All-Optical Processing of Novel Modulation Formats Using Semiconductor Optical Amplifiers

Tutorial FTuV1

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The 90th OSA Annual Meeting — Frontiers in Optics 2006 / Laser Science XXII
October 8–12, 2006, Rochester (NY), USA

Acknowledgements

Many thanks to all who have contributed to the content presented here:

Philipp Vorreau
Andrej Marculescu
René Bonk
M. H. Chaudhary
Jin Wang
Gunnar Böttger
Alexander-Boris Bolles
Yang Jiao

This work was supported by the

- European project TRIUMPH (grant IST-027638 STP), by the
- Center for Functional Nanostructures (CFN) of the Deutsche Forschungsgemeinschaft (DFG) within Projects A3.1 and A4.4, and by the
- DFG Research Training Group 786 "Mixed Fields and Nonlinear Interactions" at the University of Karlsruhe, Karlsruhe, Germany.

What is this tutorial about?

NRZ-OOK has been the data format of choice for decades:

- Nonreturn-to-zero on/off keying (NRZ-OOK, low complexity)

Bit rates $\geq$ 40 Gbit/s/ch need novel OOK formats or regeneration:

- DB (CD tolerance $\geq$ 120 ps/nm)
- VSB-CSRZ (spectral efficiency $\geq$ 0.8 bit/s/Hz)

Bit rates $\geq$ 40 Gbit/s/ch with novel phase modulation formats:

- RZ-DPSK (nonlinear tolerance)
- RZ-DQPSK (CD tol. $\geq$ 120 ps/nm, DGD tolerance $\geq$ 20 ps, spectral efficiency $\geq$ 0.8 bit/s/Hz, nonlinear tolerance)

SOA with fast XPM / XGM (cross-phase / gain modulation) act as

- all-optical logic gates, and as
- all-optical wavelength converters and regenerators.

Optical Wavelength Division Multiplexing (WDM)

- Internet: Need for bandwidth B

- Optical transmission systems

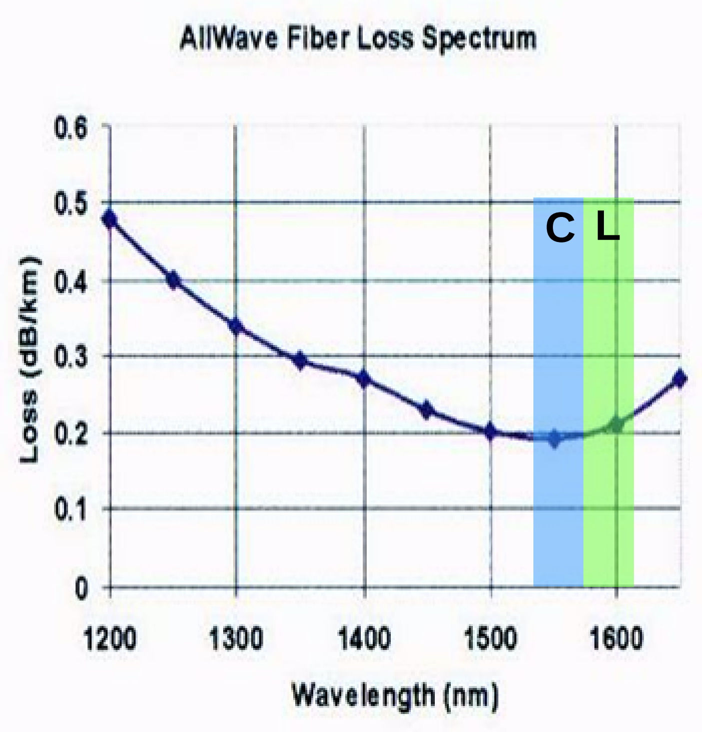
  fibres: $B \approx$ 65 THz (450 nm)

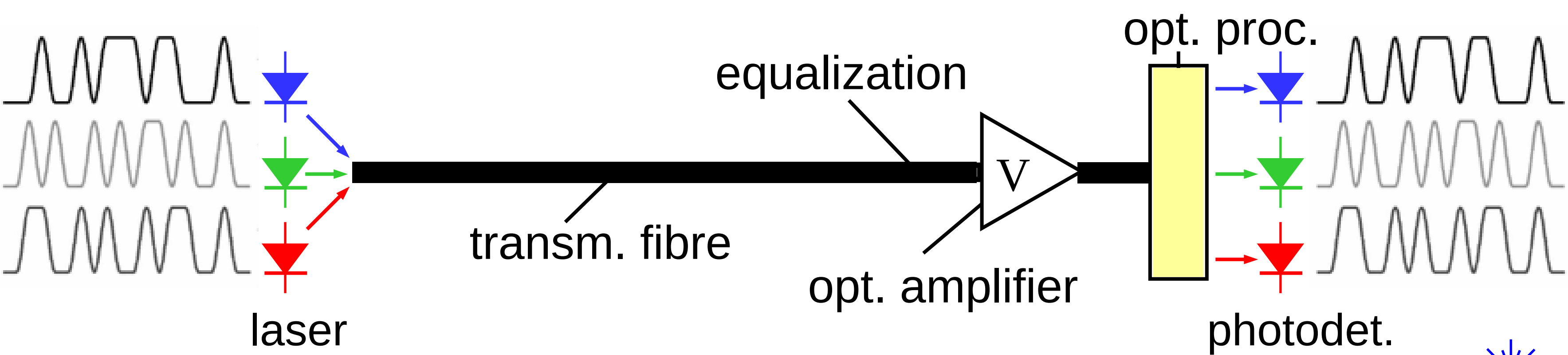
  amplifiers: $B \approx$ 10 THz (80 nm)

  wavelength division multiplexing

  channels: $\Delta f \approx$ 5, 10, 25, 50, 100 GHz

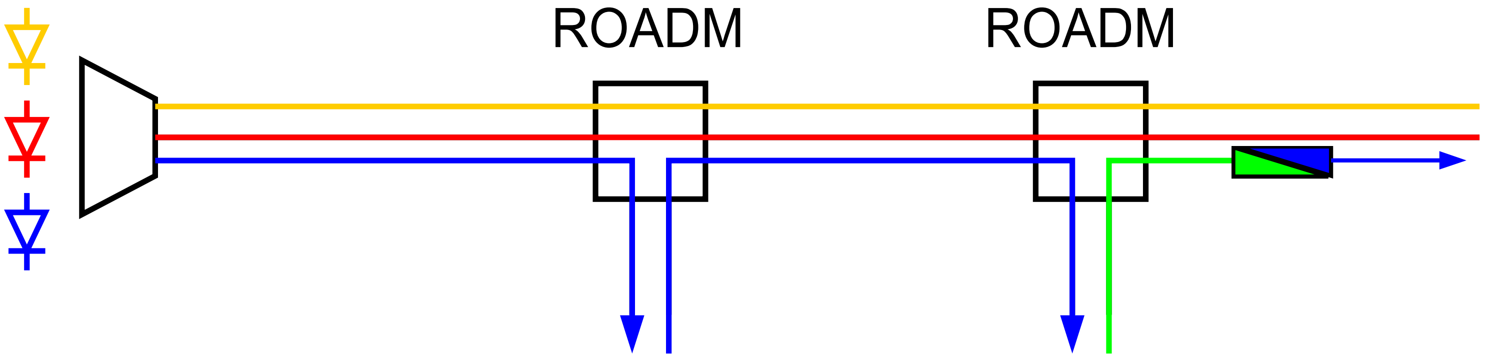
  capacity: 40 Gbit/s $\times$ 100 ch = 4 Tbit/s





The Need for All-Optical Processing — Wavelength Blocking

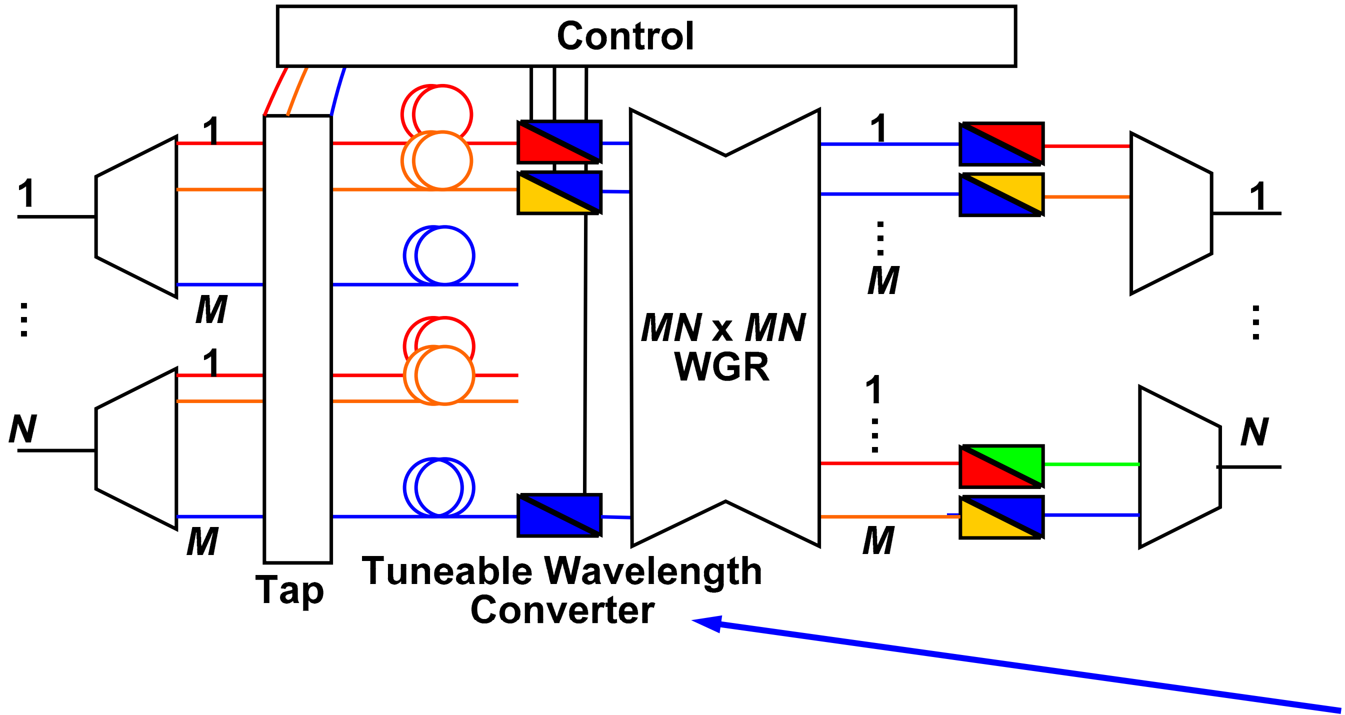
Optical transparent wavelength division multiplexing (WDM) networks need reconfigurable optical add-drop multiplexers (ROADM):



All-optical wavelength converters prevent wavelength blocking.

The Need for All-Optical Processing — Space Switching

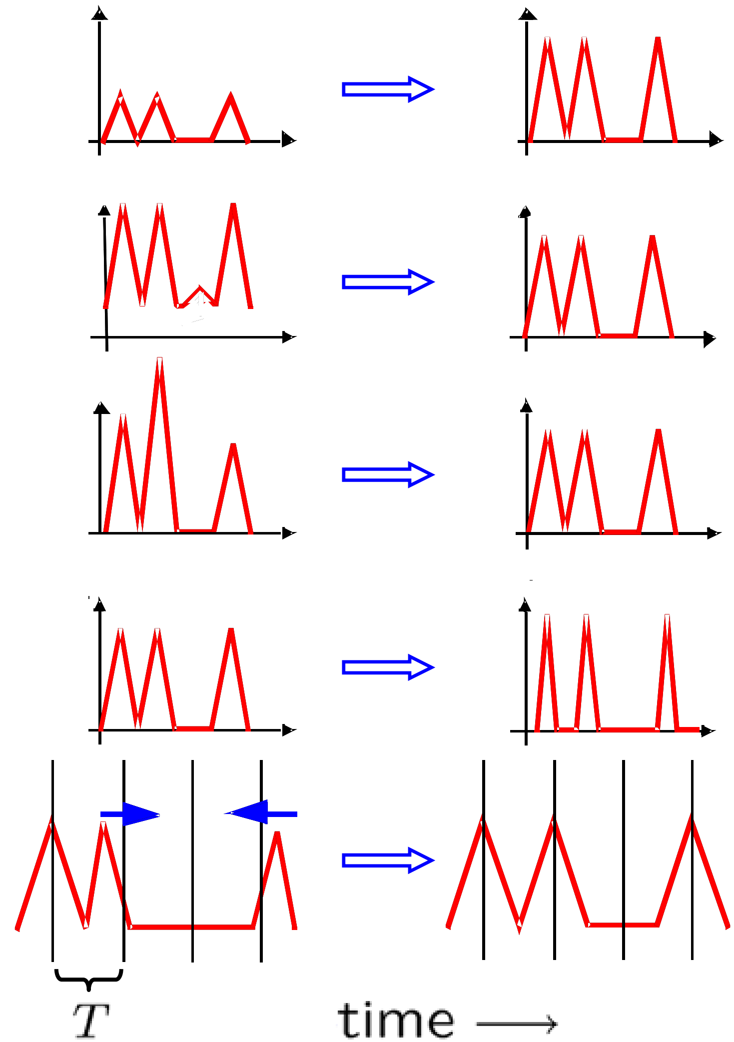
Optical cross-connect (OXC) in a meshed network:



- Sub-nanosecond guard time for reconfiguring a tunable laser
- Space-switching via fast wavelength switching and WGR
- Wavelength mapping

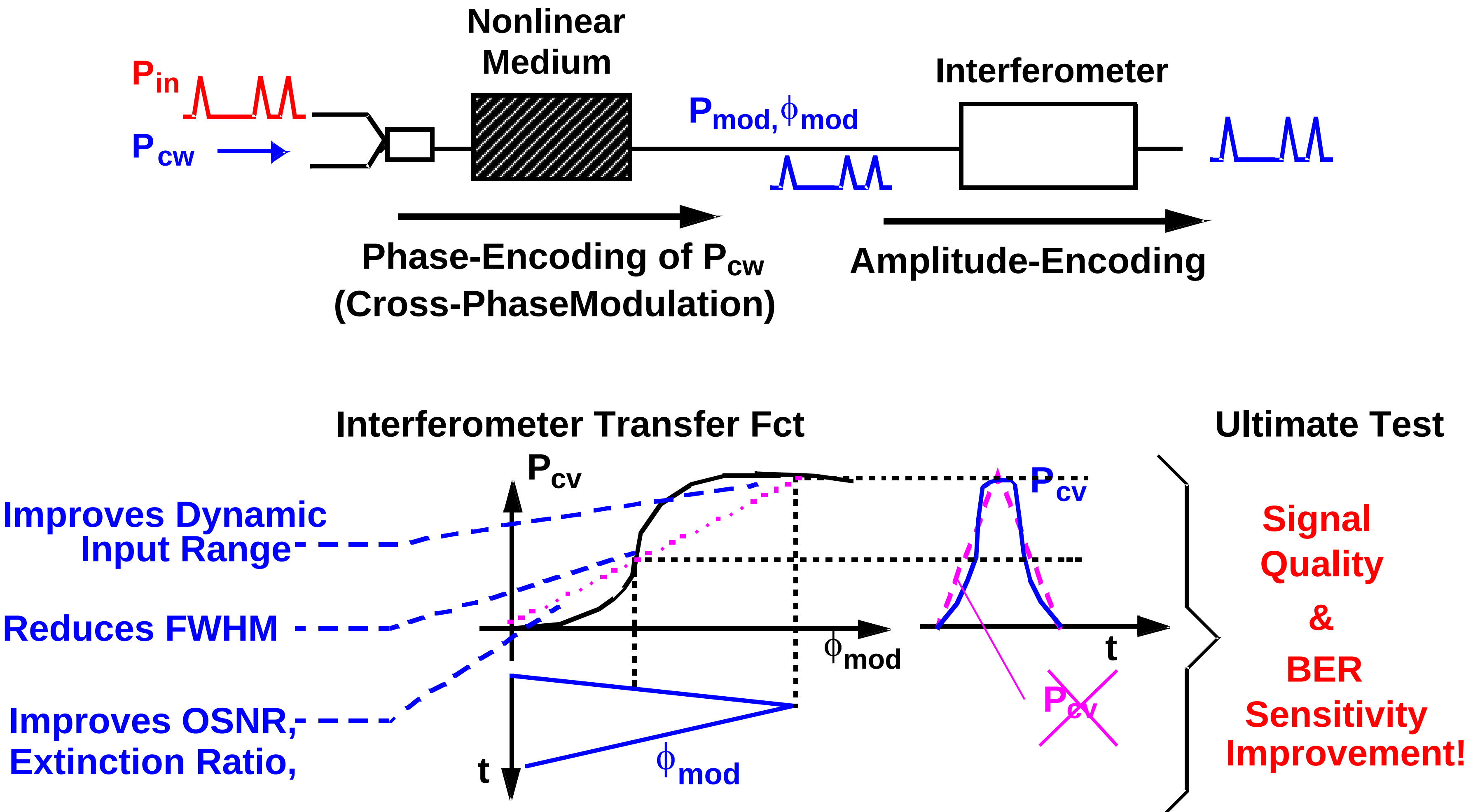
The Need for All-Optical Processing — Regeneration

- **3R**
  - **2R**
    - **R**eamplification
    - **R**eshaping
      - OSNR and extinct. ratio
      - amplitude fluctuations
      - pulse width
  - **R**etiming



Ultimate criterion: Signal quality Q

Regeneration and Transfer Function



Outline

- Modulation techniques
  - Analogue, digital, coding
  - Symbol diagrams, spectra
  - Benefits, transmission capacity
- SOA gain and phase recovery
  - Gain-phase coupling
  - Physical explanation
- SOA signal processing
  - Logic gate
  - OOK wavelength converter
  - DPSK wavelength converter
- Summary

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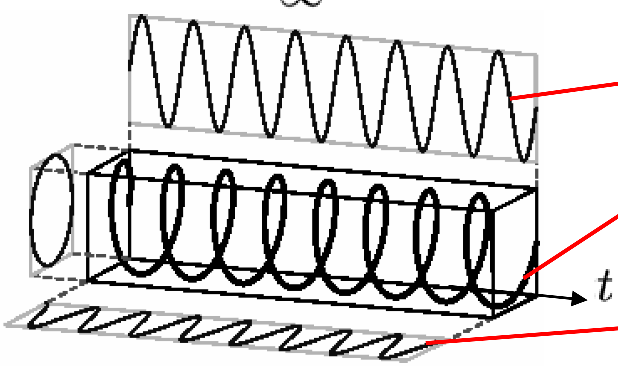
Analytic Time Signals

Analytic signals are frequency-causal (only positive freq.), example:

$$\underline{a}(t) = A_0\, \mathrm{e}^{\mathrm{j}\,\omega_0 t} \quad \circ\!\!-\!\!\bullet \quad \breve{a}(f) = \int_{-\infty}^{+\infty} \underline{a}(t)\, \mathrm{e}^{-\mathrm{j}\,2\pi f t}\, \mathrm{d}t = A_0\, \delta\,(f - f_0)$$

Analytic signal is generated from its real $a(t) = \Re\{\underline{a}(t)\}$ or imaginary part $a_i(t) = \Im\{\underline{a}(t)\}$ by Hilbert trafo, i. e. by convolution ($*$):

$$a_i(t) = \frac{1}{\pi}\mathcal{P}\int_{-\infty}^{+\infty} \frac{a(t')}{t - t'}\,\mathrm{d}t' = a(t) * \frac{1}{\pi t}, \quad a(t) = -\frac{1}{\pi}\mathcal{P}\int_{-\infty}^{+\infty} \frac{a_i(t')}{t - t'}\,\mathrm{d}t' = -a_i(t) * \frac{1}{\pi t}$$



$a_i(t) = \sin(\omega_0 t)$

$\underline{a}(t) = \exp(\mathrm{j}\,\omega_0 t) = a(t) + \mathrm{j}\, a_i(t)$

$a(t) = \cos(\omega_0 t)$

Quadrature (Hilbert) filter $\breve{\mathcal{H}}(f)$ with impulse response $\mathcal{H}(t) = \dfrac{1}{\pi t}$:

$$\breve{\mathcal{H}}(f) = -\mathrm{j}\,\mathrm{sgn}(f), \qquad \mathrm{sgn}(f) = \begin{cases} +1, & f > 0 \\ -1, & f < 0 \end{cases}$$

Analogue Amplitude Modulation

Analytic narrowband modulation signal:

$$\underline{s}(t) = s(t) + \mathrm{j}\, s_i(t)$$

Narrowband-modulated analytic carrier:

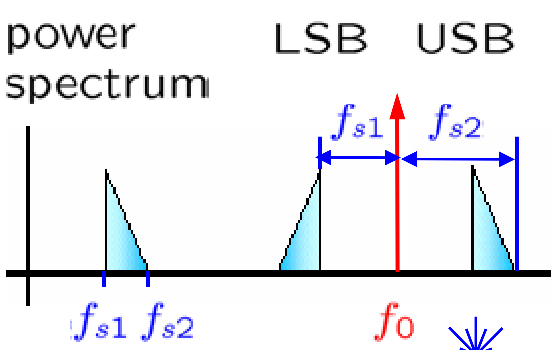
$$\underline{a}_s(t) = a_s(t) + \mathrm{j}\, a_{si}(t) = \underline{s}(t) A_0 \exp\left(\mathrm{j}\,\omega_0 t\right)$$
$$= A_0 \left[s(t) + \mathrm{j}\, s_i(t)\right] \left[\cos\left(\omega_0 t\right) + \mathrm{j} \sin\left(\omega_0 t\right)\right],$$

real part: $$a_s(t) = A_0 \left[s(t) \cos\left(\omega_0 t\right) - s_i(t) \sin\left(\omega_0 t\right)\right],$$

imag. part: $$a_{si}(t) = A_0 \left[s(t) \sin\left(\omega_0 t\right) + s_i(t) \cos\left(\omega_0 t\right)\right]$$

Amplitude modulation (AM) $s(t) = 1 + m \cos\left(\omega_s t\right)$, $s_i(t) = 0$, AM index m, symmetric sidebands for $\underline{s}(t) = s(t)$ real:

$$a_{\mathrm{AM}}(t) = \left\{1 + m \cos\left(\omega_s t\right)\right\} A_0 \cos\left(\omega_0 t\right)$$
$$= A_0 \cos\left(\omega_0 t\right) + \frac{m}{2} A_0 \cos\left[\left(\omega_0 - \omega_s\right) t\right]$$
$$+ \frac{m}{2} A_0 \cos\left[\left(\omega_0 + \omega_s\right) t\right]$$



Incoherent Rx with a_{AM}^2-operation

Analogue Intensity Modulation

Intensity modulation (IM) $s^2(t) = 1 + p\cos(\omega_s t)$, $s_i(t) = 0$, IM index p (here: $p \ll 1$):

$$a_{IM}(t) = \sqrt{1 + p\cos(\omega_s t)}\, A\cos(\omega_0 t)$$

$$\approx \left\{1 + \tfrac{p}{2}\cos(\omega_s t) - \tfrac{p^2}{8}\cos^2(\omega_s t) + \ldots\right\} A\cos(\omega_0 t)$$

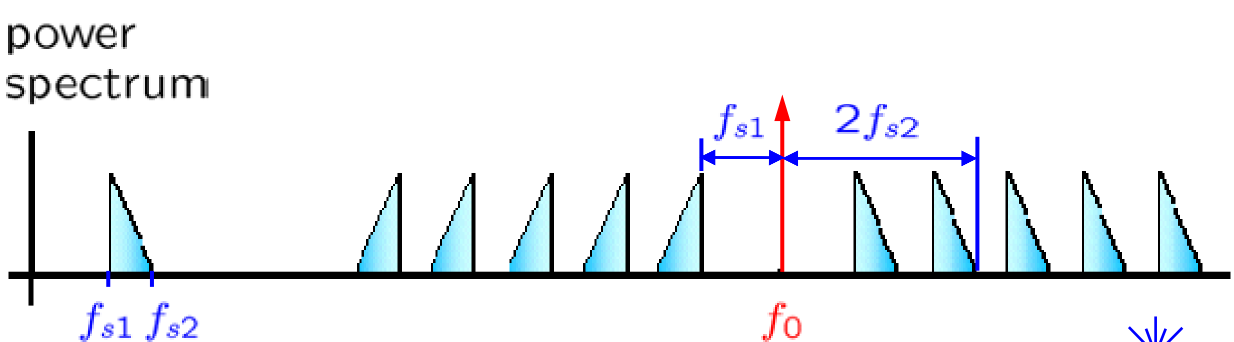
$$\approx \left\{1 - \tfrac{p^2}{16} + \ldots\right\} A\cos(\omega_0 t)$$

$$+\left\{\tfrac{p}{4} + \tfrac{3p^3}{128} + \ldots\right\} A\left\{\cos[(\omega_0 - \omega_s)t] + \cos[(\omega_0 + \omega_s)t]\right\}$$

$$+\left\{-\tfrac{p^2}{32} + \ldots\right\} A\left\{\cos[(\omega_0 - 2\omega_s)t] + \cos[(\omega_0 + 2\omega_m)t]\right\}$$

$$+\left\{\tfrac{p^3}{128} + \ldots\right\} A\left\{\cos[(\omega_0 - 3\omega_s)t] + \cos[(\omega_0 + 3\omega_s)t]\right\}$$

Incoherent Rx
with a_{IM}^2-operation



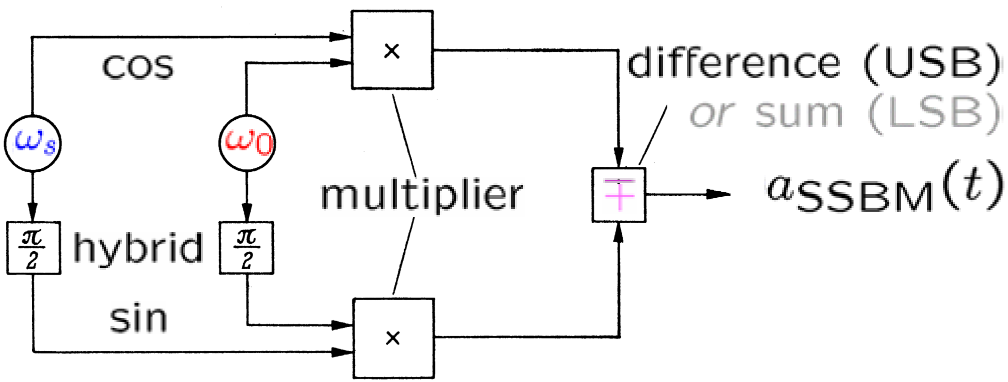
Analogue Single and Vestigial Sideband Modulation

Single-sideband (SSB) modulation $\underline{s}(t) = m \exp(\mathrm{j}\omega_s t)$, USB/LSB:

$$\underline{a}_{\mathrm{SSBM}}(t) = m \exp(\pm \mathrm{j}\omega_s t)\, A_0 \exp(\mathrm{j}\omega_0 t) = m A_0 \exp\left[\mathrm{j}(\omega_0 \pm \omega_s)\, t\right]$$

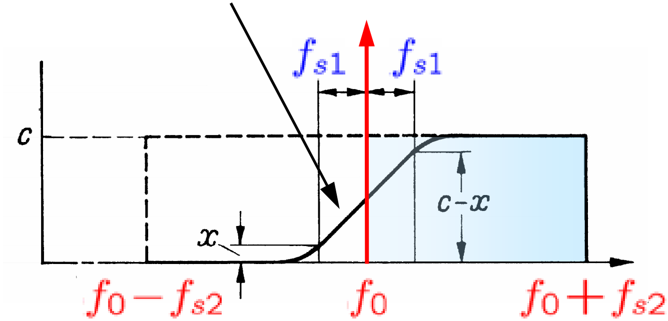
$$a_{\mathrm{SSBM}}(t) = m A_0 \left[\cos(\omega_s t) \times \cos(\omega_0 t) \mp \sin(\omega_s t) \times \sin(\omega_0 t)\right]$$

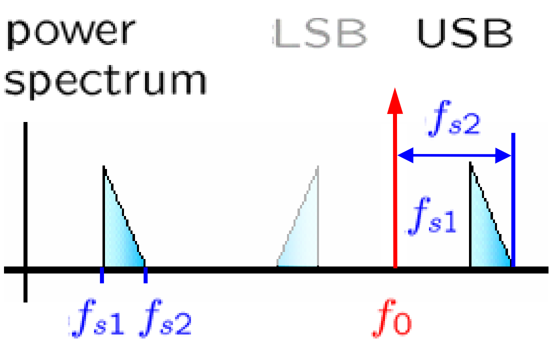
$$a_{\mathrm{SSBM},i}(t) = m A_0 \left[\cos(\omega_s t) \times \sin(\omega_0 t) \pm \sin(\omega_s t) \times \cos(\omega_0 t)\right]$$



Vestigial sideband mod.

with finite-slope filter:





Coherent Rx

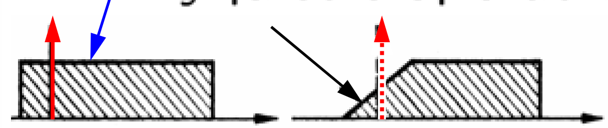
DSB: φ-synchr. LO

SSB: asynchr. LO

VSB: vestigial f_0

At Tx partial filtering,

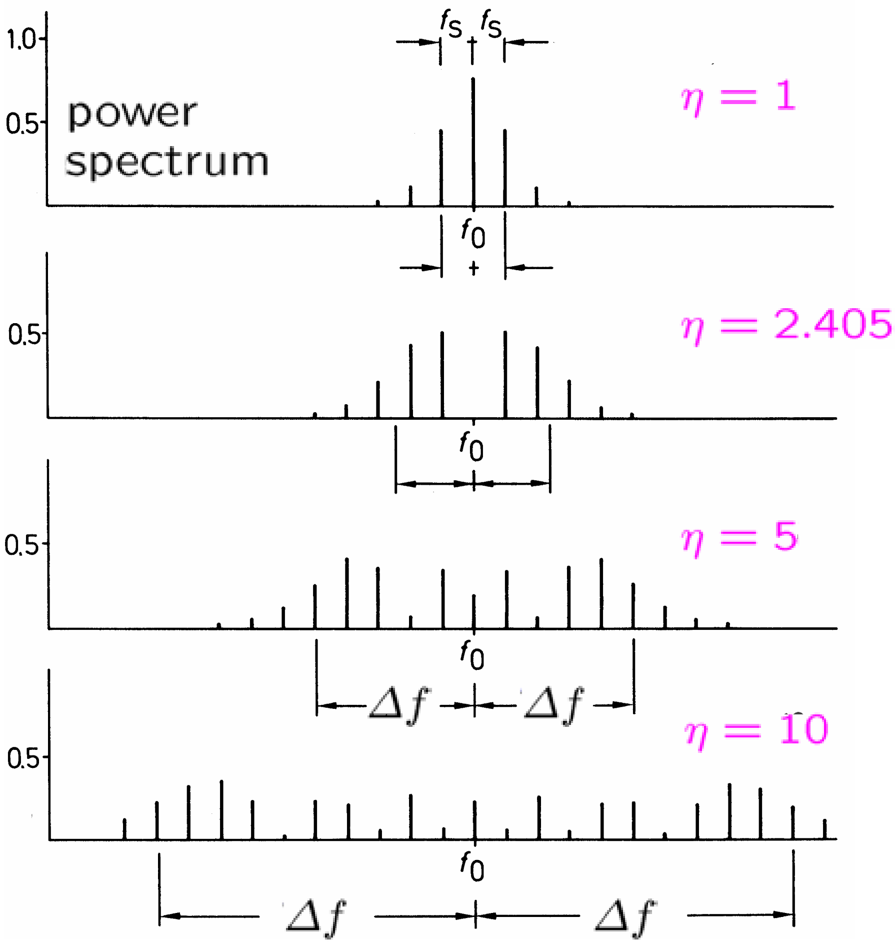
Nyquist slope at Rx:



Analogue Angle Modulation

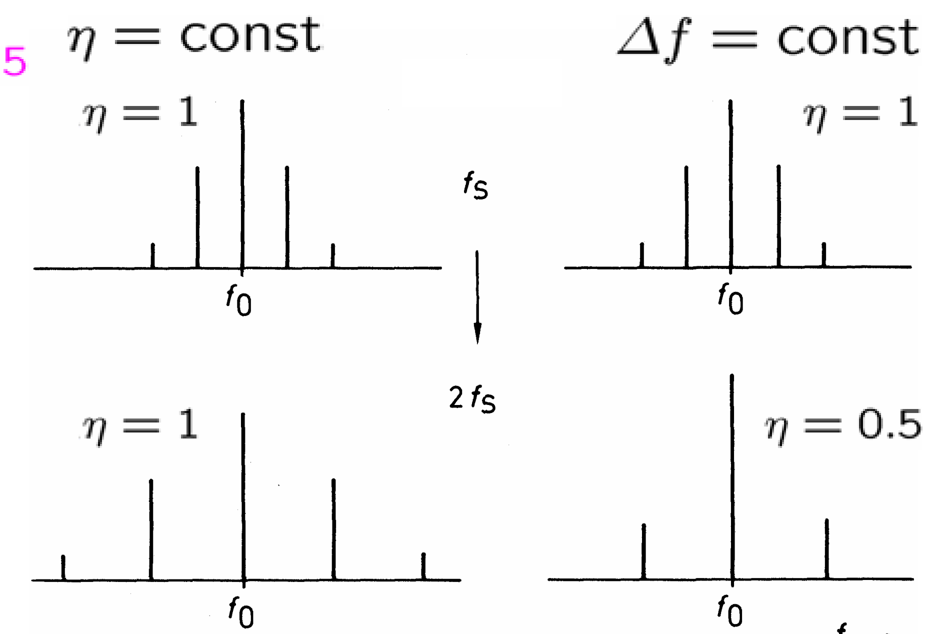
Phase/frequency modulation (PM/FM) $s(t) = \eta \sin(\omega_s t)$, index η:

$$\underline{a}_\eta(t) = A_0 \exp\left[\mathrm{j}\left[\omega_0 t + \eta \sin(\omega_s t)\right]\right] = A_0 \sum_{n=-\infty}^{+\infty} \mathrm{J}_n(\eta) \exp\left[\mathrm{j}\left(\omega_0 + n\,\omega_s\right) t\right]$$



Frequency deviation: $\Delta f = \eta f_s$

PM — spectra — FM



unchanged — changed

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Time Functions for a Binary-Modulated Carrier

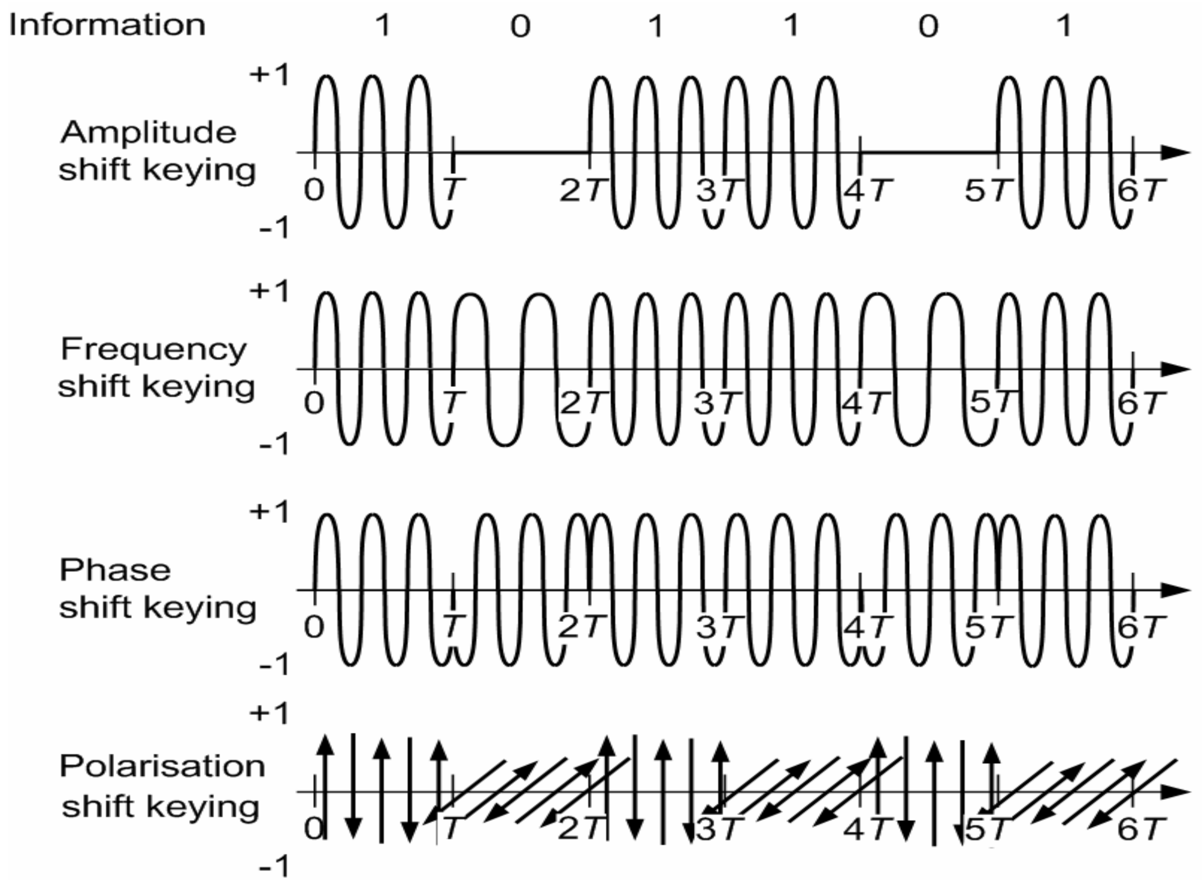
Unipolar ASK: No phase change between mark and space
OOK: Unipolar ASK, high/zero power for mark/space
Bipolar ASK: π-phase change between alternating bit slots
$\pi/2$-ASK: $\pi/2$-phase change between alternating bit slots

ASK OOK:

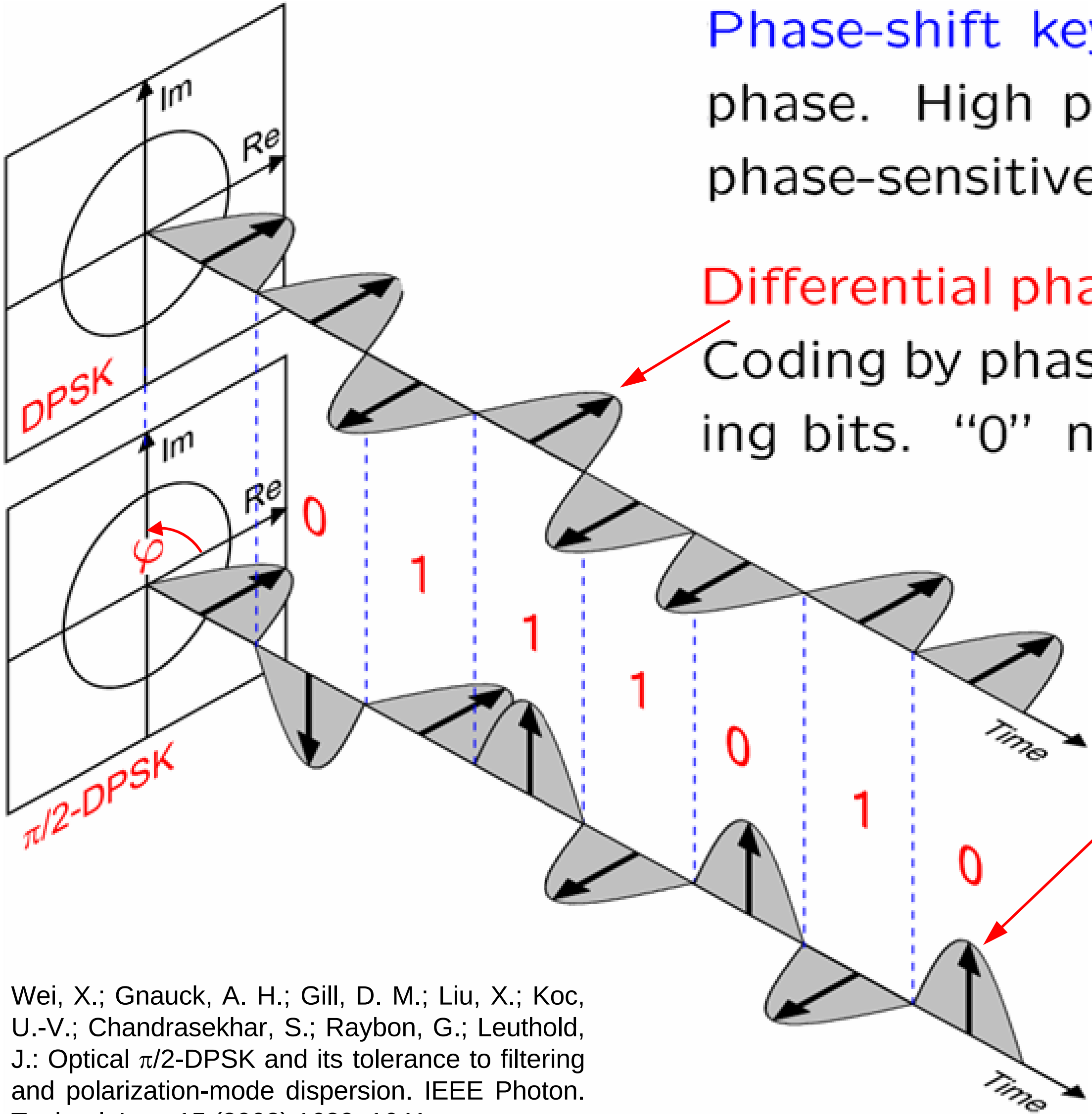
FSK:

PSK:

PolSK:



(Binary) Phase-Shift Keying



Phase-shift keying (BPSK): Coding by phase. High phase purity Tx, coherent phase-sensitive Rx, higly stable LO.

Differential phase-shift keying (DBPSK): Coding by phase *difference* of neighbouring bits. "0" no, "1" π-change.

$\pi/2$-DBPSK:

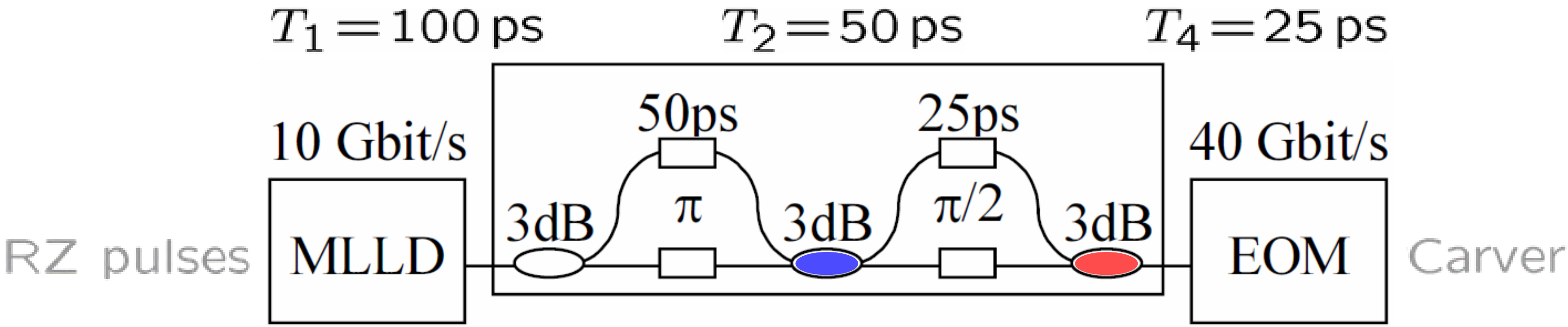
"0" $\Delta\varphi = -\pi/2$ (cw),

"1" $\Delta\varphi = +\pi/2$ (ccw).

DPSK with progressive $\pi/2$-phase per bit.

Wei, X.; Gnauck, A. H.; Gill, D. M.; Liu, X.; Koc, U.-V.; Chandrasekhar, S.; Raybon, G.; Leuthold, J.: Optical π/2-DPSK and its tolerance to filtering and polarization-mode dispersion. IEEE Photon. Technol. Lett. 15 (2003) 1639–1641

Generation of Alternating-Phase Optical Pulses



(i) Pulses interleaved by $T_1/2 = 50$ ps differ by carrier phase π

(ii) Pulses interleaved by $T_2/2 = 25$ ps differ by carrier phase $\frac{\pi}{2}$

(i) π-alternating phase
Carrier-suppressed (CS) RZ

(ii) Progressive $\pi/2$ phase increase
Nbo impulses differ by phase π

- $\pi/2$-AP-ASK-OOK: Reduced intersymbol interference (ISI) wrt to middle impulse, robust wrt intrachannel four-wave mixing
- $\pi/2$-DPSK: High tolerance to polarisation mode dispersion

Schnarrenberger, M., Sotobashi, H., Chujo, W. and Freude, W.: Novel intersymbol interference reduction technique by bit synchronized $\pi/2$ phase shift. Proc. Institute of Electronics, Information and Communication Engineers (IEICE Japan) Spring Conference, Hiroshima, 28.–31.03.2000

Douglas M. Gill, D. G.; Gnauck, A. H.; Liu, X.; Wei, X.; Su, Y.: $\pi/2$ alternate-phase on-off keyed 42.7 Gb/s long-haul transmission over 1980 km of standard single-mode fiber. IEEE Photonics Technol. Lett. 16 (2004) 906–908

Wei, X; Leuthold, J.; Dorrer, C.; Gill, D. M.; Liu, X.: Chirp reduction of $\pi/2$ alternate-phase pulses by optical filtering. Technical Digest Optical Fiber Communication Conference (Ofc'05), Anaheim (CA), USA, 06.–11.03.2005. Paper JWA42

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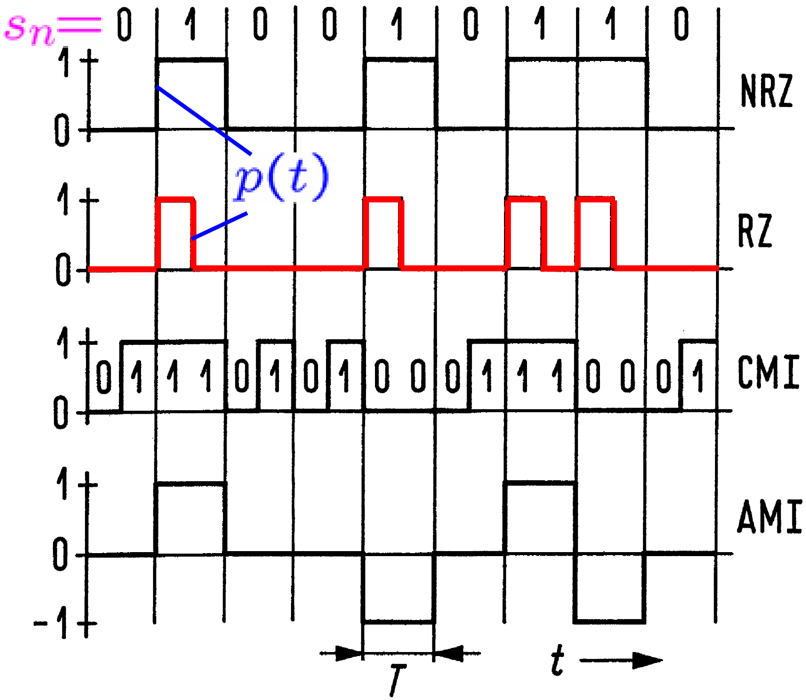
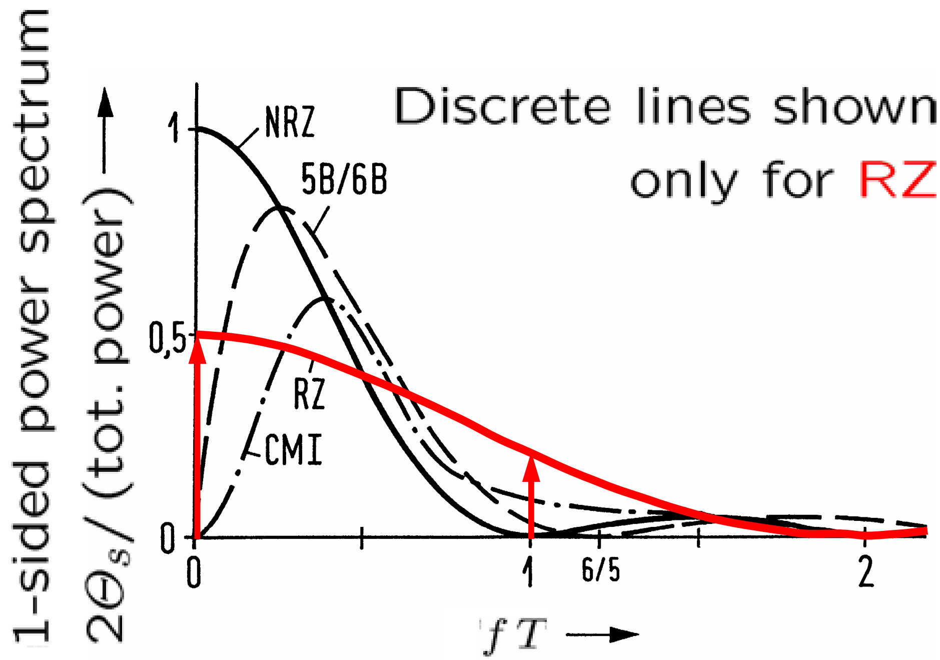
Coding Schemes and Calculation of One-Sided PRBS Spectra



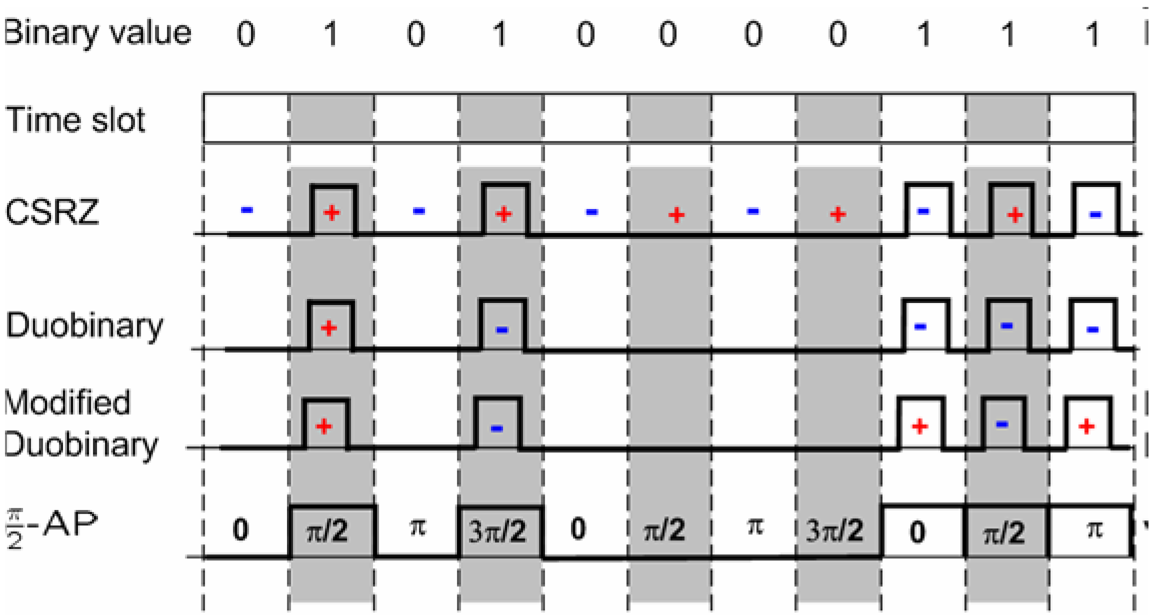


NRZ/RZ: $s(t) = \sum_{n=-\infty}^{+\infty} s_n\, p(t-nT) = \sum_{n=-\infty}^{+\infty} s_n\, p(t) * \delta(t-nT)$

2-sided power spectr.: $\Theta_s(f) = \frac{1}{4T} |\bar{p}(f)|^2 \left[1 + \frac{1}{T} \sum_{n=-\infty}^{+\infty} \delta(f-n/T)\right]$

Hölzler, E.; Holzwarth, H.: Pulstechnik, Vol. I, 2. Ed. ("Pulse technology", in German). Berlin: Springer 1982 (**General PRBS spectra**, Eq. (6.48,49))
Cattermole, K. W.; O'Reilly, J. J. (Eds.): Mathematical topics in telecommunications. Vol. 2: …randomness… London: Pentech 1984 (Chapter 15)
Grau, G.; Freude, W.: Optische Nachrichtentechnik, 3. Ed. Berlin: Springer 1991 (Sect. 7.2)
Agrawal, G. P.: Lightwave technology. Telecommunication systems. Hoboken (NJ): John Wiley & Sons 2005 (Sect. 2.2)
Ip, E.; Kahn, J. M.: Power spectra of return-to-zero optical signals. J. Lightw. Technol. 24 (2006) 1610–1618

Bipolar Binary ASK Coding Schemes



CSRZ: Carrier-suppressed RZ, π-phase change from bit to bit
DB: Duobinary, high/zero power for mark/space,
$0/\pi$-phase for even/odd number of “0” since last “1”
AMI: Modified duobinary, π-phase from “1” to subsequent “1”
$\frac{\pi}{2}$-AP: Progressive $\pi/2$-alternating phase change for improving ISI

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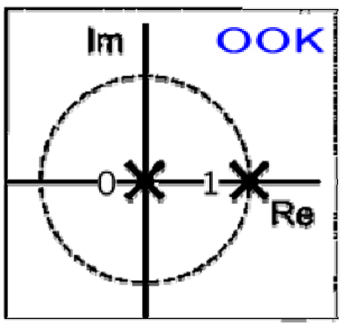
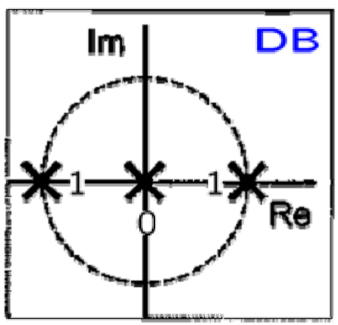
Symbol Diagrams for Digital Modulation Formats

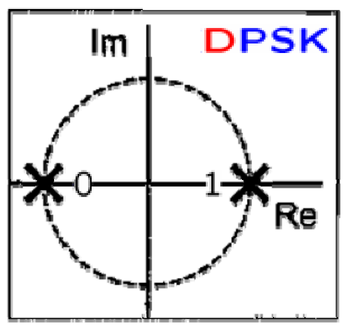
Analytic digital modulation signal:

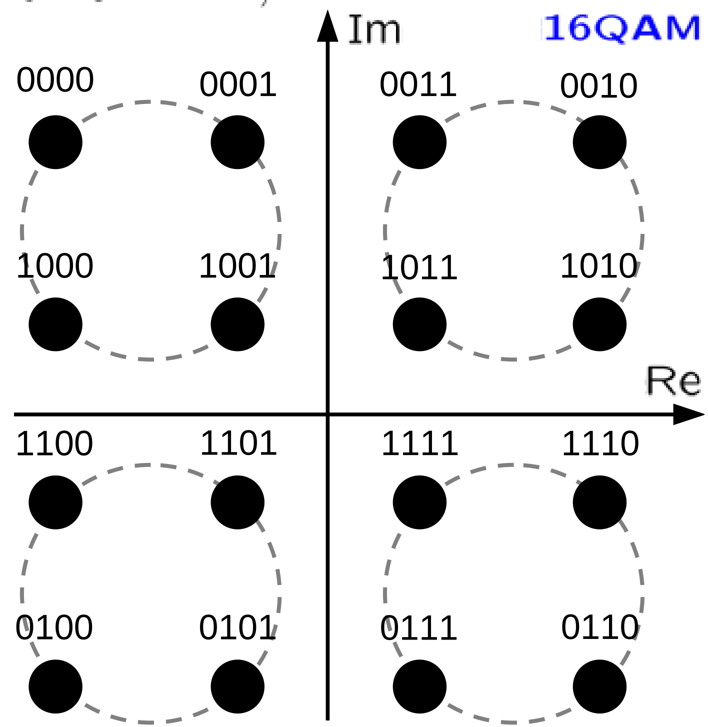
$$\underline{s}(t) = \sum_{n=-\infty}^{+\infty} \underline{s}_n \, p(t - nT) = \sum_{n=-\infty}^{+\infty} \left(s_n + \mathrm{j}\, s_{n,i}\right) p(t - nT)$$

Symbol diagram for $\mathrm{Re}\{\underline{s}_n\} = s_n$ and $\mathrm{Im}\{\underline{s}_n\} = s_{n,i}$:

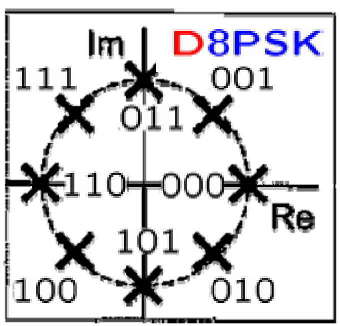


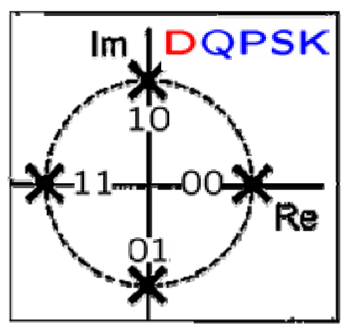






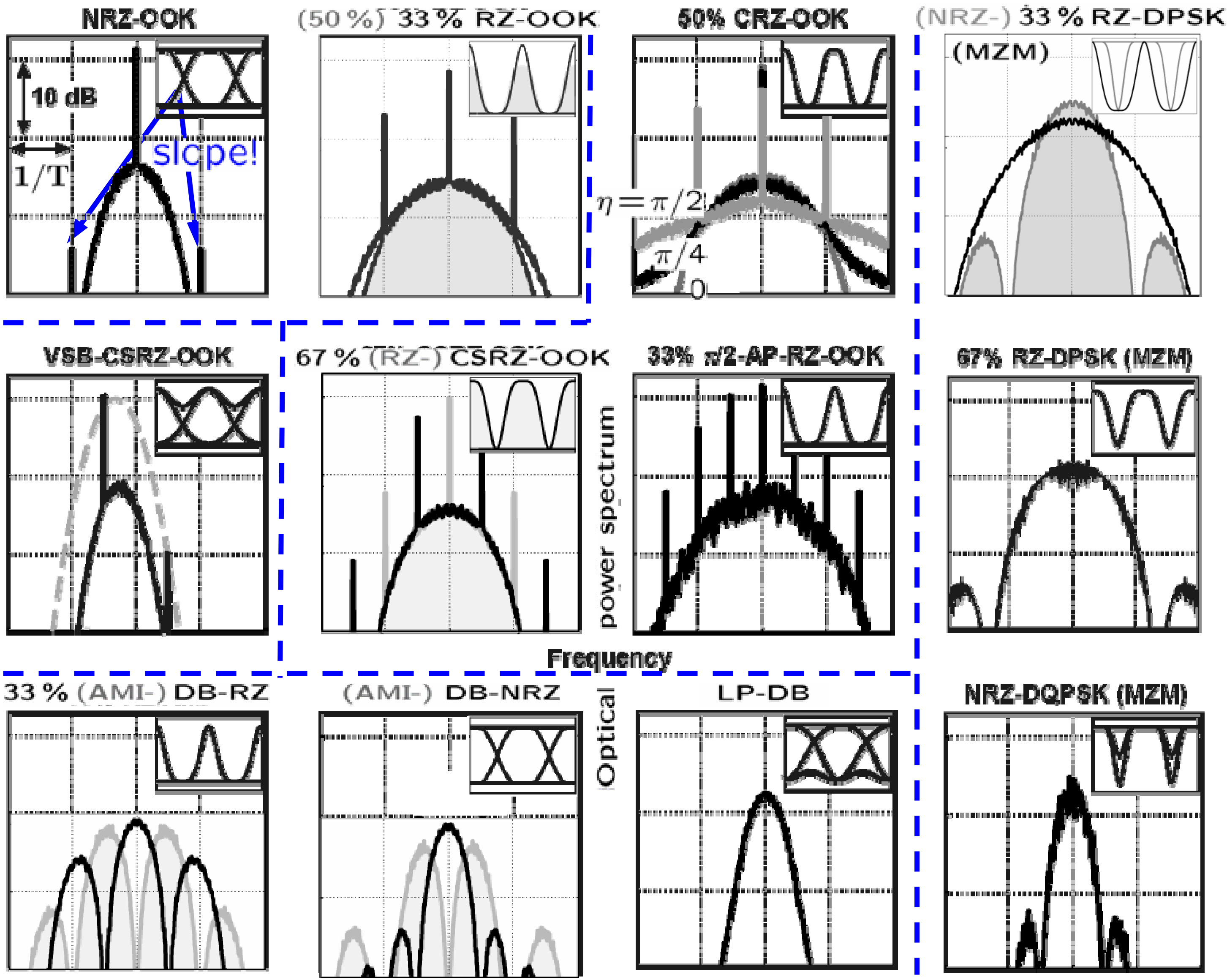
Differential bit mapping to Gray code symbols





Kikuchi, N.; Sekine, K.; Sasaki, S.: Proposal of inter-symbol interference (ISI) suppression technique for optical multilevel signal generation. Ecoc'06 Tu4.2.1

Spectra for Amplitude- and Phase-Coded Modulation Formats



Compiled and modified materials from:

Gnauck, A. H.: Advanced amplitude- and phase coded formats for 40-Gb/s fiber transmission. Proc. 17th Annual Meeting of the IEEE Lasers and Electro-Optics Society (LEOS 2004), Puerto Rico, USA, November 7–11, 2004. Paper WR1

Gnauck, A. H.; Liu, X.; Wei, X.; Gill, D. M.; Burrows, E. C.: Comparison of modulation formats for 42.7-Gb/s single-channel transmission through 1980 km of SSMF. IEEE Photon. Technol. Lett. 16 (2004) 909–911

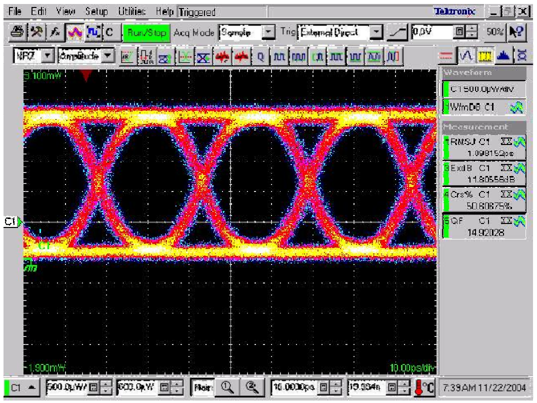
Winzer, P. J.: Optical transmitters, receivers, and noise. Wiley Encyclopedia of Telecommunications (2002) http://www.mrw.interscience.wiley.com/eot/articles/eot404

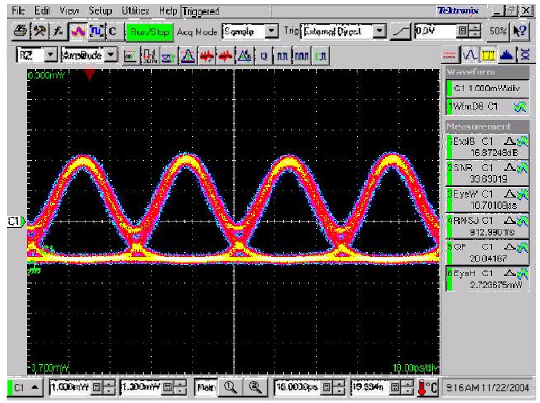
Eye Diagrams and Spectra for NRZ, CSRZ, 33 % RZ at 40 Gbit/s

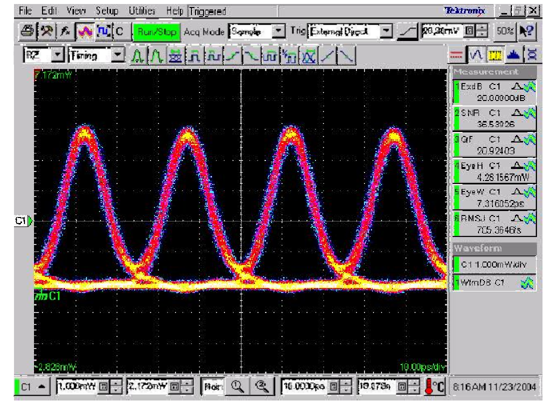
NRZ
Non Return to Zero

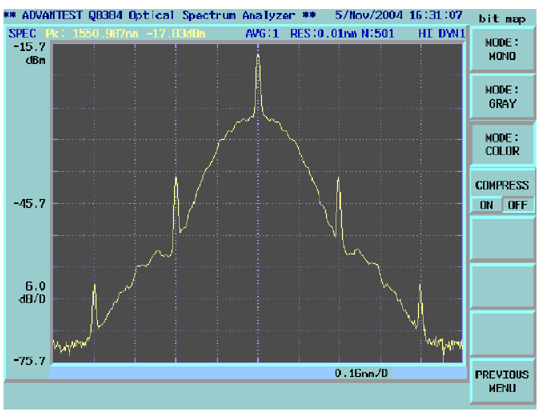
CS-RZ
Carrier-Suppressed Return to Zero

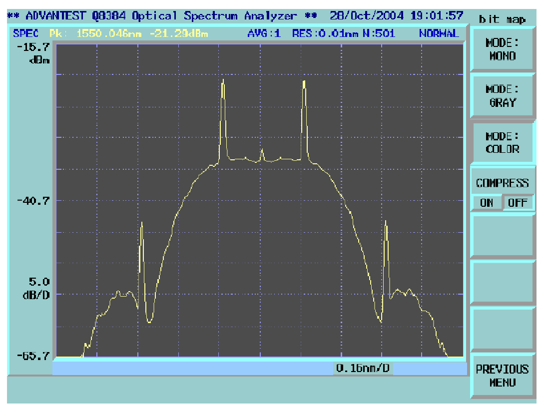
33% RZ
Return to Zero

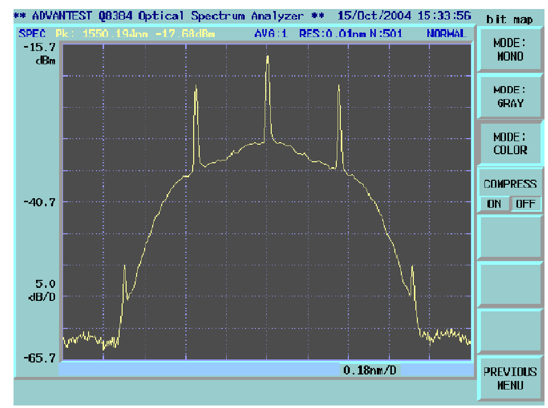












Pincemin, E. et al.: Robustness of the OOK modulation formats at 40 Gbit/s in the practical system infrastructure. Ecoc'05 We4.P.112
Gosselin, S.; Joindot, M.: Key drivers and technologies for future optical networks. Ecoc'06 We2.2.1 (Tutorial, Slide 43)

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40 Gbit/s Digital Modulation Formats

40 GHz baud (symbol) rate (1 bit / baud):

On-off keying (OOK) Non-return-to-zero (NRZ), chirped NRZ, RZ (duty cycle 33; 50 %), chirped RZ (CRZ, x %), carrier-suppressed RZ (CSRZ, 66 %), chirped CSRZ

Duobinary (DB) NRZ-DB, chirped NRZ-DB, RZ-DB (33; 50 %), CRZ-DB, CSRZ-DB, chirped CSRZ-DB

Vestigial sideband (VSB) SB/carrier (partially) filtered

Different. (**binary**) **phase shift keying (D**(**B**)**PSK)** NRZ-DPSK, chirped NRZ-DPSK, RZ-DPSK (33; 50 %), CRZ-DPSK, CSRZ-DPSK, chirped CSRZ-DPSK

20 GHz baud rate (2 bit / baud):

Diff. quaternary PSK (DQPSK) (N)RZ, CSRZ (33; 50; 66 %)

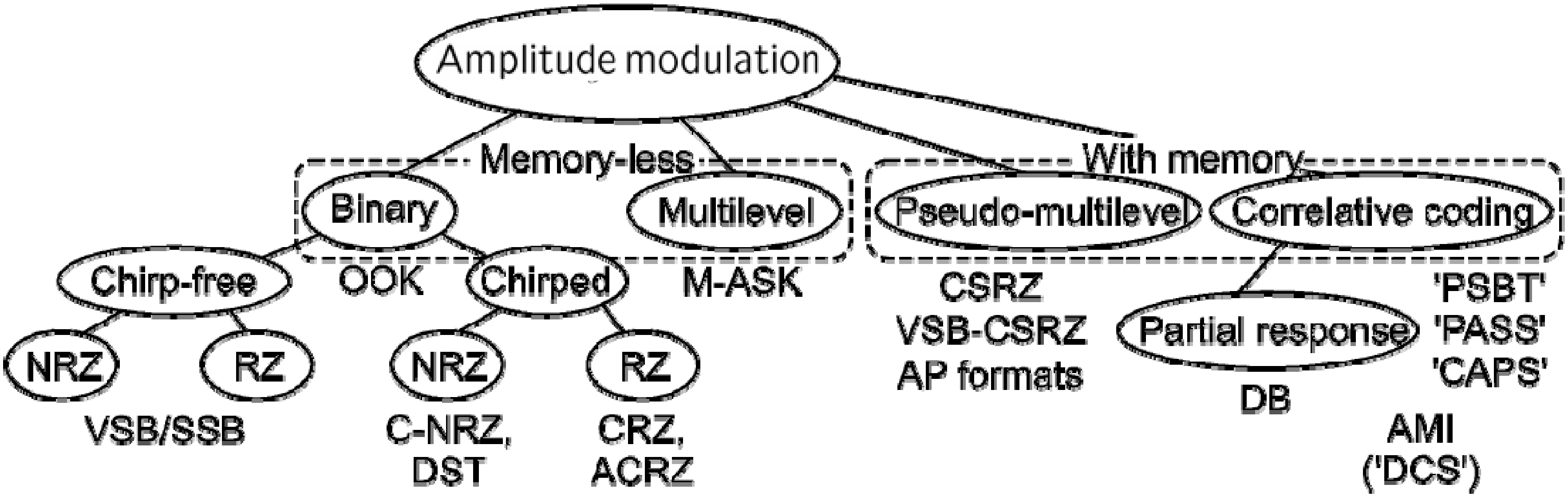
5 GHz baud rate (3 bit / baud):

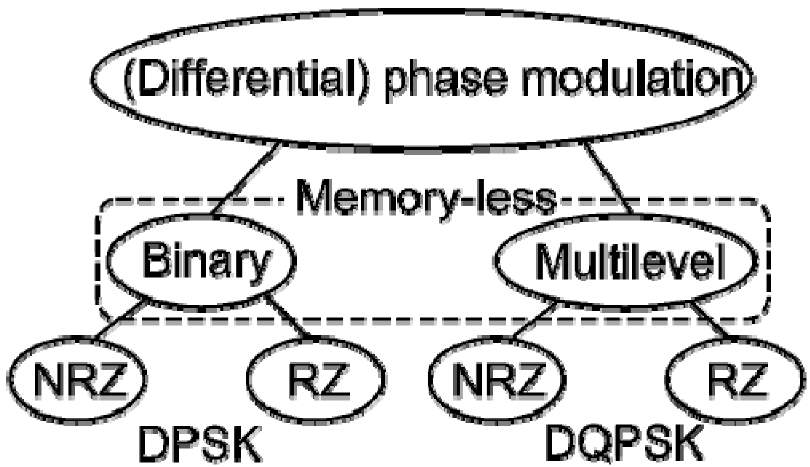
Differential octonary PSK (D8PSK)

2.5 GHz baud rate (4 bit / baud):

Seno-denary quadrature amplitude modulation (16QAM)

A Family of Amplitude and Phase Modulation Formats





Winzer, P. J.; Essiambre, R.-J.: Advanced optical modulation formats. Proc. IEEE 94 (2006) 952–985. Fig. 2

Performance Values of Various Modulation Formats at 40 Gbit/s

Required OSNR at BER $= 10^{-3}$ (7 %-FEC $\Rightarrow < 10^{-12}$, 42.7 Gbit/s)

Modulation format	TX complexity	RX complexity	$OSNR_{req}$ Back-to-back	$OSNR_{req}$ 10 OADMs (0.4 b/s/Hz)	$OSNR_{req}$ 5 OADMs (0.8 b/s/Hz)	CD [ps/nm] (2-dB pen.)	DGD [ps] (1-dB pen.)
NRZ-OOK	1 MZM	1 PD	15.9 dB	18.2 dB	n/a	54	8
50% RZ-OOK	1-2 MZMs	1 PD	14.4 dB	15.8 dB	n/a	48	10
67% CSRZ-OOK	2 MZMs	1 PD	14.9 dB	14.2 dB	n/a	42	11
DB	1 MZM	1 PD	16.6 dB	14.2 dB	18.4 dB	211 (152)	6
33%RZ-AMI	1-2 MZMs, 1 DI	1 PD	13.4 dB	14.8 dB	n/a	49	10
VSB-NRZ-OOK	1 MZM + 1 OF	1 PD	16.4 dB	15.6 dB	17.3 dB	63 (155)	6
VSB-CSRZ	2 MZMs + 1 OF	1 PD	14.8 dB	14.7 dB	16.7 dB	51 (154)	11
NRZ-DPSK	1 MZM	1 DI + 2 PDs	11.7 dB	12.1 dB	17.6 dB	74 (161)	10
50% RZ-DPSK	1-2 MZMs	1 DI + 2 PDs	11.1 dB	11.5 dB	17.0 dB	50 (161)	10
NRZ-DQPSK	2 nested MZMs	2 DIs + 4 PDs	13.2 dB	12.6 dB	12.9 dB	168 (176)	20
50% RZ-DQPSK	2 nested MZMs + 1 PC	2 DIs + 4 PDs	12.2 dB	12.0 dB	12.0 dB	161 (186)	21

85 GHz 43 GHz
filter BW

PD: photodiode; OF: optical filter; PC: pulse carver; 100 GHz ITU ch spacing;
12.5 GHz noise reference bandwidth

Winzer, P. J.; Essiambre, R.-J.: Advanced optical modulation formats. Proc. IEEE 94 (2006) 952–985. Table 4

Best Transmission Capacities in the Laboratory

Recent data:

- 40 Gbit/s over 10^6 km (33 % RZ, Lucent El. Lett. 02)
- 160×42.7 Gbit/s over 3 200 km (Lucent Ofc03 PD)
- 373×10 Gbit/s over 11 000 km (Tyco OFC03 PD)
- 185×42.7 Gbit/s over 8 700 km (KDD Ecoc03 PD)
- 89×42.7 Gbit/s over 4 000 km (CSRZ-DPSK, Lucent Ecoc03 Tu4.6)
- 64×10 Gbit/s over 13 100 km (RZ, Tyco Ecoc03 Tu4.6)
- 149×42.7 Gbit/s over 6 120 km (DPSK, Alcatel Ofc04 PDP36)
- 151×43 Gbit/s over 4 080 km (DQPSK, Alcatel Ecoc05 PD)
- 640 Gbit/s over 480 km (DQPSK, HHI Ecoc05 We3.2.2)

Maximum capacity transmitted over one fiber today: ~ 7 Tbit/s

Leuthold, J.; Raybon, G.; Su, Y.; Essiambre, R.; Cabot, S.; Jaques J.; Kauer, M.: 40 Gbit/s transmission and cascaded all-optical wavelength conversion over 1 000 000 km. Electron. Lett. 38 (2002) 890–892

Gosselin, S.; Joindot, M.: Key drivers and technologies for future optical networks. Ecoc'06 We2.2.1 (Tutorial, Slide 12)

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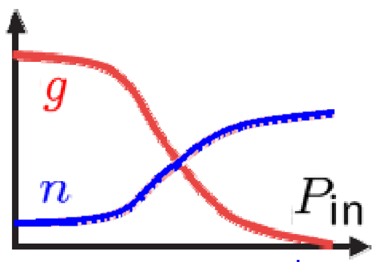
Semiconductor Optical Amplifier (SOA) for Signal Processing

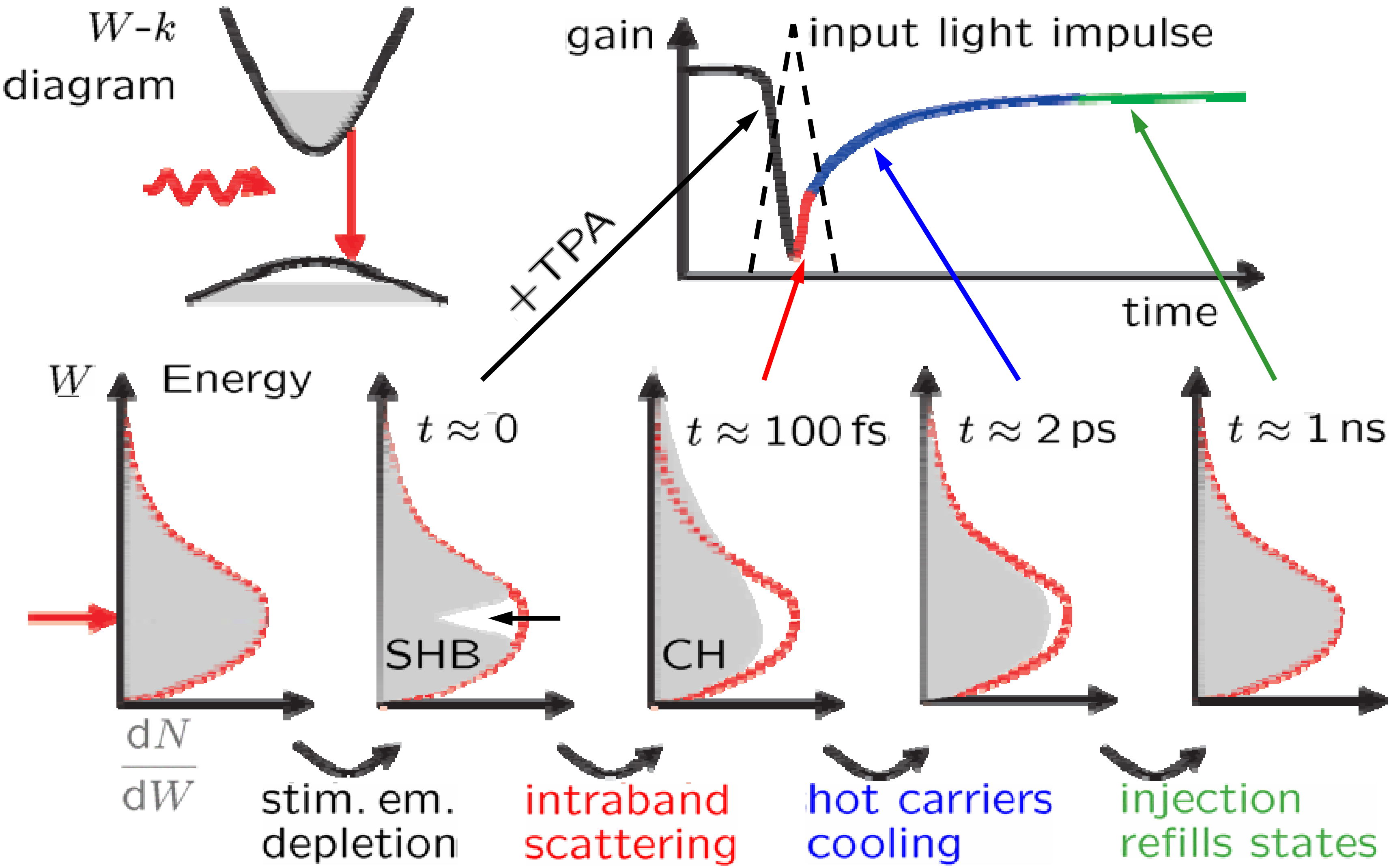
- ∗ SOA carrier lifetimes $\tau \sim 0.1 \ldots 1\,\text{ns}$ (EDFA: $\tau \sim 10\,\text{ms}$)
- ∗ Transient gain variation. For Gbit / s data rates:
  - ⋆ makes WDM amplifier application difficult, but is
  - ⋆ good for nonlinear operations, i. e., signal processing.
- ∗ Fast intraband processes may be exploited, namely:
  - • saturation of power gain constant $g(f) = -2k_0 n_i(f)$, and its
  - • associated change of refractive index $n(f)$:
    - ⋄ analytic refractive index $\underline{n}(f) = n(f) - \mathrm{j}\, n_i(f)$,
    - ⋄ power gain $G = \exp(gz)$, field $\propto \sqrt{G}\,\exp\left[\mathrm{j}\,(\omega t - k_0\, n\, z)\right]$
- ∗ $g(f, N)$ and $n(f, N)$ depend on carrier concentration N, and are coupled via the Kramers-Kronig (Hilbert transform) relation:

$$n(f) = 1 - \frac{2}{\pi} \int_0^\infty f' \, \frac{-n_i(f')}{f'^2 - f^2}\, \mathrm{d}f' = 1 - \frac{c}{2\pi^2} \int_0^\infty \frac{g(f')}{f'^2 - f^2}\, \mathrm{d}f'$$



Nussenzveig, H. M.: Causality and dispersion relations. Vol. 95 in "Mathematics in science and engineering", Ed. R. Bellmann. New York: Academic Press 1972. Sect. 1.6

Carrier/Gain Depletion and Recovery in an SOA



Modified from: Mørk, J. et al. IEEE LEOS Newsletter 16 (2002) 21–24. Fig. 2. — Mørk, J. et al. Optics & Photonics News July (2003) 42–48

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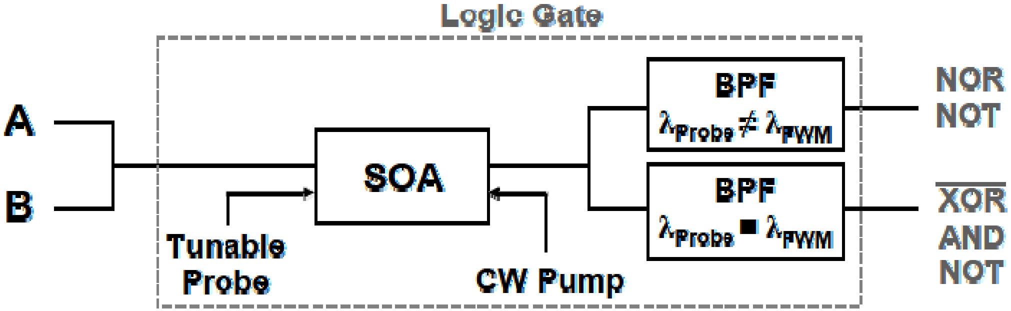
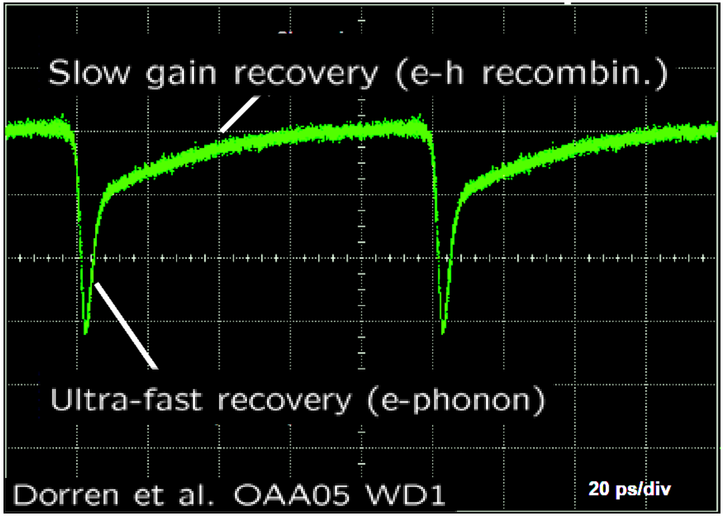
Reconfigurable Optical Logic Gate with SOA

Key ideas:

- Non-interferometric structure based on single SOA
- FWM and XGM exploited simultaneously
- Counter-propagating CW pump speeds up SOA gain recovery





Berrettini, G.; Malacarne, A.; Ghelfi, P.; Bogoni, A.; Potí, L.: Reconfigurable all-optical logic gate based on a single SOA with improved dynamics. Ofc 2006 Paper OFJ5

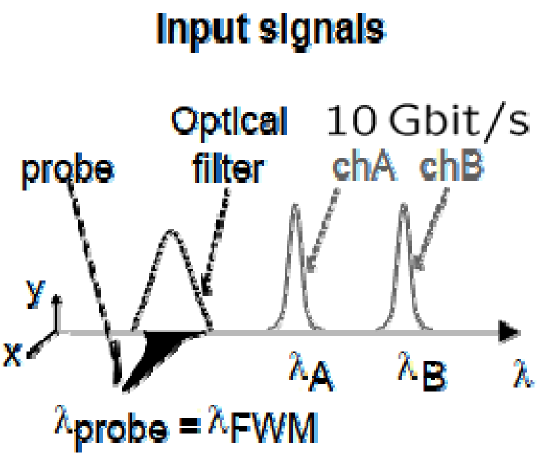
Berrettini, G.; Simi, A.; Malacarne, A.; Bogoni, A.; Potí, L.: Ultrafast integrable and reconfigurable XNOR, AND, NOR, and NOT photonic logic gate. IEEE Photon. Technol. Lett. 18 (2006) 917–919

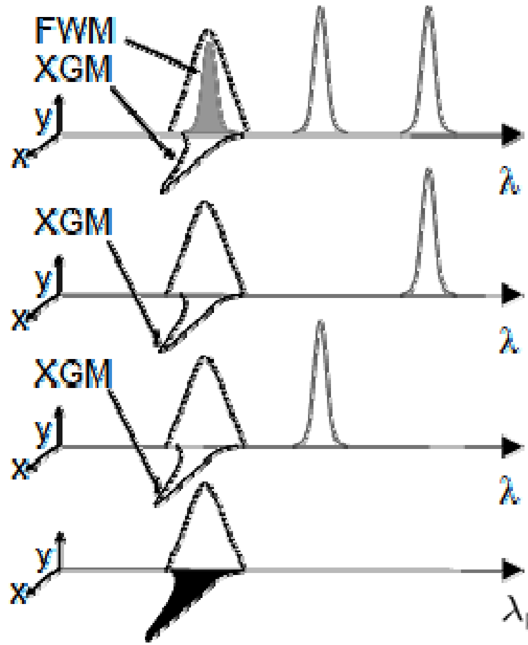
Dorren, H. J. S.; Hill, M. T.; Liu, Y.; Tangdiongga, E.; Smit, M. K.; Khoe, G. D.: Optical signal processing and telecommunication applications. Optical Amplifiers and Their Applications (OAA), 7–10 August 2005, Budapest, Hungary. Paper WD1

Dorren, H. J. S.; Yang, X.; Mishra, A. K.; Li, Z.; Ju, H.; de Waardt, H.; Khoe, G.-D.; Simoyama, T.; Ishikawa, H.; Kawashima, H.; Hasama, T.: All-optical logic based on ultrafast gain and index dynamics in a semiconductor optical amplifier. IEEE J. Sel. Topics Quantum Electron. 10 (2004) 1079–1092

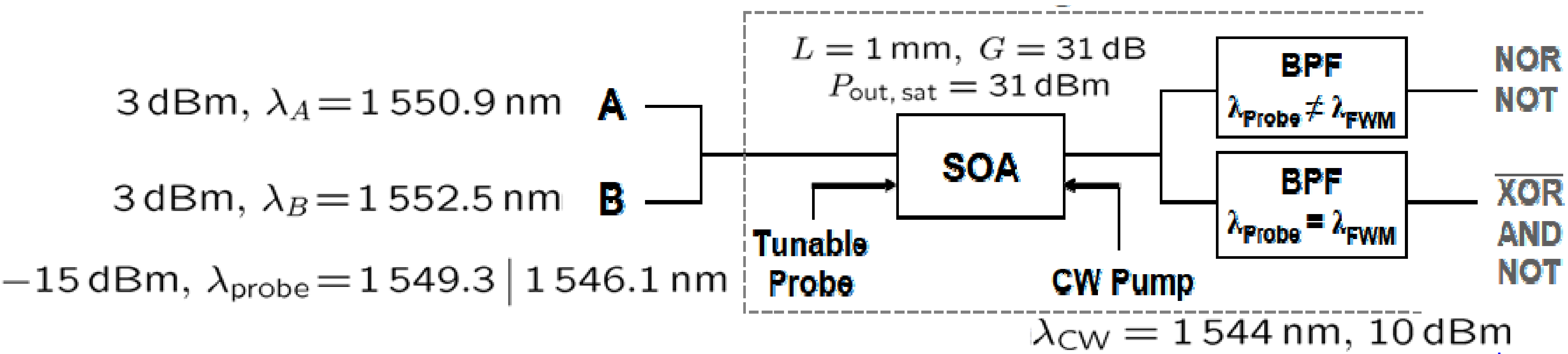
Kang, I. ; Dorrer C. ; Leuthold, J. : All-optical XOR operation of 40 Gbit/s phase-shift-keyed data using four-wave mixing in semiconductor optical amplifier. Electron. Lett. 40 (2004) No. 8

Optical Logic XNOR Gate



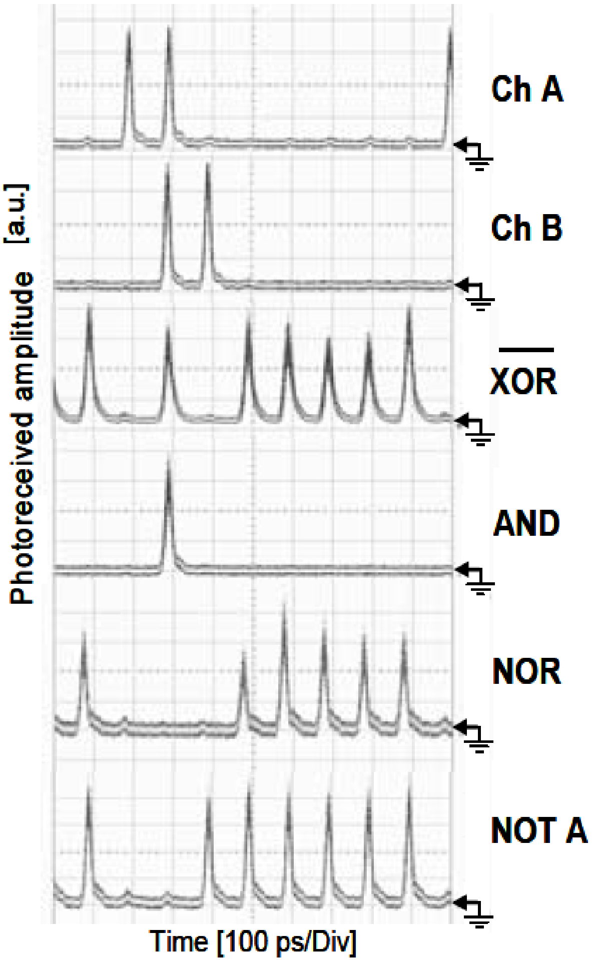


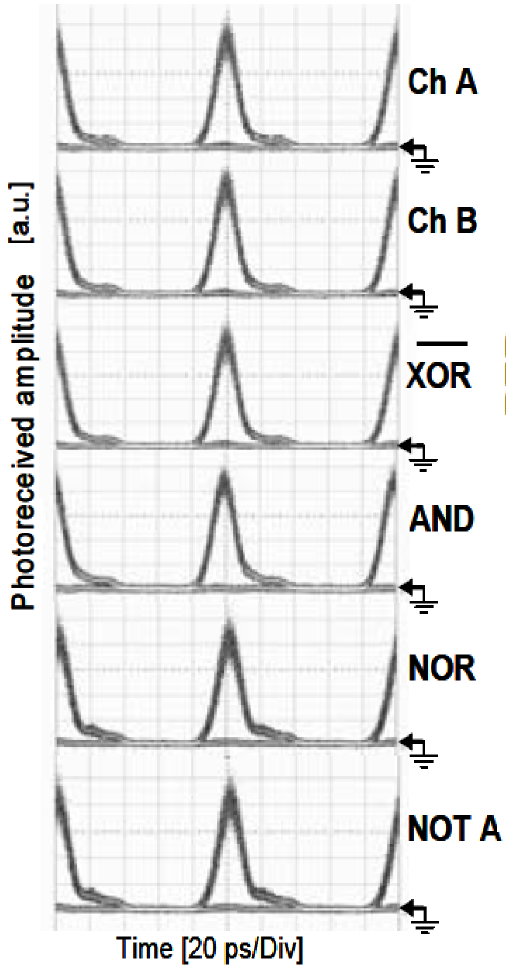
	FWM+XGM	FWM	XGM	1 ch
Case	$\overline{XOR}$	AND	NOR	NOT
11	1	1	0	–
01	0	0	0	0
10	0	0	0	0
00	1	0	1	1
	$\lambda_{probe} = \lambda_{FWM}$	~~λ_{probe}~~	$\lambda_{probe} \neq \lambda_{FWM}$	

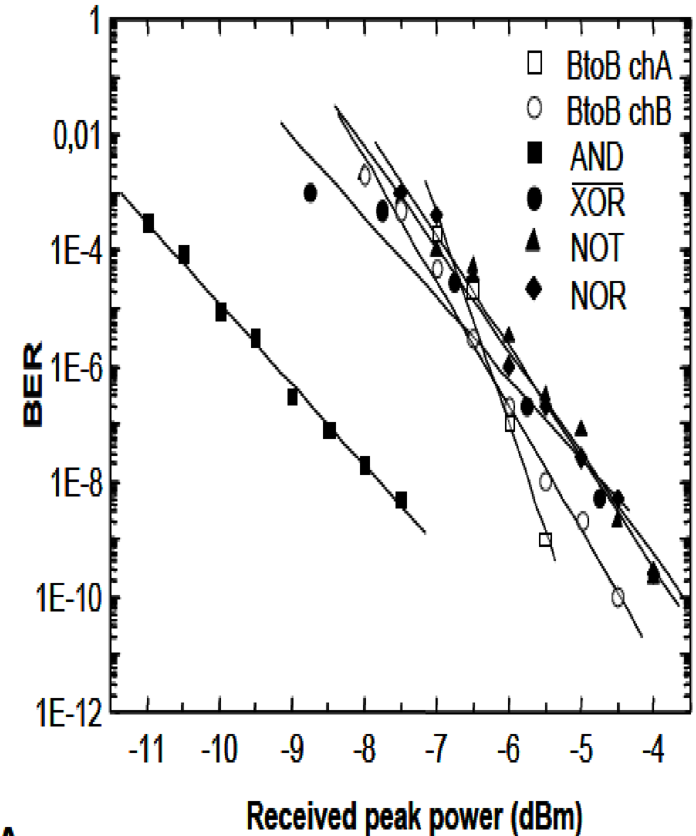


Berrettini et al. Ofc'06 Paper OFJ5, Photon. Technol. Lett. 18 (2006) 917–919

Optical Logic XNOR Gate — Performance at 10 Gbit/s







Power penalty 0.5 dB, AND with regeneration (−2 dB penalty, noise compression in SOA)

Berrettini et al. Ofc'06 Paper OFJ5, Photon. Technol. Lett. 18 (2006) 917–919

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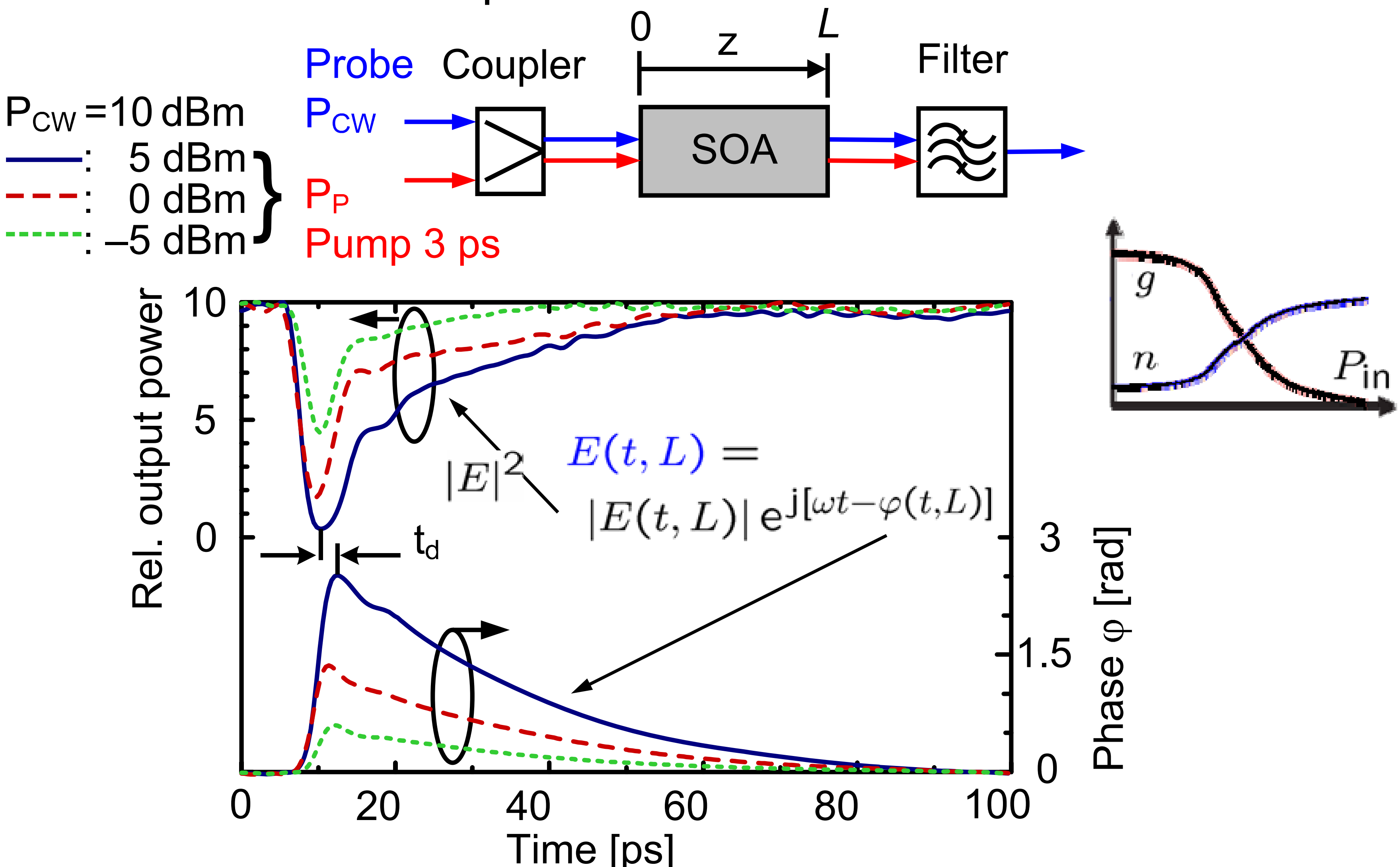
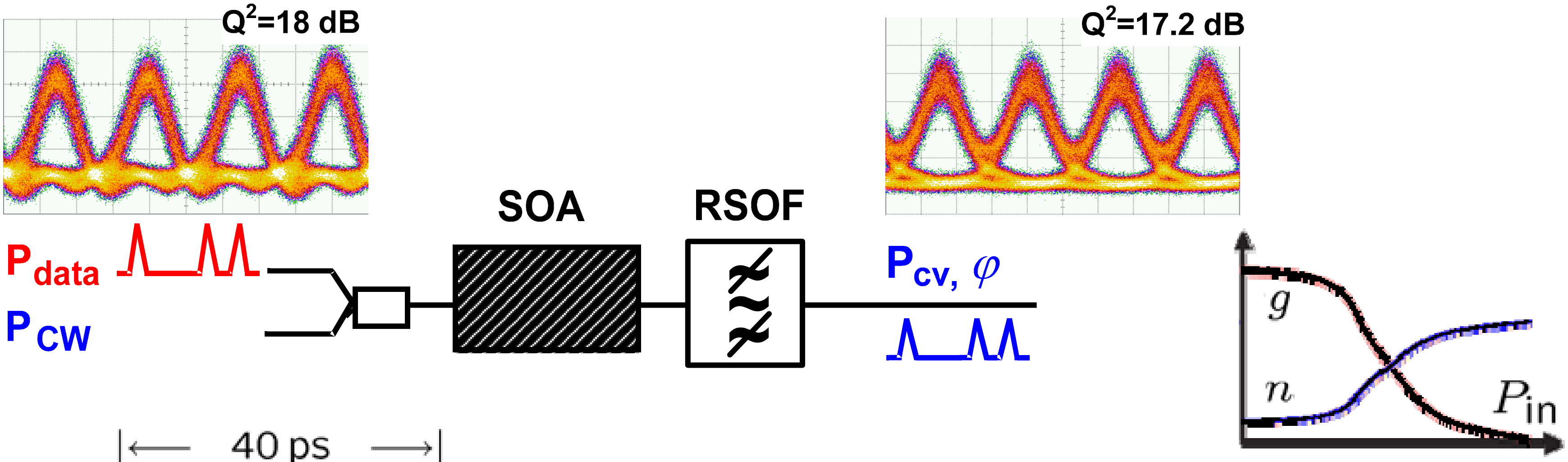
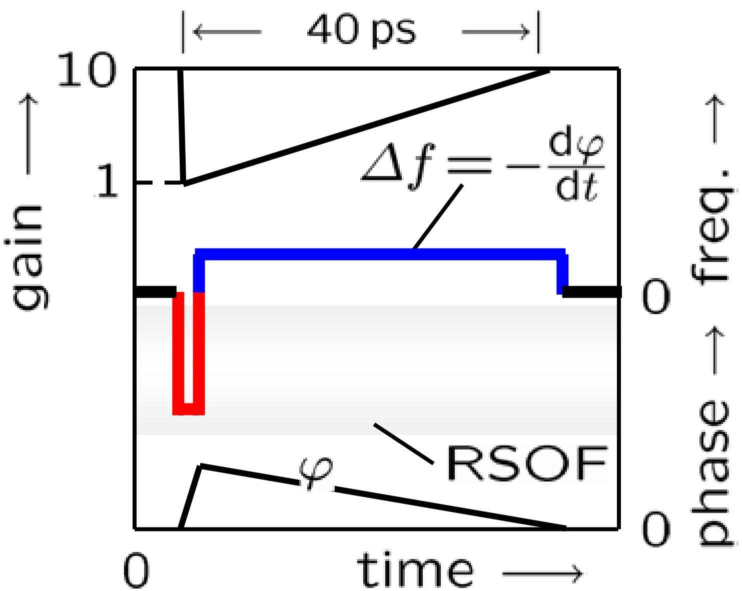
Measured Output Power and Phase for an SOA



Wang, J.; Maitra, A.; Poulton, C. G.; Freude, W.; Leuthold, J.: Temporal dynamics of the alpha factor in semiconductor optical amplifiers. J. Lightw. Technol. (Aug. 2006, submitted)

SOA λ-Converter & Red Shift Optical Filter (RSOF)



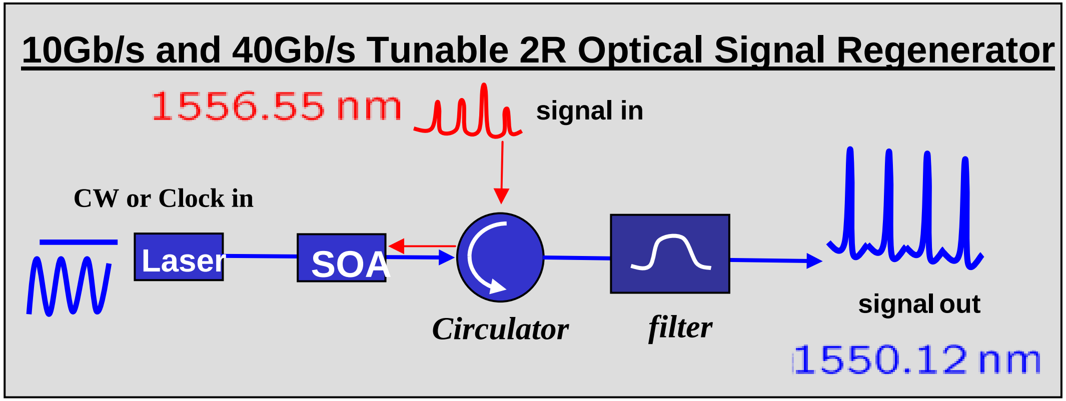


- $P_{\text{data}} = 0 \rightarrow P_{\text{cv}} = 0$ by filter
- $P_{\text{data}} \neq 0 \rightarrow$ red-chirped P_{cv} passes RSOF
- In effect, this is the action of a low-pass filter (integrator).

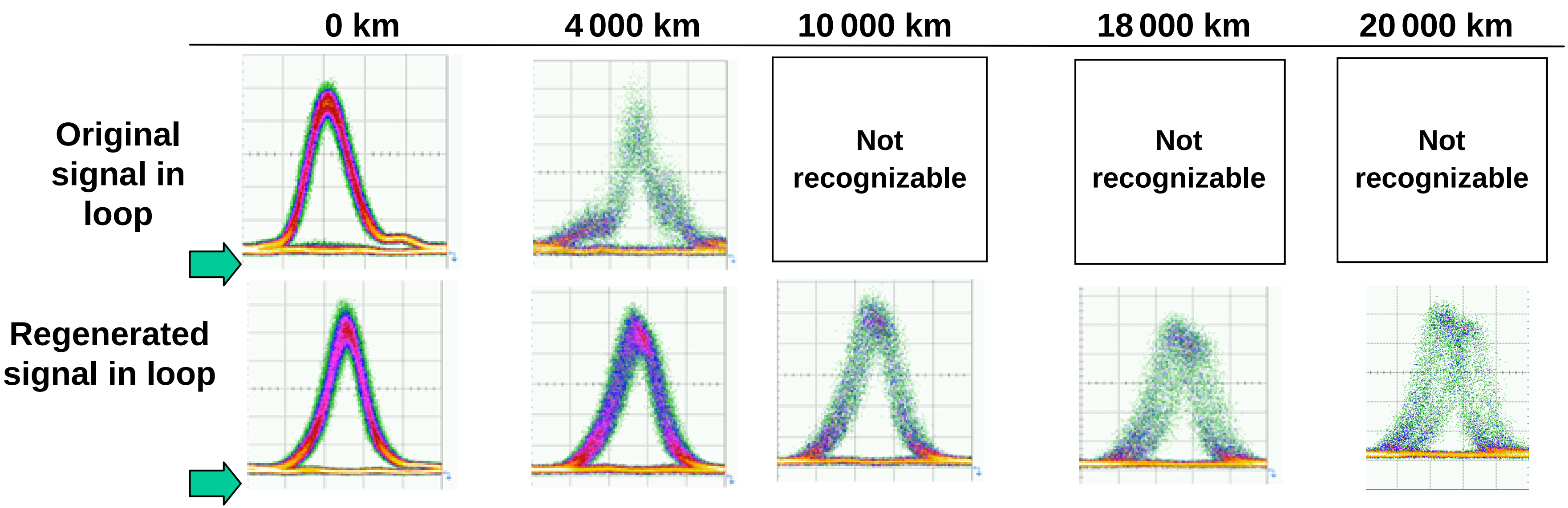
Leuthold, J.; Ryf, R.; Maywar, D. N.; Cabot, S.; Jaques, J.; Patel, S. S.: Regenerative all-optical wavelength converter in a transparent demonstration over 42 nodes and 16800 km. J. Lightwave Technol. 21 (2003) 2863–2870

Chayet, H.; Ben Ezra, S.; Shachar, N.; Tzadok, S.; Tsadka, S.; Leuthold, J.: Regenerative all-optical wavelength converter based on semicon-ductor optical amplifier and sharp frequency response filter. Ofc 2004 ThS2

2R or 3R Regeneration with SOA λ-Converter and RSOF

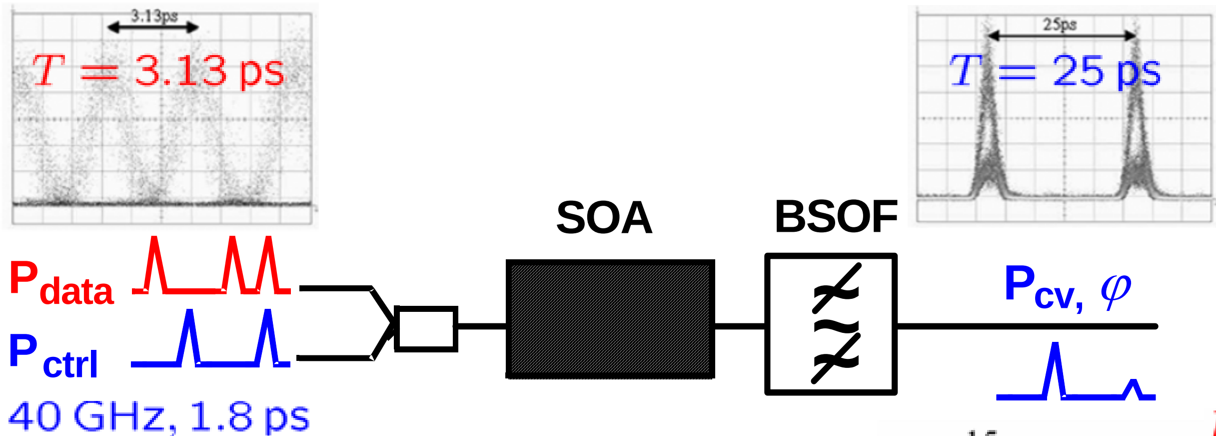


10 Gb/s, RZ,
PRBS: 2^{31}-1

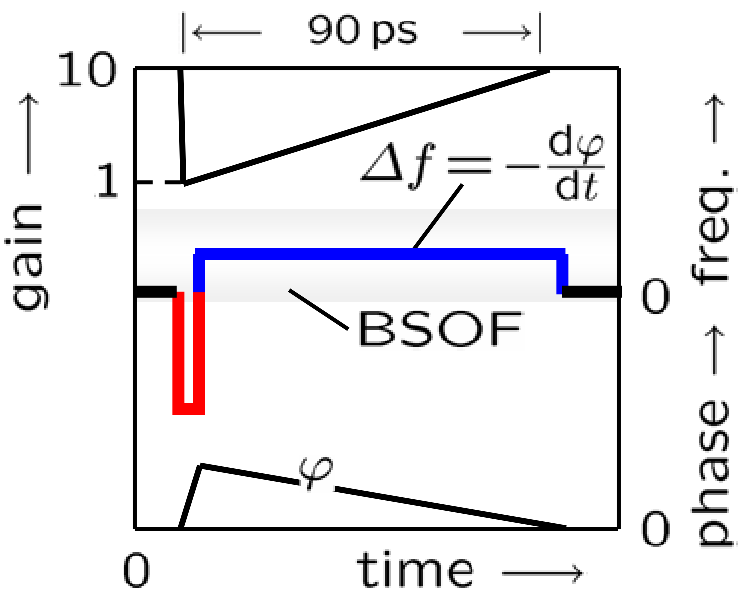


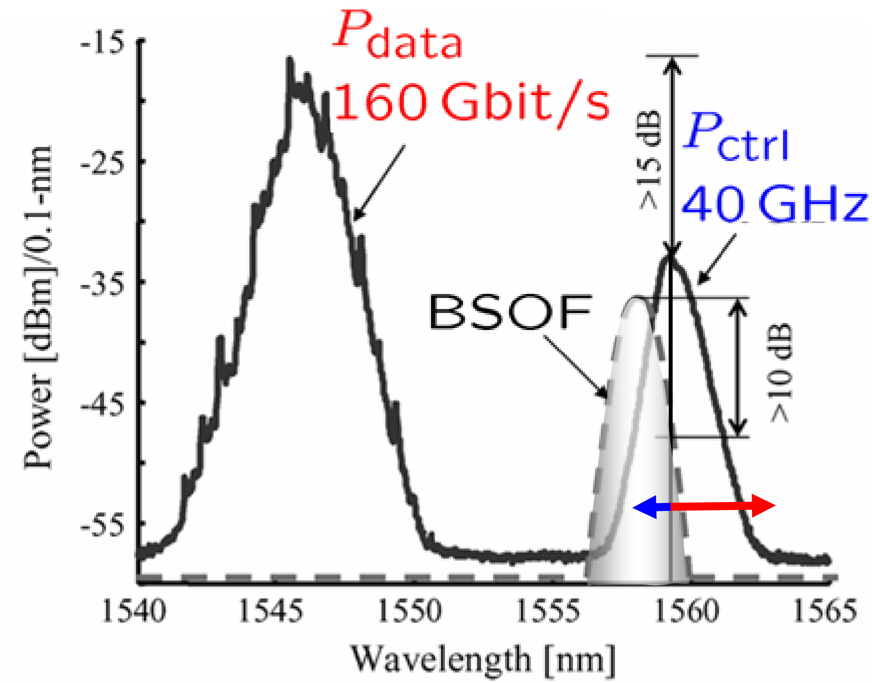
Chayet, H.; Ben Ezra, S.; Shachar, N.; Tzadok, S.; Tsadka, S.; Leuthold, J.: Regenerative all-optical wavelength converter based on semiconductor optical amplifier and sharp frequency response filter. Ofc 2004 Paper ThS2 (**Kailight Photonics**)

OOK 320-to-40 Gbits/s Demux & Blue Shift Optical Filter (BSOF)



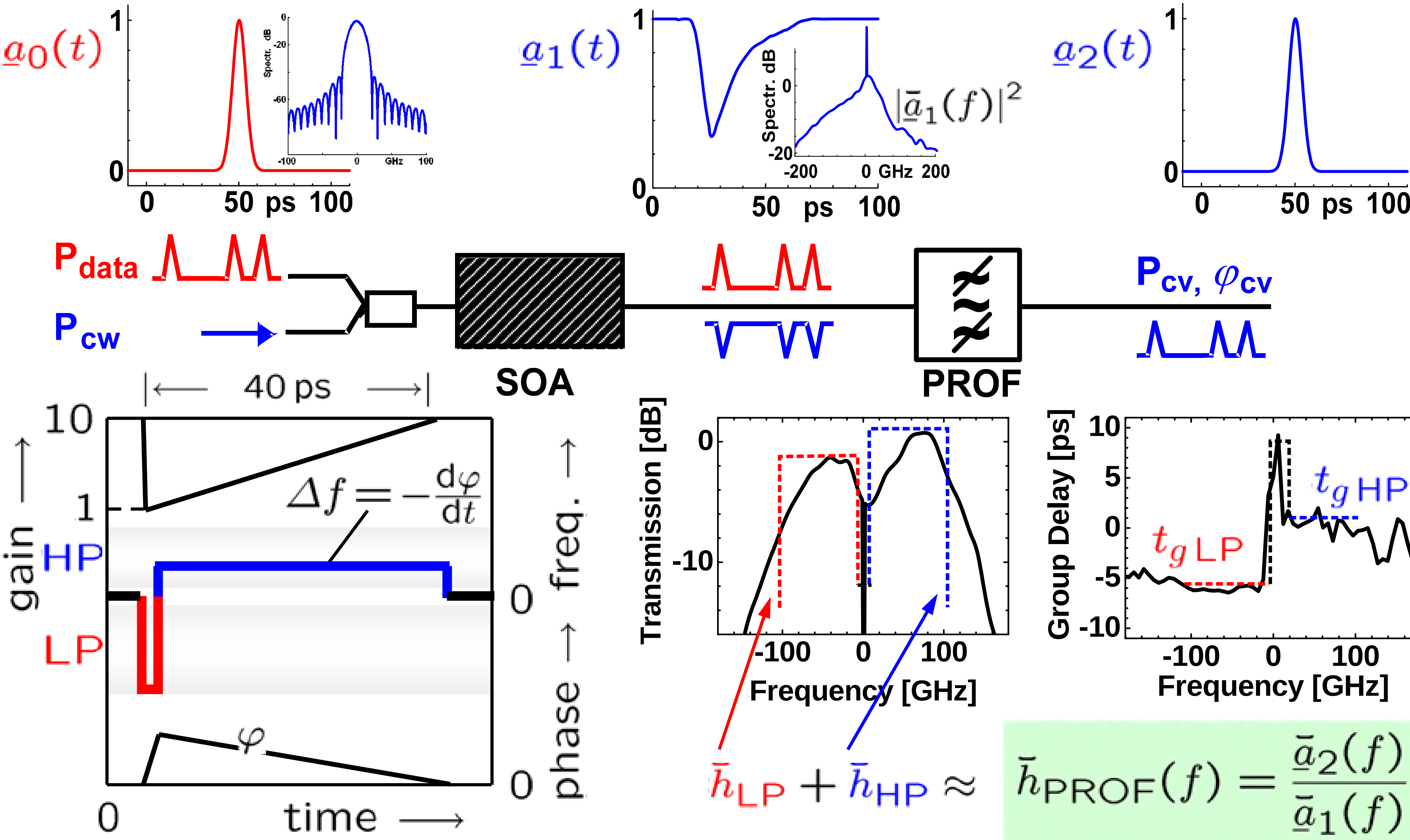
- In effect, this is the action of a high-pass filter (differentiator).





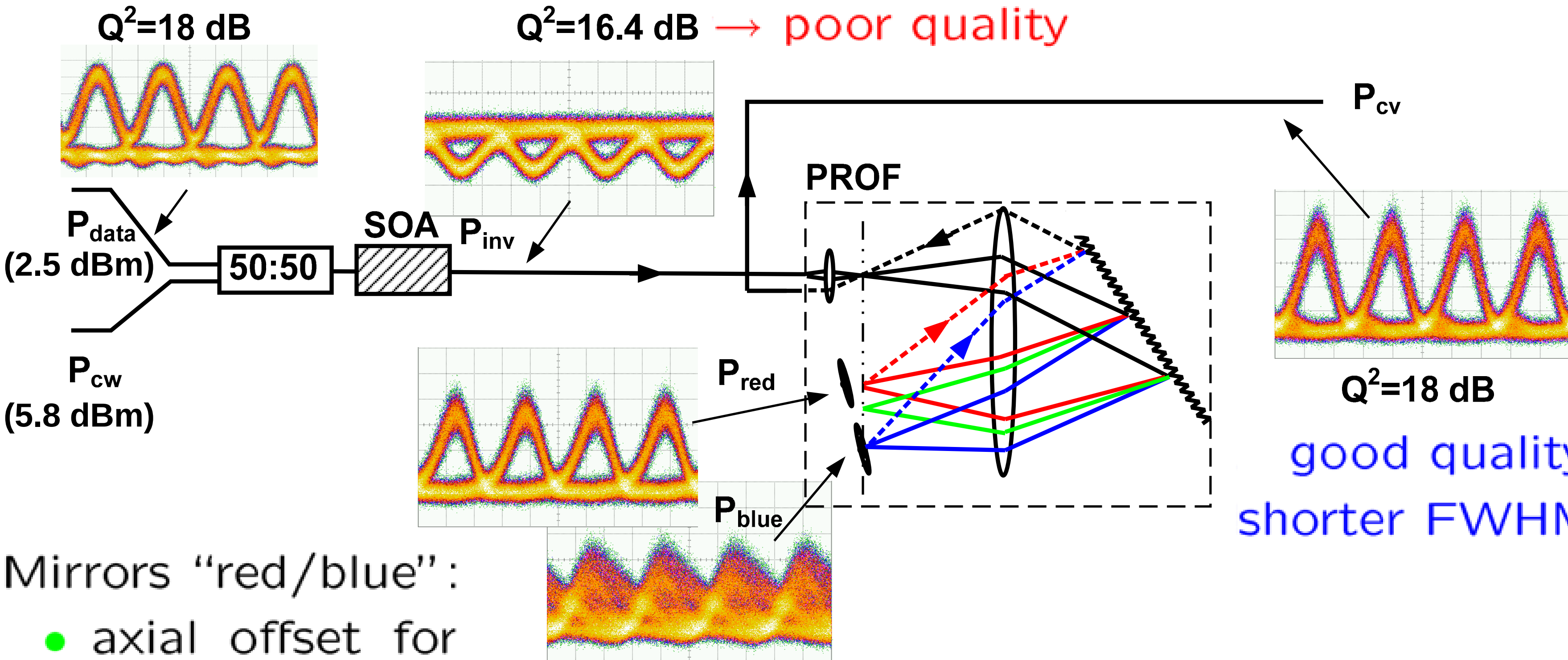
Tangdiongga, E.; Liu, Y.; de Waardt, H.; Khoe, G. D.; Dorren, H. J. S.: 320-to-40-Gb/s demultiplexing using a single SOA assisted by an optical filter. IEEE Photon. Technol Lett. 18 (2006) 908–910

SOA λ-Converter & Pulse Reformatting Filter (PROF)



Leuthold, J.; Marom, D. M.; Cabot, S.; Jaques, J. J.; Ryf, R.; Giles, C. R.: All-optical wavelength conversion using a pulse reformatting optical filter. J. Lightwave Technol. 22 (2004) 186–192

Eye Diagrams for 40 Gbit/s Non-Inverted RZ→RZ λ-Converter



Mirrors "red/blue":

- axial offset for attenuation
- tilt for delay

Different PROF setting: Good-quality bit-inverted operation.

Leuthold, J.; Marom, D. M.; Cabot, S.; Jaques, J. J.; Ryf, R.; Giles, C. R.: All-optical wavelength conversion using a pulse reformatting optical filter. J. Lightwave Technol. 22 (2004) 186–192

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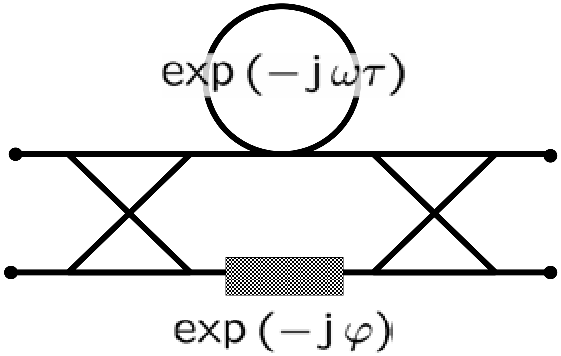
Mach-Zehnder Interferometer Field Transfer Function

$\underline{a} = A\,\mathrm{e}^{\mathrm{j}\,\omega t}$



$$\underline{a}_\Sigma = \mathrm{j}\,A\,\mathrm{e}^{\mathrm{j}\,\omega t}\,\mathrm{e}^{-\mathrm{j}\,\frac{\omega\tau+\varphi}{2}}\cos\left(\frac{\omega\tau-\varphi}{2}\right)$$

$$\underline{a}_\Delta = \mathrm{j}\,A\,\mathrm{e}^{\mathrm{j}\,\omega t}\,\mathrm{e}^{-\mathrm{j}\,\frac{\omega\tau+\varphi}{2}}\sin\left(\frac{\omega\tau-\varphi}{2}\right)$$

<u>Field transfer functions:</u>

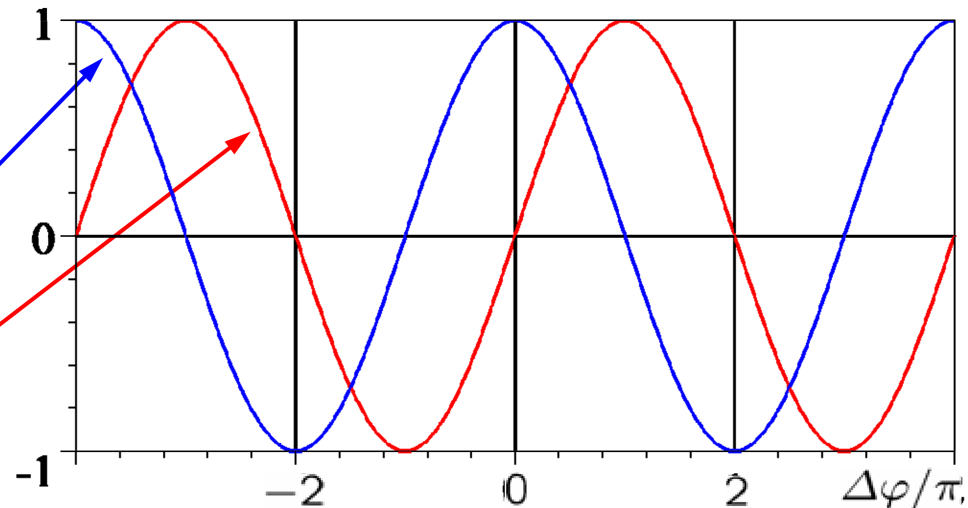
$$T_\Sigma(f) = \frac{\underline{a}_\Sigma}{\underline{a}} = \mathrm{j}\,\mathrm{e}^{-\mathrm{j}\,\frac{\omega\tau+\varphi}{2}}\cos\left(\frac{\omega\tau-\varphi}{2}\right),\quad T_\Delta(f) = \frac{\underline{a}_\Delta}{\underline{a}} = \mathrm{j}\,\mathrm{e}^{-\mathrm{j}\,\frac{\omega\tau+\varphi}{2}}\sin\left(\frac{\omega\tau-\varphi}{2}\right)$$

<u>MZM</u>: $\omega_0\tau = \varphi_1,\ \varphi = \varphi_2,$

$\varphi_1 + \varphi_2 = 2\phi,\ \varphi_1 - \varphi_2 = \Delta\varphi:$

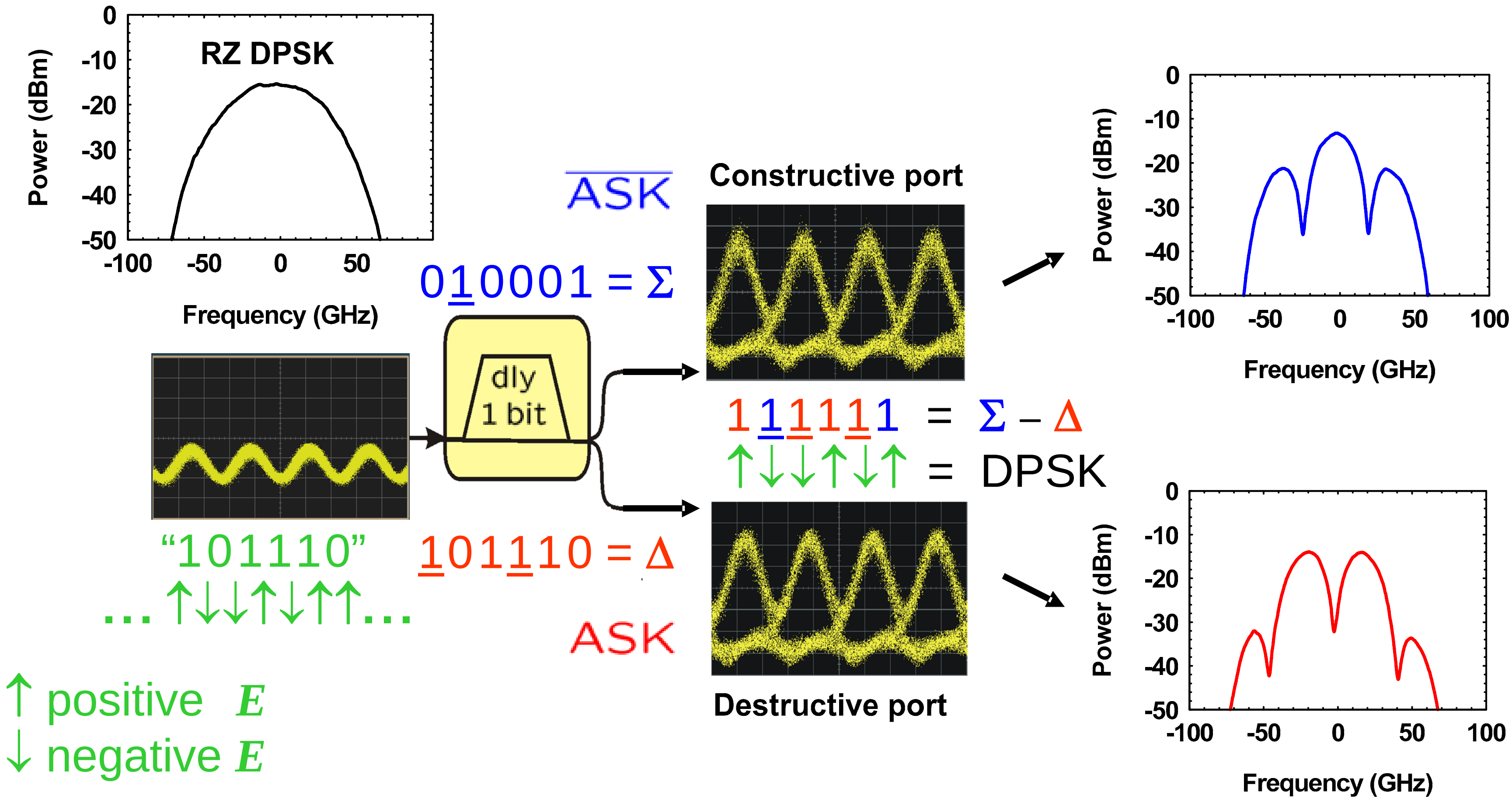
$$T_\Sigma(f_0,\tau) = \mathrm{j}\,\mathrm{e}^{-\mathrm{j}\,\phi}\cos\left(\frac{\Delta\varphi}{2}\right)$$

$$T_\Delta(f_0,\tau) = \mathrm{j}\,\mathrm{e}^{-\mathrm{j}\,\phi}\sin\left(\frac{\Delta\varphi}{2}\right)$$



Push-push: $\phi(t)$ — Push-pull: $\Delta\varphi(t)$

DPSK Receiver — DPSK → ASK Conversion



DPSK phase noise ⟶ ASK amplitude (and phase) noise

DPSK amplitude noise ⟶ ASK amplitude noise

Penninckx, D.; Bissessur, H.; Brindel, P.; Gohin, E.; Bakhti, F.: Optical differential phase shift keying (DPSK) direct detection considered as a duobinary signal. Proc. Ecoc 2001 456–457. Paper We.P.40

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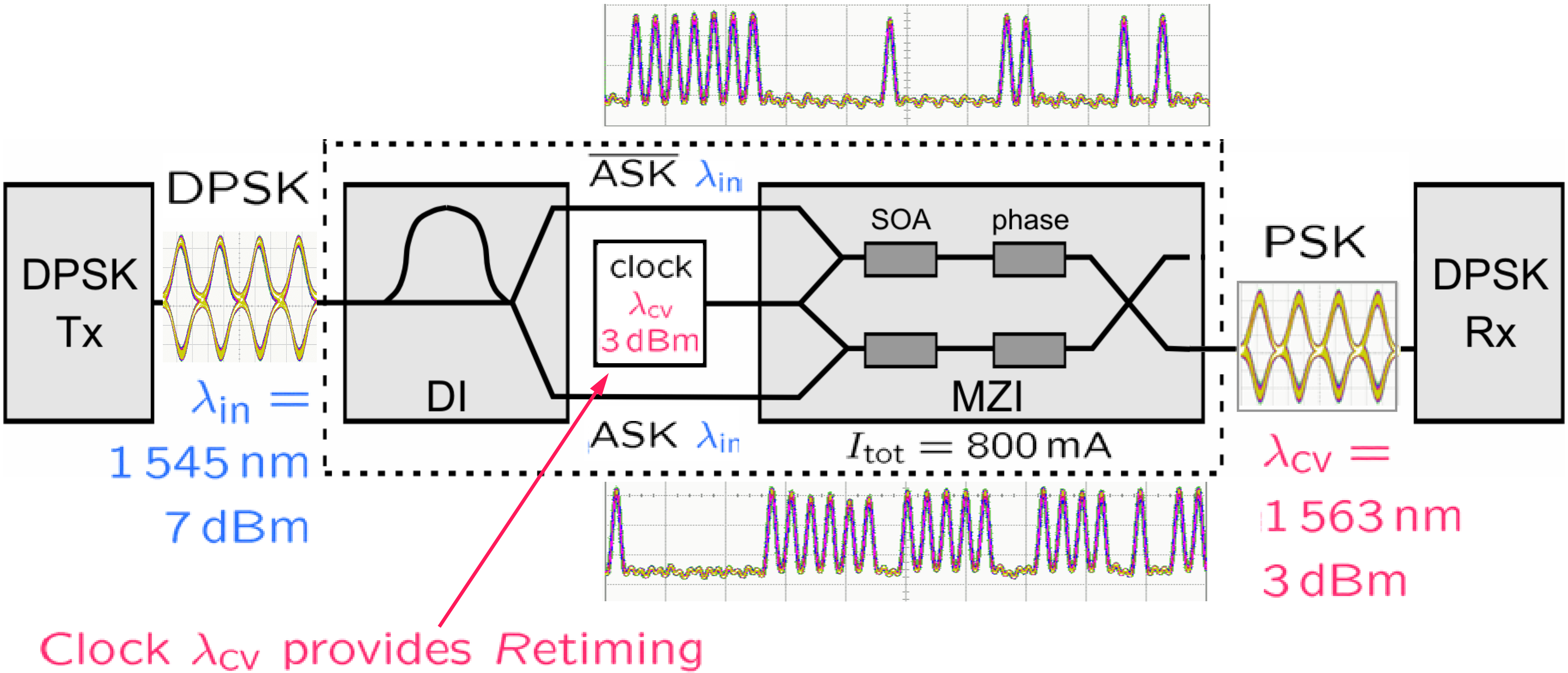
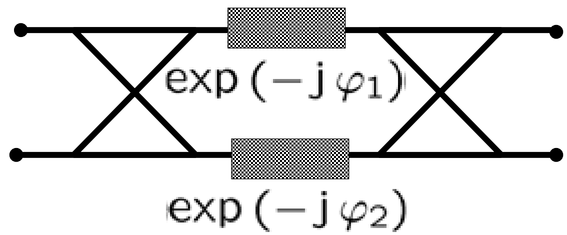
All-Optical DPSK λ-Converter



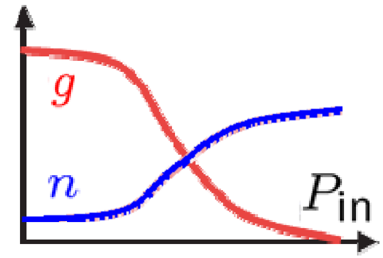
Sartorius, B.; Bornholdt, C.; Slovak, J.; Schlak, M.; Schmidt, Ch.; Marculescu, A.; Vorreau, P.; Tsadka, S.; Freude, W.; Leuthold, J.: All-optical DPSK wavelength converter based on MZI with integrated SOAs and phase shifters. Ofc 2006 OWS6

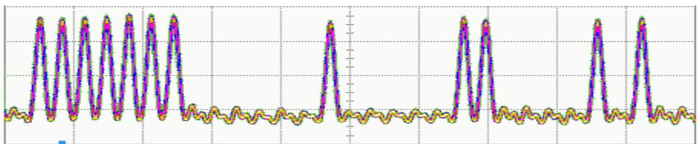
Kang, I.; Dorrer, C.; Zhang, L.; Rasras, M.; Buhl, L.; Bhardwaj, A.; Gomez, S.; Wong-Foy, A.; Chen, Y. F.; Patel, S.; Neilson, D. T.; Jaques, J.; Giles, C. R.: Regenerative all optic wavelength conversion of 40 Gb/s DPSK signals using a semiconductor optical amplifier Mach-Zehnder interferometer. Ecoc 2005 Proc. 6 (2005) 29-31. PDP-Th4.3.3

DPSK λ-Conversion Process by Cross-Phase Modulation (XPM)



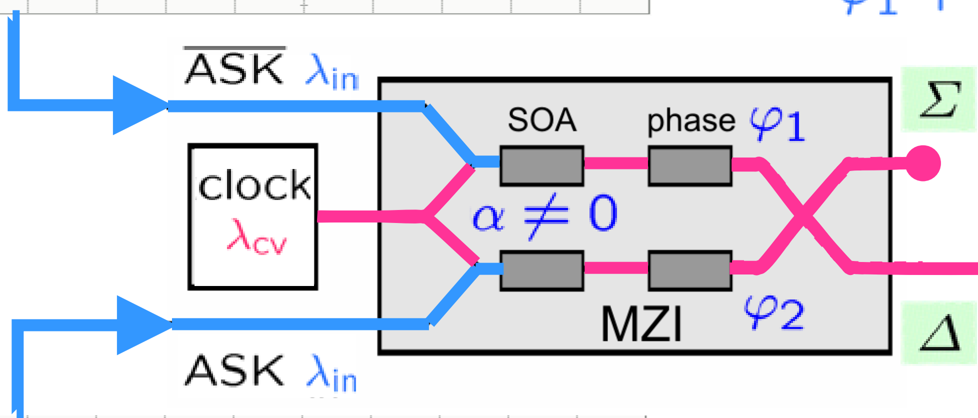
$\varphi_{1,2} = k_0 n_{1,2} L$

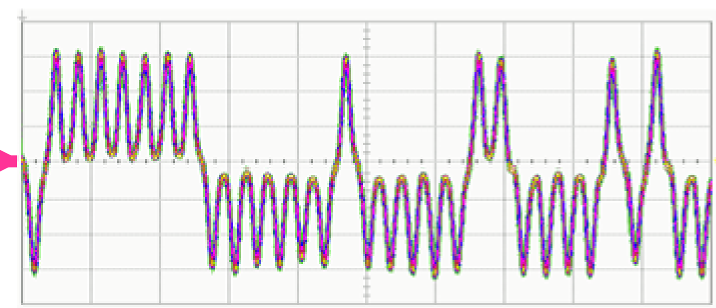


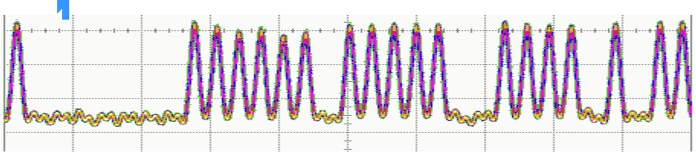


$\overline{\text{ASK}}$ data:

$\varphi_1 + \pi \;\rightarrow\; \Delta = \mathrm{j}\,\mathrm{e}^{-\mathrm{j}\frac{\pi}{2}} \sin\left(\frac{\pi}{2}\right) = +1$







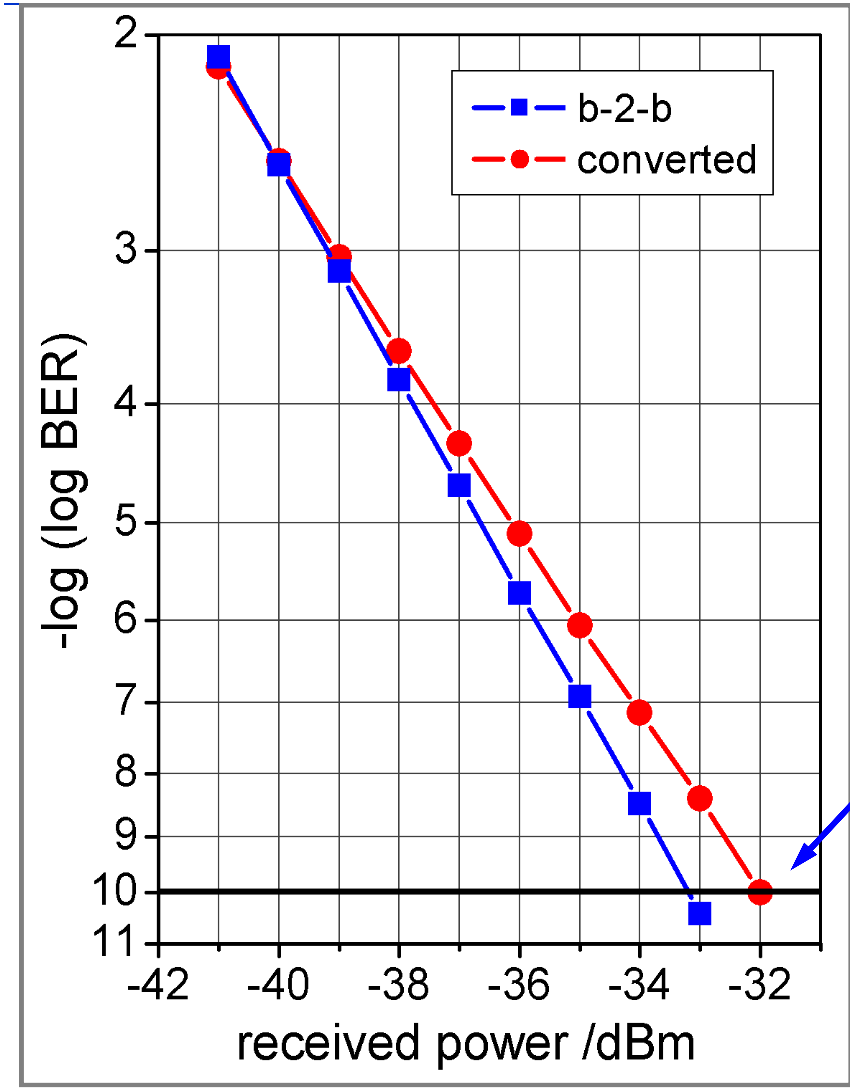
ASK data:

$\varphi_2 + \pi \;\rightarrow\; \Delta = \mathrm{j}\,\mathrm{e}^{-\mathrm{j}\frac{\pi}{2}} \sin\left(-\frac{\pi}{2}\right) = -1$

No data, $\varphi_1 = 0$:

phase tuning $\Delta\varphi = \varphi_1 - \varphi_2 = 0 \;\rightarrow\; \Delta = \mathrm{j}\,\mathrm{e}^{-\mathrm{j}\,0} \sin\left(\frac{\Delta\varphi}{2}\right) = 0$

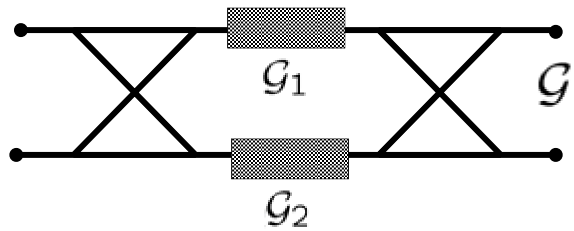
DPSK λ-Conversion Results for 31 Gbit/s



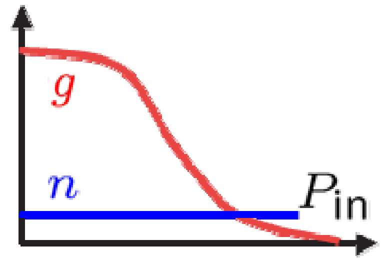
- Error-free λ-conversion
- For BER $= 10^{-10}$
  1 dB penalty only

Sartorius, B.; Bornholdt, C.; Slovak, J.; Schlak, M.; Schmidt, Ch.; Marculescu, A.; Vorreau, P.; Tsadka, S.; Freude, W.; Leuthold, J.: All-optical DPSK wavelength converter based on MZI with integrated SOAs and phase shifters. Ofc 2006 OWS6

DPSK λ-Conversion Process by Cross-Gain Modulation (XGM)

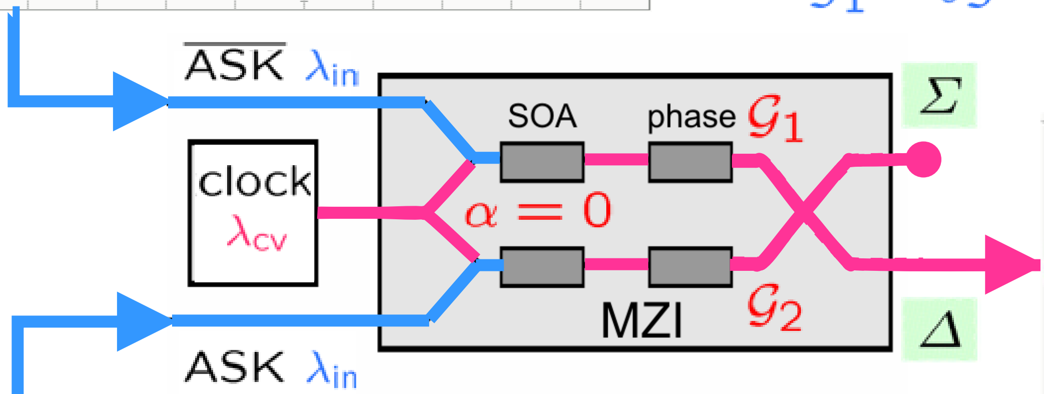


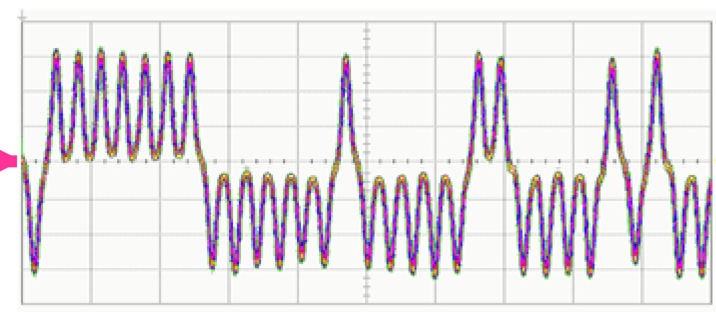
$$\mathcal{G}_{1,2} = \exp\left(\frac{g_{1,2}}{2}L\right)$$

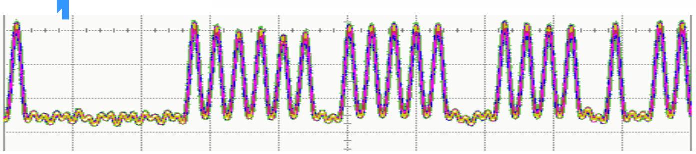


$\overline{\text{ASK}}$ data:

$\mathcal{G}_1 - \delta\mathcal{G} \rightarrow \Delta = +\delta\mathcal{G}$







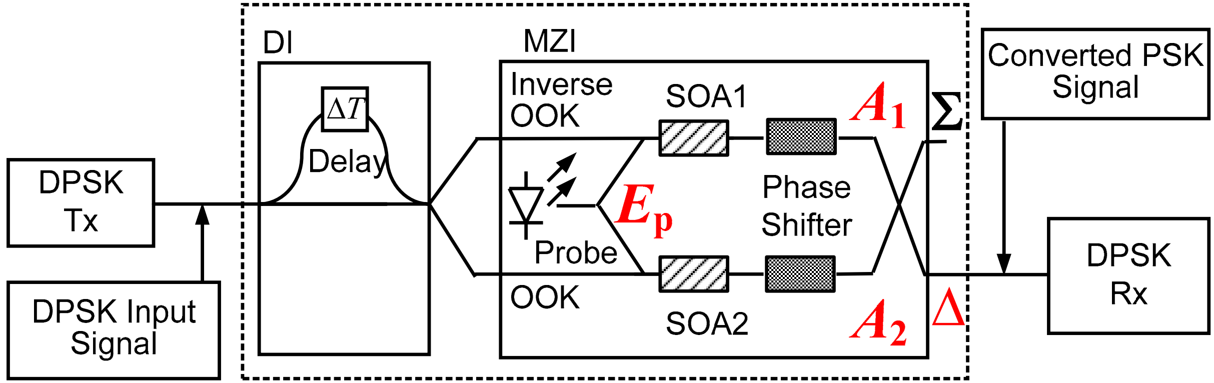
ASK data:

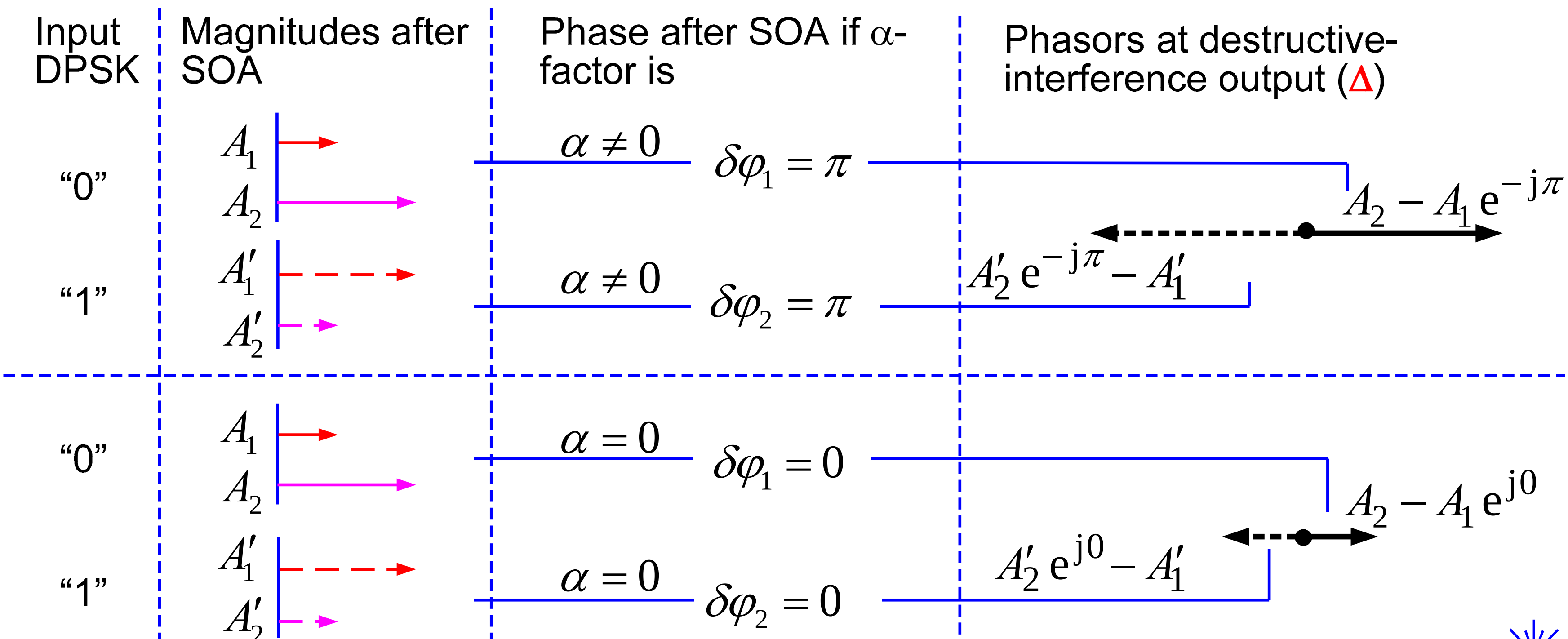
$\mathcal{G}_2 - \delta\mathcal{G} \rightarrow \Delta = -\delta\mathcal{G}$

No data, $\varphi_{1,2} = 0$:

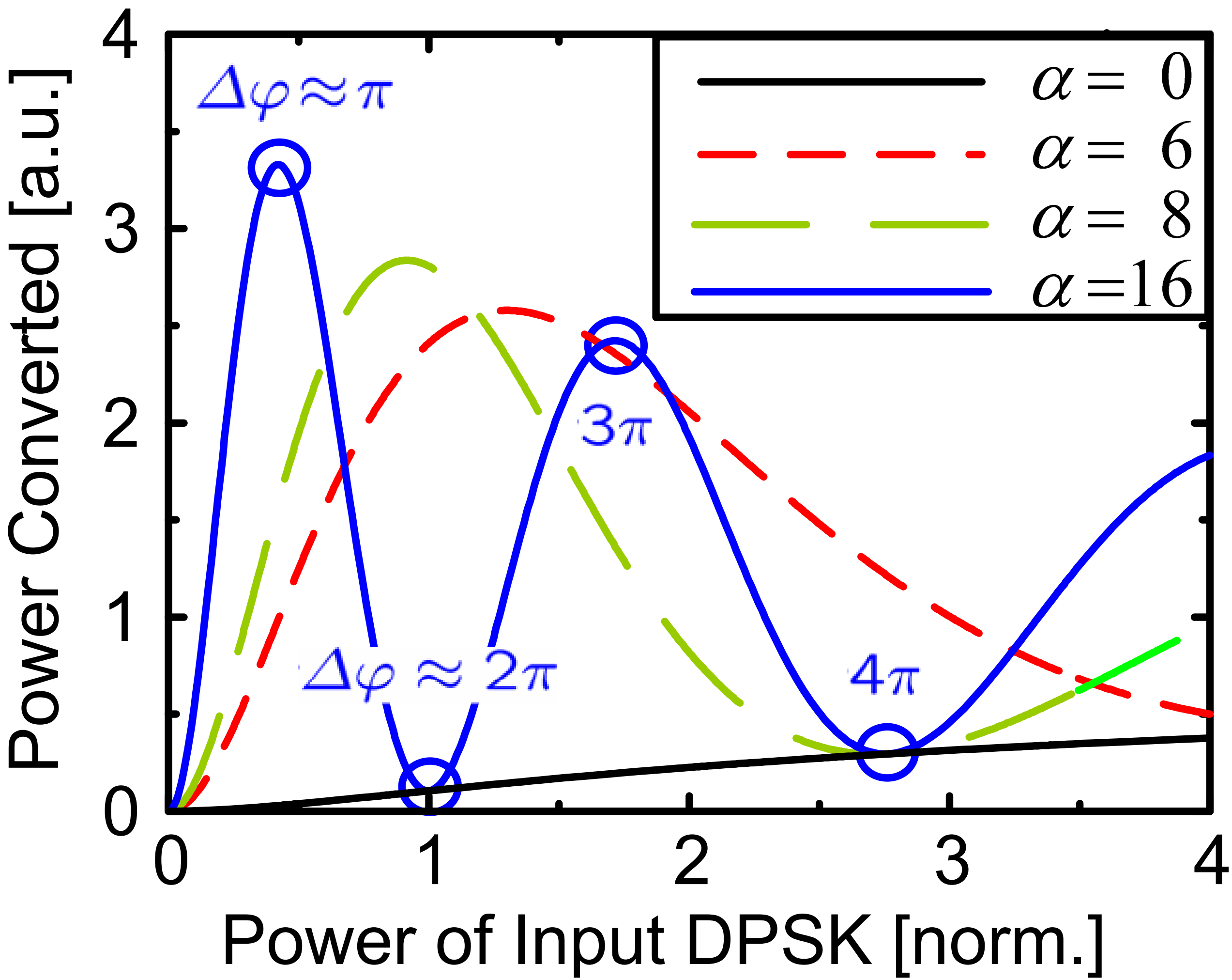
gain tuning $\Delta\mathcal{G} = \mathcal{G}_2 - \mathcal{G}_1 = 0 \rightarrow \Delta = \Delta\mathcal{G} = 0$

DPSK λ-Conversion by (XPM & XGM) *or* XGM



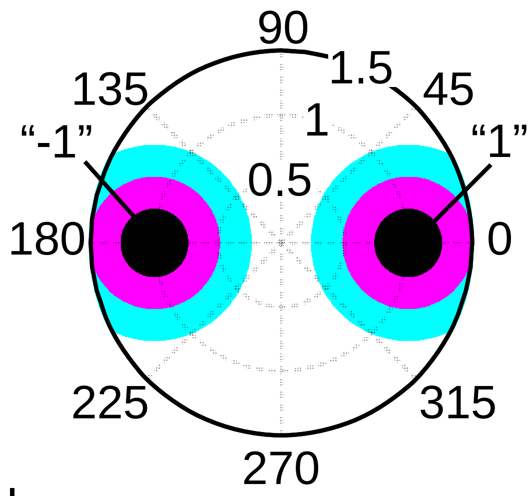


DPSK λ-Converter Operating Point for Various SOA α-Factors



DPSK λ-Converter — Symbol Diagrams and Regeneration

Input DPSK signal



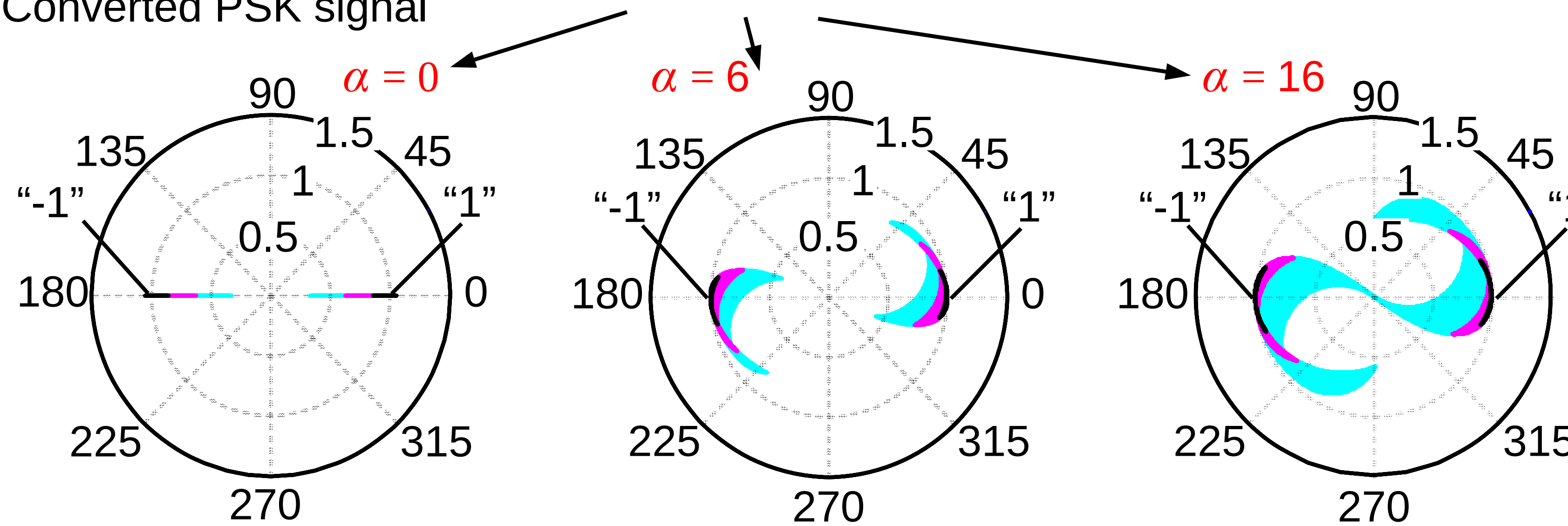
Shaded areas show phase and amplitude jitter of input DPSK signal. Jitter $(\mathrm{d}A/A_s)\cdot\exp(\mathrm{j}\varphi)$ with

- $\mathrm{d}A/A_s$: 75 %
- $\mathrm{d}A/A_s$: 50 %
- $\mathrm{d}A/A_s$: 25 %

and random $\varphi \in [-\pi, \pi]$.

A_s is the operating point amplitude.

Converted PSK signal

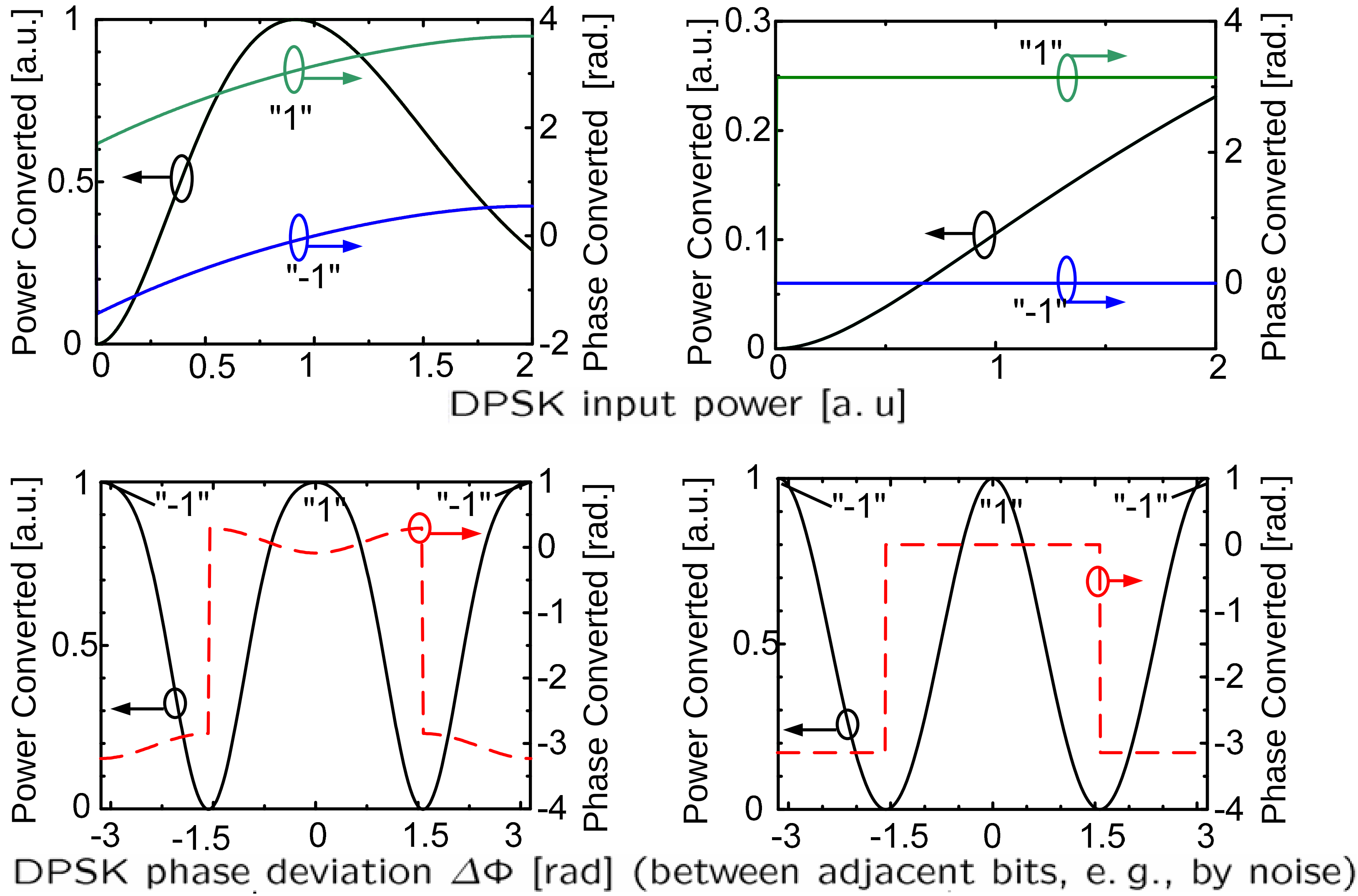


Vorreau, P.; Marculescu, A.; Wang, J.; Böttger, G.; Sartorius, B.; Bornholdt, C.; Slovak, J.; Schlak, M.; Schmidt, Ch.; Tsadka, S.; Freude, W.; Leuthold, J.: Cascadability and regenerative properties of SOA all-optical DPSK wavelength converters. IEEE Photon. Technol. Lett. (2006) (in press)

$\alpha = 8$

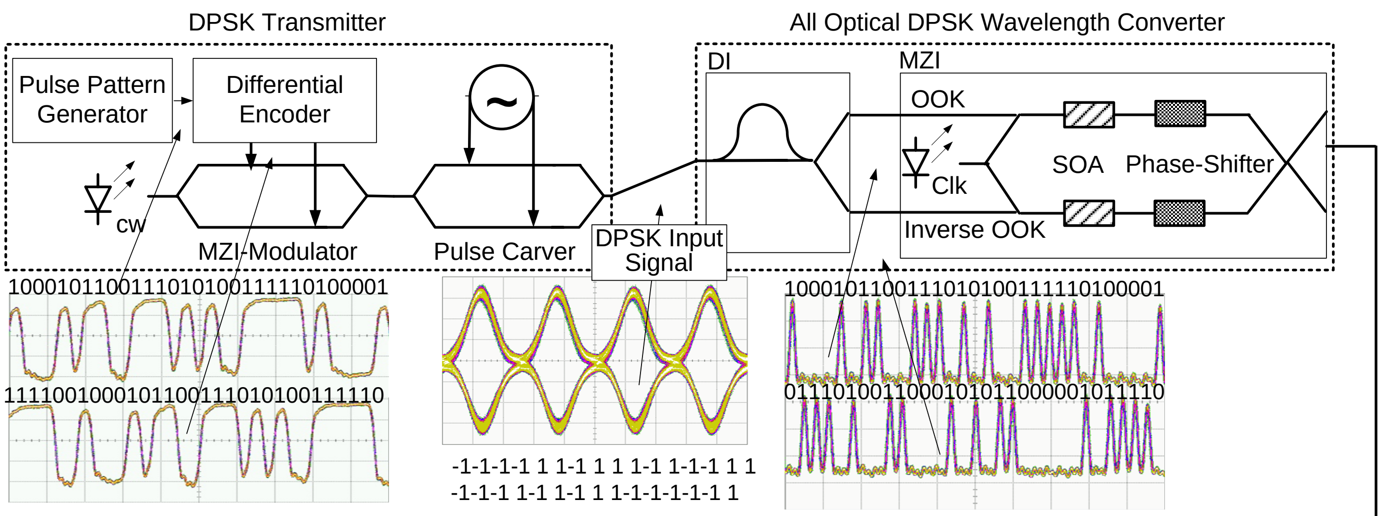
DPSK λ-Converter — Regeneration

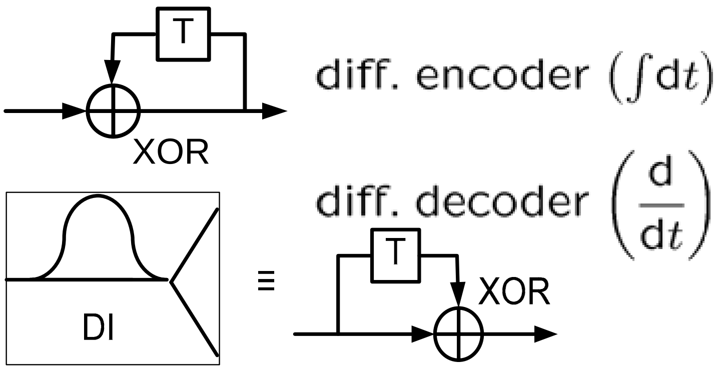
$\alpha = 0$



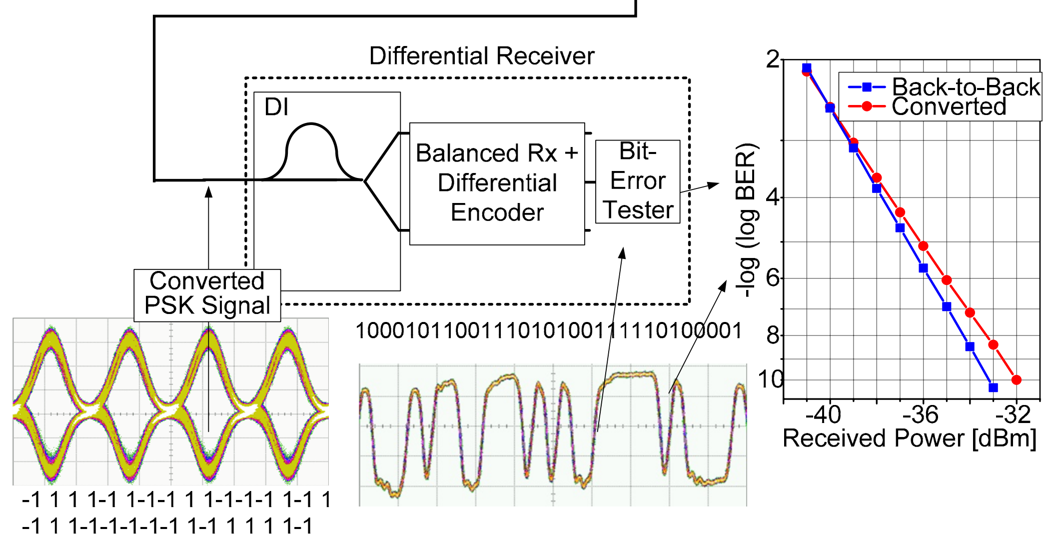
Vorreau, P.; Marculescu, A.; Wang, J.; Böttger, G.; Sartorius, B.; Bornholdt, C.; Slovak, J.; Schlak, M.; Schmidt, Ch.; Tsadka, S.; Freude, W.; Leuthold, J.: Cascadability and regenerative properties of SOA all-optical DPSK wavelength converters. IEEE Photon. Technol. Lett. (2006) (in press)

DPSK λ-Converter — Set-Up and Performance



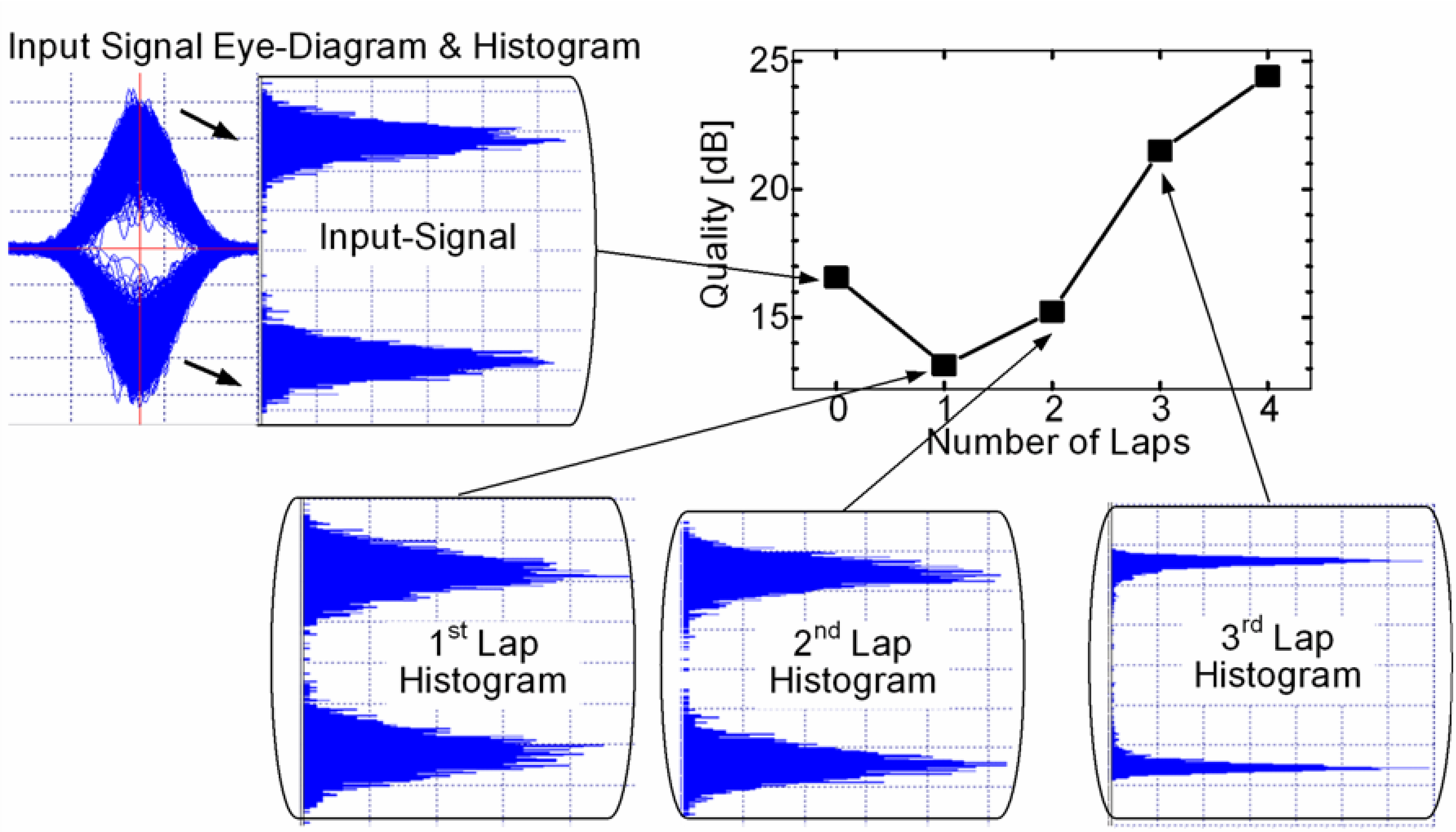


Any number of AOWC can be cascaded for an equal number of DI and differential encoders



Vorreau, P.; Marculescu, A.; Wang, J.; Böttger, G.; Sartorius, B.; Bornholdt, C.; Slovak, J.; Schlak, M.; Schmidt, Ch.; Tsadka, S.; Freude, W.; Leuthold, J.: Cascadability and regenerative properties of SOA all-optical DPSK wavelength converters. IEEE Photon. Technol. Lett. (2006) (in press)

DPSK λ-Converter — Cascadability



Vorreau, P.; Marculescu, A.; Wang, J.; Böttger, G.; Sartorius, B.; Bornholdt, C.; Slovak, J.; Schlak, M.; Schmidt, Ch.; Tsadka, S.; Freude, W.; Leuthold, J.: Cascadability and regenerative properties of SOA all-optical DPSK wavelength converters. IEEE Photon. Technol. Lett. (2006) (in press)

Outline

- Modulation techniques
  - Analogue, digital, coding
  - Symbol diagrams, spectra
  - Benefits, transmission capacity
- SOA gain and phase recovery
  - Gain-phase coupling
  - Physical explanation
- SOA signal processing
  - Logic gate
  - OOK wavelength converter
  - DPSK wavelength converter
- Summary

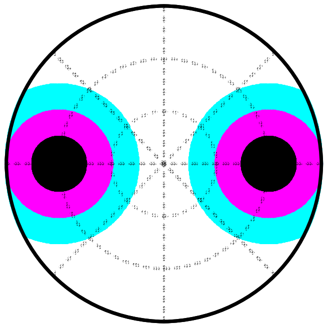
Summary

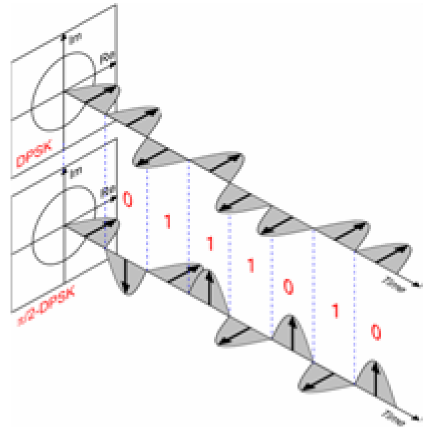
Standard modulation format:

- OOK

Novel modulation formats:

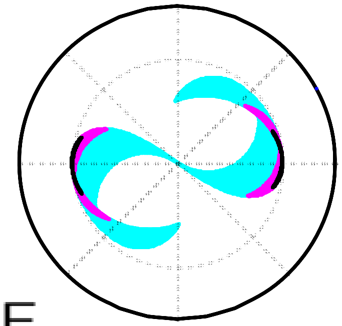
- Phase shaping OOK
- DPSK

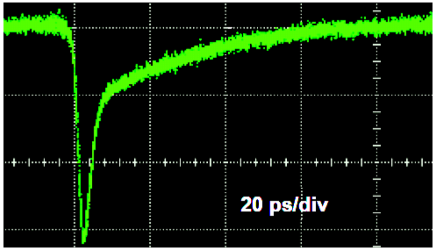




SOA gain and phase recovery:

- Ultrafast
- Logic gates





SOA wavelength converter:

- OOK with RSOF, BSOF, PROF
- DPSK

SOA DPSK wavelength converter:

- Regeneration
- Cascadability