Optical Parametric Regeneration for Phase-Modulated Signals

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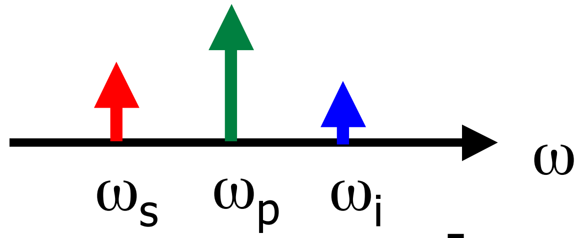
Outline

- 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



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

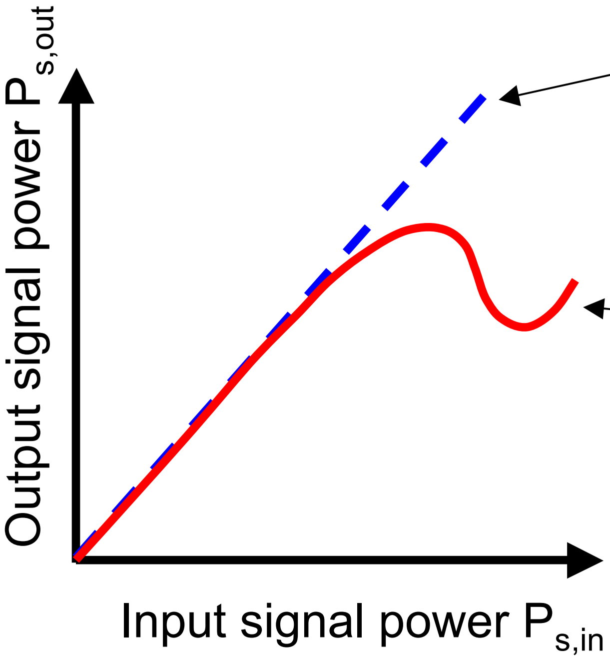
$$\Delta\beta = -2\beta(\omega_p) + \beta(\omega_s) + \beta(\omega_i) = \beta_2(\omega_p)(\Delta\omega)^2$$

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

⇒ The system behaves as a linear system and

the gain $\dfrac{P_s(L)}{P_s(0)} = \dfrac{\left|E_s(L)\right|^2}{\left|E_s(0)\right|^2} = G$ becomes a constant.

Saturation of Parametric Amplification



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

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

$$P_{s,out} = P_{s,in} + \frac{\eta_1 \eta_3 \mathrm{sn}^2 \xi}{\eta_1 - \eta_3 + \eta_3 \mathrm{sn}^2 \xi}$$

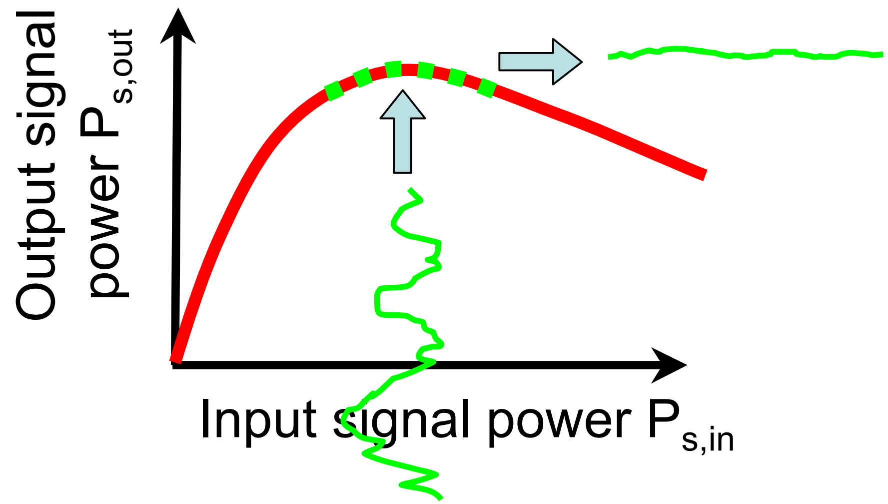
$$\xi = \sqrt{7\eta_4(\eta_3 - \eta_1)}\, \gamma L / 2$$

(Analytical solution using Jacobi elliptical functions. Y.Chen, JOSA B6,1986(1989), G. Cappellini and S. Trillo, JOSA B8, 824(1991))

For high input signal powers and/or long fiber lengths,
$|E_s|, |E_i| << |E_p|$ 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.

Saturation of Parametric Amplification



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

  K. Inoue, EL36, 1016 (2000).

  Y. Su et al., EL36, 1103 (2000).
- Amplitude regeneration using higher-order FWM products.

  E. Ciaramella and S. Trillo, PTL12, 849 (2000).

  K. Inoue, PTL13, 338 (2001).

  Radic et al., PTL15, 957 (2003).
- Regeneration of PSK signals

  M. Matsumoto, PTL17, 1055 (2005).

  K. Croussore and G. Li, EL43, 177 (2007).

  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.

This Presentation

Amplitude Regeneration (Limiting) of PSK Signals Using Saturation of Phase-Insensitive FOPA.

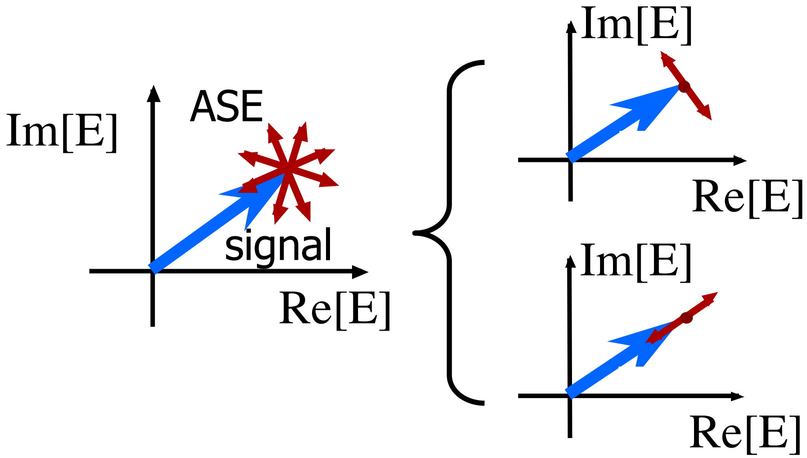
1. Linear and Nonlinear Phase Noise in PSK Signal Transmission

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

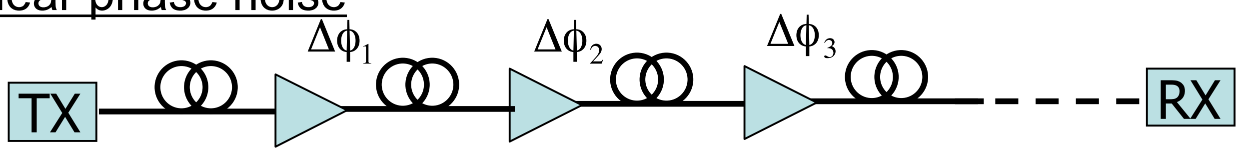
ASE induces phase and amplitude noise to the signal.



Phase noise
→ Linear phase noise

Amplitude noise
→ Nonlinear phase noise

1. Linear phase noise



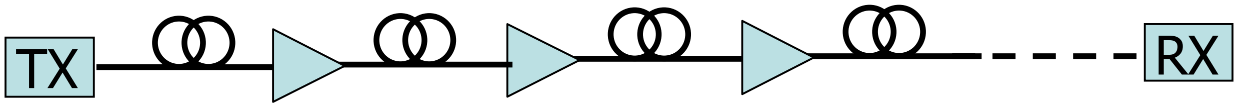
$<\Delta\phi^2> \propto N$

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

ΔP_3 → $\Delta\phi_2 \propto (N-2)\Delta P_3$

ΔP_2 → $\Delta\phi_2 \propto (N-1)\Delta P_2$

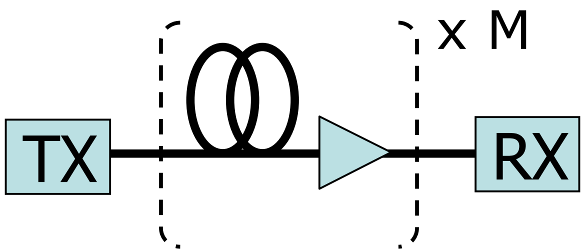
ΔP_1 → $\Delta\phi_1 \propto N\Delta P_1$



$<\Delta\phi^2> \propto N^3$

Amplitude regeneration of PSK signals suppresses nonlinear phase noise.

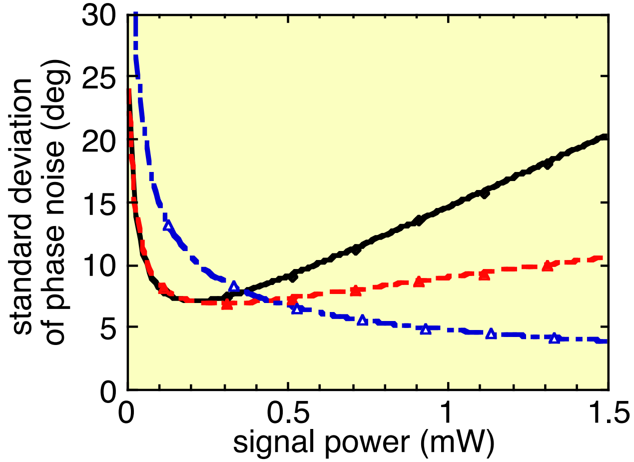
Reduction of Nonlinear Phase Noise



$$<\delta\phi^2> = <\delta\phi_s^2> + <\delta\phi_a^2>$$

source inline amp.

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



No amplitude limiter (Gordon and Mollenauer, 1990)

Amplitude limiter inserted after the transmitter

Amplitude limiter inserted every span

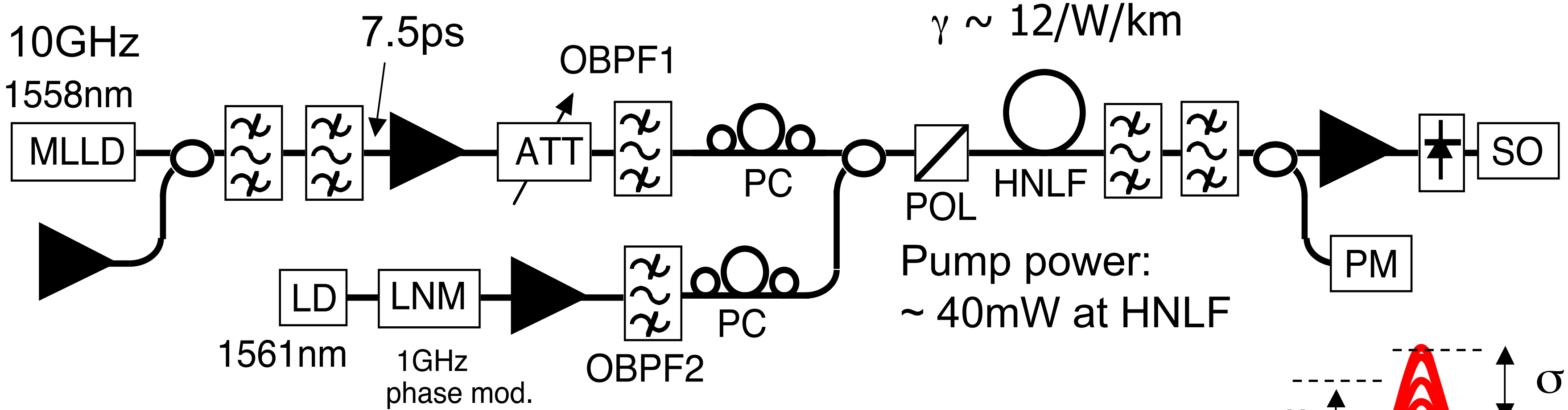
(40km x 5spans, loss 22dB/span, γ=3.5/W/km, 10Gb/s short-pulse RZ)

Amplitude limiter enhances nonlinear tolerance of PSK signal transmission.

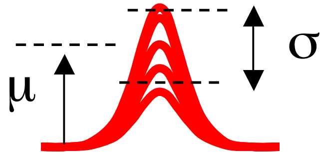
- ✓ Longer transmission distance
- ✓ Larger amplifier span

Experiment of Amplitude Reshaping

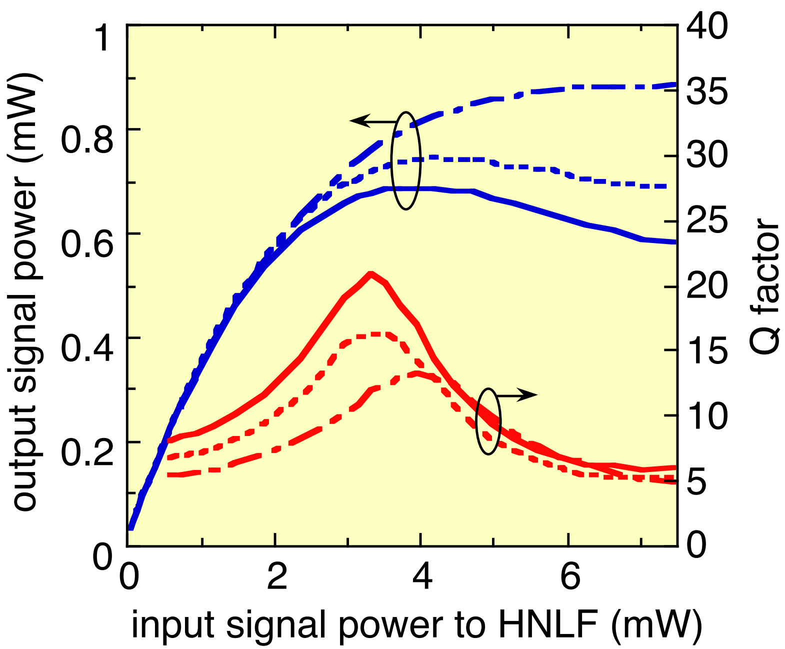
HNLF: length 1.5km, λ_0 1556nm
γ ~ 12/W/km



Pump power:
~ 40mW at HNLF



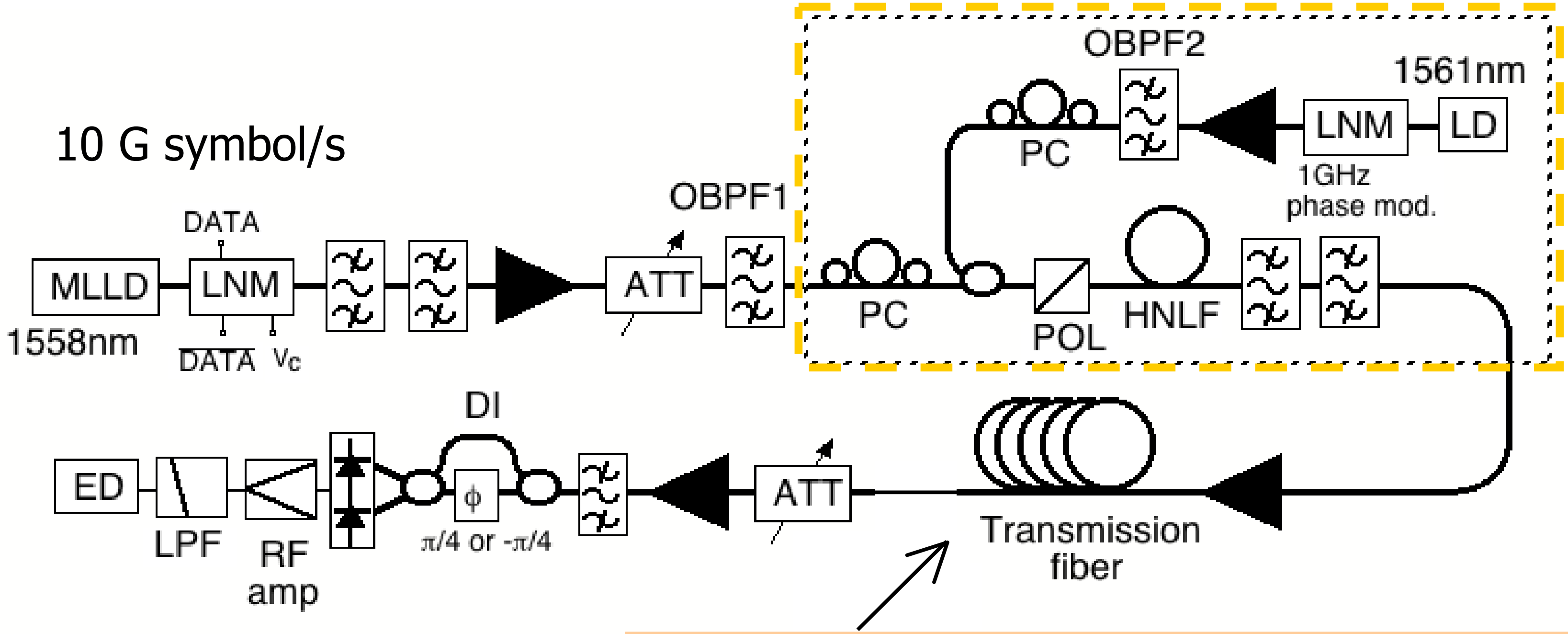
$Q = \mu/\sigma$



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

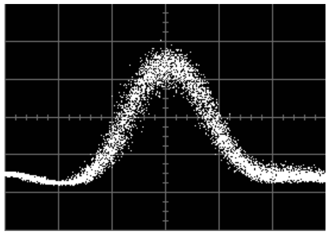
Q is increased by a factor ~2.8.

Experiment of DQPSK Signal Transmission

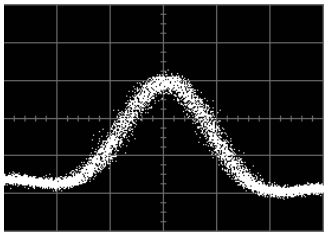


- DDMF(Densely Dispersion-Managed Fiber) 40km
- SMF 50km +DCF

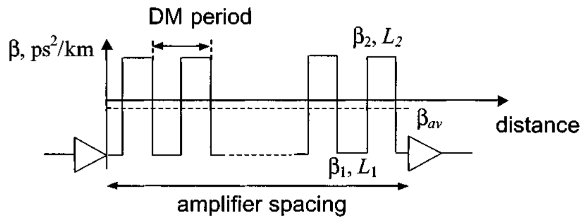
Pulse shapes



Before limiter

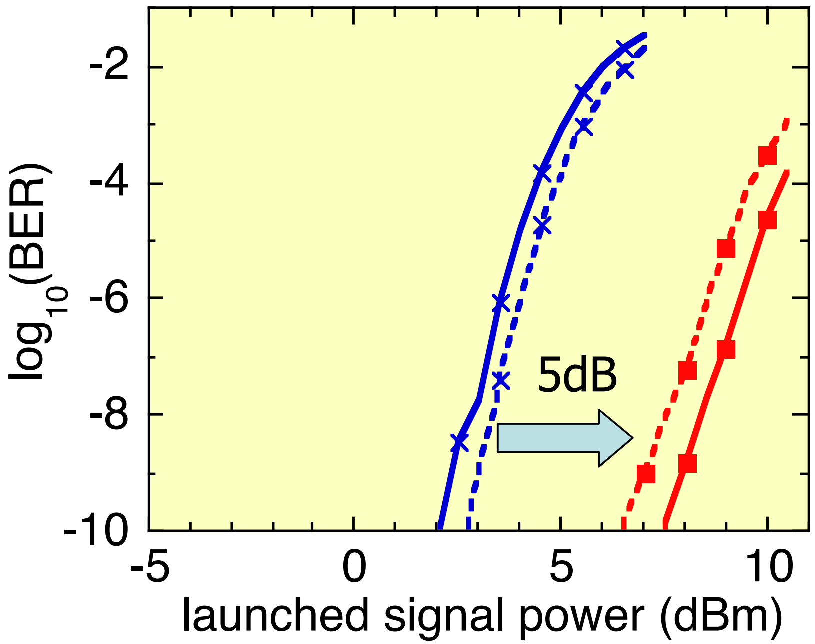


After limiter

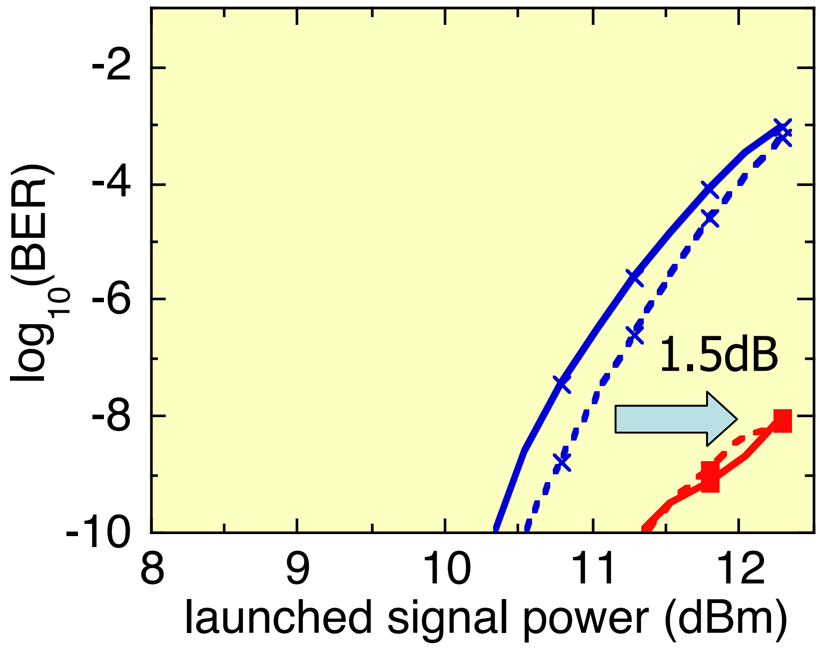


Dispersion:
±3ps/nm/km
2km x 20sections
γ~3.5/W/km

Experiment of DQPSK Signal Transmission



DDMF



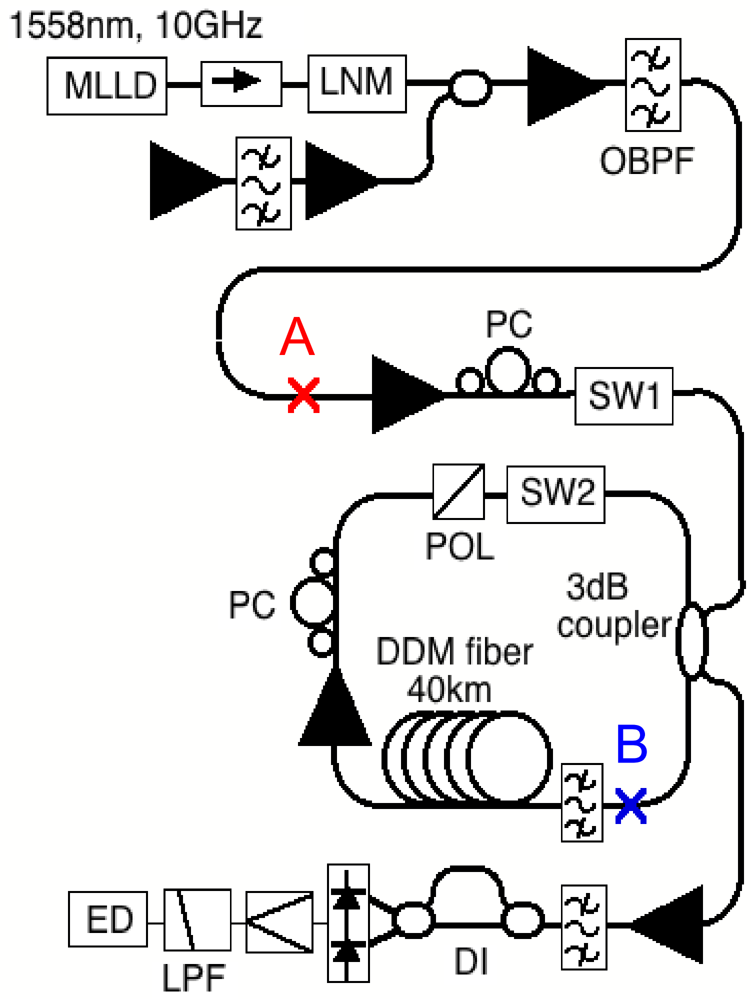
SMF+DCF

Blue curves : amplitude limiter removed

Red curves : amplitude limiter inserted

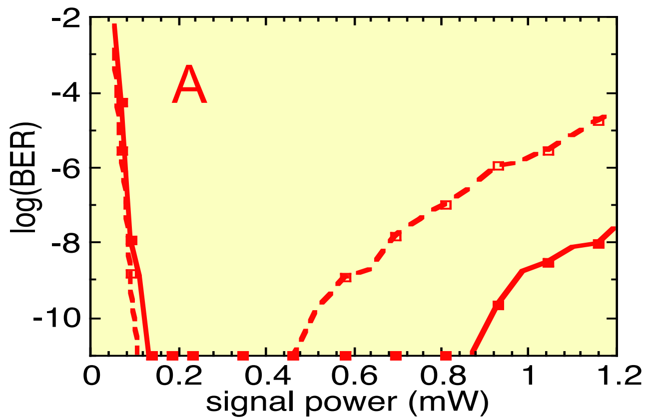
Experiment of DPSK Signal Transmission

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

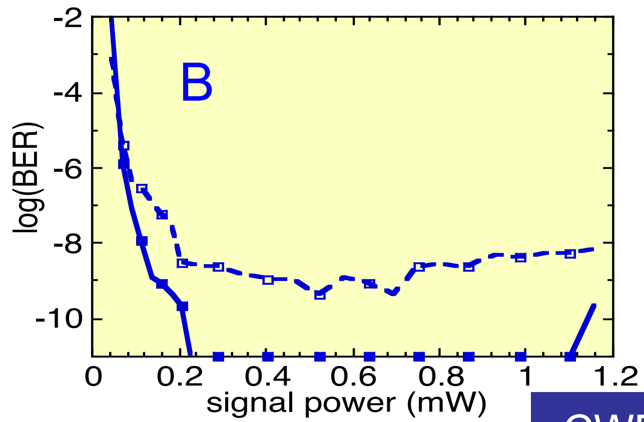


A limiter is inserted either before recirculating loop (A) or inside the loop (B).

solid: pump ON, dashed: pump OFF



TX OSNR: 21.5dB/0.1nm

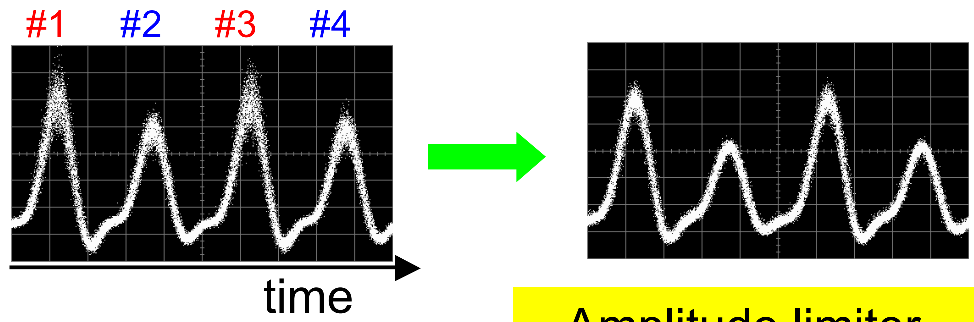


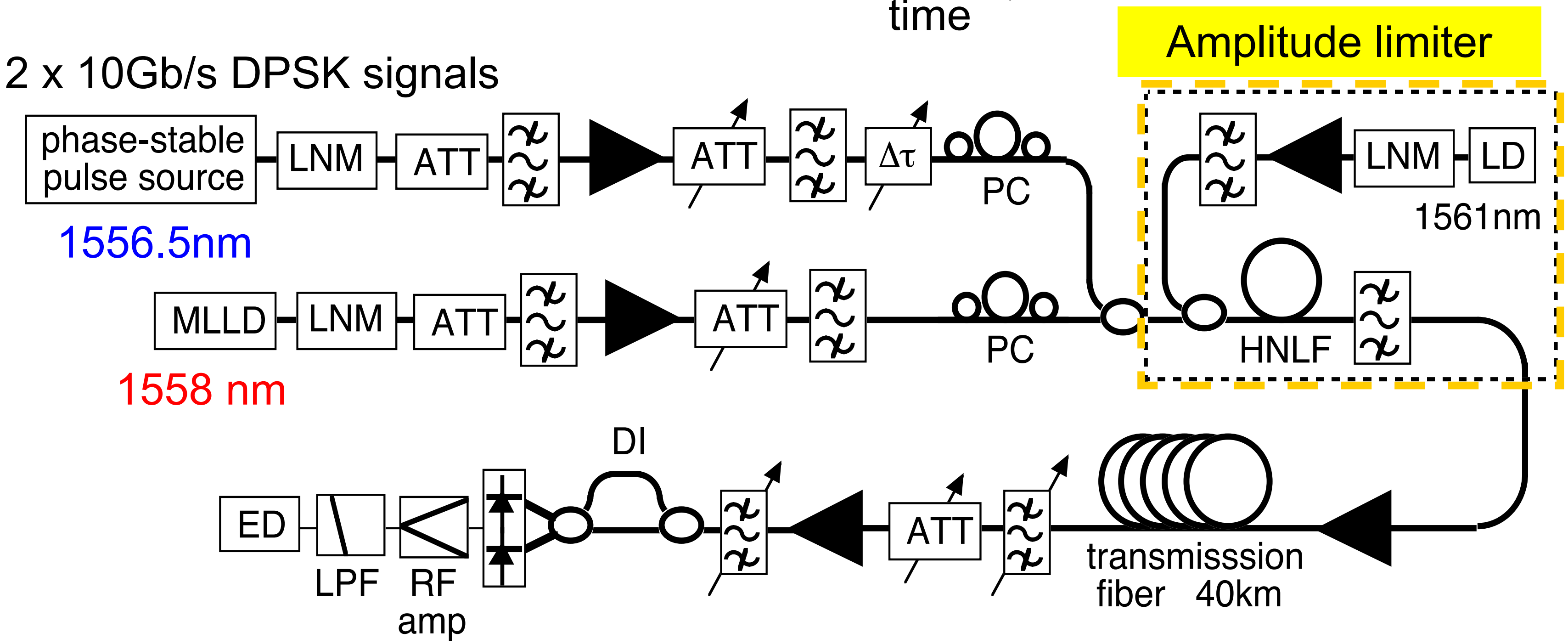
TX OSNR: 25.7dB/0.1nm

Multi-Channel Reshaping

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

pulses #2,#4 : λ_1
pulses #1,#3 : λ_2

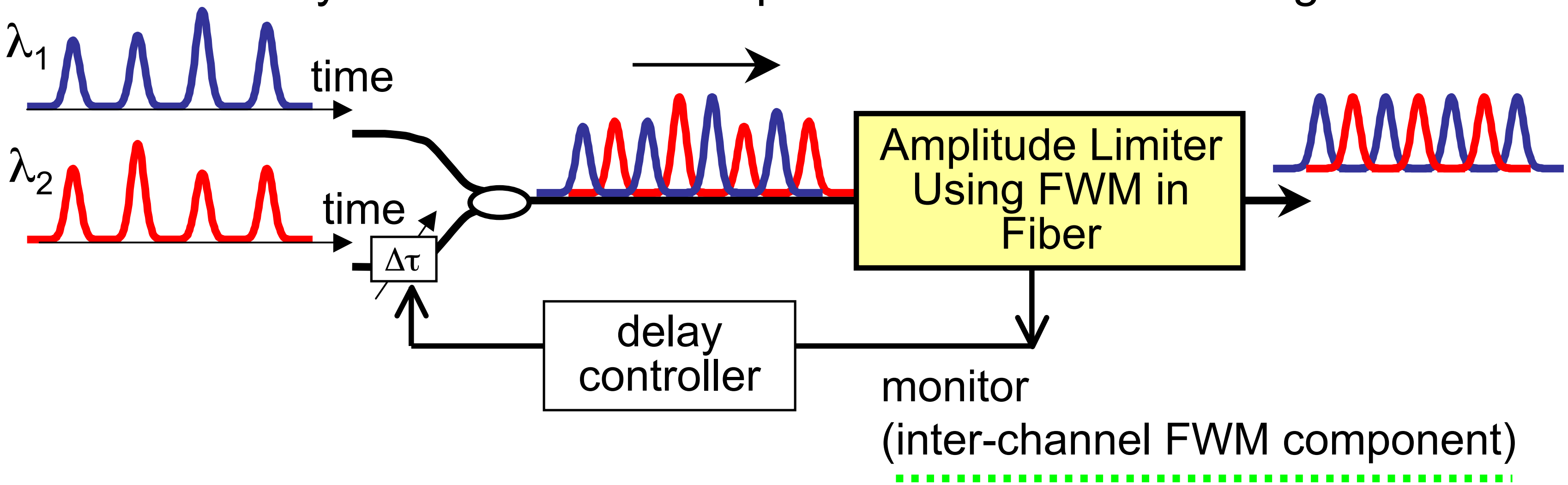




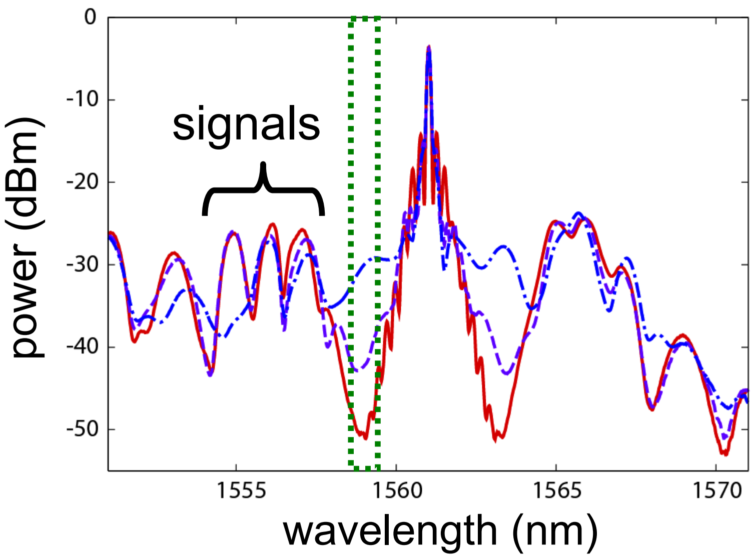
DPSK signals at λ_1=1556.5 and λ_2=1558nm are time-interleave-multiplexed and reshaped by the regenerator.

Multi-Channel Reshaping

Time synchronization is required for time interleaving.



Three-channel spectra



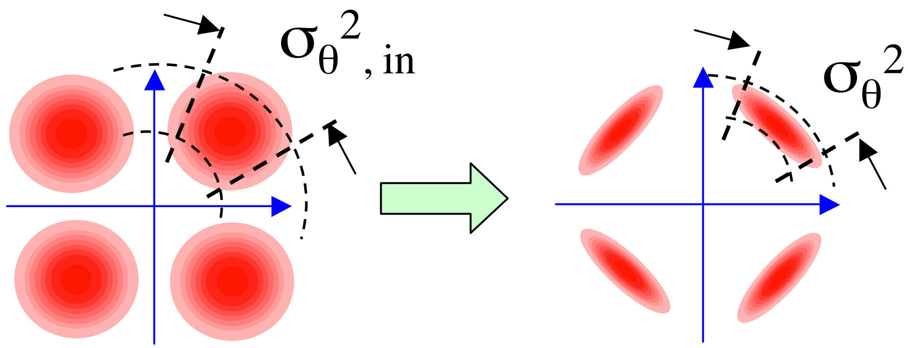
Red: time-interleaved

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.



$$\sigma_{\theta}^{2}{}_{, out} = \sigma_{\theta}^{2}{}_{, in} + \alpha$$

Extra phase noise should be minimized.

$$[A_p + \Delta A_p] e^{i(\theta_p + \Delta\theta_p(t))}$$

$$[A_s + \Delta A_s] e^{i\theta_s} \rightarrow \text{FOPA} \rightarrow A_s e^{i(\theta_s + \Delta\theta_s)}$$

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

M. Sköld et al., OE16, 5974(2008), M. Matsumoto, OL33, 1638 (2008), R. Elschner and K. Petermann, ECOC2009, 3.3.4 (2009), S. Moro et al., OE18, 21449 (2010).

Generation of Extra Phase Noise in the Limiter

1. Translation from pump noise to signal phase noise

$$
\begin{cases}
dE_p/dz = i\gamma |E_p|^2 E_p \\
dE_s/dz = i\gamma\left(2|E_p|^2 E_s + E_p^2 E_i^* e^{-i\Delta\beta z}\right) \\
dE_i/dz = i\gamma\left(2|E_p|^2 E_i + E_p^2 E_s^* e^{-i\Delta\beta z}\right)
\end{cases}
$$

Solution for the output signal phase

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

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).

Generation of Extra Phase Noise in the Limiter

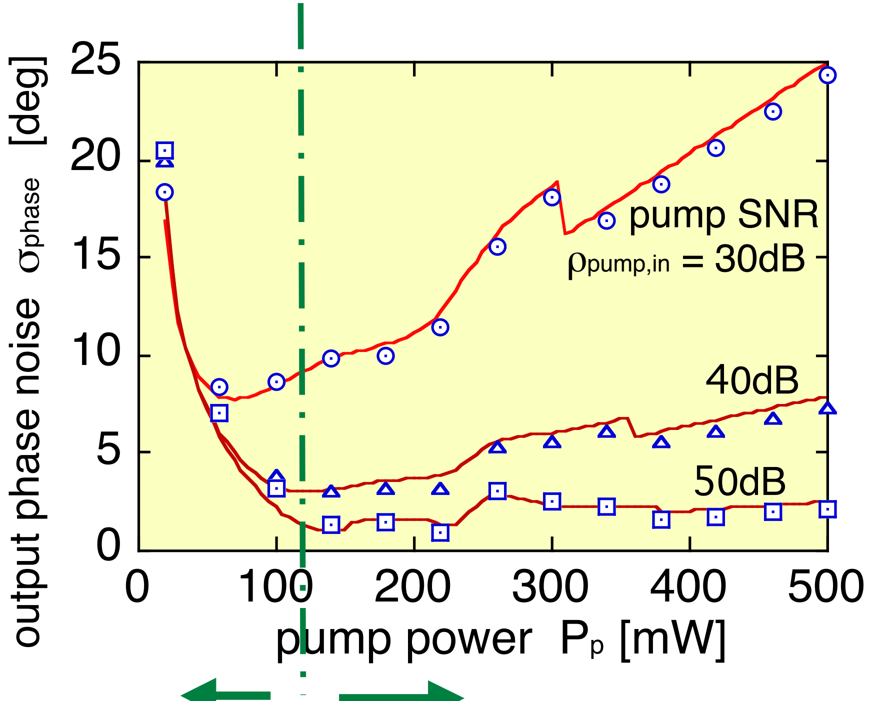
2. Phase noise generated by the input signal amplitude noise

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

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

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

Output phase noise vs pump power



$\rho_{sig,in} = 20\,dB$

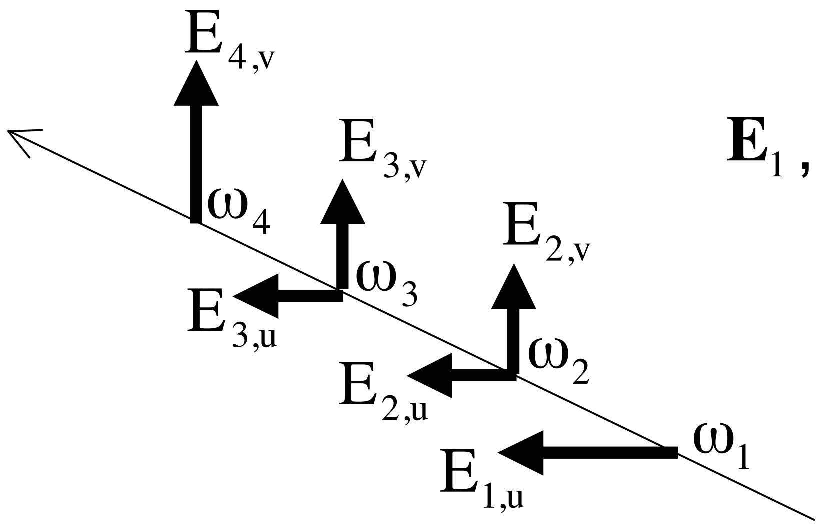
signal-induced phase noise dominates.

pump-induced phase noise dominates.

Polarization Dependency

For practical use of the limiter, polarization dependency should be avoided.

Use of two orthogonally polarized pumps is a candidate.



$\mathbf{E}_1$, $\mathbf{E}_4$: pump

$\mathbf{E}_2$: signal

$\mathbf{E}_3$: idler

Polarization Dependency

- Random and rapid polarization rotation
- No PMD

} Manakov eq. model

$$\frac{d\mathbf{E}_1}{dz} = i\frac{8}{9}\gamma\left[\left(\sum_{m=1}^{4}|\mathbf{E}_m|^2\right)\mathbf{E}_1 + \sum_{m\neq 1}(\mathbf{E}_1\cdot\mathbf{E}_m^*)\mathbf{E}_m + \left[(\mathbf{E}_2\cdot\mathbf{E}_4^*)\mathbf{E}_3 + (\mathbf{E}_3\cdot\mathbf{E}_4^*)\mathbf{E}_2\right]e^{-i\Delta\beta z}\right]$$

$$\frac{d\mathbf{E}_2}{dz} = i\frac{8}{9}\gamma\left[\left(\sum_{m=1}^{4}|\mathbf{E}_m|^2\right)\mathbf{E}_2 + \sum_{m\neq 2}(\mathbf{E}_2\cdot\mathbf{E}_m^*)\mathbf{E}_m + \left[(\mathbf{E}_1\cdot\mathbf{E}_3^*)\mathbf{E}_4 + (\mathbf{E}_4\cdot\mathbf{E}_3^*)\mathbf{E}_1\right]e^{i\Delta\beta z}\right]$$

$$\frac{d\mathbf{E}_3}{dz} = i\frac{8}{9}\gamma\left[\left(\sum_{m=1}^{4}|\mathbf{E}_m|^2\right)\mathbf{E}_3 + \sum_{m\neq 3}(\mathbf{E}_3\cdot\mathbf{E}_m^*)\mathbf{E}_m + \left[(\mathbf{E}_1\cdot\mathbf{E}_2^*)\mathbf{E}_4 + (\mathbf{E}_4\cdot\mathbf{E}_2^*)\mathbf{E}_1\right]e^{i\Delta\beta z}\right]$$

$$\frac{d\mathbf{E}_4}{dz} = i\frac{8}{9}\gamma\left[\left(\sum_{m=1}^{4}|\mathbf{E}_m|^2\right)\mathbf{E}_4 + \sum_{m\neq 4}(\mathbf{E}_4\cdot\mathbf{E}_m^*)\mathbf{E}_m + \left[(\mathbf{E}_2\cdot\mathbf{E}_1^*)\mathbf{E}_3 + (\mathbf{E}_3\cdot\mathbf{E}_1^*)\mathbf{E}_2\right]e^{-i\Delta\beta z}\right]$$

$$\mathbf{E}_m = \begin{bmatrix} E_{m,u} \\ E_{m,v} \end{bmatrix}, \text{ (m=1~4)} \qquad \Delta\beta = \beta(\omega_1) + \beta(\omega_4) - \beta(\omega_2) - \beta(\omega_3)$$

Polarization Dependency

Orthogonally polarized pumps : $\mathbf{E}_1 = \begin{bmatrix} \sqrt{P_0} \\ 0 \end{bmatrix}, \quad \mathbf{E}_4 = \begin{bmatrix} 0 \\ \sqrt{P_0} \end{bmatrix}$

1. Pump undepleted case ($|\mathbf{E}_2|, |\mathbf{E}_3| << |\mathbf{E}_1|, |\mathbf{E}_4|$)

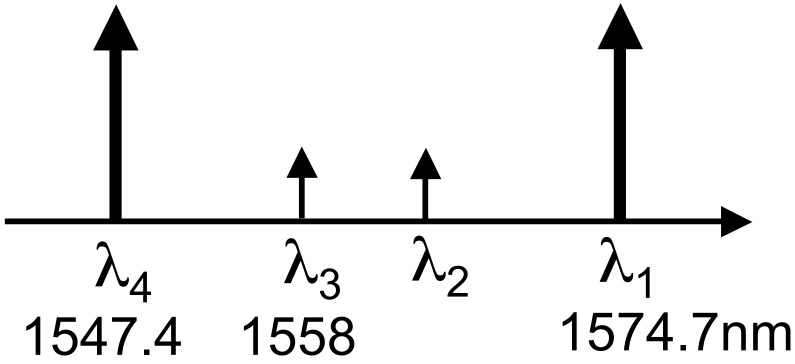
$$\mathbf{E}_2 = \begin{bmatrix} E_{2,u} \\ E_{2,v} \end{bmatrix} \qquad \begin{bmatrix} E_{3,u} \\ E_{3,v} \end{bmatrix} = \mathbf{E}_3$$

- $E_{2,u}$ 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.

⇨ Parametric amplification becomes polarization independent. (e.g., K. K. Y. Wong et al., PTL14, 913 (2002).)

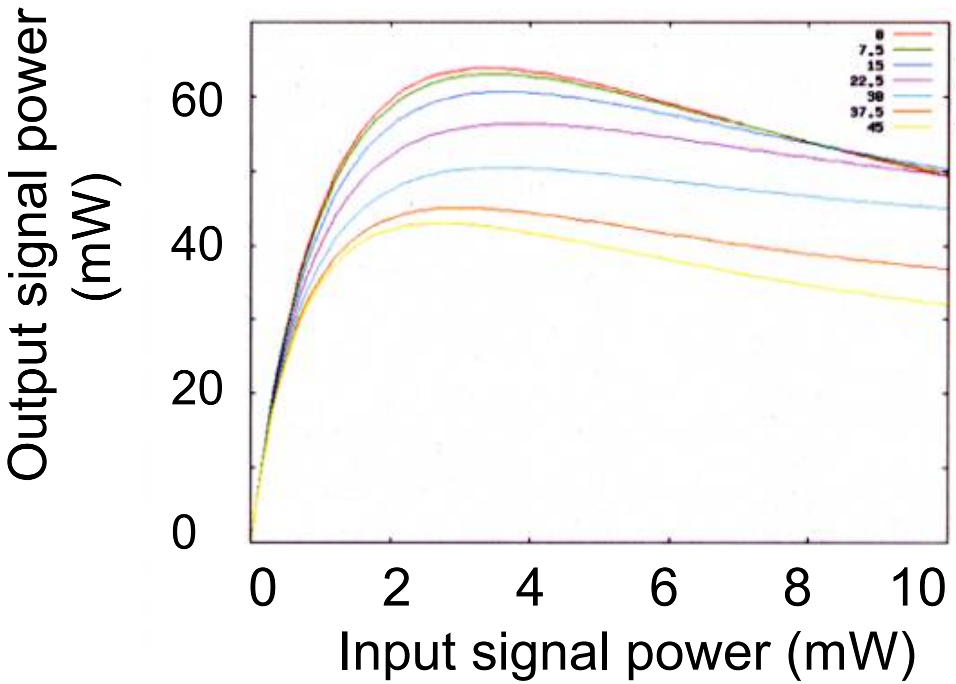
2. When $\mathbf{E}_2$ and $\mathbf{E}_3$ grow comparable to $\mathbf{E}_1$ and $\mathbf{E}_4$, the above argument does not hold.
(P. Velanas et al., LEOS Win.Topical 2009, MC2.6)

Polarization Dependency



λ_0=1562.5nm
$d D/d\lambda$=0.03ps/nm^2/km
γ=17/W/km
L=1km
P_0=23dBm

Saturation of output power for different input signal polarizations



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

Polarization Independent Amplitude Limiter

Two-stage polarization-diversity FOPA

(S. Watanabe et al., OECC2009, TuD3.)

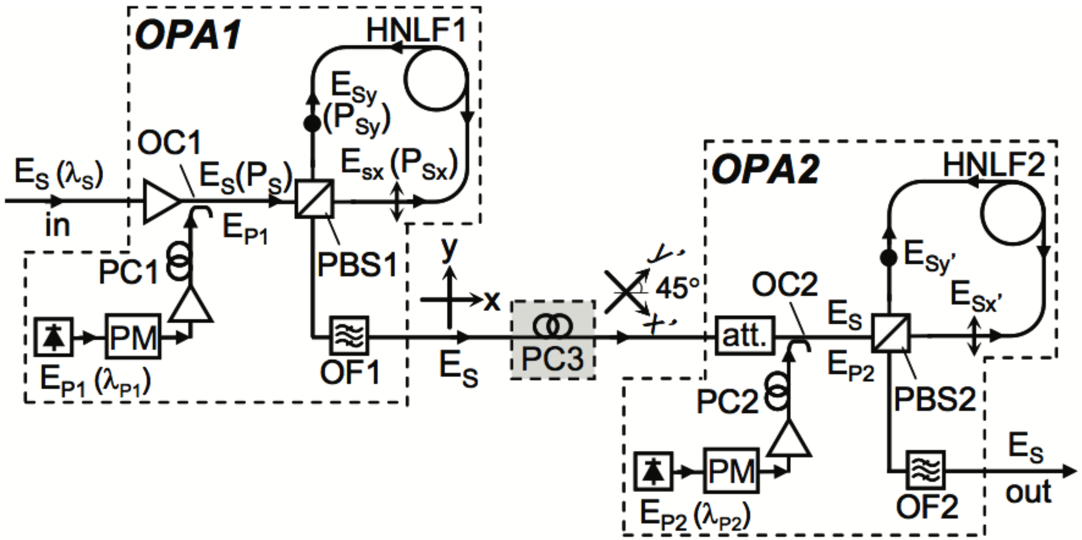


Fig. 1 Setup of polarization-independent OPA-limiter

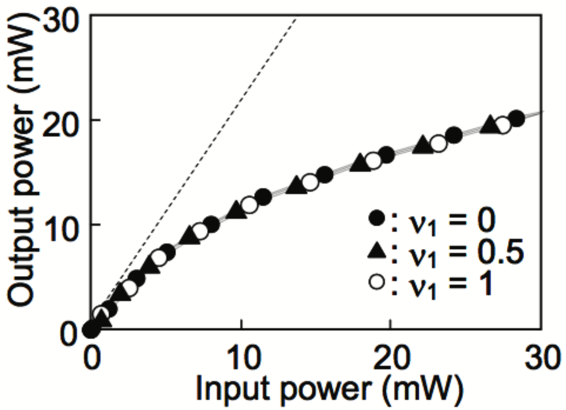
$\lambda_{p1} \sim \lambda_{01} = 1563\text{nm}$

$\lambda_{p2} \sim \lambda_{02} = 1564\text{nm}$

$\gamma \sim 25/\text{W/km}$

L=500m

$P_{p1} = P_{p2} = 26\text{dBm}$



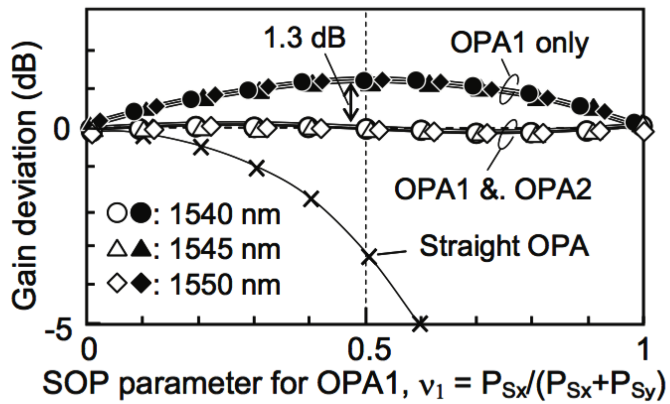


Fig. 2 Gain deviation versus SOP of input signal.

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.