# All-Optical Signal Processing and Optical Regeneration

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# Outline

- Introduction
- Major Nonlinear Effects in Optical Fibers
- Ultrafast Optical Switching Techniques
- Wavelength Conversion of WDM channels
- High-Speed Optical Signal Processing
- All-optical Regeneration Schemes
- Concluding Remarks

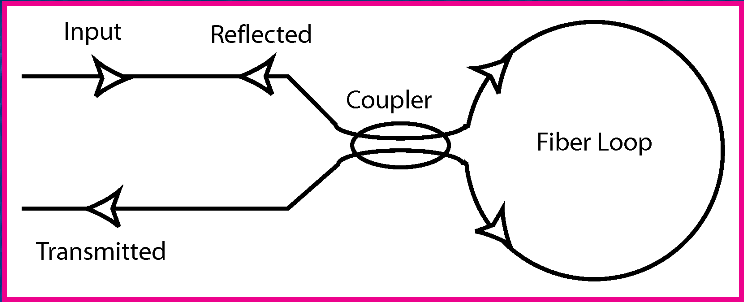
# Introduction

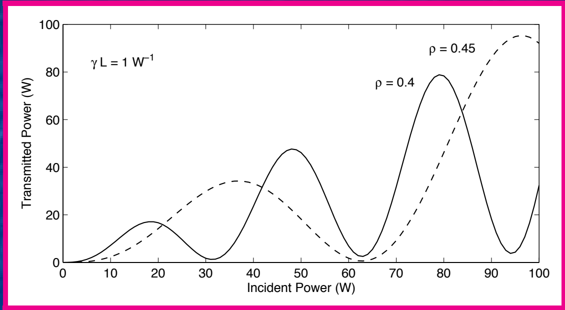
- Nonlinear effects inside optical fibers can be used for high-speed processing of optical signals.
- Ultrafast optical switching demonstrated as early as 1989 using a nonlinear fiber-loop mirror.
- The required loop length and input power depend on the nonlinear parameter $[\gamma = 2\pi n_2/(\lambda A_{\text{eff}})]$.
- Both can be reduced by employing highly nonlinear fibers with $\gamma > 10$ W$^{-1}$/km.
- High-speed switching possible because of the non-resonant nature of fiber nonlinearity.
- Useful for a variety of signal-processing applications.

# Optical Switching Techniques

- An interferometer (Mach–Zehnder or Sagnac type) is often employed in practice.
- Self-Phase Modulation (SPM) can be used for power-dependent transmission of an input signal.
- Cross-Phase Modulation (XPM) allows better control of switching using suitable control pulses.
- Four-Wave Mixing (FWM) provides parametric gain and creates new wavelengths only over the duration of pump pulses.
- All of them exploited for telecom applications such as wavelength conversion, channel demultiplexing, data-format conversion, and all-optical regeneration.

# Nonlinear Fiber-Loop Mirrors



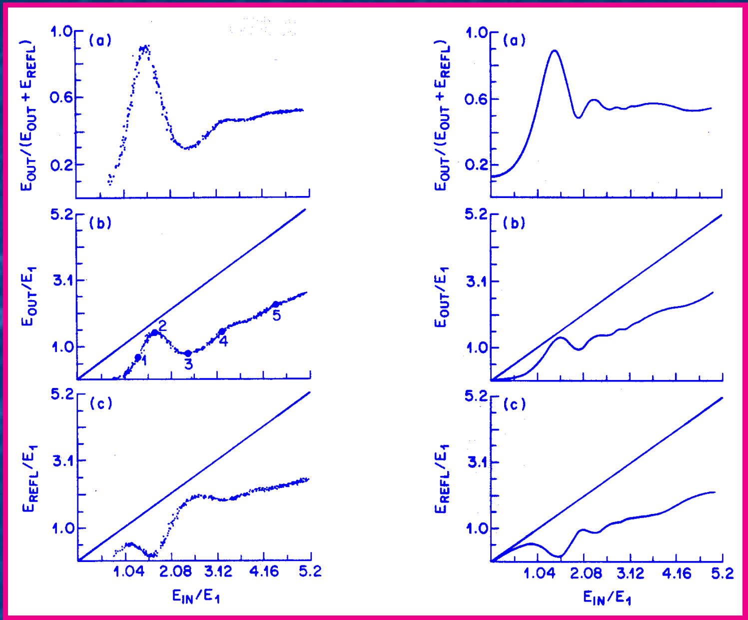




- An example of the Sagnac interferometer.
- Transmissivity depends on the SPM-induced phase shift:

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

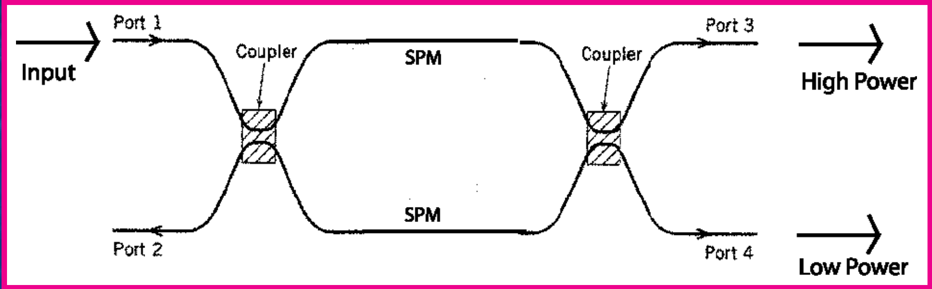
- $f$ is fraction of power diverted to coupler's cross port.
- $T = 0$ for a 3-dB coupler (loop acts as a perfect mirror).
- Power-dependent transmission for $f \neq 0.5$.

# Soliton Switching




- Experimental demonstration using 300-fs optical pulses (Islam et al., Opt. Lett. **16**, 811, 1989).
- 100-m-long Sagnac loop with $f = 0.52$ was employed.

# Mach–Zehnder interferometers

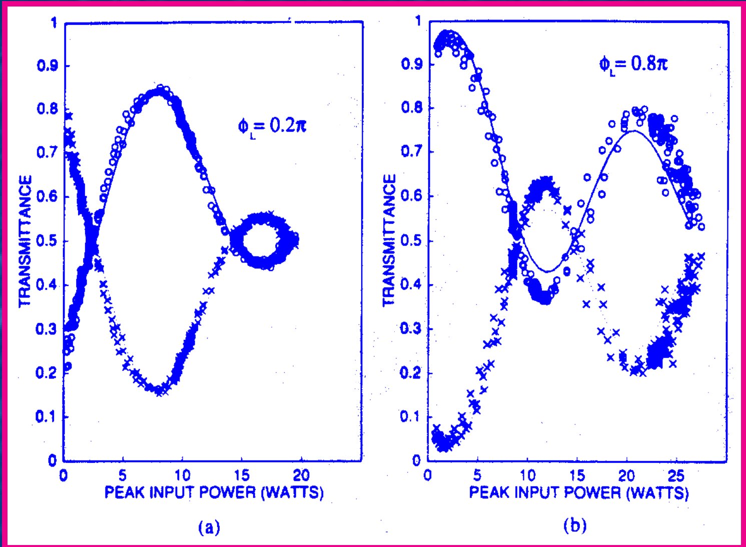



- A Mach–Zehnder interferometer (MZI) made using two 3-dB couplers exhibits SPM-induced optical switching.
- Optical field accumulates linear and nonlinear phase shifts in each MZI arm.
- Transmission through the bar port of MZI is given by

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

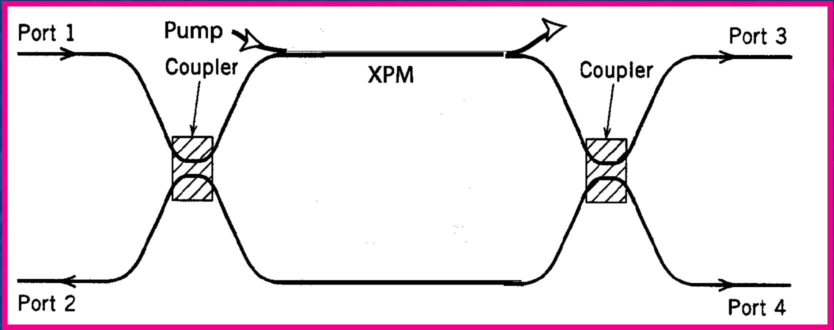
- $T$ changes considerably with input power $P_0$.

# SPM-Based Switching



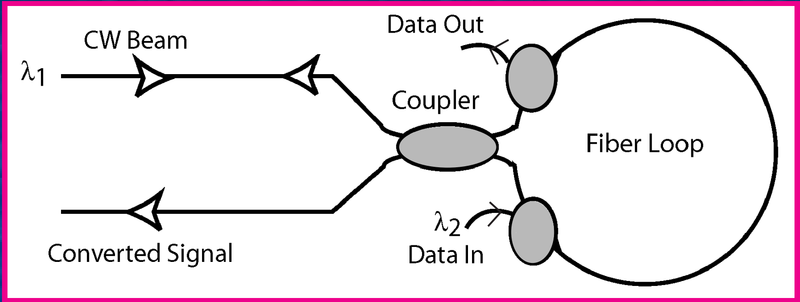

- Experimental demonstration around 1990 by several groups (Nayar et al., Opt. Lett. 16, 408, 1991).
- Switching required long fibers and high peak powers.
- Required power is reduced for highly nonlinear fibers (large $\gamma$).

# XPM-Induced Switching




- A Mach–Zehnder or a 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.
- Switching time is limited by the walk-off effects.

# XPM-Based Wavelength Converters




- Data pulses impose XPM-induced phase shift only in one direction.
- Walk-off effects result from group-velocity mismatch:

$$\frac{\partial A_1}{\partial z} + \frac{i\beta_{21}}{2}\frac{\partial^2 A_1}{\partial T^2} = i\gamma_1(|A_1|^2 + 2|A_2|^2)A_1$$

$$\frac{\partial A_2}{\partial z} + d_w\frac{\partial A_2}{\partial T} + \frac{i\beta_{22}}{2}\frac{\partial^2 A_2}{\partial T^2} = i\gamma_2(|A_2|^2 + 2|A_1|^2)A_2.$$

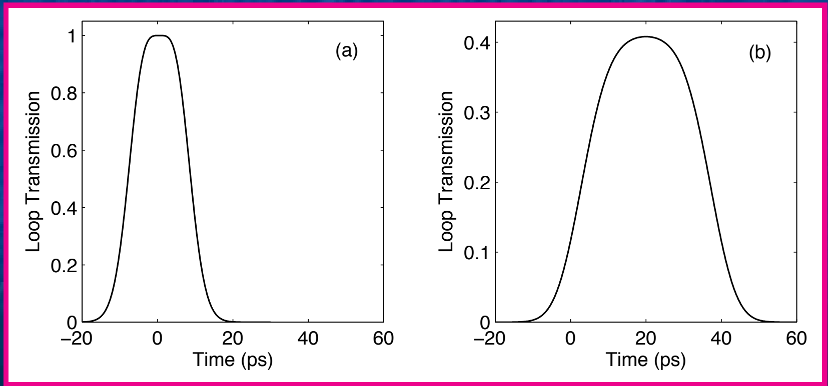
- Group-velocity mismatch governed by $d_w = 1/v_{g1} - 1/v_{g2}$.

# XPM-Induced Switching Window

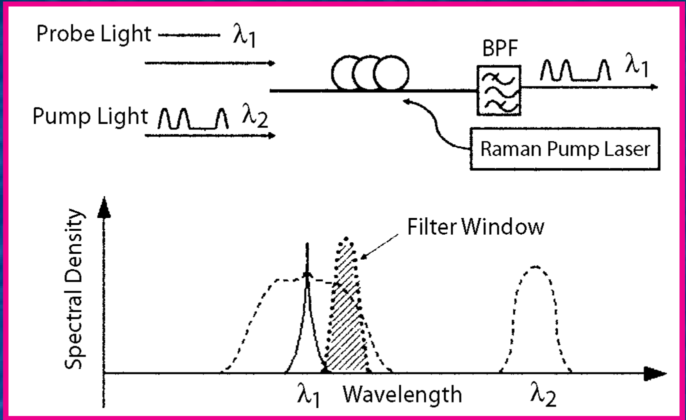
- XPM-induced phase shift for Gaussian pulses (FWHM $= 1.66T_0$):

$$\phi_1(T) = \phi_{\max}\frac{\sqrt{\pi}T_0}{T_W}\left[\operatorname{erf}\left(\frac{T}{T_0}\right) - \operatorname{erf}\left(\frac{T-T_W}{T_0}\right)\right].$$

- Total time delay $T_W = d_w L$ for a loop of length $L$.
- (a) $T_0 = 10$ ps, $T_W = 2$ ps and (b) $T_0 = 10$ ps, $T_W = 40$ ps.



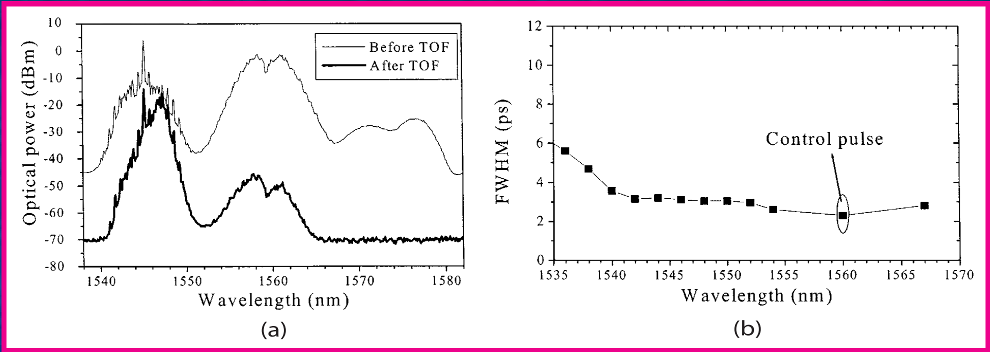
# Filter-Based Wavelength Converters




Wang et al., IEEE JLT **23**, 1105 (2005)

- This technique does not require an interferometer.
- Spectrum of a CW probe broadens because of pump-induced XPM.
- An optical filter blocks the pump and transfers data to probe.
- Raman amplification improves the device performance.

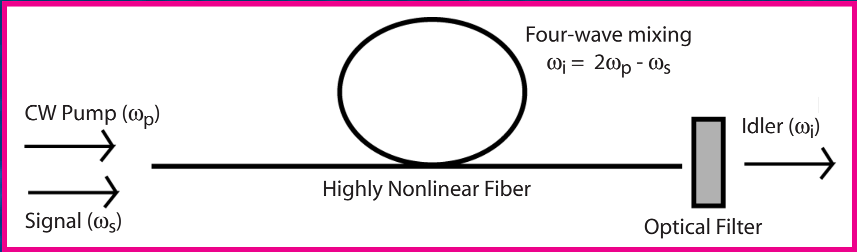
# Experimental Results




J. Yu et al., IEEE Photon. Technol. lett. **13**, 833 (2001)

- Wavelength conversion at 80 Gb/s using a 1-km-long fiber with $\gamma = 11\ \mathrm{W}^{-1}/\mathrm{km}$ and a 1.5-nm-bandwidth tunable optical filter.
- Wavelength conversion at 160 Gb/s realized by 2004 [Rau et al., IEEE PTL **16**, 2520 (2004)].
- Raman gain can be used to improve the conversion efficiency [Wang et al., IEEE JLT **23**, 1105 (2005)].

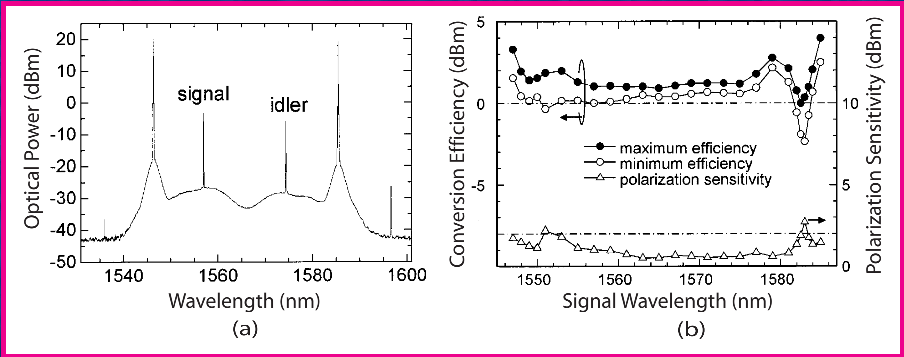
# FWM-Based Wavelength Converters




- Parametric amplification (FWM) of a signal bit stream inside an optical fiber.
- Signal amplification is accompanied by generation of an idler wave at $\omega_i = 2\omega_p - \omega_s$.
- The idler mimics the bit pattern of the signal precisely because FWM occurs only during temporal slices allocated to 1 bits.
- An optical filter blocks the pump and original signal but passes the idler at the new wavelength.

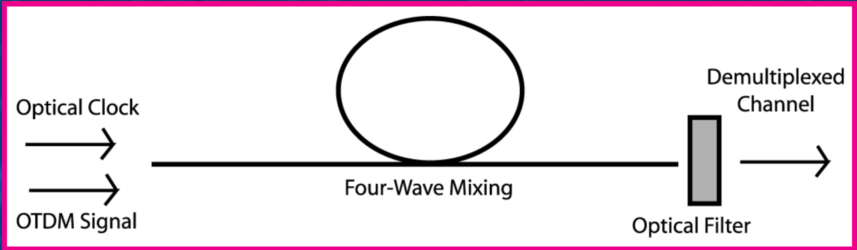
# Dual-Pump Wavelength Converters

- Dual-pump configuration can provide nearly uniform parametric gain over a wide bandwidth.
- It also allows polarization-independent operation of the device.
- (a) Output spectrum and (b) conversion efficiency of a dual-pump wavelength converter made with 1-km-long fiber ($\gamma = 18\ \mathrm{W}^{-1}/\mathrm{km}$).




T. Tanemura et al., IEEE PTL **15**, 1573 (2003)

# FWM-Based Demultiplexing

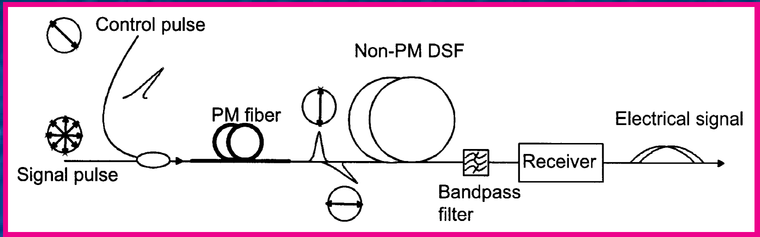



- FWM is used Often for demultiplexing a single channel from an OTDM bit stream.
- Optical clock (a pulse train at the single-channel bit rate) acts as the pump for FWM.
- Idler pulses are created in only those time slots in which the signal and pump pulses are present simultaneously.
- Optical filter blocks pump and signal pulses, resulting in an output that belongs to a specific channel at the idler wavelength.

# FWM-Based Demultiplexing

- FWM was used for demultiplexing as early as 1991.
- By 1996, demultiplexing of a 500-Gb/s OTDM bit stream was demonstrated using clock pulses of 1-ps duration.
- An advantage of using FWM is that the demultiplexed channel is also amplified through FWM inside the same fiber.
- A problem with FWM-based demultiplexers is related to polarization sensitivity of the FWM process itself.
- A polarization-diversity scheme was used as early as 1993 [T. Hasegawa et al., IEEE PTL **5**, 947 (1993)].
- A simpler implementation of this scheme was adopted in 2004.

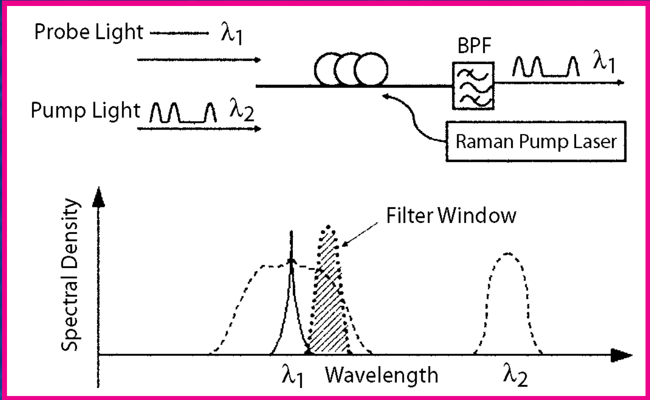
# FWM-Based Demultiplexing




Sakamoto et al., IEEE PTL **16**, 563 (2004)

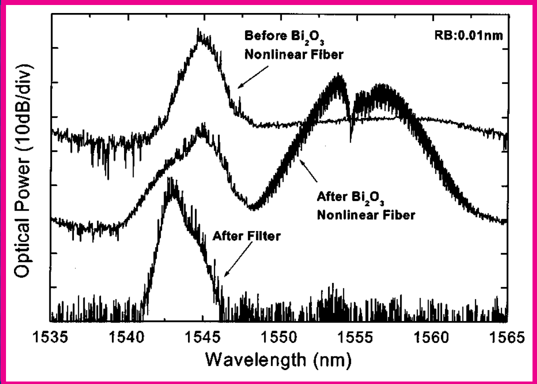
- A short piece of polarization-maintaining (PM) fiber attached to the input port of a highly nonlinear fiber.
- Control clock pulses are polarized at 45°.
- PM fiber splits the control and signal pulses into two parts.
- Polarization diversity is realized within the same nonlinear fiber.
- Demultiplexing a 160-Gb/s bit stream into 10-Gb/s channels was realized with <0.5 dB polarization sensitivity.

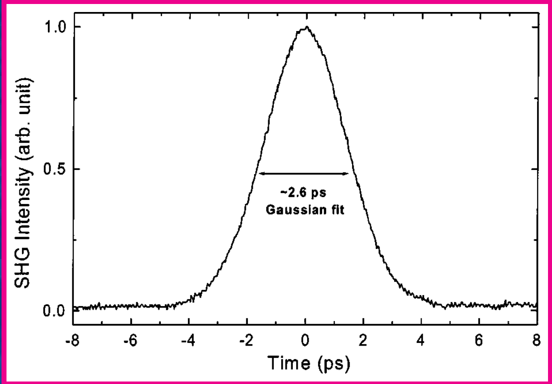
# XPM-Based Demultiplexing




- XPM can also be used for demultiplexing OTDM channels.
- This scheme is similar to that used for wavelength conversion.
- OTDM signal acts as a probe, while intense clock pulses at $\lambda_2$ play the role of the pump.
- Clock pulses shift the spectrum through XPM.
- An optical filter is used to select these pulses.

# XPM-Based Demultiplexing



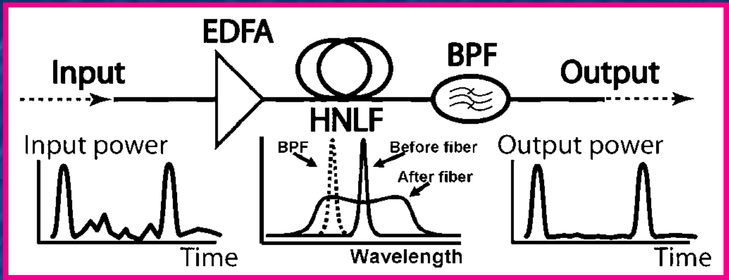

Lee et al., Opt. Lett. **30**, 1267 (2005)

- A 1-m-long piece of bismuth-oxide fiber was used in a 2005 experiment for demultiplexing a 160-Gb/s bit stream ($\gamma \sim 1100$ W$^{-1}$/km).
- 3.5-ps control pulses at 10 GHz were amplified to ensure $\gamma P_0 L \approx 10$ even for a 1-m-long fiber.
- Measured switching window was relatively narrow.

# All-Optical Regeneration

- Optical signal is degraded considerably during its propagation inside the fiber link.
- Optical amplifiers can be used to manage fiber losses, but they degrade the signal by adding ASE noise and timing jitter.
- An optical regenerator transforms the degraded bit stream into its original form by performing three functions known as Reamplification, Reshaping, and Retiming.
- Such devices are referred to as "3R regenerators."
- Devices that perform only reamplification and reshaping are called 2R regenerators.
- Many nonlinear techniques have been developed that make use of SPM, XPM, and FWM.

# SPM-Based 2R Regenerators




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.
- Basic idea proposed by Mamyshev in 1998.

# Simple Theory

- If we neglect dispersion, only phase is affected by SPM:

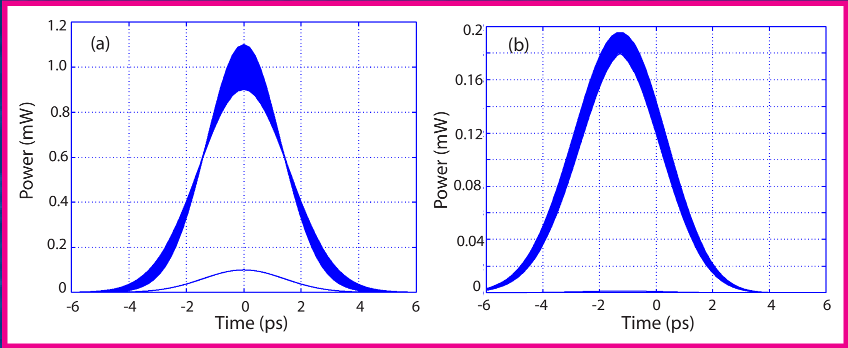
$$U(L,t) = U(0,t)\exp[i\gamma P_0 L|U(0,t)|^2].$$

- Optical filter acts in the spectral domain:

$$U_f(t) = \mathscr{F}^{-1}\big(H_f(\omega-\omega_f)\mathscr{F}[U(L,t)]\big).$$

- Regenerator performance depends mainly on two parameters: $\phi_{\rm NL} \equiv \gamma P_0 L$ and filter offset $\omega_f$.
- Optimum value of $\phi_{\rm NL}$ is close to $3\pi/2$ because spectrum then exhibits two peaks with a sharp dip at the original wavelength.
- Optimum value of filter offset is around $\omega_f = 3/T_0$ for Gaussian pulses with $P(t) = P_0\exp(-t^2/T_0^2)$.

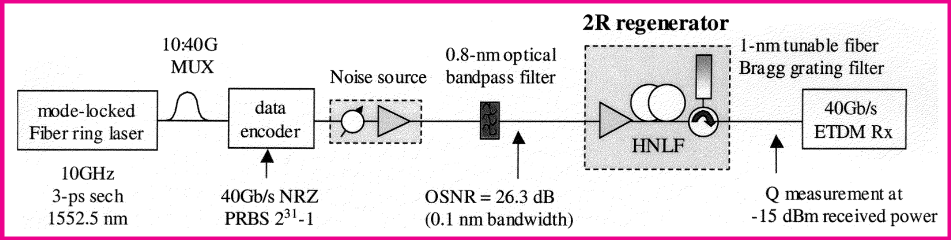
# Numerical Simulations




Johannisson et al., IEEE PTL **17**, 2667 (2005)

- 160-Gb/s bit stream was used with 2-ps-wide Gaussian pulses.
- Peak power of each input pulse varied by up to 10%.
- Noise in "0 bit" slots removed completely by the filter.
- Noise in peak power of 1 bits is reduced from 10% to 4.6% because of a step-like transfer function.

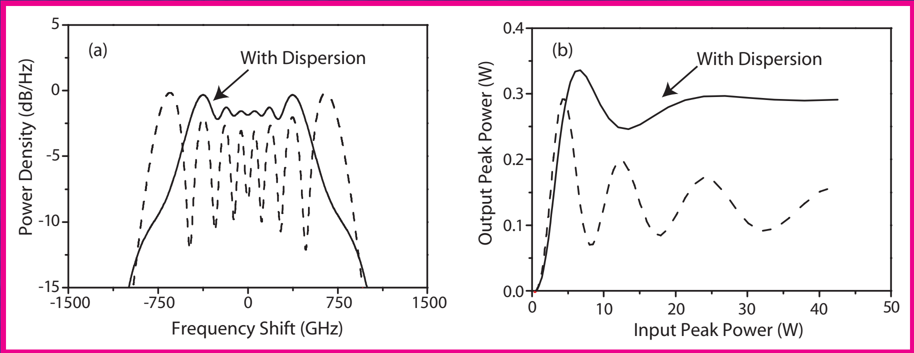
# Experimental Results




Her et al., IEEE PTL **16**, 200 (2004)

- SPM-based regenerator operating at 40 Gb/s with 8.25-ps pulses.
- Regenerator consists of an EDFA, a 2.5-km-long fiber, and a 1-nm-bandwidth tunable filter (a fiber grating).
- Input power must be optimized in practice.
- Dispersive effects within the fiber cannot be ignored.
- Operation in the normal-dispersion regime is desirable.

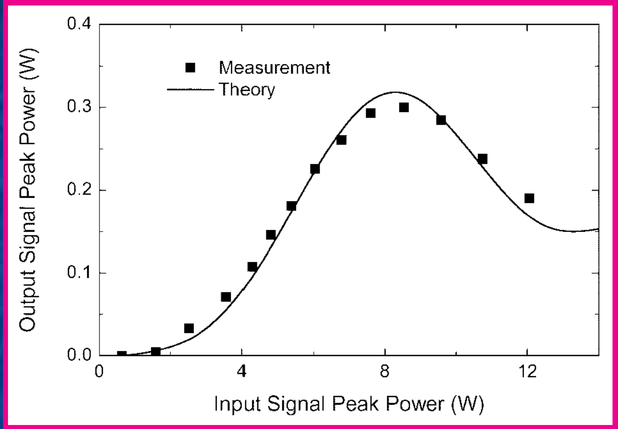
# Chalcogenide fibers




Fu et al., Opt. Express **13**, 7637 (2005)

- A 2.8-m-long chalcogenide fiber used in a 2005 experiment. Large value of $\gamma$ (1200 $W^{-1}$/km) reduced the peak power to $\sim$1 W.
- Fiber exhibited large normal dispersion ($\beta_2 > 600$ ps$^2$/km).
- It helped performance by reducing the dispersion length.
- Even two-photon absorption helped in this experiment.

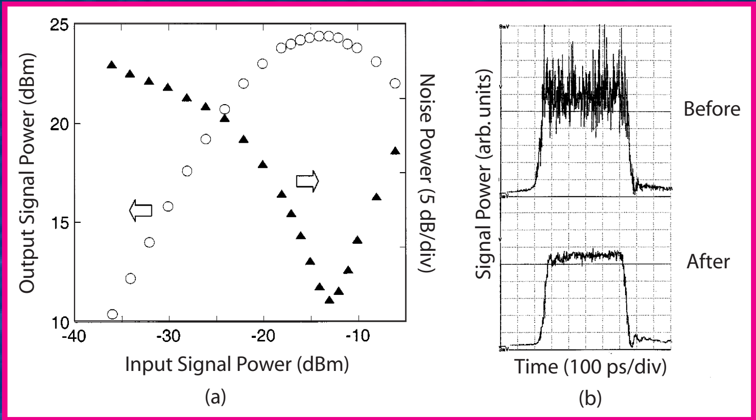
# Bismuth-Oxide fibers




Lee et al., IEEE PTL **18**, 1296 (2006)

- A 1-m-long bismuth-oxide fiber was used in a 2006 experiment.
- Fiber exhibited high normal dispersion ($\beta_2 > 330$ ps$^2$/km).
- Measured power-transfer function agreed well with theory.

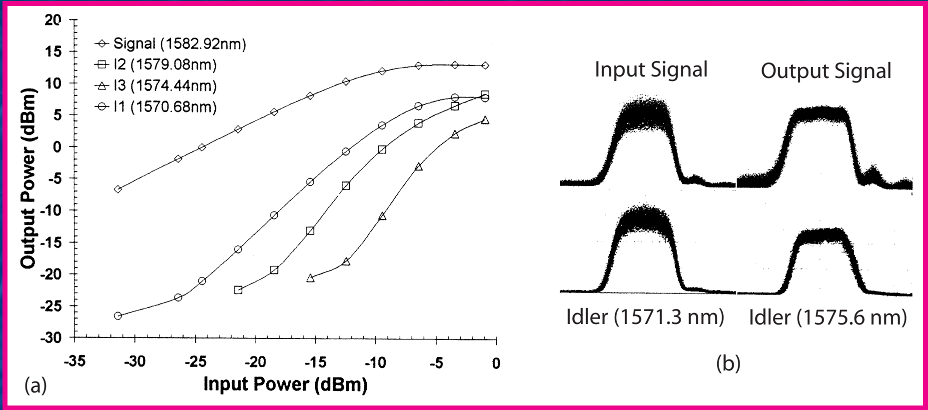
# FWM-Based 2R Regenerators




Inoue and Mukai, IEEE JLT **20**, 969 (2002)

- Gain of any amplifier saturates for large signal powers.
- Because of gain saturation, fluctuations in peak power of a pulse are reduced by a large factor.
- Figure shows improvement realized for a 2.5-km-long fiber pumped with 500-ps pulses (peak power 1.26 W).

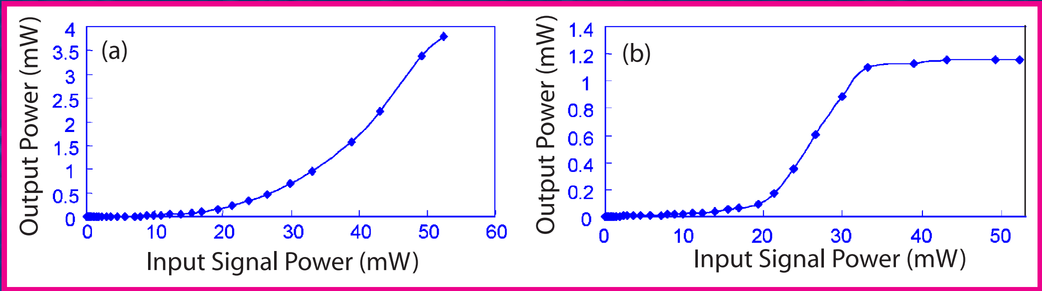
# FWM-Based 2R Regenerators




Radic et al., IEEE PTL **15**, 957 (2003)

- Parametric amplifiers display a nonlinear transfer function.
- Dual pumps create multiple idlers (wavelength multicasting).
- All idlers carry signal information with less noise.
- Useful to regenerate copies of the signal at different wavelengths.

# FWM-Based 2R Regenerators




Yamashita et al., IEEE PTL **18**, 1054 (2006)

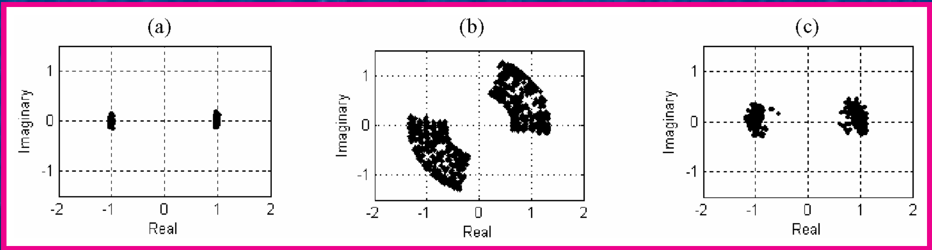
- Performance of FWM-based regenerators can be improved by cascading two parametric amplifiers in series.
- The output of first amplifier is filtered to select an idler.
- Transfer functions for the first and second stages are shown.
- Notice the improved step-like response for this scheme.

# Regenerations of DPSK Signals

- DPSK format codes data in phase difference of two neighboring bits.
- Any optical regenerator for DPSK signals should not change this phase difference.
- Combination of soliton effects, saturable absorption, and narrow-band filtering can be used to reduce amplitude noise and reshape pulses without affecting their phase.
- FWM can also be used by operating a parametric amplifier in the saturation regime if pump phase does not change much over two bit durations.
- These schemes reduce amplitude noise of RZ pulses (while preserving their phases) but they do not reduce phase noise.

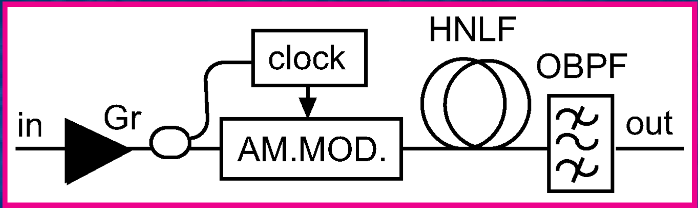
# Regenerations of DPSK Signals

- Phase noise can be reduced using phase-sensitive amplification inside a Sagnac interferometer.
- A 6-km-long Sagnac loop was employed to provide >13 dB of phase-sensitive gain at a pump power of 100 mW .
- The extent of improvement is evident in constellation diagrams.
- Both the amplitude and phase noise are reduced significantly: (a) No noise, (b) with noise, and (c) phase-sensitive amplification.




Croussore et al., Opt. Express **14**, 2085 (2006)

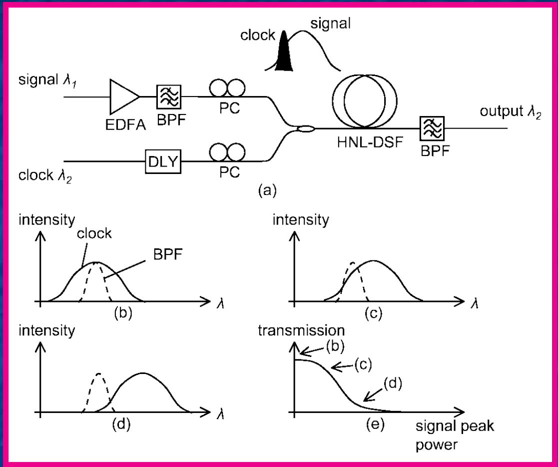
# Optical 3R Regenerators




M. Matsumoto, IEEE JLT **22**, 1472 (2004)

- 3R regenerators perform retiming function and reduce timing jitter.
- An SPM-based 3R regenerator can be built by adding a modulator to the scheme used for 2R regeneration.
- Many other schemes have been proposed in recent years.
- Combination of a dispersion-compensating fiber and a fiber grating is found to be effective in suppressing timing jitter [Striegler et al., IEEE PTL **17**, 1310 (2005)].

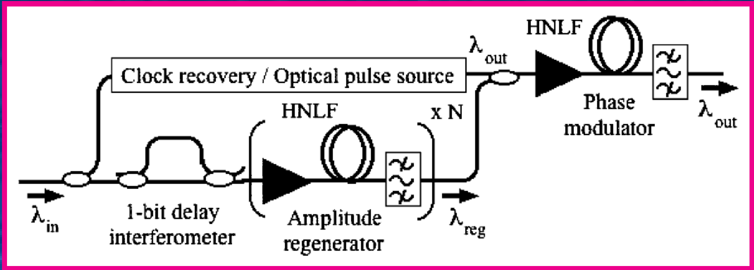
# XPM-Based 3R Regenerators




Suzuki et al., IEEE PTL **17**, 423 (2005)

- Clock pulses at $\lambda_2$ are narrower than signal pulses.
- XPM-induced wavelength shift of clock pulses results in a power-transfer function shown in part (e).
- Results in a wavelength-converted signal with a reverse bit pattern.

# DPSK 3R Regenerators




M. Matsumoto, IEEE PTL **19**, 273 (2007)

- A Mach–Zehnder interferometer with 1-bit delay is added before an SPM-based 2R regenerator.
- It converts DPSK signal into an OOK signal.
- The output is fed into a second fiber together with an optical clock.
- XPM transfers data to clock pulses, regenerating DPSK signal.

# Concluding Remarks

- Optical fibers exhibit a variety of nonlinear effects.
- SPM, XPM, and FWM can be exploited to make ultrafast optical switches.
- These nonlinear effects can be used to make devices such as wavelength converters, channel demultiplexers, and data-format converters.
- Such devices easily operate at bit rates of 100 Gb/s or more.
- New kinds of fibers enhance the nonlinear effects and reduce the required fiber length to below 10 meter.
- Nonlinear effects are also useful for making all-optical regenerators.
- SPM-based 2R and 3R regenerator are likely to find commercial applications.