Optical Parametric Regeneration for Phase-Modulated Signals

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Outline

- Introduction
  - Saturation of Fiber-Optic Parametric Amplification

- Parametric Regeneration of Phase-Modulated Signals
  - Nonlinear Phase Noise in PSK Signal Transmission
  - Experiment of DPSK and DQPSK Signal-Amplitude Regeneration (Limiting)

- Issues
  - Generation of Extra Phase Noise in the Regenerator
  - Polarization Dependency
Four-Wave Mixing in Fibers

Three-wave coupled equations for partially degenerate FWM

\[
\begin{align*}
\frac{dE_p}{dz} &= i\gamma \left[ |E_p|^2 E_p + 2(|E_s|^2 + |E_i|^2)E_p + 2E_p^*E_sE_i e^{i\Delta\beta z} \right] \\
\frac{dE_s}{dz} &= i\gamma \left[ |E_s|^2 E_s + 2(|E_p|^2 + |E_i|^2)E_s + E_p^*E_i e^{-i\Delta\beta z} \right] \\
\frac{dE_i}{dz} &= i\gamma \left[ |E_i|^2 E_i + 2(|E_p|^2 + |E_s|^2)E_i + E_p^*E_s e^{-i\Delta\beta z} \right]
\end{align*}
\]

\[\Delta\beta = -2\beta(\omega_p) + \beta(\omega_s) + \beta(\omega_i) = \beta_2(\omega_p)(\Delta\omega)^2\]

When \(|E_s|\) and \(|E_i|\) are much smaller than \(|E_p|\), the equations can be linearized with respect to \(E_s\) and \(E_i\).

The system behaves as a linear system and the gain

\[
\frac{P_s(L)}{P_s(0)} = \frac{|E_s(L)|^2}{|E_s(0)|^2} = G
\]

becomes a constant.
Saturation of Parametric Amplification

For high input signal powers and/or long fiber lengths, \(|E_s|, |E_i| \ll |E_p|\) is not satisfied.

The system is no longer linear with respect to \(E_s\) and \(E_i\). The gain \(G\) changes with the input signal power.

\[
G = 1 + \left(\gamma P_p/g\right)^2 \sinh^2(gL)
\]

\[
g = \sqrt{-}(\Delta\beta/2)(\Delta\beta/2 + 2\gamma P_p)
\]

\[
P_{s,\text{out}} = P_{s,\text{in}} + \frac{\eta_1 \eta_3 \sn^2(\xi)}{\eta_1 - \eta_3 + \eta_3 \sn^2(\xi)}
\]

\[
\xi = \sqrt{7\eta_4 (\eta_3 - \eta_1)} \gamma L / 2
\]

Saturation of parametric amplification is detrimental in amplification applications.

- Crosstalk between channels mediated by pump depletion in WDM signal amplification
- Intra-pulse gain saturation in high-speed signal amplification

It can be used for ultrafast signal processing.

- Ultrafast all-optical switching (e.g., H. Sunnerud et al., ECOC2007, 5.3.5.)
- Ultrafast regeneration of amplitude levels
Previous Studies

• Level equalization using saturation of FOPA
  Y. Su et al., EL36, 1103 (2000).

• Amplitude regeneration using higher-order FWM products.
  Radic et al., PTL15, 957 (2003).

• Regeneration of PSK signals
  M. Matsumoto, PTL17, 1055 (2005).
  C. Peuchelet et al., PTL21, 872 (2009).
  F. Futami et al., OFC2007, OThB3 (2007).

• Regenerative wavelength conversion
  M. Gao et al., OL35, 3468 (2010).

Studies discussing saturation of FOPA in phase-sensitive mode are not included.
Amplitude Regeneration (Limiting) of PSK Signals Using Saturation of Phase-Insensitive FOPA.

1. Linear and Nonlinear Phase Noise in PSK Signal Transmission

2. Experiments of DPSK and DQPSK Signal Regeneration and Transmission

3. Issues
   - Signal- and Pump-Induced Phase Noise
   - Polarization Dependency
Linear and Nonlinear Phase Noise

ASE induces phase and amplitude noise to the signal.

1. Linear phase noise

\[ \text{TX} \quad \Delta \phi_1 \quad \Delta \phi_2 \quad \Delta \phi_3 \quad \text{RX} \]

\[ <\Delta \phi^2> \propto N \]

2. Nonlinear phase noise induced by the amplitude noise & SPM

\[ \Delta P_1 \quad \Delta P_2 \quad \Delta P_3 \]

\[ \begin{align*}
\Delta \phi_1 & \propto N \Delta P_1 \\
\Delta \phi_2 & \propto (N-1) \Delta P_2 \\
\Delta \phi_3 & \propto (N-2) \Delta P_3
\end{align*} \]

\[ <\Delta \phi^2> \propto N^3 \]

Amplitude regeneration of PSK signals suppresses nonlinear phase noise.
Reduction of Nonlinear Phase Noise

\[
< \delta \phi^2 > = < \delta \phi_s^2 > + < \delta \phi_a^2 >
\]

source
inline amp.

\[
< \delta \phi_a^2 > = \frac{N_a B M}{2 P_p} + P_p (\gamma L_{eff})^2 N_a B \frac{M(M-1)(2M-1)}{3}
\]

No amplitude limiter
(Gordon and Mollenauer, 1990)

Amplitude limiter inserted after the transmitter

Amplitude limiter inserted every span

(40km x 5spans, loss 22dB/span, \( \gamma = 3.5/W/km \), 10Gb/s short-pulse RZ)

Amplitude limiter enhances nonlinear tolerance of PSK signal transmission.

✓ Longer transmission distance
✓ Larger amplifier span
Experiment of Amplitude Reshaping

HNLF: length 1.5km, $\lambda_0$ 1556nm
$\gamma \sim 12$/W/km

$\sigma = \frac{\mu}{\sigma}$

$Q$ is increased by a factor $\sim 2.8$.

OSNR of input signal
- 13dB/0.1nm
- 15dB/0.1nm
- 17dB/0.1nm

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Experiment of DQPSK Signal Transmission

10 G symbol/s

1558nm

MLLD \rightarrow LNM \rightarrow ATT \rightarrow OBPF1

EDI \rightarrow \pi/4 or -\pi/4 \rightarrow ATT

Transmission fiber

OBPF2

LNM \rightarrow LD

1GHz phase mod.

- DDMF (Densely Dispersion-Managed Fiber) 40km
- SMF 50km +DCF

Pulse shapes

Before limiter

After limiter

Dispersion:

\pm 3\text{ps/nm/km}

2km x 20sections

\gamma \sim 3.5/W/km
Experiment of DQPSK Signal Transmission

Blue curves: amplitude limiter removed
Red curves: amplitude limiter inserted

DDMF

SMF+DCF

log_{10}(BER)

launched signal power (dBm)
Experiment of DPSK Signal Transmission

40km x 5span transmission of 10Gb/s short-pulse DPSK signal

A limiter is inserted either before recirculating loop (A) or inside the loop (B).

solid: pump ON, dashed: pump OFF

TX OSNR:
A: 21.5dB/0.1nm
B: 25.7dB/0.1nm
Multi-Channel Reshaping

Multi-channel signals can share a cw pump if they are time-interleaved.

DPSK signals at $\lambda_1=1556.5$ and $\lambda_2=1558$nm are time-interleave-multiplexed and reshaped by the regenerator.
Multi-Channel Reshaping

Time synchronization is required for time interleaving.

\[
\lambda_1 \quad \lambda_2
\]

time \hspace{1cm} \Delta \tau

delay controller

Amplitude Limiter Using FWM in Fiber

monitor
(inter-channel FWM component)

Three-channel spectra

Red: time-interleaved
Blue: overlapped

(S. Tanabe and M. Matsumoto, ECOC2009, 9.1.5)
Generation of Extra Phase Noise in the Limiter

In the (phase-insensitive) parametric regenerator, amplitude noise is suppressed while the phase noise is preserved.

\[ \sigma_{\theta, \text{out}}^2 = \sigma_{\theta, \text{in}}^2 + \alpha \]

Extra phase noise should be minimized.

Nonlinear processes in fiber (SPM, XPM, FWM) translate fluctuations in pump and signal amplitudes and frequencies into output signal phase fluctuation.

1. Translation from pump noise to signal phase noise

\[
\begin{align*}
\frac{dE_p}{dz} &= i\gamma |E_p|^2 E_p \\
\frac{dE_s}{dz} &= i\gamma \left( 2|E_p|^2 E_s + E_p^2 E^*_i e^{-i\Delta \beta z} \right) \\
\frac{dE_i}{dz} &= i\gamma \left( 2|E_p|^2 E_i + E_p^2 E^*_s e^{-i\Delta \beta z} \right)
\end{align*}
\]

Solution for the output signal phase

\[
\theta_s(L) = \theta_s(0) + \tan^{-1}\left[ \left( \gamma P_p / g \right) \left( 1 + \Delta \beta / (2\gamma P_p) \right) \tanh(gL) \right] + \gamma P_p L - \Delta \beta / 2
\]

2nd term ➔ phase noise originated from the dependency of the parametric gain on the instantaneous pump amplitude and frequency.

3rd term ➔ phase noise originated from the pump nonlinear phase noise.

S. Moro et al., OE18, 21449 (2010).
2. Phase noise generated by the input signal amplitude noise

\[
dE_s/dz = i\gamma \left[ |E_s|^2 E_s + 2(|E_p|^2 + |E_i|^2)E_s + E_p^2 E_i^* e^{-i\Delta z} \right]
\]

\[
E_m = A_m e^{i\theta_m} \quad (m = s, p, i)
\]

\[
d\theta_s/dz = \gamma \left[ A_s^2 + 2A_p^2 + 2A_i^2 + (A_p^2 A_i / A_s) \cos \theta \right]
\]

Output phase noise vs pump power

*signal-induced phase noise dominates.*

* pump-induced phase noise dominates.

\[ \rho_{\text{pump, in}} = 30 \text{dB} \]

\[ \rho_{\text{sig, in}} = 20 \text{dB} \]
For practical use of the limiter, polarization dependency should be avoided.

Use of two orthogonally polarized pumps is a candidate.
Polarization Dependency

- Random and rapid polarization rotation
- No PMD

Manakov eq. model

\[
\frac{dE_1}{dz} = i \frac{8}{9} \gamma \left[ \left( \sum_{m=1}^{4} |E_m|^2 \right) E_1 + \sum_{m \neq 1} \left( E_1 \cdot E_m^* \right) E_m + \left( (E_2 \cdot E_4^*) E_3 + (E_3 \cdot E_4^*) E_2 \right) e^{-i\Delta \beta z} \right]
\]

\[
\frac{dE_2}{dz} = i \frac{8}{9} \gamma \left[ \left( \sum_{m=1}^{4} |E_m|^2 \right) E_2 + \sum_{m \neq 2} \left( E_2 \cdot E_m^* \right) E_m + \left( (E_1 \cdot E_3^*) E_4 + (E_4 \cdot E_3^*) E_1 \right) e^{i\Delta \beta z} \right]
\]

\[
\frac{dE_3}{dz} = i \frac{8}{9} \gamma \left[ \left( \sum_{m=1}^{4} |E_m|^2 \right) E_3 + \sum_{m \neq 3} \left( E_3 \cdot E_m^* \right) E_m + \left( (E_1 \cdot E_2^*) E_4 + (E_4 \cdot E_2^*) E_1 \right) e^{i\Delta \beta z} \right]
\]

\[
\frac{dE_4}{dz} = i \frac{8}{9} \gamma \left[ \left( \sum_{m=1}^{4} |E_m|^2 \right) E_4 + \sum_{m \neq 4} \left( E_4 \cdot E_m^* \right) E_m + \left( (E_2 \cdot E_1^*) E_3 + (E_3 \cdot E_1^*) E_2 \right) e^{-i\Delta \beta z} \right]
\]

\[
E_m = \begin{bmatrix} E_{m,u} \\ E_{m,v} \end{bmatrix}, \quad (m=1\sim 4) \quad \Delta \beta = \beta(\omega_1) + \beta(\omega_4) - \beta(\omega_2) - \beta(\omega_3)
\]
Orthogonally polarized pumps: \[ E_1 = \begin{bmatrix} \sqrt{P_0} \\ 0 \end{bmatrix}, \quad E_4 = \begin{bmatrix} 0 \\ \sqrt{P_0} \end{bmatrix} \]

1. Pump undepleted case (\[ |E_2|, |E_3| << |E_1|, |E_4| \])

\[
E_2 = \begin{bmatrix} E_{2,u} \\ E_{2,v} \end{bmatrix} \leftrightarrow \begin{bmatrix} E_{3,u} \\ E_{3,v} \end{bmatrix} = E_3
\]

- \(E_{2,u}\) and \(E_{3,v}\) are coupled with each other exactly the same way as \(E_{2,v}\) and \(E_{3,u}\) are coupled.
- The two sets \((E_{2,u}, E_{3,v})\) and \((E_{2,v}, E_{3,u})\) are independent.

\[ \text{Parametric amplification becomes polarization independent.} \quad \text{(e.g., K. K. Y. Wong et al., PTL14, 913 (2002).)} \]

2. When \(E_2\) and \(E_3\) grow comparable to \(E_1\) and \(E_4\), the above argument does not hold.

(P. Velanas et al., LEOS Win.Topical 2009, MC2.6)
Polarization Dependency

Saturation of output power for different input signal polarizations:

- Output power varies with input polarization.
- Saturation behavior is similar for different input polarizations.

\[ \lambda_0 = 1562.5 \text{nm} \]
\[ \frac{dD}{d\lambda} = 0.03 \text{ps/nm}^2/\text{km} \]
\[ \gamma = 17 \text{W/km} \]
\[ L = 1 \text{km} \]
\[ P_0 = 23 \text{dBm} \]
Two-stage polarization-diversity FOPA
(S. Watanabe et al., OECC2009, TuD3.)

\[ \lambda_{p1} \sim \lambda_{01} = 1563\text{nm} \]
\[ \lambda_{p2} \sim \lambda_{02} = 1564\text{nm} \]
\[ \gamma \approx 25/W/km \]
\[ L = 500\text{m} \]
\[ P_{p1} = P_{p2} = 26\text{dBm} \]

Receiver sensitivity was improved by ~2.5dB at 40Gb/s NRZ-OOK.
Conclusion

- **Saturation of FOPA**
  - FOPA is easily saturated at relatively small input signal powers.
  - Saturation is ultrafast.
  - Signal phase is almost preserved.

  Saturated FOPA can be used as an amplitude limiter (regenerator) suitable for PSK signals.

- **Experiments**
  - 10Gb/s DPSK and 20Gb/s DQPSK transmission performance was improved by reduction of nonlinear phase noise.

- **Extra phase noise generated by the limiter**
  - A compromise exists between signal- and pump-induced extra phase noise.

- **Polarization sensitivity**
  - Moderately polarization insensitive operation is possible.