Fiber optics parametric amplifiers and their applications for signal regeneration

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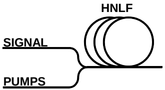
Motivation

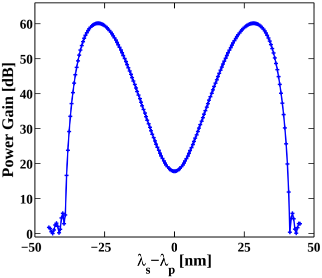
Fiber optics parametric amplifiers:

- High flat gain over a wide bandwidth at arbitrary wavelengths
- Low noise figure



Furthermore

- Optical signal processing
  - Wavelength conversion
  - Optical sampling
  - Multicasting
  - Signal Regeneration



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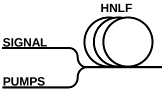

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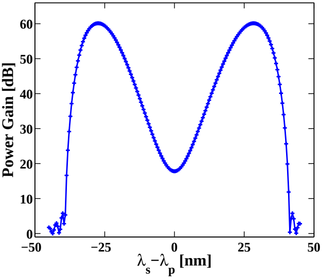


Outline

Introduction

Saturation effects
- Amplitude regeneration

Phase sensitive amplification
- Phase regeneration

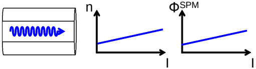
Saturated phase sensitive amplification
- Advanced modulation formats regeneration

Conclusions

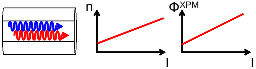
Kerr Nonlinearities

$$\boxed{n = n_0 + n_2 I}$$

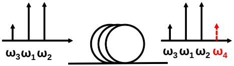
- Self-Phase Modulation $\Longrightarrow$ $\dfrac{dA_1}{dz} \propto i\gamma |A_1|^2 A_1$



- Cross-Phase Modulation $\Longrightarrow$ $\dfrac{dA_1}{dz} \propto 2i\gamma |A_2|^2 A_1$



- Four-wave Mixing $\Longrightarrow$ $\dfrac{dA_4}{dz} \propto 2i\gamma A_1 A_2 A_3^*$



Energy conservation $\Rightarrow$ $\omega_4 = \omega_1 + \omega_2 - \omega_3$

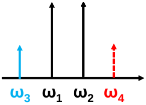
Momentum conservation $\Rightarrow$ $\beta^{(4)} = \beta^{(1)} + \beta^{(2)} - \beta^{(3)}$

Parametric Processes

Four-wave model:

$$\frac{dA_i}{dz} = i\gamma \left[\underbrace{|A_i|^2 A_i}_{SPM} + \underbrace{2 \sum_{l \neq i} |A_l|^2 A_i}_{XPM} + \underbrace{2 A_m A_n A_o^* e^{-i\epsilon \Delta\beta z}}_{FWM} \right].$$

- $\Delta\beta = \beta^{(4)} + \beta^{(3)} - \beta^{(2)} - \beta^{(1)}$
- $\epsilon = 1$, if $i = 1$ or 2 then o = 3 - i, m = 3, n = 4;
- $\epsilon = -1$, if $i = 3$ or 4 then o = 7 - i , m = 1, n = 2.



Phase-Matching Condition:

Phase mismatch $\kappa = \Delta\beta + \Delta\beta_{NL}$

$\Downarrow$

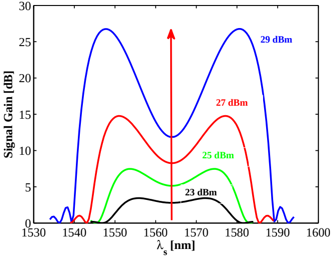
Linear and nonlinear mismatch cancels out

$$\boxed{\Delta\beta_{NL} \approx \gamma P_1 P_2 \quad \Rightarrow \quad \Delta\beta < 0}$$

M.E. Marhic, "Fiber Optical Parametric Amplifiers, Oscillators and related devices", Cambridge University Press (2008)

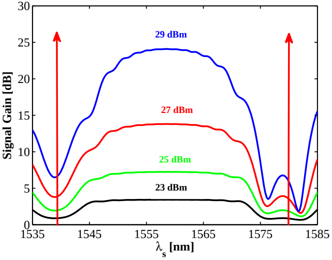
Fiber Optics Parametric Amplifiers

Single Pump



- Wide but un-uniform gain
- $\lambda_p \gtrsim \lambda_0$

Dual Pump



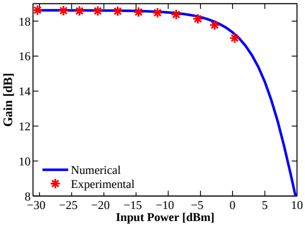
- Flat gain
- $\lambda_0 \approx (\lambda_{p1} + \lambda_{p2})/2$
- Lower power/pump

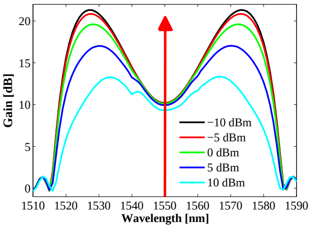
Saturation effects

In the unsaturated regime with perfect phase matching $\Delta\beta = -2\gamma P_T$

$$\boxed{G_{max} = \frac{1}{4}\exp\left(2\gamma P_T L\right)}$$

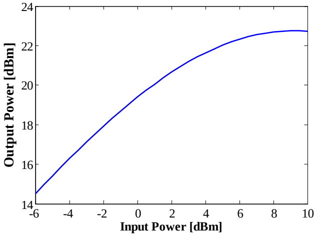
Signal power increases $\Rightarrow$ Pumps get depleted $\Rightarrow$ Gain decreases





Saturation Regime

Amplitude Regeneration

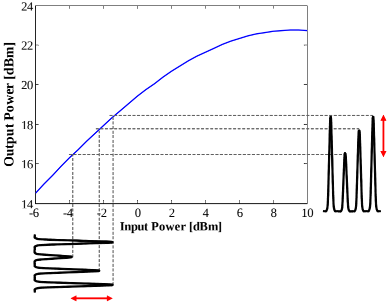


Signal power increases

$\Rightarrow$ Pumps get depleted

$\Rightarrow$ Gain decreases

Amplitude Regeneration



Signal power increases

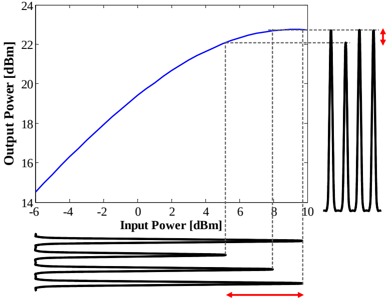
⇒ Pumps get depleted

⇒ Gain decreases

Unsaturated Regime

- High amplification

Amplitude Regeneration



Signal power increases

⇒ Pumps get depleted

⇒ Gain decreases

Unsaturated Regime

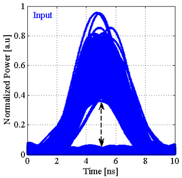
- High amplification

Saturation Regime

- Lower amplification
- Remove amplitude fluctuations

Regeneration of Modulated Signals

On-Off Keying



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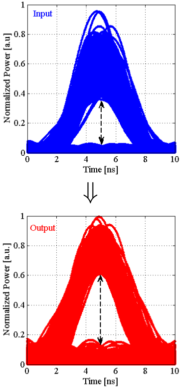

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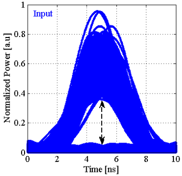

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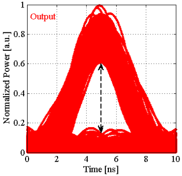
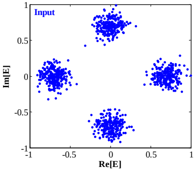


Quadrature Phase Shift Keying



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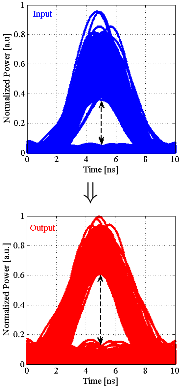

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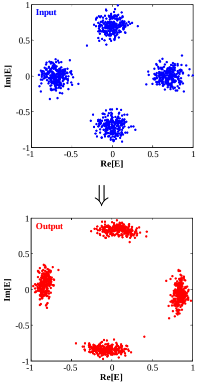

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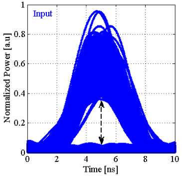

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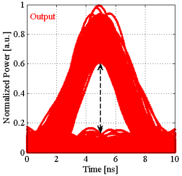

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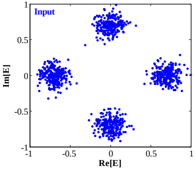

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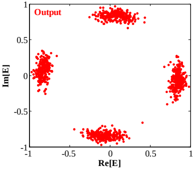
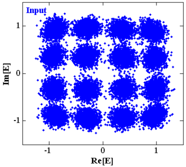


Quadrature Amplitude Modulation



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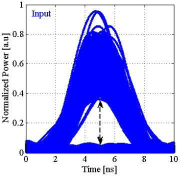

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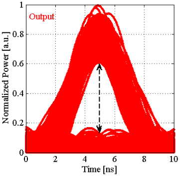

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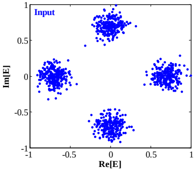

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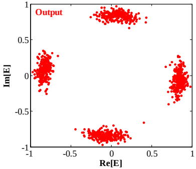

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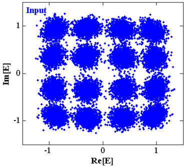

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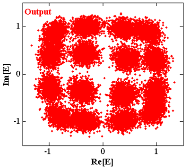

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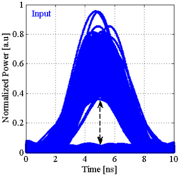

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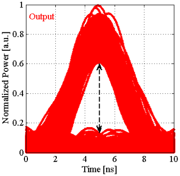

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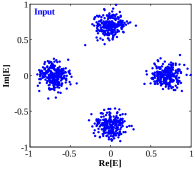

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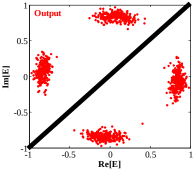

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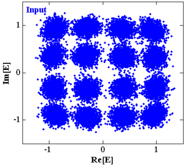

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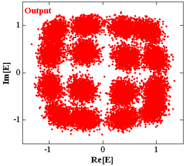

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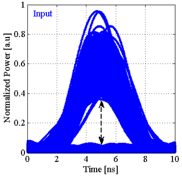

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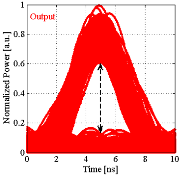

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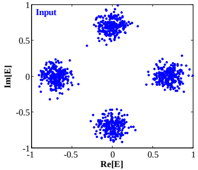

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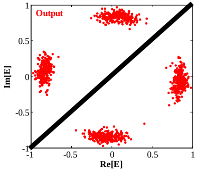

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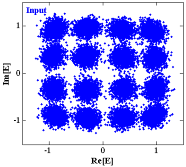

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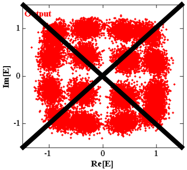


Phase Sensitive and Insensitive Amplification

Assuming undepleted pumps and $\Delta\beta = 0$:

$$\begin{pmatrix} A_S(L) \\ A_I^*(L) \end{pmatrix} = \begin{pmatrix} \cosh(\gamma L_{eff} P_T) & i\sinh(\gamma L_{eff} P_T) \\ -i\sinh(\gamma L_{eff} P_T) & \cosh(\gamma L_{eff} P_T) \end{pmatrix} \begin{pmatrix} A_S(0) \\ A_I^*(0) \end{pmatrix}$$

Signal, pumps and idler in input

$$G_S = 1 + 2\sinh^2(\gamma L_{eff} P_T) - 2\sinh(\gamma L_{eff} P_T)\cosh(\gamma L_{eff} P_T)\sin(\theta)$$

with $\theta = \Phi_I + \Phi_S - \Phi_{P1} - \Phi_{P2}$.

Phase Sensitive Amplification

Signal and pumps in input

$$G_S = 1 + \sinh^2(\gamma L_{eff} P_T)$$

Phase Insensitive Amplification

P.A. Andrekson, ECOC 2010, We.6.E.1

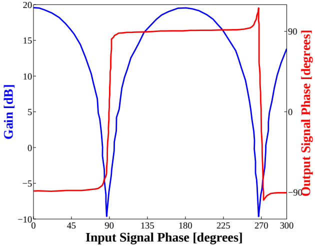
Phase Regeneration

- Both signal and idler in input

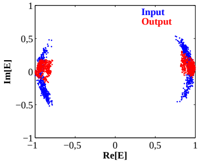
  $\Rightarrow \; G_S \propto \sin(\Phi_I + \Phi_S - \Phi_{P1} - \Phi_{P2})$

- Degenerate signal-idler scheme

  $\Rightarrow \; G_S \propto \sin(2\Phi_S - \Phi_{P1} - \Phi_{P2})$

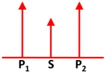


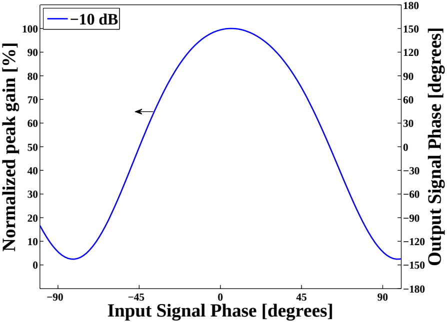
$\boxed{180^\circ\text{-periodicity for phase regeneration}}$



Saturation in Phase Sensitive Amplifiers

Dual-Pump degenerate scheme





Varying the signal-to-pump ratio:

- Gain peaks separated by 90°

  BUT

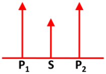
- No effects on the phase

NEVERTHELESS

$\boxed{\text{A } 180^\circ \text{ relative phase shift between the pumps shifts gain and phase profiles}}$

J. Kakande, et al., *ECOC* (2010), Th10C2.

Saturation in Phase Sensitive Amplifiers



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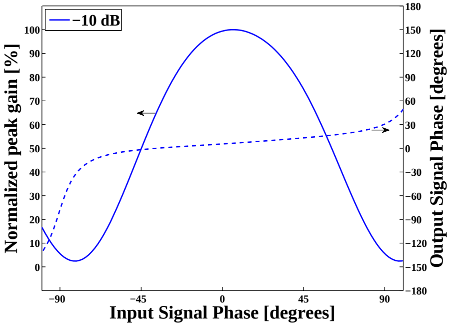

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Saturation in Phase Sensitive Amplifiers

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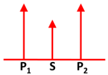

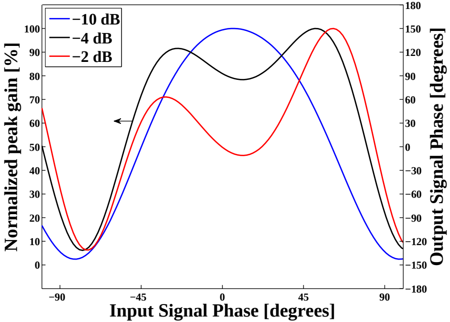

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Saturation in Phase Sensitive Amplifiers

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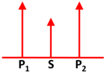

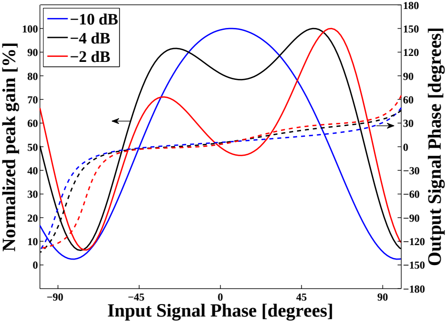

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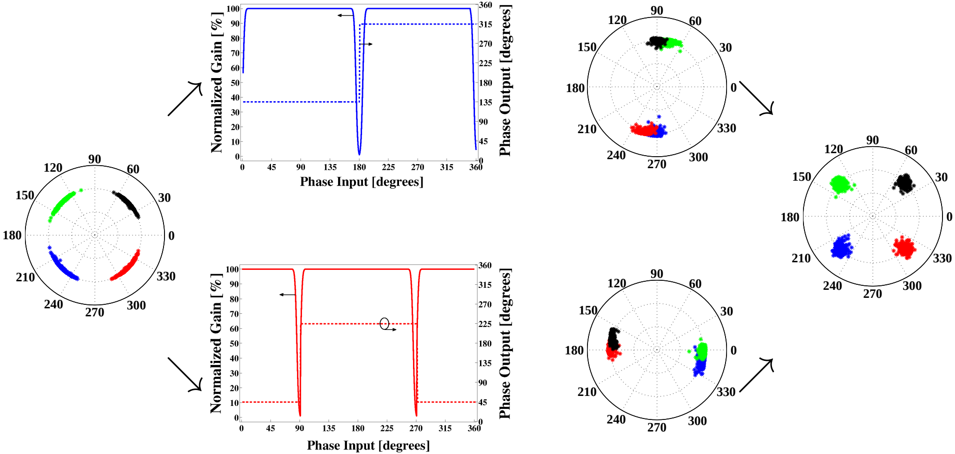
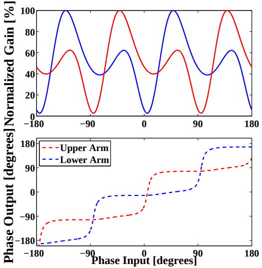
Saturation and Interference



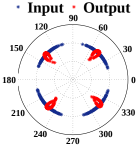
F. Da Ros, *IPC* (2011), M.M.3

Optimized Trends

Single Arms

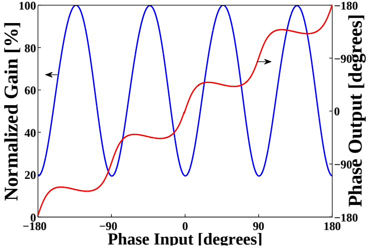


$\mathbf{R_s = 28}$ Gbaud

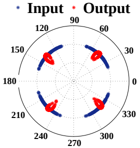


$\Longrightarrow$

Overall



$\mathbf{R_s = 40}$ Gbaud



F. Da Ros, *IPC* (2011), M.M.3

Conclusions

- Fiber optic parametric amplifiers not only provide high, wide and flat gain at arbitrary wavelength but also show a strong potential for all-optical signal processing.
- Two of the most promising properties that can be exploited are saturation and phase sensitive amplification.
- Saturation in FOPAs enables to reduce the amplitude noise on optical signal regardless of the bitrate.
- Phase sensitive amplification allows reducing phase noise for phase modulated signals.
- Phase sensitive amplification in the saturated regime leads the way towards advanced modulation formats regeneration.

Questions

Thank you for the attention.