Innovative Modulation Schemes for Future Optical WDM-Transmission

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Introduction

Innovative modulation formats have impact on transmission performance of optical networks.

They may:

- \+ increase bandwidth efficiency (i.e. narrowing of channel spacing)
- \+ increase transmission span reach
- \+ increase system margin and tolerances
- – increase system complexity and equipment cost
- – not be in compliance with existing standards

Outline

1. Introduction
2. Modulation of Optical Carriers
3. Options for Alternative Modulation Formats
    a. Duobinary Signaling
    b. Single Sideband
    c. Differential (Q)PSK
4. Comparison of Modulation Formats in WDM Transmission
5. Conclusions

Modulation: Basics

Modulation of a carrier signal (here: laser light) = mapping of information into one or more parameters of the carrier, i.e

- Amplitude
- Phase (or frequency as $\omega = d\phi/dt$)
- Polarization

Carrier = real-valued band-pass signal (electrical field):

$$E(t) = a(t)\cos[\omega_C t + \phi(t)] = \mathrm{Re}\{\underbrace{a(t)e^{j\phi(t)}}_{A(t)} \cdot e^{j\omega_C t}\}$$

$A(t)$: Complex Envelope

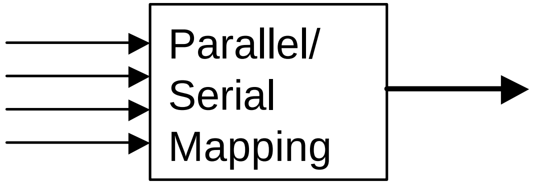
•carries information

•Determines modulation format

Modulation: Basics

Digital transmission of bits b with bit rate $r_b=1/T_b$

$M=2^m$ bits collected → one complex symbol $d(k)$, symbol rate $r_S=1/T_S=r_b/M$



Binary Bits

Parallel/
Serial
Mapping

M-ary Symbols

Complex symbols: $d(k) = d_R(k) + jd_I(k)$

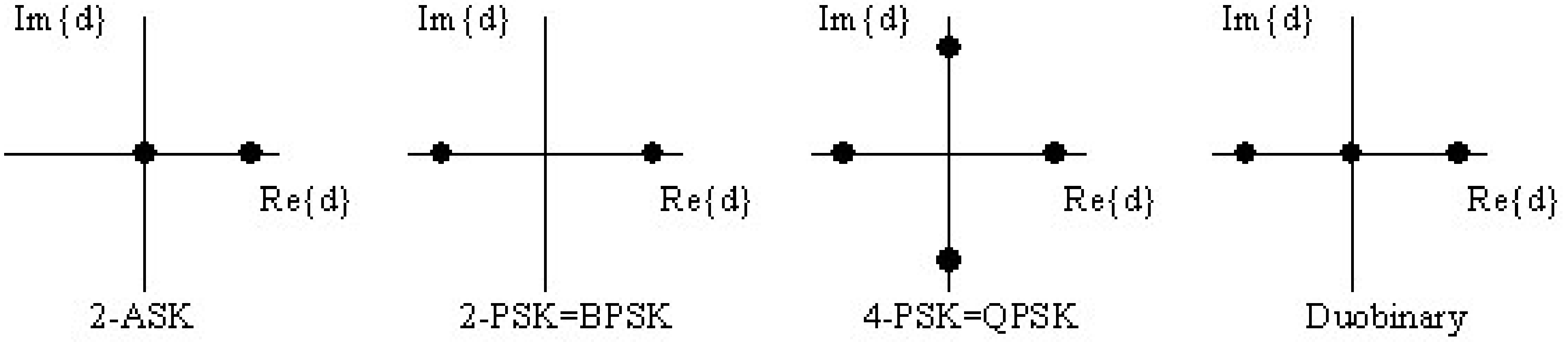
Complex envelope: $A(t) = A_R(t) + jA_I(t) = a(t)e^{jf(t)} = \sum_k d(k) \cdot \overbrace{h(t-kT_S)}^{\text{Pulse shape}}$

Transmitted field: $E(t) = \left[\sum_k d_R(k)h(t-kT_S)\right]\cos(w_c t) - \left[\sum_k d_I(k)h(t-kT_S)\right]\sin(w_c t)$

Orthogonal carriers, 2 data streams

Linear Modulation: Constellations

In the class of linear modulation → format is determined by constellation



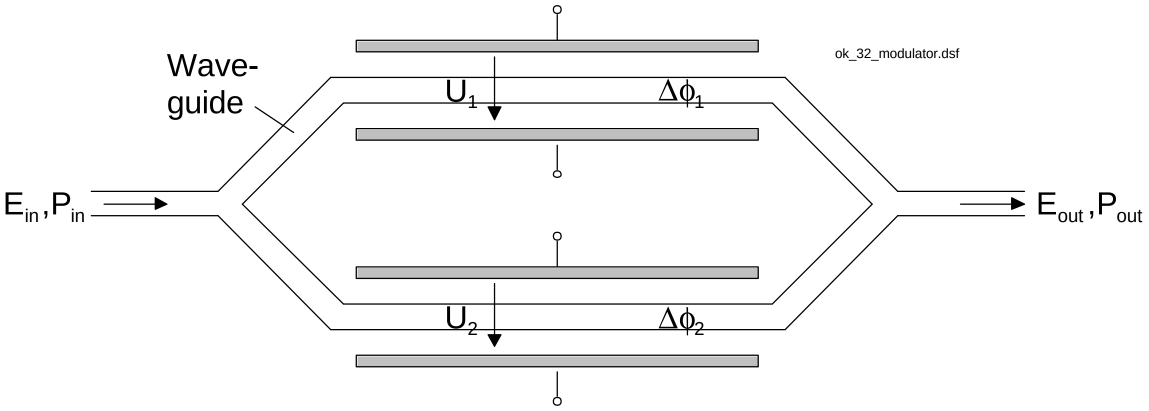
Noise performance → Minimum distance between symbols!

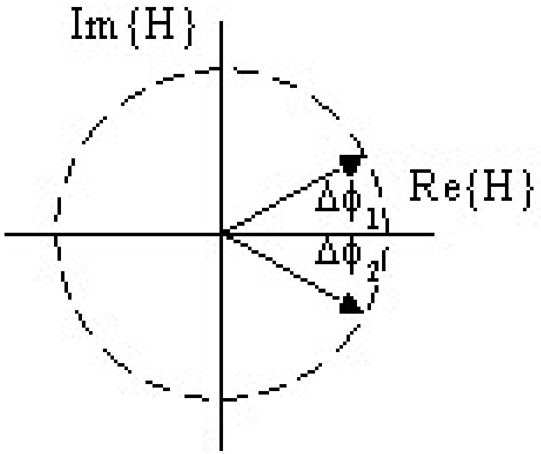
Modulation Formats: Some Options

- Amplitude
  - RZ/NRZ (2-ASK with different pulse shape)
  - VSB/SSB
  - Multilevel (4-ASK, 8-ASK)
- Phase
  - DPSK
  - DQPSK
  - CPM = continuous phase mod.
- Frequency
  - MSK = minimum shift keying
  - FSK = frequency shift keying
- Hybrid
  - CS-RZ, chirped RZ/NRZ, partial response (e.g. duobinary)

Optical Modulator: Mach-Zehnder Interferometer

Mach-Zehnder Modulator for arbitrary phase/amplitude modulation





By driving and/or biasing a MZM apropriately, arbitrary constellations in complex plane can be implemented!

Innovative Formats: Duobinary Signaling

- Reduced bandwidth (approx. Factor of 2 against NRZ)
- Highly dispersion tolerant → increase uncompensated transmission reach
- Carrier suppressed format: relaxed SBS suppression requirements
- Increased spectral efficiency
- Low implementation complexity → upgrade of conventional IM/DD possible

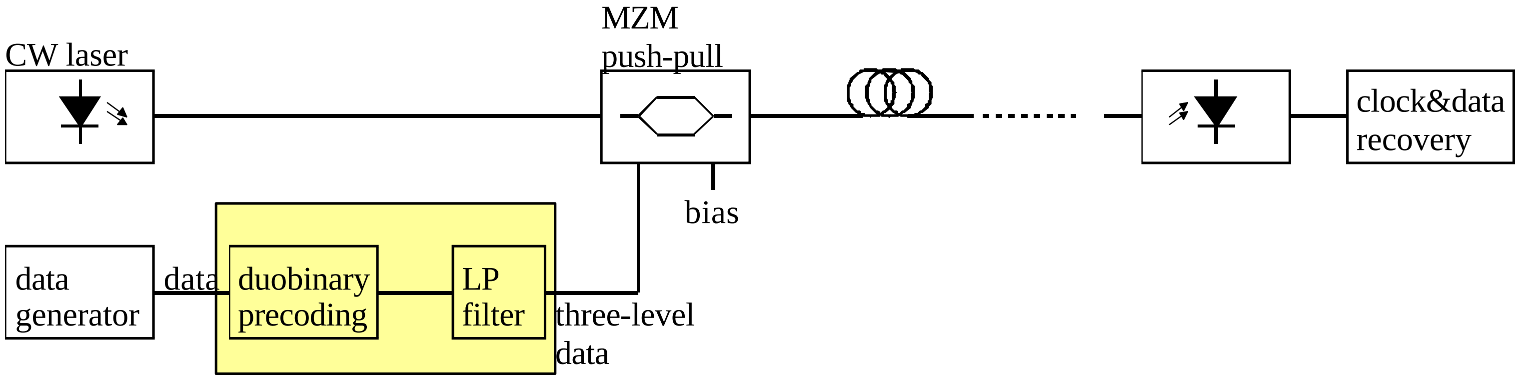
Duobinary Signaling - How it Works!

- Optical transmitted signal: (pseudo)-three-level symbols {***+1,0,-1***} using $2V_\pi$ MZM drive signal
- Coding rule:
  - “0”-bit → ***0***
  - “1”-bit → +***1*** or –***1***, *depending on …?*
- Coding rule narrows spectrum of optical transmit signal
- IM/DD-RX detects magnitude squared of opt. Signal
  - ***0***-symbol → “0”-bit
  - +***1***-symbol and –***1***-symbol → “1”-bit

  } coding rule inverted!
- Low implementation complexity
  - Implementation of coding rule in transmitter
  - Conventional IM/DD receiver
  - → simple upgrade of conventional IM/DD schemes

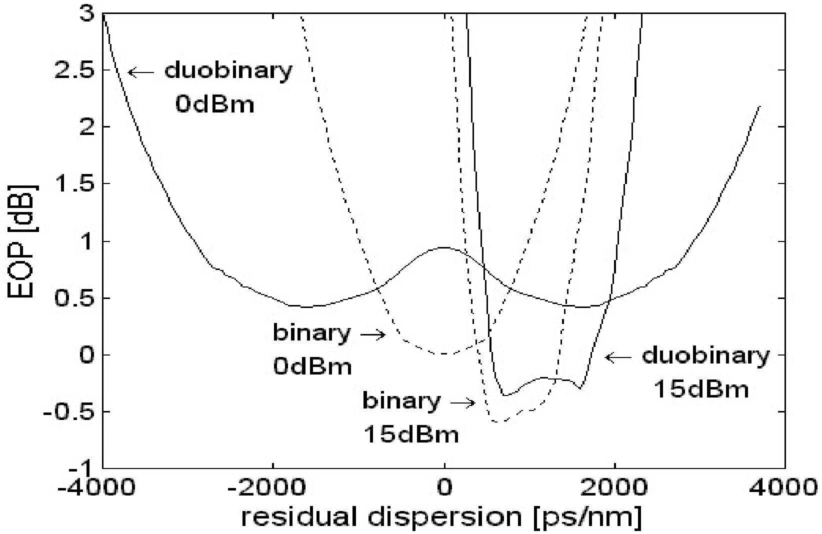
Duobinary Signaling - Implementation

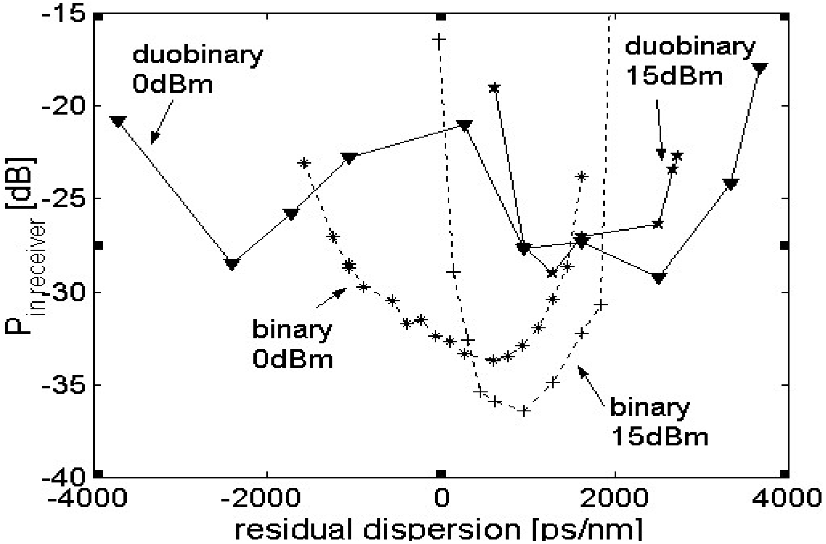
- Duobinary precoder = differential encoder → IC-solution
- Duobinary filter: LP with cut-off frequency of $f_b/4$



Duobinary Encoding

Duobinary Signaling - Dispersion Tolerance





Simulation 10Gb/s

Measurement 10Gb/s

- Improved dispersion tolerance
- High sensitivity to non-linear fibre effects (SPM)

Innovative Formats: SSB/VSB

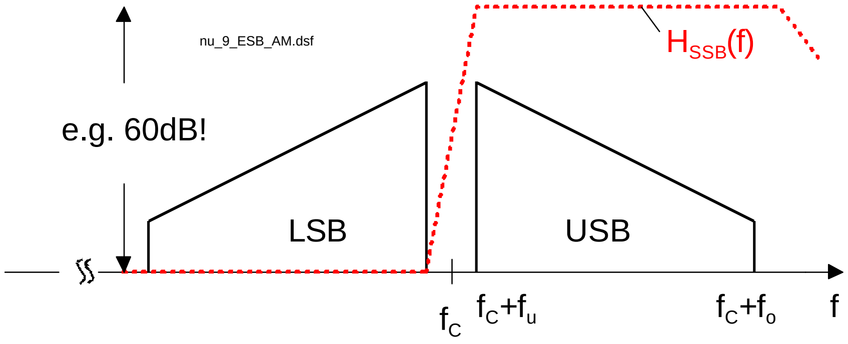
- Single Side Band (SSB) or Vestigial Side Band (VSB)
- Reduced bandwidth (approx. factor 2 against conventional double-sideband ASK = DSB)
- Highly dispersion tolerant
- Increased spectral efficiency
- Medium to high implementation complexity
- Extinction ratio problems! → reduced receiver sensitivity

SSB/VSB – How it Works!

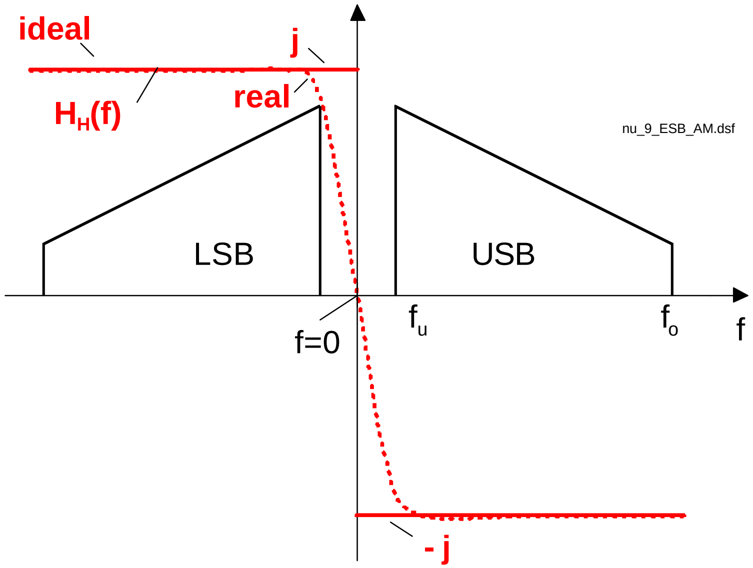
- Conventional: Double side-band ASK
- However: Redundancy → one side-band (either lower or upper) is redundant (one SB contains full information!)
- Eliminate one side-band by
  - Filtering in optical domain
  - Filtering in electrical domain
- SSB/VSB RX requires coherent detection!
- However direct (intensity) detection possible, but carrier component required!
- Direct detection results in distortions!

SSB/VSB – Sideband Suppression

- Optical SSB/VSB filter
- Filtering in optical (band-pass) domain

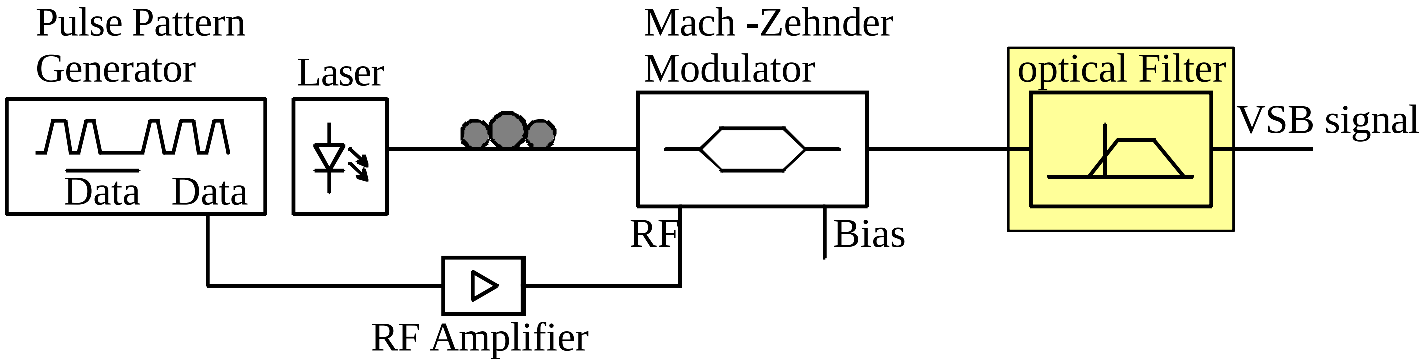


- Hilbert Transformer = Phase response Filter
- Filtering in electrical (base-band) domain



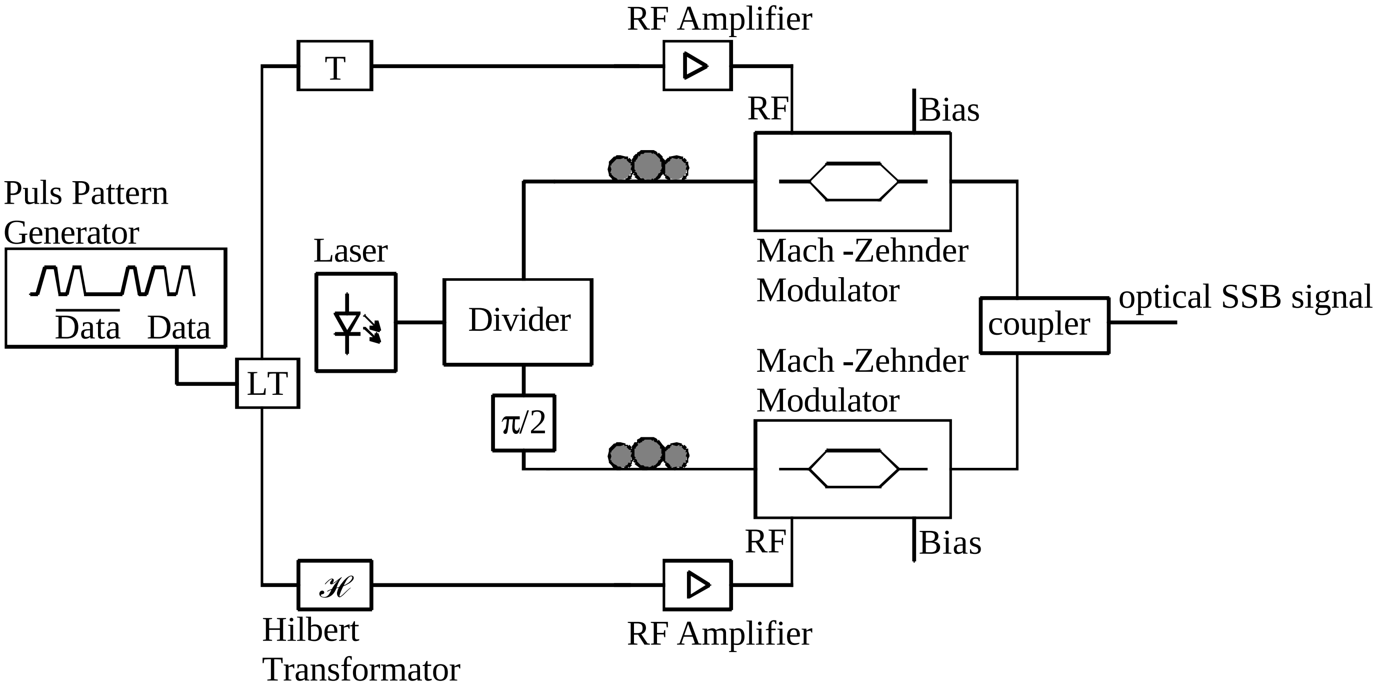
SSB/VSB – Implementation: Optical Filter

- Optical filtering of conventional IM (DSB) signal
- Steep filter slope required
- Approximation through sideband attenuation
- Used for Tb/s-experiments by Alcatel



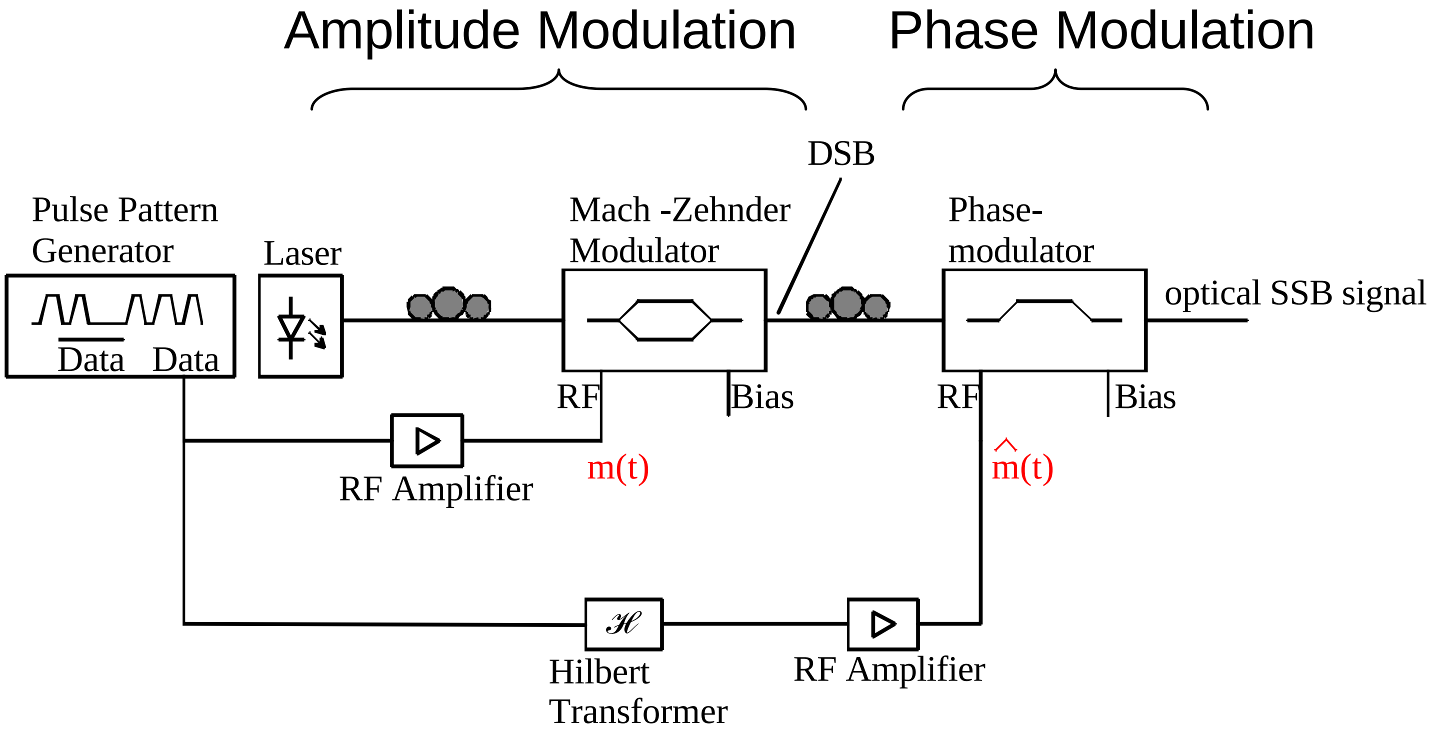
SSB/VSB – Implementation: Phase Method

- Phase inversion of one sideband in electrical base-band domain (Hartley)
- Hilbert transformer may be approximated by FIR (finite impulse response) filter



SSB/VSB – Implementation: Electrical Hilbert Transformer

Reduced complexity compatible SSB with electrical Hilbert Transformer



SSB/VSB – Implementation: Electrical Hilbert Transformer 2

transfer function of SSB transmitter

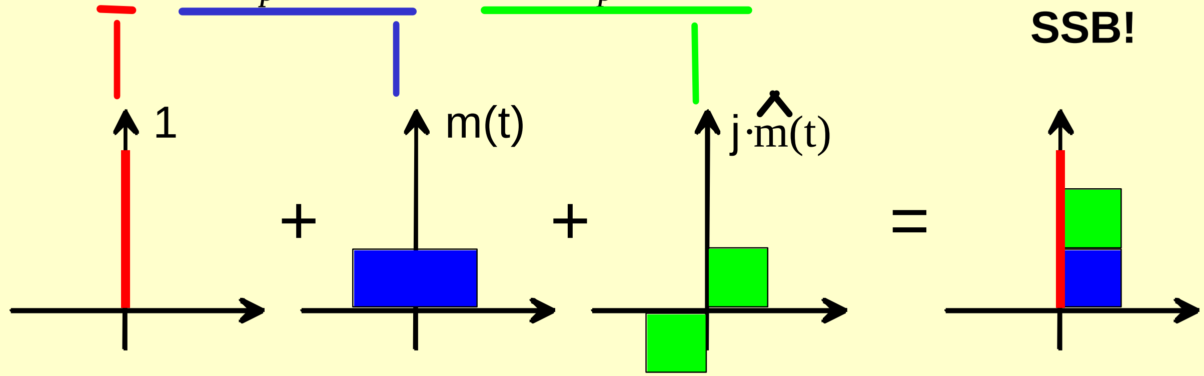
$$E_{out}(t) = \underbrace{E_{in}\cdot\cos\left(\frac{p}{2}\,\frac{m(t)-U_{bias}}{U_p}\right)}_{\textbf{AM}}\cdot\underbrace{\exp\left\{j\,\frac{p}{2}\cdot\frac{\hat{m}(t)}{U_p}\right\}}_{\textbf{PM}}$$

$m(t)$ - data signal

$\hat{m}(t)$ - Hilbert transformed data signal

Approximation for a linear driven MZ-modulator

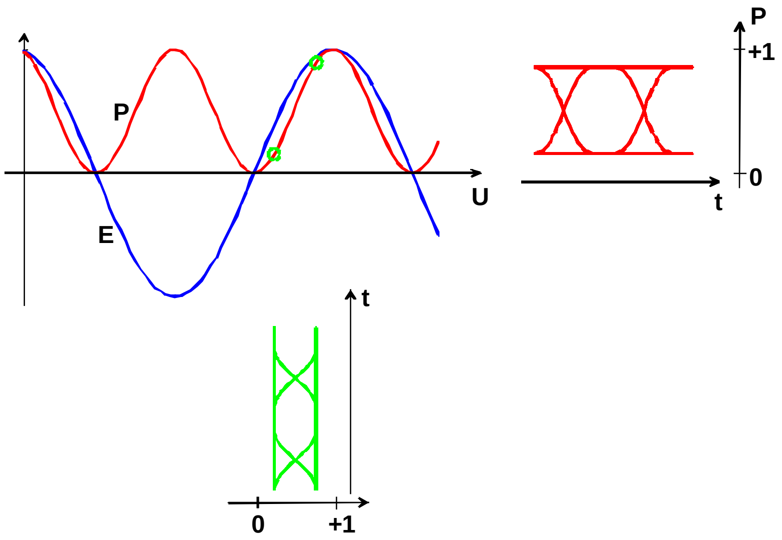
$$E_{out}(t) \approx \frac{E_{in}}{\sqrt{2}}\left[\,\underline{1} + \underline{\frac{p}{2U_p}\cdot m(t)} + \underline{j\cdot\frac{p}{2U_p}\cdot\hat{m}(t)} + \ldots\right]$$



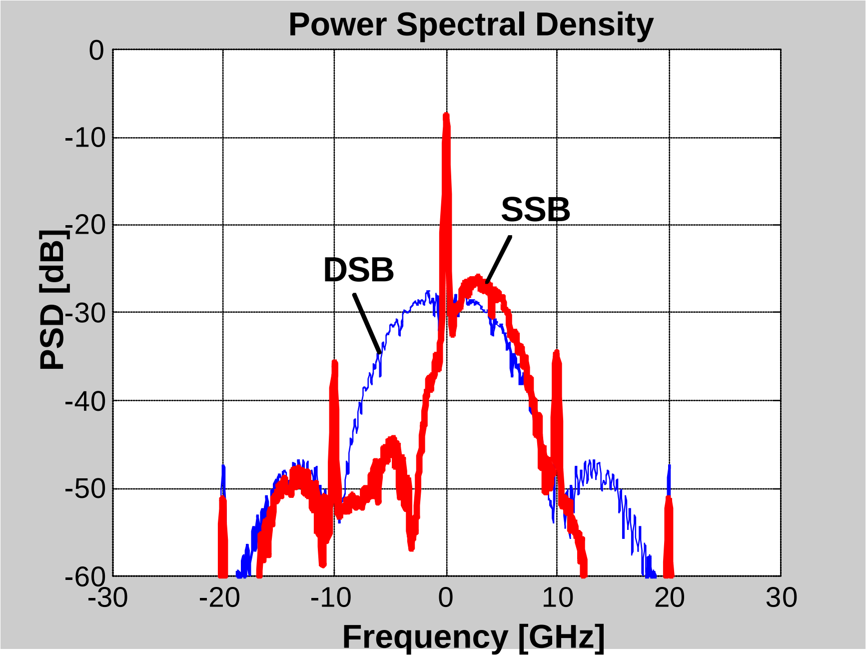
SSB/VSB: Performance

- Method used: Electrical H.T.
- Method requires approx. linear MZM drive conditions for good side-band suppression

  → Extinction ratio reduced!



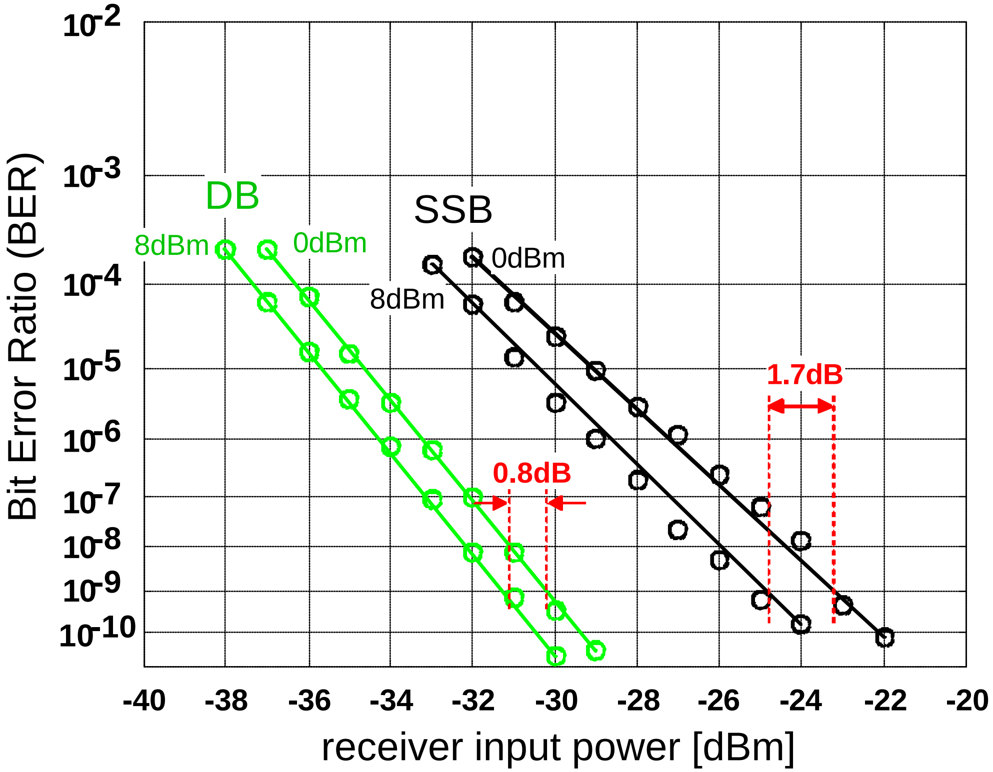
Transfer characteristic of the Mach-Zehnder modulator for power *P* and electrical field *E*



Optical power spectral density (simulation)

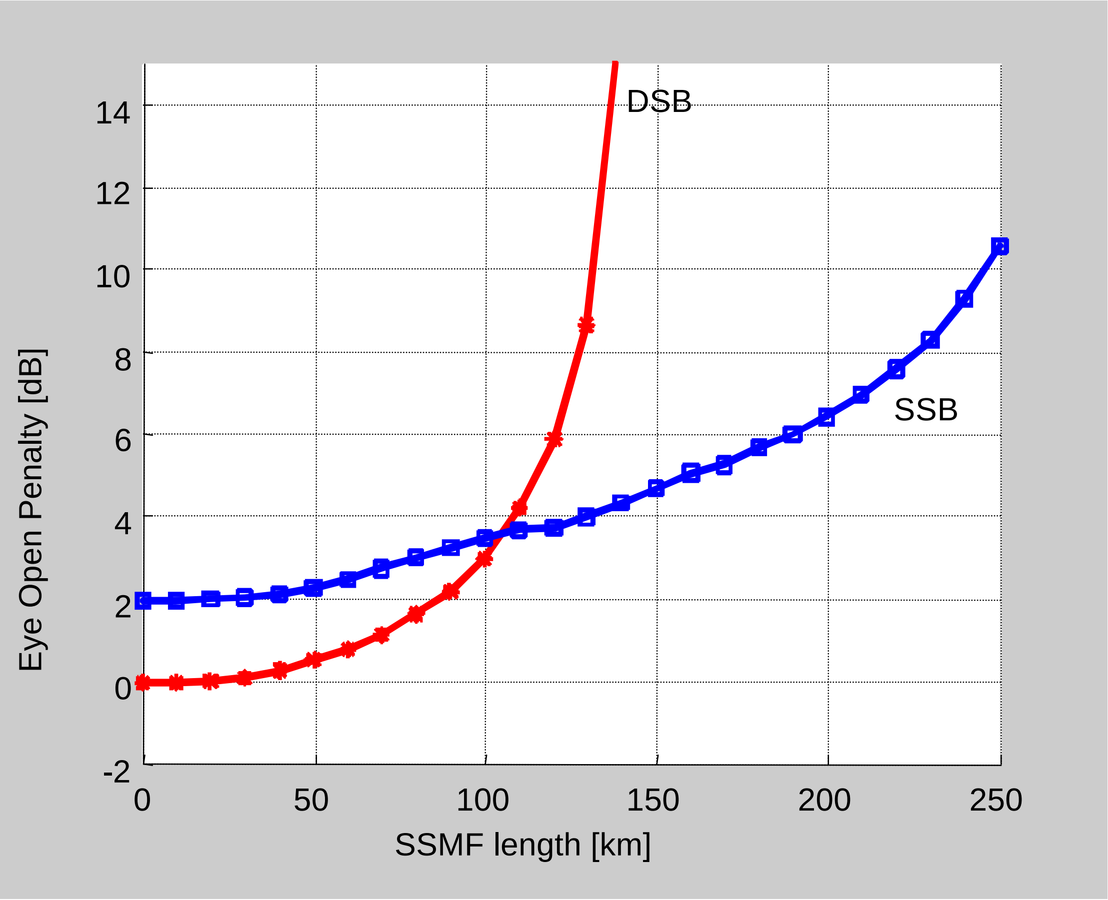
SSB/VSB: Experimental comparison DB vs. SSB

- 200km uncompensated SSMF, 10Gb/s
- Compare SSB with duobinary
- Linear and non-linear fiber regime
- SSB approx. 6dB penalty, due to reduced extinction ratio



SSB/VSB: Dispersion Tolerance DSB vs. SSB

- Simulation result, 10Gb/s
- Linear fiber
- SSB: Extinction ratio optimized for maximum reach
- DSB: maximum extinction ratio



wr, APOC 2003; slide 22

Binary Differential PSK (D-2-PSK)

- Symbols: +1, -1
- NRZ or RZ pulse shape possible
  - RZ: +1,-1 identical optical intensity
    - → optical intensity = periodic function of time
    - → advantage in XPM environment
- Improved noise performance vs. conventional IM/DD , if balanced receiver used (3dB)
- Differential scheme → avoids coherent detection
- Additional DPSK receiver (MZDI) necessary!
- Differential precoder necessary!

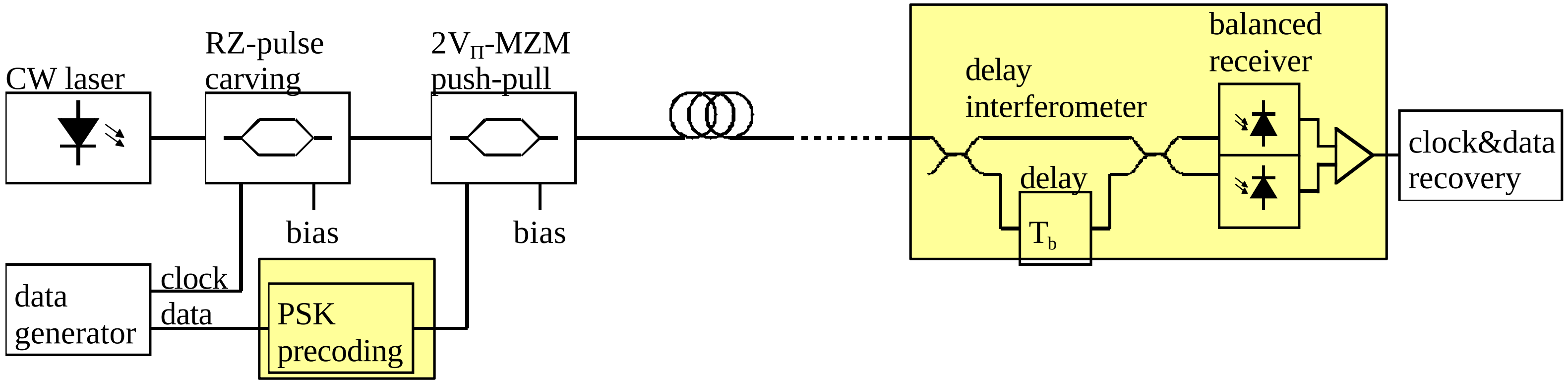
Binary DPSK

- DPSK precoder = differential encoder (same as for duobinary)
- Functionality of MZDI receiver. Phase $f(k) \in \{0, p\}$

$$\left[\cos(w_c t + f(k)) + \cos(w_c t - a + f(k-1))\right]^2 = \underbrace{\ldots + 2\cos(\ldots)\cdot\cos(\ldots) + \ldots}_{\cos\left[\, f(k) - f(k-1) - \underbrace{a}_{=0} \,\right]}$$

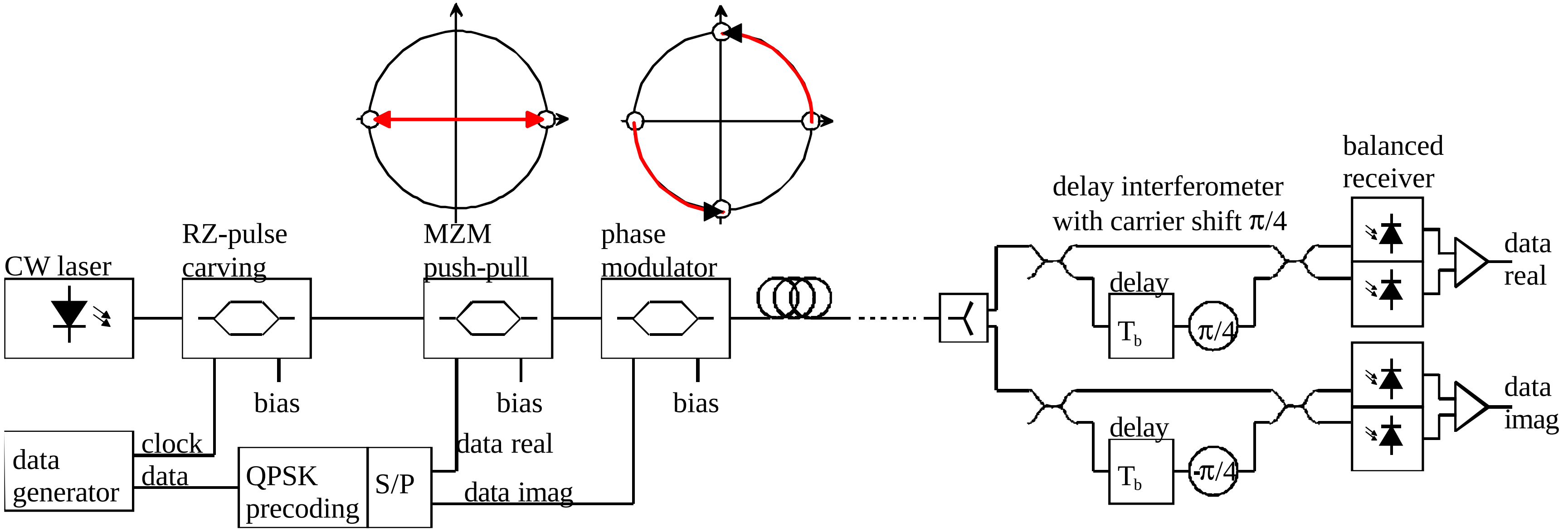
High if $f(k) = f(k\text{-}1)$,

Low if $f(k) \neq f(k\text{-}1)$



Quaternary DPSK

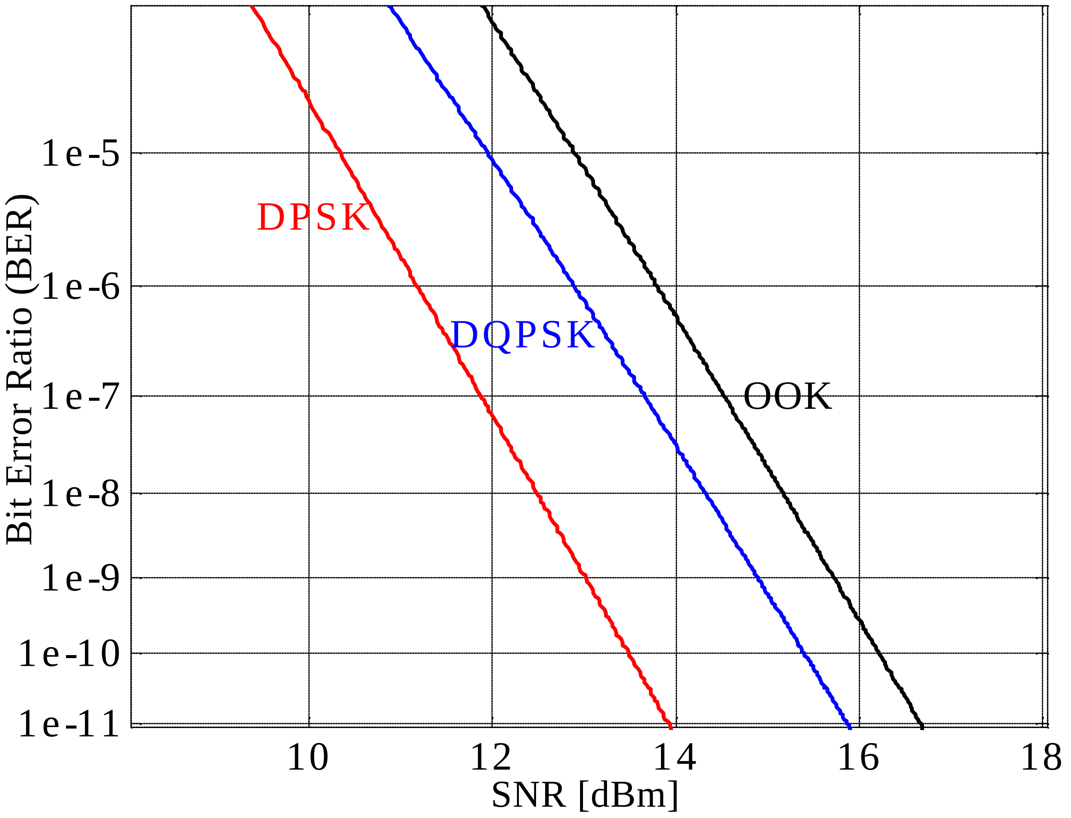
- Our solution: serial DQPSK-transmitter → reduced complexity, relaxed phase control
- 2 parallel data streams (real & imaginary) with speed and bandwidth requirements of single data stream!
- Quaternary differential precoder required



DPSK: Receiver Sensitivity - Theory

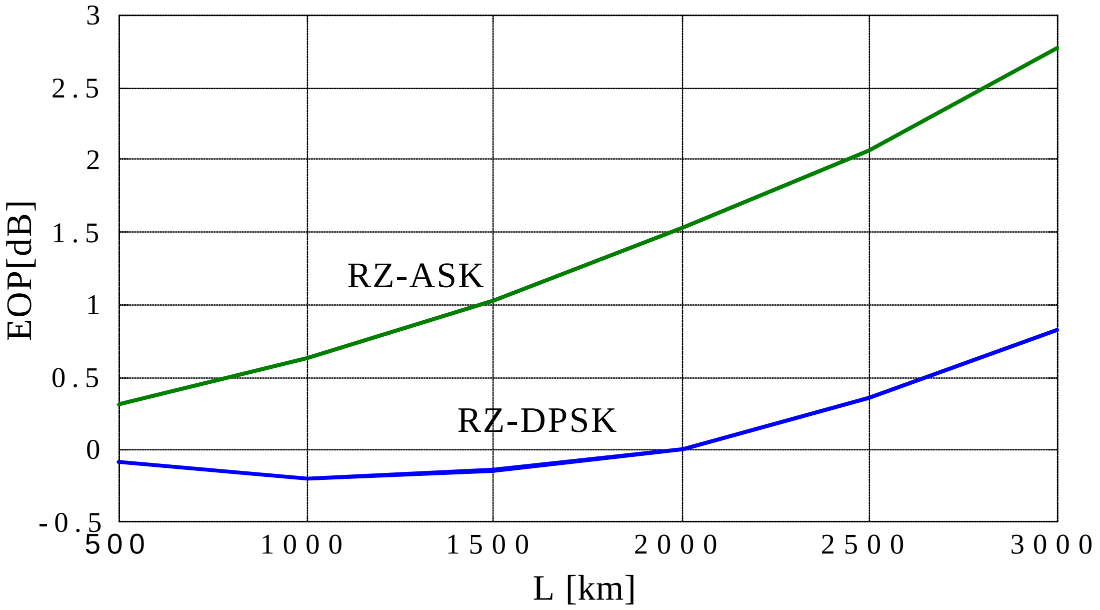
- Ideal coherent/synchronous detection:

  → both DPSK & DQPSK 3dB sensitivity improvement due to enlarged symbol distance (constellation!) vs. OOK=IM/DD!
- DPSK with MZDI = non-coherent: 0.2dB loss
- DQPSK with MZDI = non-coherent: 2dB loss



DPSK with RZ pulse shape in WDM: Robustness towards XPM

- RZ: periodic optical intensity →suppression of XPM-induced phase modulation
- RZ-DPSK extends transmission distance significantly!



Simulation result: 8x10Gb/s WDM,

channel spacing: 100GHz,

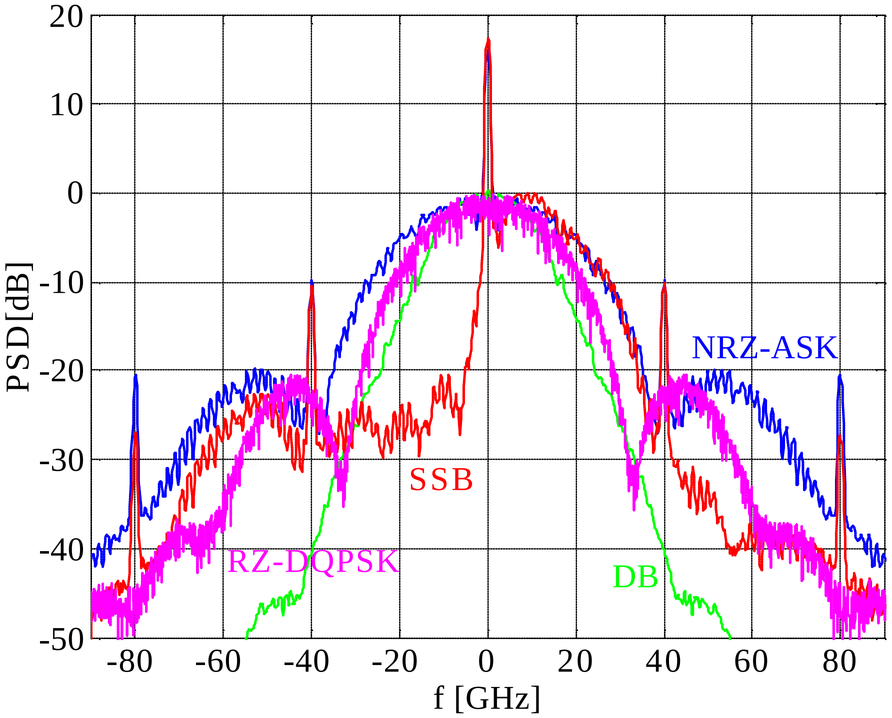
launch power: 9dBm/channel

span length: 100km SSMF, dispersion comp.

Modulation Formats in WDM Transmission

Power spectral density of various modulation formats at

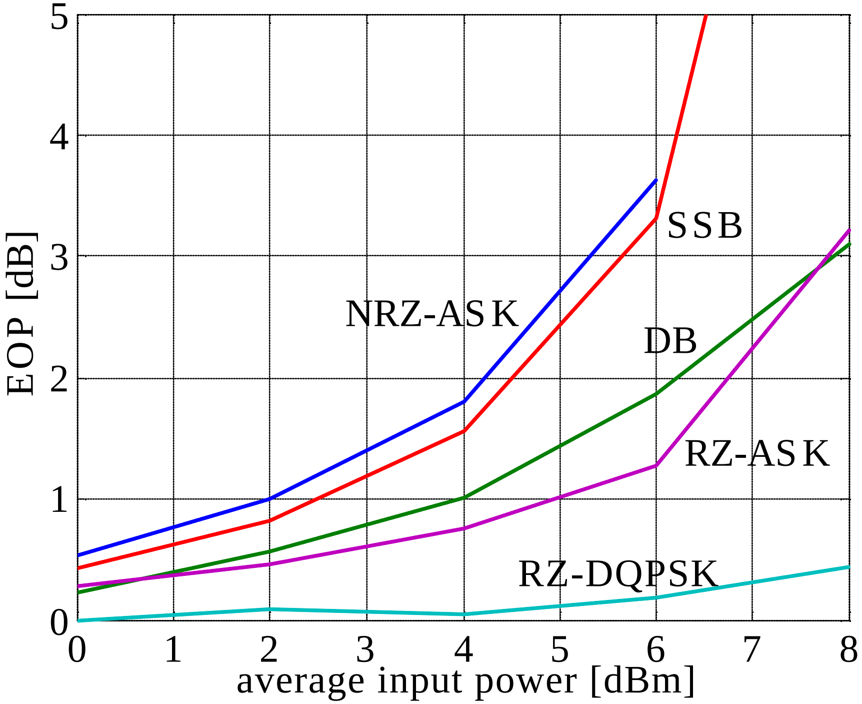
40Gb/s

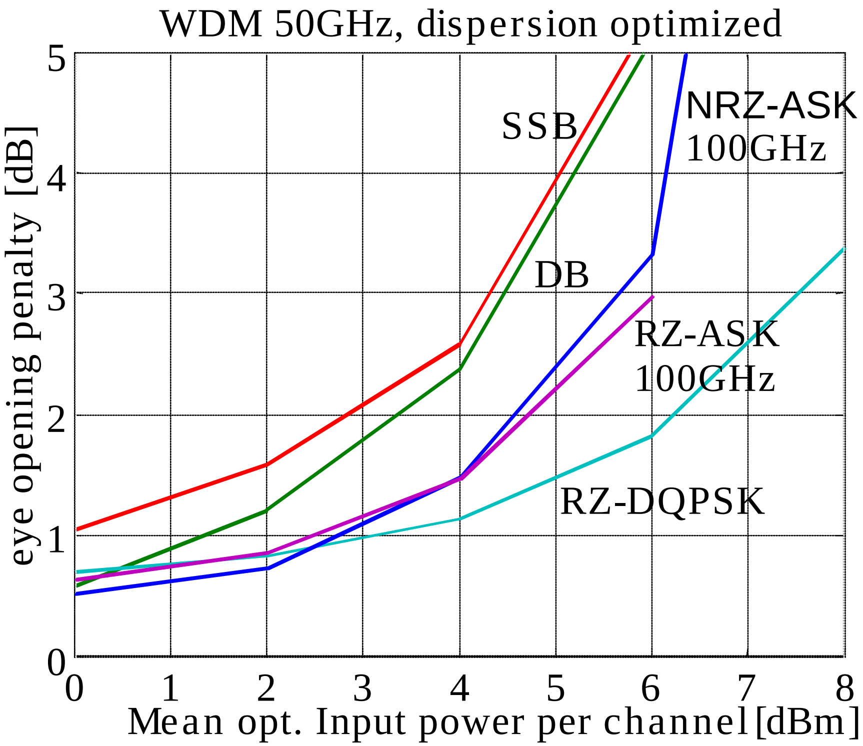


	DB	RZ-DQPSK	SSB	NRZ-ASK
Δf [GHz]	48	56	40	70

Two-sided spectral width for a decay of 20dB for DB, SSB, RZ-DQPSK and NRZ-ASK at 40Gb/s

Modulation Formats and WDM: Intermodulation 0.8b/s/Hz



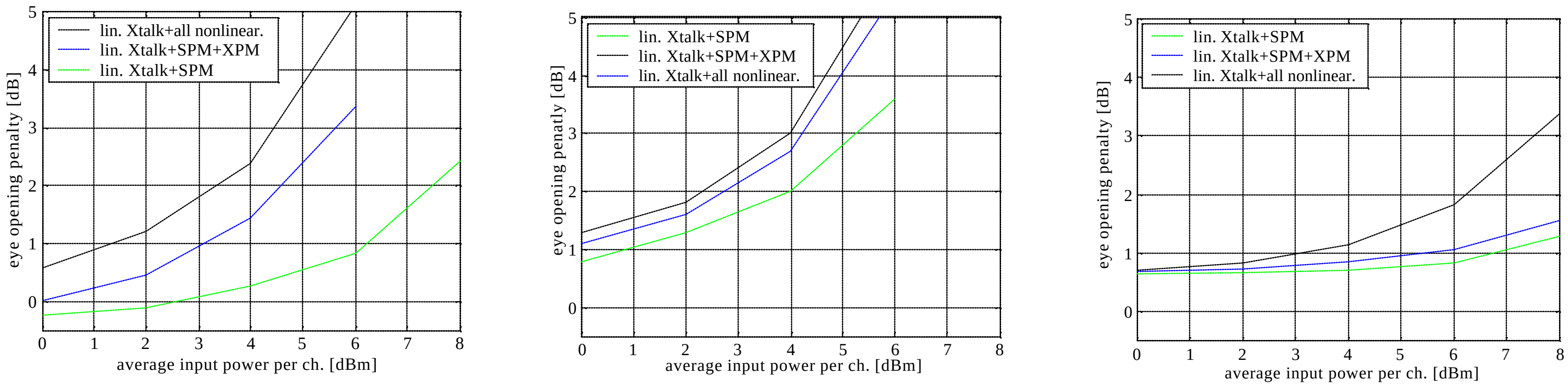


- Single channel: 4 spans 100km SSMF, Dispersion optimized, 40Gb/s
- RZ-DQPSK most robust against SPM and chrom. Dispersion!

- WDM 8x40Gb/s, Δf=50GHz: 4 spans 100km SSMF, Dispersion optimized
- RZ-DQPSK most robust against WDM intermodulation (XPM,FWM,SPM, linear cross-talk!)

Modulation Formats in WDM: Intermodulation

	Linear cross-talk	SPM	XPM	FWM
DB	☺		☹	
SSB		☹		☺
RZ-DQPSK		☺	☺	☹



Sensitivity to nonlinear fibre effects, SSMF, 40Gb/s, Δf=50GHz, 0.8b/s/Hz

Conclusions

- Duobinary: low complexity, high benefit through spectral narrowing → promising candidate for system upgrade now!
- SSB/VSB: solution with optical filtering → moderate system improvement for reasonable additional complexity
- DPSK: medium complexity → high benefit through improved receiver sensitivity and WDM intermodulation robustness
- DQPSK: medium to high complexity → but doubles channel capacity
- Other advanced formats: (MSK, CPM, M-PSK, M-QAM) worth investigating in optical environment! → constraints: complexity and chirp!