VPI University Program

Photonics Curriculum Version 7.0

Lecture Series

VPIphotonics™

Optical Modulators and Modulation Formats

Tx2

Developed in cooperation with
Acreo AB

Author: M. Forzati

Module Prerequisites

- FOC1, FOC2
- Tx1, Rx1
- Fiber1, Fiber2

Module Objectives

- Digital Data Modulation and basics of modulation formats
- Light modulation devices: PM, IM, EAM and MZM
- Amplitude Shift Keying transmitters and receivers
- Phase Shift Keying transmitters and receivers
- System implications

Digital data modulation (I)

- **Information is encoded as a series of *symbols* chosen from a finite set (an *alphabet*), e.g.:**
  - Binary alphabet: [0 1]. Each symbol carries 1 bit of information.
  - Quaternary alphabet: [00 01 10 11], [A B C D]. Each symbol carries 2 bits of information
  - 8-ary alphabet: [000 001 … 111], [A B C D E F G H]. Each symbol carries 3 bits of information

- **Each symbol is represented by a specific parameter of the light signal**
  - *Intensity* → Amplitude Shift Keying (**ASK**)
  - *Phase* → Phase Shift Keying (**PSK**)
  - *Frequency* → Frequency Shift Keying (**FSK**)
  - *State of polarization (SOP)* → Polarisation Shift Keying (PolSK)

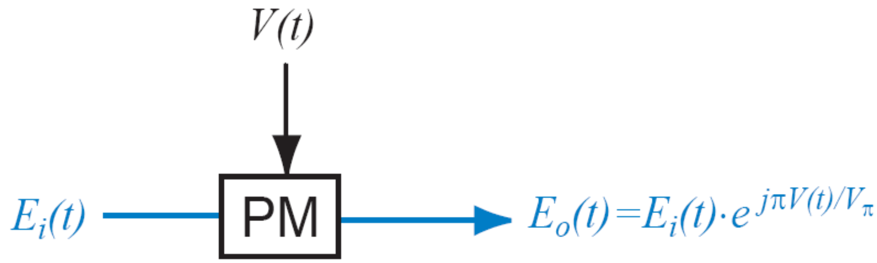
or a combination of them (APSK, QAM, PSK-PolMux)

Digital data modulation (II)

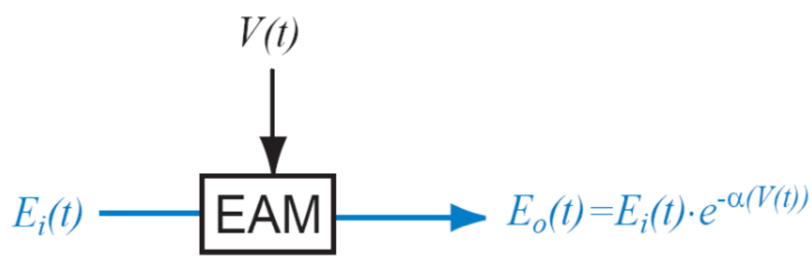
- The **wavelength** degree of freedom is used to transmit several information channels, each at a specific wavelength (WDM)
- Modulating the **SOP** is generally not straightforward at high speed. **PolSK** is generally used in combination with ASK or PSK as an extra degree of freedom
  - to make the signal robust against specific impairments such as non-linear effects (e.g. in Alternate Polarisation)
  - to increase the spectral efficiency (e.g. in **PolMux-DQPSK**)
- **Amplitude Shift Keying** is straightforward to generate and detect
  - virtually all commercial systems deployed until now use ASK
- **Phase Shift Keying** is more complicated to detect, but is more robust against several transmission impairments (increased transmission distance)
  - it is currently being extensively investigated in research and development

Light modulation devices (I)

- Phase modulator (PM)
  - Changes the material refractive index, and consequently the phase of the output light signal as a response to a voltage signal
  - Light intensity is independent of the voltage signal

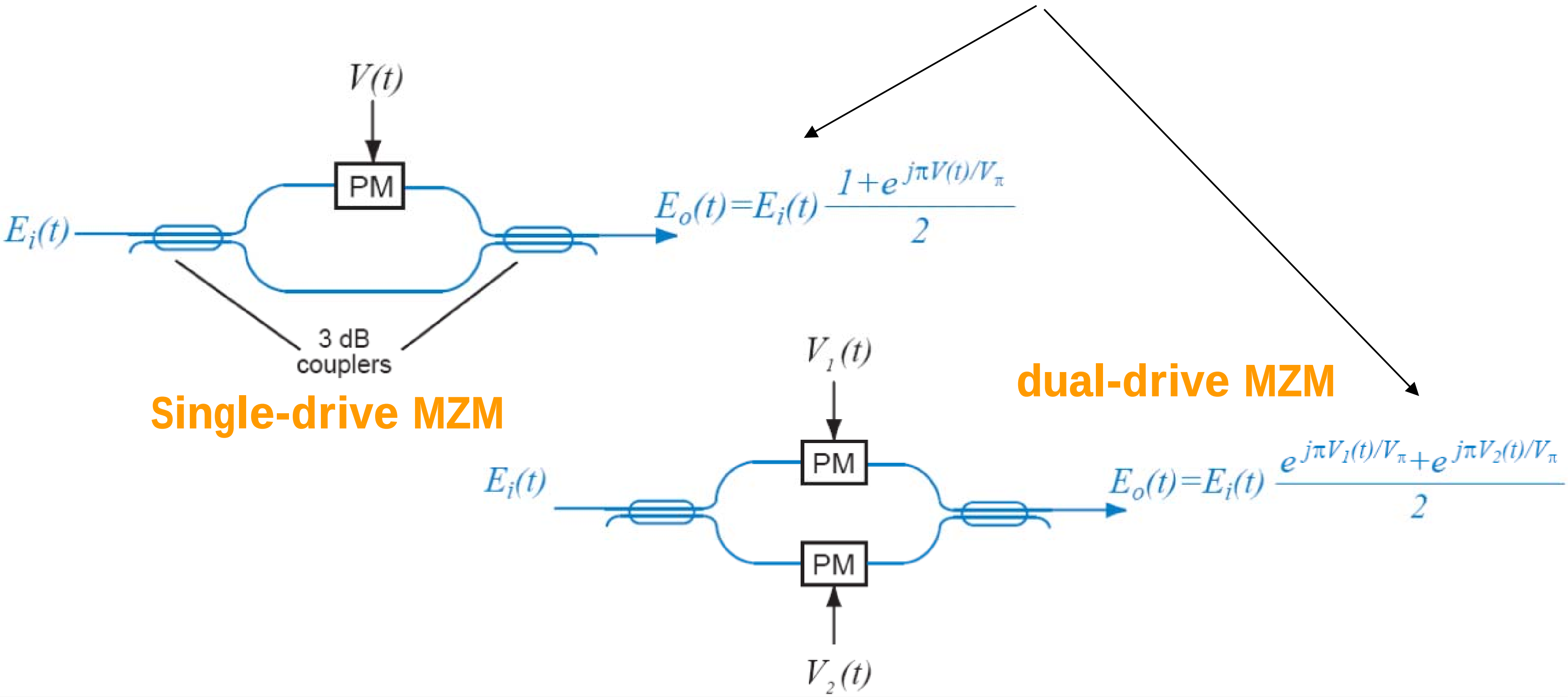


- Electro-absorption (EA) Intensity modulator
  - Changes the material absorption coefficient, and consequently the intensity of the output light as a response to a voltage signal



Light modulation devices (II)

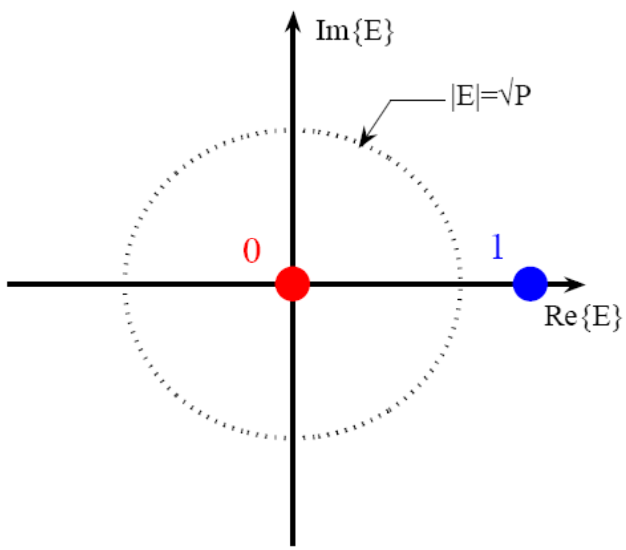
- Mach-Zehnder Modulator (MZM)
  - Performs the sum of the input signal with a phase-modulated copy of itself
  - Phase **and** intensity are modulated as response to a voltage signal



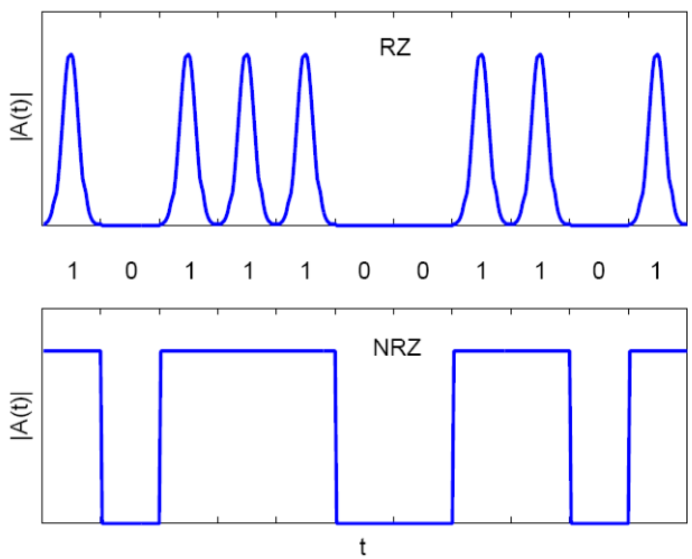
Amplitude shift Keying and On-Off Keying

- **Photo-detectors** only detect the intensity of light and not the phase or other parameters.
- In ASK modulation, the information can be extracted by direct detection.
- ASK is typically used with a binary alphabet; binary ASK is also known as **On-Off Keying** (OOK).

Signal constellation diagram

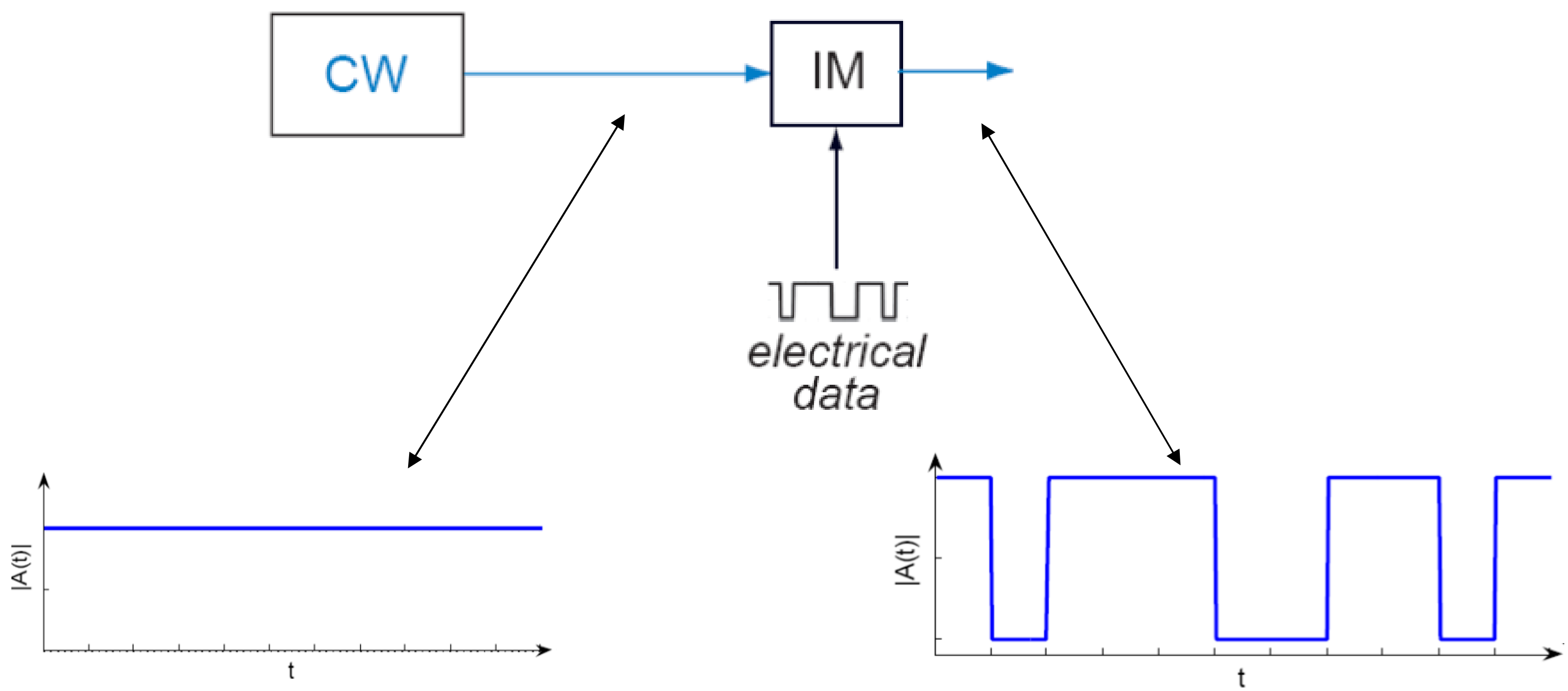


Example of OOK signals



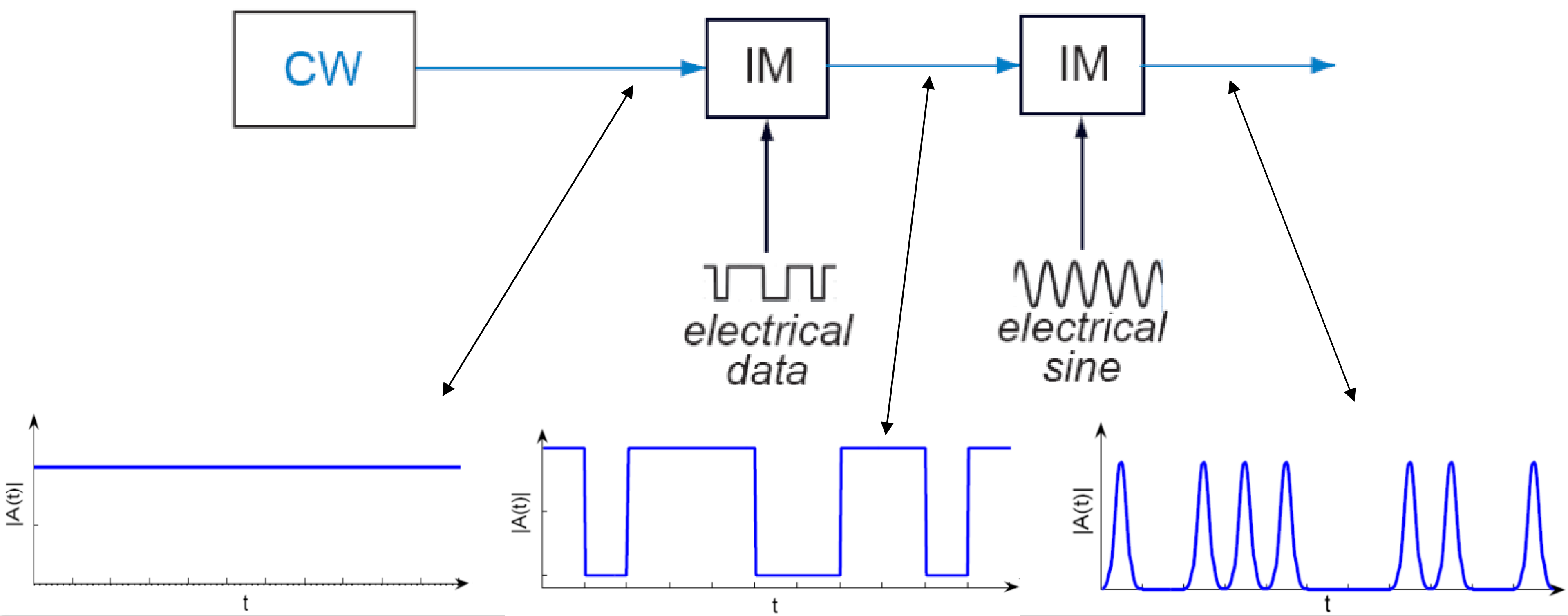
OOK generation: NRZ-OOK

- A continuous-wave (**CW**) laser and an **intensity modulator** are needed to generate an NRZ-OOK signal (the electrical data is normally in NRZ format).



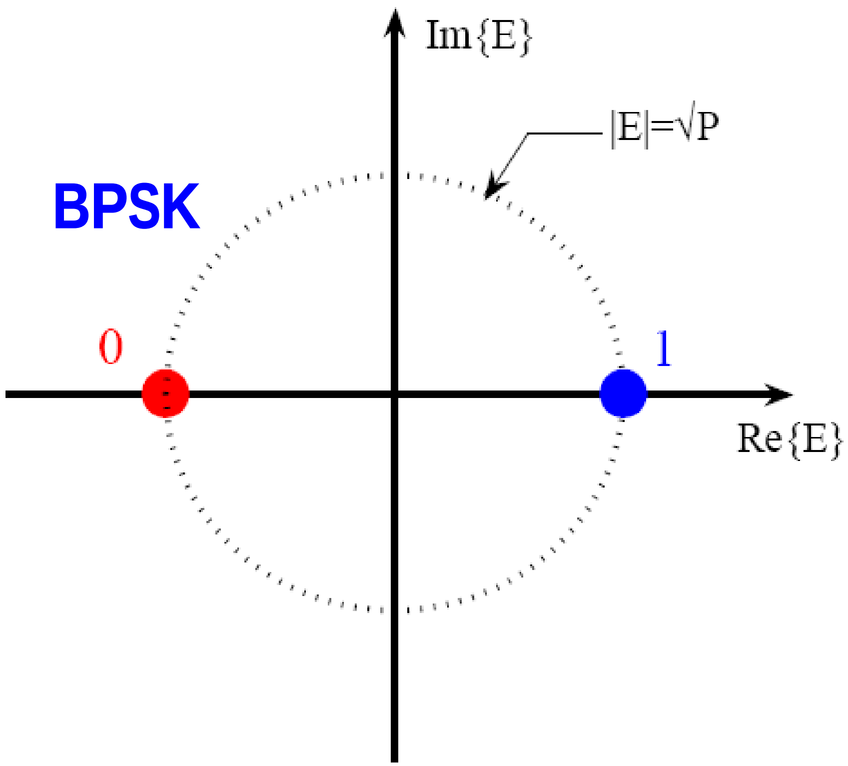
OOK generation: RZ-OOK

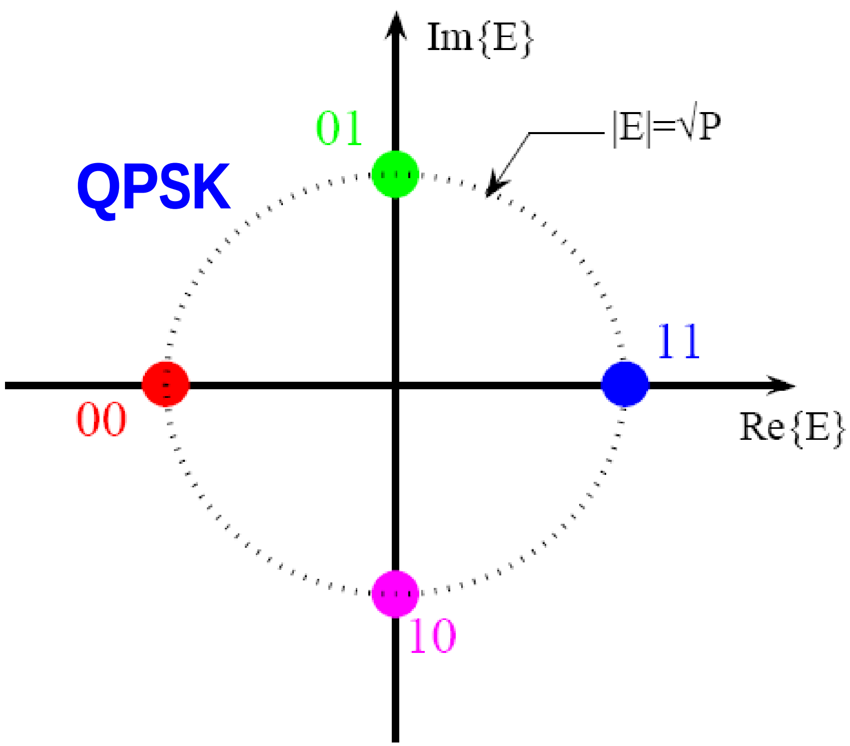
- Two intensity modulators and a CW laser are needed to generate an RZ-OOK signal. An alternative is to use a **pulsed laser** followed by an intensity modulator.
- Note that data and pulse-carving sine signal must be properly aligned



Phase Shift Keying (PSK)

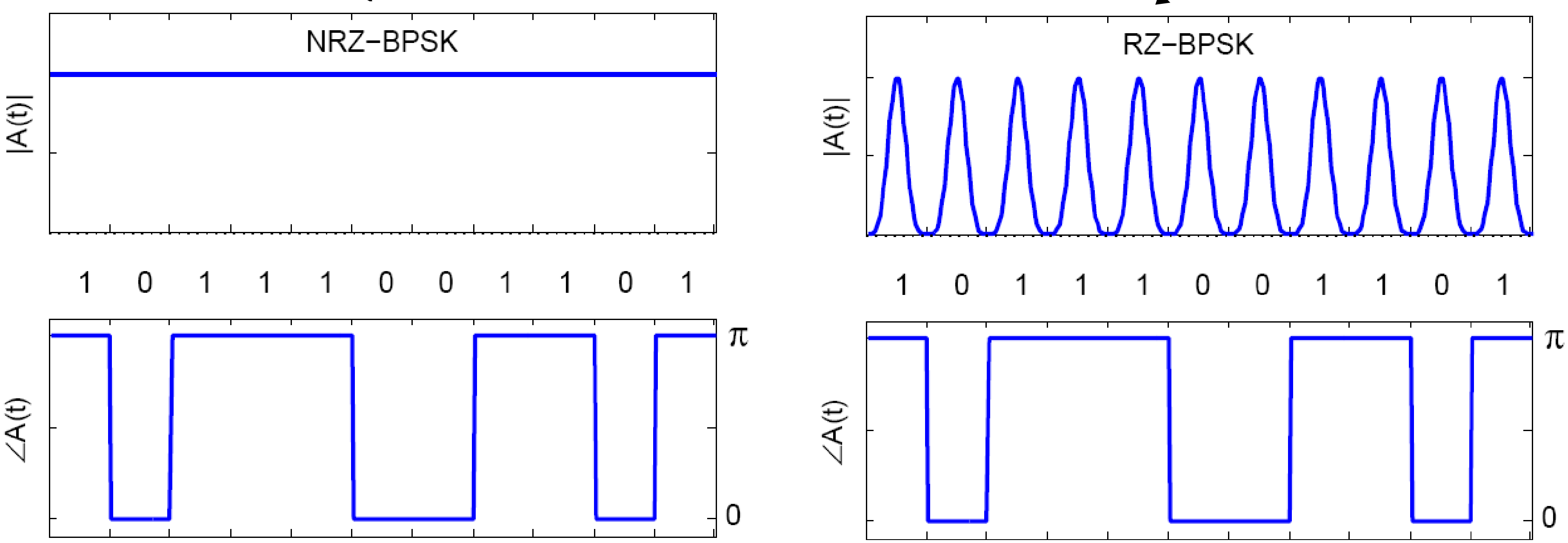
- In Phase Shift Keying modulation, the information is carried in the phase of the signal
- PSK with 2 levels (BPSK), 4 levels (QPSK), 8 levels (8PSK) are the most studied cases.





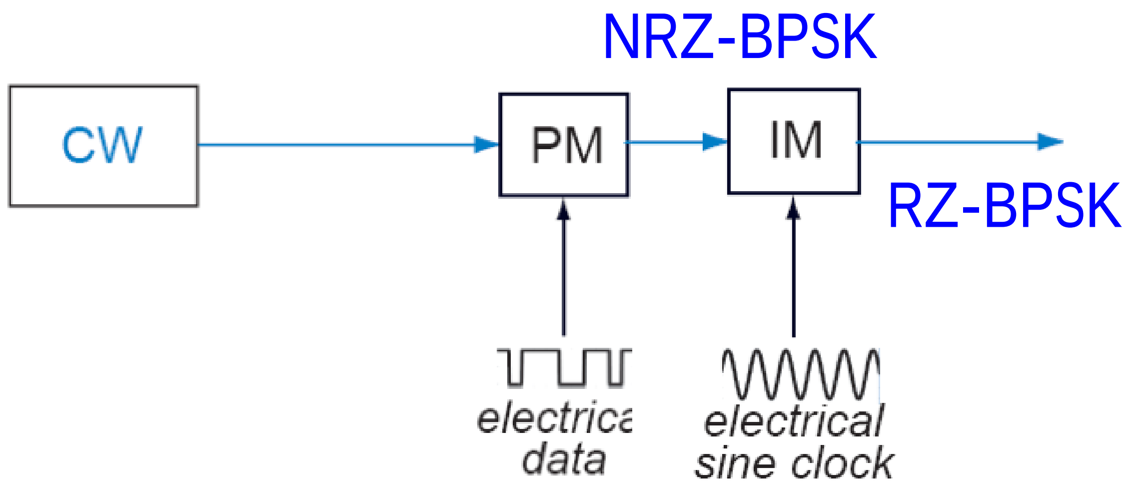
NRZ-PSK and RZ-PSK

- In PSK, as in the case of ASK, light can be constant over a bit slot (NRZ), or pulsed (RZ)



PSK implementation with Phase Modulator

- PSK can be generated by means of a Phase Modulator (PM)
- For RZ-PSK, an additional intensity modulator (IM) is required following the PM.



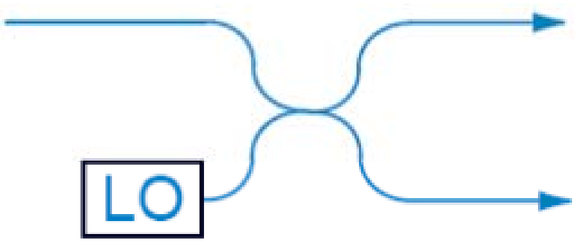
- The electrical data signal is written directly on the phase of the optical signal: The signal is faithfully reproduced including imperfections due to limited bandwidth or extinction ratio

PSK and Differential PSK (DPSK)

- Because photo-detectors cannot detect the phase of the signal, the received signal needs to be compared with a reference phase before being detected. The **reference phase** can be given by

a Local Oscillator:

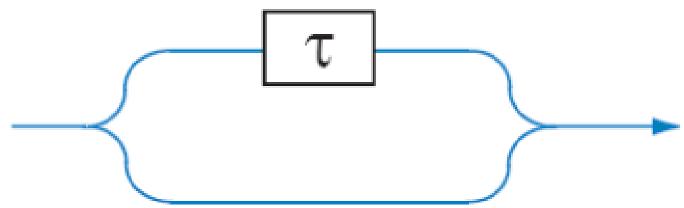
Coherent Detection



Detected amplitude is proportional to the phase difference between current symbol and LO

the received signal itself:

Differential Detection



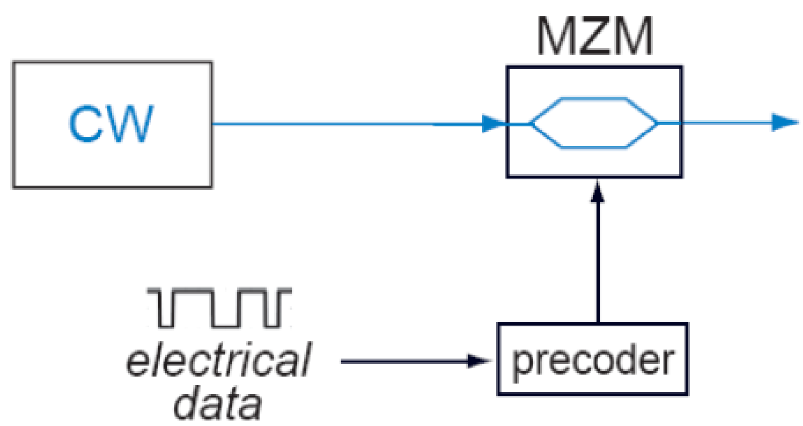
Detected amplitude is proportional to the phase difference between successive symbols

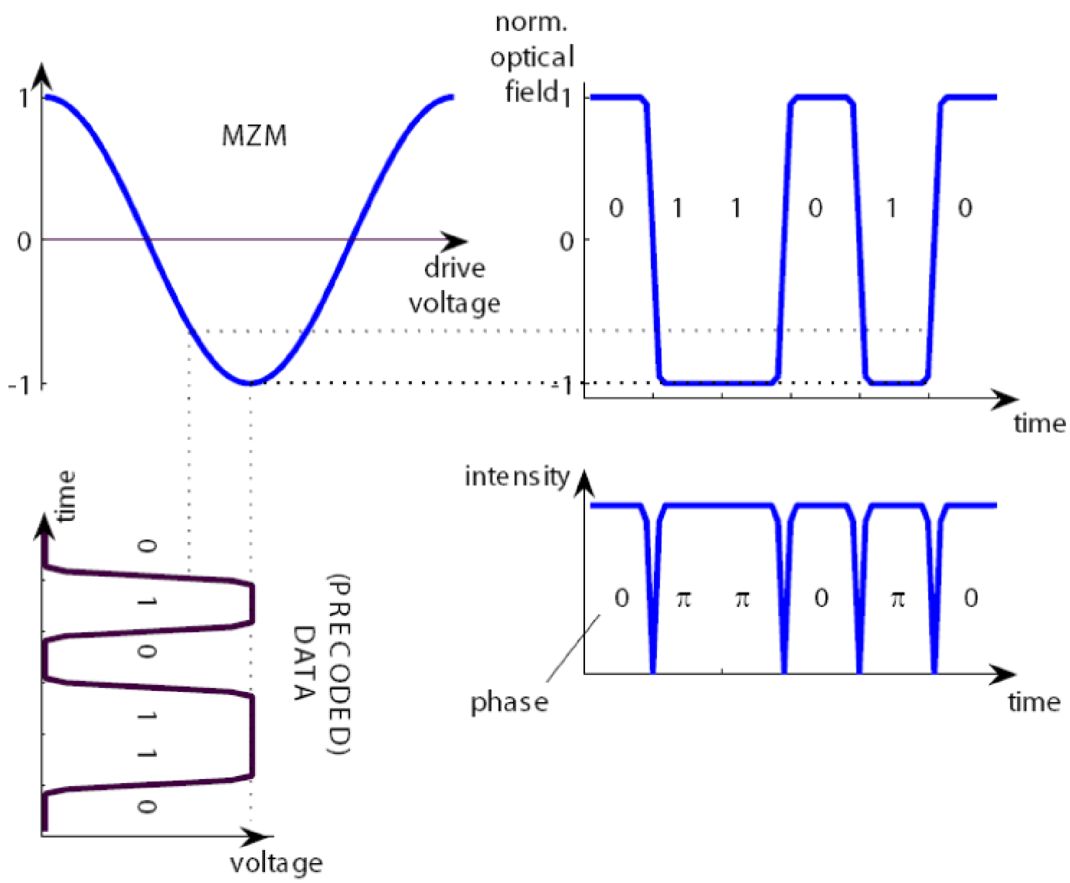
Differential PSK (DPSK)

- Although coherent detection is receiving increased interest, it is mainly DPSK which is used in today's systems
- In DPSK a "1" is represented by a phase change, and a "0" by no phase change
- Data needs to be differentially pre-coded at the transmitter
- At the receiver, the phase of a symbol is compared with the phase of the previous symbol to extract the transmitted data.

DPSK implementation with Mach-Zehnder Modulator

- (D)PSK can be generated by means of a Mach-Zehnder Modulator (MZM)

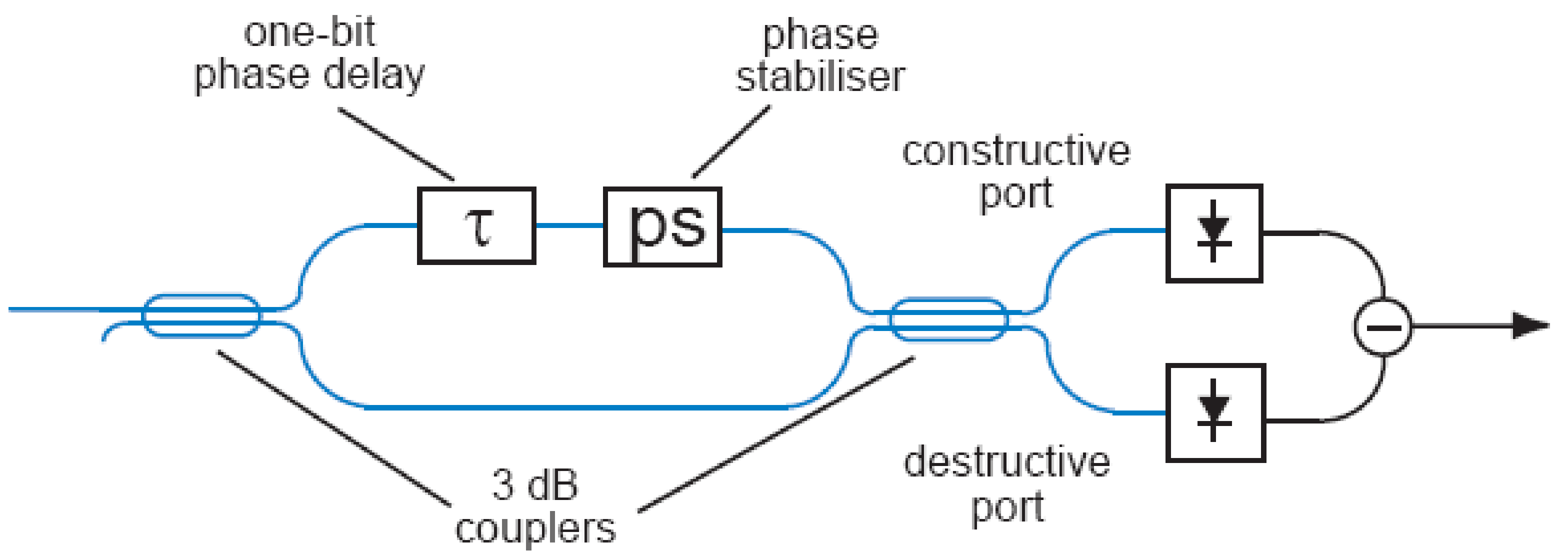




- This ensures clean phase transitions even for drive signals with limited bandwidth and extinction ratio

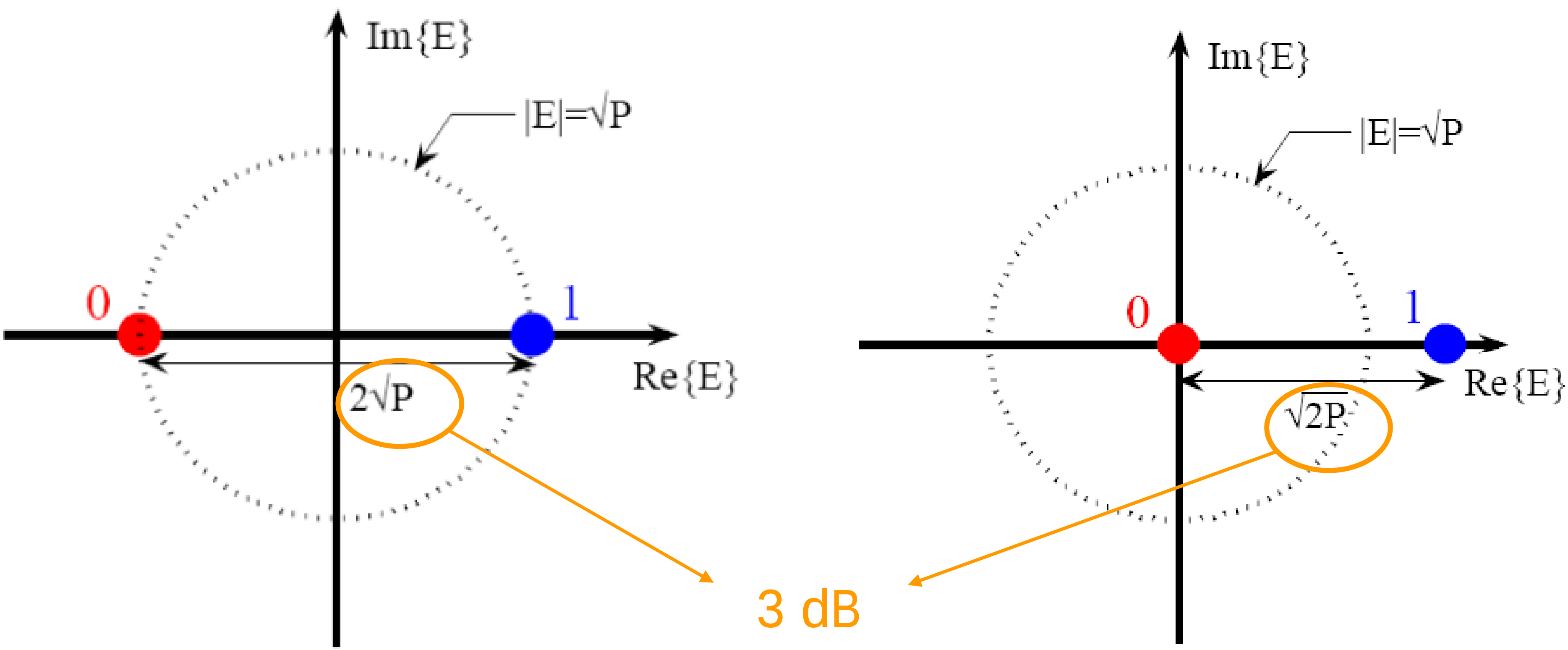
DPSK: Balanced detector

- In a **Mach-Zehnder Interferometer** (MZI) with a one-bit delay on one arm. If the phase is properly stabilised
  - Phase shift between consecutive bits → full power on the constructive port, no power on the destructive port → electric **+1**
  - No phase shift between consecutive bits → no power on the constructive port → full power on the destructive port electric **-1**



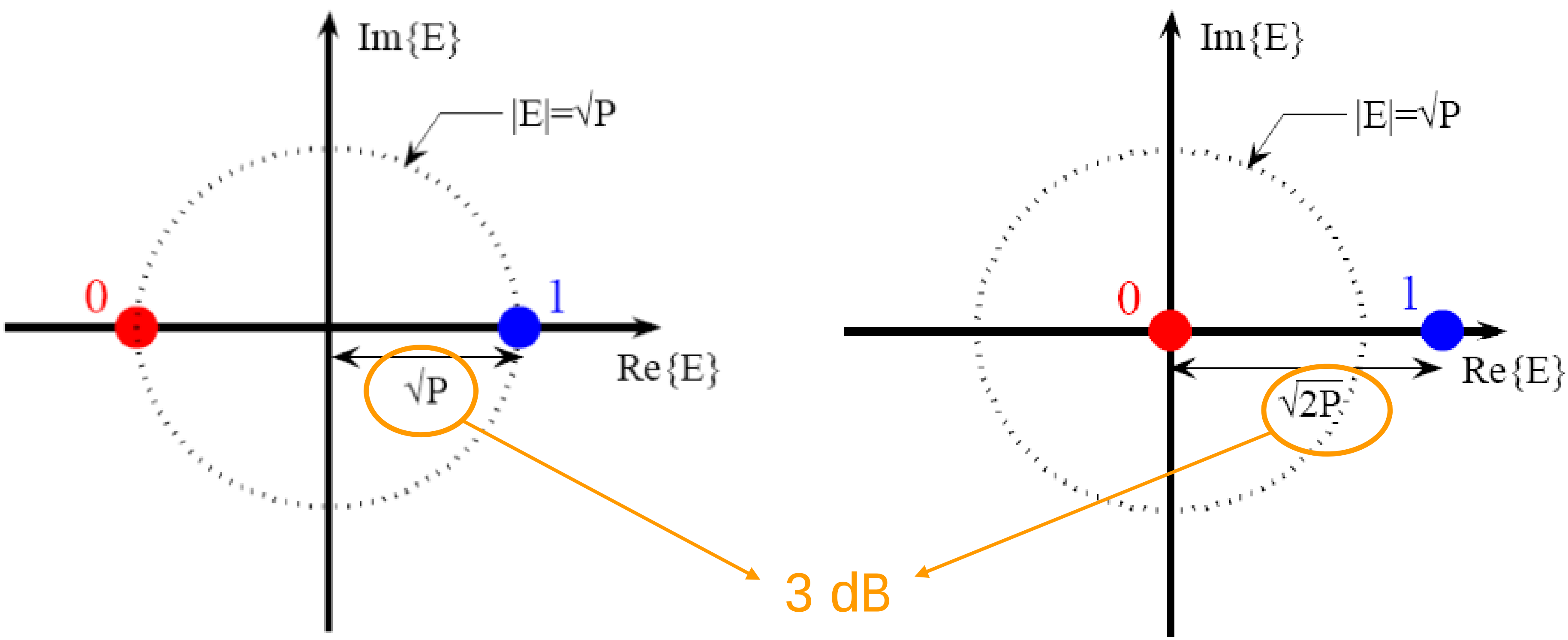
PSK vs. ASK: noise tolerance at the receiver

- In PSK the distance between signals is larger than in OOK for a given average power *P*.
- Consequently PSK can tolerate worse noise levels at the receiver → better receiver sensitivity).



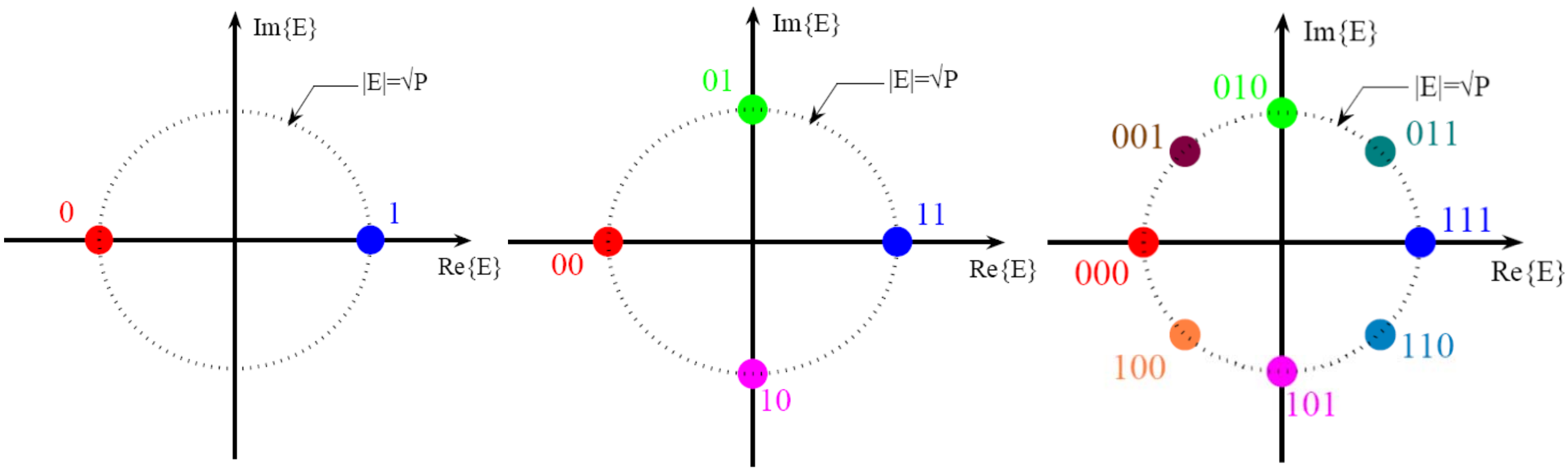
PSK vs. ASK: power tolerance

- In PSK the peak power is 3 dB lower than in OOK for a given average power *P*.
- Consequently PSK should tolerate higher power levels (non-linear tolerance)



Differential Quadrature Phase Shift Keying (DQPSK)

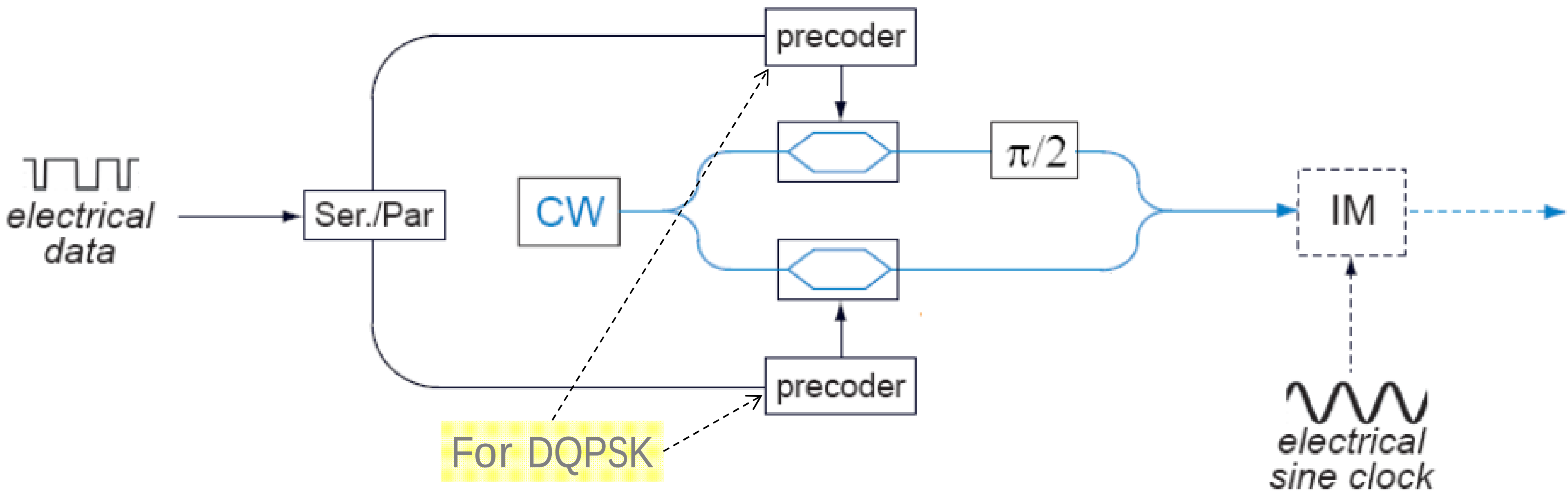
- Multilevel PSK has been demonstrated and studied recently



- Four levels (Quadrature Phase Shift Keying, QPSK) optimal signal constellation (efficient use of signal space)

DQPSK transmitter

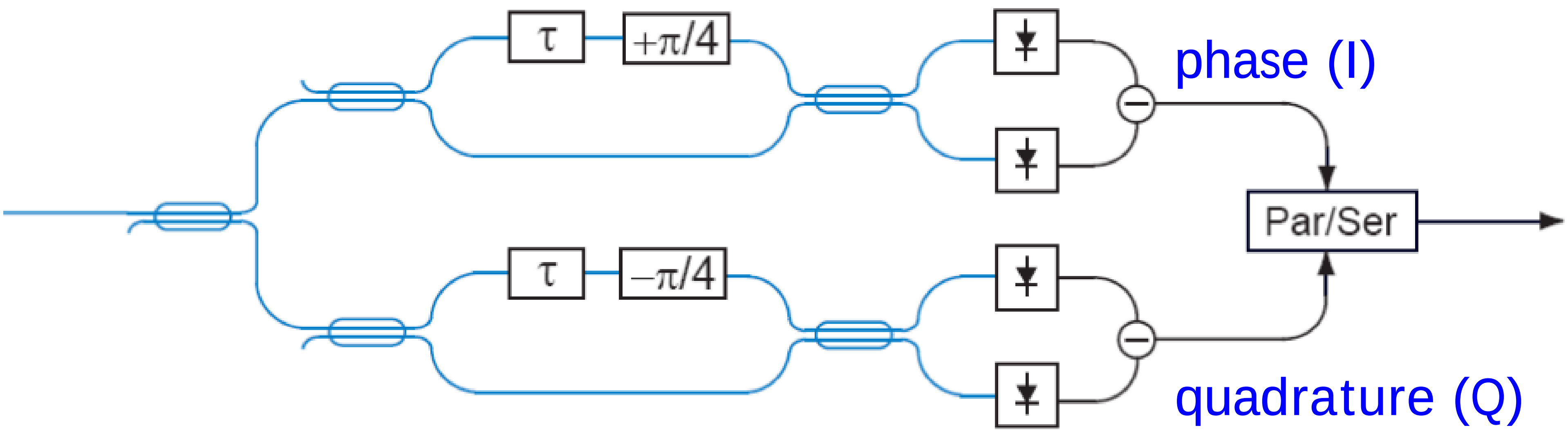
- DQPSK can be generated by two dual-drive MZM, each giving the in-phase or quadrature component of the DQPSK signal.



- Because two bits per symbol are transmitted, the symbol rate is half the bit rate

DQPSK receiver

- DQPSK detection is performed by means of two balanced detectors, each giving the in-phase or in-quadrature component of the DQPSK signal.



DQPSK vs. DPSK and OOK

- In DQPSK the symbol rate is half the bit rate, consequently, with respect to DPSK and OOK:

The distance between data pulses is double

The pulses are double as wide, i.e. the spectrum is narrower

Increased tolerance to polarisation mode dispersion (PMD)

Increased tolerance to tight filtering (better spectral efficiency attainable)

Increased tolerance to chromatic dispersion

System considerations

Scheme	Tx com-plexity	Rx com-plexity	Receiver sens'ty	CD tolerance	PMD tolerance	Nonlinear tolerance	Filt. tol. Spect. eff.
NRZ-OOK	Low	Low	Poor	Low	Low	Lowest	Low
RZ-OOK	Moderate	Low	OK	Lowest	Moderate	Low	Low
DPSK	Moder-ately high	Moder-ately high	Best	Moderate	Moderate	Moderate	Moderate
QDPSK	High	High	Good	High	High	Moderate	High

Summary

- Digital Data Modulation and basics of modulation formats
- Light modulation devices: PM, IM, EAM and MZM
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- Phase Shift Keying transmitters and receivers
- System implications

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