Self-Phase Modulation in Optical Fiber Communications: Good or Bad?

Govind P. Agrawal

Institute of Optics
University of Rochester
Rochester, NY 14627

◀◀
▶▶
◀
▶
Back
Close

Outline

- Historical Introduction
- Self-Phase Modulation and its Applications
- Modulation Instability and Optical Solitons
- Optical Switching using Fiber Interferometers
- Cross-Phase Modulation and its Applications
- Impact on Optical Communication Systems
- Concluding Remarks

Back
Close

Historical Introduction

- Celebrating 40th anniversary of Self-Phase Modulation (SPM):
  F. Demartini et al., Phys. Rev. 164, 312 (1967);
  F. Shimizu, PRL 19, 1097 (1967).
- Pulse compression though SPM was suggested by 1969:
  R. A. Fisher and P. L. Kelley, APL 24, 140 (1969)
- First observation of optical Kerr effect inside optical fibers:
  R. H. Stolen and A. Ashkin, APL 22, 294 (1973).
- SPM-induced spectral broadening in optical fibers:
  R. H. Stolen and C. Lin Phys. Rev. A 17, 1448 (1978).
- Prediction and observation of solitons in optical fibers:
  A. Hasegawa and F. Tappert, APL 23, 142 (1973);
  Mollenauer, Stolen, and Gordon, PRL 45, 1095 (1980).

◀◀
▶▶
◀
▶
Back
Close

Self-Phase Modulation

- Refractive index depends on optical intensity as (Kerr effect)

$$n(\omega, I) = n_0(\omega) + n_2 I(t).$$

- Intensity dependence leads to nonlinear phase shift

$$\phi_{\mathrm{NL}}(t) = (2\pi/\lambda) n_2 I(t) L.$$

- An optical field modifies its own phase (SPM).
- Phase shift varies with time for pulses.
- Each optical pulse becomes chirped.
- As a pulse propagates along the fiber, its spectrum changes because of SPM.

◀◀
▶▶
◀
▶
Back
Close

Nonlinear Phase Shift

- Pulse propagation governed by Nonlinear Schrödinger Equation

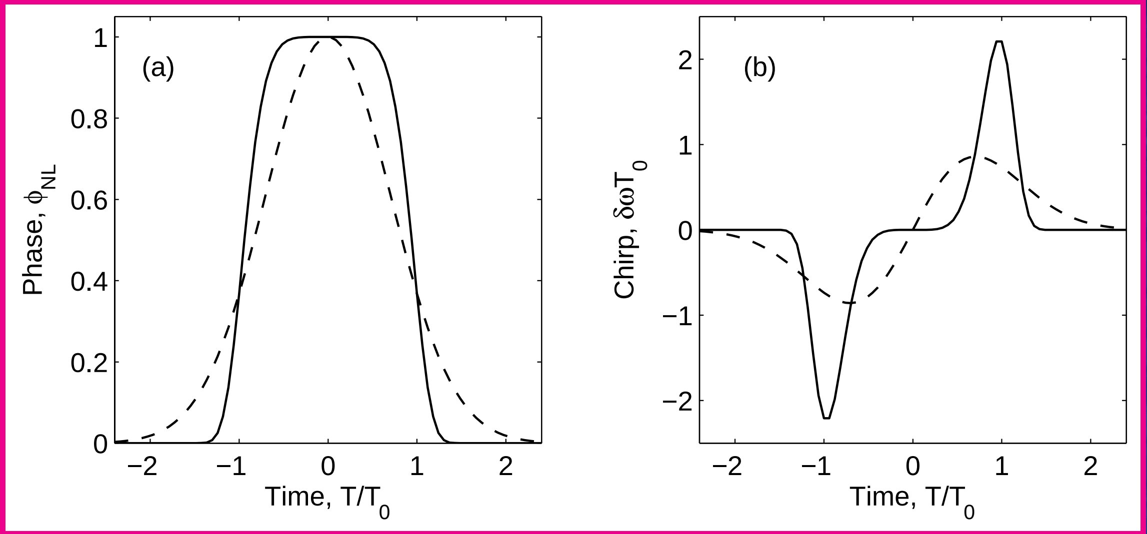
$$i\frac{\partial A}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \gamma|A|^2 A = 0.$$

- Dispersive effects within the fiber included through β_2.
- Nonlinear effects included through $\gamma = 2\pi n_2/(\lambda A_{\text{eff}})$.
- If we ignore dispersive effects, solution can be written as

$$A(L,t) = A(0,t)\exp(i\phi_{\text{NL}}), \quad \text{where} \quad \phi_{\text{NL}}(t) = \gamma L|A(0,t)|^2.$$

- Nonlinear phase shift depends on input pulse shape.
- Maximum Phase shift: $\phi_{\max} = \gamma P_0 L = L/L_{\text{NL}}$.
- Nonlinear length: $L_{\text{NL}} = (\gamma P_0)^{-1}$.

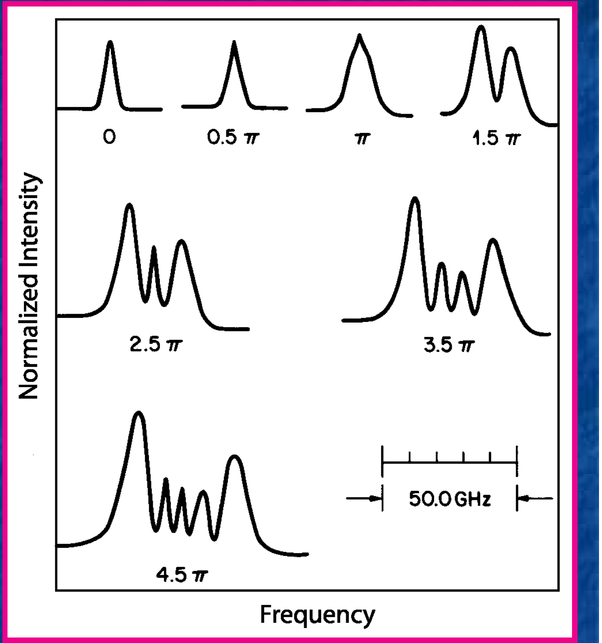
SPM-Induced Chirp



- Super-Gaussian pulses: $P(t) = P_0 \exp[-(t/T)^{2m}]$.
- Gaussian pulses correspond to the choice $m = 1$.
- Chirp is related to the phase derivative $d\phi/dt$.
- SPM creates new frequencies and leads to spectral broadening.

SPM-Induced Spectral Broadening

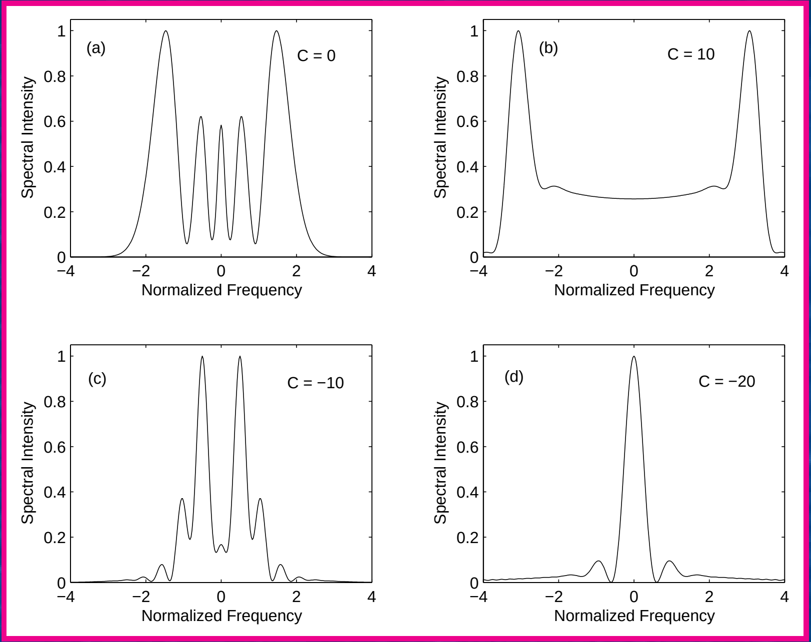
- First observed inside fibers by Stolen and Lin (1978).
- 90-ps pulses transmitted through a 100-m-long fiber.
- Spectra are labelled using $\phi_{\max} = \gamma P_0 L$.
- Number M of spectral peaks: $\phi_{\max} = (M - \frac{1}{2})\pi$.



- Output spectrum depends on shape and chirp of input pulses.
- Even spectral compression can occur for suitably chirped pulses.

Back
Close

SPM-Induced Spectral Narrowing



- Chirped Gaussian pulses with $A(0,t) = A_0 \exp[-\frac{1}{2}(1+iC)(t/T_0)^2]$.
- If $C < 0$ initially, SPM produces spectral narrowing.

SPM: Good or Bad?

- SPM-induced spectral broadening can degrade performance of a lightwave system.
- Modulation instability often enhances system noise.

On the positive side . . .

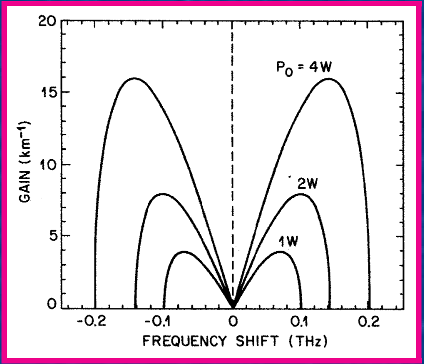
- Modulation instability can be used to produce ultrashort pulses at high repetition rates.
- SPM often used for fast optical switching (NOLM or MZI).
- Formation of standard and dispersion-managed optical solitons.
- Useful for all-optical regeneration of WDM channels.
- Other applications (pulse compression, chirped-pulse amplification, passive mode-locking, etc.)

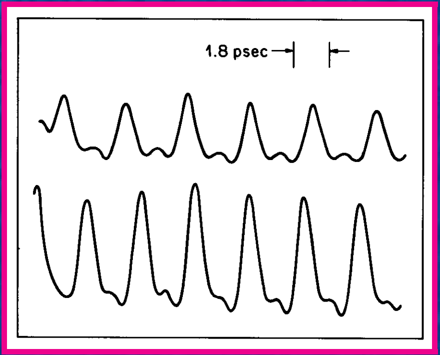
◀◀
▶▶
◀
▶
Back
Close

Modulation Instability

Nonlinear Schrödinger Equation

$$i\frac{\partial A}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \gamma|A|^2 A = 0.$$



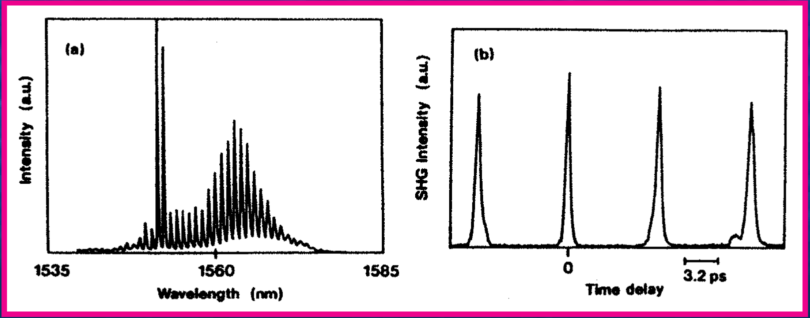


- CW solution unstable for anomalous dispersion $(\beta_2 < 0)$.
- Useful for producing ultrashort pulse trains at tunable repetition rates [Tai et al., PRL 56, 135 (1986); APL 49, 236 (1986)].

Back
Close

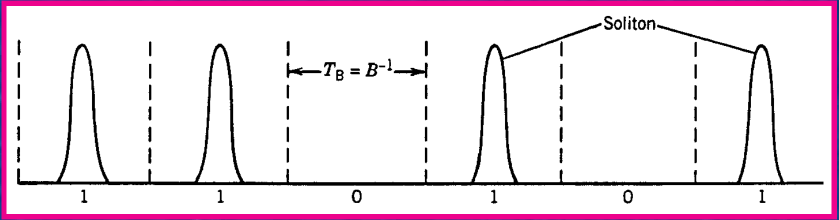
Modulation Instability

- A CW beam can be converted into a pulse train.
- Two CW beams at slightly different wavelengths can initiate modulation instability and allow tuning of pulse repetition rate.
- Repetition rate is governed by their wavelength difference.
- Repetition rates ∼100 GHz realized by 1993 using DFB lasers (Chernikov et al., APL 63, 293, 1993).



Optical Solitons

- Combination of SPM and anomalous GVD produces solitons.
- Solitons preserve their shape in spite of the dispersive and nonlinear effects occurring inside fibers.
- Useful for optical communications systems.



- Dispersive and nonlinear effects balanced when $L_{\mathrm{NL}} = L_D$.
- Nonlinear length $L_{\mathrm{NL}} = 1/(\gamma P_0)$; Dispersion length $L_D = T_0^2/|\beta_2|$.
- Two lengths become equal if peak power and width of a pulse satisfy $P_0 T_0^2 = |\beta_2|/\gamma$.

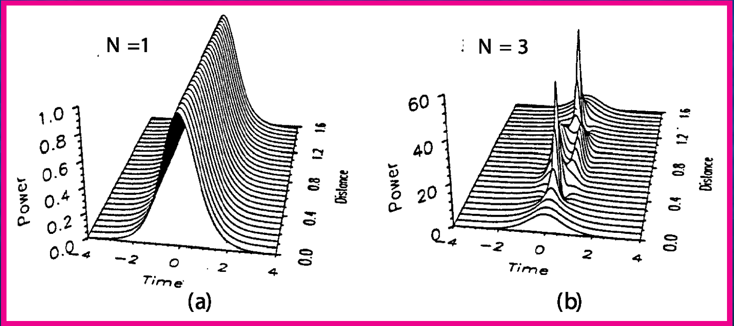
◀◀
▶▶
◀
▶
Back
Close

Fundamental and Higher-Order Solitons

- NLS equation: $i\frac{\partial A}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \gamma|A|^2 A = 0.$
- Solution depends on a single parameter: $N^2 = \frac{\gamma P_0 T_0^2}{|\beta_2|}.$
- Fundamental $(N = 1)$ solitons preserve shape:

$$A(z,t) = \sqrt{P_0}\,\mathrm{sech}(t/T_0)\exp(iz/2L_D).$$

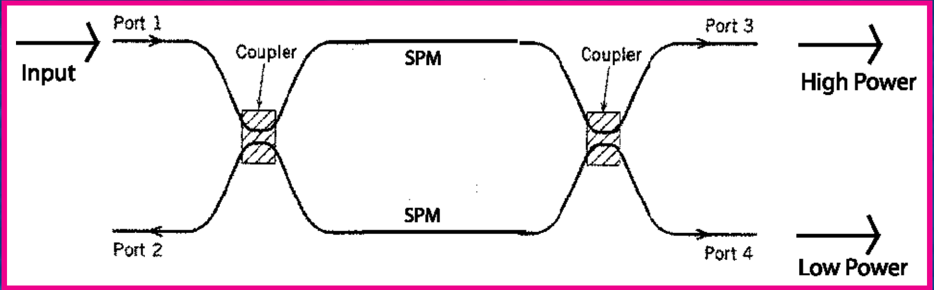
- Higher-order solitons evolve in a periodic fashion.



(a) (b)

Back
Close

Optical Switching



- A Mach-Zehnder interferometer (MZI) made using two 3-dB couplers exhibits SPM-induced optical switching.

- In each arm, optical field accumulates linear and nonlinear phase shifts.

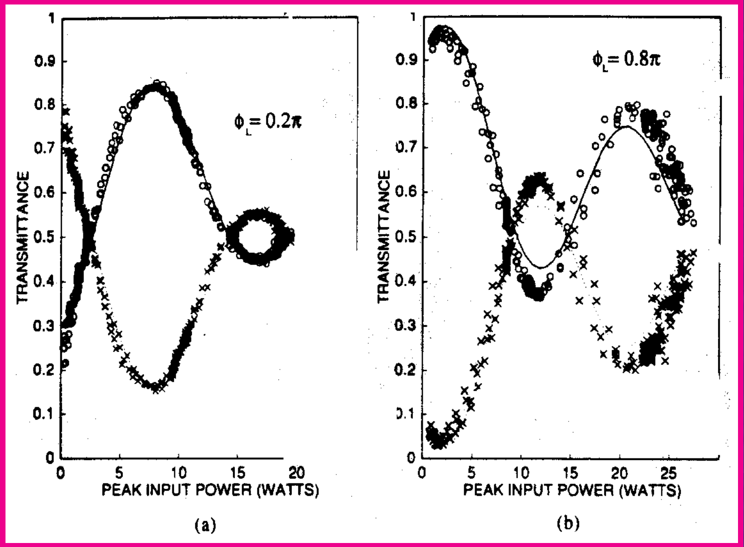
- Transmission through the bar port of MZI:

$$T = \sin^2(\phi_L + \phi_{\rm NL}); \qquad \phi_{\rm NL} = (\gamma P_0/4)(L_1 - L_2).$$

- T changes with input power P_0 in a nonlinear fashion.

Back
Close

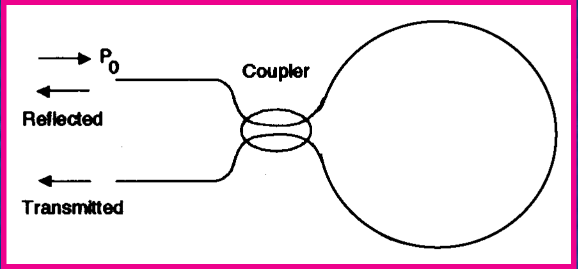
Optical Switching (continued)

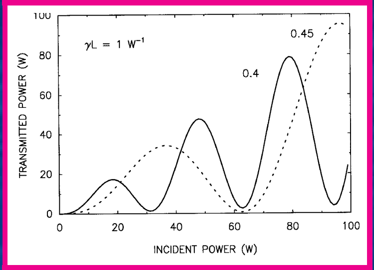


(a) (b)

- Experimental demonstration around 1990 by several groups (Nayar et al., Opt. Lett. 16, 408, 1991).
- Switching requires long fibers and high peak powers.
- Required power is reduced for highly nonlinear fibers (large γ).

Nonlinear Optical-Loop Mirror





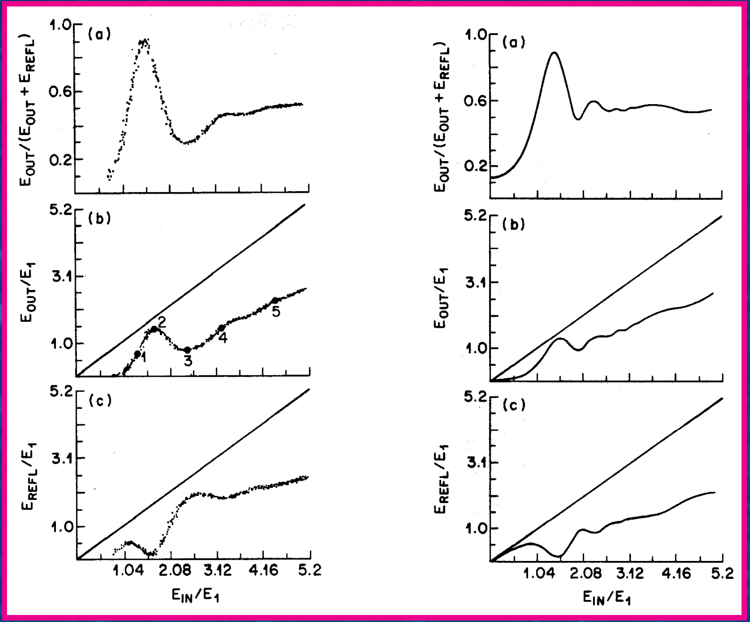
- An example of the Sagnac interferometer.
- Transmission through the fiber loop:

$$T = 1 - 4f(1-f)\cos^2[(f-\tfrac{1}{2})\gamma P_0 L].$$

- $f =$ fraction of power in the CCW direction.
- $T = 0$ for a 3-dB coupler (loop acts as a perfect mirror)
- Power-dependent transmission for $f \neq 0.5$.

◀◀
▶▶
◀
▶
Back
Close

NOLM Switching (continued)



- Experimental demonstration using ultrashort optical pulses (Islam et al., Opt. Lett. 16, 811, 1989).
- $T_0 = 0.3$ ps, $E_0 = 33$ pJ, $f = 0.52$, 100-m loop.

Cross-Phase Modulation

- Consider two optical fields propagating simultaneously.
- Nonlinear refractive index seen by one wave depends on the intensity of the other wave as

$$\Delta n_{\mathrm{NL}} = n_2(|A_1|^2 + b|A_2|^2).$$

- Total nonlinear phase shift in a fiber of length L:

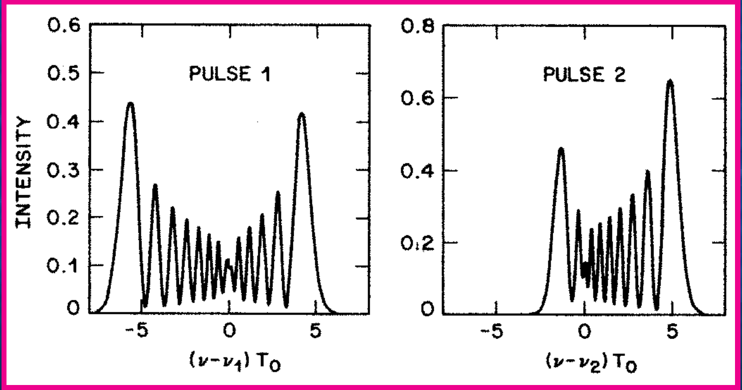
$$\phi_{\mathrm{NL}} = (2\pi L/\lambda) n_2[I_1(t) + bI_2(t)].$$

- An optical beam modifies not only its own phase but also of other copropagating beams (XPM).
- XPM induces nonlinear coupling among overlapping optical pulses.

Back
Close

XPM-Induced Chirp

- Fiber dispersion affects the XPM considerably.
- Pulses belonging to different WDM channels travel at different speeds.
- XPM occurs only when pulses overlap.
- Asymmetric XPM-induced chirp and spectral broadening.



XPM: Good or Bad?

- XPM leads to interchannel crosstalk in WDM systems.
- It can produce amplitude and timing jitter.

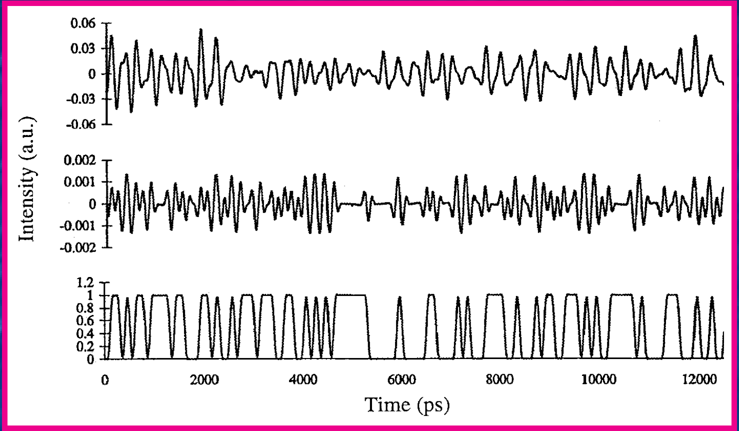
On the other hand . . .

XPM can be used beneficially for

- Nonlinear Pulse Compression
- Passive mode locking
- Ultrafast optical switching
- Demultiplexing of OTDM channels
- Wavelength conversion of WDM channels

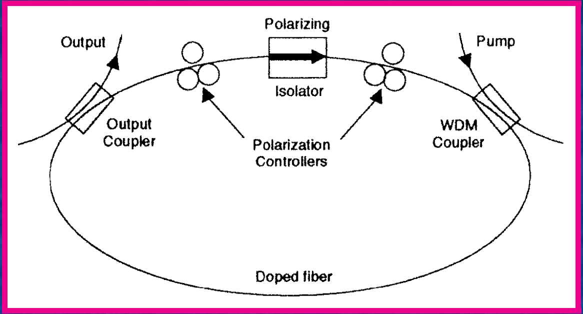
◀◀
▶▶
◀
▶
Back
Close

XPM-Induced Crosstalk



- A CW probe propagated with 10-Gb/s pump channel.
- Probe phase modulated through XPM.
- Dispersion converts phase modulation into amplitude modulation.
- Probe power after 130 (middle) and 320 km (top) exhibits large fluctuations (Hui et al., JLT, 1999).

XPM-Induced Mode Locking

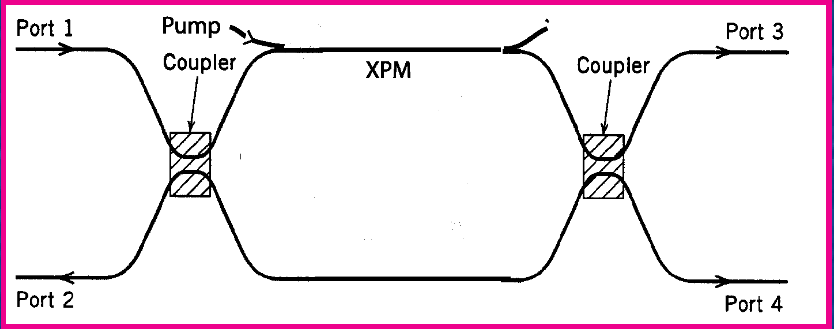


- Different nonlinear phase shifts for the two polarization components: nonlinear polarization rotation.

$$\phi_x - \phi_y = (2\pi L/\lambda)n_2[(I_x + bI_y) - (I_y + bI_x)].$$

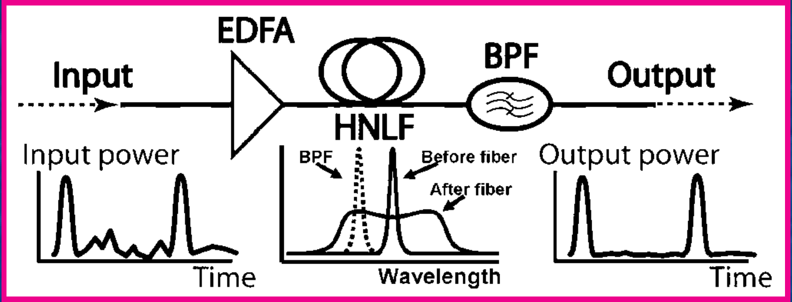
- Pulse center and wings develop different polarizations.
- Polarizing isolator clips the wings and shortens the pulse.
- Can produce ~100 fs pulses.

XPM-Induced Switching



- A Mach–Zehnder or Sagnac interferometer can be used.
- Output switched to a different port using a control signal that shifts the phase through XPM.
- If control signal is in the form of a pulse train, a CW signal can be converted into a pulse train.
- Ultrafast switching time (<1 ps).

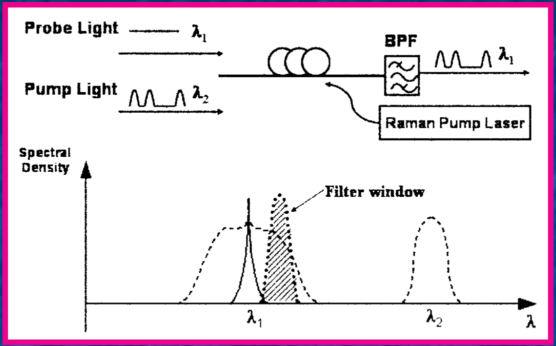
SPM-Based 2R Optical Regenerator



Rochette et al., IEEE J. Sel. Top. Quantum Electron. 12, 736 (2006).

- SPM inside a highly nonlinear fiber broadens channel spectrum.
- Optical filter selects a dominant spectral peak.
- Noise in "0 bit" slots is removed by the filter.
- Noise in "1 bit" slots is reduced considerably because of a step-like transfer function.

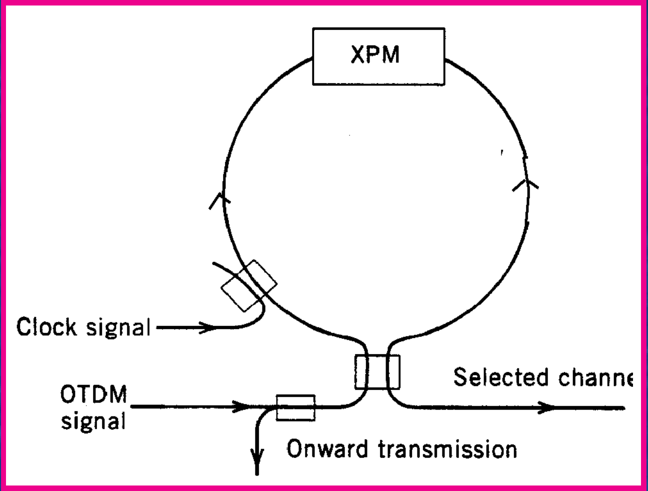
XPM-Based Wavelength Converter



Wang et al., IEEE J. Lightwave Technol. **23**, 1105 (2005).

- WDM channel at λ_2 requiring conversion acts as a pump.
- A CW probe is launched at the desired wavelength λ_1.
- Probe spectrum broadens because of pump-induced XPM.
- An optical filter blocks pump and transfers data to probe.
- Raman amplification improves the device performance.

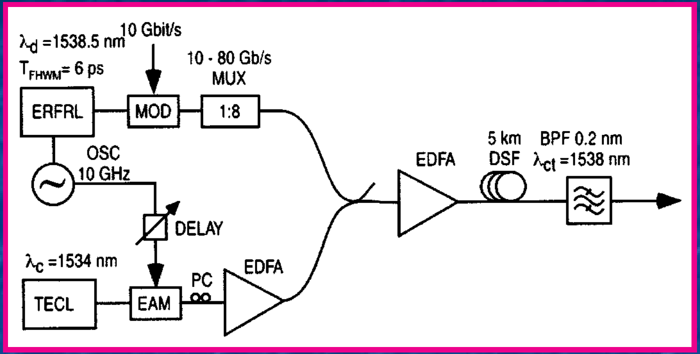
XPM-Induced Demultiplexing



- XPM can be used to demultiplex Optical TDM channels.
- Control Clock is a pulse train at single-channel bit rate.
- Only pulses overlapping with the clock pulses are transmitted by the nonlinear optical loop mirror.

Back
Close

XPM-Induced Demultiplexing



Olsson and Blumenthal, IEEE Photon. Technol. Lett. **13**, 875 (2001).

- Use of a Sagnac interferometer is not necessary.
- Configuration similar to the wavelength-conversion scheme.
- A pulse train at the single-channel bit rate acts as the pump.
- Only pulses overlapping with the pump pulses experience XPM and are transmitted by the optical filter.

Back
Close

Concluding Remarks

- SPM and XPM are feared by telecom system designers because they can affect system performance adversely.
- Fiber nonlinearities can be managed thorough proper system design.
- SPM and XPM are useful for many device and system applications: optical switching, soliton formation, wavelength conversion, all-optical regeneration, demultiplexing, etc.
- Photonic crystal and other microstructured fibers have been developed for enhancing the nonlinear effects.
- Non-silica fibers (chalcogenides, Bismuth oxide, etc.) are also useful for enhancing the nonlinear effects.
- SPM and XPM effects in such highly nonlinear fibers are likely to find new applications.

◀◀
▶▶
◀
▶
Back
Close