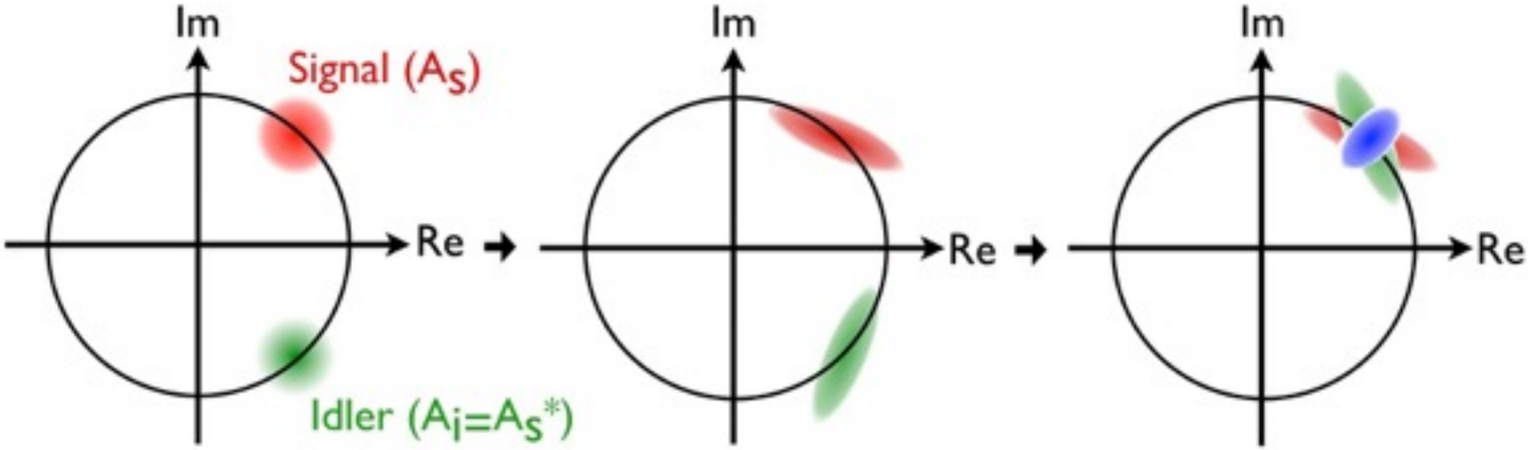
Nonlinear distortion mitigation by conjugation

Magnus Karlsson
Chalmers University of Technology
Sweden
email: magnus.karlsson@chalmers.se

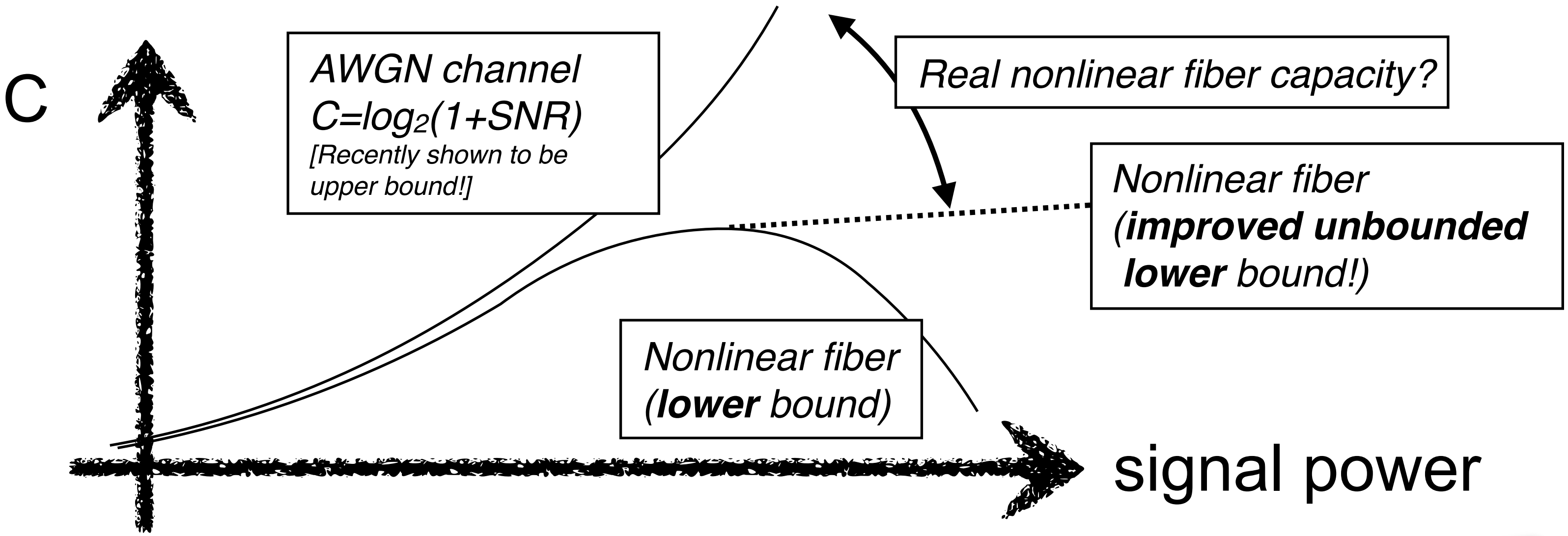


Outline

1. Introduction: information theory, capacity - why optical compensation?
2. Phase conjugation: what, when why, how.
3. Examples of recent Chalmers work
   – PSAs
   – conjugate data repetition
   – Self-homodyne reception
4. How can we get *significantly* more than 3 dB of gain?

1. Introduction: Nonlinear distortion - optical compensation?

What about Shannon capacity in fibers?



<u>If you get a *decreasing* capacity curve you are either:</u>

- computing a lower bound
- using an improper channel model, e.g.,
  - depending on signal power,
  - infinite memory
- not optimizing over enough modulation formats
- using multichannel transmission with particular behavioral models

<u>Reading list:</u>

R-J. Essiambre et al., JLT 2010
(Capacity in fiber systems)
E. Agrell, TCom. 2015
(Capacity and lower bound)
E. Agrell et al. JLT 2014,
(channels with memory)
E. Agrell and M. Karlsson, JLT 2015
(multiuser channels)
G. Kramer et al., ArXiv 2015
(upper bound)

How can we increase throughput?

- More channels in parallel
  - time (TDM, limited by electronic speeds)
  - wavelength/frequency (WDM, limited by optical amplifier bandwidth)
  - spatial - cores, modes, polarizations (SDM, unlimited !?!)
- Better channel hardware
  - novel fibers (lower loss, lower NL, less (or more!) dispersion)
  - better amplifiers (distributed, phase-sensitive, broadband)
  - faster and more advanced Tx/Rx (high-speed electronics, more DSP)
- Higher order modulation formats+coding
  - requires high SNR (limited by nonlinearities)
  - coded modulation, optimized for the optical channel
  - may require NL mitigation

NL crosstalk in one channel

- For a single channel, 1000 km SMF, a pulse can interact with hundreds of neighbors.
- Thus to counteract NL crosstalk, a sequence of 100-300 symbols must be jointly processed.
- NL backpropagation!
- Cf. bit framing for decoding.

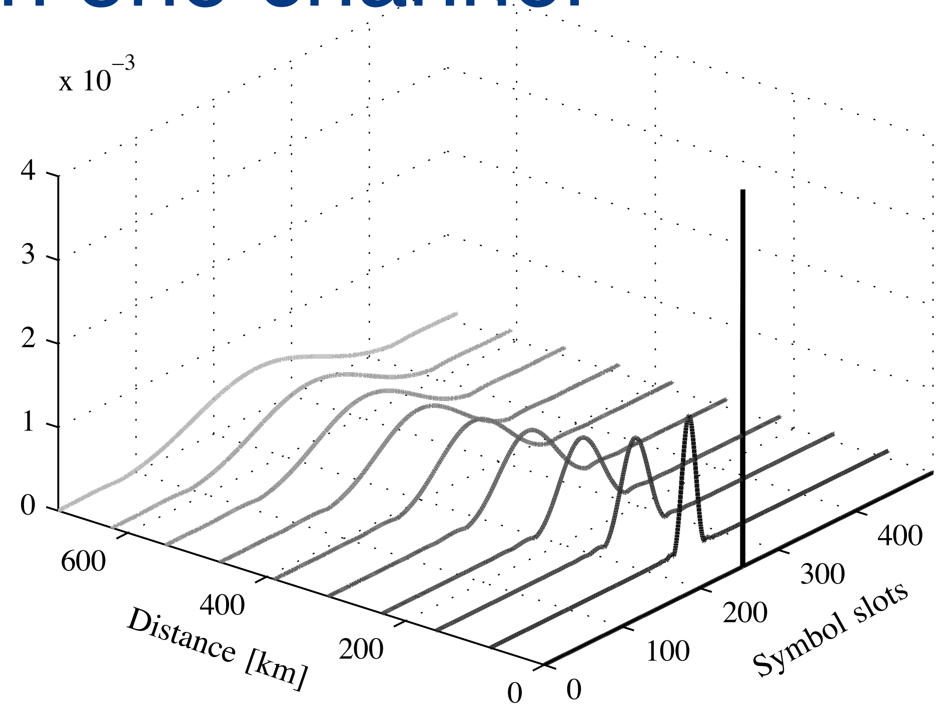
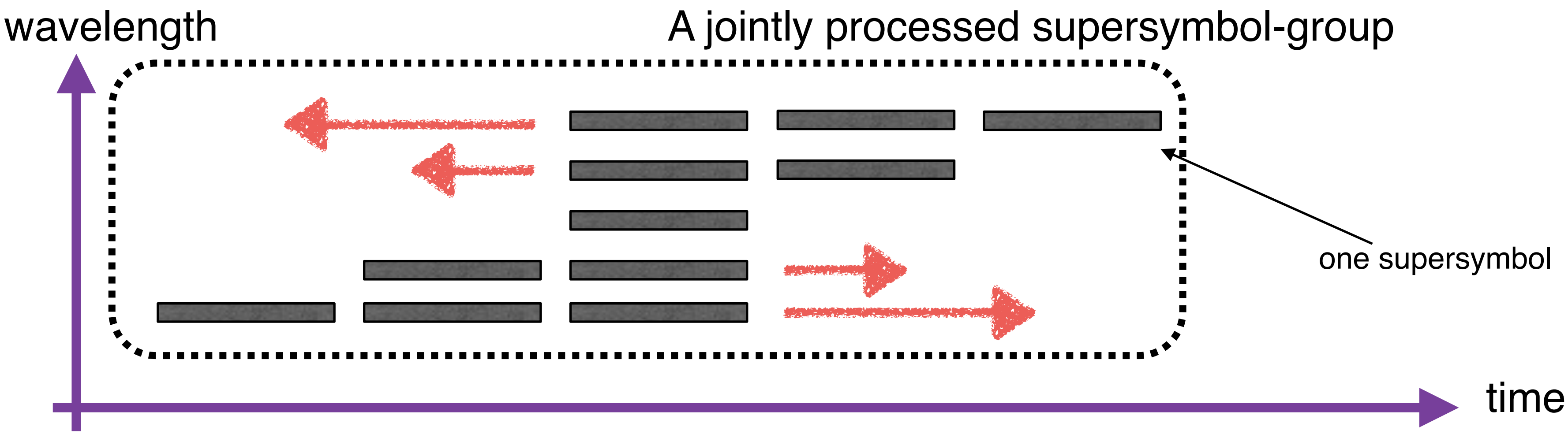


Fig. 1. Amplitude for a linearly propagating 15.6 ps raised-cosine pulse (compatible with 32 GBaud) over 700 km fiber with $\beta_2 = -21.7$ ps^2/km.

A jointly processed supersymbol

NL crosstalk in WDM



- Dispersive walk-off makes the “supersymbols” from adjacent wavelengths interfere nonlinearly.
- One then needs to process joint ***groups of supersymbols*** in the NL backpropagation.
- PMD issues
- Incompatible with add/drop lambda-networking.
- Full phase and pol (?) reference knowledge required.

<u>Reading list:</u>

X. Li et al., Opt Exp. 2008.
(single ch. backrprop)
E. Ip and J. Kahn, JLT 2009.
(single ch. backrprop)
R. Maher et al., Nat Sci Rep. 2015.
(WDM backrprop, single det.)
E. Temprana et al., Op. Exp. 2015.
(WDM backprop, multiple det.)

Why Optics and not DSP for equalization?

+ Not limited by electronic bandwidths
+ Usually more power efficient (than DSP)
+ WDM (and SDM?) may scale nicer than DSP
– Less mature hardware, imperfections, complexity, losses.

- Performance?
- Potential?
- Fundmental limits? (NL phase noise)

"Nonlinear interference is noise"

Essiambre, Poggiolini, Ellis, Shtaif, Mecozzi, Dar
Johannisson, Karlsson

"Nonlinear interference is not noise"

Agrell, Kramer, Durisi, Secondini, Karlsson

"Opportunistic? Me?"

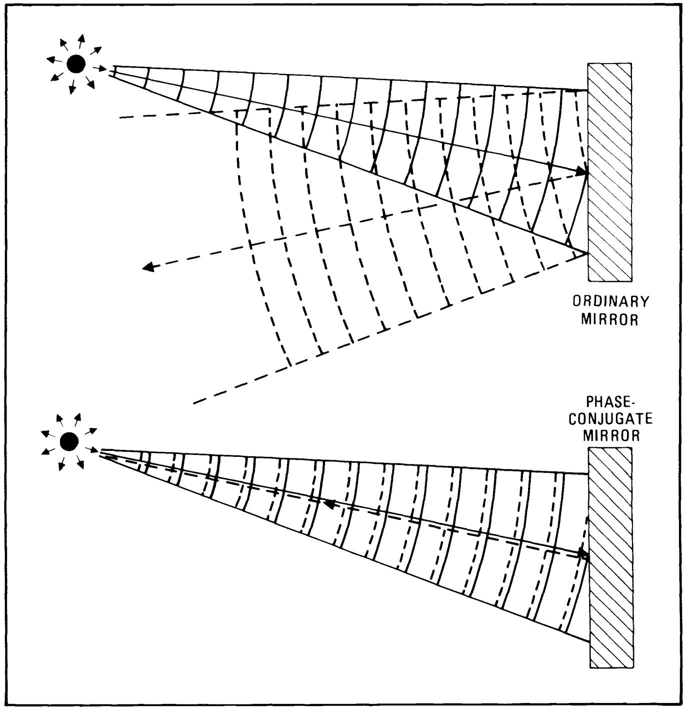
Karlsson

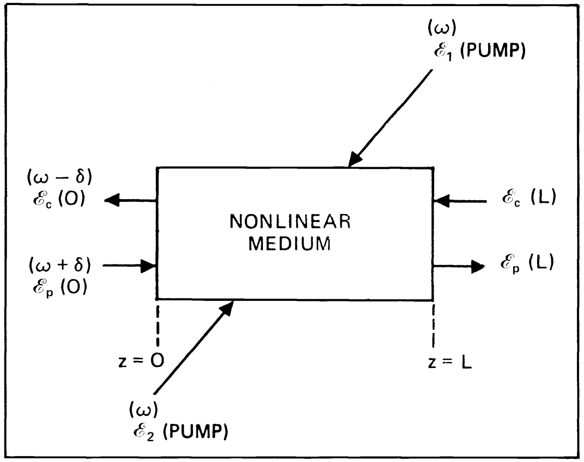
"Those are my principles, and if you don't like them… …well I have others."

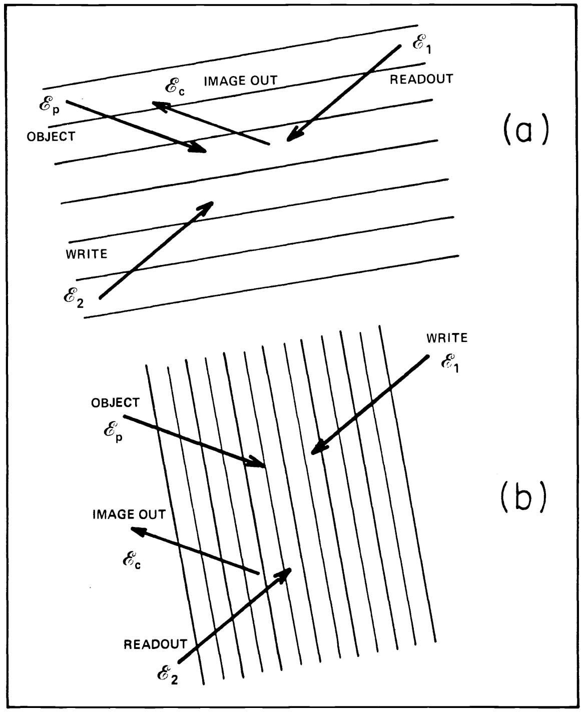
G. Marx

2. Phase conjugation

Phase-conjugation, spatial



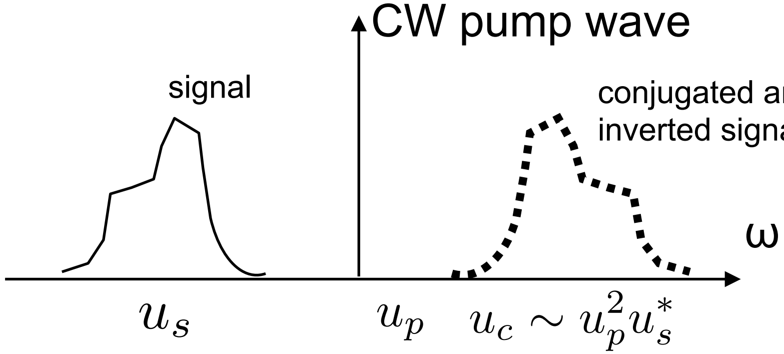




[D. Pepper, Opt. Eng -82.]

- Phase conjugation can be interpreted as time reversal.
- Interpreted from FWM in terms of induced gratings.

Phase conjugation, temporal



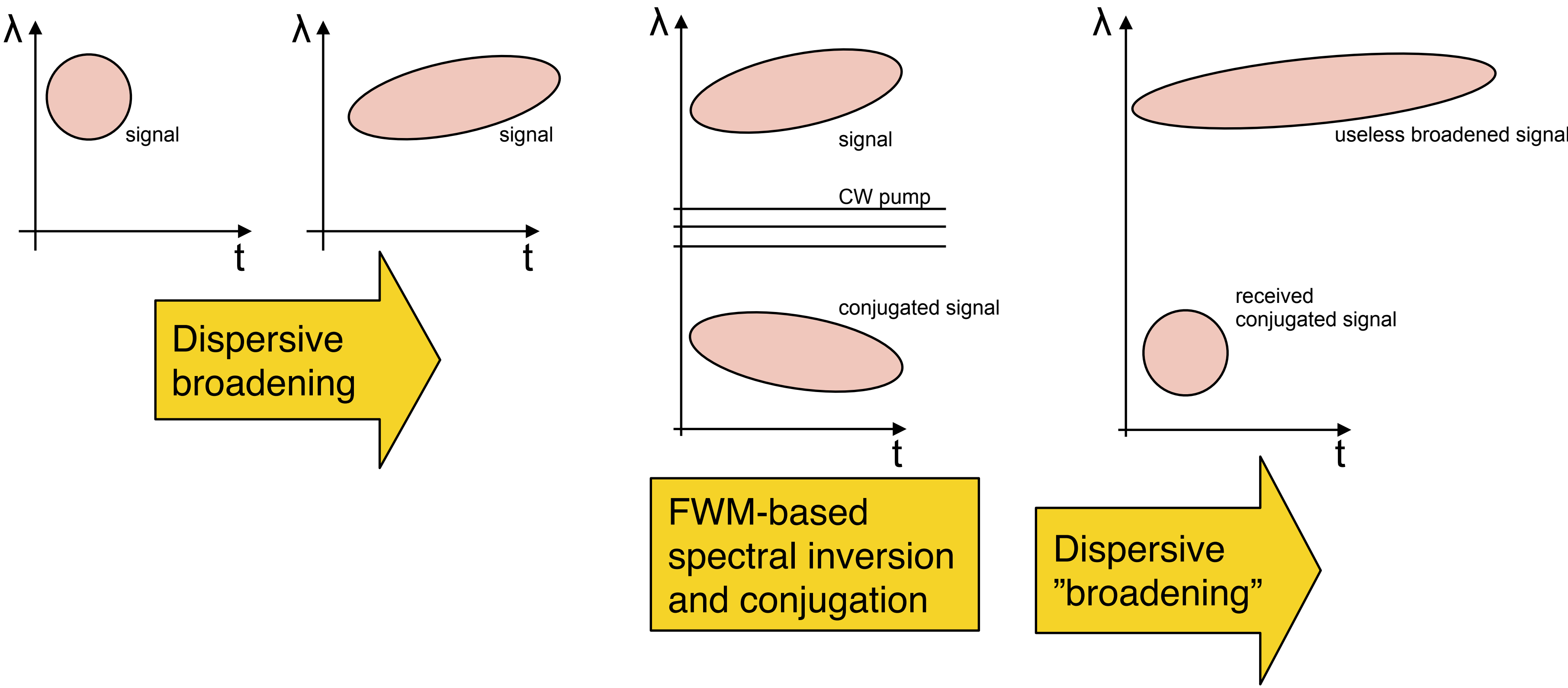
$$\tilde{u_s}(\omega) = \int u_s(t)\exp(i\omega t)dt$$

$$\tilde{u_c}(\omega) = \tilde{u_s}(-\omega)^*$$

$$u_c(t) = \int \tilde{u_s}^*(-\omega)\exp(-i\omega t)d\omega = \left(\int \tilde{u_s}(\omega)\exp(-i\omega t)d\omega\right)^* = u_s(t)^*$$

- Every frequency component is conjugated and spectrally mirrored in the CW pump.
- Conjugation in time = (conjugation+spectral inversion) in frequency

Mid-span spectral inversion



- Phase conjugation can be interpreted as time reversal.
- Interpreted from FWM in terms of induced gratings.

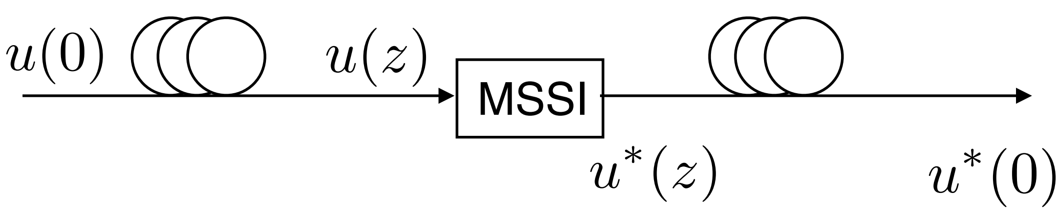
MSSI vs backprop

$$i\frac{\partial u}{\partial z}+\frac{\beta(z)}{2}\frac{\partial^2 u}{\partial t^2}+\gamma(z)|u|^2u=0$$

accnt. for losses and varying disp.

$$-i\frac{\partial u^*}{\partial z}+\frac{\beta(z)}{2}\frac{\partial^2 u^*}{\partial t^2}+\gamma(z)|u|^2u^*=0$$

if u(z) is a solution then u^*(-z) is a solution provided $\beta(z)$ $\gamma(z)$ are symmetric.



Quantum mechanical aspects

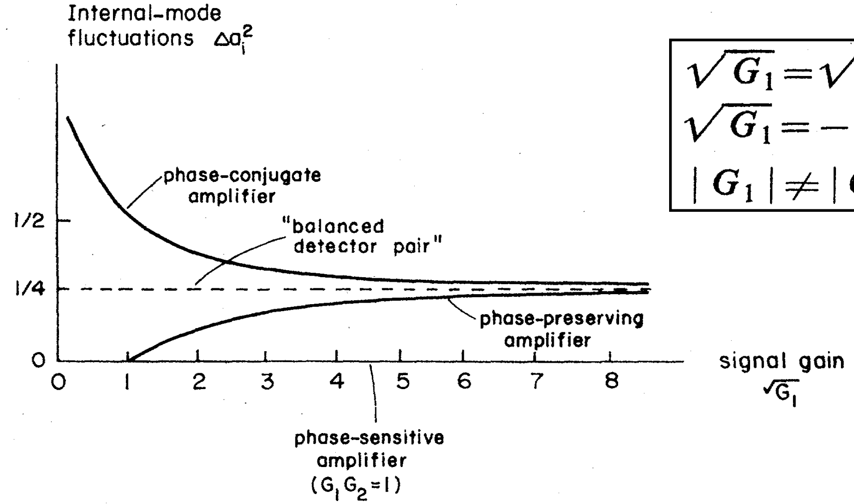


FIG. 3. Internal-mode fluctuations vs signal gain for a phase preserving amplifier, a phase-conjugate amplifier, a phase-sensitive amplifier, and "balanced detector pair."

$$\sqrt{G_1} = \sqrt{G_2} \quad \text{(phase-preserving amplifier)},$$
$$\sqrt{G_1} = -\sqrt{G_2} \quad \text{(phase-conjugate amplifier)},$$
$$|G_1| \neq |G_2| \quad \text{(phase-sensitive amplifier)},$$

[Yamamoto & Haus, Rev. Mod. Phys-86]

- Phase conjugation has the same 3dB quantum limit as phase-insensitive amplification @ G >> 1.
- The NF -> inifinity for small gain (cf phase-insensitive amp)
- Cannot be done without a penalty in terms of added noise.
- Noiseless quantum cloning is forbidden.

History of PC for distortion mitigation in fiber

Midspan spectral inversion

79: Yariv et al., proposal
80: Yariv, Pepper, NL distortions
81: Fischer, Yevick, NLSE compens.
82: Pepper, Review in Opt. Eng.

93: Jopson, EL, Exp. demo, pol. indep.
94: Pieper, EL, NL comp exp.
96: Watanabe, JLT, symmetry reqs. for disp, att, NL
96: Hedekvist, JLT, Exp.
97: Lorattanasane, JLT, num studies

04: Woods, Shtaif, WDM sim.
06: Jansen, JSTQE, WDM exp.
09: Minzioni, Fib.Int.Opt., rev.

12: Lu, Lowery, OE, OFDM
12, Pelusi, OE,Tunable PC
14: Phillips, OE, WDM Pol.indep. exp.
14: Sackey, ECOC, WDM Pol.indep. exp.
15: Hu, Jopson, JLT, WDM Pol.indep. exp.
15: Ellis, OE, multiple PC

1980 1990 2000 2010

09: Sjödin, ECOC, self-homodyne
10: Johannisson, PTL, self-homodyne

Self-homodyne and Conjugate twin channels

13: Olsson, ECOC,PSA (2 wavelengths)
13: Liu, NP, Twin waves (2 polarizations)
14: Tian, OE, (2 wavelengths+DSP)
15: Eliasson, OE, (2 timeslots)
15: Le, Ellis, JLT, (2 CO-OFDM pilots)
15: Le, Ellis, JLT, (2 OFDM channels)

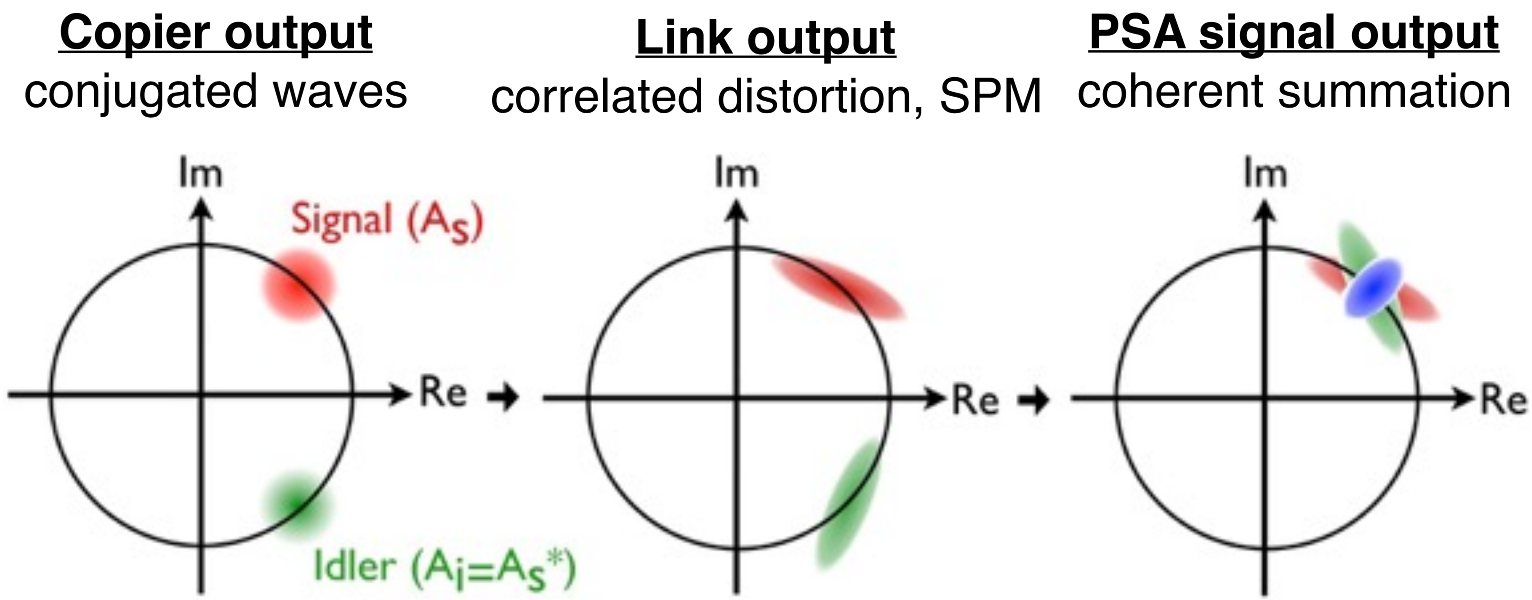
**Motive:
dispersion compensation**

**Motive:
NL compensation**

3. Examples of recent Chalmers work

- PSA as twin wave compensation
- Conjugate data repetition
- Self-homodyne reception

Nonlinear distortion mitigation in copier-PSA-links

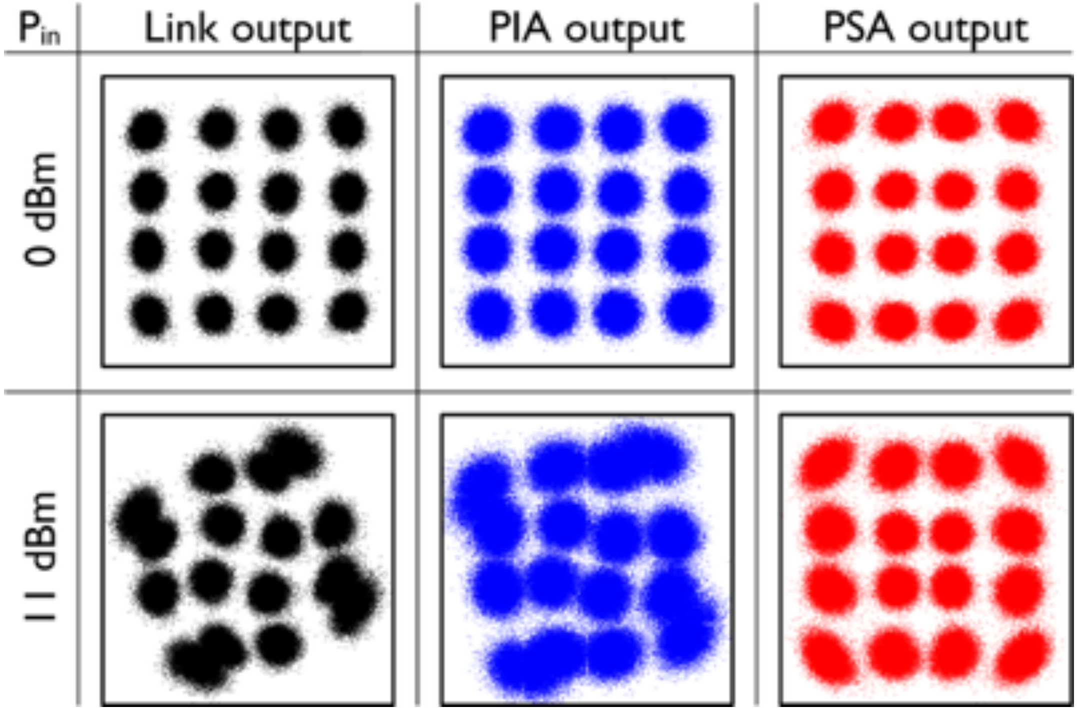


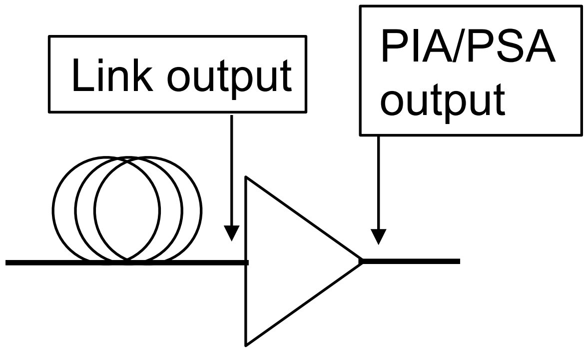
The coherent superposition in the PSA will counteract nonlinear self-phase modulation. To do this in DSP is known as *twin-wave transmission**.

*[*X. Liu et al., Nat. Phot. 2013]*

[Olsson, Corcoran et al., ECOC 2012, 2013, OFC 2014]

Transmission of 16-QAM data

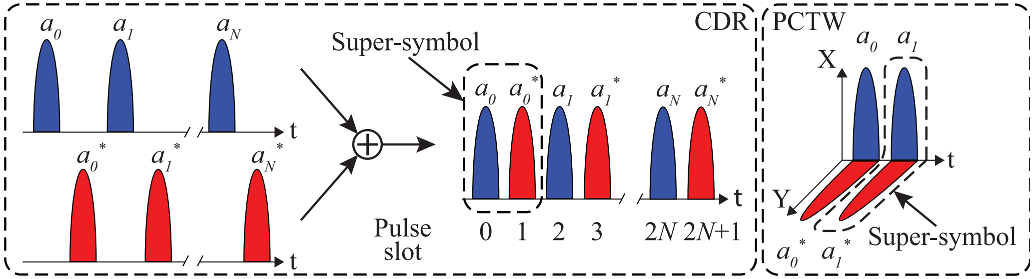




Transmission of 16-QAM, 10 GBd (40 Gb/s) signal over 105 km link with large nonlinear distortion mitigation.
Linear regime: PSA less noisy than PIA
Nonlinear regime: PSA constellation mitigated.

[S.L.I. Olsson, et al., OFC 2014, paper Th1H.3]

Conjugate data repetition - twin beams in time



- CDR and PCTW have same performance, but CDR may be easier to implement.
- Doubles the reach at the same datarate.

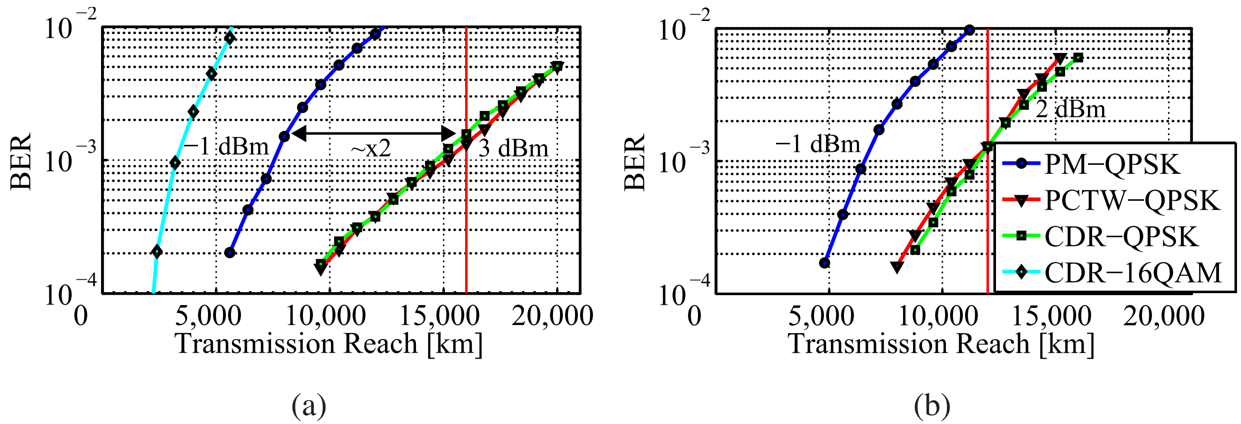
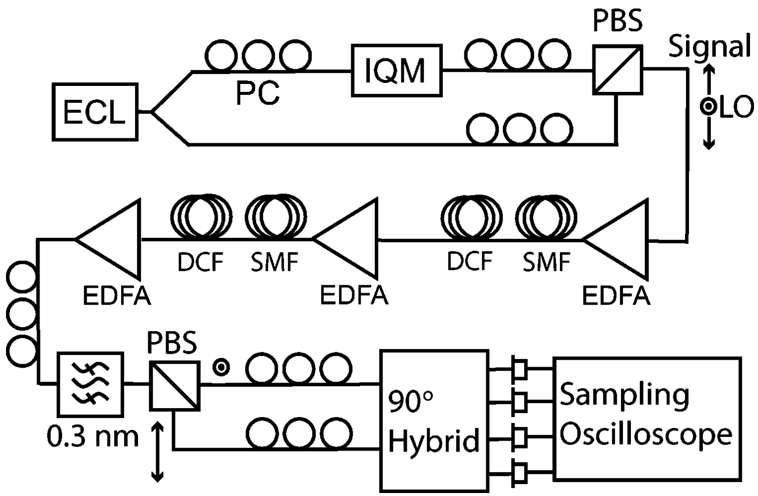


Fig. 3. Simulated BER as a function of transmission distance for (a) single channel and (b) 7-channel WDM for 28 GBaud PM-QPSK, 56 GBaud PCTW-QPSK, 56 GBaud CDR-QPSK and 28 GBaud CDR-16QAM. Optimum launch powers are specified in the figures. The distance where the dispersion map is perfectly symmetric is marked with a vertical red line.

H. Eliasson et al., Optics Express 2015

Self homodyne nonlinear mitigation



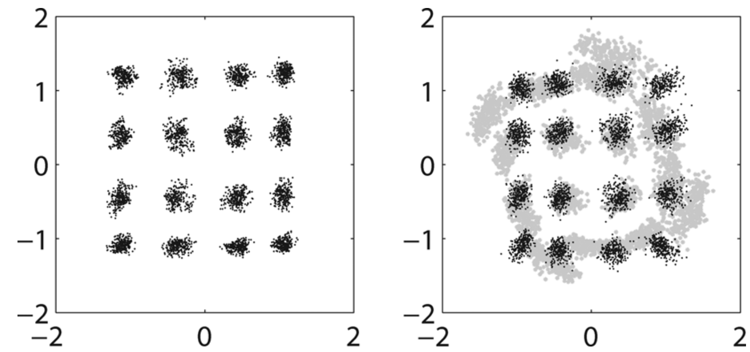


Fig. 7. Measured 16-QAM constellations at 10 GBd. Left: Back-to-back constellation. Right: Constellation after transmission with 7-dBm launch power with (black dots) and without (gray stars) matched receiver paths.

- The LO co-propagates with signal in the orthogonal polarization.
- LO and signal obtains the same NL phase shifts (via XPM in the Manakov model).
- This is undone when the LO and signal beats in the coherent receiver. $i_{det} \sim 2Re(u_{LO}^{*} u_{sig})$
- Compare and contrast with coherent superposition.

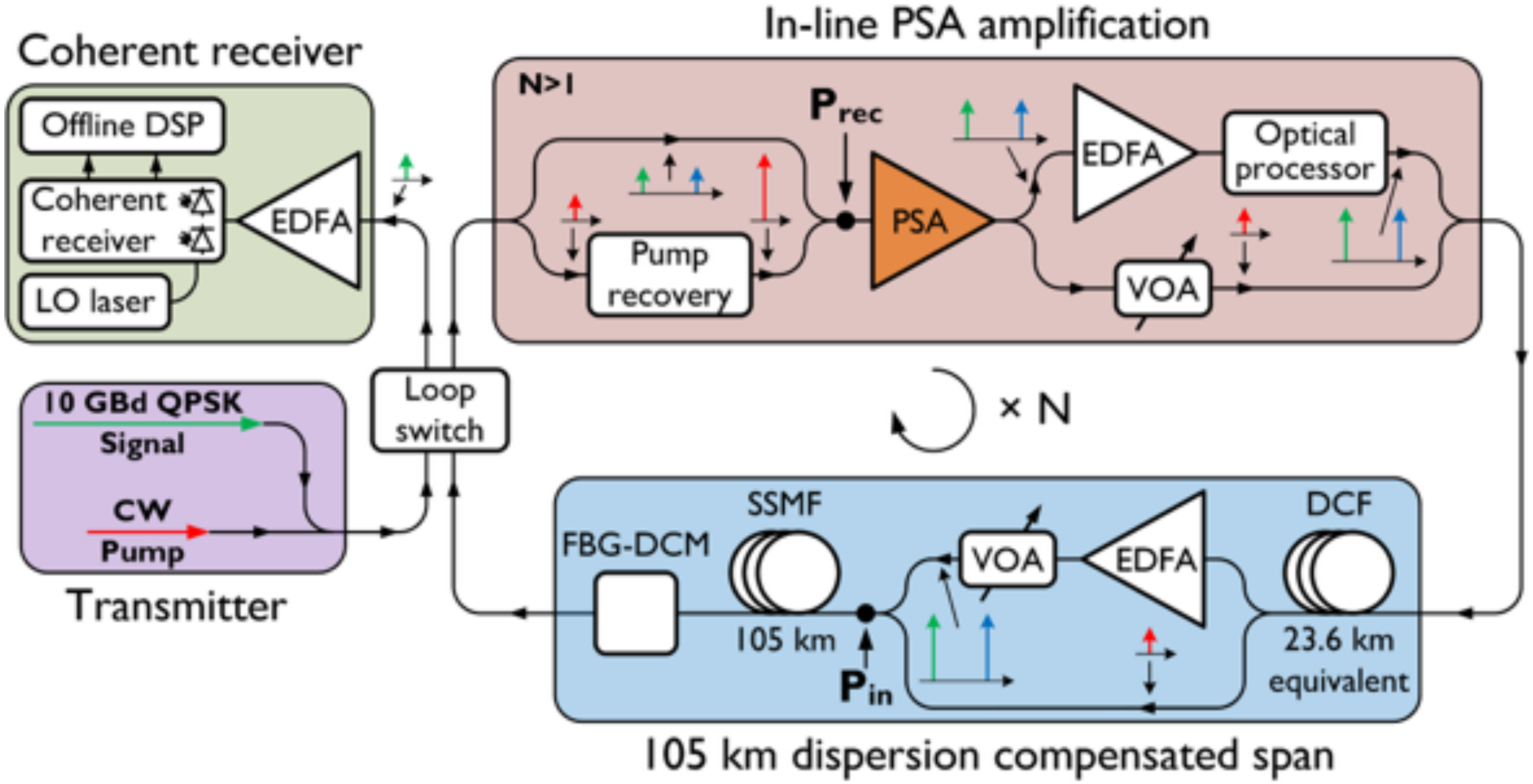
P. Johannisson et al., PTL 2010

4. How can we get beyond 3 dB of improvement?

Distributed or periodic conjugation!

- PSA-based links
- Raman-based superpos. links

Phase-sensitive amplifier loop experiment

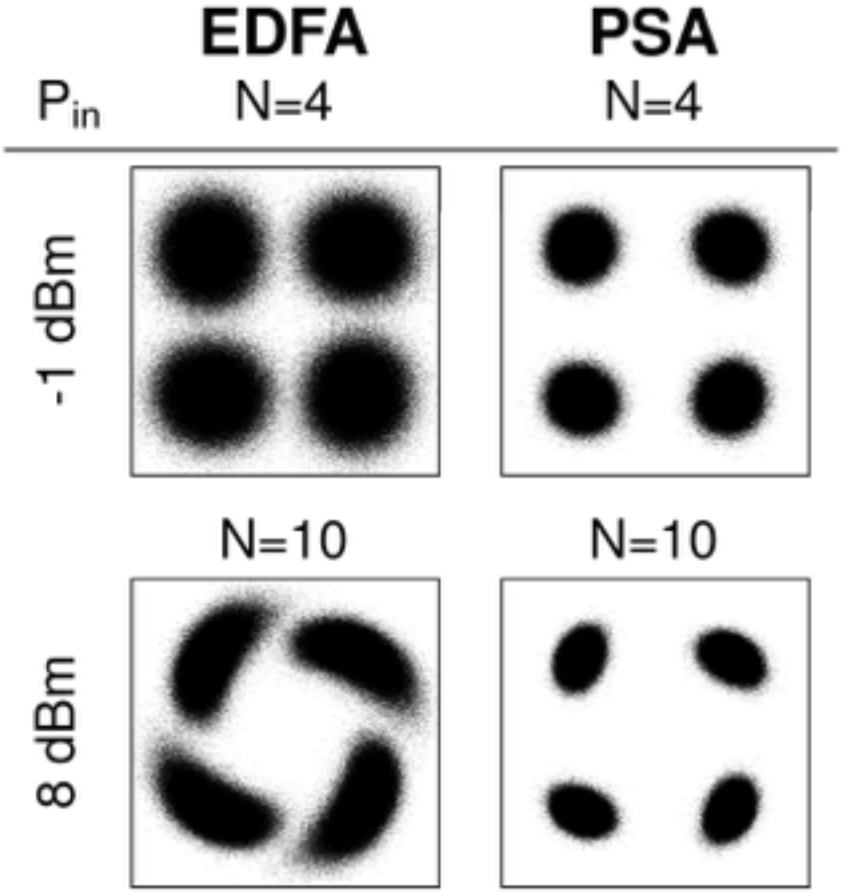


- First PSA high-gain, long-haul loop experiment.

S. Olsson et al., ECOC 2014

Phase sensitive amplifiers

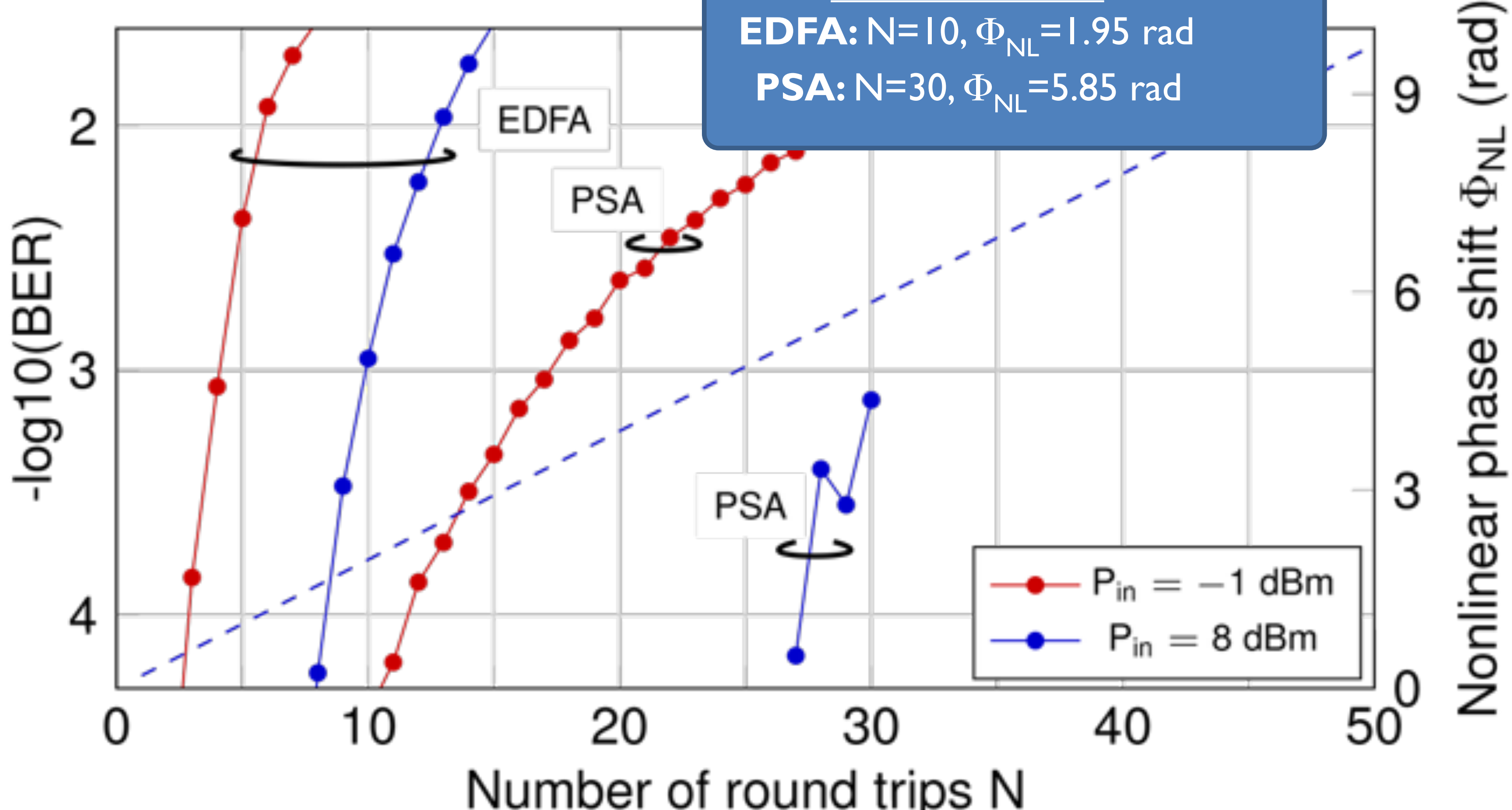
- Can provide higher sensitivity than PIAs (e.g. EDFAs) (PSAs have 0 dB quantum-limited noise figure).
- Capable of mitigating nonlinear transmission distortions (PSAs perform coherent superposition of signal and idler).



S. Olsson et al., ECOC 2014

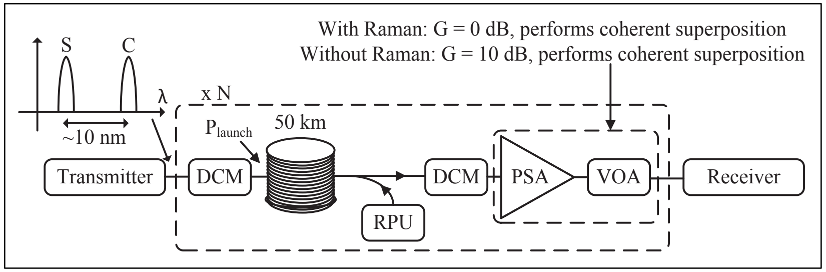
Comparison Nonlinear Regime

At BER=1×10^{-3}
EDFA: N=10, Φ_{NL}=1.95 rad
PSA: N=30, Φ_{NL}=5.85 rad

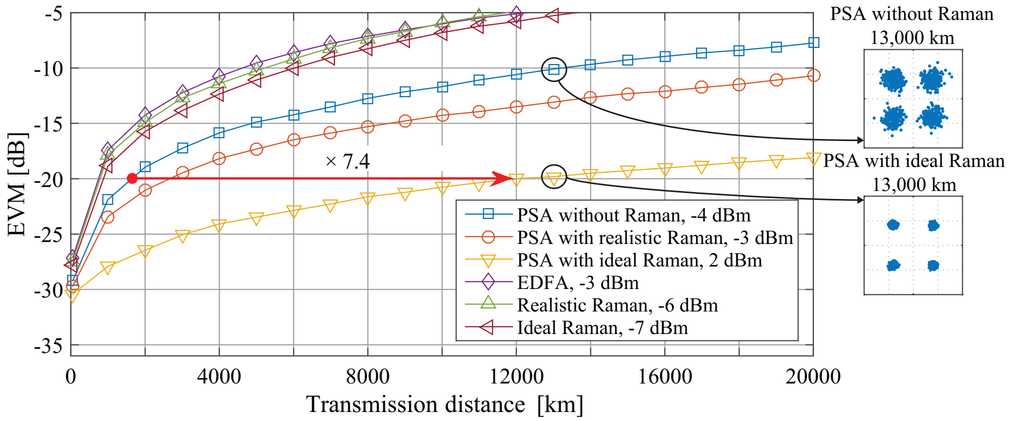


S. Olsson et al., ECOC 2014

Raman+PSA links



- Use Raman amplification for power symmetry.
- Passive disp comp.
- PSA for coherent superpos. (but not gain).
- Huge improvement in performance.
- cf. A. Ellis et al. OpEx (2015)



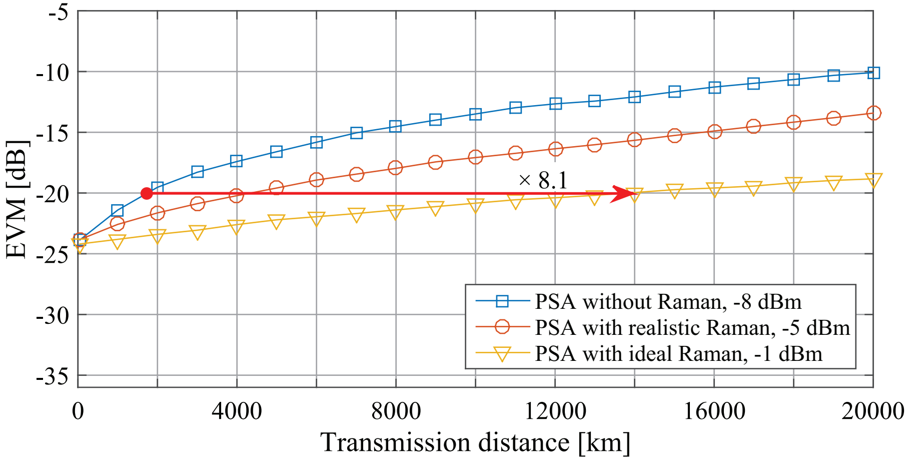


Fig. 8: EVM as a function of transmission distance for 5-channel WDM 28 GBaud QPSK systems at optimum launch powers.

H. Eliasson et al., subm to Optics Express 2015

Conclusions

- Regular phase conjugation and various twin beam transmission schemes give typically 3 dB improvements.
- Greater improvement can be achieved by going to distributed, or repeated, conjugation/superposition.
- Fundamental limits still unknown. Is there a maximum NL phase shift that can be cancelled before NL phase noise kicks in?

- How much NL phase shift can your scheme tolerate?
- Distributed PSA (or PC) are the only one giving

$$\boxed{\phi_{NL} = \int_{\mathrm{systemlength}} \gamma P(z) dz > \pi}$$

…perhaps?

Further reading:

- **MSSI:**
  - D. Pepper, ”Nonlinear Optical Phase Conjugation”, Optical Engineering 21 (2), pp.158 (1982).
  - S. L. Jansen, D. van den Borne, P. M. Krummrich, S. Spälter, G.-D. Khoe, and H. de Waardt, ”Long-Haul DWDM Transmission Systems Employing Optical Phase Conjugation”, Journal of Selected Topics of Quantum Electronics 12, pp. 505-520 (2006)
  - P. Minzioni, ”Nonlinearity Compensation in a Fiber-Optic Link by Optical Phase Conjugation ”, Fiber and Integrated Optics 28, pp. 179–209, (2009).
- **Self-homodyne:**
  - P. Johannisson, M. Sjödin, M. Karlsson, E. Tipsuwannakul, and P. Andrekson, ”Cancellation of Nonlinear Phase Distortion in Self-Homodyne Coherent Systems”, IEEE Phot. Technol. Lett. 22, p.802-804 (2010).
- **Conjugate data repetition:**
  - H. Eliasson, P. Johannisson, M. Karlsson and P. A. Andrekson, ”Mitigation of nonlinearities using conjugate data repetition”, Optics Express 23, pp. 2392-2402 (2015).
- **Multiple phase conjugation:**
  - A. D. Ellis, M. E. McCarthy, M. A. Z. Al-Khateeb, and S. Sygletos, ”Capacity limits of systems employing multiple optical phase conjugators”, Optics Express 23, pp. 20382-20393 (2015).