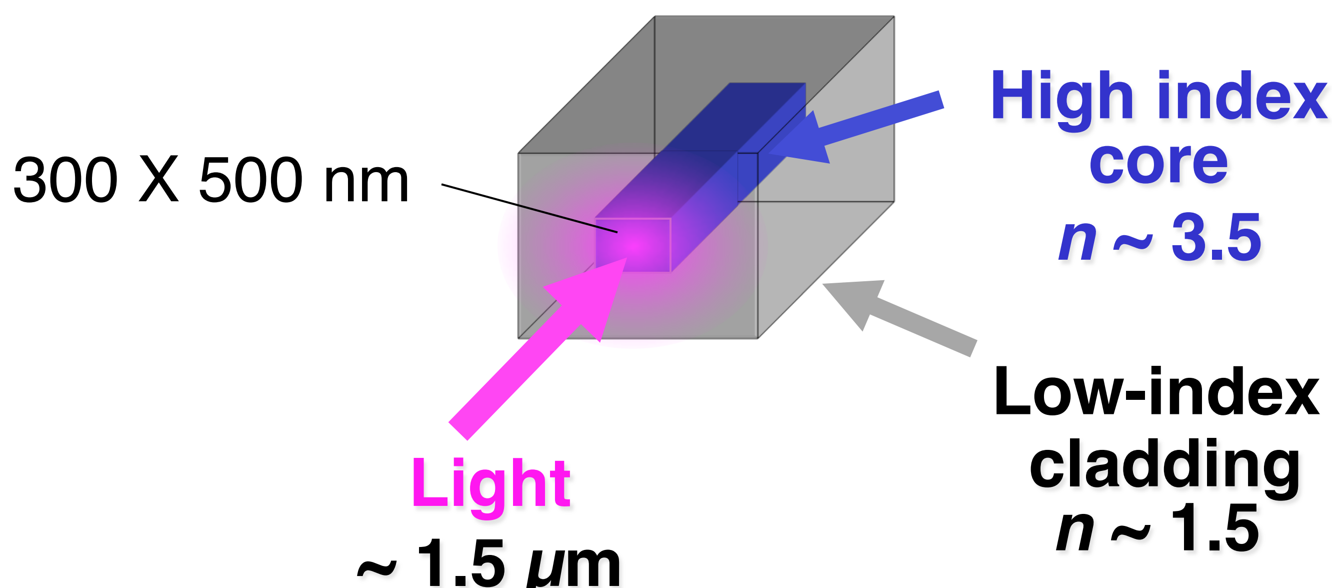
- Generation of high-density Rb vapor
- Few-photon resonant nonlinear interactions

Outline: Silicon Nonlinear Nanophotonics

- Linear & nonlinear properties of nanowaveguides
- Four-wave mixing (FWM) in Si nanowaveguides
  - Dispersion engineering
  - Ultra-broadband wavelength conversion
- Optical parametric oscillator
  - broad-band frequency comb
  - ultrashort-pulse generation

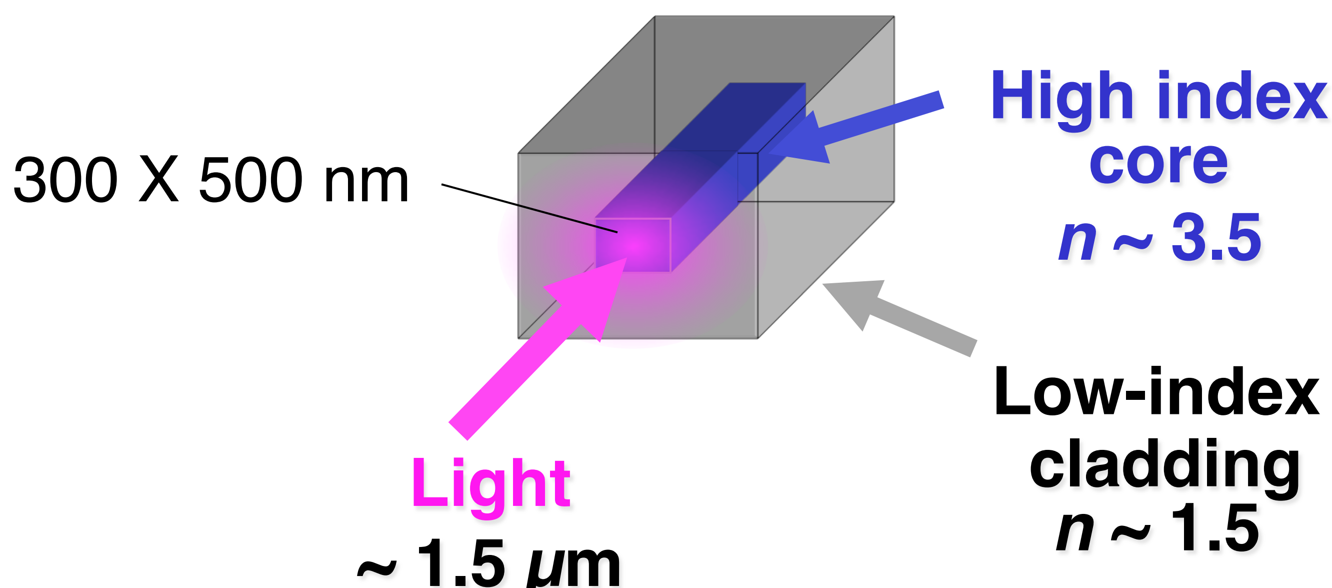
Nonlinear Optical Devices in Si Nanowaveguides

- High index contrast – tight optical confinement
  - compact structures, much smaller than the wavelength
  - enhanced nonlinearity (1000 X silica)
  - dispersion engineering
- Massively parallel devices enable ultra-high bandwidth processing.



Nonlinear Optical Devices in Si Nanowaveguides

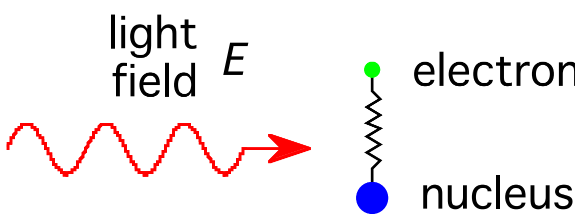
- High index contrast – tight optical confinement
  - compact structures, much smaller than the wavelength
  - enhanced nonlinearity (1000 X silica)
  - **dispersion engineering - critical for phase matching**
- Massively parallel devices enable ultra-high bandwidth processing.

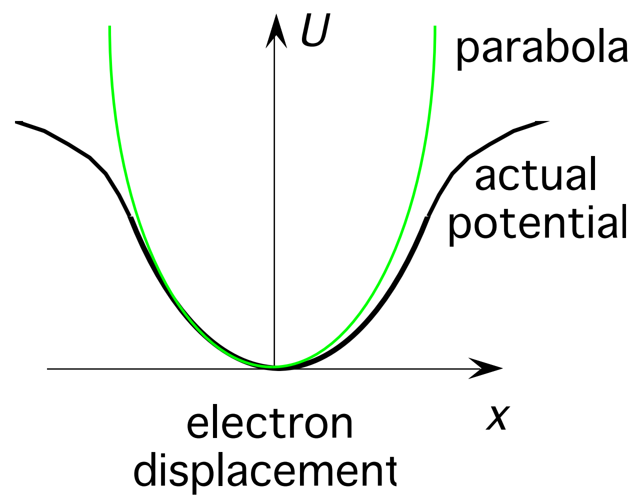


Laser-Matter Interactions: Nonlinear Optics

[see *Nonlinear Optics*, 2nd Ed., Boyd (2003)]

- 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

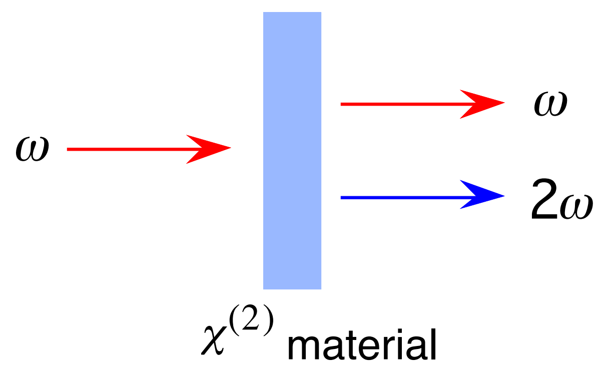
2nd-Order Nonlinear Processes

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

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

$$P^{(2)}(t) = \chi^{(2)}E^2(t) = \chi^{(2)}\frac{A^2}{2}(\underbrace{1}_{\text{dc}} + \underbrace{\cos 2\omega t}_{\text{second-harmonic}})$$

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., $n_\omega = n_{2\omega}$)

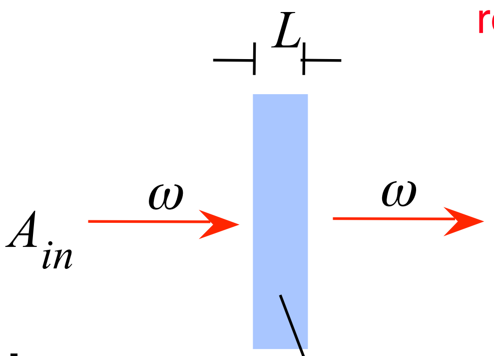
3rd-Order Nonlinear Processes

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

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

intensity-dependent refractive index

third-harmonic (usually not phasematched)



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

$$n = n_0 + n_2 I$$

intensity

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

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

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

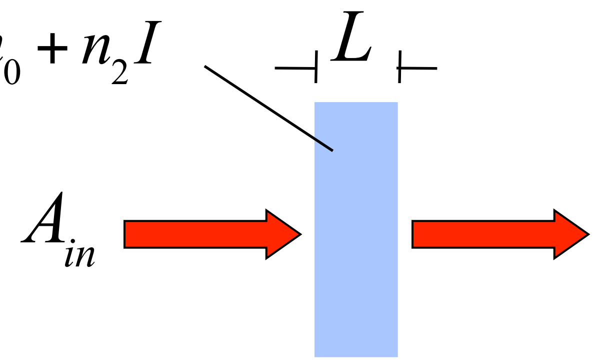
<u>All materials exhibit a nonlinear refractive index. (usually $n_2 > 0$)</u>

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

Self- and Cross-Phase Modulation

- Self-phase modulation (SPM)

$$n = n_0 + n_2 I$$

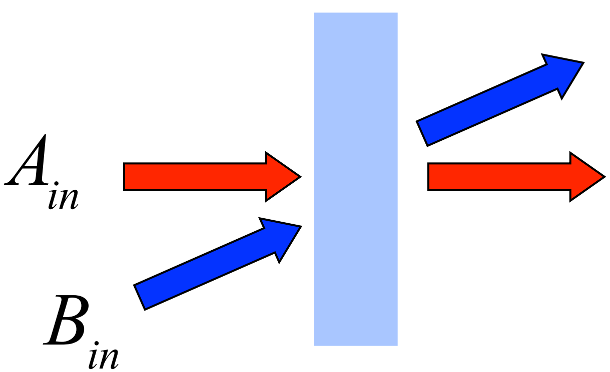


$$A_{out} = A_{in} e^{i\phi_{nl}}$$

SPM

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

- Cross-phase modulation (XPM)

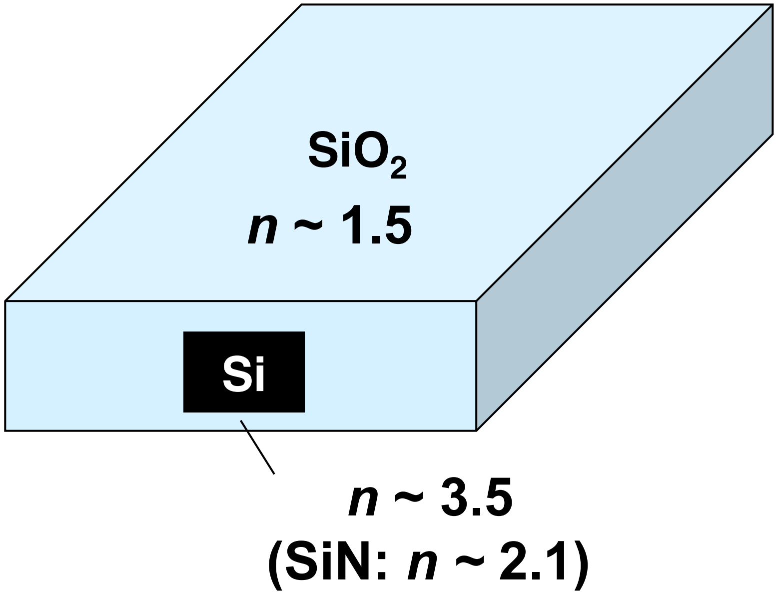


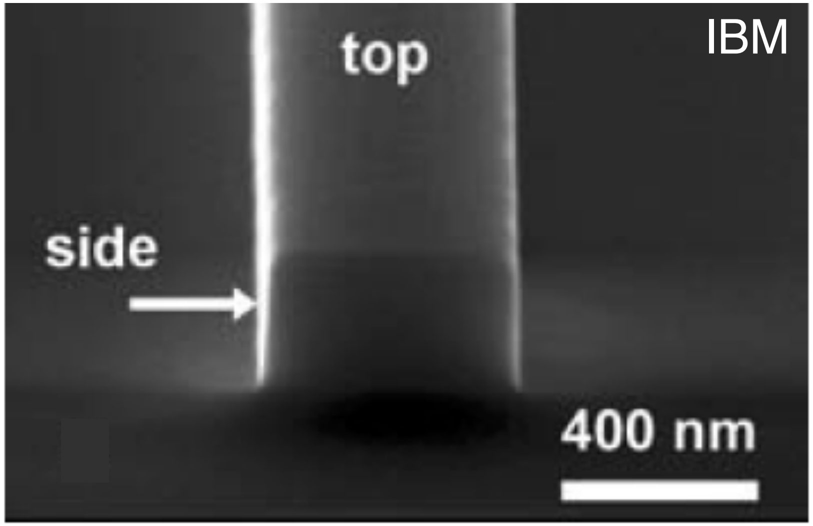
$$A_{out} = A_{in} e^{i\phi_{nl}}$$

XPM

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

Nonlinear Optics in Silicon-Based Nanowaveguides

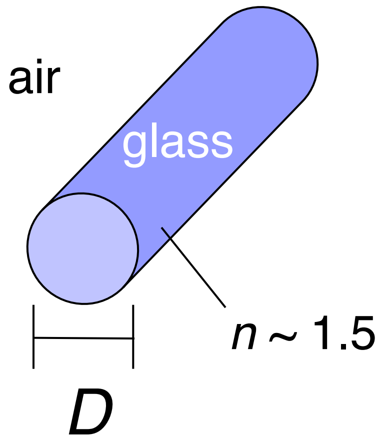


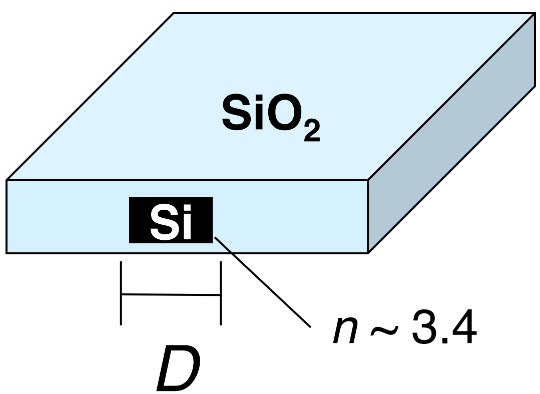


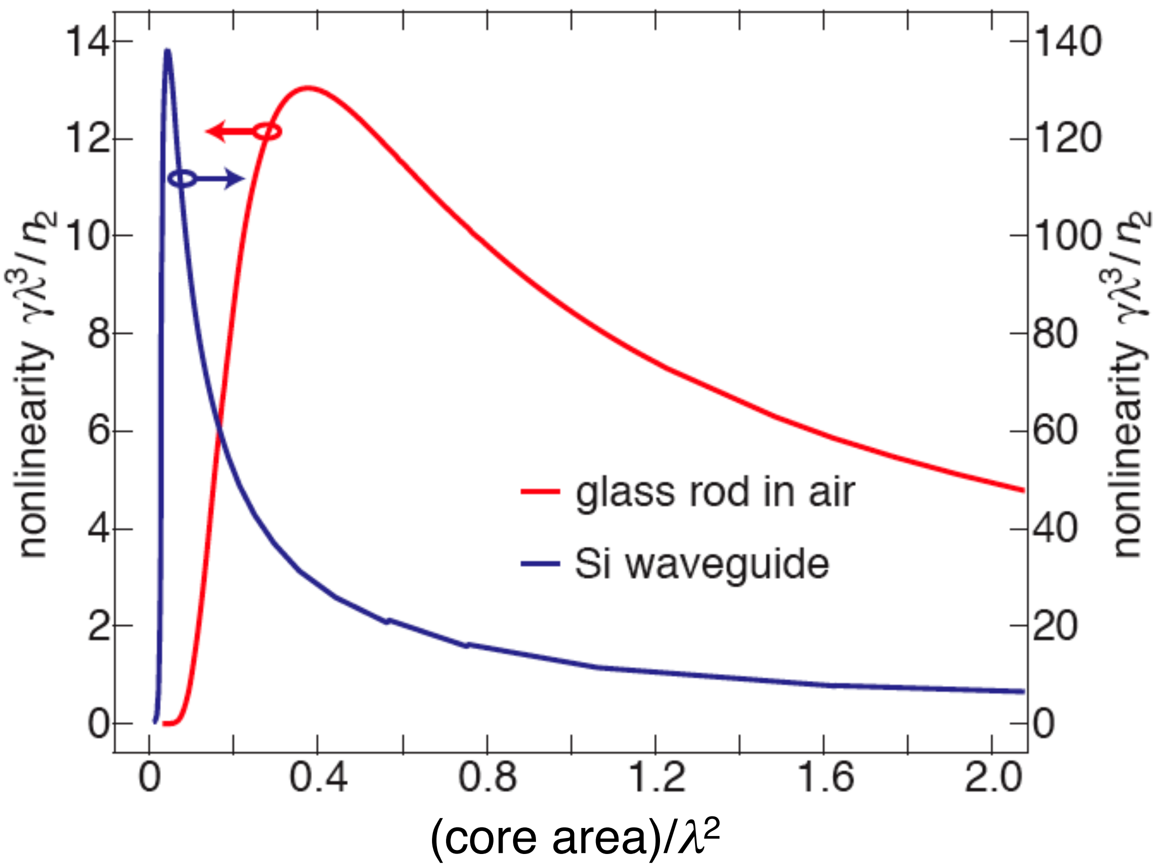
Absorption edge: Silicon => ~ 1.1 μm Si_3N_4 => ~ 400 nm

- Nonlinearity of Silicon 100X (Si_3N_4: 10X) silica
- Light confined to a region < than a wavelength.
- Dispersion can be engineered.

Confinement Properties of Ultra-Small-Core Waveguides





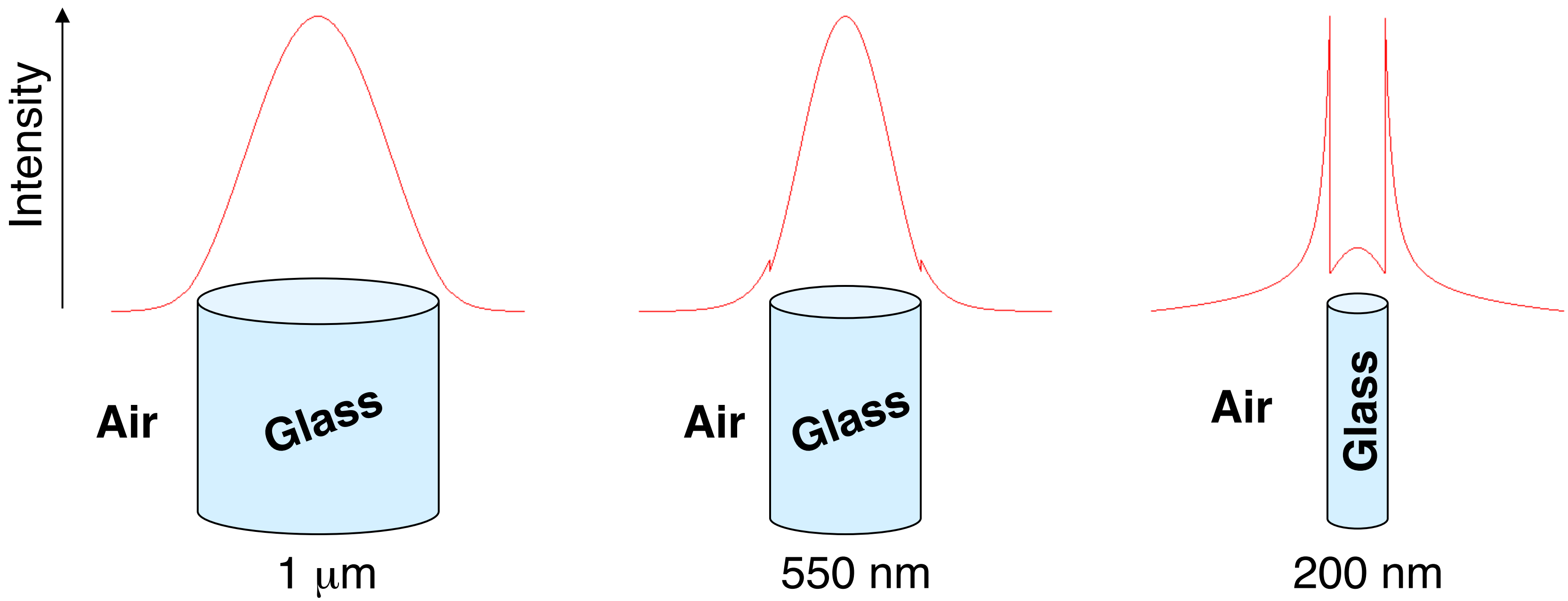


$$\boxed{D_{optimal} < \lambda}$$

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

Light Localization in Nanowires

$\lambda = 800$ 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; 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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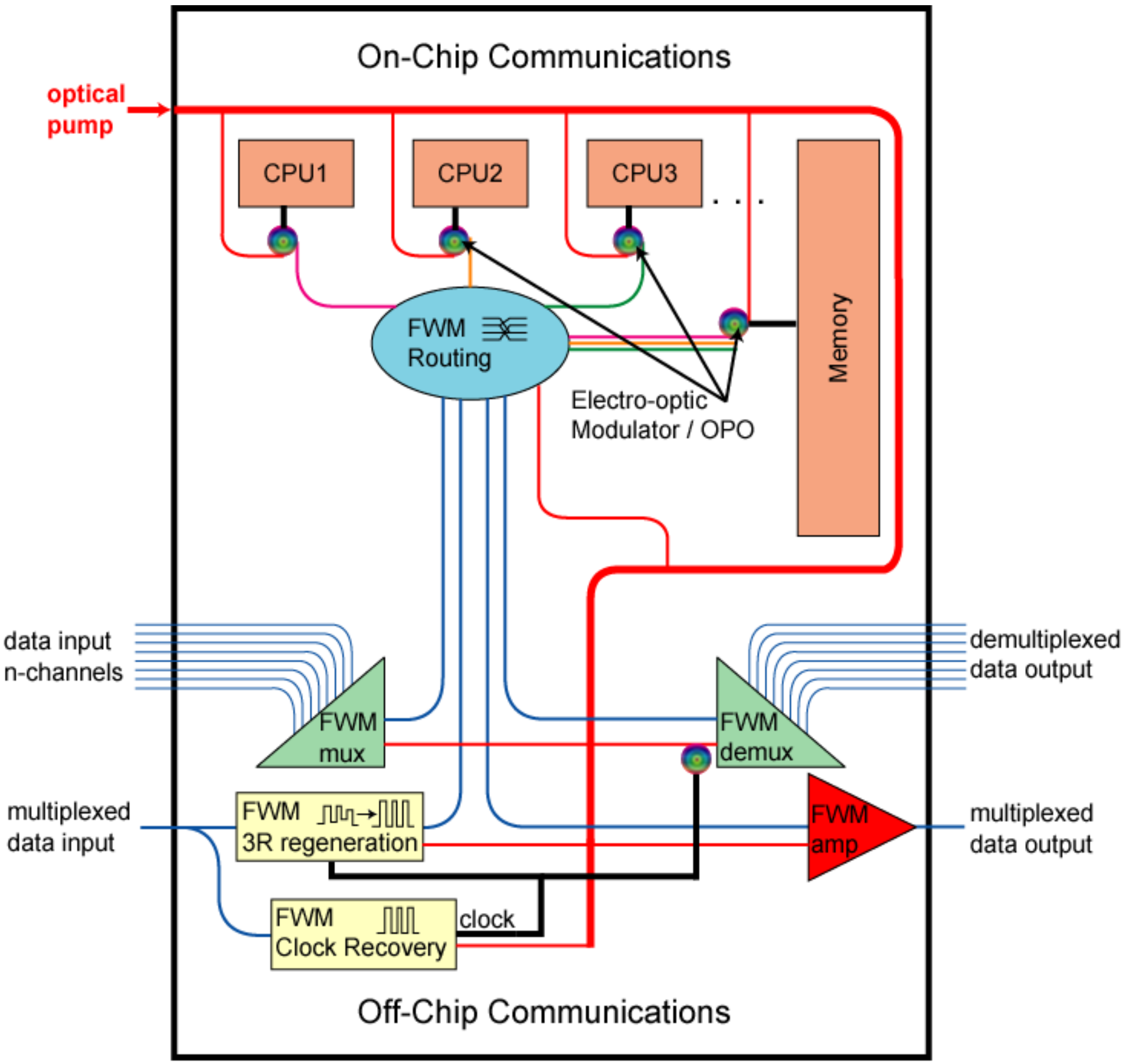
Reviews: Foster, et al. *Opt. Express* **16**, 1300 (2008)

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

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

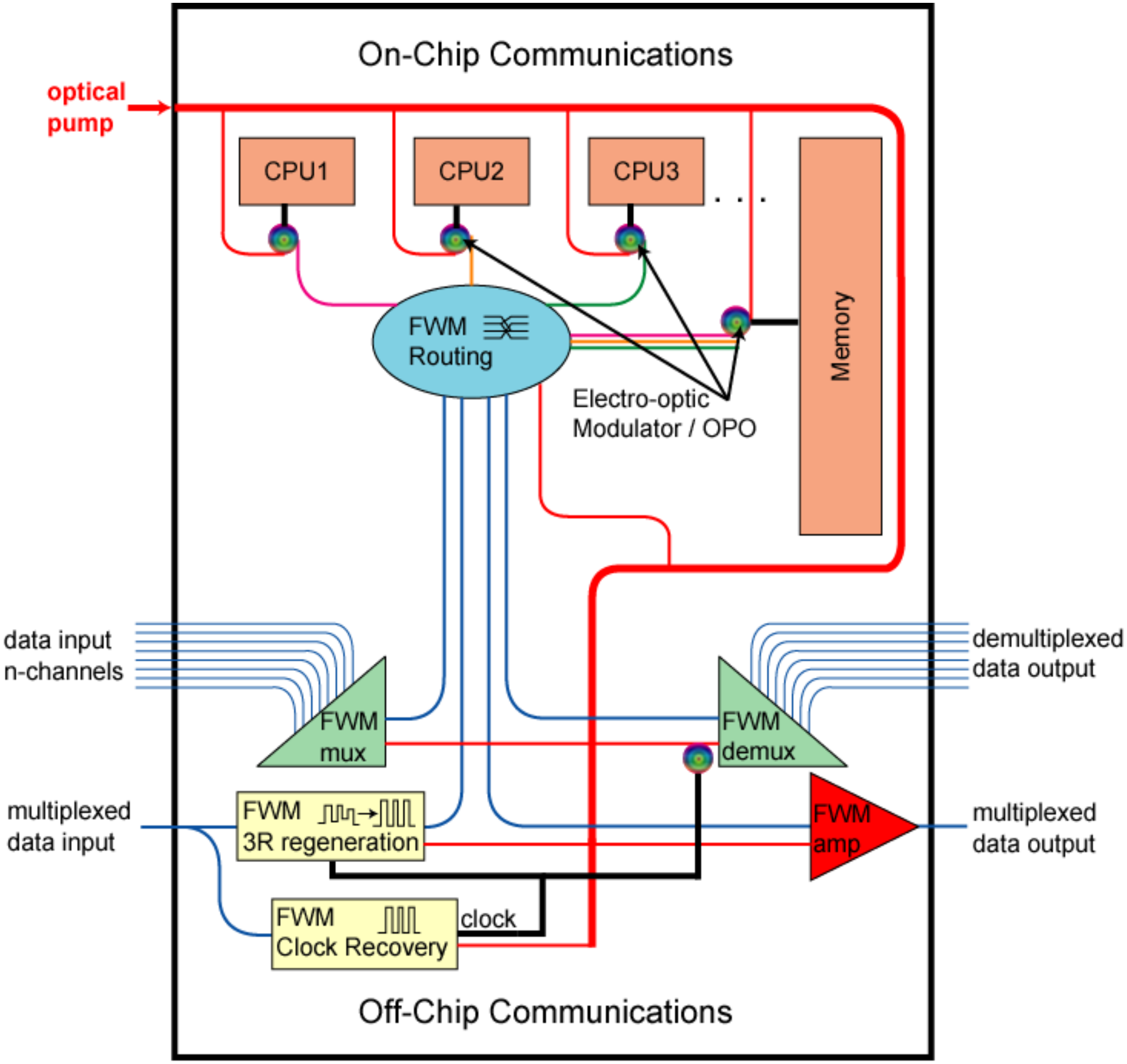
Nonlinear Photonics on Silicon Chip



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
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- A-D conversion
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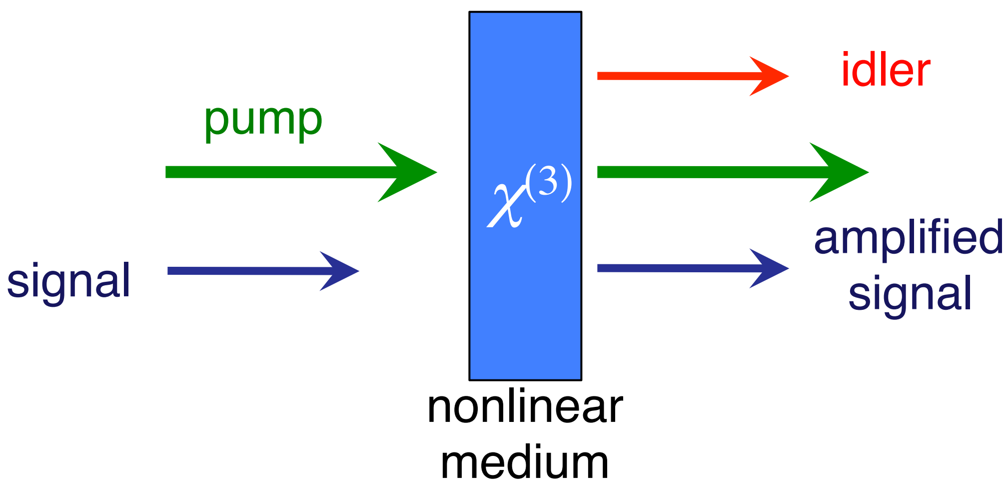
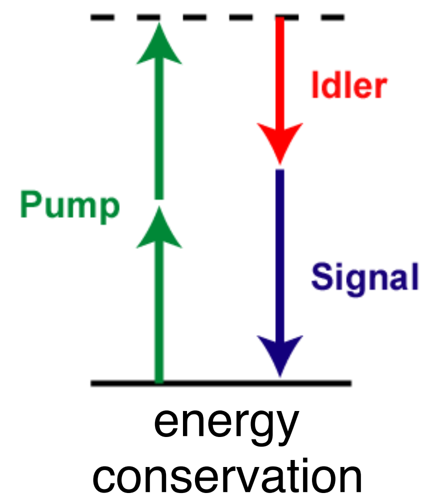
<u>All performed via four-wave mixing.</u>

Four-Wave Mixing





<u>input field</u>

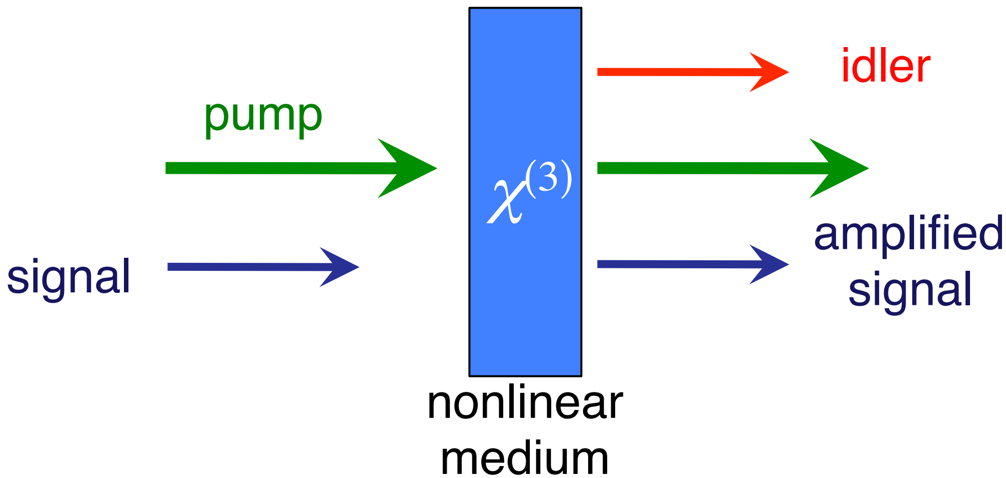
$$E_{input} = E_p + E_s = A_p e^{-i\omega_p t} + A_s e^{-i\omega_s t} + c.c.$$

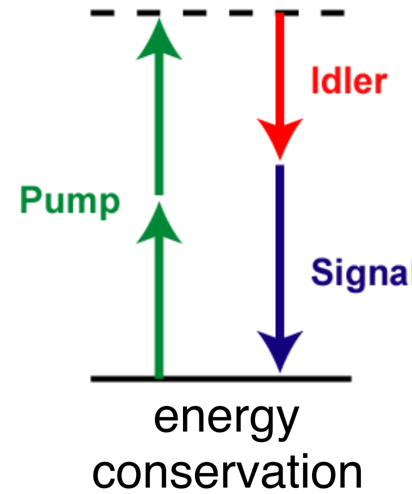
<u>nonlinear polarization</u>

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

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

Four-Wave Mixing





input field

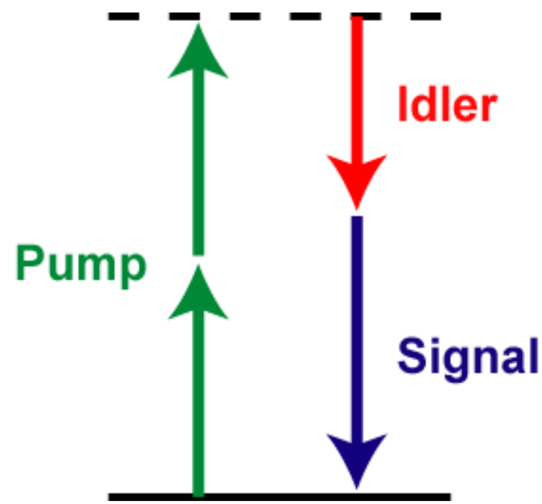
$$E_{input} = E_p + E_s = A_p e^{-i\omega_p t} + A_s e^{-i\omega_s t} + c.c.$$

nonlinear
polarization

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

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

Phase Matching in Four-Wave Mixing

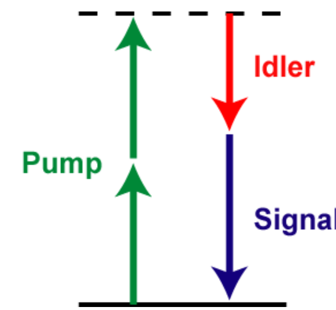


- Energy conservation: $2\omega_p - (\omega_s + \omega_i) = 0$
- Momentum conservation: $\Delta k = 2k_p - (k_s + k_i) + \Delta k_{nl}$
  - Balance of GVD and effects of self-phase modulation & cross-phase modulation

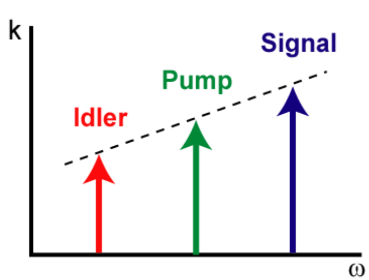
group-velocity dispersion: $\boxed{\mathrm{GVD} \propto -\dfrac{d^2 n}{d\lambda^2} \geq 0}$

Phase Matching in Four-Wave Mixing

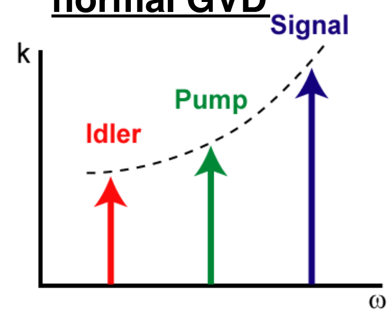
- Energy conservation: $2\omega_p - (\omega_s + \omega_i) = 0$
- Momentum conservation: $\Delta k = 2k_p - (k_s + k_i) + \Delta k_{nl}$
  - Balance of GVD and effects of self-phase modulation & cross-phase modulation
  - Want $\Delta k\, L < 1$



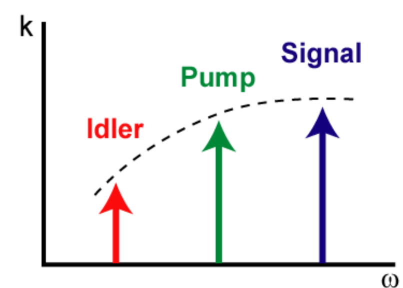
No dispersion, no SPM/XPM



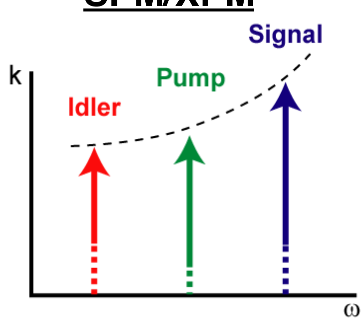
normal GVD



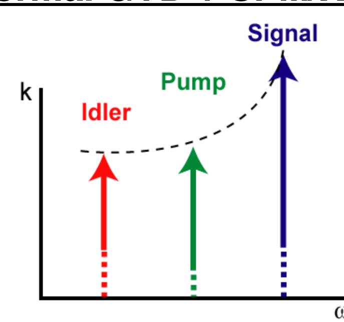
anomalous GVD



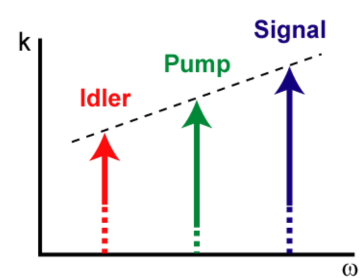
SPM/XPM



normal GVD + SPM/XPM



anomalous GVD + SPM/XPM



Four-Wave Mixing in Si Chip

Si Waveguide

$A \sim 0.1\ \mu m^2 << \lambda^2$ $L \sim 1$ cm

FWM efficiency $\sim \gamma\ P_{pump}\ L$

nonlinear parameter

<u>Large Effective Nonlinearity</u>

$$\gamma_{Si} \sim 300\ (\mathrm{W \cdot m})^{-1} \sim 10^4 \gamma_{glass}$$

<u>Large Conversion Bandwidth</u>

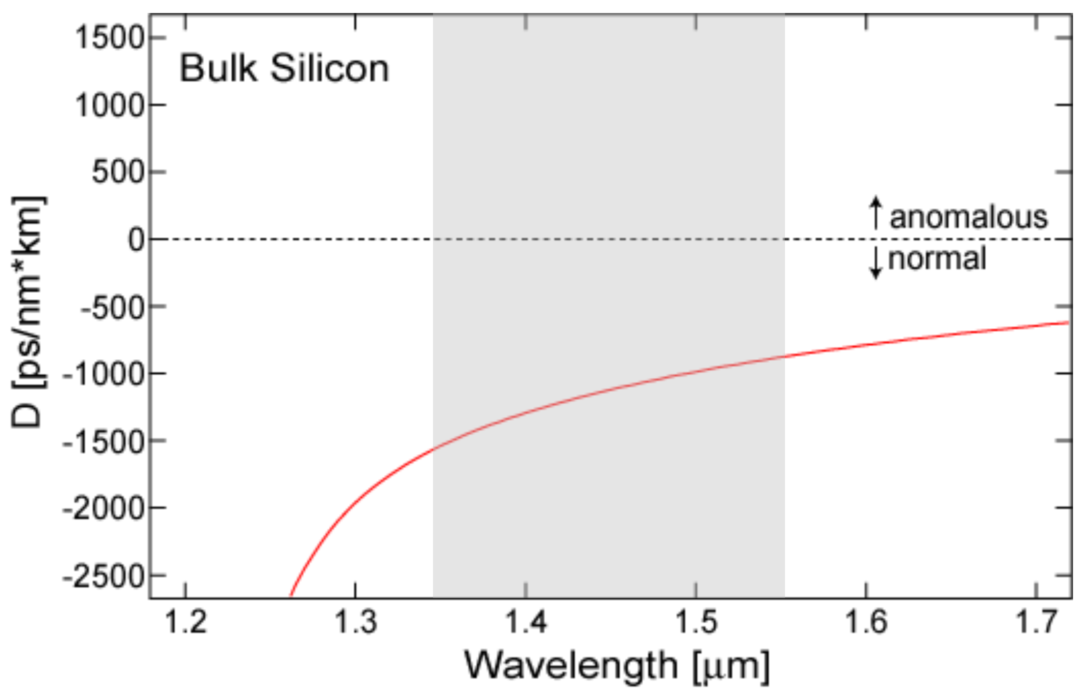
$$\Delta\omega \propto 1 / L$$

- **Advantages:**
  - **Highly compact, scalable, CMOS compatible**
  - **High effective nonlinearity.**
  - **Potential for very high bandwidth.**

Challenge: Large Normal GVD of Si

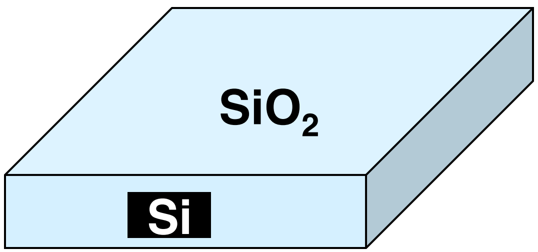
- Bulk Silicon
  - absorption band edge @ 1.1 μm
  - Si @ 1.55 μm: ***D* ~ − 1000 ps/(nm*km)**
    [silica glass @ 1.5 μm: ***D* ~ 20 ps/(nm*km)**]

GVD



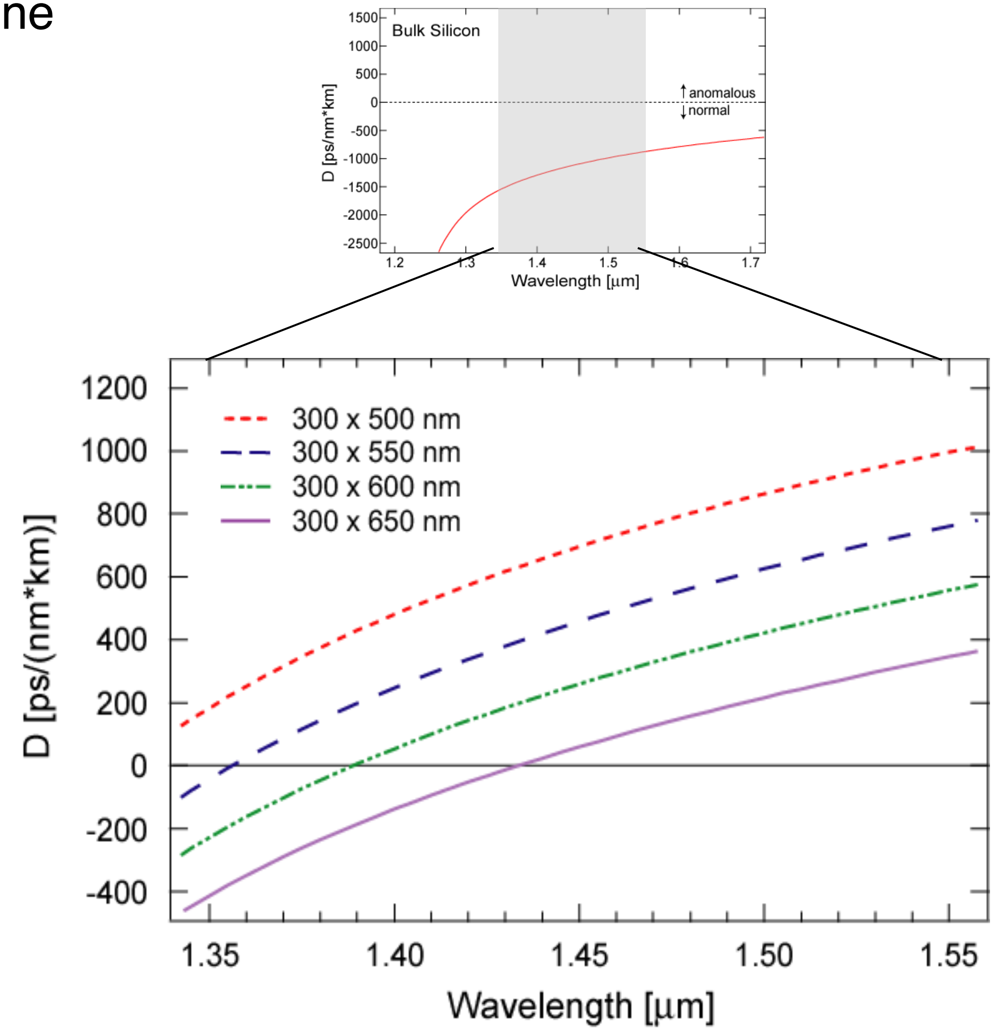
Tailoring of GVD in Si Waveguides

- Utilize waveguide dispersion to tune GVD.



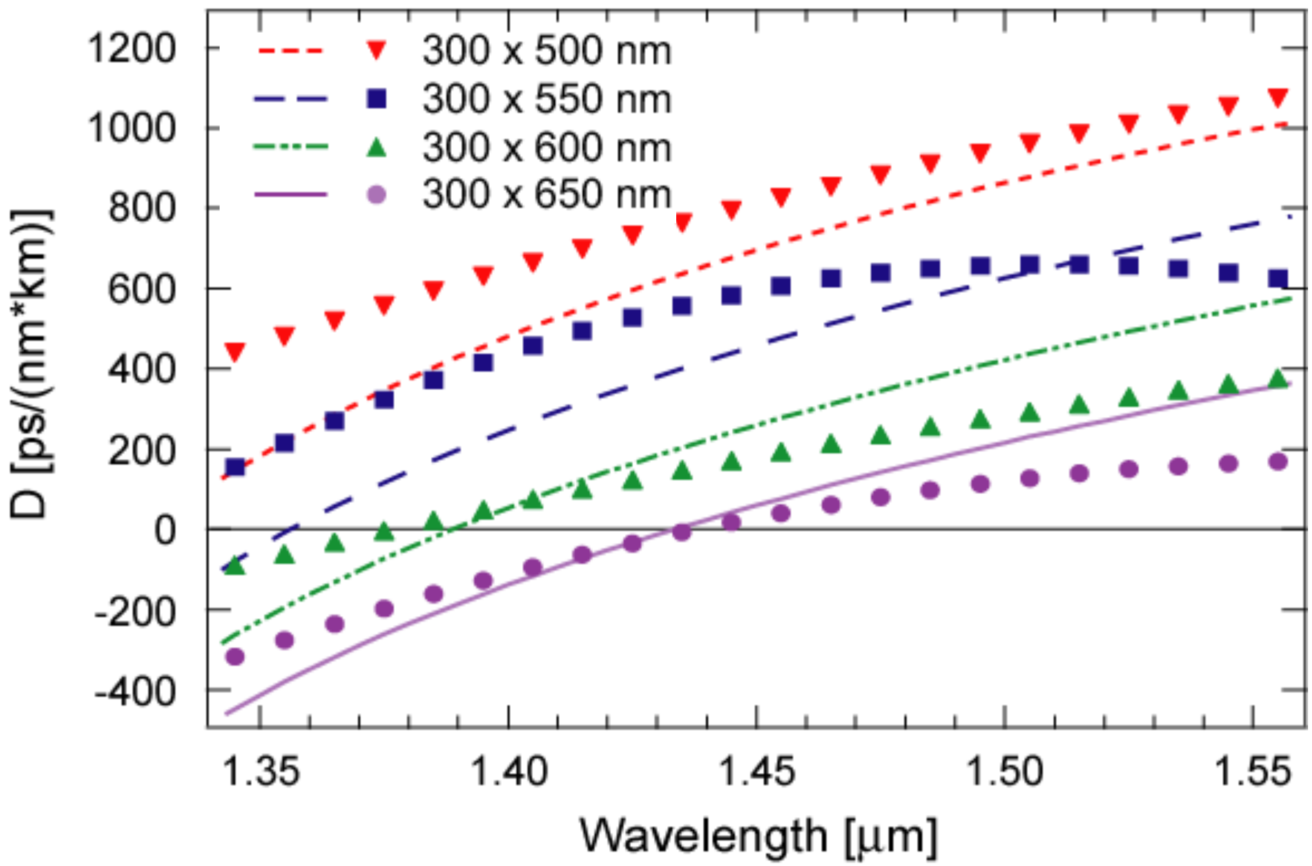
- GVD can be tuned by varying waveguide shape and size.

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



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

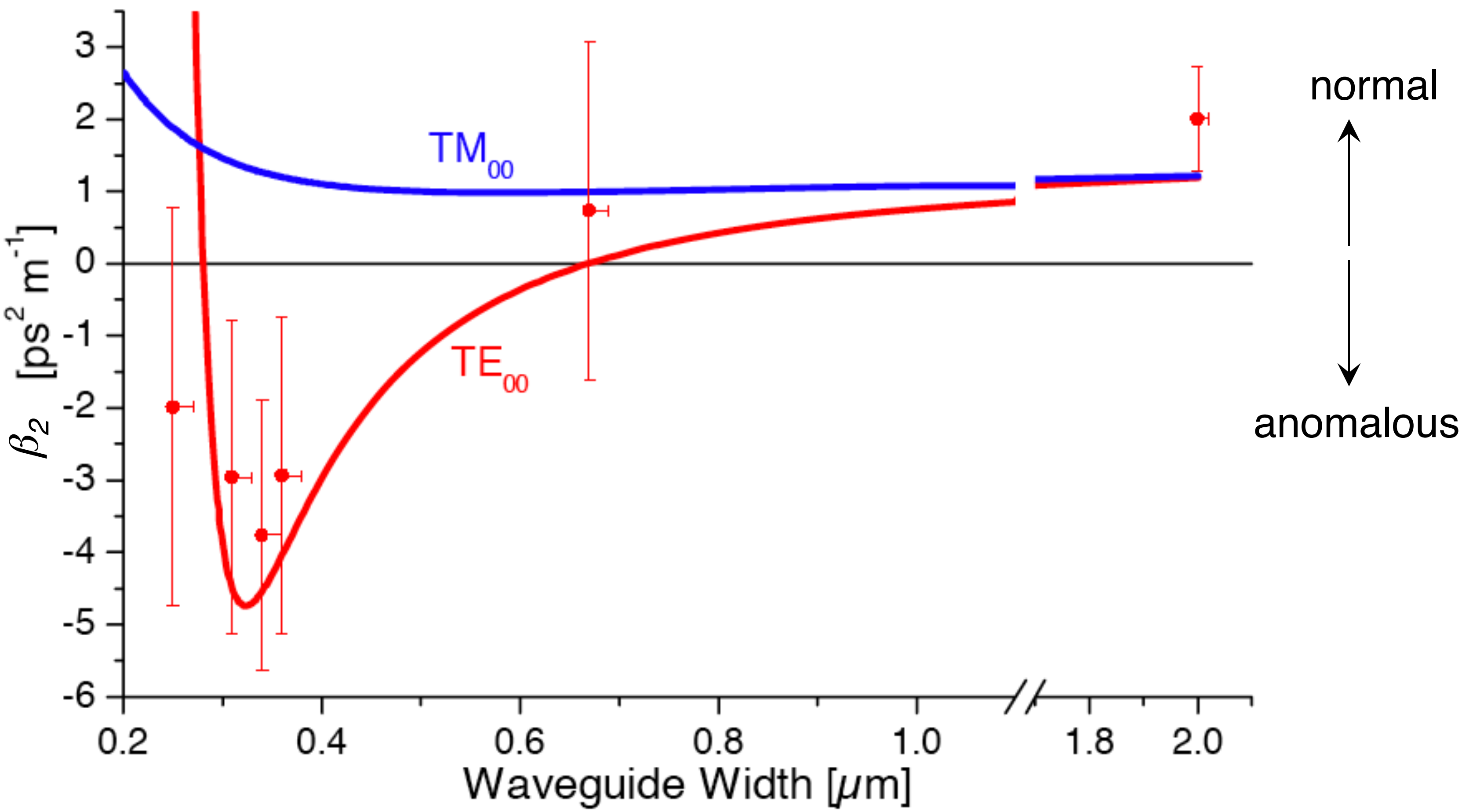
Measurement of Anomalous-GVD in Si Waveguides



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

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

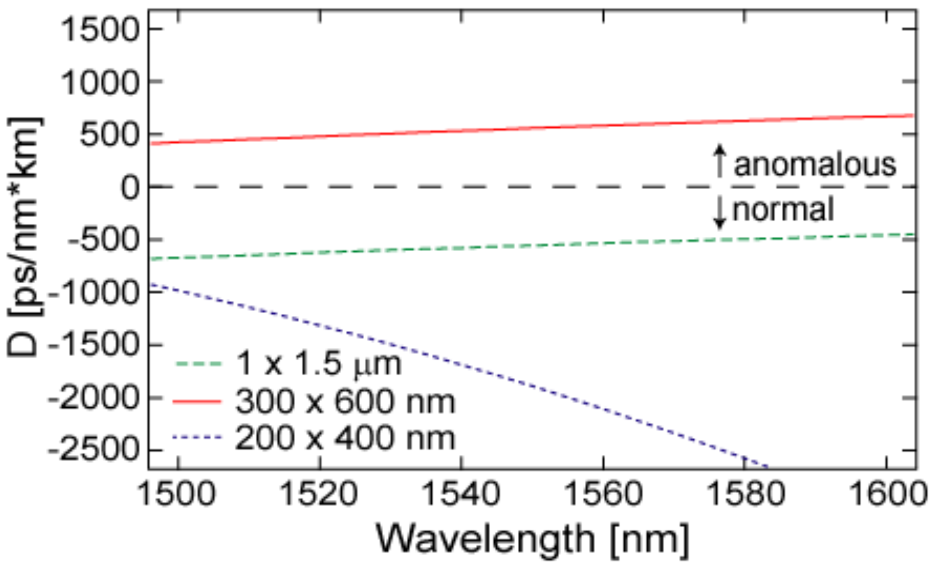
Dispersion Control in AlGaAs Waveguides

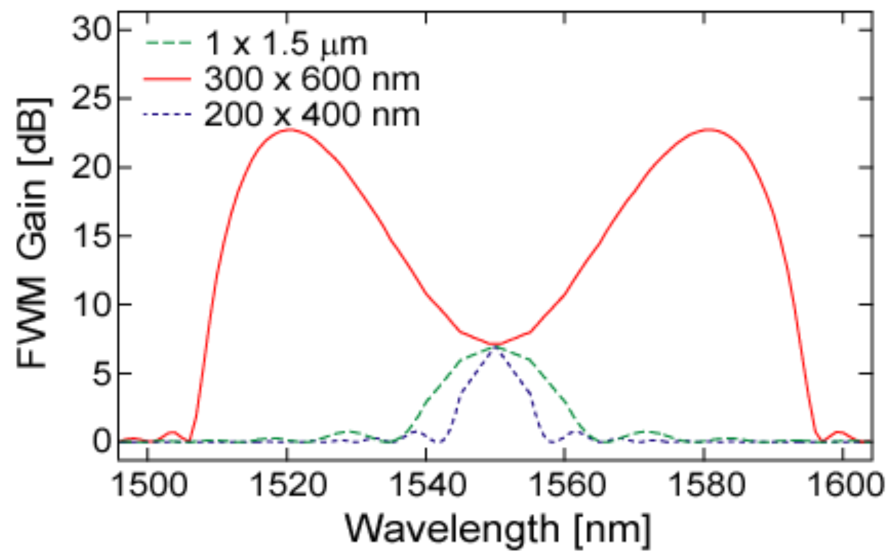


Meier, Mohammed, Jugessur, Qian, Mojahedi, and Aitchison, *Opt. Express* **15**, 12755 (2007).

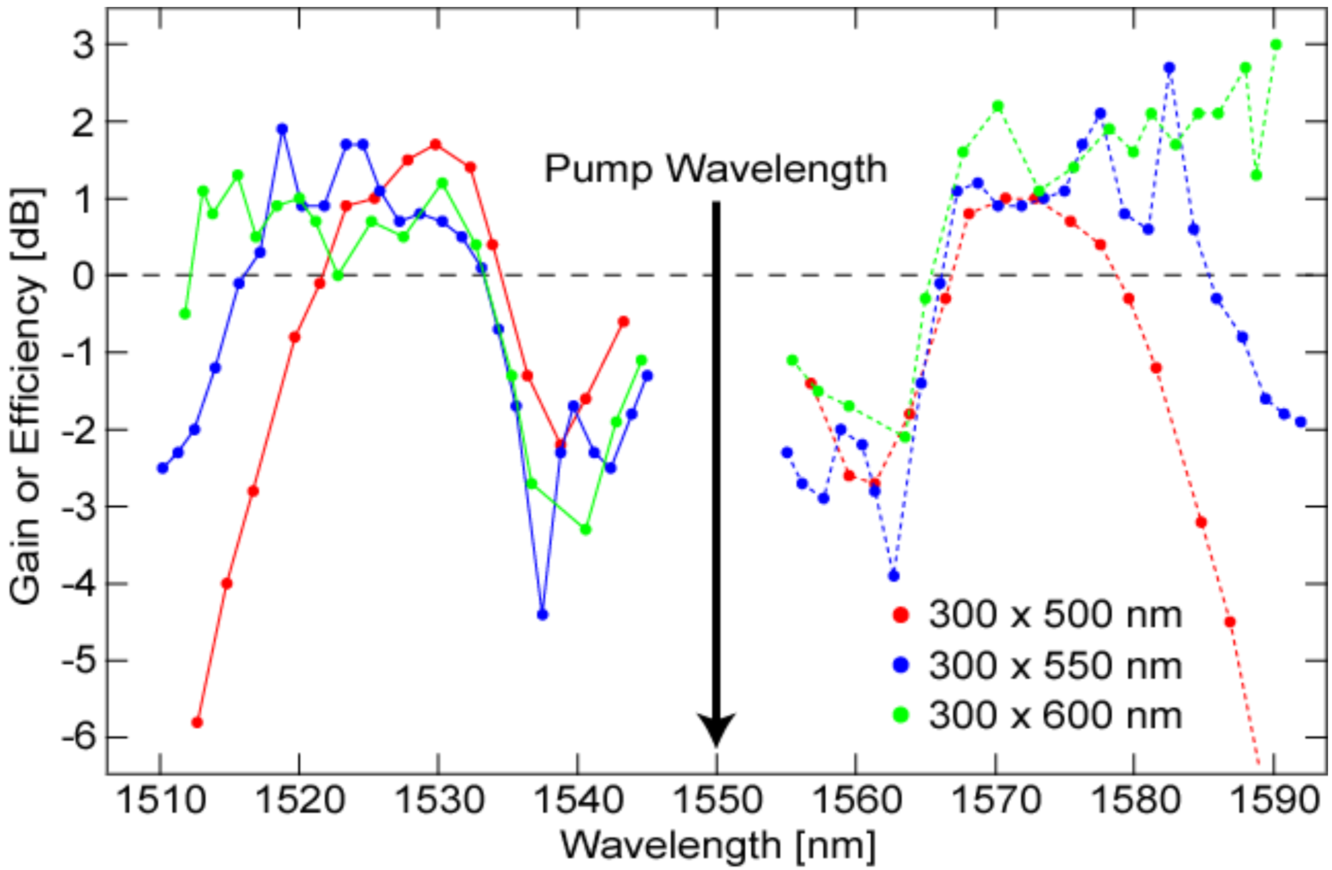
Phase-Matched Four-Wave Mixing

- Broad regions of FWM gain predicted.





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).

Four-Wave Mixing Amplification

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

50 dB parametric on-chip gain in silicon photonic wires

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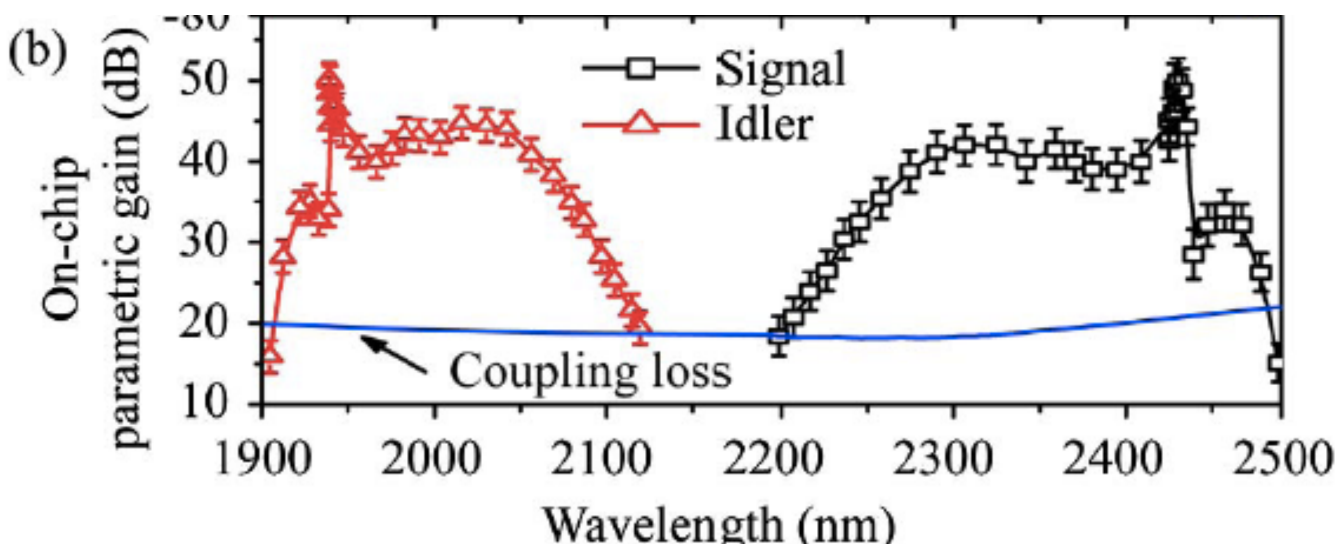
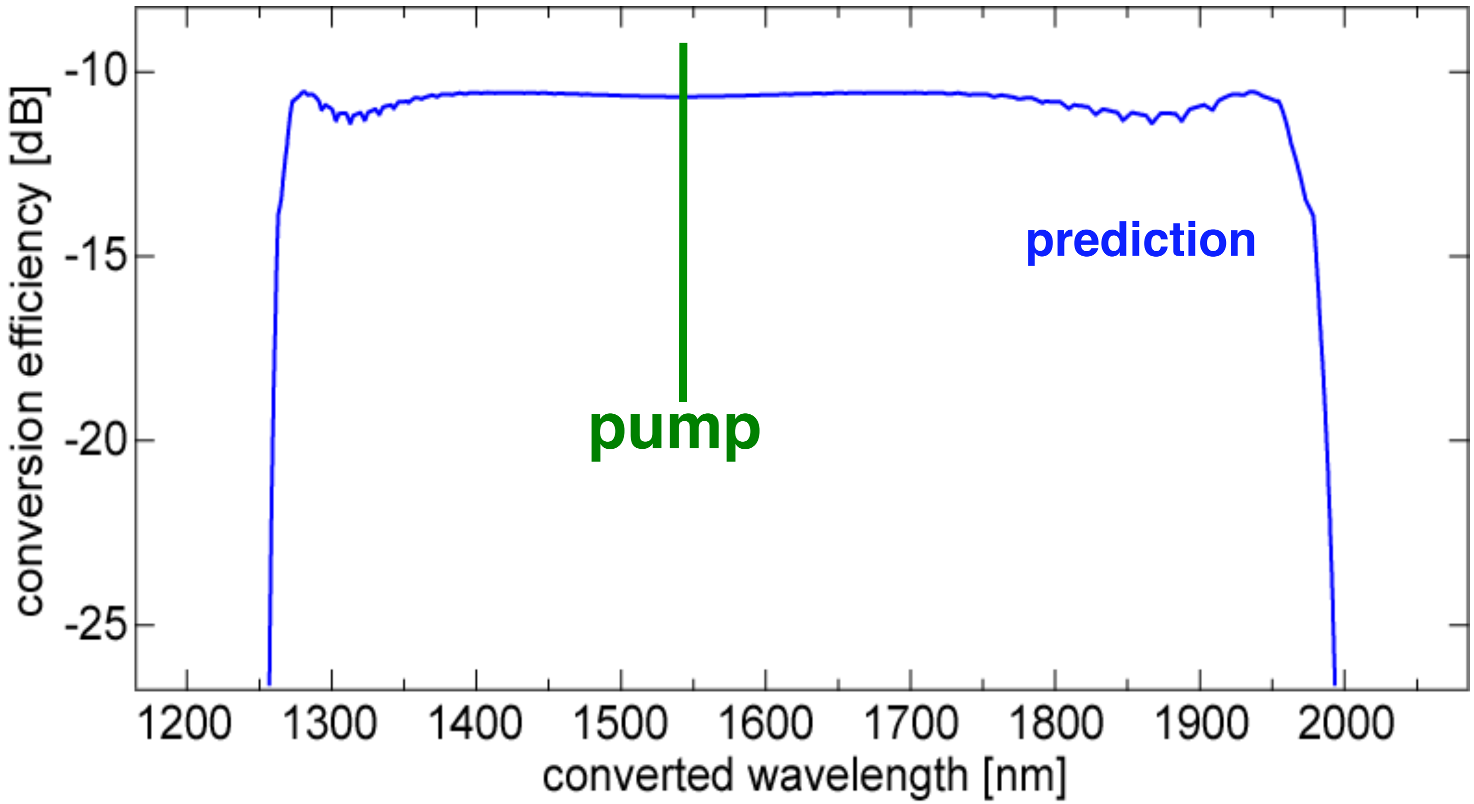
[4]*Current address: OFS Labs, 19 Schoolhouse Road, Somerset, New Jersey 08873, USA*
**Corresponding author: wgreen@us.ibm.com*



Broadband Wavelength Conversion

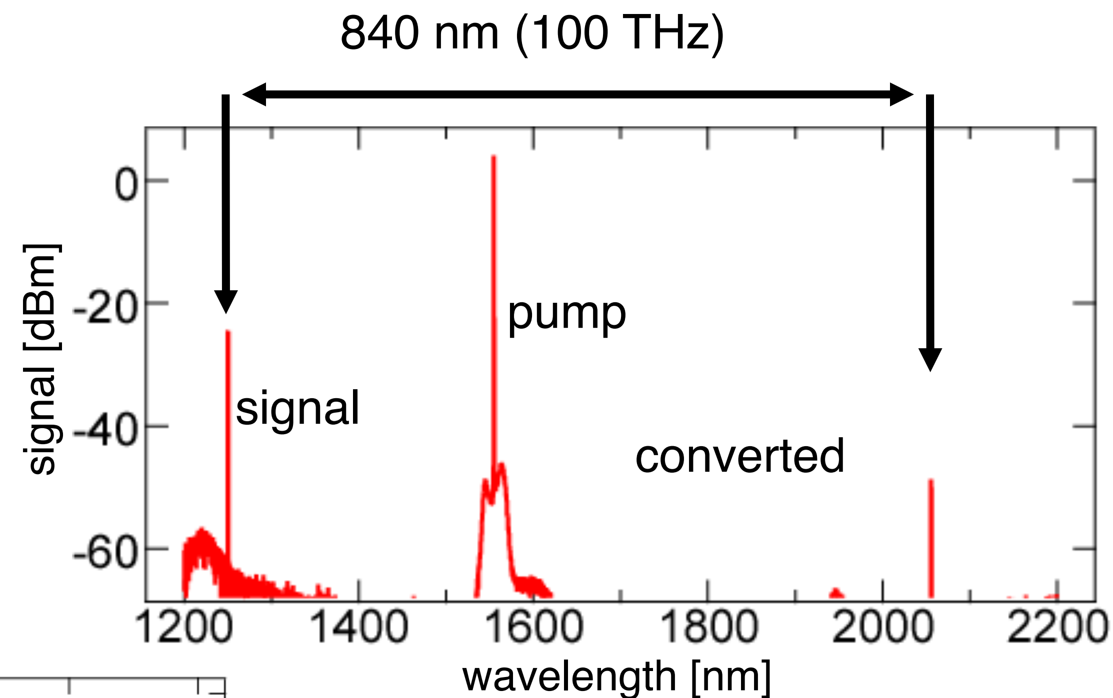


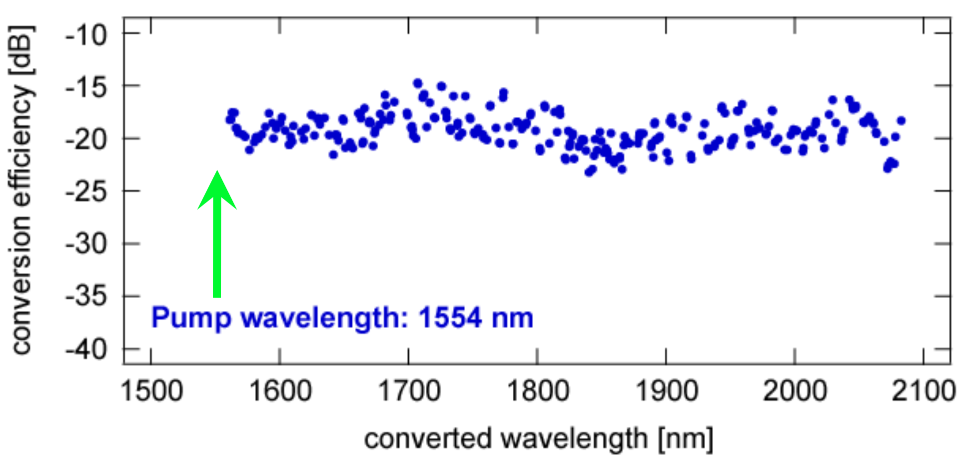
- Pump wavelength **0.2 nm** from zero-GVD point
- **750-nm** bandwidth

Ultrabroad-Band Conversion

Continuous-wave conversion from 1240 nm to 2080 nm

peak pump power ~ 50 mW



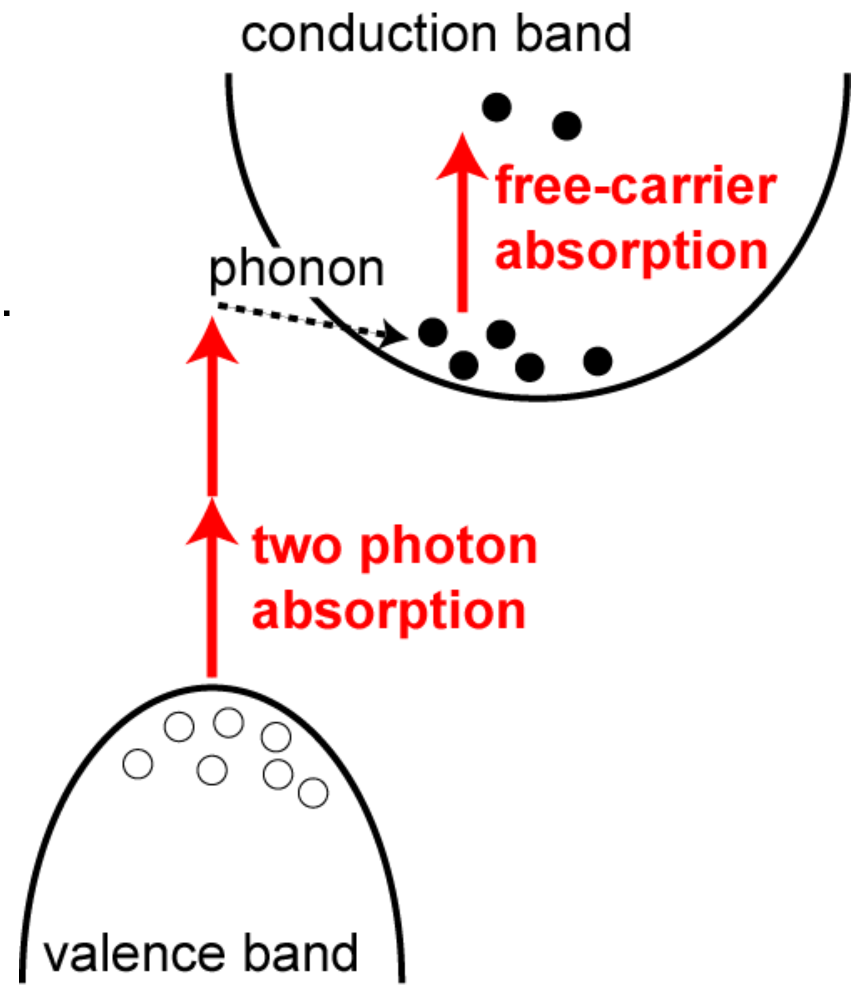


Continuously and instantaneously tunable

Foster, et al., *Opt. Express* (2007).
Turner-Foster, et al., *Opt. Express* (2010)

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.

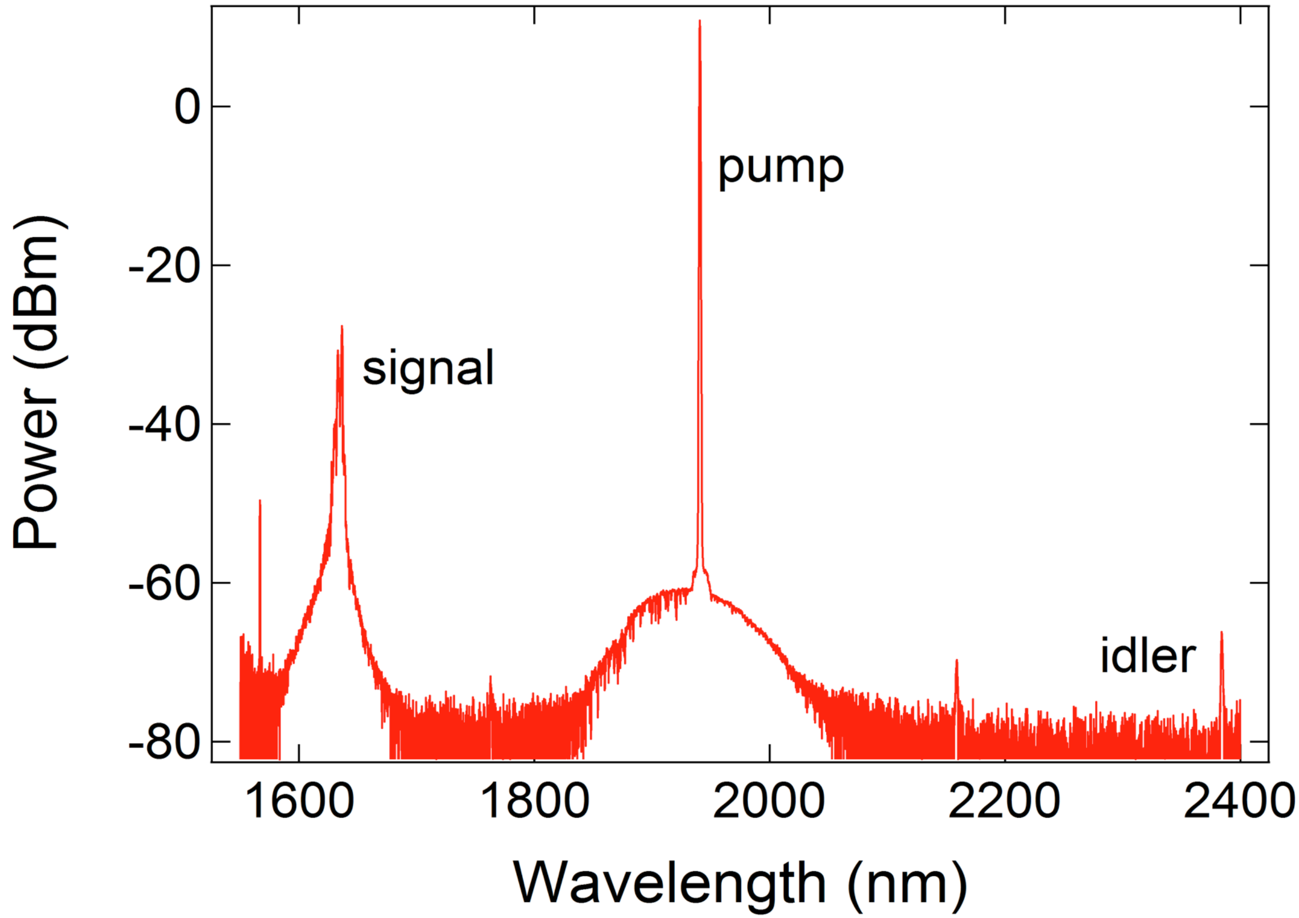


Solution:

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

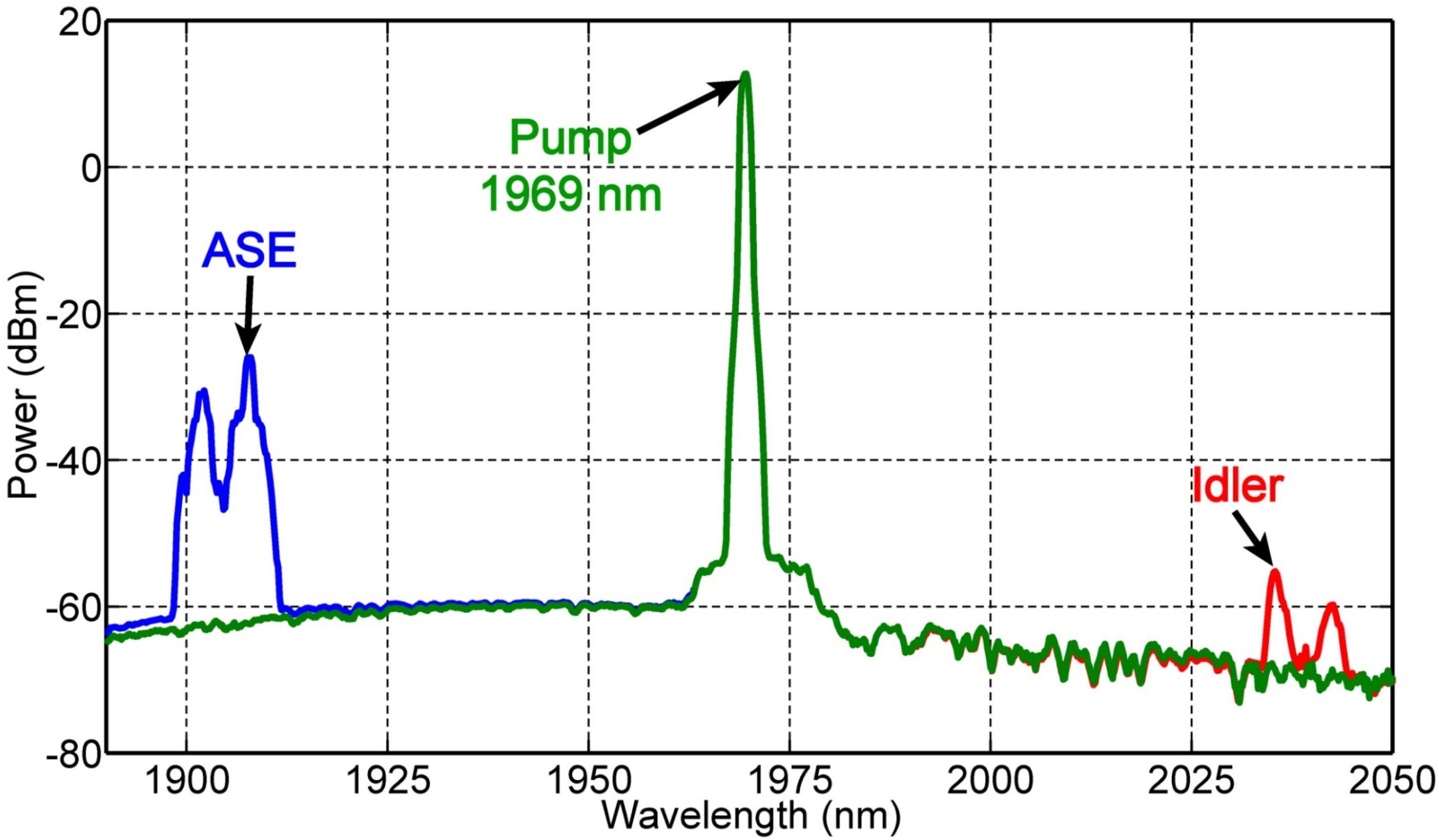
Mid-IR Frequency Conversion

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



- Pulsed conversion (w/ gain) [Zlatanovic et al. (2010); Kuyken et al. (2010, 2011).]
- Silicon-on-sapphire platform for longer MIR wavelengths [Baehr-Jones et al. (2010)]

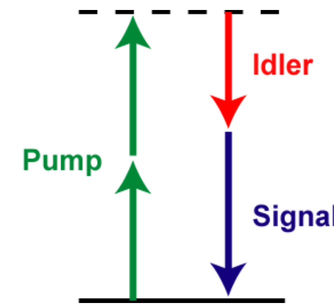
Frequency Conversion of Incoherent Source

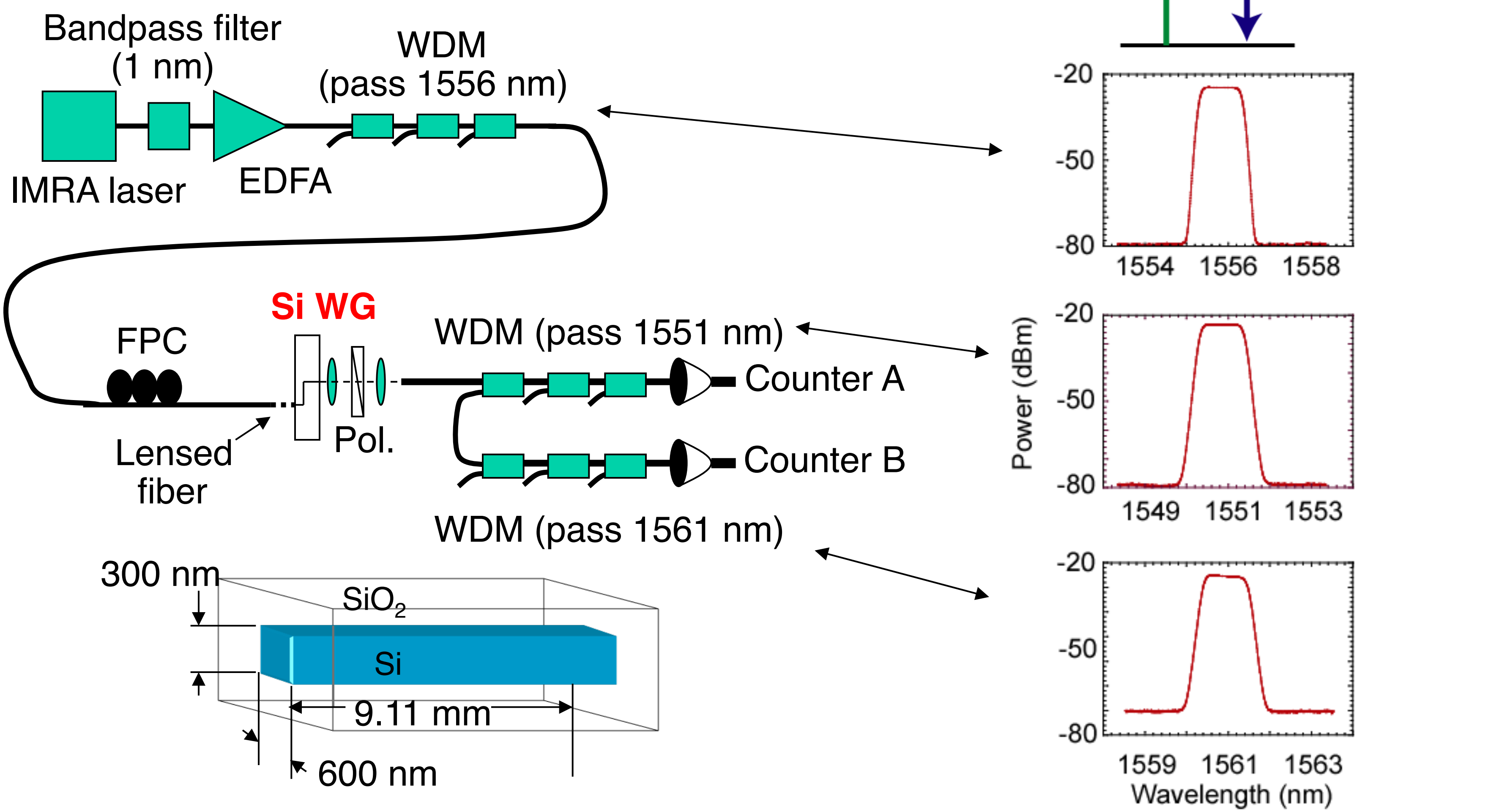


- 50-mW pump at 1969 nm, ASE from thulium fiber amplifier

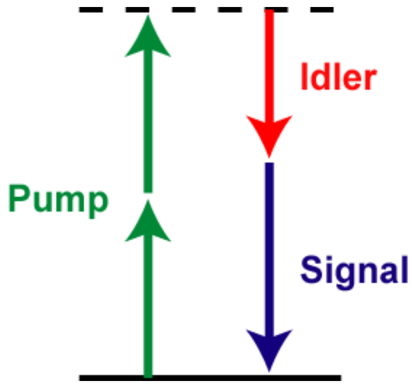
FWM in Silicon: Source for Correlated Photons

- Raman scattering can be avoided.

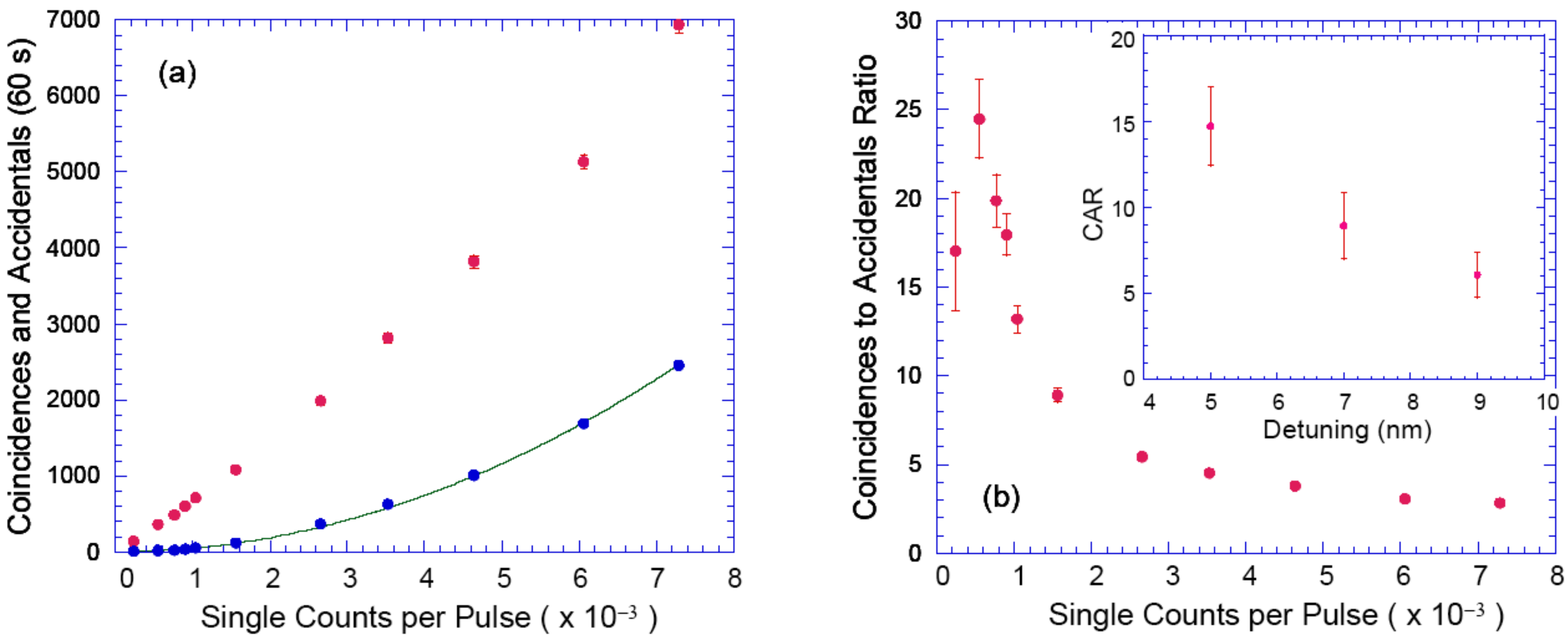




Generation of Correlated Photons in Si



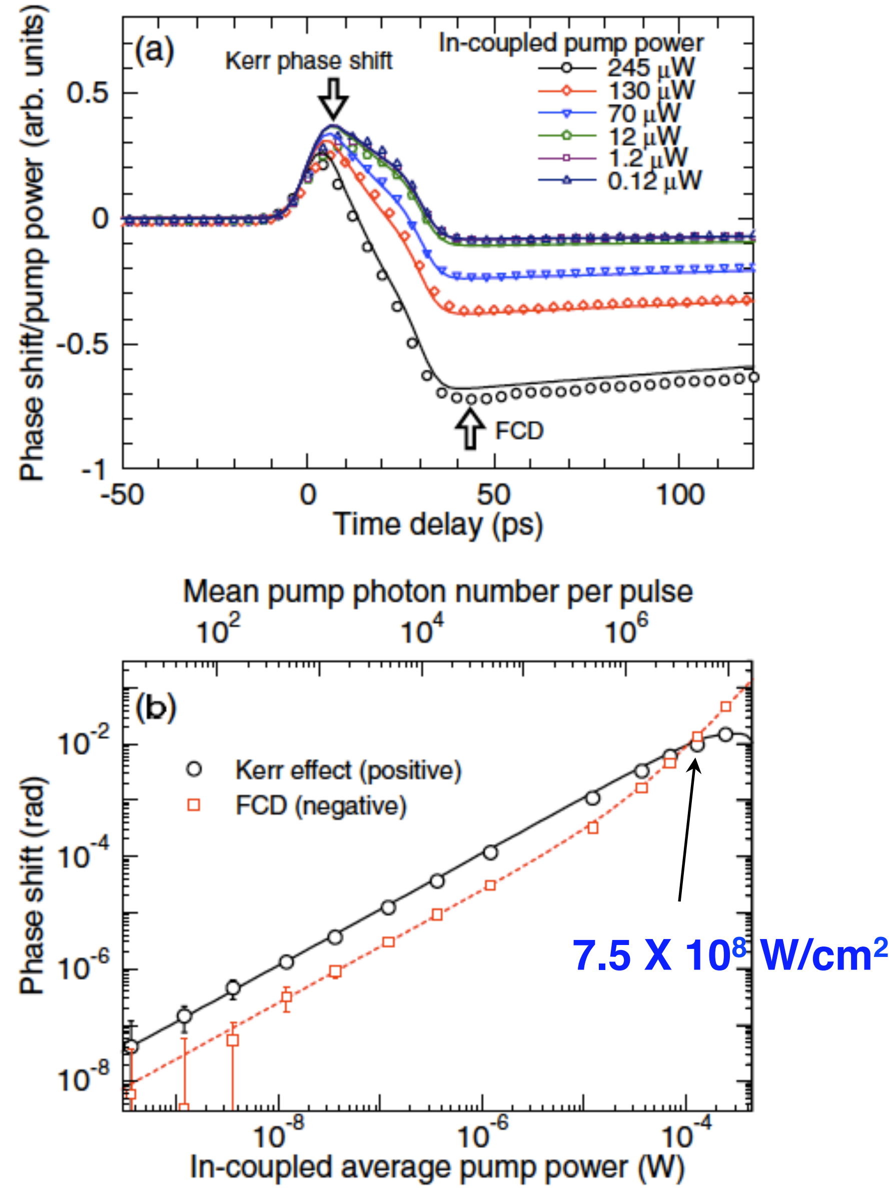
- Results show good quantum characteristics.
- Raman scattering can be avoided.



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

Contribution of Free-Carriers Spoils Correlations

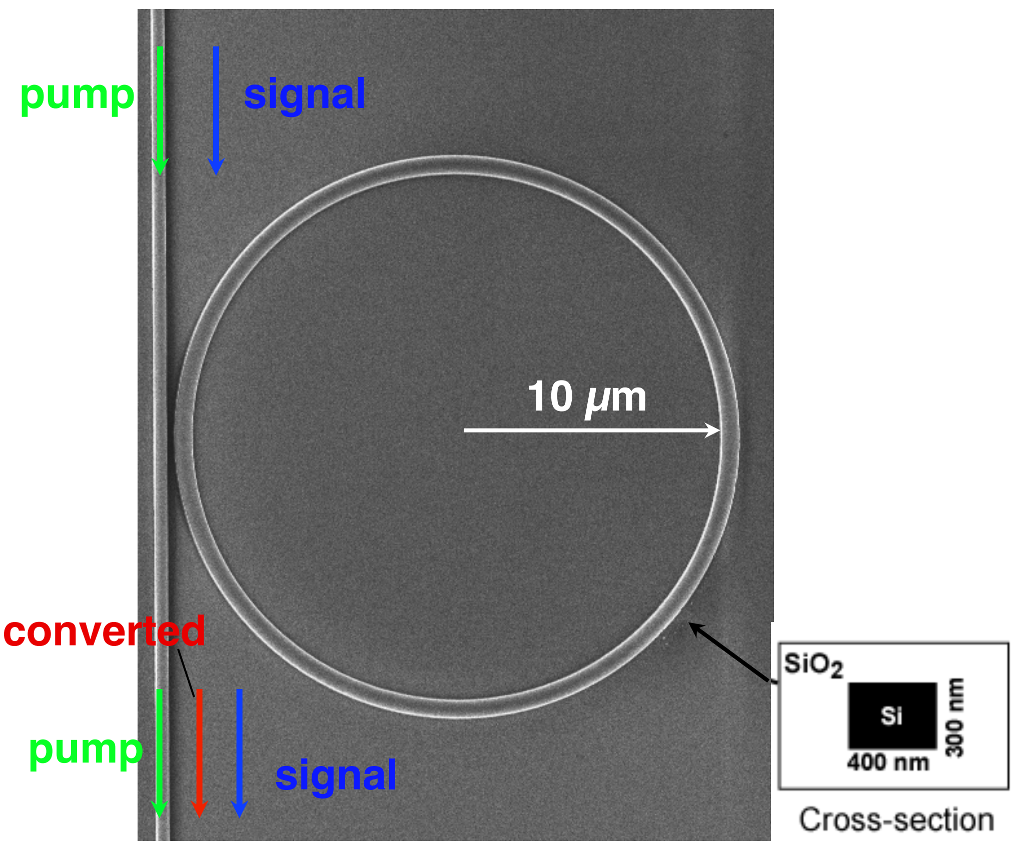
- Plasma dispersion effect leads to generation of blue photons.
- $\chi^{(3)}$ due to free-carriers comparable to electronic for peak intensities ~ 7.5 X 10^8 W/cm^2

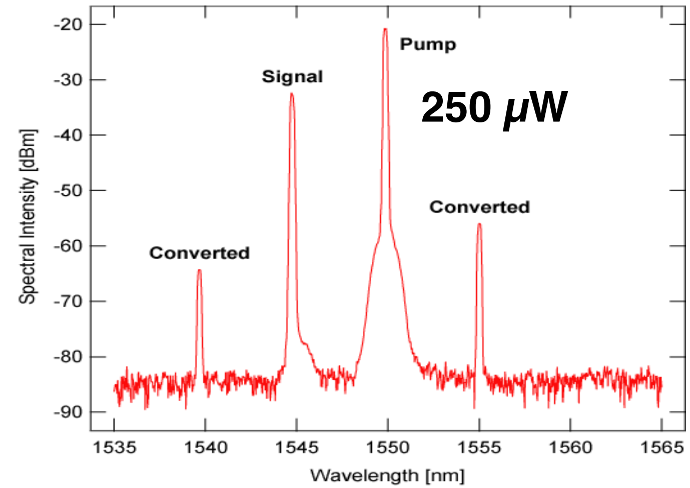


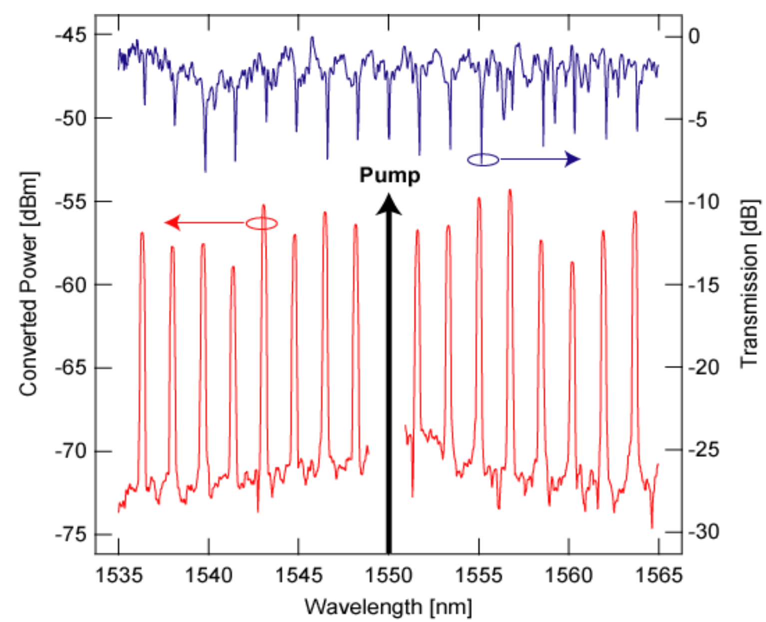
Matsuda, *et al.*, Appl. Phys. Lett. **95**, 171110 (2009).

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).

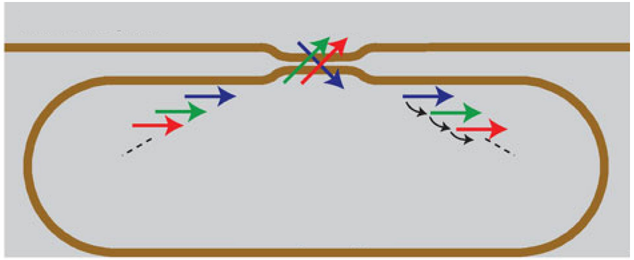
Outline: Silicon Nonlinear Nanophotonics

- Linear & nonlinear properties of nanowaveguides
- Four-wave mixing (FWM) in Si nanowaveguides
  - Dispersion engineering
  - Ultra-broadband wavelength conversion
- Optical parametric oscillator
  - broad-band frequency comb
  - ultrashort-pulse generation

On-Chip Oscillators

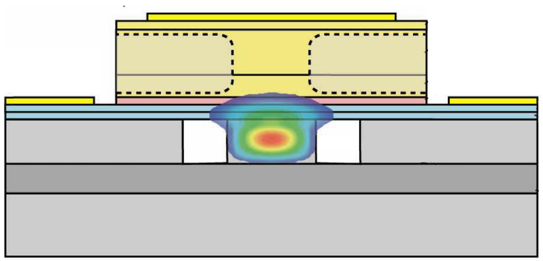
- On-chip optical networks
- Dense wavelength-division multiplexing
- Need an integrated source in the C-band

<u>Raman (silicon)</u>



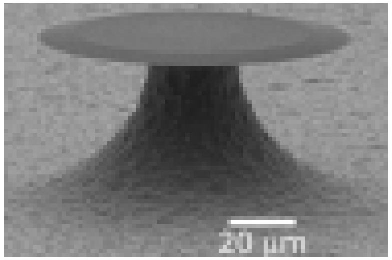
- Paniccia (Intel)
- Jalali (UCLA)

<u>Hybrid (silicon/III-V)</u>



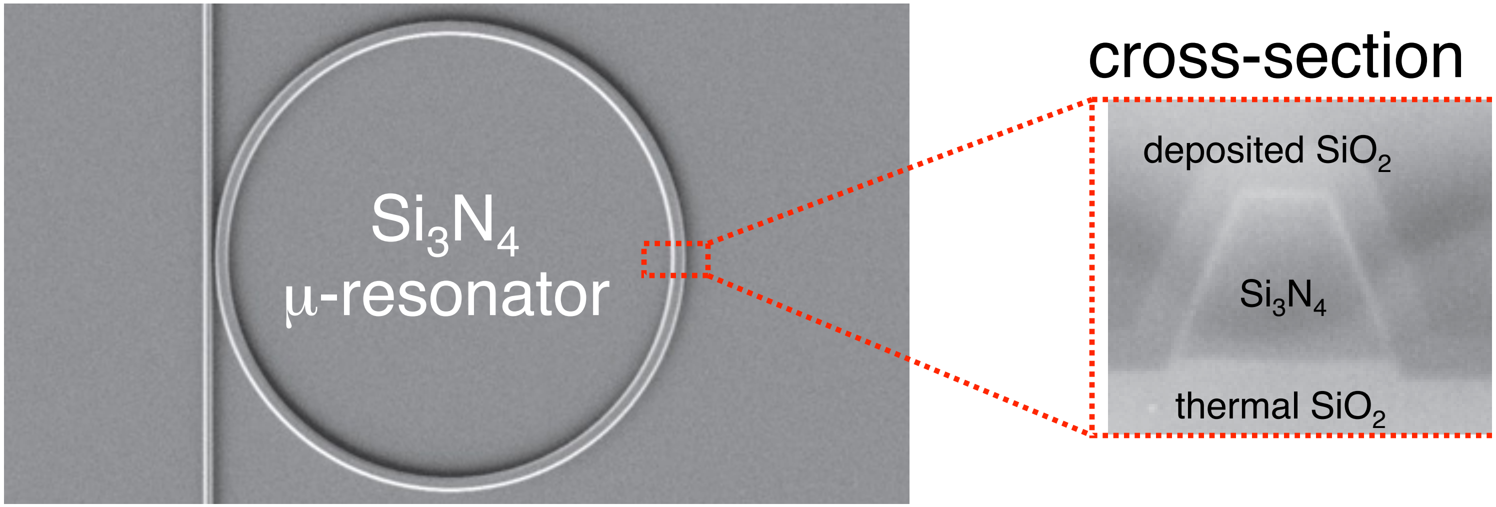
-Bowers, Pannicia
(UCSB,Intel)

<u>Erbium (silica)</u>



-Vahala, Polman
(CalTech, AMOLF)

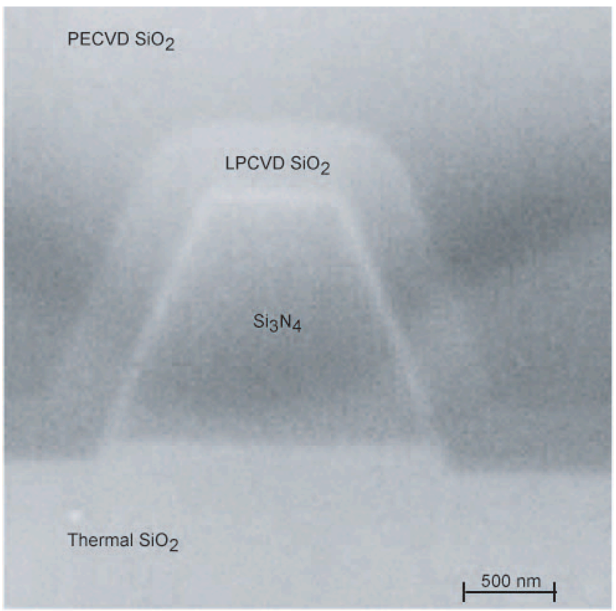
Chip-Based Silicon-Nitride Microrings

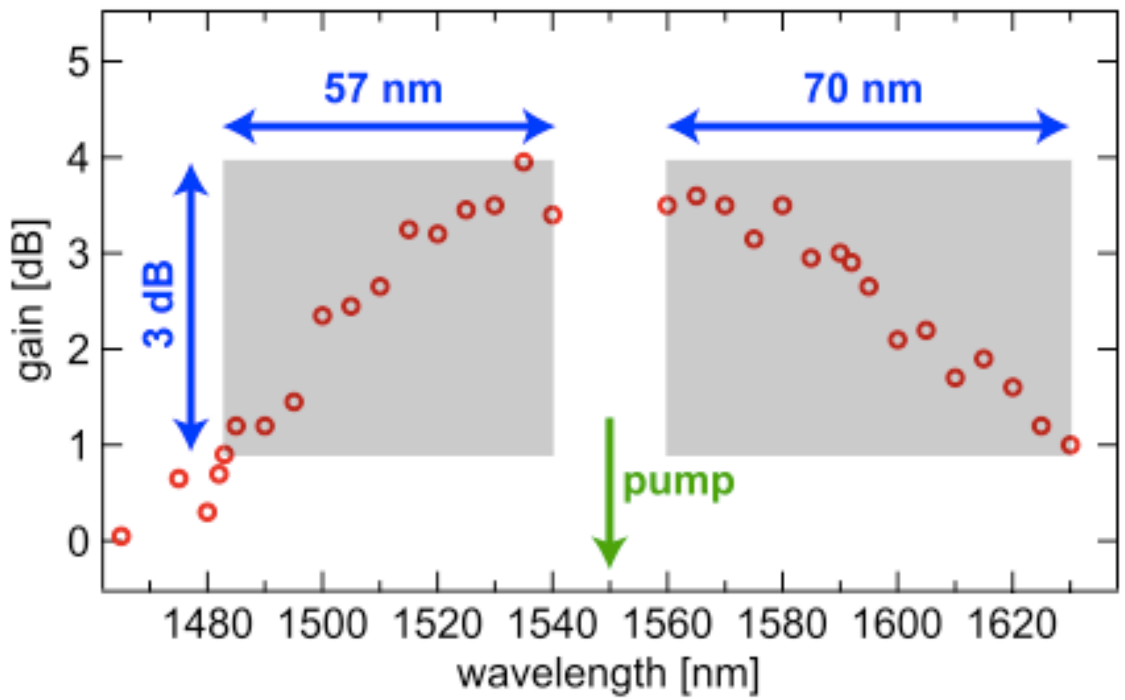


- CMOS-compatible material
- Fully monolithic and sealed structures and couplers
- High-Q resonators → $Q = 3\times10^6$ [Gondarenko, et al., *Opt. Express* (2009).]
- High nonlinearity → $n_2 \sim 10\times$ silica [Ikeda, et al., Opt. Express (2008).]
- Waveguide dispersion can be engineered [Turner-Foster, et al., *Opt. Express* (2006); Tan, Ikeda, Sun, and Fainman, Appl. Phys. Lett. (2010).]

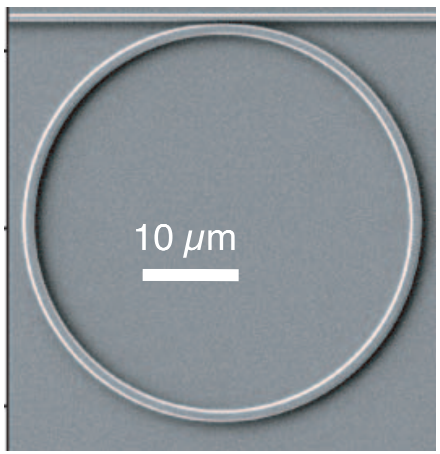
FWM Gain in Si Nitride

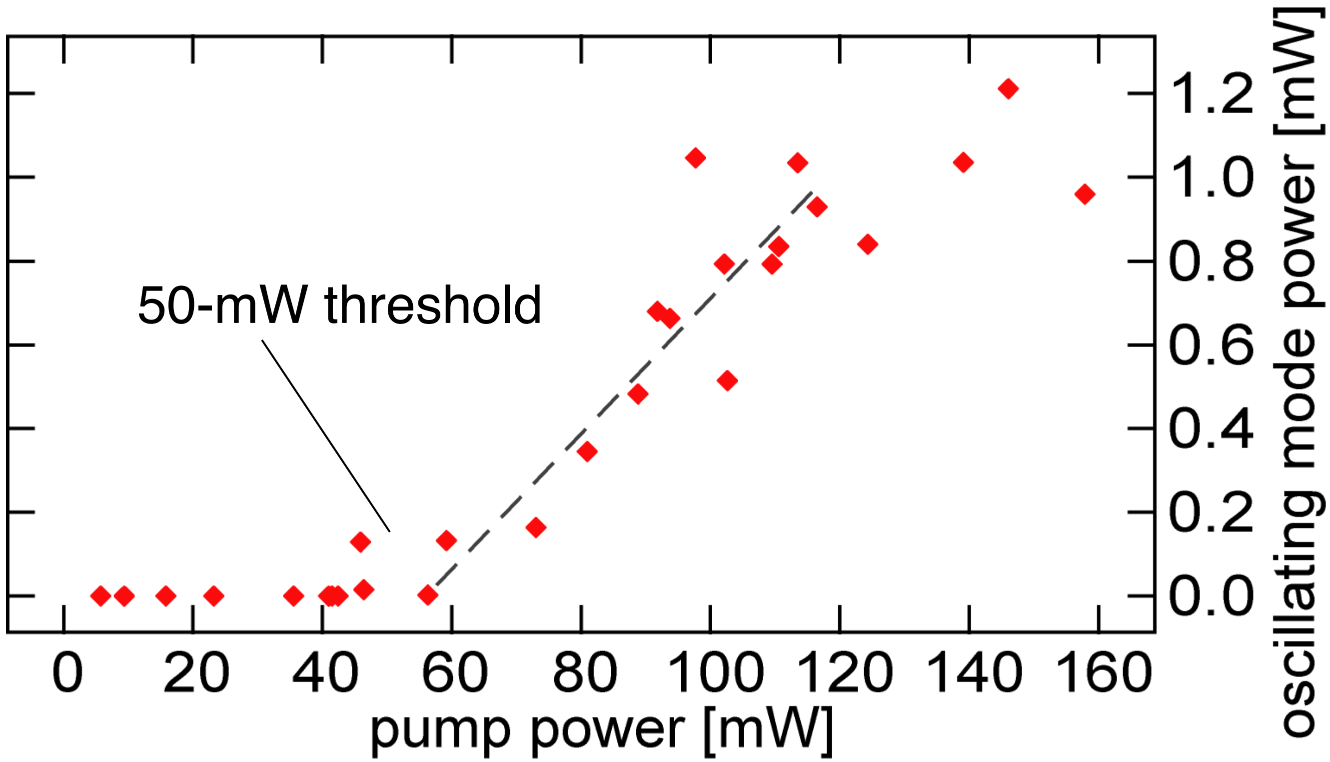
- Dispersion engineered for anomalous GVD.
- 6-cm-long waveguide.



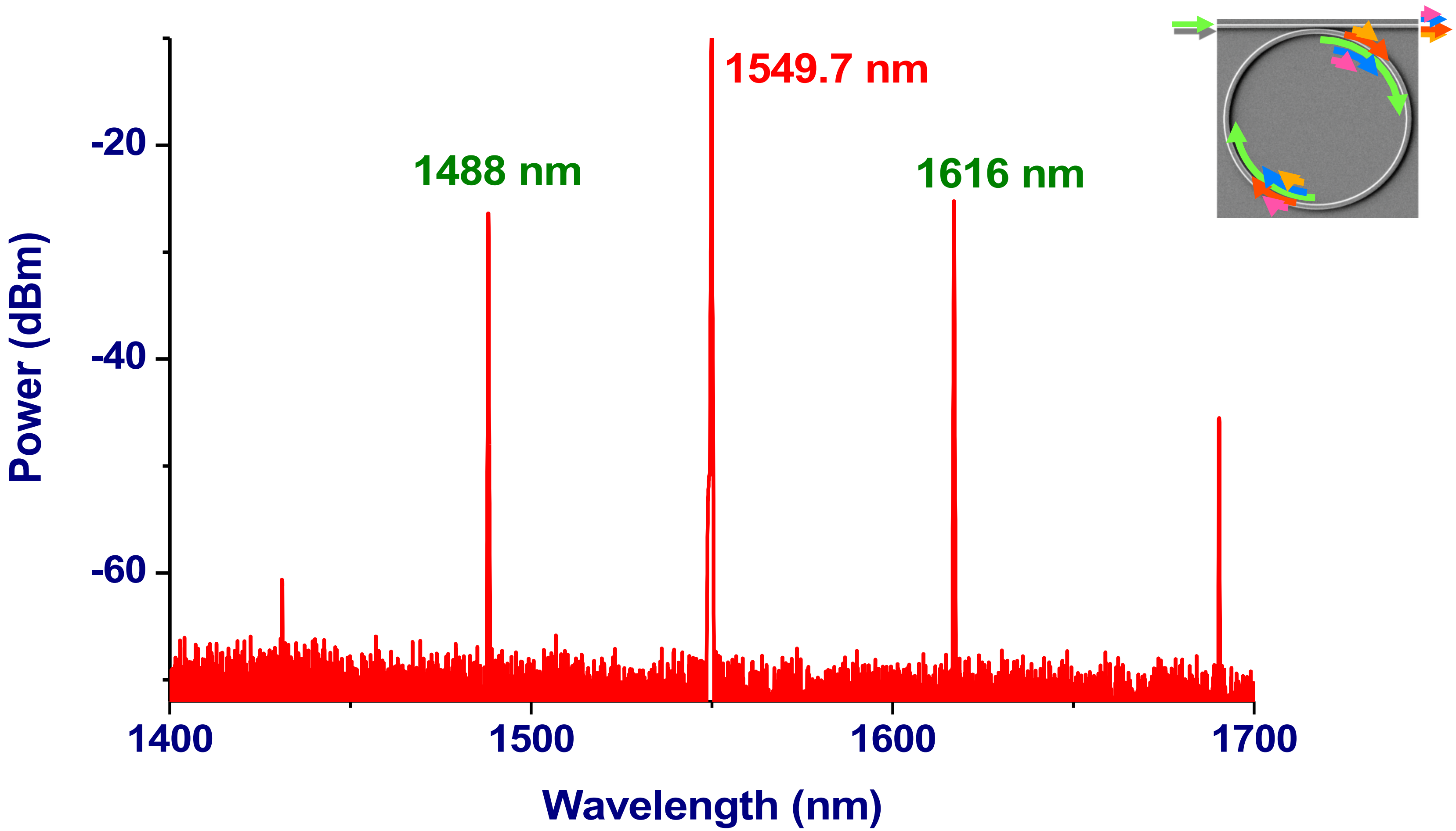


Threshold for Oscillation in SiN Microring

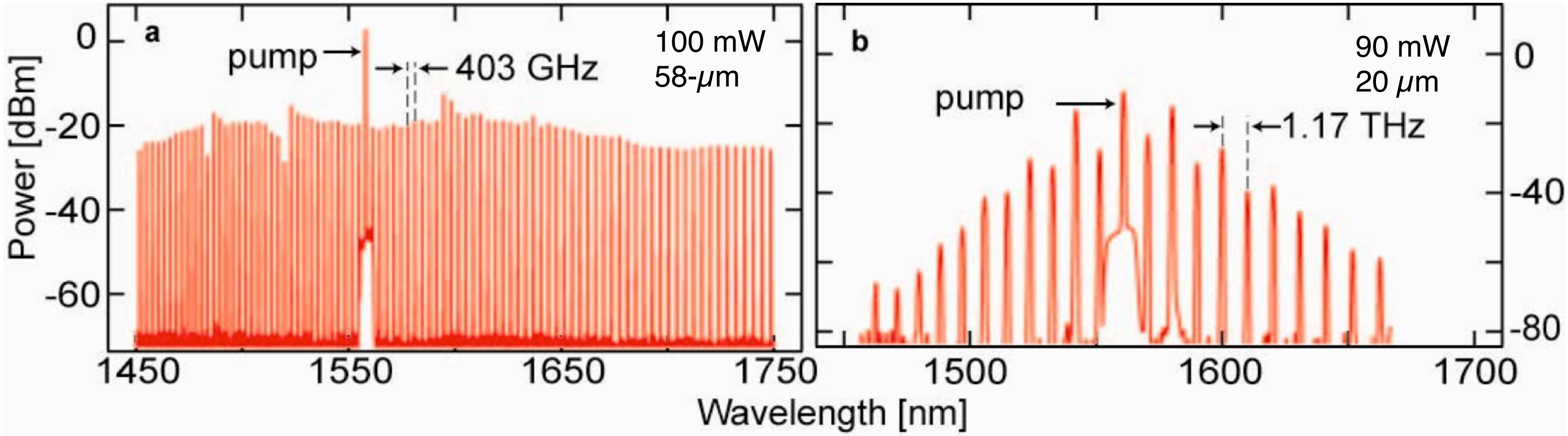


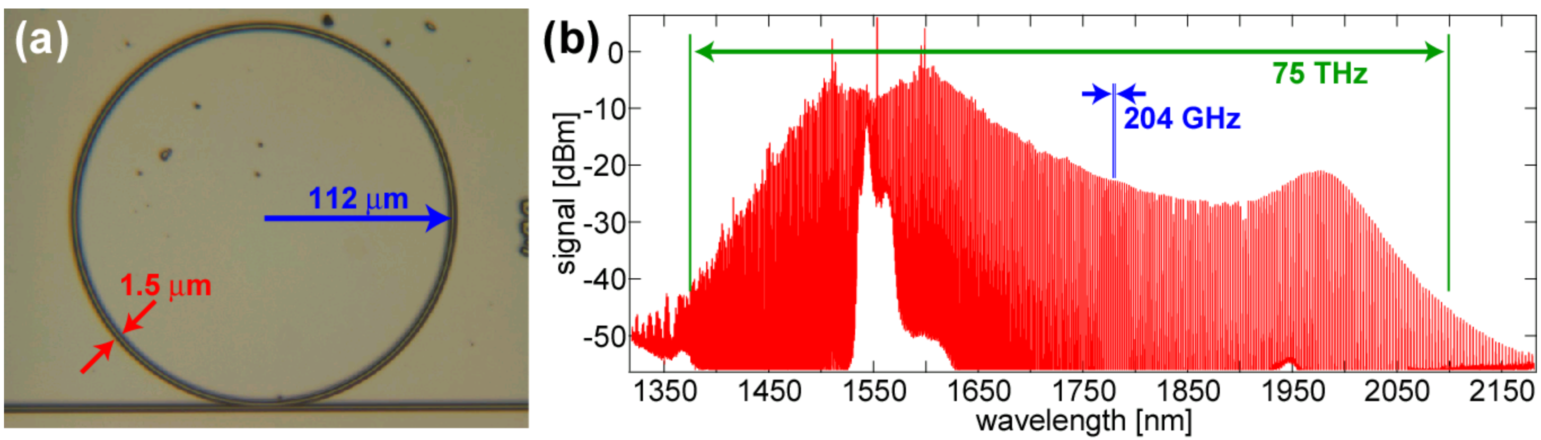


Triply-Resonant OPO – Near Threshold



Chip-Based FWM Frequency Comb

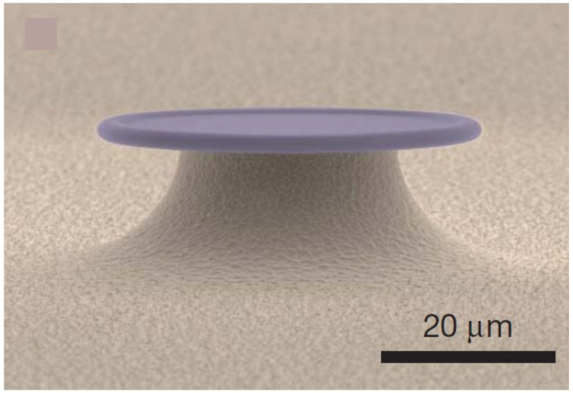


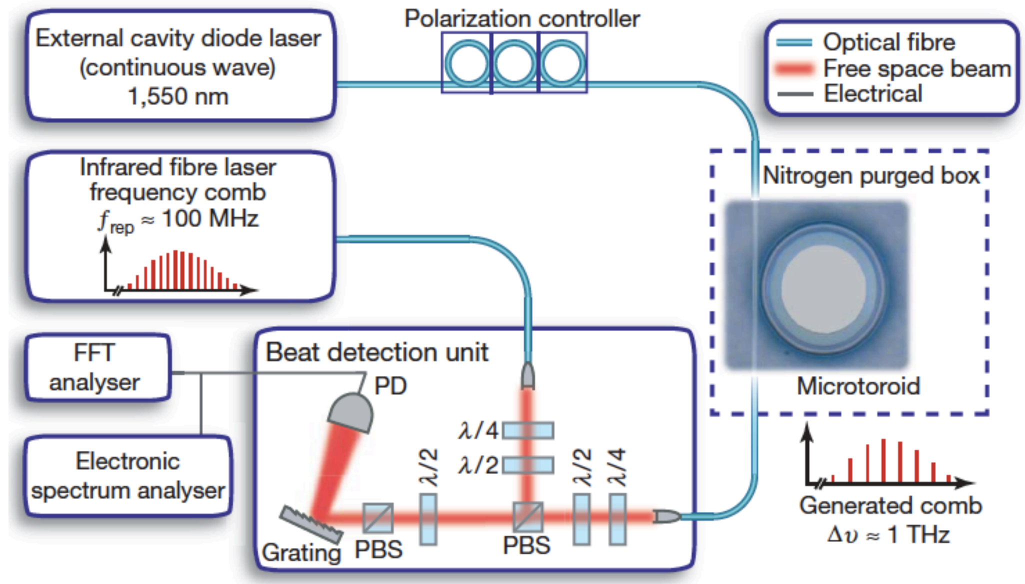


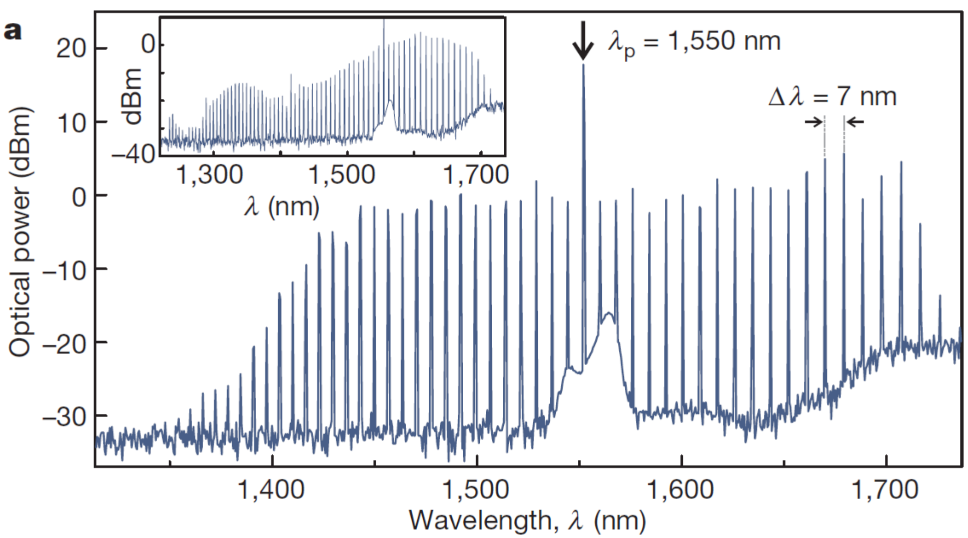
- Octave-spanning comb possible with suitable waveguide design and sufficiently high powers (> 500 mW).

Levy, Gondarenko, Foster, Turner-Foster, Gaeta, and Lipson, *Nature Photon.* **4**, 37 (2010).

Comb Generation via Parametric Mixing in Microtoroids







Kippenberg, et al., *Phys. Rev. Lett.* (2004).

Del' Haye, et al., *Nature* (2007).

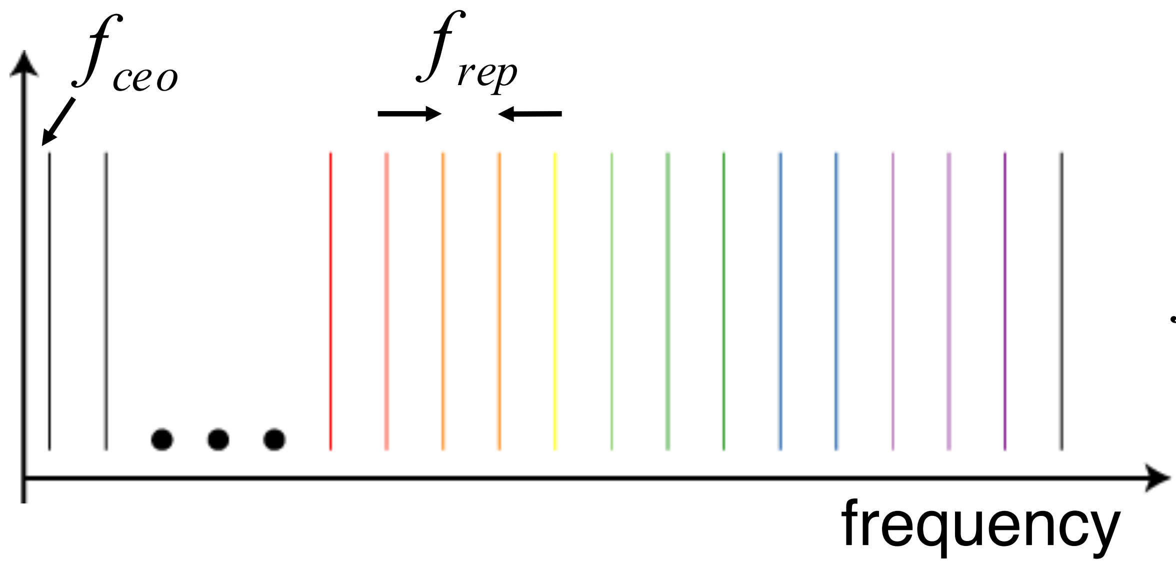
Optical Frequency Combs

100's of THz span with mHz precision

Direct link between optical and microwave frequencies

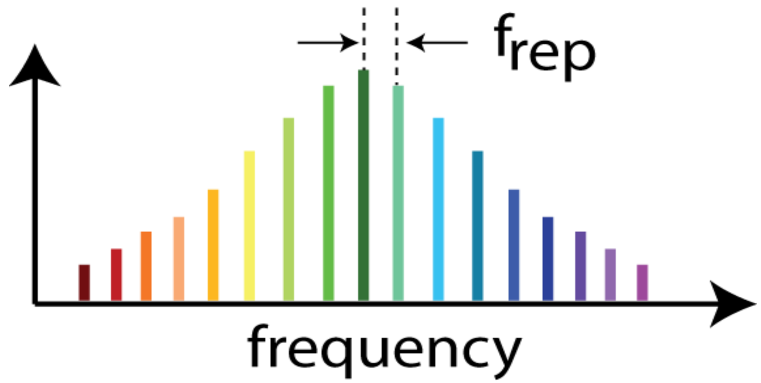
Telle, et al., Appl. Phys. B (1999).

Diddams, et al., Phys. Rev. Lett. (2000).



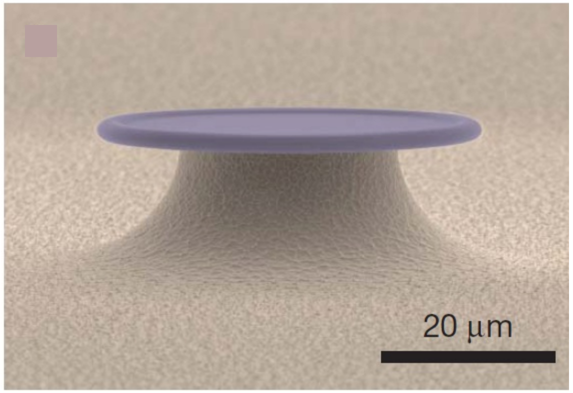
$$f_m = mf_{rep} + f_{ceo}$$

Applications of Frequency-Comb Technology



- Optical clockwork
- Astronomical spectral calibration
- Chemical/biological sensing
- Optical communications & interconnects
- Tests of fundamental laws and constants (*R*, Lamb shift, fine-structure constant)
- Navigation (GPS)
- Very-long baseline interferometry
- Arbitrary-waveform generation
- Coherent control of molecules and reactions

Microresonator-Based Parametric Combs

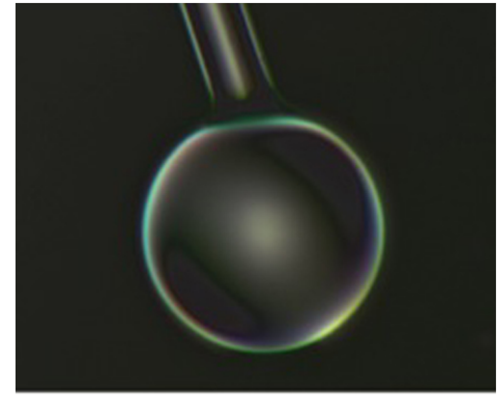


silica μ-toroids

Del' Haye, et al., *Nature* (2007).
Del' Haye, et al., *PRL* (2008).

CaF_2 resonators

Savchenkov, et al., *PRL* (2008).
Grudinin, et al., *Opt. Lett.* (2009).
Liang, et al., *Opt. Lett.* (2011)
Papp & Diddams, *PRA* (2011)



silica μ-spheres

Agha, et al., *Opt. Express* (2009).

Also: glass microrings [Razzari, et al. *Nature Phot.* (2010)]
highly nonlinear fiber cavity [Braje, et al., *Phys. Rev. Lett.* (2009).]

Demonstrated properties in these platforms:

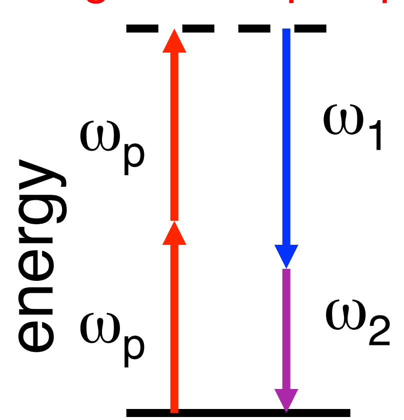
- full stabilization to a reference [Del'Haye, et al., *PRL* (2008).]
- spacings as small as 10 GHz [Braje, et al., *PRL* (2009).].
- span up to 160 THz (full octave) [Del' Haye, et al., *PRL* (2011).]

Review article: Kippenberg, Holzwarth, & Diddams, *Science* (2011)

Microresonator Comb Generation

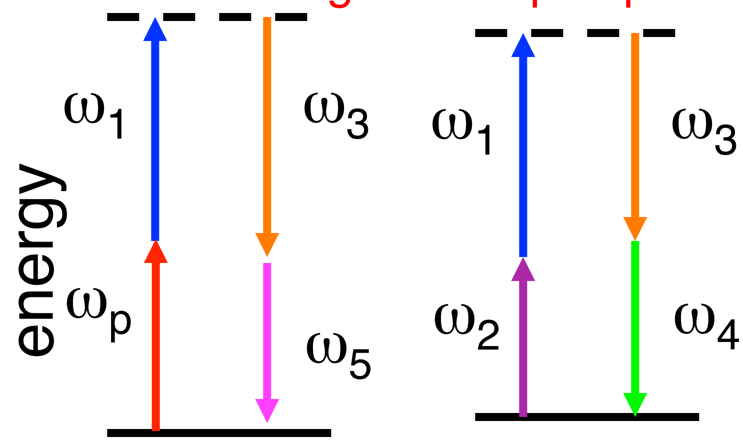
Four-wave mixing → amplification and λ-conversion

degenerate pump



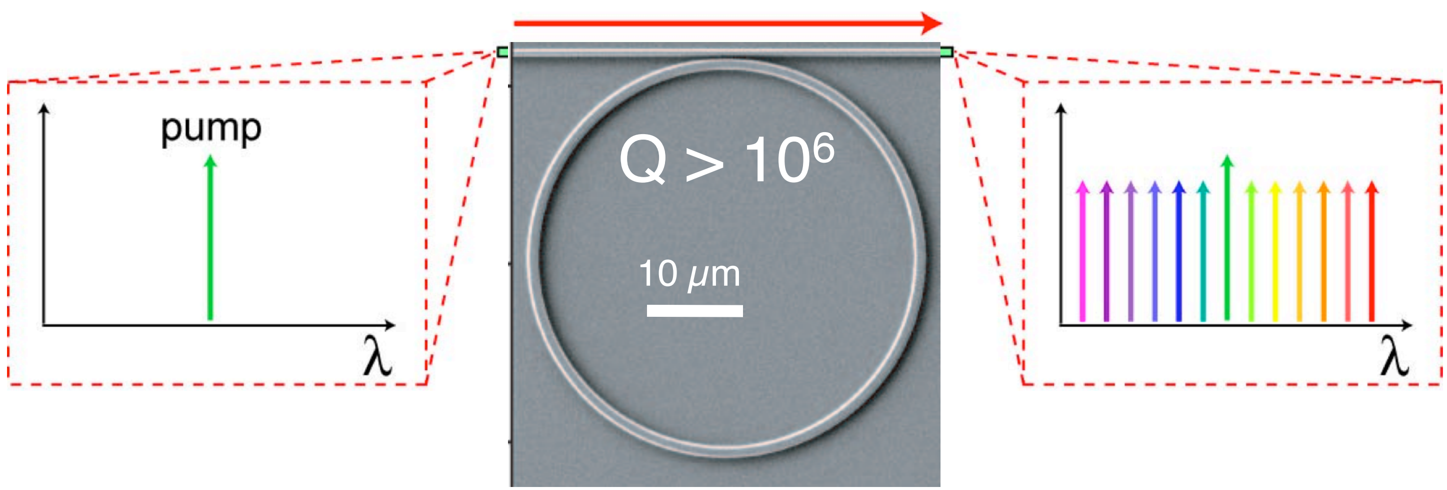
and

non-degenerate pump

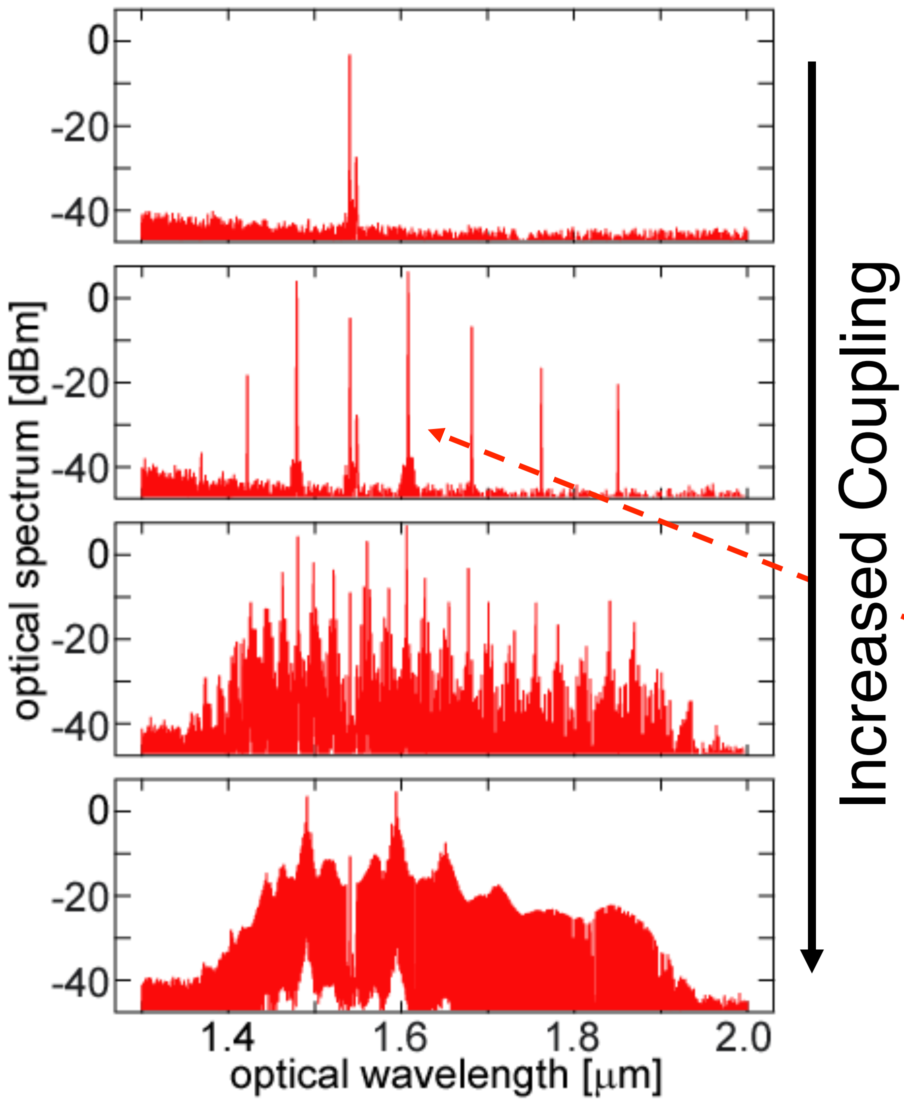


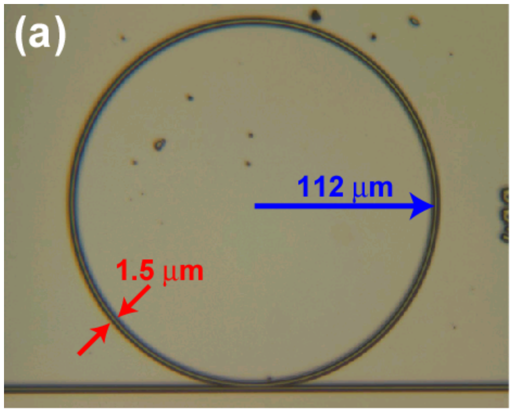
etc.

Pump power >> threshold → cascaded oscillation



Comb Generation Dynamics





$Q \sim 3{\times}10^5$

FSR ~ 204 GHz

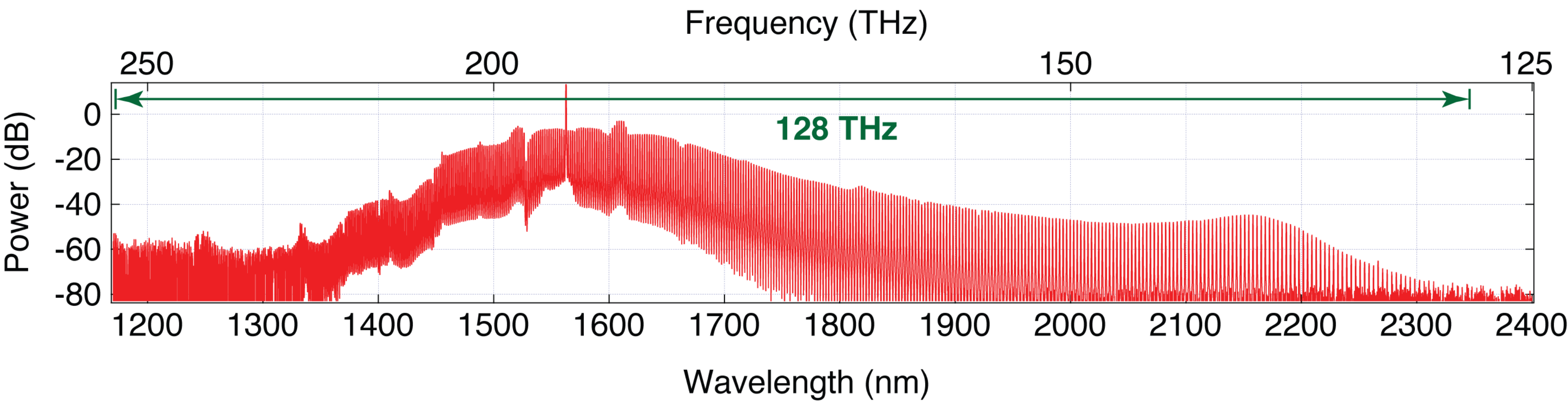
Initial oscillation far from pump

Comb fills in with greater coupled power

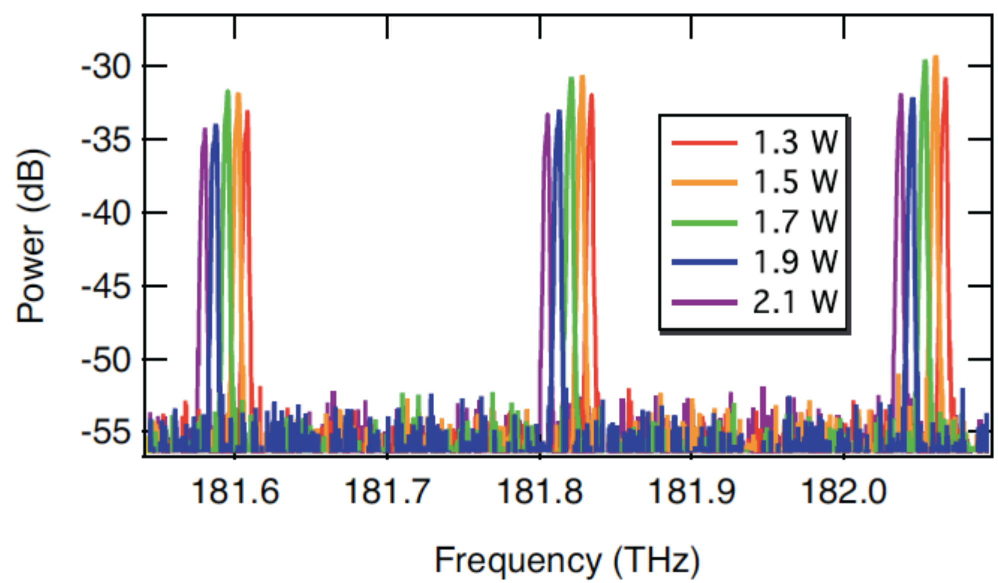
Foster, et al., *Optics Express* (2010).

Herr, et al. *Nature Phot.* (2012).

Octave-Spanning Comb

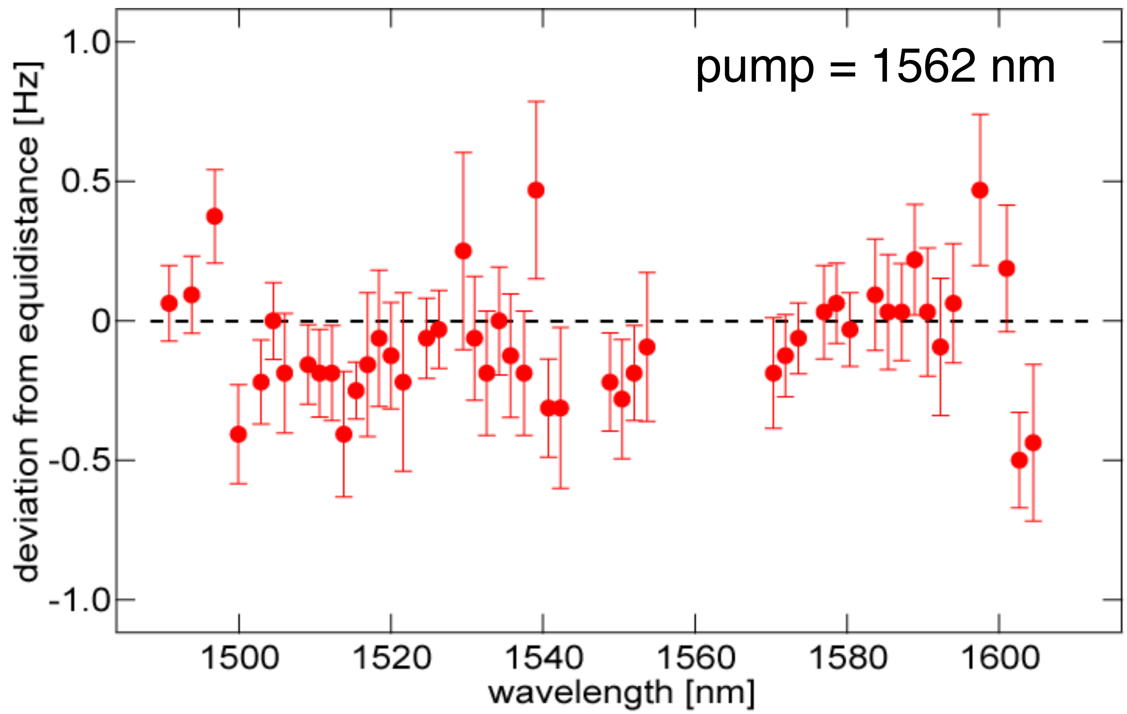


- Stable, robust (hours)
- Tunable mode spacing with pump power or heater
  - 30-GHz tuning



Okawachi, et al., *Opt. Lett.* (2011).

Sub-Hz Equidistance Results

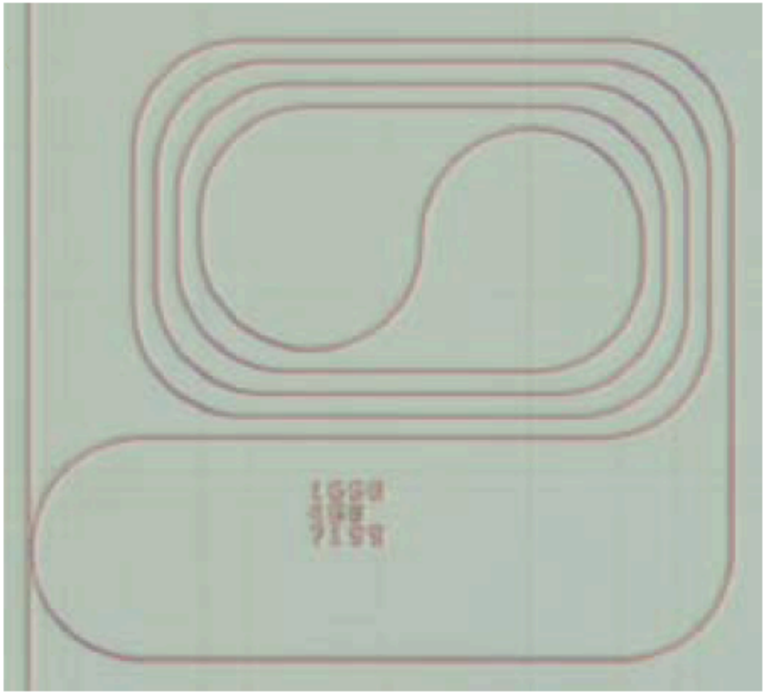


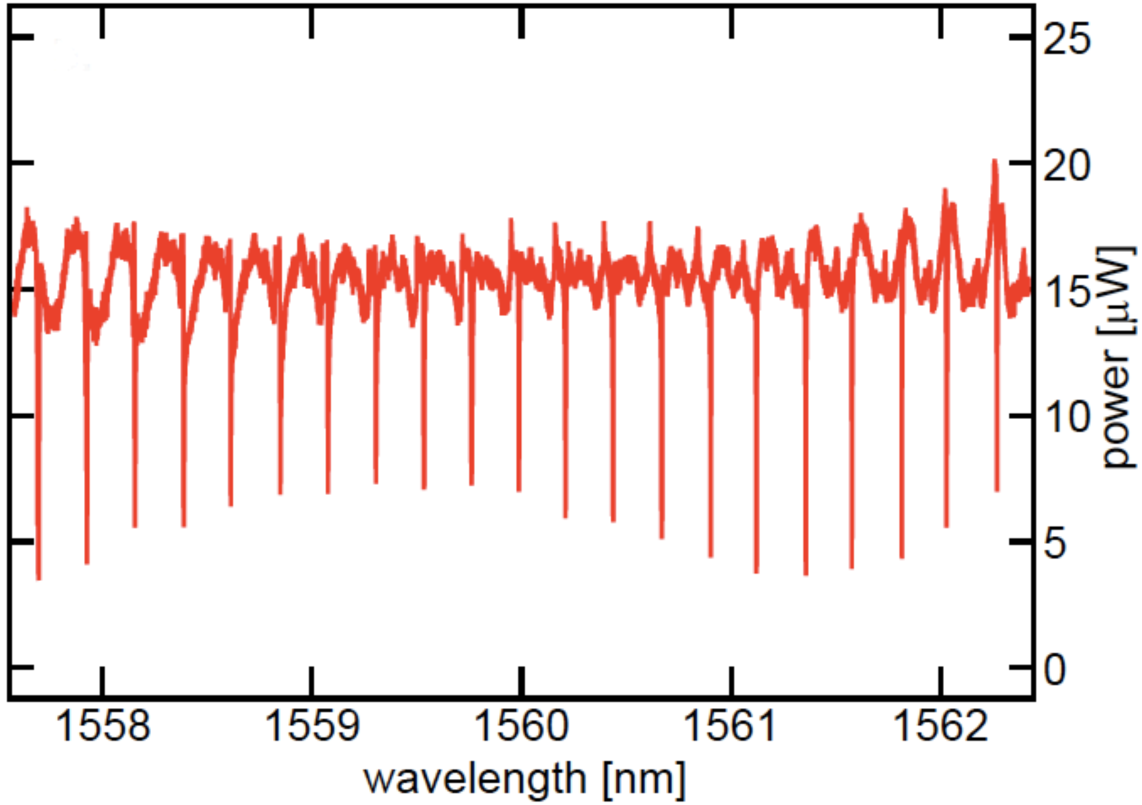
< 0.5 Hz equidistance over 115 nm (14.5 THz)

- 3×10^{-14} × measurement bandwidth
- 3×10^{-15} × optical frequency

Foster, et al., *Opt. Express* (2011).

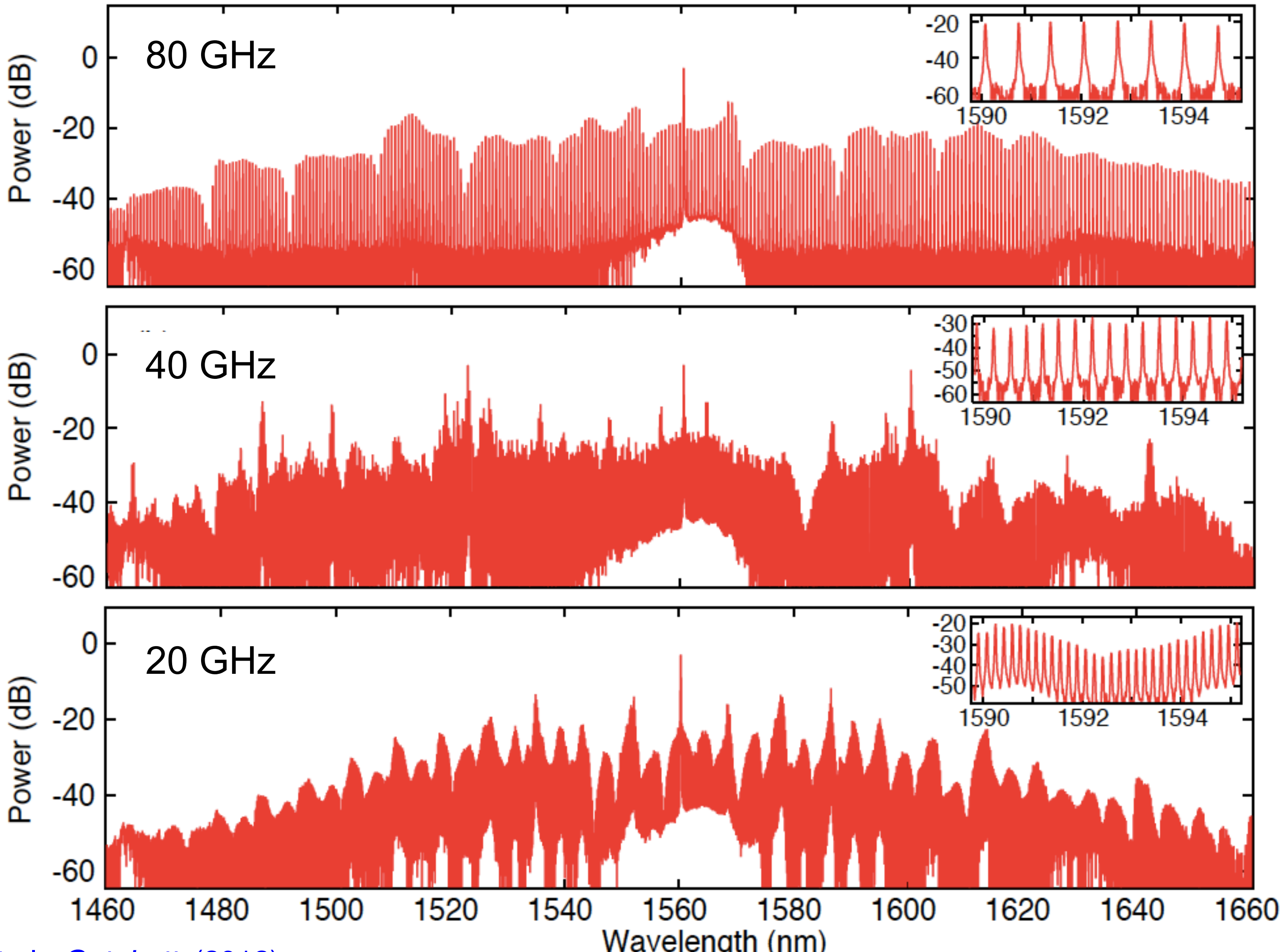
Spiral Resonator for Low Repetition Rate Comb Generation





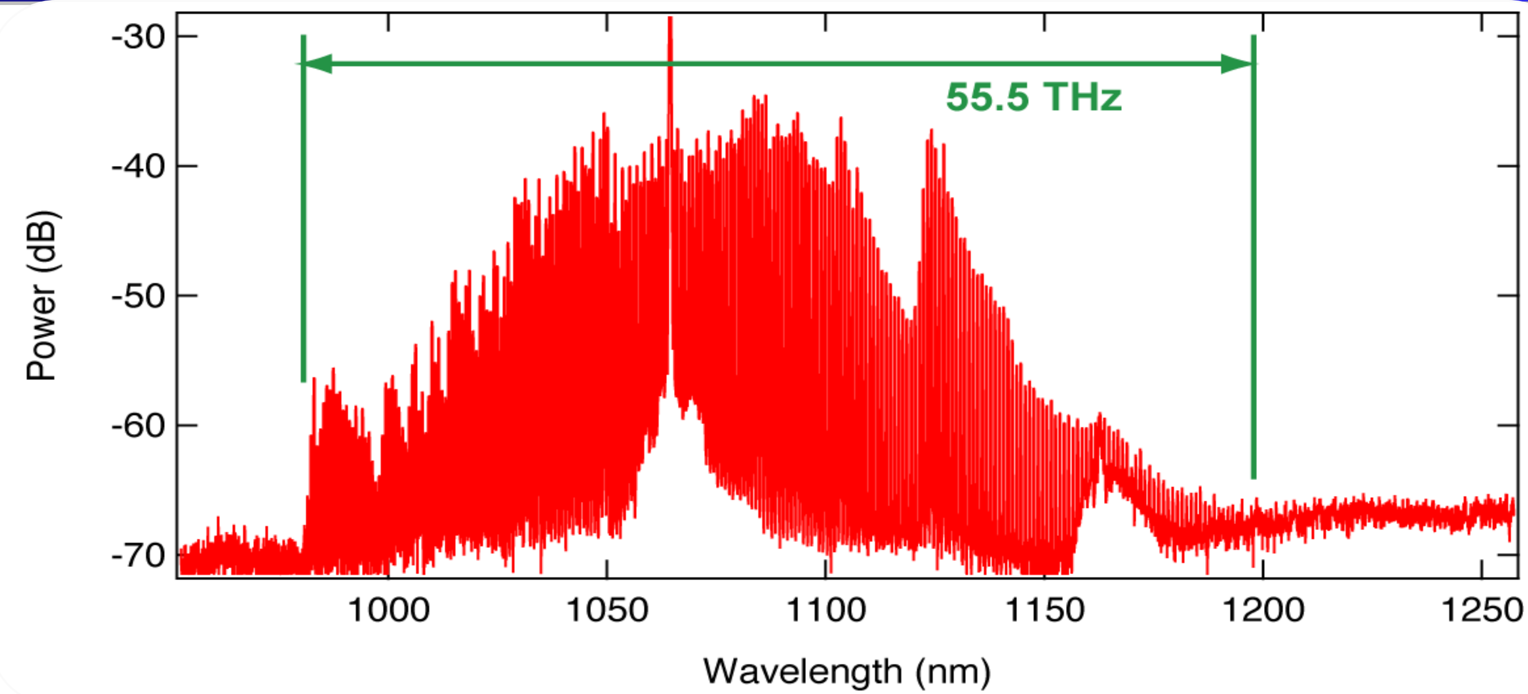
- Micrograph of 20-GHz spiral resonator
- Resonator length is 7.2 mm

Sub-100-GHz Combs

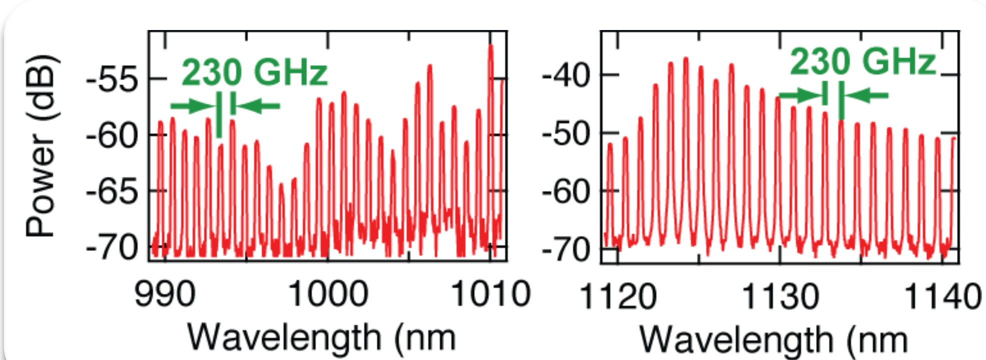


Johnson, et al., *Opt. Lett.* (2012).

Frequency Comb Generation at 1 μm



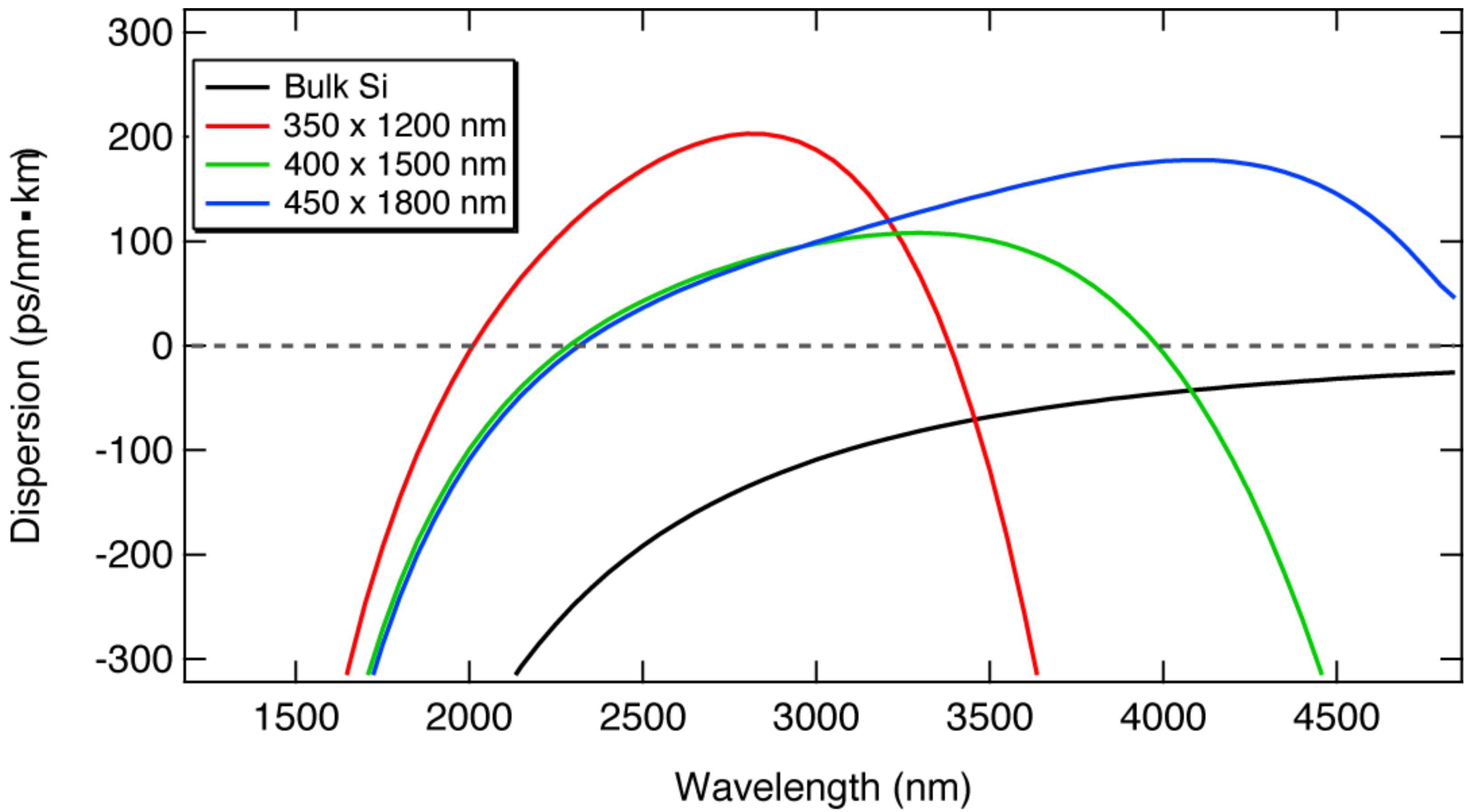
- 725 x 1000 nm cross section,
- Oscillation threshold < 80mW
- 55.5 THz span comb
- 230 lines with 230-GHz spacing



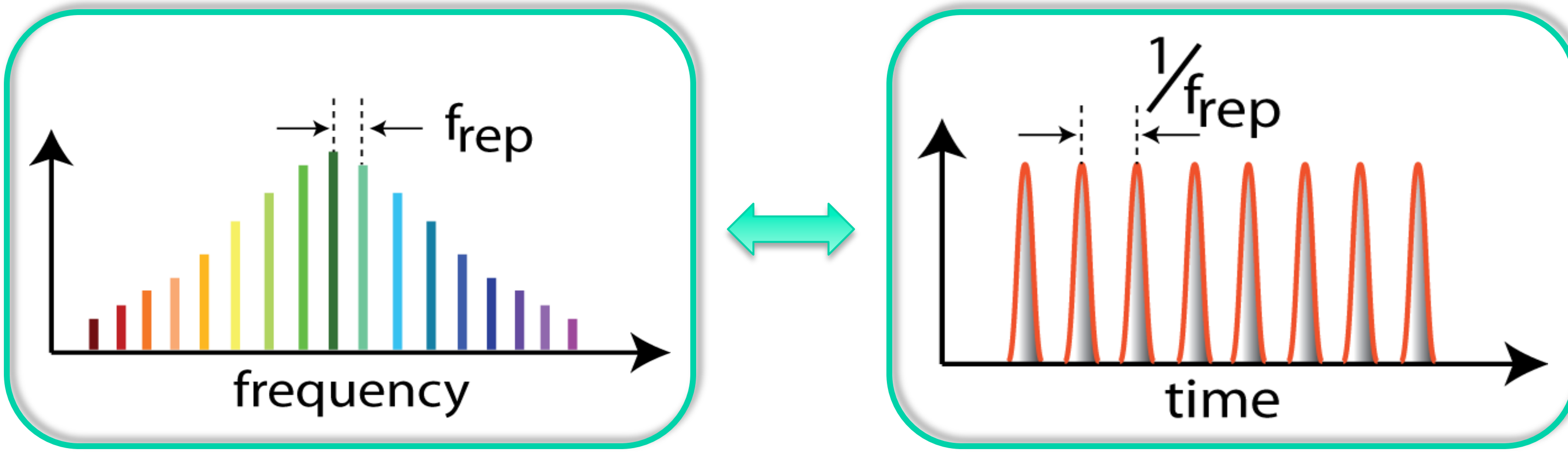
Saha, et al., in preparation (2012).

Potential Mid-IR Frequency Comb

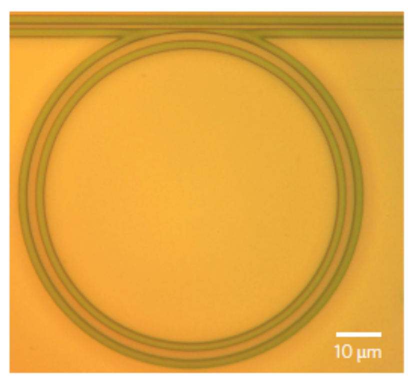
- Large gain with pulsed pump (ns or ps) **[Liu et al. (2010); Zlatanovic et al. (2010); Kuyken et al. (2011)]**



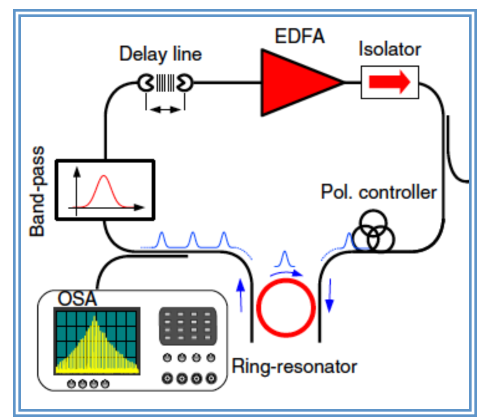
Pulse Generation



Few ps pulses
Papps & Diddams
Phys. Rev. A (2011).

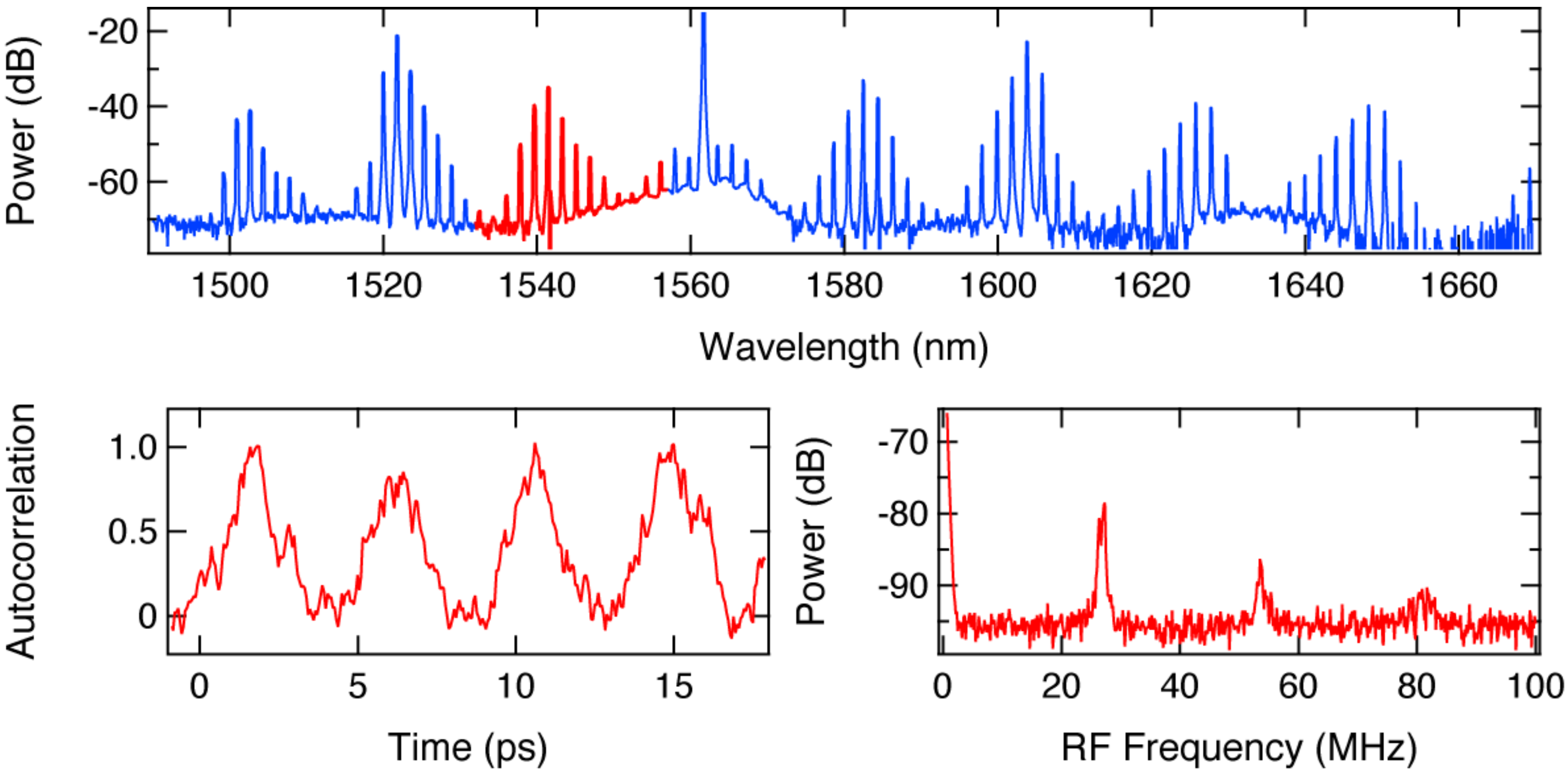


430 fs pulses,
External modulation
Ferdous et al.,
Nature Photon.(2011).



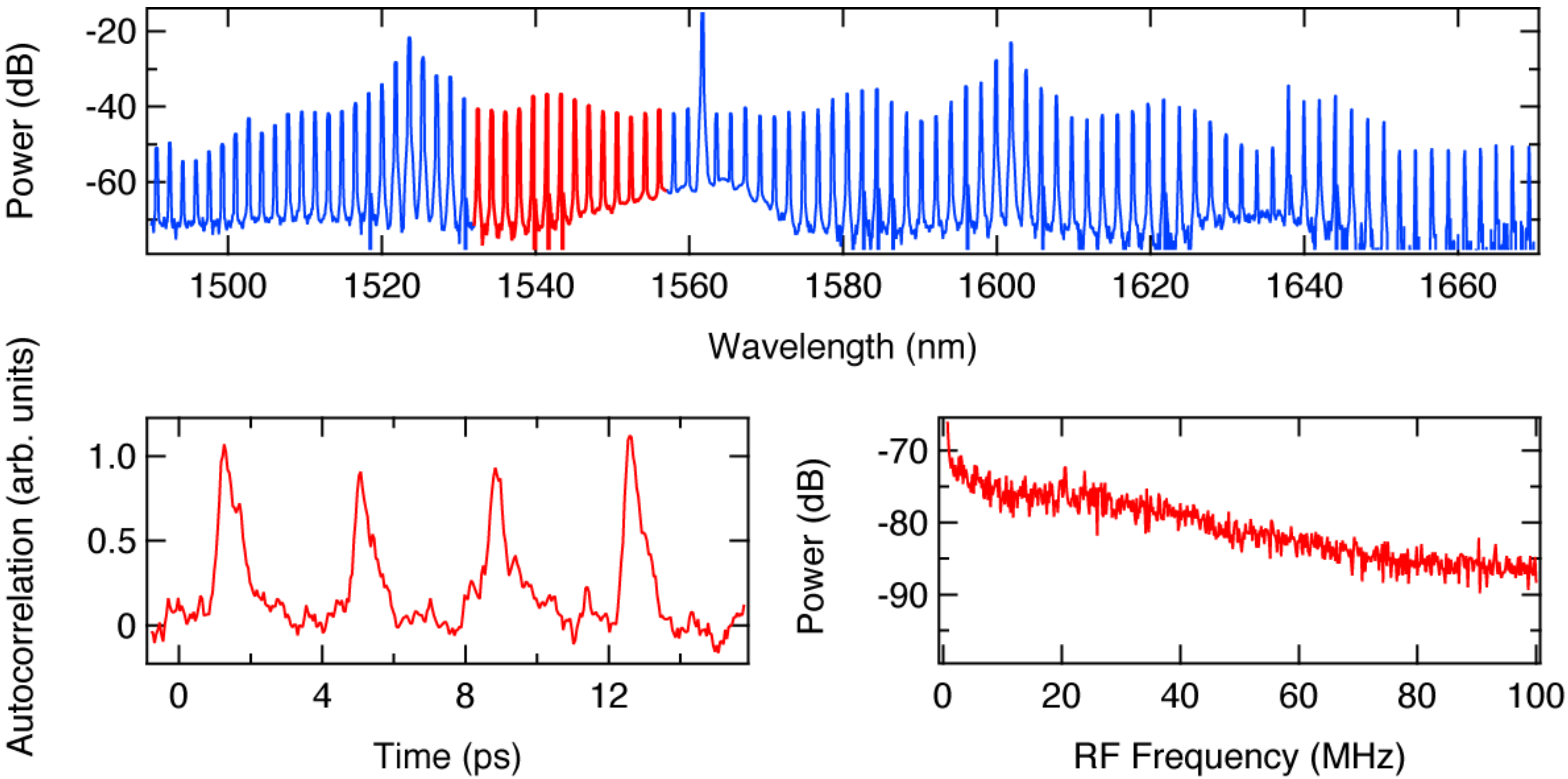
Few ps pulses,
External cavity
Peccianti et al.,
Nature Comm. (2012).

Comb Generation Dynamics

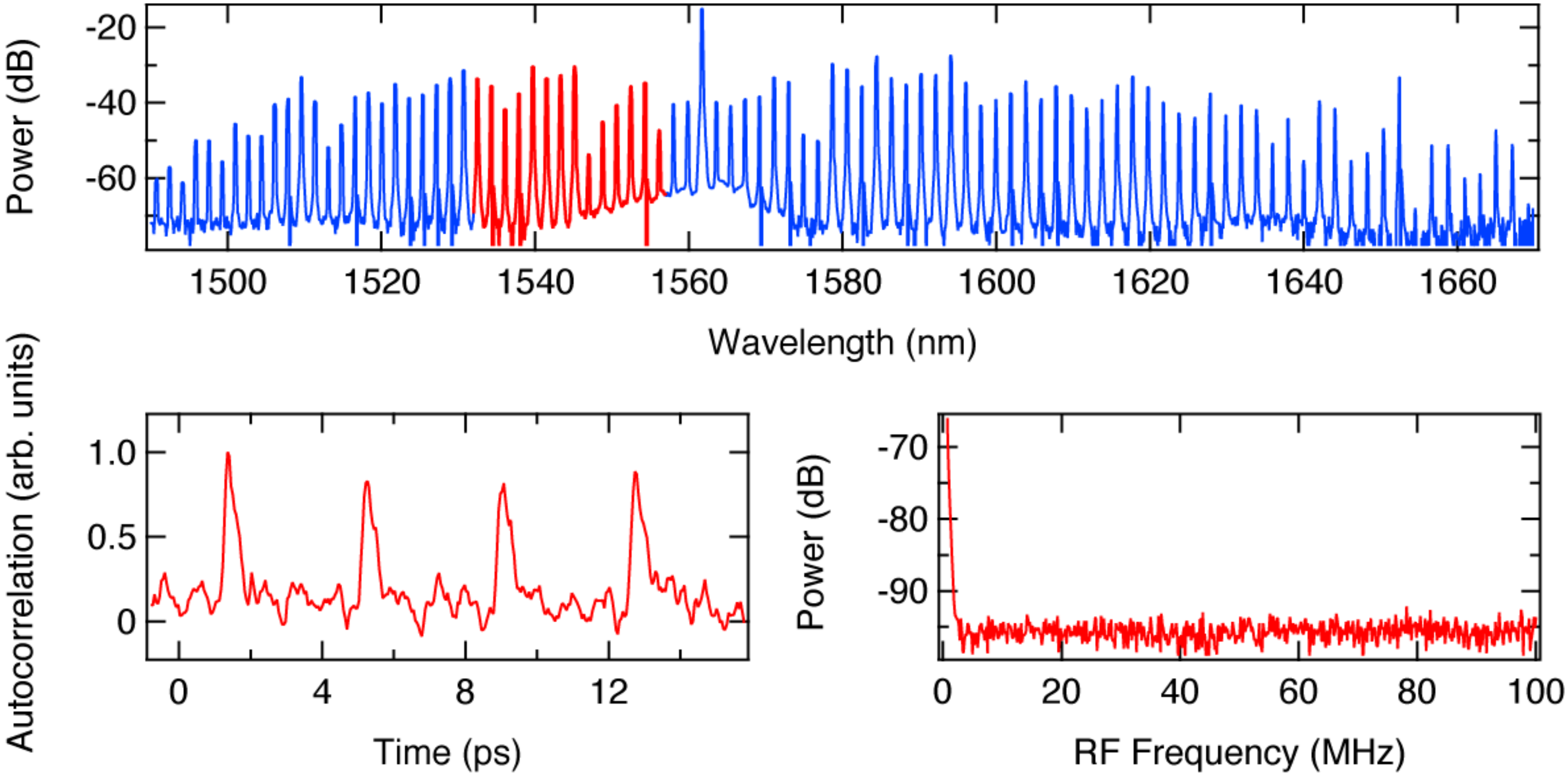


Herr, et al., arXiv (2012).

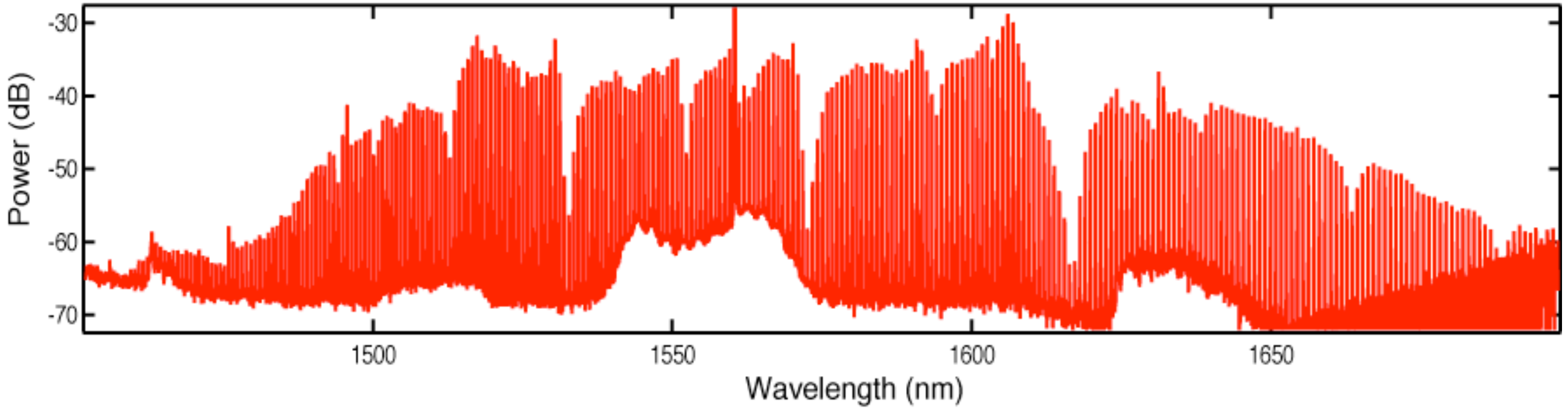
Temporal and Spectral Comb Generation Dynamics

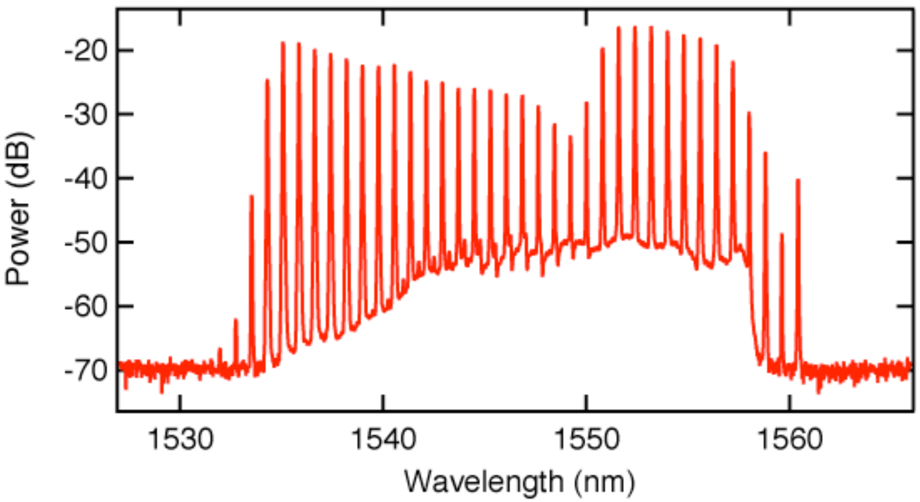


Temporal and Spectral Comb Generation Dynamics

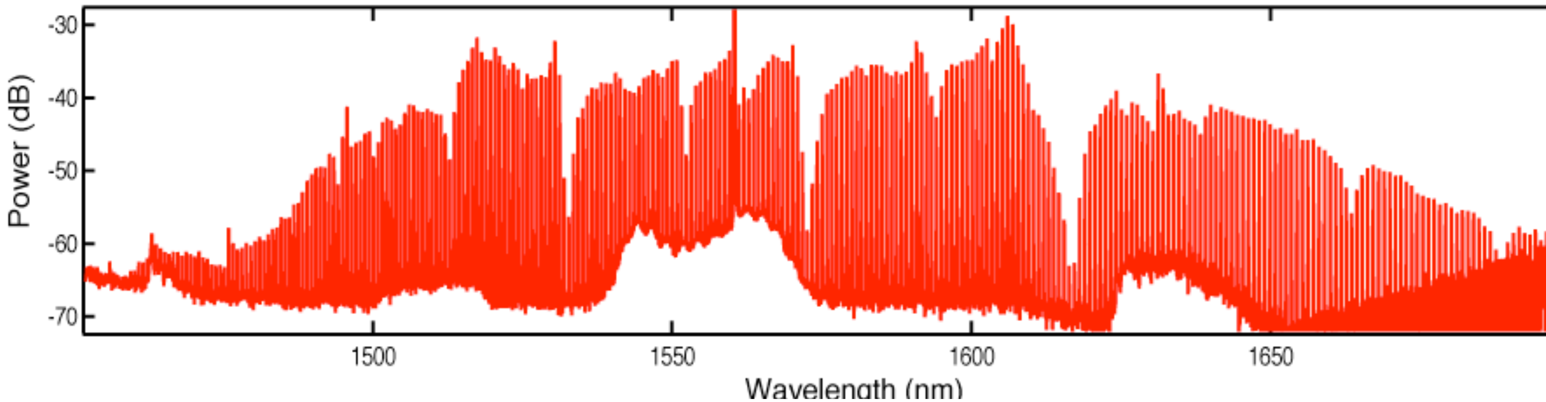


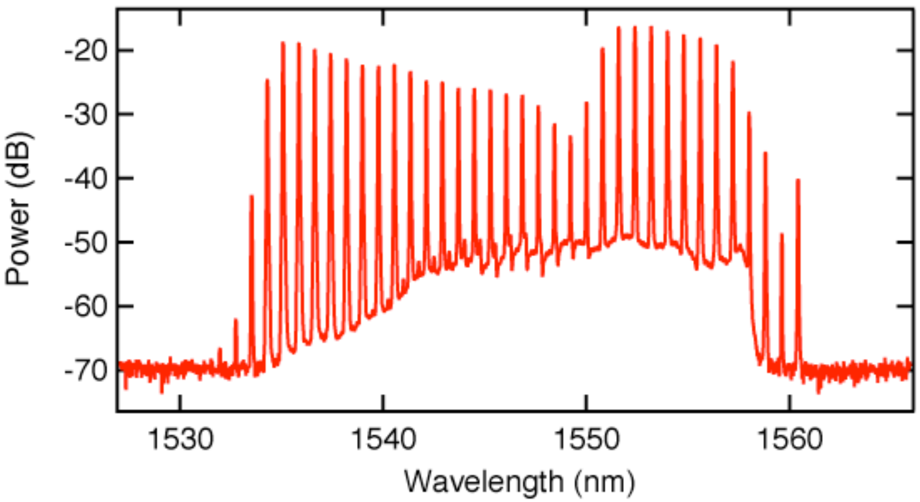
Ultrashort Pulse Generation

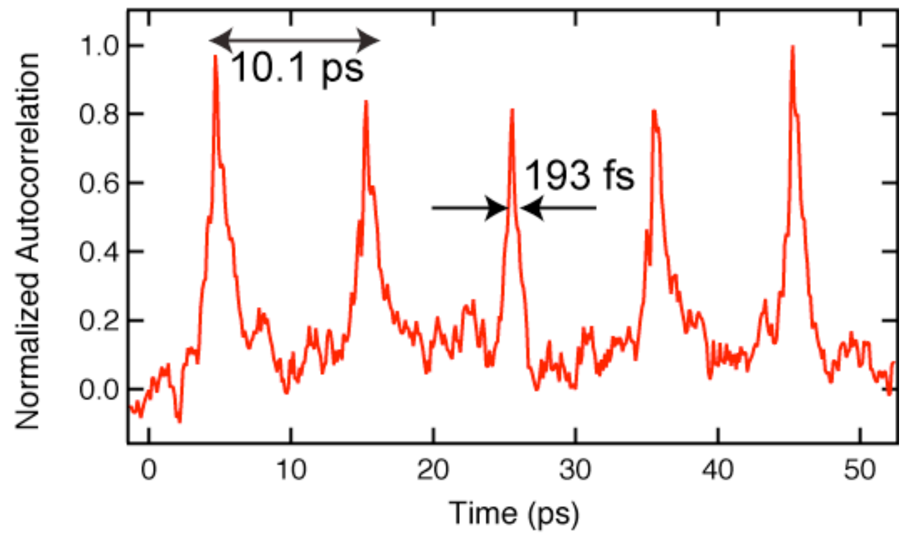




Ultrashort Pulse Generation



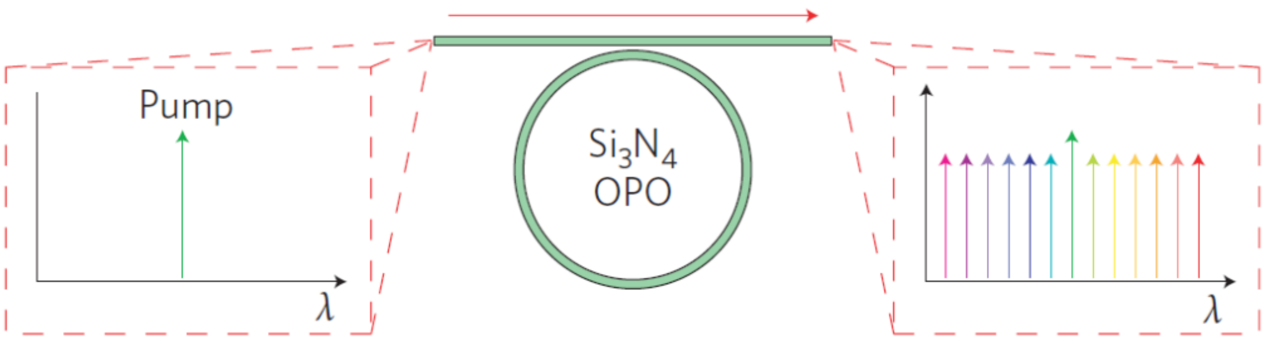




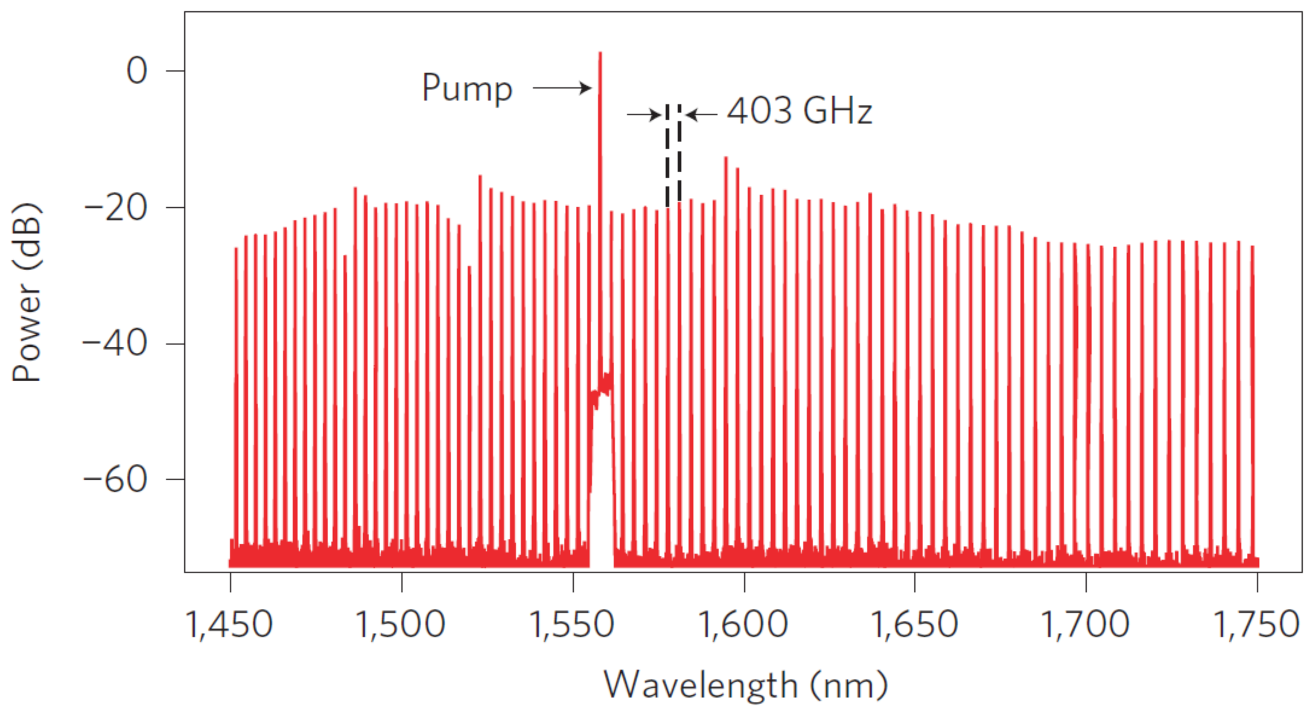
Chip-scale ultrafast sources: 20 – 1000 GHz repetition rate
10 – 1000 fs duration
0.8 – 6 μm wavelength

Saha, et al., submitted (2012).

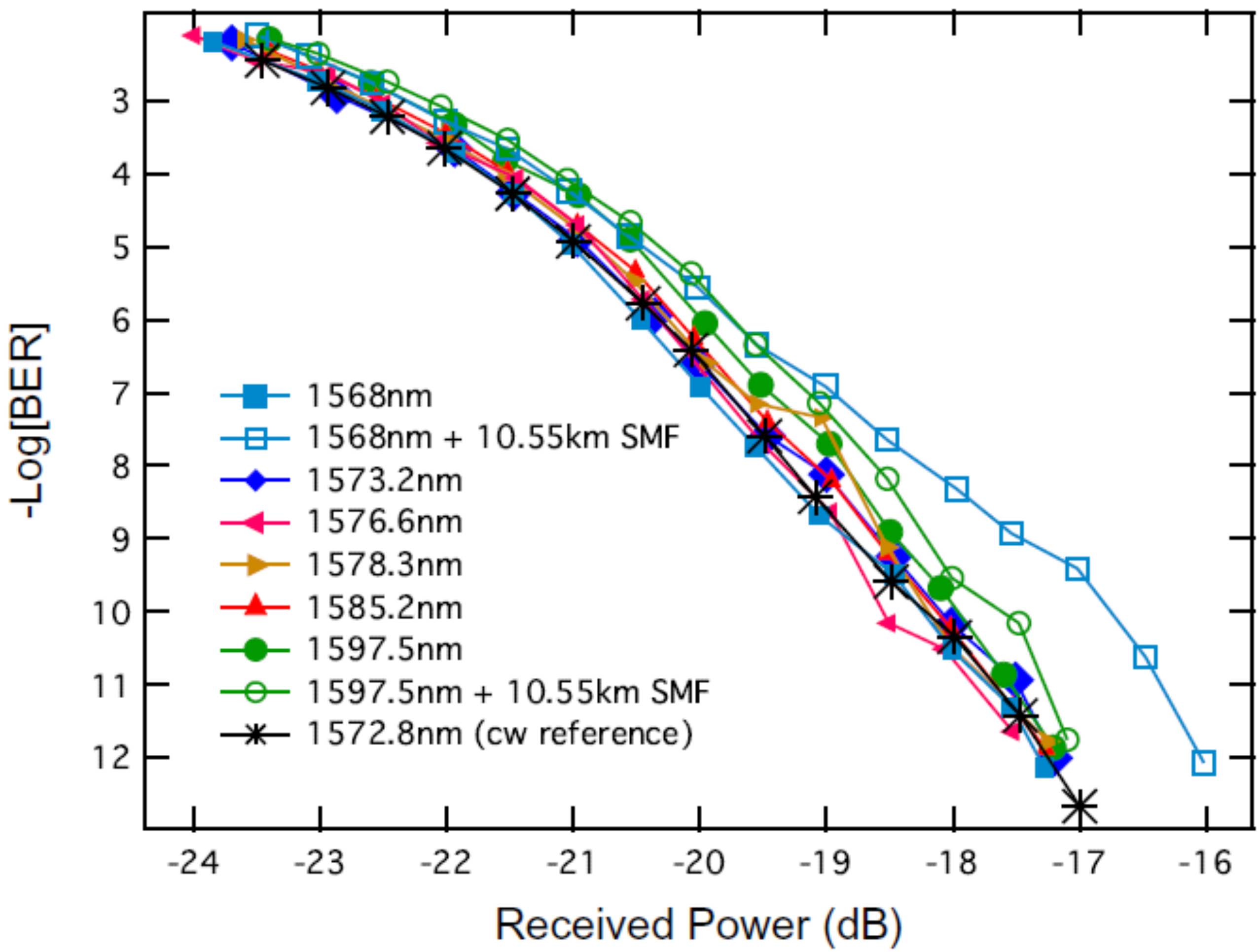
Multiple Wavelength Source

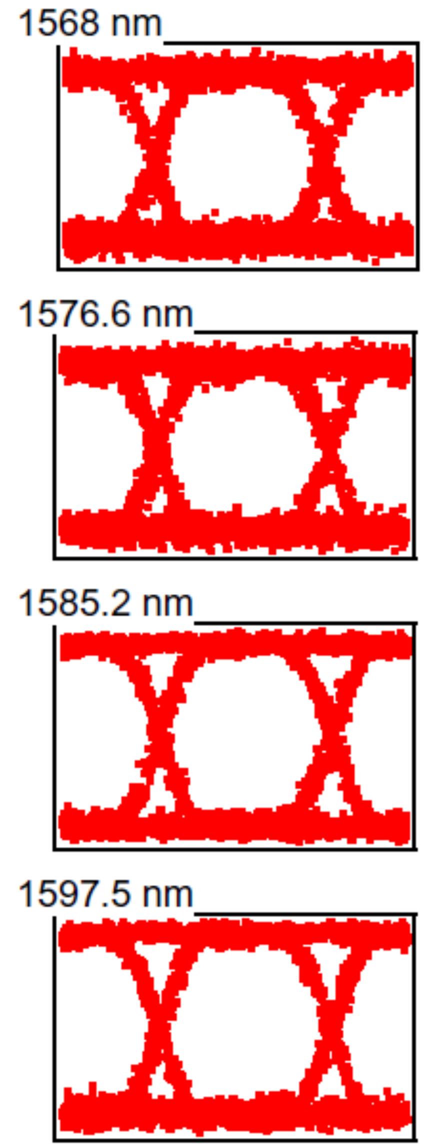


Single diode laser → multiple wavelength source for WDM



Bit-Error-Rate Performance



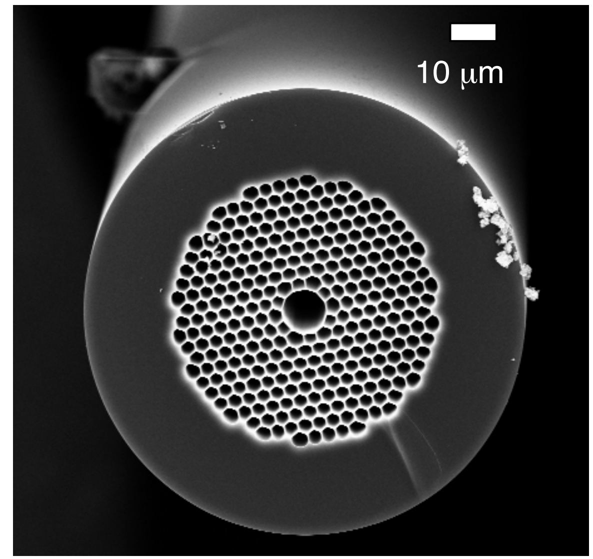


Outline: Nonlinear Optics in Nanostructured Materials

<u>Silicon-Based Nonlinear Nanophotonics</u>

- Four-wave mixing with mW's
- Optical parametric oscillation & frequency comb generation
- Ultrashort pulse generation

<u>Gas-Filled Photonic Crystal Fibers</u>



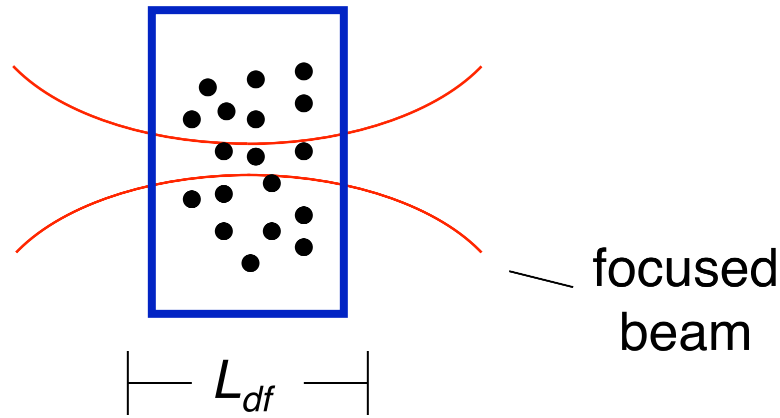
- Generation of high-density Rb vapor
- Few-photon resonant nonlinear interactions

Outline

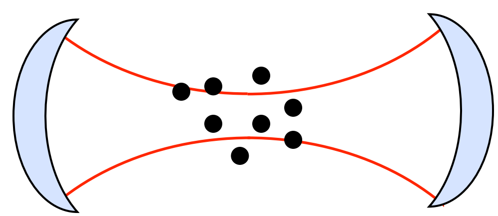
- Introduction
  - Rubidium filled Photonic Bandgap Fiber system
- Ultralow Power Two-Photon Absorption
  - Few-Photon Intensity Modulation
- Ultralow Power Cross-Phase Modulation
  - Few-Photon Cross-Phase Shift

Geometries for Interactions with Atoms/Molecules

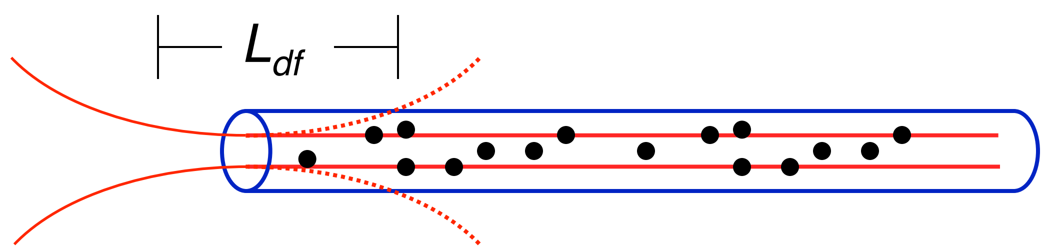
- Bulk focused geometry



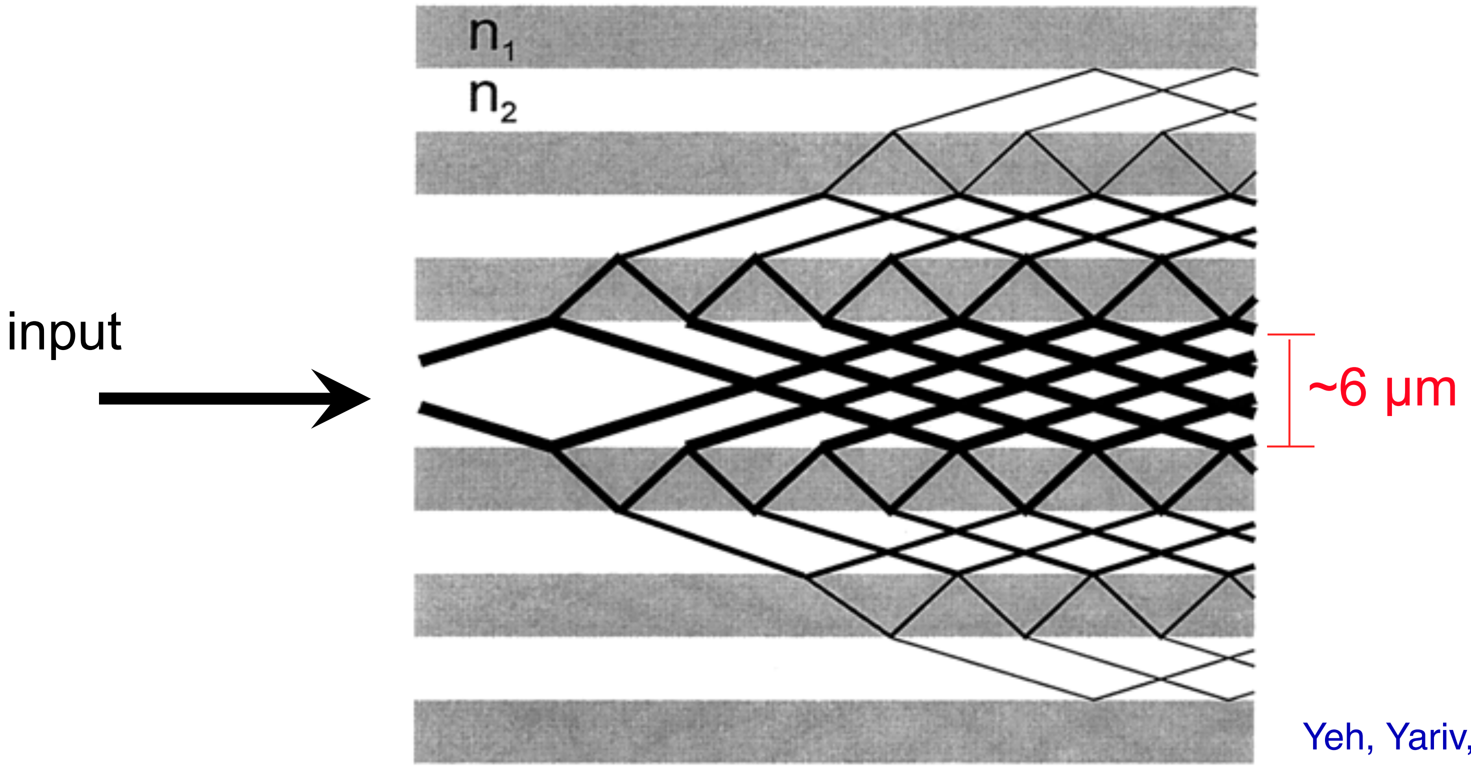
- Cavity



- Hollow fiber (?)



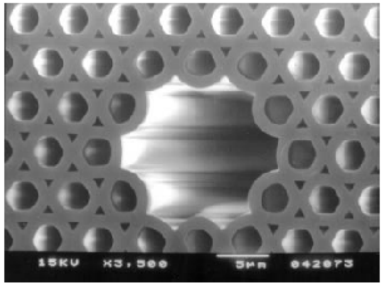
Photonic Band-Gap Guidance



Yeh, Yariv, & Hong (1977)

- **Light guided by interference, not total internal reflection.**
- Guiding properties strongly wavelength dependent.

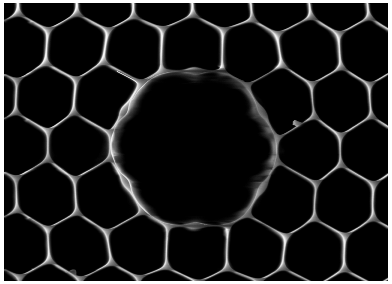
Development of Photonic Band Gap Fibers



Knight *et al*, Science (1998)

Cregan *et al*, Science (1999)

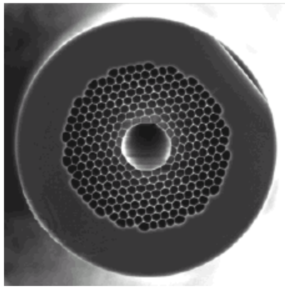
Band-gap guidance in low-index region.



Smith et al., Nature (2003)

Loss ~ 13 dB/km

Air-filling fraction ~ 94%

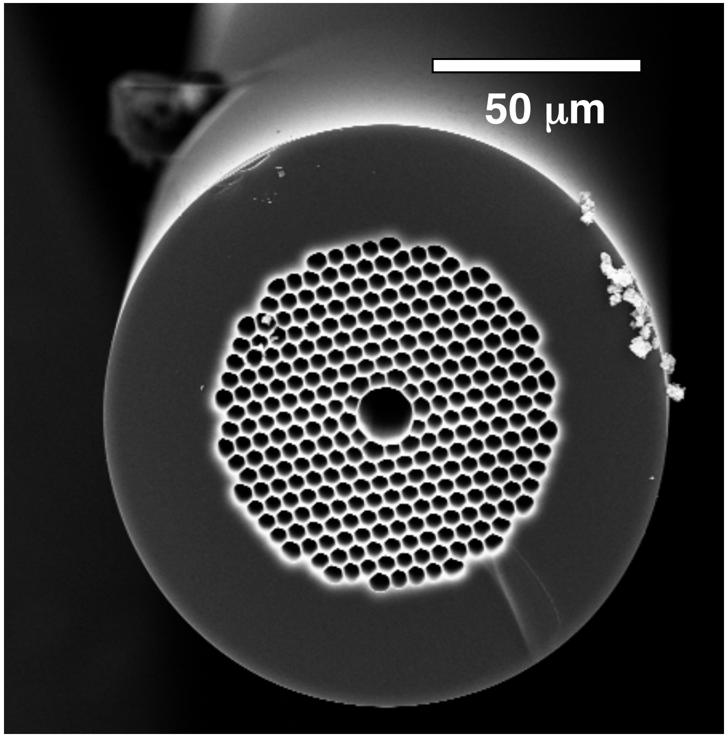


B. J. Mangan et al., OFC (2004)

Loss ~ 1.7 dB/km

multimode

Photonic Band-Gap Fibers



- Guidance in low-index, highly confining region.
  - Gases (e.g., air, Xe, C_2H_2, Rb) can be injected into core.
- Extremely strong or weak interactions are possible.

Coherent Resonant Interactions with Gases

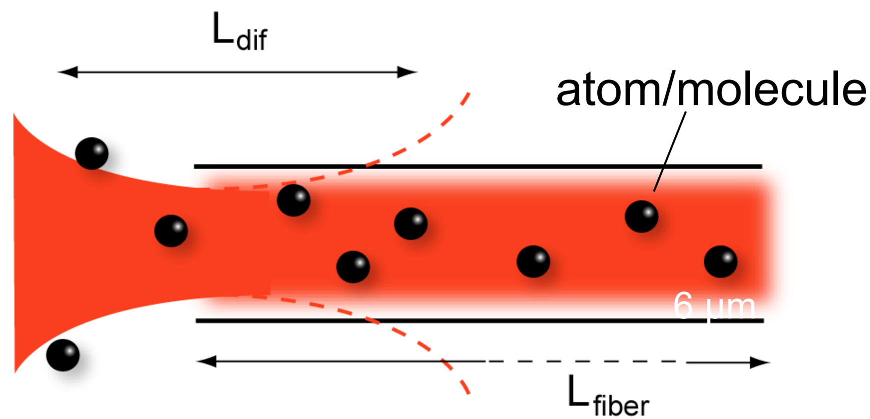
$$\text{effective interaction} \propto N \times \sigma \times \frac{L}{A}$$

length

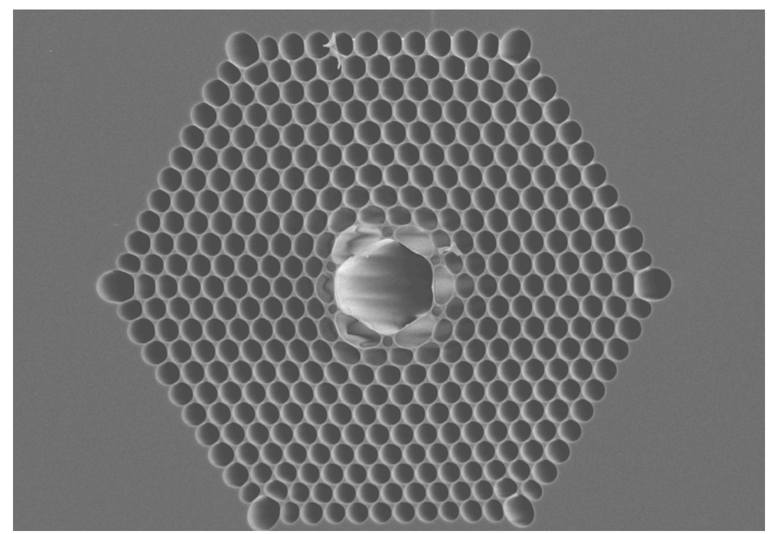
area

density

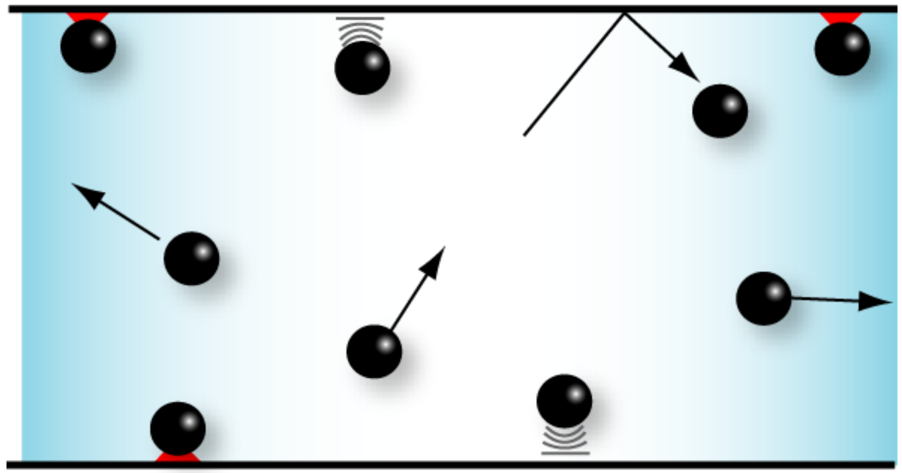
atomic/mol cross-section



- Extremely large enhancement of nonlinear interactions with atoms/molecules.
- Ultra-slow delay lines, coherent light storage in a medium, single-photon switching.

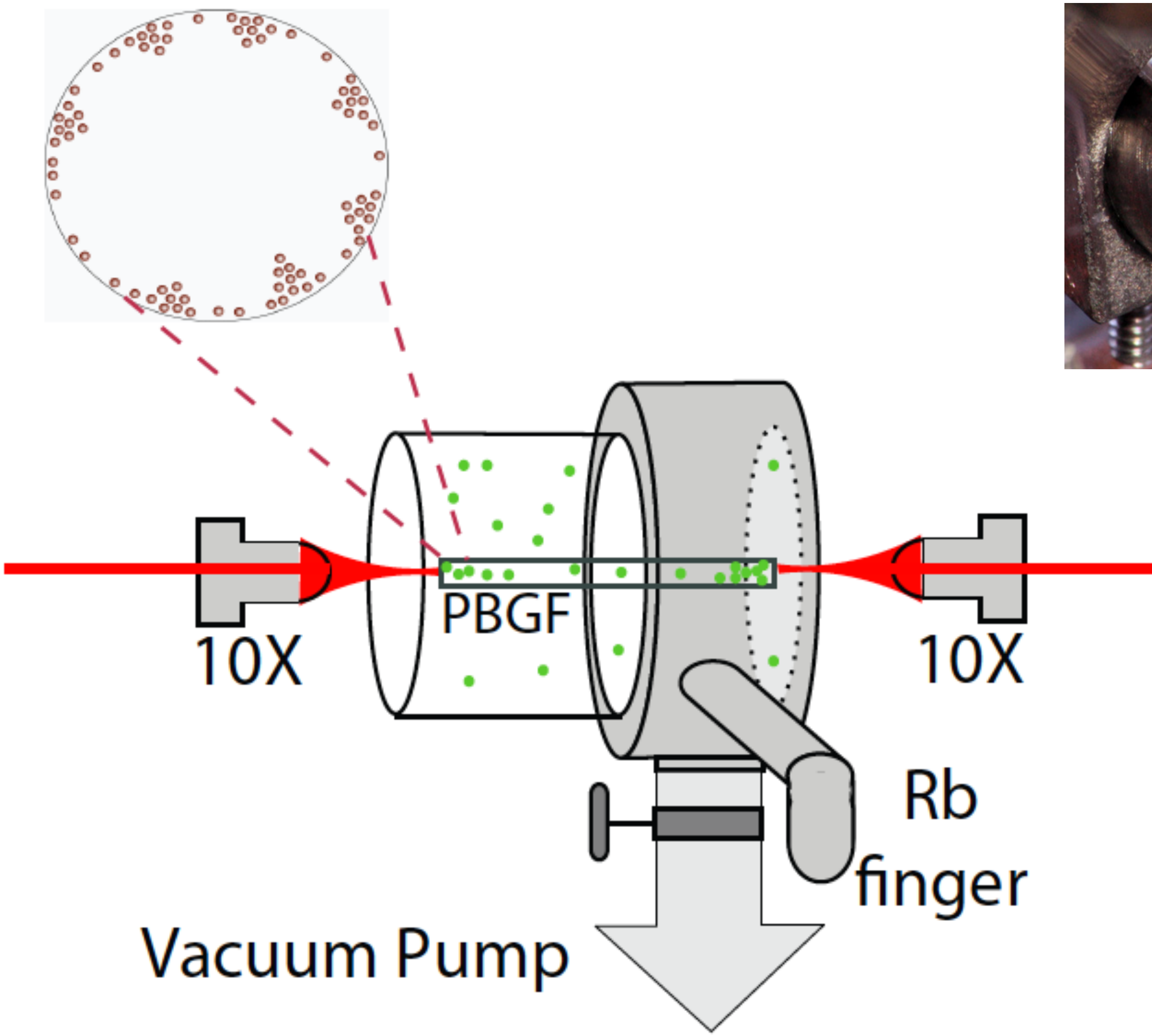


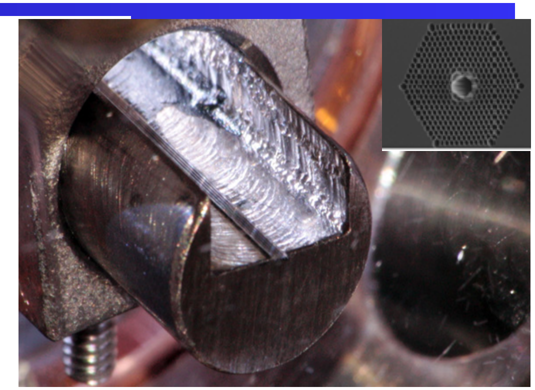
Rb in PBGF's: Strong Interactions with Silica Walls



- **Physiosorption**: Atoms stick to the wall for a finite amount of time
- **Chemisorption**: Atoms "lost'" to the wall
- **Spin Decoherence**: Wall collisions destroy coherence
- **For 6-μm core, these issues are particularly severe.**

Loading Rubidium in PBGF

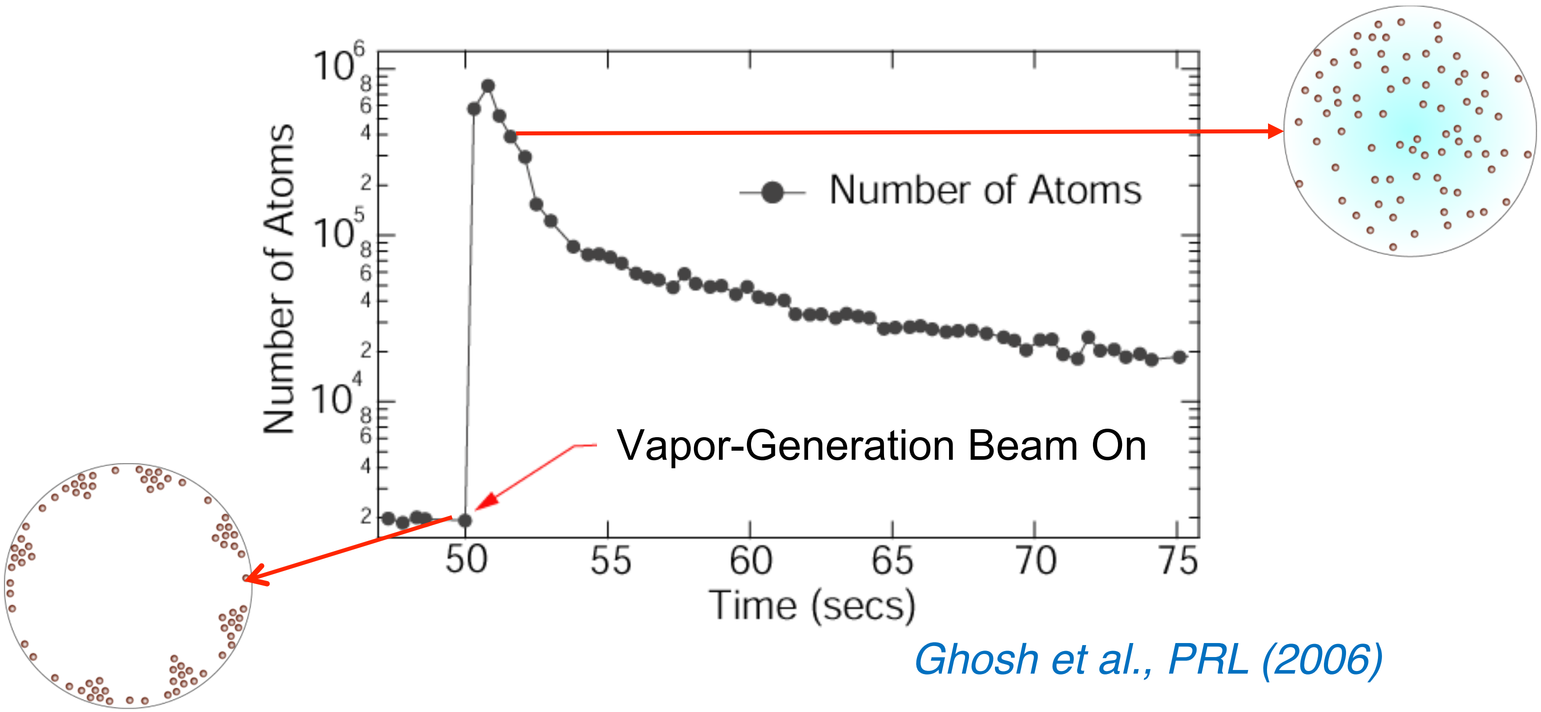




Rb diffuses into the core ➔ forms nano-clusters

[Bhagwat, et al., PRA (2009)]

Generation of Rb Vapor



Ghosh et al., PRL (2006)

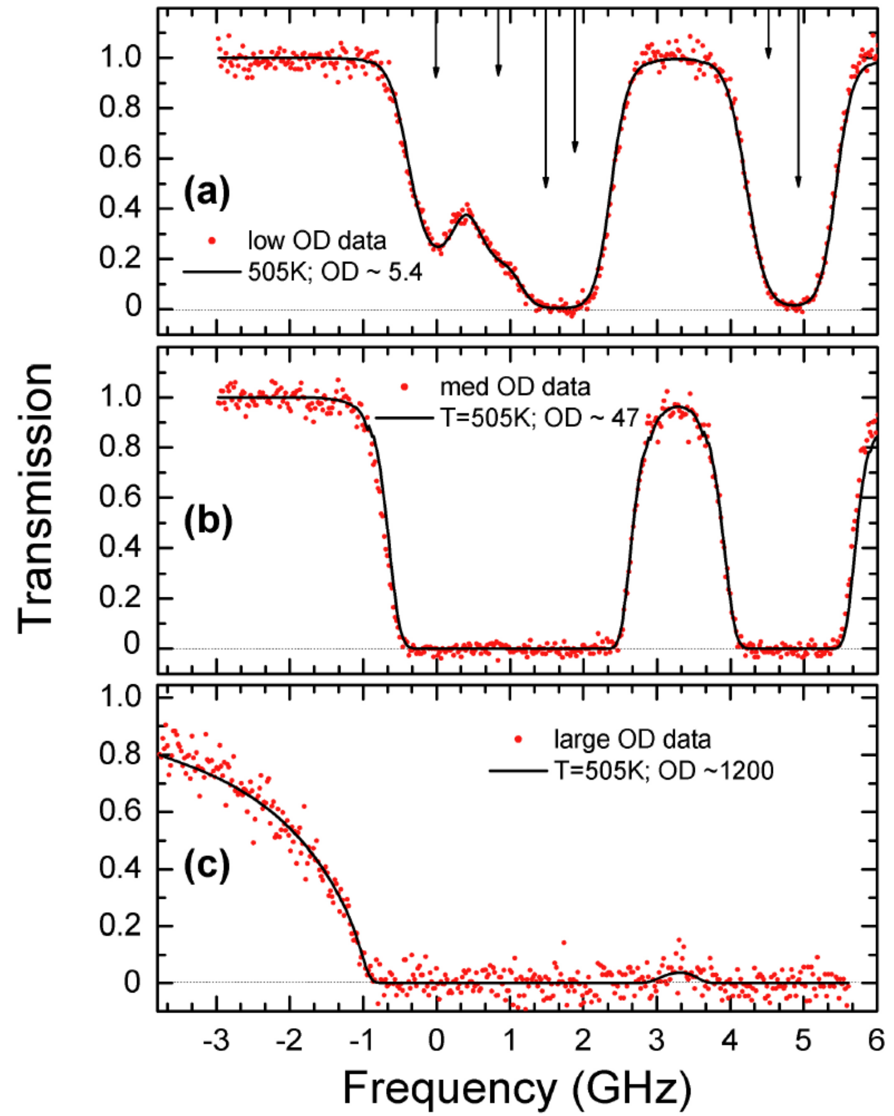
- Off-resonant laser (~805 nm) used to heat nano-clusters.
- As more nano-clusters are heated, Rb vapor density increases.

- Generation beam power and duration sets vapor density.

Gozzini et al., Nuovo Cimento (1993)

Controllable High Rb Densities in PBGF

- Simple cell design.
- Controlled high densities at room temperature.



Slepkov, Bhagawat, Venkataraman, Londero, and Gaeta (2008).

Outline

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  - Few-Photon Intensity Modulation
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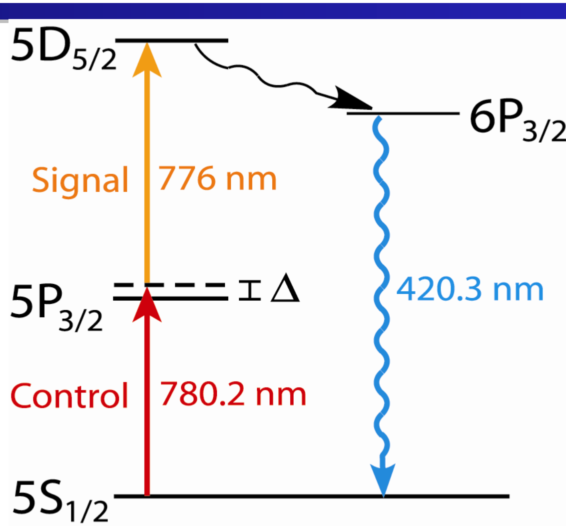
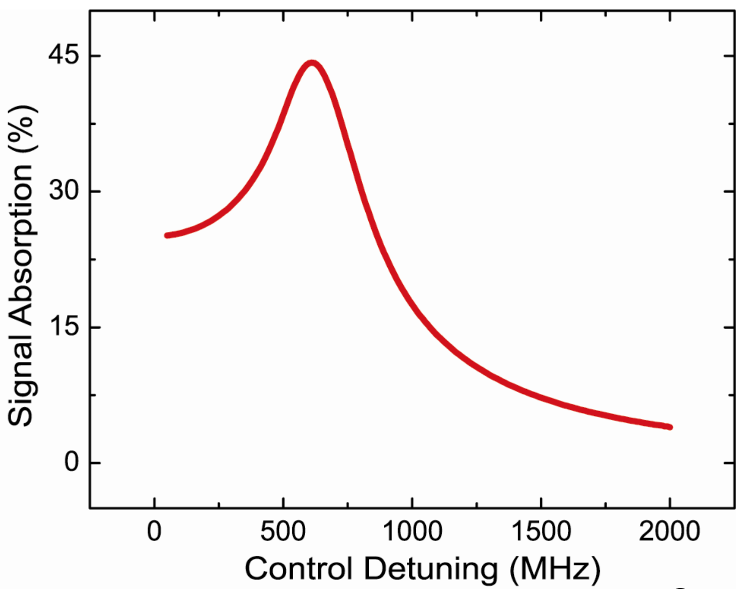
Non-Degenerate Two-Photon Absorption





Absorption of $I_S \propto e^{\beta/\alpha}$

- Estimate of optimal nonlinear absorption

$$\frac{dI_C}{dz} = -\alpha I_C - \beta I_C I_S$$

$$\frac{dI_S}{dz} = \beta I_S I_C$$

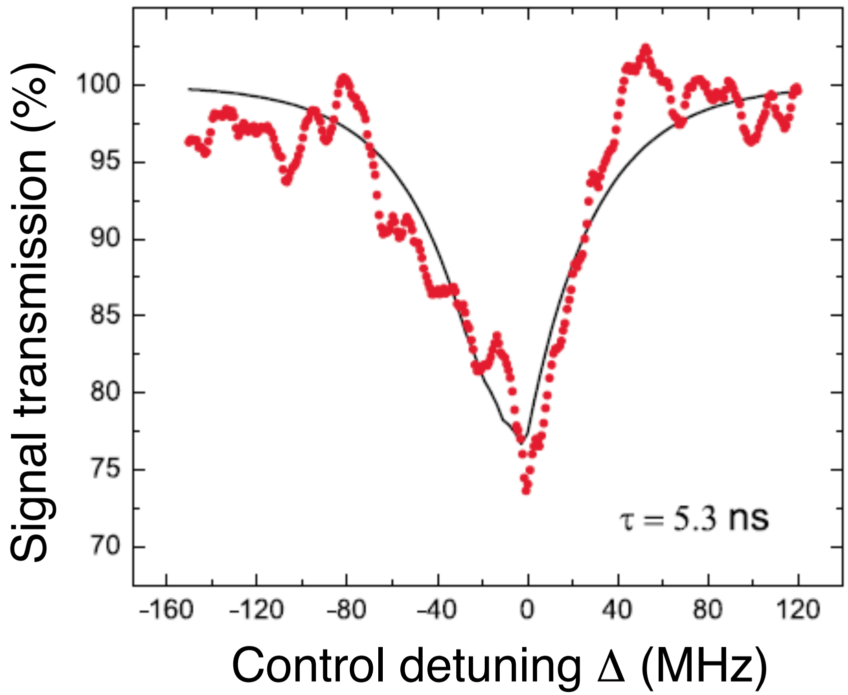
$\alpha \rightarrow$ Linear absorption coefficient

$I_C \rightarrow$ Intensity of control beam

$I_S \rightarrow$ Intensity of signal beam

$$\boxed{\Delta \sim 600 \text{ MHz}}$$

All-Optical Modulation at Ultralow Power

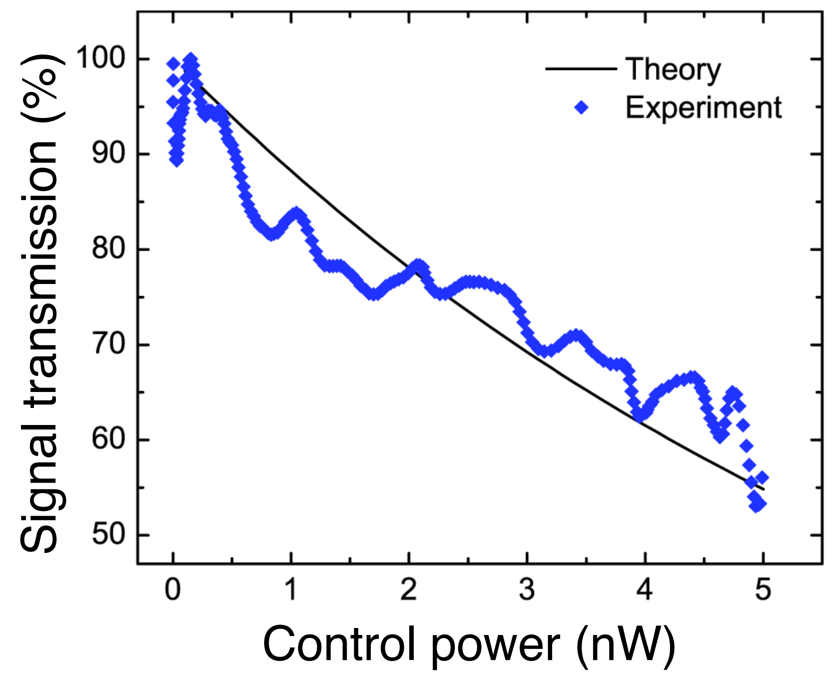


- Transit-time limited profile:

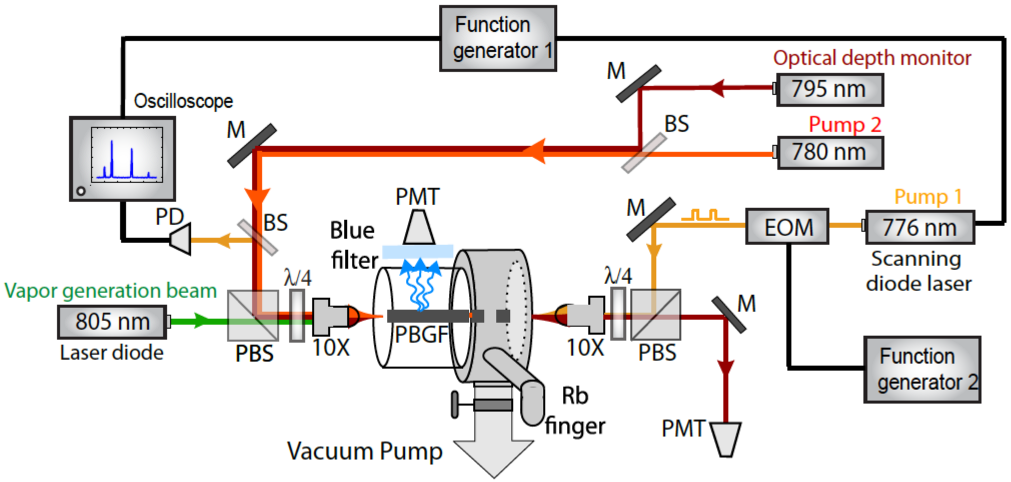
$$T(\Delta) = 1 - Ae^{-\tau|\Delta|}$$

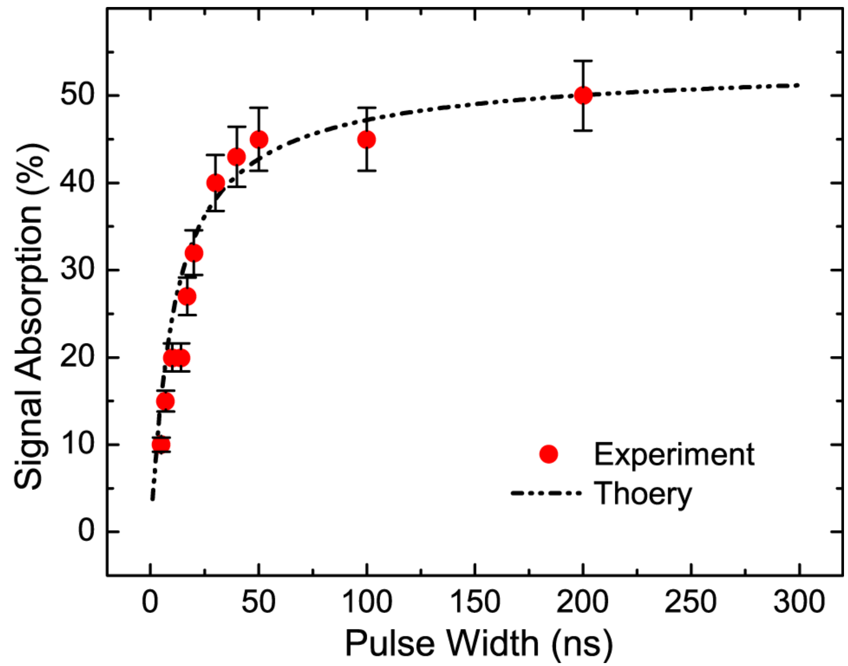
[S. N. Bagayev, et al., (1994)]

- > 25% all-optical modulation
- 825 pW in control beam
- 600 pW in signal beam



Few-Photon Switching using TPA





- Theory assumes transit-time τ = 5 ns
- Power of *1 photon* = $\dfrac{hc}{\lambda} \times \dfrac{1}{\tau} = 51\,\text{pW}$
- Control beam ➔ **16 photons** (825 pW)
- Signal beam ➔ **12 photons** (600 pW)

- Modulation bandwidth up to 50-MHz.

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  - Few-Photon Cross-Phase Shift

Large XPM for Quantum Logic

- Large Kerr nonlinearity → QND measurement of photon number
  Imoto et al., PRA (1985)

- Single-photon π-phase shift → Fredkin gate (universal for quantum computing)
  Milburn, PRL (1989)

- Quantum phase gates and all-optical quantum computers
  Chuang and Yamamoto, PRA (1995)

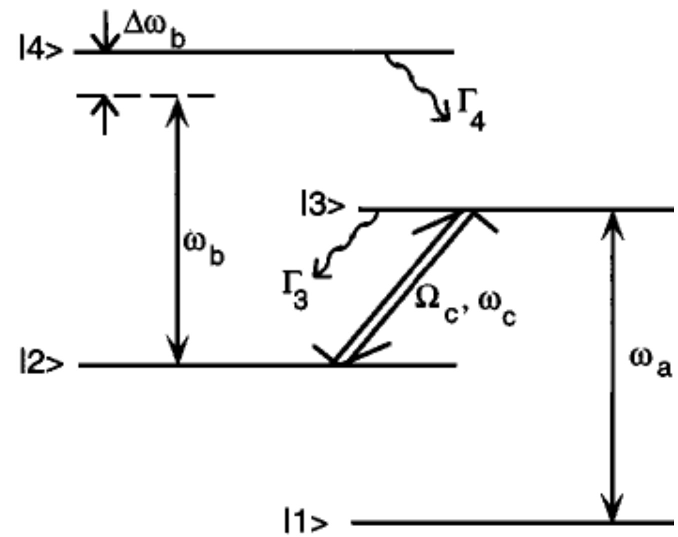
- Single-photon Kerr nonlinearities do not help quantum computation (high-fidelity, large phase shift impossible)
  Shapiro, PRA (2006)
  Gea-Banacloche, PRA (2010)

Quest for Large Cross-Phase Shifts (XPS)

- EIT-based schemes in atomic vapor

  Schmidt and Imamoglu, Opt. Lett. (1996)

  Lukin and Imamoglu, PRL (2000)



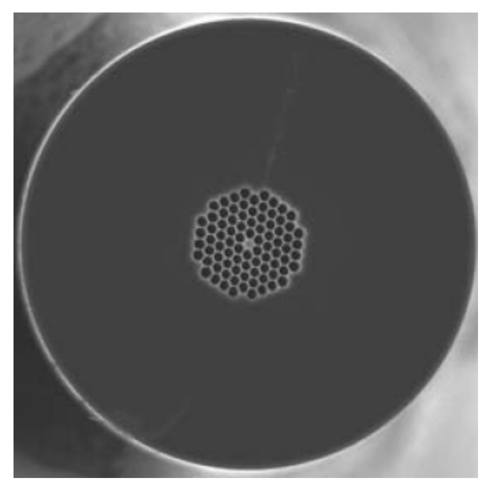
- XPS upto ~10^{-6} radians per photon in cold atom experiments

  Shiau et al., PRL (2011)

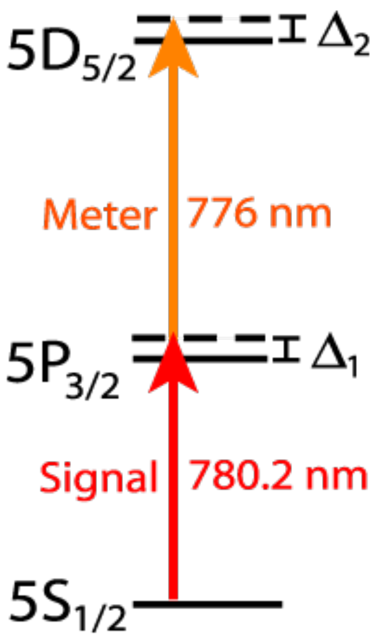
  Lo et al., PRA (2010)

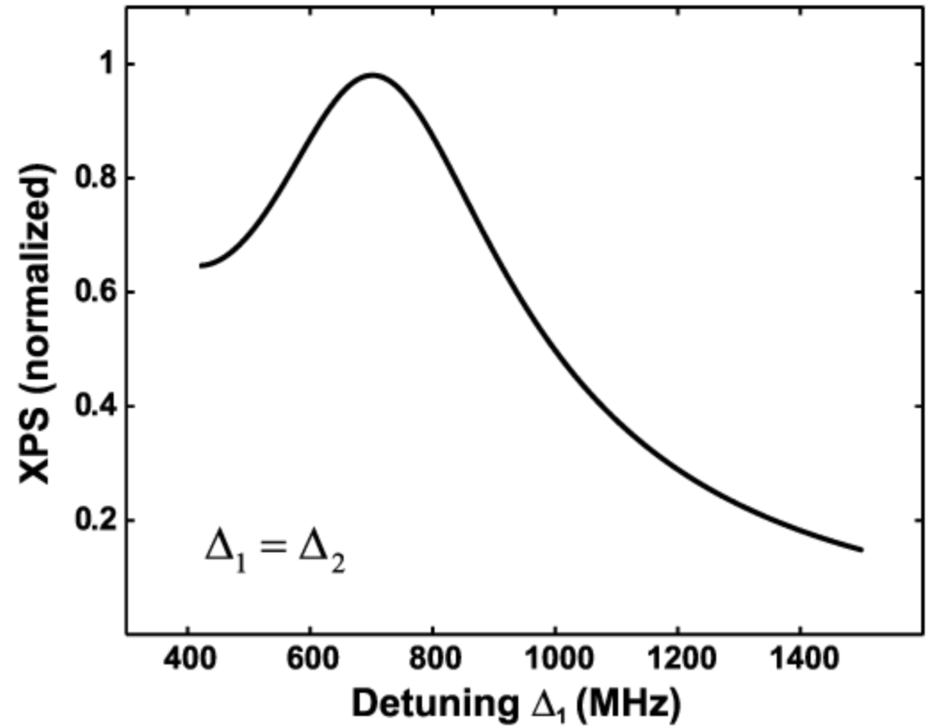
- XPS of ~10^{-7} radians per photon in microstructured fiber (solid glass core)

  Matsuda et al., Nat. Photon. (2009)



Two-Photon Transition Level Scheme





- ***Nonlinear Refractive Index***

$$n_2 \propto \frac{N \mu_1^2 \mu_2^2}{\Delta_1^2 \Delta_2}$$

N – Atomic density

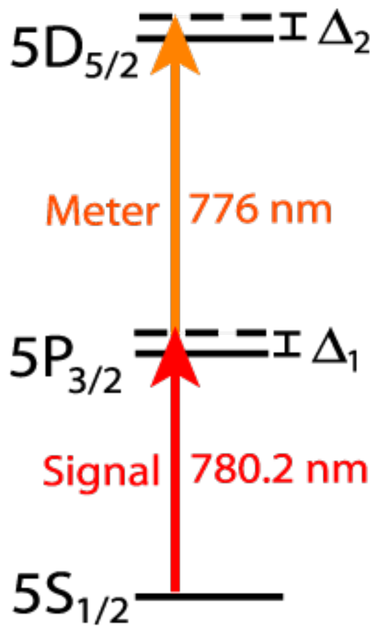
$$\boxed{\Delta_1 \sim \Delta_2 \sim 700\ \text{MHz}}$$

$$\boxed{\phi \propto n_2 P_S}$$

XPS

Signal power

Polarization Rotation Measurement



- Selection rules (signal and meter need to have same circular polarization for XPM)
  Olson et al., Am. J. Phys. (2006)

- Signal polarization - (right circular polarization) σ^+

measure y-component

<u>Meter polarization at input</u>

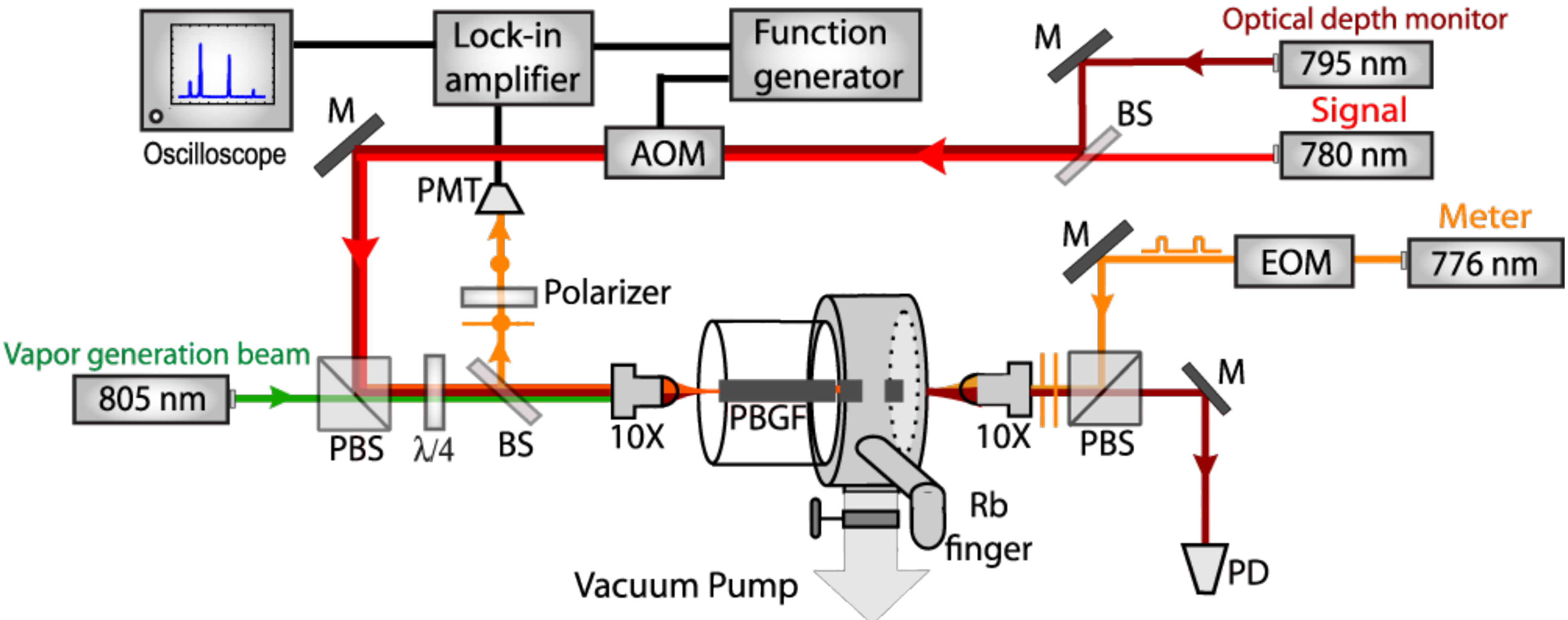
$$x = \frac{1}{\sqrt{2}}\left(\sigma^+ + \sigma^-\right)$$

<u>Meter polarization at output</u>

$$\frac{1}{\sqrt{2}}\left(\sigma^+ + e^{-i\phi}\sigma^-\right) \approx x - \boxed{\left(\frac{\phi}{2}\right) y}$$

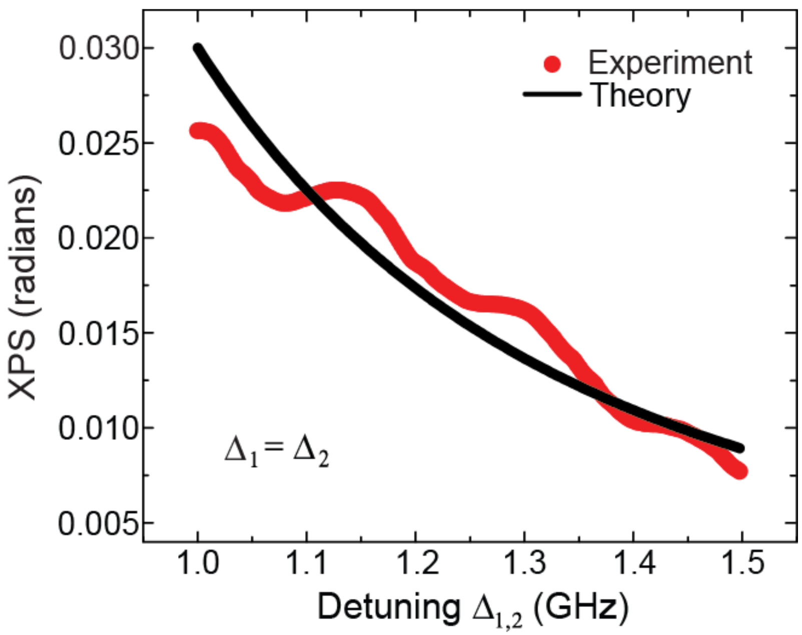
where $\phi = 1$ is the cross-phase shift

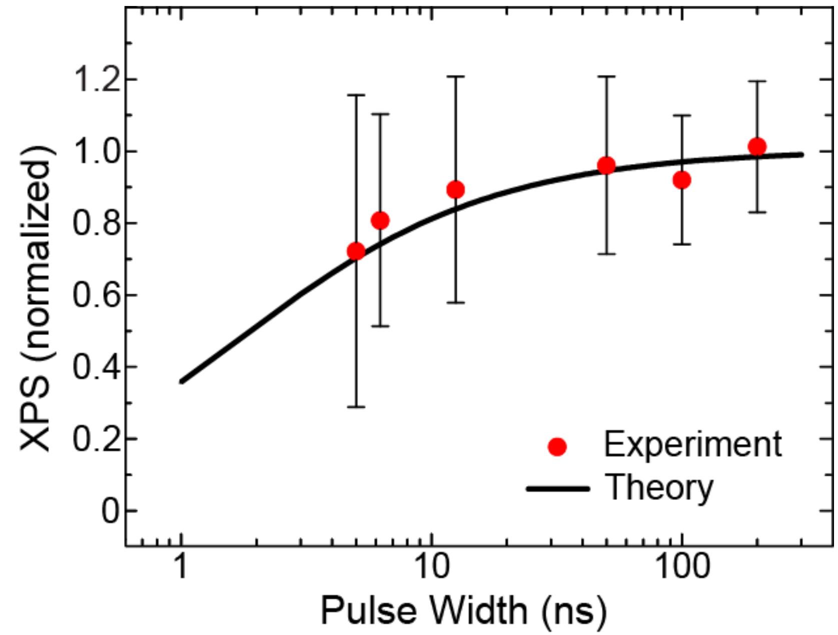
Experimental Setup



- Counter propagating beams eliminate Doppler broadening
- 795-nm beam monitors OD
- Lock-in detection to improve signal-to-noise ratio

All-Optical Phase Modulation





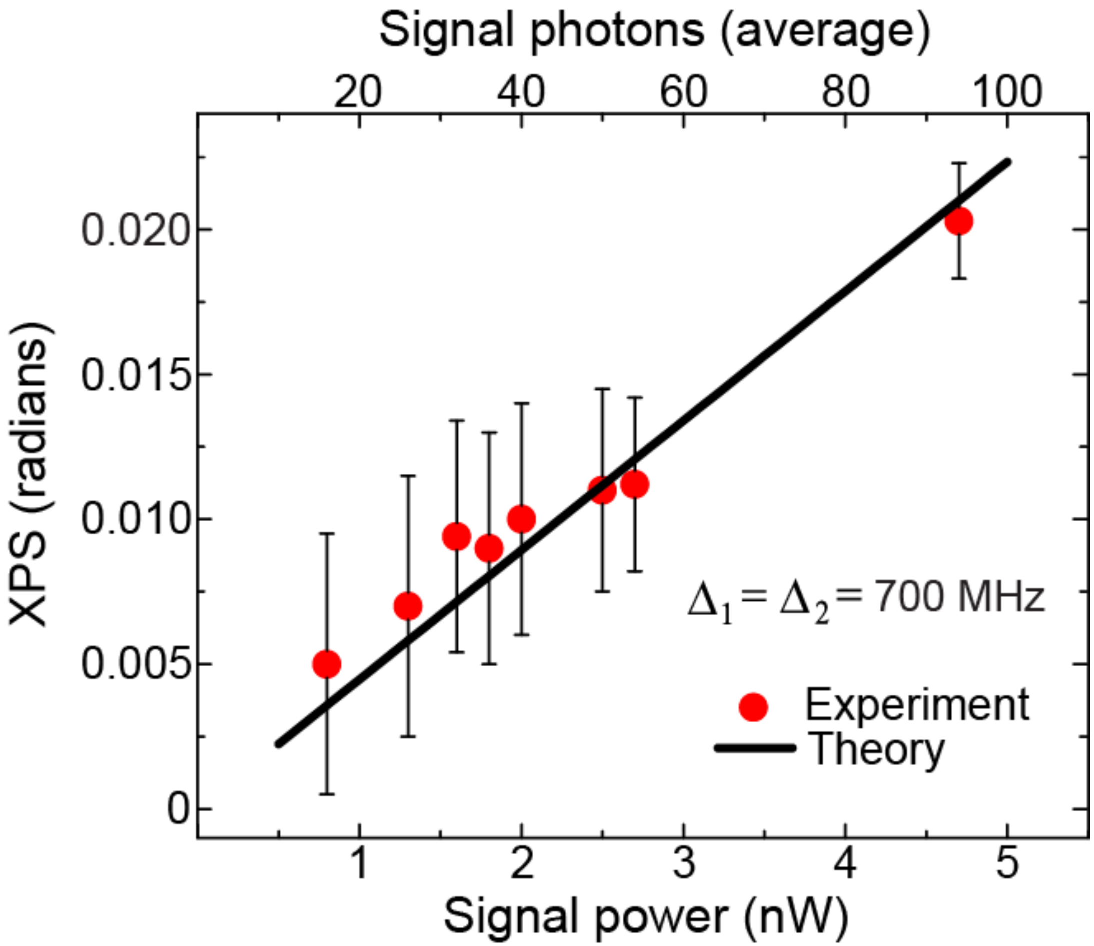
Non-demolition measurement
(signal absorption <1%)

- 50 nW signal power
- 2 μW meter power
- OD ~ 50

Response time <5 ns

- 20 nW signal power
- 10 μW meter power
- 20% duty cycle pulse train

Few-Photon Cross-Phase Modulation



OD ~ 100

Phase shift: 0.3 mrad per signal photon

Experimental estimate: $n_2 \sim 3 \times 10^{-6} \mathrm{cm}^2/\mathrm{W}$

Future

- CMOS-compatible ultrafast (> 100 GHz) optical processors
- Broadband (> 100 nm) optical amplifiers in a CMOS chip
- Mid-IR sources
- Multiple-wavelength CMOS-compatible source
- Robust chip-based optical clock

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DARPA

NSF

CNF Cornell NanoScale Science and Technology Facility