Parametric processing of classical and quantal signals

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Outline of lectures

- Brief introduction to optical communications.
- Basic classical physics of parametric devices.
- Some conventional applications of parametric devices.
- Basic quantum physics of parametric devices.
- Signals, noise and information in parametric links.
- Some novel applications of parametric devices:
  - Photon generation and frequency conversion in quantum information systems.

Selected milestones in communications

1958 Schawlow and Townes invent the laser

F & B

1970 Corning reports first low-loss optical fiber

1983 AT&T installs first commercial fiber system in US

F & B

1987 EDFA invented

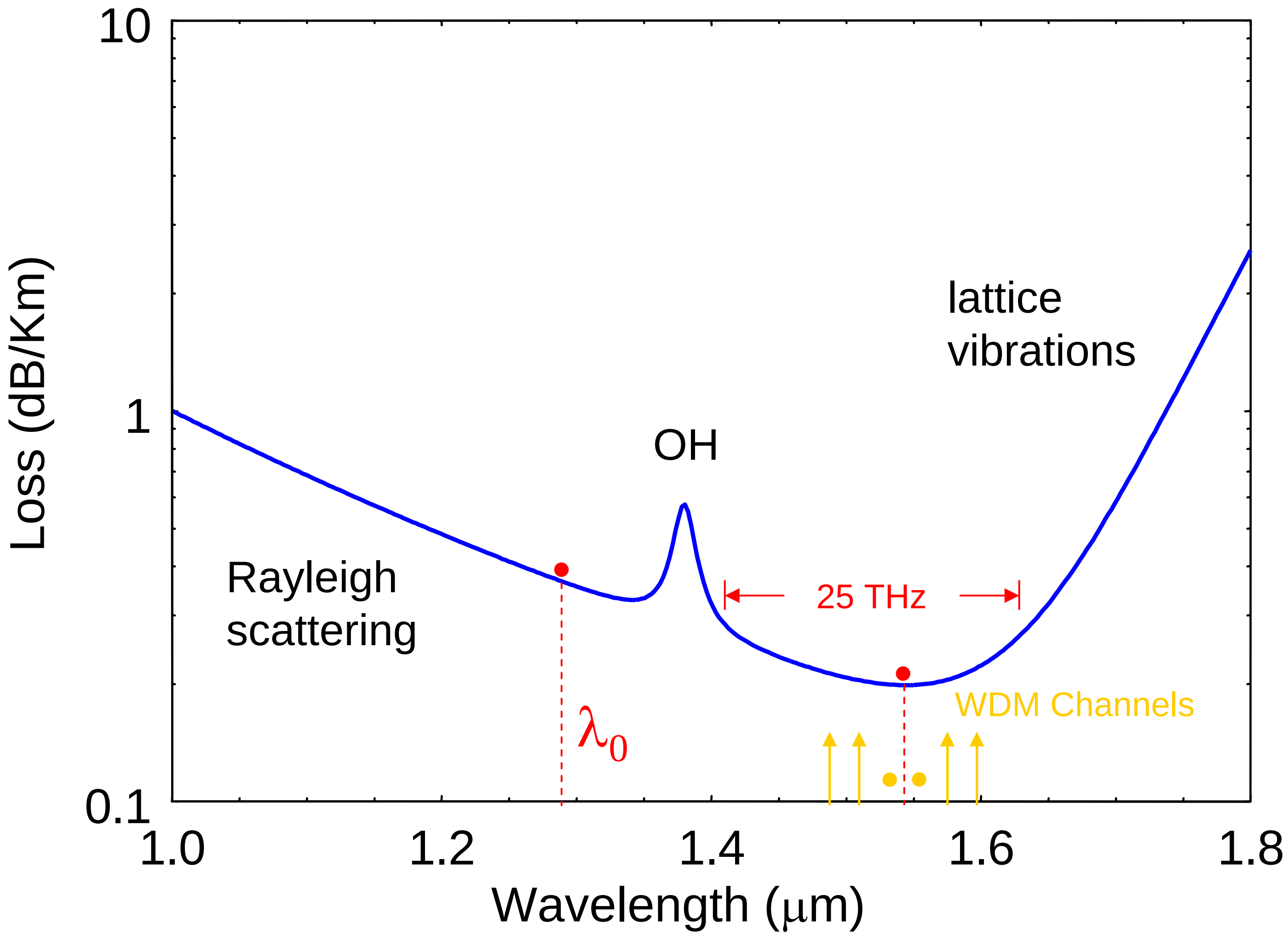
1989 AT&T's Roaring Creek WDM field trial

1996 1 Tb/s WDM transmission (Fujitsu, AT&T, NTT)

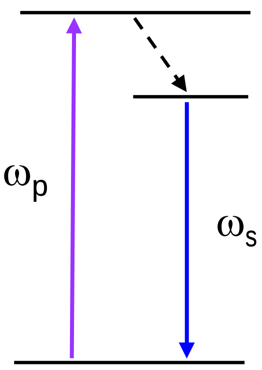
1960 1970 1980 1990 2000 t

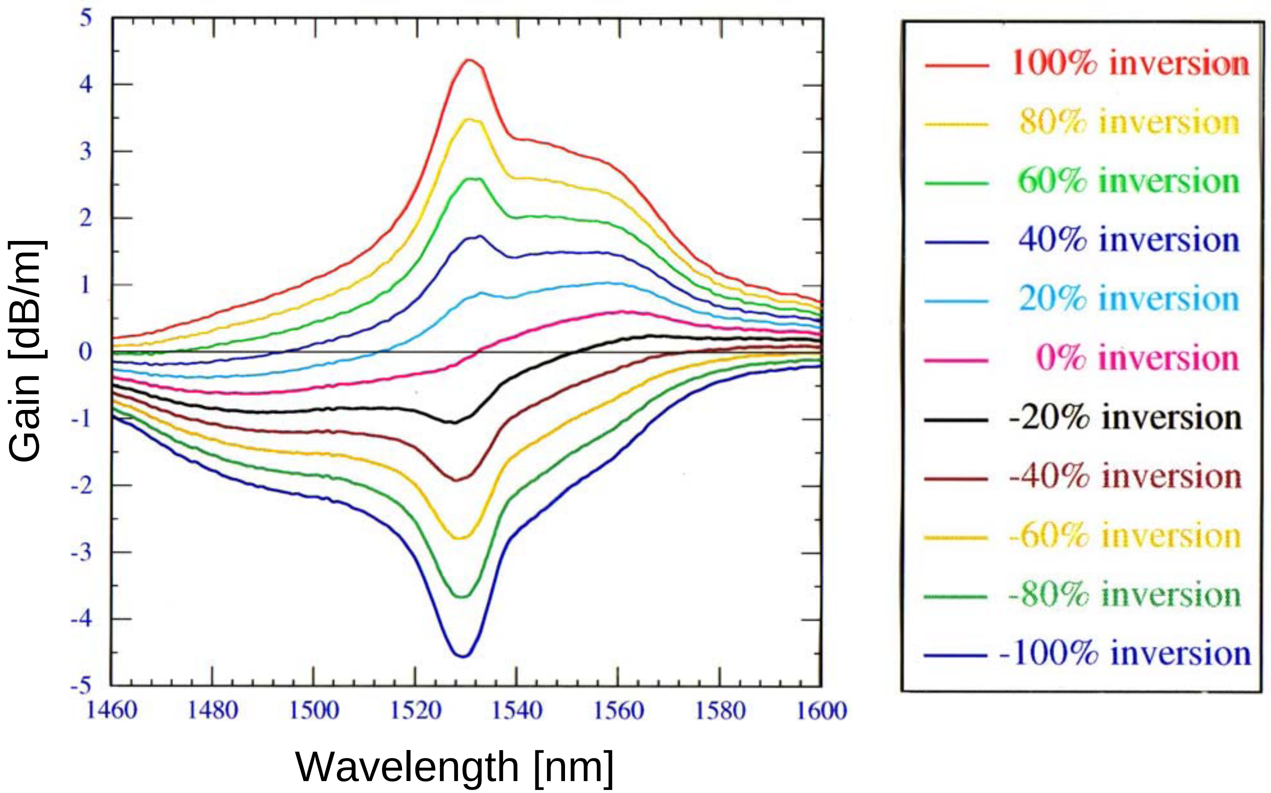
Kao 1966

Loss of a single-mode fiber



Gain profile of an EDFA

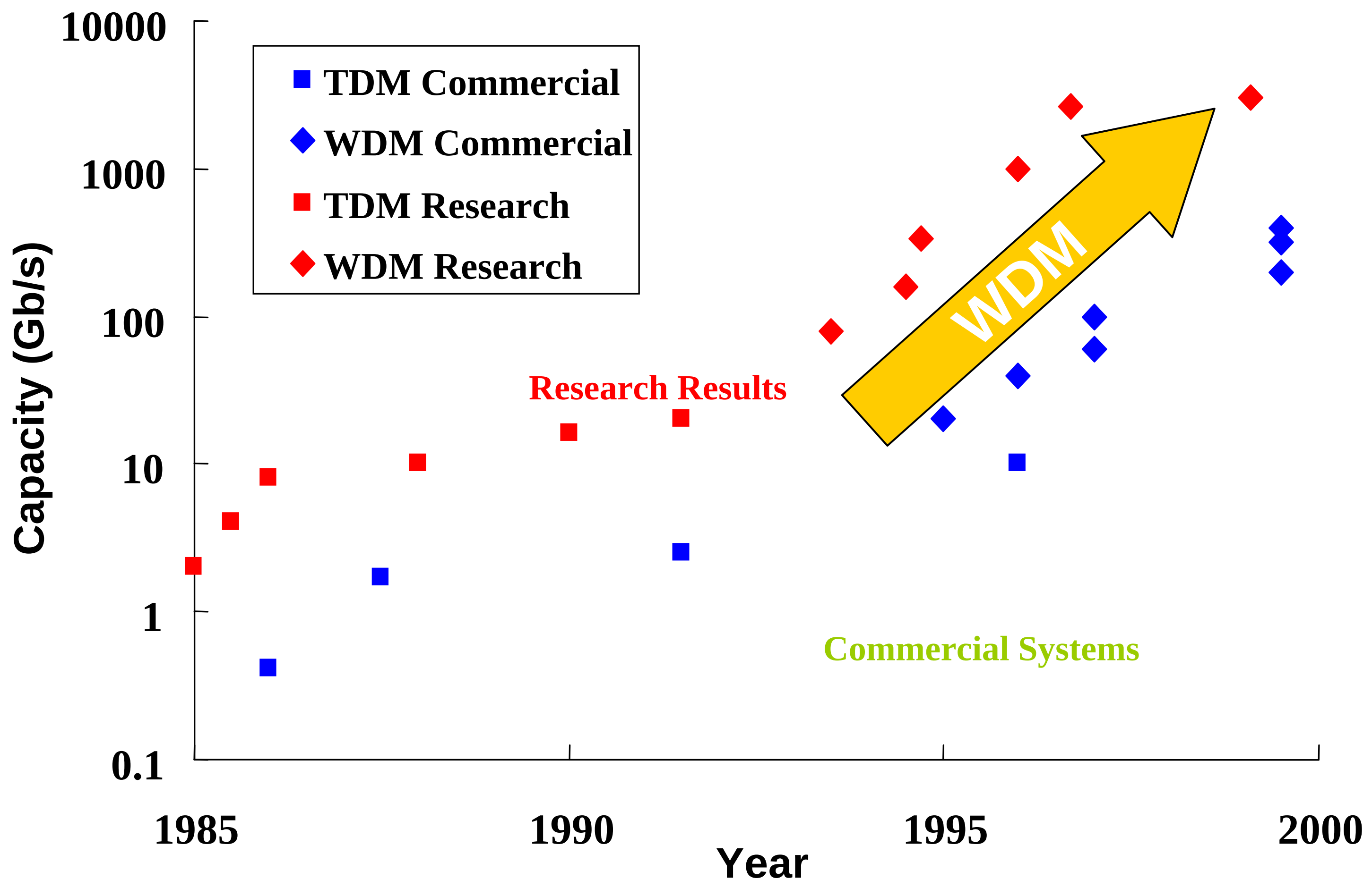




- Erbium-doped silicate fiber pumped by a semiconductor laser.

[J. Zyskind]

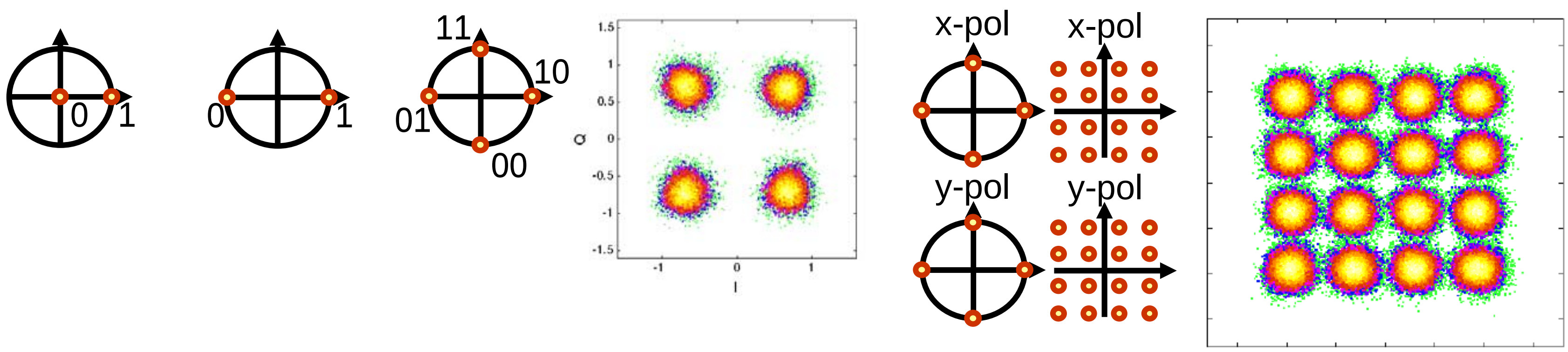
Progress in single-fiber transmission capacity



- Current capacity exceeds 50 Tb/s.

[A. Gnauck, J. Lightwave Technol. **26**, 1032 (2008).]

Advanced modulation formats



- Until 2000, systems used on-off keying (OOK), which has 2 constellation points per symbol and requires only direct detection.
- 2002: Differential phase-shift keying (DPSK) was introduced, with 2 points per symbol, self-homodyne detection.
- 2005: Differential quadrature phase-shift keying (DQPSK).
- 2010: 16 quadrature-amplitude modulation (16-QAM) . . .
- Complex constellations require homodyne detection (local oscillator).

[P. Winzer, Photon. Soc. News **23** (1), 4 (2009); S. Chandrasekhar, OFC, paper OMU5 (2011).]

What characteristics should an amplifier have?

- Broad-bandwidth
  - To amplify 128 channels separated by 0.4 nm a bandwidth of 51 nm is required. The gain nonuniformity (ripple) should be minimal.
- Polarization insensitive
  - Transmission fibers do not preserve the signal polarizations, so the polarization dependence of the gain should be minimal.
- Low noise
  - Noise makes a signal hard to read. An amplifier should emit minimal noise.
- Similar criteria apply to other parametric devices, such as frequency convertors, phase conjugators and buffers (delay elements).

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Linear evolution (dispersion)

- Define the electric-field amplitude $E(t,z) = A(t,z)\exp(ik_0z - i\omega_0t)$, where ω_0 and $k_0 = k(\omega_0)$ are the carrier frequency and wavenumber, and $A(t,z)$ is the slowly-varying wave amplitude (envelope) .

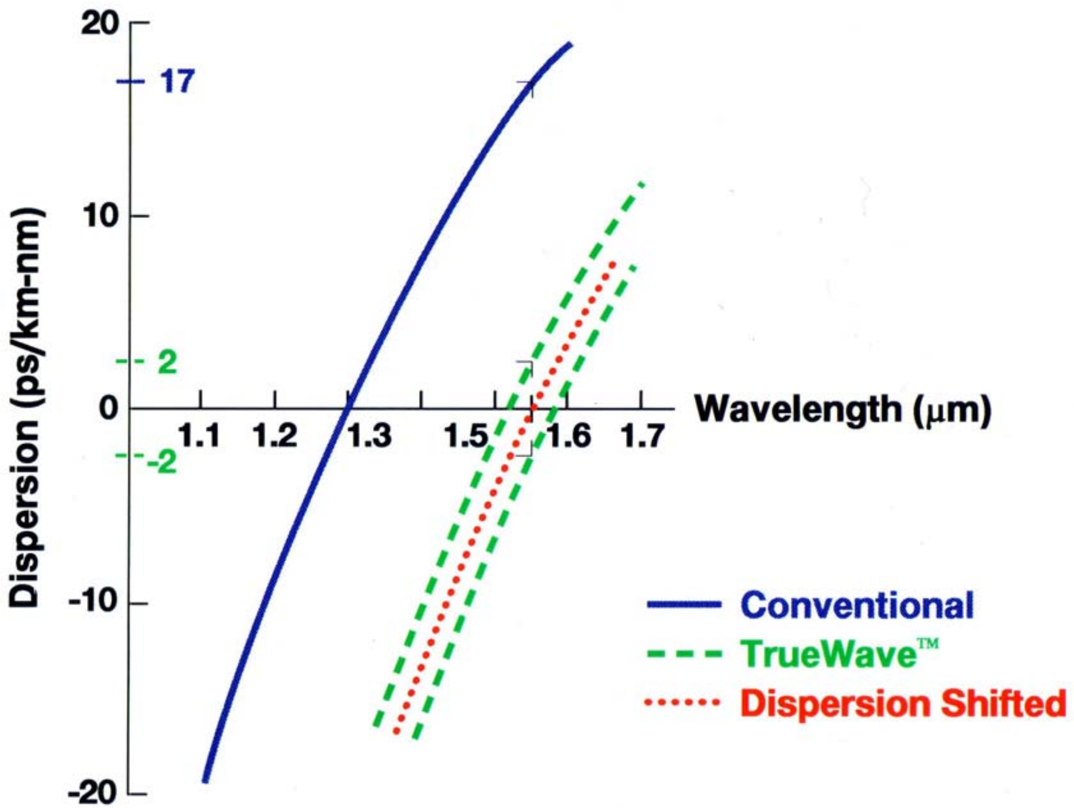
- In the frequency domain, $d_zA(\omega,z) = i\beta(\omega)A(\omega,z)$, where $d_z = d/dz$ and the envelope wavenumber $\beta(\omega) = k(\omega_0+\omega) - k(\omega_0) = \Sigma_{n\geq 1} \beta_n\omega^n/n!$, $\beta_n = k^{(n)}(\omega_0)$.

- In the time domain, $d_zA(t,z) = i\beta(id_t)A(t,z)$, where $d_t = d/dt$ ($\omega \leftrightarrow id_t$). Explicitly, $d_zA(t,z) = i\Sigma_{n\geq 1} \beta_n(id_t)^n/n!\ A(t,z)$.

- For n = 1, $d_zA = -\beta_1 d_tA$: convection $\rightarrow A(t - \beta_1 z)$.

- For n = 2, $d_zA = -i\beta_0^{(2)}d_{tt}A/2$: (second-order) dispersion $\rightarrow \dfrac{\exp[-t^2/2(\tau^2 - i\beta_2 z)]}{[\pi(\tau^2 - i\beta_2 z)]^{1/2}}$

Dispersion of different fibers



- The zero-dispersion wavelength (ZDW) of the fiber can be controlled by varying the cladding material and structure.

Nonlinear evolution (nonlinearity)

- In a third-order nonlinear medium, $d_zE(t) \approx i(2\pi k_0)P^{(3)}(t)$, where $P^{(3)} = \chi^{(3)}E^3$.
- Let $E(t,z) = A(t,z)\exp(i\theta) + \text{c.c.}$, where $\theta = k_0z - \omega_0t$. Then

  $$E^3 = A^3\exp(i3\theta) + 3|A|^2A\exp(i\theta) + \text{c.c.}$$

- Third-harmonic generation (THG) and self-action, for which

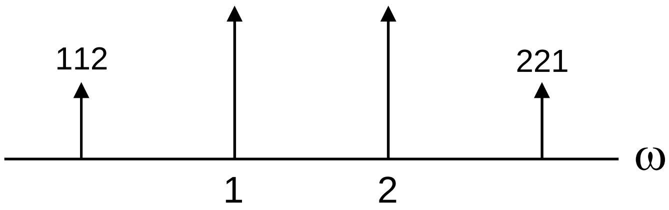
  $$d_zA(t) = i\gamma|A(t)|^2A(t),$$

  where γ is the (Kerr) nonlinearity coefficient (instantaneous response).
- If $A = B_1\exp(i\theta_1)$, then RS $= i\gamma|B_1|^2B_1\exp(i\theta_1)$; self-phase modulation (PM)
- If $A = B_1\exp(i\theta_1) + B_2\exp(i\theta_2)$, the RS has many terms.

  $\exp(i\theta_1)$: RS $\approx i\gamma(|B_1|^2 + 2|B_2|^2)B_1$; self- and cross-PM.

  $\exp[i(2\theta_1 - \theta_2)]$: RS $\approx i\gamma B_1^2B_2^*$; harmonic generation at $\omega_3 = 2\omega_1 - \omega_2$, also called four-wave mixing (FWM).

  There are similar terms with $1 \leftrightarrow 2$.



Several types of fiber exist

- Most of the cited results were obtained using small-effective-area fibers, also called highly-nonlinear fibers (HNFs), with γ = 10 / Km-W.

- Some of the results were obtained using micro-structured fibers (MSFs), also called photonic-crystal fibers, with γ = 10 – 100. Their dispersion properties can be customized for specific applications!

- Bismuth-doped fibers have γ = 100 – 1000.

- Chalcogenide fibers have γ > 1000.

[K. Hansen, Opt. Express **11**, 1503 (2003); J. Lee, J. Lightwave Technol. **24**, 22 (2006); P. Russell, J. Lightwave Technol. 24, 4729 (2006); M. Pelusi, J. Sel. Top. Quantum Electron. **14**, 529 (2008); M. Hirano, J. Sel. Top. Quantum Electron. **15**, 103 (2009).]

Scalar nonlinear Schrodinger equation

- Light-wave propagation in a fiber is governed by the generalized nonlinear Schrodinger equation (NSE)

$$d_z A(t) = - \alpha A(t) + i\beta(id_t)A(t) + i\gamma|A(t)|^2 A(t).$$

- NSE governs wave propagation in a variety of weakly-nonlinear media.
- Includes convection, dispersion, (gain) loss, PM and FWM.
- Excludes polarization effects.
- Excludes time-dependent fiber responses, which cause stimulated Brillouin and Raman scattering (SBS and SRS), and wave steepening.
- Excludes quantum fluctuations produced by gain and loss (later).

[G. Agrawal, *Nonlinear Fiber Optics* (Elsevier, 2006); R. Boyd, *Nonlinear Optics* (Elsevier, 2008); L. Mollenauer, *Solitons in Optical Fibers* (Elsevier, 2006).]

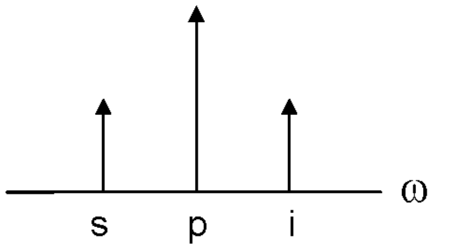
Degenerate four-wave mixing

- In degenerate FWM, also called modulation interaction (MI), a strong pump (p) drives a weak signal and idler (s, i). The frequency-matching (FM) condition is $2\omega_p = \omega_s + \omega_i$.

$$d_z A_s = i(\beta_s + 2\gamma|A_p|^2)A_s + i\gamma A_p^2 A_i^*,$$

$$d_z A_p \approx i(\beta_p + \gamma|A_p|^2)A_p,$$

$$d_z A_i = i(\beta_i + 2\gamma|A_p|^2)A_s + i\gamma A_p^2 A_s^*.$$



- Remove pump phase factor: $A_j(z) = B_j(z)\exp[i(\beta_p + \gamma P)z]$, where $P = |A_p|^2$.

$$d_z B_s = i(\beta_s - \beta_p + \gamma P)B_s + i\gamma B_p^2 B_i^*,$$

$$d_z B_i = i(\beta_i - \beta_p + \gamma P)B_i + i\gamma B_p^2 B_s^*.$$

- Conjugate the i-equation and look for eigenvalues (MI wavenumbers) k.

$$k = (\delta_s - \delta_i)/2 \pm [(\delta_s + \delta_i)^2/4 - (\gamma P)^2]^{1/2}, \text{ where } \delta_j = \beta_j - \beta_p + \gamma P.$$

- Define the (wavenumber) mismatch $\delta = (\delta_s + \delta_i)/2 = (\beta_s - 2\beta_p + \beta_i)/2 + \gamma P$.
- If $|\delta| > \gamma P$, then k is real; the MI is stable, (s and i) sidebands do not grow.
- If $|\delta| < \gamma P$, then k is imaginary; the MI is unstable, sidebands grow.

[C. McKinstrie, J. Sel. Top. Quantum Electron. **8**, 538 & 956 (2002).]

When is the MI unstable?

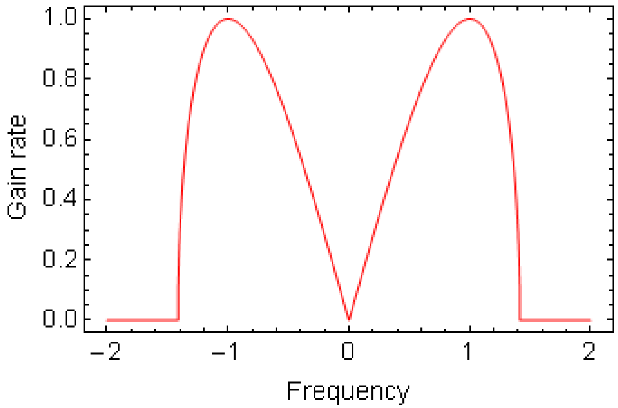
- Expand the wavenumbers about the pump frequency.

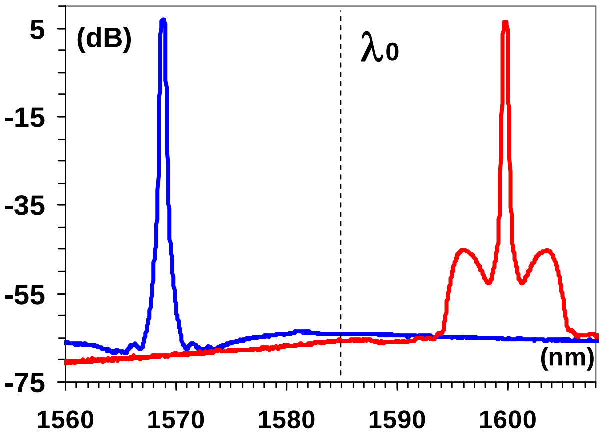
$$\beta_j(\omega_j) = \beta_0(\omega_p) + \beta_1(\omega_p)(\omega_j - \omega_p) + \beta_2(\omega_p)(\omega_j - \omega_p)^2/2;\ \omega_{s,i} = \omega_p \pm \omega,$$

$$2\delta = [\beta_0(\omega_p) + \beta_1(\omega_p)\omega + \beta_2(\omega_p)\omega^2/2] - 2\beta_0(\omega_p)$$

$$+ [\beta_0(\omega_p) - \beta_1(\omega_p)\omega + \beta_2(\omega_p)\omega^2/2] + 2\gamma P = \beta_2(\omega_p)\omega^2 + 2\gamma P.$$

- If $\beta_2(\omega_p) > 0$ (normal dispersion), then $|\delta| > \gamma P$; MI is stable.
- If $-4\gamma P < \beta_2(\omega_p)\omega^2 < 0$ (anomalous dispersion), then $|\delta| < \gamma P$; MI is unstable.
- The maximal spatial growth rate γP is attained when $\omega = (2\gamma P/|\beta_2|)^{1/2}$.
- In the presence of higher-order dispersion, extra gain bands can exist.





Input-output equations for MI

- Let $B_s = C_s \exp[i(\delta_s - \delta_i)z/2]$ and $B_i = C_i \exp[i(\delta_i - \delta_s)z/2]$. Then the MI equations can be written in the symmetric form

  $$d_z C_s = i\delta C_s + i\gamma B_p^2 C_i^*, \quad d_z C_i^* = -i\delta C_i^* - i\gamma (B_p^*)^2 C_s,$$

  where the (common) mismatch $\delta = (\delta_s + \delta_i)/2$.

- The solutions of the MI equations can be written in the input-output form

  $$C_s(z) = \mu(z)C_s(0) + \nu(z)C_i^*(0), \quad C_i^*(z) = \nu^*(z)C_s(0) + \mu^*(z)C_i^*(0),$$

  where the transfer (Green) functions

  $$\mu(z) = \cos(kz) + i\delta\sin(kz)/k, \quad \nu(z) = i\gamma B_p^2 \sin(kz)/k$$

  and the MI wavenumber $k = [\delta^2 - (\gamma P)^2]^{1/2}$.

- Notice that $|\mu(z)|^2 - |\nu(z)|^2 = 1$, from which it follows that

  $$|C_s(z)|^2 - |C_i(z)|^2 = [|\mu(z)|^2 - |\nu(z)|^2][|C_s(0)|^2 - |C_i(0)|^2] = |C_s(0)|^2 - |C_i(0)|^2.$$

- Sideband photons are created in pairs (linear theory)!

[C. McKinstrie, Opt. Express **12**, 5037 (2004).]

Conservation equations for MI

- With pump-depletion included, the nonlinear MI equations are

$$d_z A_s = i(\beta_s + 2\gamma|A_p|^2)A_s + i\gamma A_p^2 A_i^*,$$

$$d_z A_p = i(\beta_p + \gamma|A_p|^2)A_p + i2A_s A_i A_p^*,$$

$$d_z A_i = i(\beta_i + 2\gamma|A_p|^2)A_s + i\gamma A_p^2 A_s^*.$$

- The signal equation implies that

$$d_z|A_s|^2 = i\gamma A_p^2 A_i^* A_s^* - i\gamma(A_p^*)^2 A_i A_s.$$

- By combining this and similar equations, one obtains the Manley-Rowe-Weiss (MRW) equations

$$d_z(|A_s|^2 + |A_p|^2 + |A_i|^2) = 0,$$

$$d_z(|A_s|^2 - |A_i|^2) = 0.$$

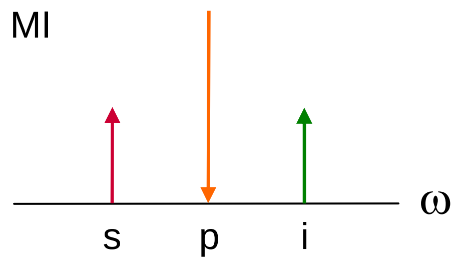
- $\mathrm{Dim}(|A|^2) = E/T$ and the photon energies $\approx h\omega_0$. $\mathrm{Dim}(|A|^2/h\omega_0) = 1/T$ (photon flux).
- Photons are created and destroyed in pairs (2 pump or 2 sideband photons):

$2\pi_p \leftrightarrow \pi_s + \pi_i$, where π_j is a photon with frequency ω_j.

- MRW and FM imply energy conservation: $d_z(|A_s|^2\omega_s + |A_p|^2\omega_p + |A_i|^2\omega_i) = 0$.

[J. Manley, Proc. IRE **44**, 904 (1956), M. Weiss, Proc. IRE **45**, 1012 (1957).]

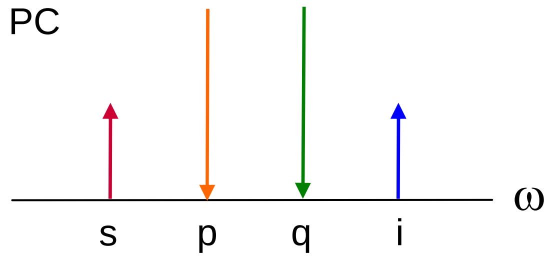
Basic properties of MI

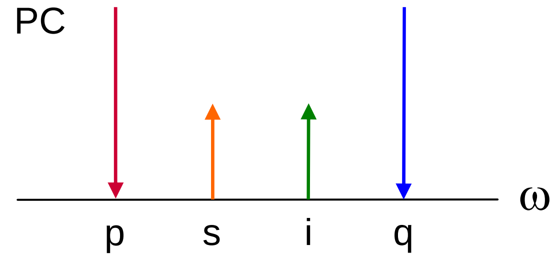


- Photons are created and destroyed in pairs: $2\pi_p \rightarrow \pi_s + \pi_i$, where π_j is a photon with frequency ω_j and (natural) wavenumber k_j.
- Frequency- and wavenumber-matching equations: $2\omega_p = \omega_s + \omega_i$, $2k_p \approx k_s + k_i$. Similar to the photon equation ($h\omega$ = energy, hk = momentum).
- MI is driven by coupling and suppressed by mismatch: $k_{MI} = [\delta^2 - (\gamma P)^2]^{1/2}$.
- A_s is coupled to A_i^* and the coupling term is γP.
- The mismatch term δ is $(k_s + k_i - 2k_p)/2 = \beta_2\omega_s^2/2 + \gamma P$.

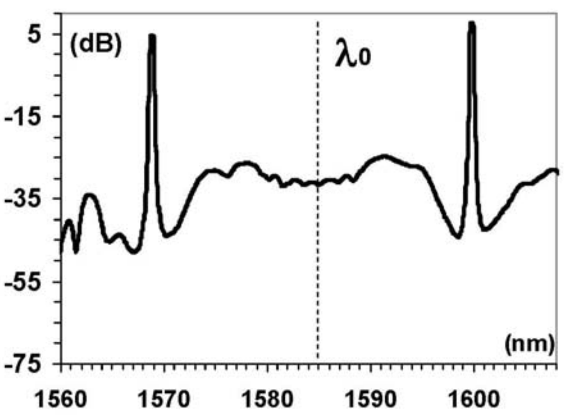
  (β_2 is evaluated at ω_p and ω_s is measured relative to ω_p).
- Narrow-bandwidth instability for $\beta_2 < 0$ and $|\omega_s| < 2|\gamma P/\beta_2|^{1/2}$.
- $|A_s|^2 - |A_i|^2$ is constant: Sideband photons are produced in pairs.

Basic properties of PC





- Photons are created and destroyed in pairs: $\pi_p + \pi_q \rightarrow \pi_s + \pi_i$, where π_j is a photon with frequency ω_j and wavenumber k_j (ω-, k-equations are similar).
- PC is driven by coupling and suppressed by mismatch: $k_{PC} = (\delta^2 - 4\gamma^2 P_p P_q)^{1/2}$.
- A_s is coupled to A_i^* and the coupling term is $2\gamma(P_p P_q)^{1/2}$.
- The mismatch term δ is $(k_s + k_i - k_p - k_q)/2 = \beta_2(\omega_s^2 - \omega_p^2)/2 + \gamma(P_p + P_q)/2$ [β_2 is evaluated at $\omega_a = (\omega_p + \omega_q)/2$ and ω_p, ω_s are measured relative to ω_a].
- Broad-bandwidth instability for $\beta_2 \approx 0$.
- $|A_s|^2 - |A_i|^2$ is constant: Sideband photons are produced in pairs.



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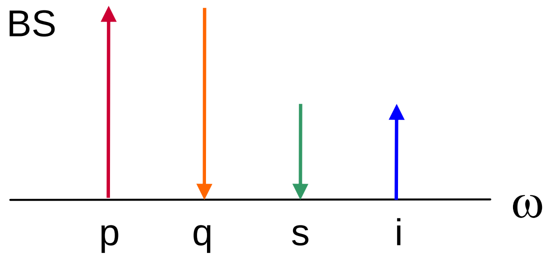
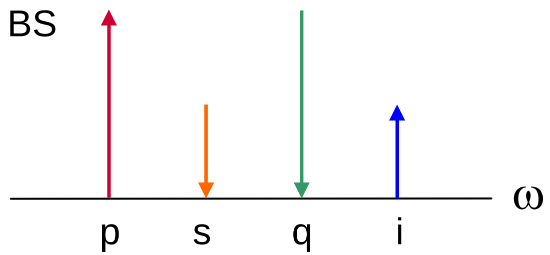
Basic properties of BS





- Photons are created and destroyed in pairs: $\pi_q + \pi_s \rightarrow \pi_p + \pi_i$, where π_j is a photon with frequency ω_j and wavenumber k_j.
- BS is driven by coupling and suppressed by mismatch: $k_{BS} = (\delta^2 + 4\gamma^2 P_p P_q)^{1/2}$.
- A_s is coupled to A_i and the coupling term is $2\gamma(P_p P_q)^{1/2}$.
- The mismatch term δ is $(k_s + k_q - k_p - k_i)/2 = \beta_2(\omega_s^2 - \omega_p^2)/2 + \gamma(P_p - P_q)/2$ [β_2 is evaluated at $\omega_a = (\omega_q + \omega_s)/2$ and ω_p, ω_s are measured relative to ω_a].
- Broad-bandwidth tunable FC for $\beta_2 \approx 0$: $\omega_i = \omega_s + \omega_q - \omega_p$.
- $|A_s|^2 + |A_i|^2$ is constant: Sideband photons are conserved ($\pi_s \rightarrow \pi_i$).

The Kerr nonlinearity is a tensor nonlinearity

- Light waves have two polarizations (HP and VP, or LCP and RCP).
- For an instantaneous isotropic medium, $P_3 \propto \gamma(E.E)E/3$.
- At the fundamental frequency, $P_3 \propto \gamma[2(A^*.A)A + (A.A)A^*]/3$, $A = [A_x, A_y]^t$.

  $P_{3x} \propto \gamma(|A_x|^2 A_x + 2|A_y|^2 A_x/3 + A_y^2 A_x^*/3)$,

  $P_{3y} \propto \gamma(2|A_x|^2 A_y/3 + |A_y|^2 A_x + A_x^2 A_y^*/3)$.
- Waves in strongly-birefringent ($\beta_x \neq \beta_y$) and rapidly-spun fibers: full Kerr nonlinearity. Self- and cross-PM, self- and cross-PR, scalar and vector FWM.
- Waves in randomly-birefringent fibers: polarization-averaged Kerr nonlinearity (Manakov nonlinearity).

  $P_{3x} = 8\gamma(|A_x|^2 + |A_y|^2)A_x/9$,

  $P_{3y} = 8\gamma(|A_x|^2 + |A_y|^2)A_y/9$.

  Self- and cross-PM, cross-PR, scalar and vector FWM.
- In all fibers, vector FWM depends on the pump and sideband polarizations.

  [K. Inoue, J. Quantum Electron. **28**, 883 (1992); C. McKinstrie, Opt. Express **12**, 2033 (2004), M. Marhic, J. Opt. Soc. Am. B **20**, 2425 (2003); C. McKinstrie, Opt. Express **14**, 8516 (2006).]

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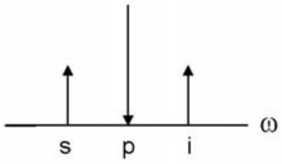
Tunable radiation generation (MI)

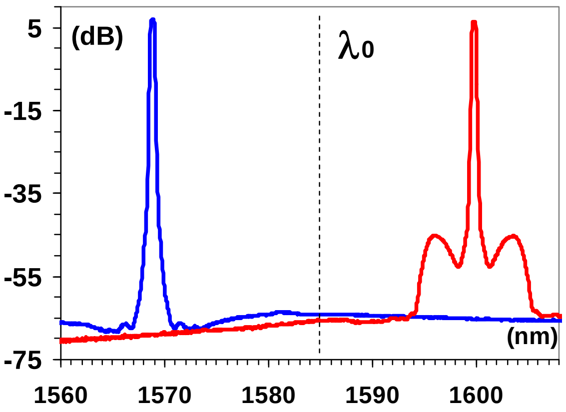


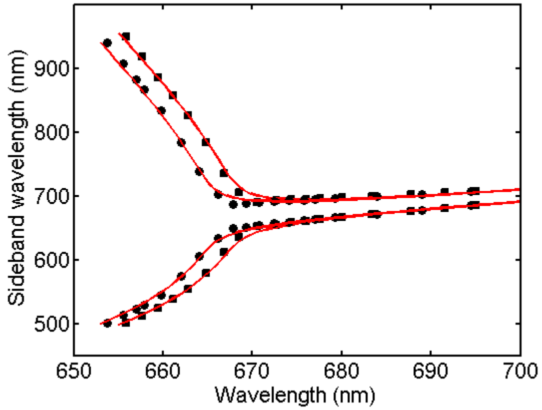
- MI is driven by pump-induced nonlinearity and suppressed by dispersion- and pump-induced wavenumber mismatch: $k_{MI} = [\delta_t^2 - (\gamma P)^2]^{1/2}$, where $\delta_t = \delta_l + \gamma P$ and $\delta_l = (\beta_s + \beta_i)/2 - \beta_p$.
- Instability occurs when $-2\gamma P < \delta_l < 0$.
- Low-frequency branch: $\delta_l \approx \beta_2\omega^2/2$

  ($\beta_2 < 0$ and $\omega^2 \approx 2\gamma P/|\beta_2|$).

  Dispersion compensates nonlinearity.
- High-frequency branch: $\delta_l \approx \beta_2\omega^2/2 + \beta_4\omega^4/24$ ($\beta_2\,\beta_4 < 0$ and $\omega^2 \approx 12|\beta_2/\beta_4|$).

  Dispersion compensates dispersion.
- The coefficients β_2 and β_4 can be positive or negative. (PC and BS are similar.)



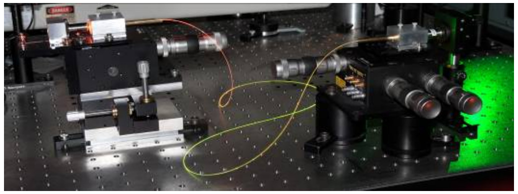


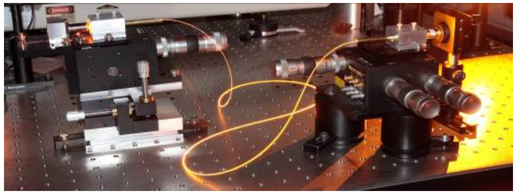
[J. Harvey, Opt. Lett. **28**, 2225 (2003); M. Hirano, J. Sel. Top. Quant. Elect. **15**, 103 (2009).]

OPO based on photonic-crystal fiber

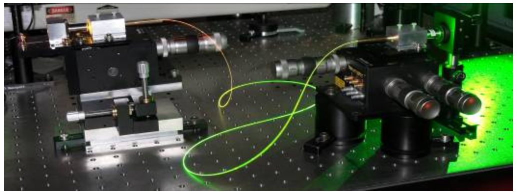
THE UNIVERSITY OF AUCKLAND

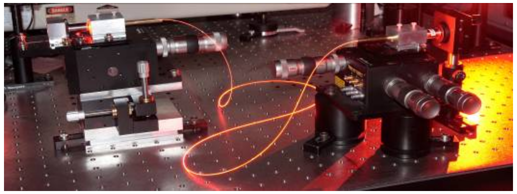
- Singly-resonant OPO: PCF (l = 1.3 m, γ = 110/Km-W), pulsed pump (τ = 8 ps, $\lambda \approx$ 710 nm, P > 15 W), dichroic mirrors. Frequency shifts from 20 – 170 THz.
- Performance was limited by pump-sideband walk-off.

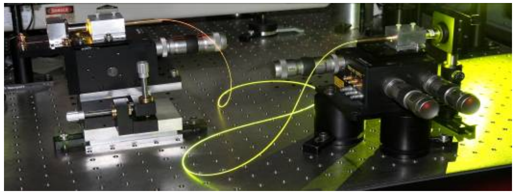


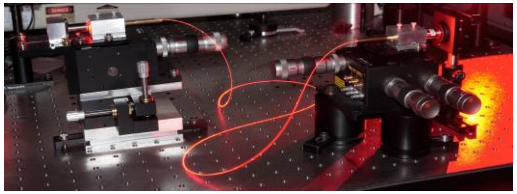


(aS: 510-690 nm)

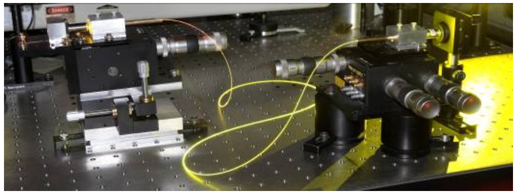






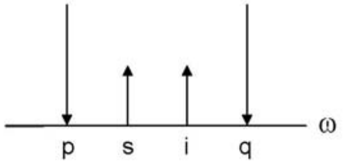


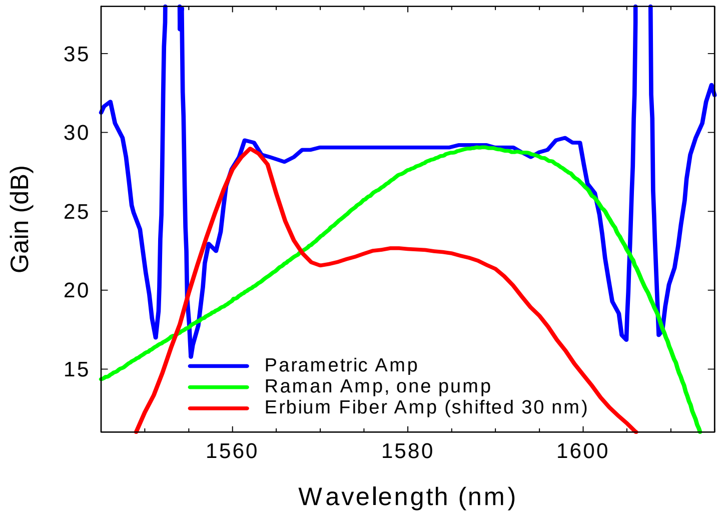
(S: 770–1150 nm)

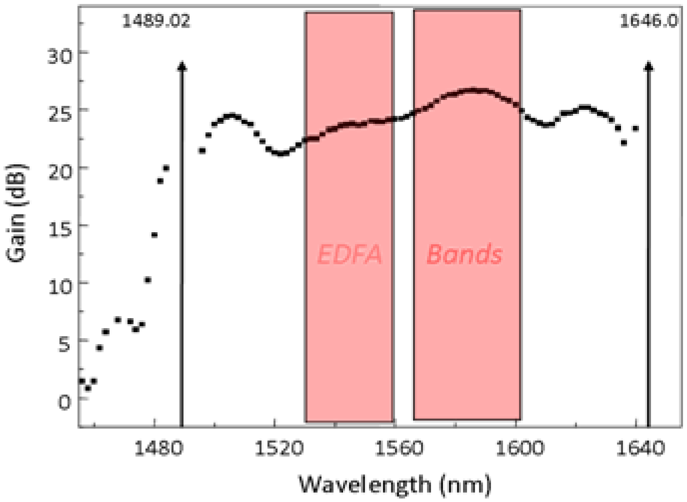


[Y. Xu, Opt. Lett. **33**, 1351 (2008); S. Murdoch, CLEO-E, paper CD3.4 (2009).]

Broad-bandwidth amplification (PC)







- Parametric amplifiers have broader gain bandwidths than their competitors.
- The current record bandwidth is 150 nm (signal plus idler).
- Perpendicular pumps provide signal-polarization-independent gain.
- Standard system with 128 channels at 10 Gb/s requires 51 nm bandwidth.
- Latest system (AL 1830) with 88 channels at 100 Gb/s requires 35 nm.

[R. Jopson (2004); J. Chavez Boggio, Photon. Technol. Lett. **21**, 612 (2009).]

Phase conjugation can reduce impairments significantly

- Pulse propagation is governed by the NS equation

$$-i\partial_z A = \beta\partial_{tt} A/2 + \gamma |A|^2 A$$

- The conjugate amplitude satisfies the conjugate equation

$$i\partial_z A^* = \beta\partial_{tt} A^*/2 + \gamma |A|^2 A^*$$

- For deterministic evolution (no random source terms) in an ideal system (no loss or odd-order dispersion), phase conjugation reverses the sense of propagation ($z \rightarrow -z$).
- Propagation reversal reduces dispersive and nonlinear (SPM, CPM and FWM) impairments simultaneously!

[B. Y. Zeldovich, Sov. Phys. JETP **15**, 109 (1972); O. Y. Nosach, Sov. Phys. JETP **16**, 435 (1972); A. Yariv, J. Opt. Soc. Am. **66**, 301 (1976); R. W. Hellwarth, J. Opt. Soc. Am. **67**, 1 (1977).]

How does dispersion compensation by PC work?

- Let ω_0 be the carrier frequency of a pulse (relative to ω_a) and suppose that

  $\beta(\omega_0+\omega) \approx \beta_0(\omega_0) + \beta_1(\omega_0)\omega + \beta_2(\omega_0)\omega^2/2$.

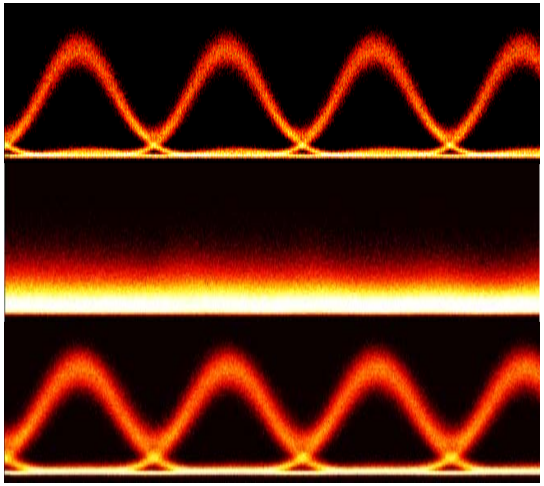
- If the input amplitude $A(t,0) = \exp(-t^2/2\tau_0^2)$, the output amplitude

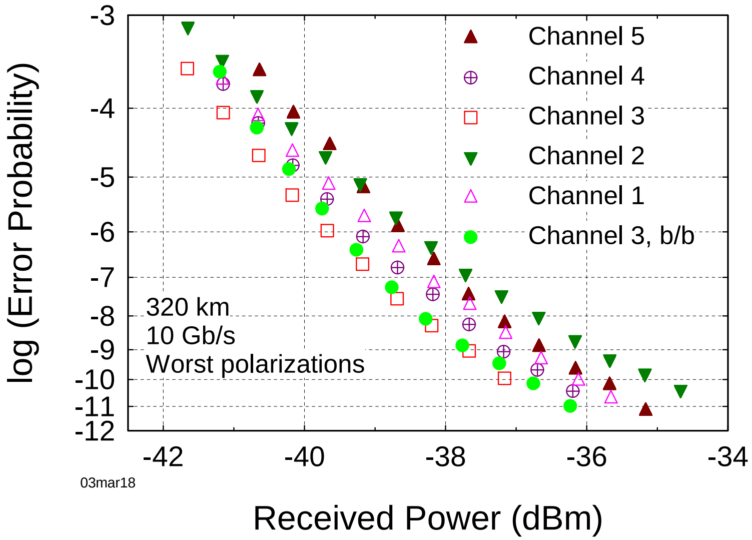
  $A(t,z) = \exp[i\beta_0 z - (t - \beta_1 z)^2/2(\tau_0^2 - i\beta_2 z)]/(1 - i\beta_2 z/\tau_0^2)^{1/2}$,

  $\tau^2(z) = \tau_0^2 + (\beta_2 z)^2/\tau_0^2$.

- Suppose that a PC is placed at a distance z_c. Then the output (Fourier) amplitude $A(-\omega_0-\omega,z) = A^*(\omega_0+\omega,0)\exp[i\beta(-\omega_0-\omega)(z-z_c) - i\beta(\omega_0+\omega)z_c]$.
  - 0th order: $\beta_0(-\omega_0)(z-z_c) - \beta_0(\omega_0)z_c \rightarrow$ overall phase
  - 1st order: $-[\beta_1(-\omega_0)(z-z_c) + \beta_1(\omega_0)z_c]\omega \rightarrow$ time delay
  - 2nd order: $[\beta_2(-\omega_0)(z-z_c) - \beta_2(\omega_0)z_c]\omega^2 \rightarrow$ pulse broadening
- If $\beta_2(-\omega_0) \approx \beta_2(\omega_0)$, $z_c \approx z/2$ restores the pulse width (undoes dispersion).
- D chirps pulse: fast ω at front, slow ω at back. PC reverses chirp: fast at back, slow at front. D unchirps pulse: fast move forward, slow move back.

Impairment reduction by phase conjugation

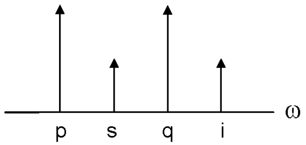




- Phase conjugation (PC) reverses the sense of propagation: dispersing pulses compress and growing distortions shrink!
- Single-channel dispersion compensation (DC) was demonstrated at 640 Gb/s (100 Km) and multiple-channel DC was demonstrated at 10 Gb/s (320 Km).
- PC also reduces impairments caused by nonlinear processes. Experiments were done with realistic 10-Gb/s links (10,000 Km).

[S. Radic, OFC 2003, PDP 12; S. Jansen, JLT **24**, 54 (2006), P. Minzioni, PTL **18**, 995 (2006); E. Myslivets, OFC 2010, PDP C6.]

Tunable wavelength conversion (BS)



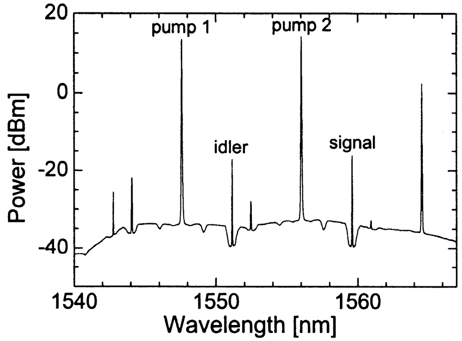
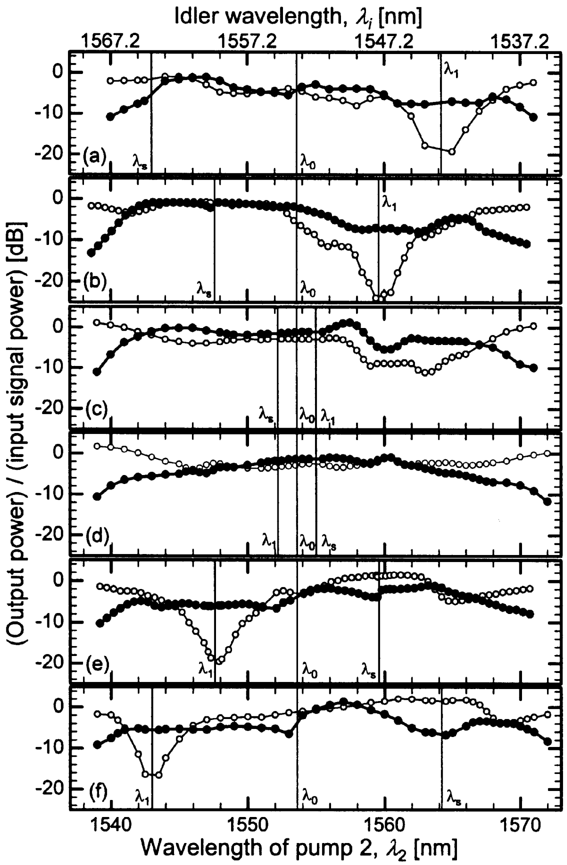


Fig. 2. Example of the optical power spectrum observed at the output of HNL-DSF (Resolution = 0.01 nm).

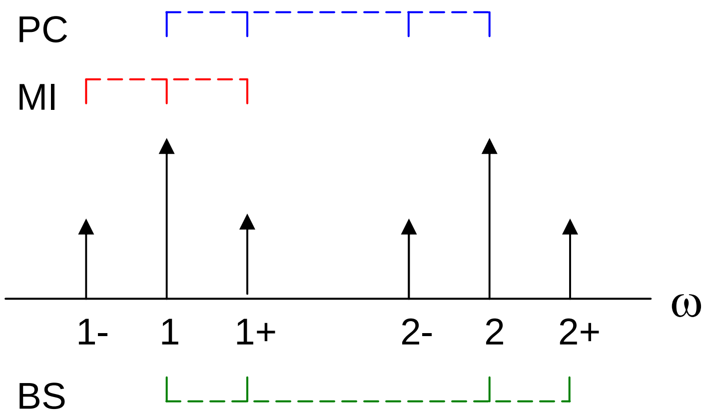


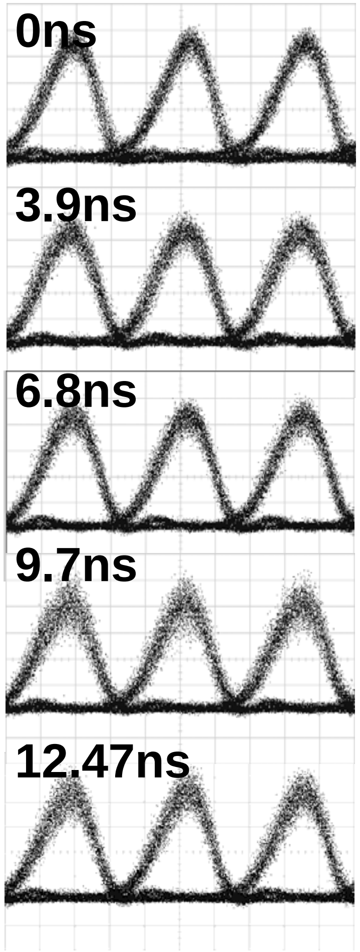
- By fixing λ_1 and λ_s, and varying λ_2, one varies λ_i (oppositely).

- A tuning range of 30 nm was demonstrated using parallel pumps.

[K. Inoue, JLT **12**, 1423 (1994); T. Tanemura, PTL **16**, 551 (2004).]

Optical buffer based on FC and dispersion





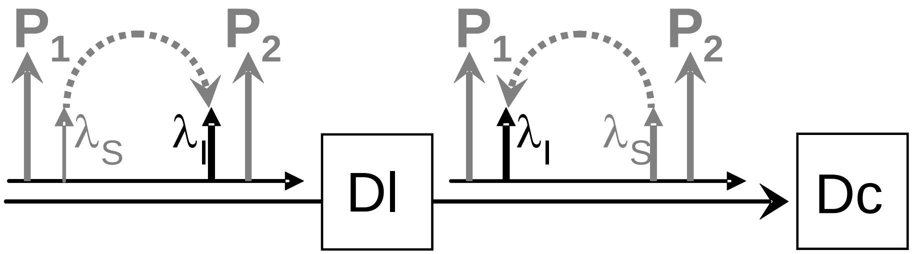
- MI, PC and BS all produce idlers that are FC copies of the signal.
- Because $\omega_i \neq \omega_s$, propagation through a dispersive medium delays (or advances) the idler relative to the signal ($\delta t = \beta_2 z \delta\omega$).
- Bit-level optical buffering is possible!
- Goal: Delays of $10^3 - 10^4$ bit slots.

[M. Burzio, Proc. ECOC, 581 (1994); S. Radic, PTL **16**, 852 (2004); J. Sharping, OE **13**, 7872 (2005); J. Ren, ECOC, paper Th4.4.3 (2006).]

Dispersion enables and limits the delays!

UCSD

- Inter-channel dispersion delays the idlers: $\delta t = \beta_2 z \delta\omega$.
- Intra-channel dispersion broadens the idlers: $\tau^2(z) = \tau_0^2 + (\beta_2 z)^2/\tau_0^2$.
- The spreading condition $\beta_2 z/\tau_0^2 < 1$ implies that $\delta t/\tau_0 < \delta\omega\tau_0$.
- The maximal delay decreases as the bit rate increases (problematic).
- For two fibers without/with PC in between, $\tau^2(z) = \tau_0^2 + (\beta_a z_1 \pm \beta_b z_2)^2/\tau_0^2$.
- If β_a > 0, the pulse acquires a positive chirp as it spreads (fast ω_- at the front, slow ω_+ at the back). PC inverts the frequencies. If β_b > 0, slow ω_+ at the front and fast ω_- at the back result in compression.



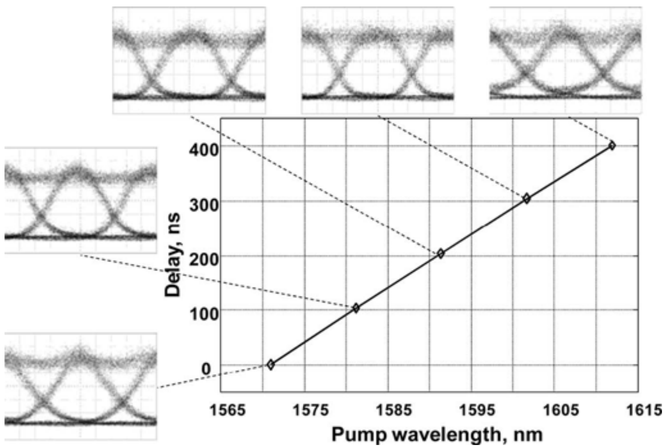
- Because the second idler is the PC of the first, Dc = Dl (re-use).

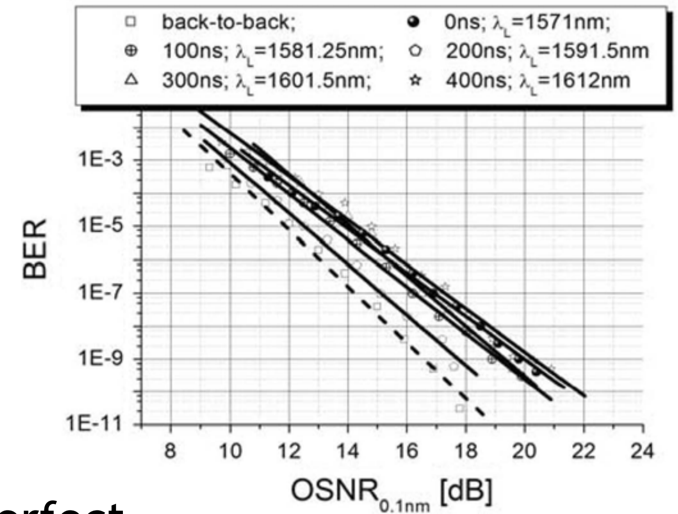
[J. Ren, ECOC, paper Th4.4.3 (2006); N. Alic, JSTQE **14**, 681 (2008).]

Significant delays were demonstrated

UCSD

- Signals were FC by a PC process, passed through a DCF (delay), back-FC by the same PC process and sent through the same DCF (compensation).
- Continuously-tunable delays from 0 – 400 ns were demonstrated at 10 Gb/s.



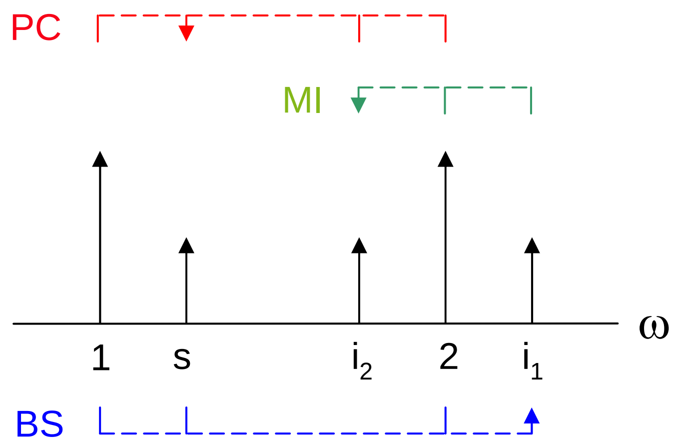


- Problem: $\beta_2(\omega_s) \neq \beta_2(\omega_i)$, so DC is imperfect.
- Namiki and Kurosu developed a better dispersion-compensation method.
- Delays of 0 – 1.8 μs at 10 Gb/s (1.6 μs at 40 Gb/s) were demonstrated.

[E. Myslivets, Photon. Technol. Lett. **21**, 251 (2009); S. Namiki, J. Lightwave Technol. **26**, 28 (2008); T. Kurosu, OFC, paper OMH2 (2009); N. Alic, OFC, paper PDPA1 (2009).]

Namiki dispersion-compensation scheme

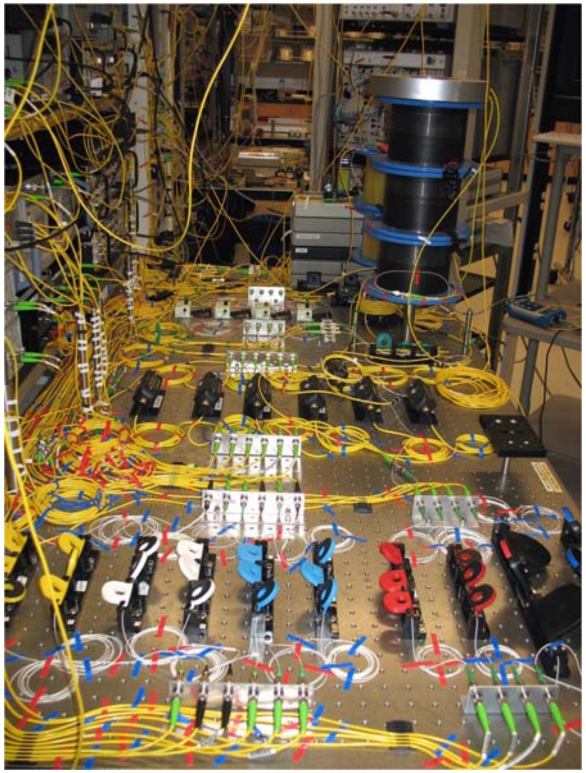
UCSD

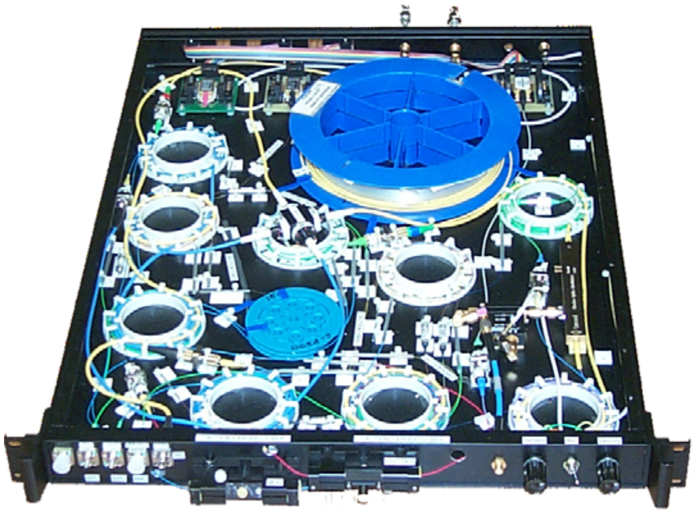


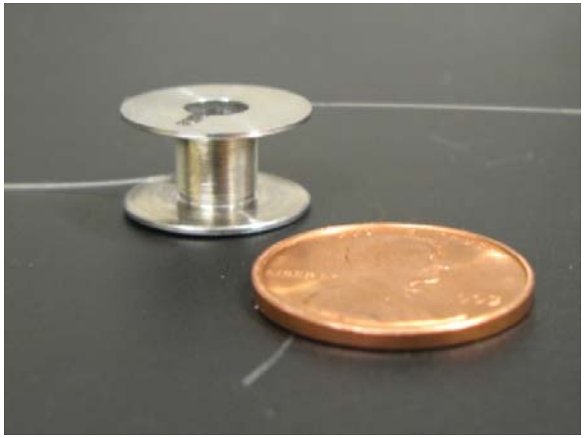
- Because of third-order dispersion, $\beta_2(\omega_i) \neq \beta_2(\omega_s)$, so DC is imperfect.
- UCSD version of this scheme was implemented in delay experiments.
- Use BS to generate a direct idler at $\omega_{i1} >> \omega_s$ and delay idler.
- Use MI to generate a conjugate idler at $\omega_{i2} \approx \omega_{i1}$, so that $\beta_2(\omega_{i2}) \approx \beta_2(\omega_{i1})$.
- Use the same delay element to DC the idler (and delay it more).
- Use PC to generate a conjugate^2 (direct) idler at ω_s.

[S. Namiki, J. Lightwave Technol. **26**, 28 (2008); T. Kurosu, OFC, paper OMH2 (2009); E. Myslivets, Opt. Express **17**, 11958 (2009).]

The incredible shrinking amplifier







(a) optical table (b) pizza box
(c) micro-coil

Summary 1

- Parametric (four-wave-mixing) processes in highly-nonlinear fibers (MI, PC and BS) are driven by pump-induced nonlinearity and inhibited by fiber dispersion.
- These processes enable a variety of optical signal-processing functions.
- Several applications relevant to optical communication systems were described: amplification, frequency conversion (with or without amplification), impairment reduction by phase conjugation and buffering (controlled delaying).
- Other applications include amplitude and phase regeneration, and stroboscopic and real-time sampling . . .

[C. McKinstrie, Opt. Photon. News **18** (3), 34 (2007).]