Optical Modulation Formats

Generic Optical Digital Communication System

A typical digital optical communication system employing channel coding is shown in Figure 5.1. **The discrete source generates the information in the form of a sequence of symbols**. The channel encoder accepts the message symbols and adds redundant symbols following a prescribed encoding rule, which is described in detail in Chapter 7. The encoder is followed by modulator that converts the encoded sequence in a form suitable for transmission over the optical channel. The modulation is done by changing some of the signal parameters (amplitude, frequency, phase) in accordance with a modulation rule. The simplest approach is to apply the amplitude change to impose data through amplitude shift keying (ASK) or to use the pulse position change. The first method is also known as intensity modulation (IM), or on-off shift keying as described in Chapter 4, while the second is referred to as pulse position modulation (PPM). In case the information is carried by phase or frequency, the modulation formats are recognized as phase shift keying (PSK) or frequency shift keying (FSK). The modulated signal propagates through the optical channel (optical fiber), which was described in detail in Chapter 3.

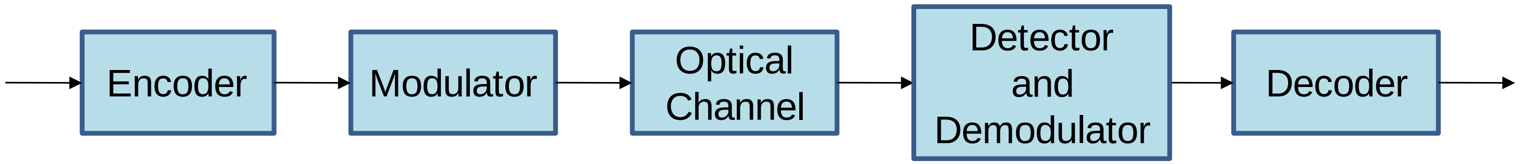
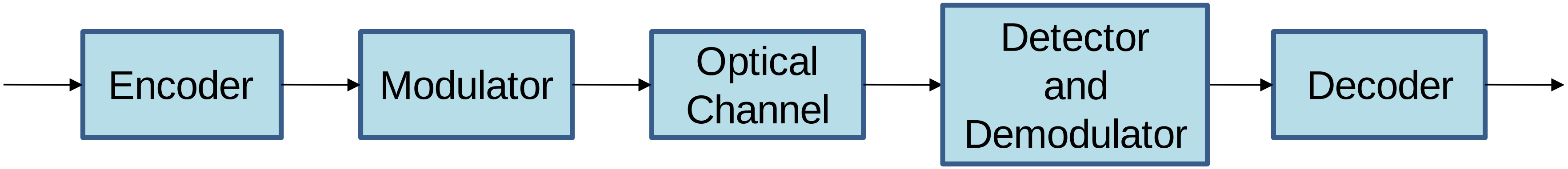


Figure 5.1 Generic point-to-point optical digital communication system

At the receiver side, the optical signal is converted back to the electrical level. In direct detection (DD) systems, the photodetector output is proportional to the incident power, which means that only information carried by the amplitude change can be correctly detected, while the phase information is lost. Since a DD scheme can distinguish only among different power levels, it can work efficiently only in combination with OOK and PPM schemes. In contrast, if coherent detection is applied, all information content carried on either phase or frequency of the signal can be retrieved, which will be discussed in detail in Chapter 6.

Digital Communication Channel



The digital optical communication can be formulated as follows :

- At any time instance, the message source **generates a symbol m_i** (i=1, 2,..., M) from the set of symbols represented as $\{m_1,m_2,...,m_M\}$.

- These symbols are generated **with a priori probabilities**: p_1, p_2,...,p_M, where p_i=$P(m_i)$ [$P(m_i)$ is a probability that just message m_i will be selected, while i=1,2,...,M]. If all symbols are equally likely, we have that p_i=1/M.

- The transmitter then converts the message source output **m_i into a *distinct* signal $s_i(t)$** suitable for transmission over the optical channel.

- **If $s_i(t)$ be a real-valued signal of duration T**, its energy is given as

$$E_i = \int_0^T s_i^2(t)\,dt \qquad (5.1)$$

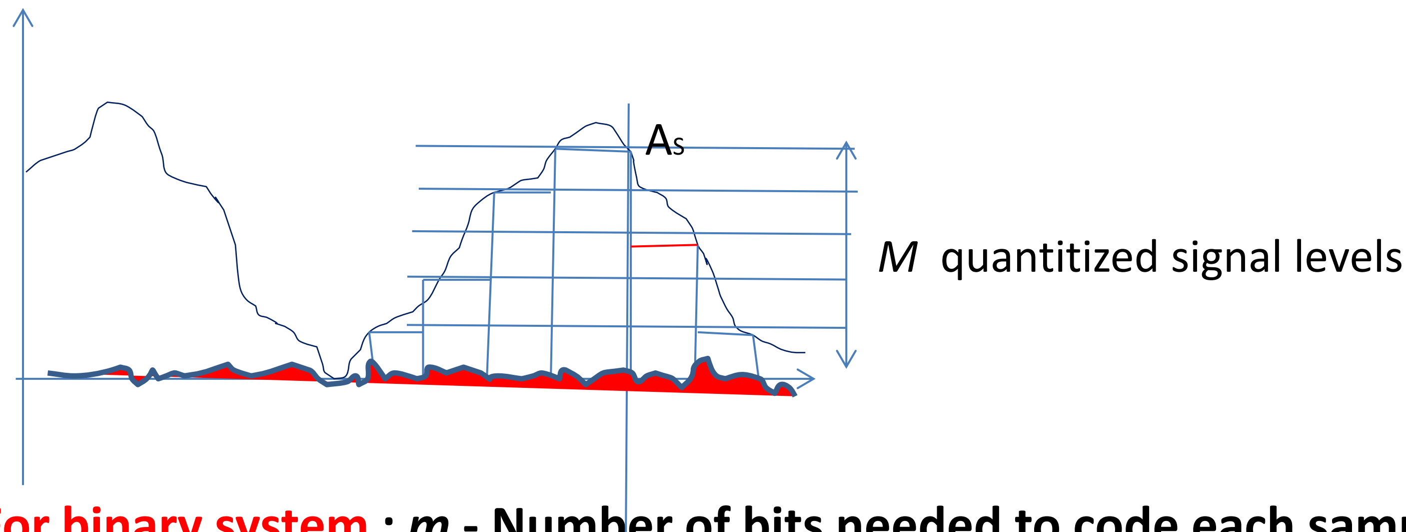
$$r(t) = s_i(t) + w(t), \begin{cases} 0 \le t \le T \\ i = 1, 2, ..., M \end{cases} \qquad (5.5)$$

Receiver side: $r(t)$ is the received signal and $w(t)$ is the AWGN originating from ASE noise

Just reminder

Analog to Digital Conversion: 3 steps

- <u>**Sampling**: based on </u>Nyquist criterion the that sampling rate should be at least two times of maximum frequency.. For voice it is 8000 samples per second (8 kSamples/s), for video 9 million samples per second (9 MSamples/s). Sampling frequency is $f_s=2f_m$.
- <u>**Quantization:** </u>Each sample to be converted to a discrete value (number) by ADC (analog to digital conversion). There is a limited number of M discrete levels, which means that an error (known as a quantization nose is created. Quantization noise is added on the top of existing, usually thermal noise.
- <u>**Coding**: </u>Each discrete sample to be converted into string of "1" and '0"s in binary representation (or some other string in other representation)



For binary system : *m* - Number of bits needed to code each sample is found from $M=2^m$; $m=\log_2 M$

Bit rate (usually denoted as B) is $B= m f_s = f_s \log_2 M=2f_m \log_2 M$.

For system with different base (base y) it is $m=\log_y M$

Advanced Modulation Formats

- Purpose
  - Increase the spectral efficiency
  - Increase overall functionality
  - Add to network savings (longer reach, more capacity, etc.)

- Modulation is closely connected with multiplexing, detection and coding applied afterwards

A monochromatic electromagnetic wave, which is used as a signal carrier, can be represented through the real part of its electric field as

$$E(t) = pA\cos(\omega t + \phi) \qquad (10.45)$$

where *A* is the wave amplitude, ω is the radial frequency, ϕ is the phase of the carrier, and **p** represents the polarization orientation. Each of these parameters (amplitude, frequency, phase, and the polarization state) can be utilized to carry information. It is done by making them time dependent and related the information content. Accordingly, four basic modulation types can be recognized. They are amplitude modulation (AM), frequency modulation (FM), phase modulation (PM), and polarization modulation (PoM). If the information is in digital form, the modulation is referred to as a shift-keying. Therefore, there are the amplitude shift keying (ASK), the frequency shift keying (FSK), the phase shift keying (PSK), and the polarization shift keying (PoSK).

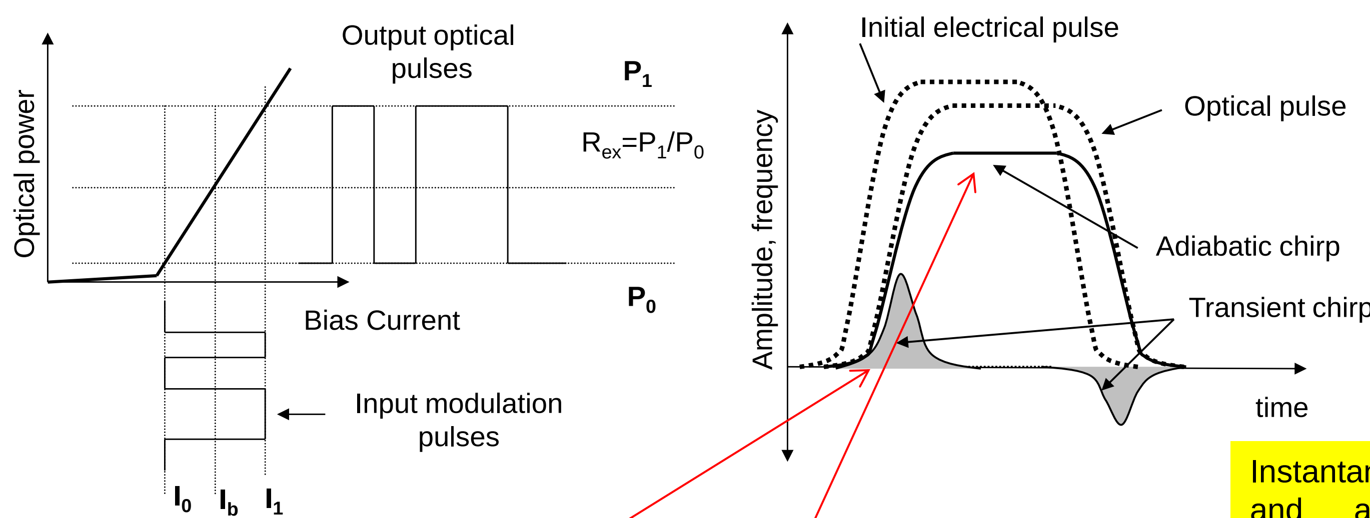
OPTICAL MODULATORS

There are two distinct modulation schemes: direct modulation used when modulation signal current is part of the overall current flowing through either laser or LED, and an external modulation of the optical carrier after his generation in semiconductor laser. Internal modulation includes the impact to the optical signal still in process of optical-wave generation, and, therefore, it is simultaneous with the light source excitation. External modulation means that there is some altering of generated referent wave after it leaves laser cavity in a device known as external optical modulator. External modulation is based on the different physical phenomena, such as: electro-optic effect, acousto-optic effect, and magneto-optic effect. The electro-optic effect found the wider application so far, and its basic principles will be explained later in this section.

The direct modulation process involves a modulation current that is added on top of DC bias current.

$$R_{ex} = 1/r_{ex} = \frac{P_1}{P_0}$$

where P_0 is the power associated with the "0" bite, and P_1 is the power related to the "1" bit



(a) (b)

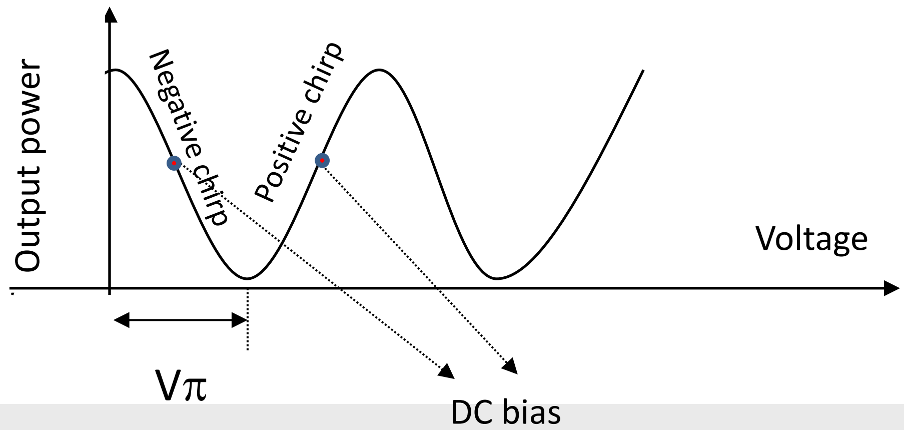
Instantaneous (transient) and adiabatic (steady) components

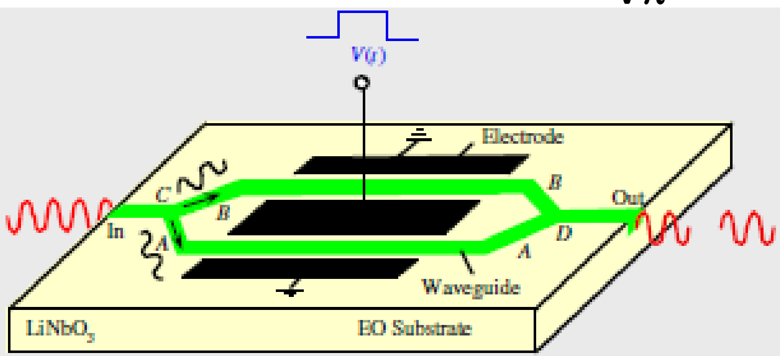
$$\delta\nu(t) = \frac{\alpha_{chirp}}{4\pi}\left[\left(\frac{d}{dt}\ln P(t)\right) + \chi P(t)\right]$$

where $P(t)$ is the time variation of the output optical power and χ is a constant related to the material and design parameters. Parameter c can vary in the range from 1 THz/W to 10 THz/W

MZ - External Modulation

$$P_{out} = P_{in} \cos^2\left(\frac{\pi V}{2V_\pi}\right)$$





$$\phi_1 = \frac{2\pi n_o}{\lambda} L = \frac{2\pi L}{\lambda}\left(n_o + \frac{1}{2} n_o^3 r_{33} \frac{V}{d}\right)$$

$$\phi_2 = \frac{2\pi n_o}{\lambda} L = \frac{2\pi L}{\lambda}\left(n_o - \frac{1}{2} n_o^3 r_{33} \frac{V}{d}\right)$$

$$\Delta\phi = \phi_1 - \phi_2 = \frac{2\pi}{\lambda} n_o^3 r_{33} \frac{L}{d} V$$

A $LiNbO_3$ MZM is operated at λ = 1550 nm wavelength. The length of the electrodes is L = 1 cm, the thickness of the waveguides is d = 10 µm. Calculate the switching voltage V_π.

- V_π means $\Delta\phi = \pi$
- $V = V_\pi = \Delta\phi \frac{\lambda}{2\pi} \frac{1}{n_o^3 r_{33}} \frac{d}{L}$

  $V = V_\pi = \pi \frac{1550\,\text{nm}}{2\pi} \frac{1}{2.272^3 \cdot 30.8\,\text{pm/V}} \frac{10\,\mu\text{m}}{1\,\text{cm}}$
- V_π = 2.145 V

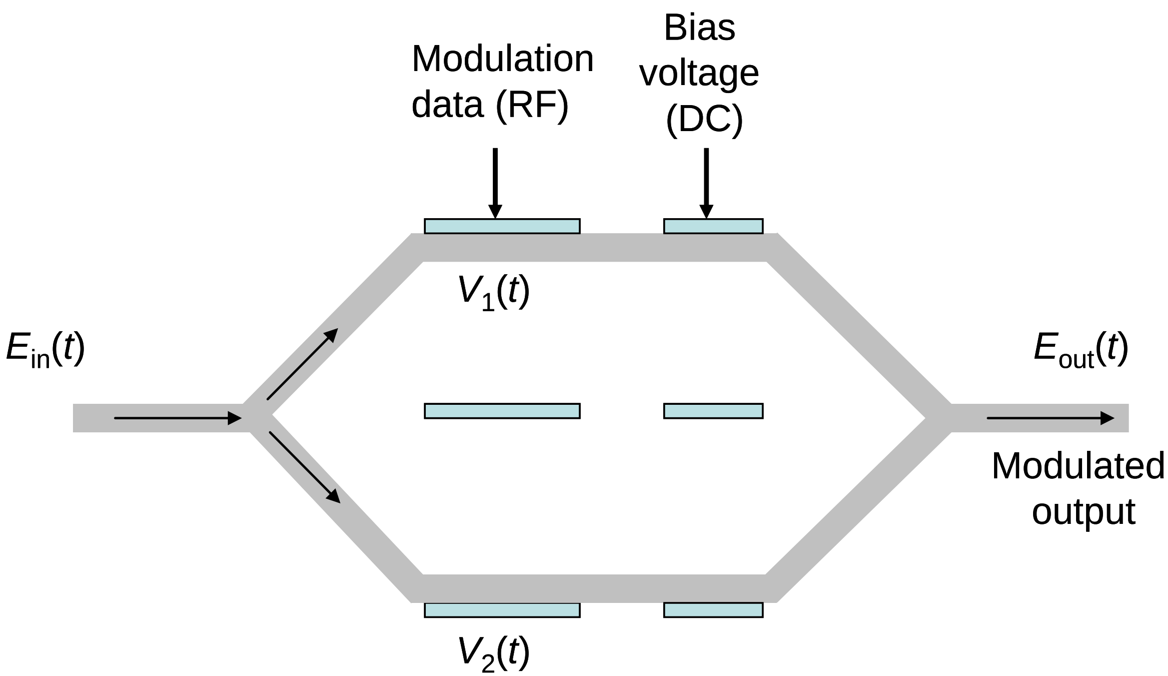


Figure 5.14 The operation principle of a Mach-Zehnder modulator (MZM).

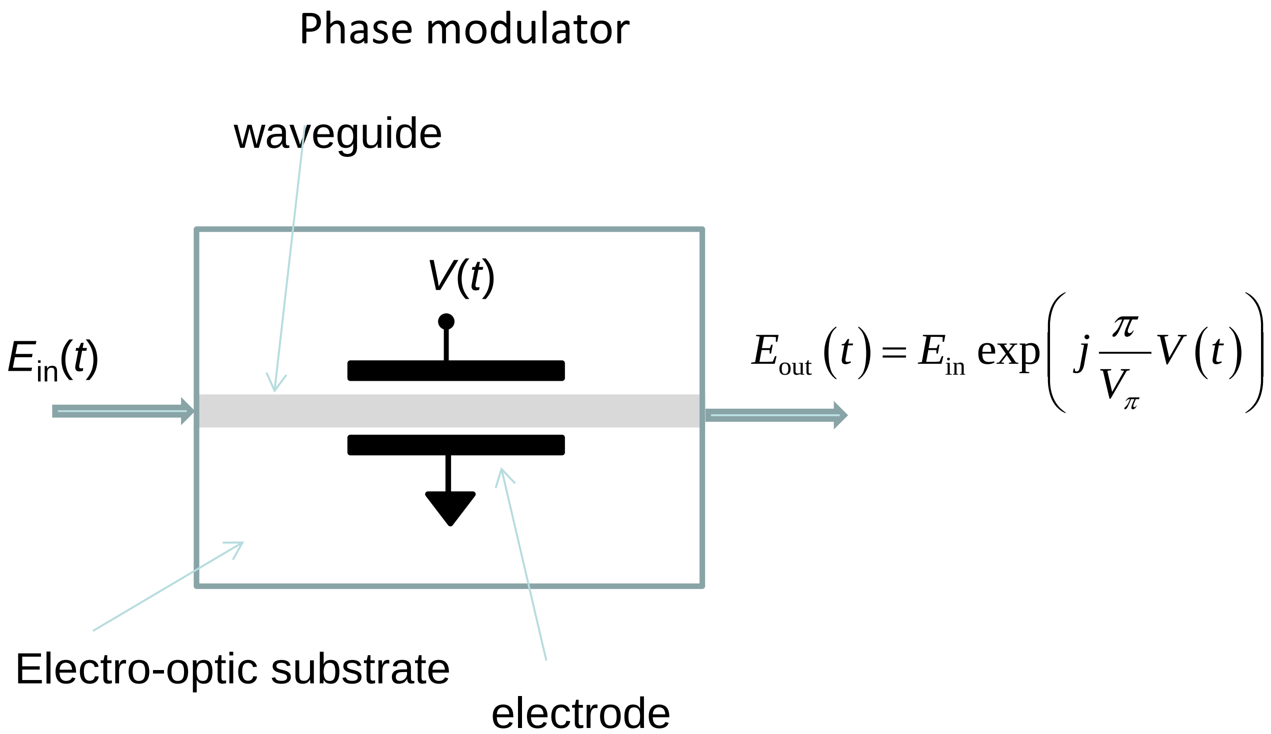
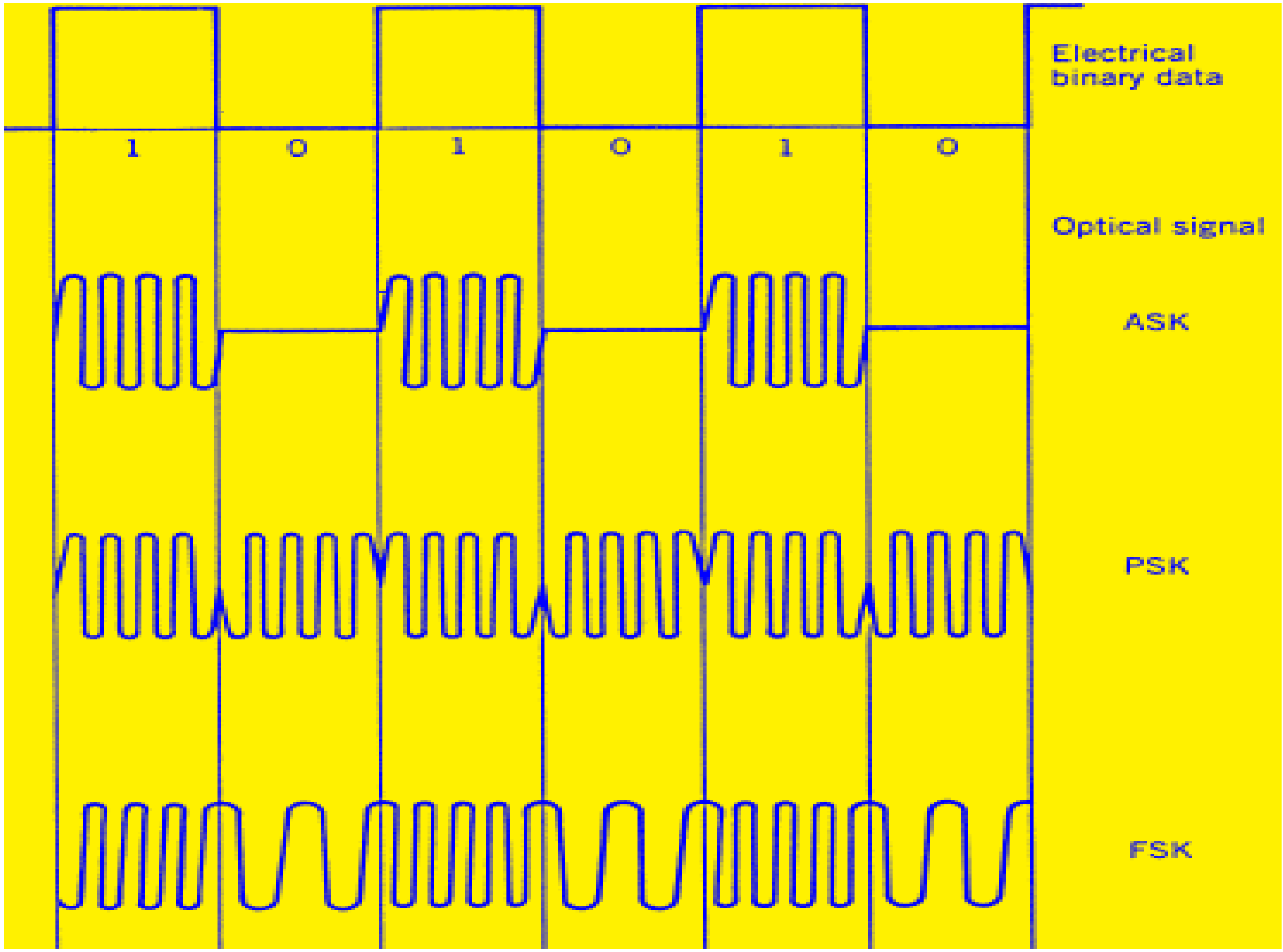


Figure 5.16 The operation principle of a phase modulator.

The electrical fields at the output and input of a phase modulator are related as follows:

$$\frac{E_{out}(t)}{E_{in}} = \exp\left(j \frac{\pi V(t)}{V_\pi}\right) \quad (5.62)$$

Digital/Binary Modulation Formats



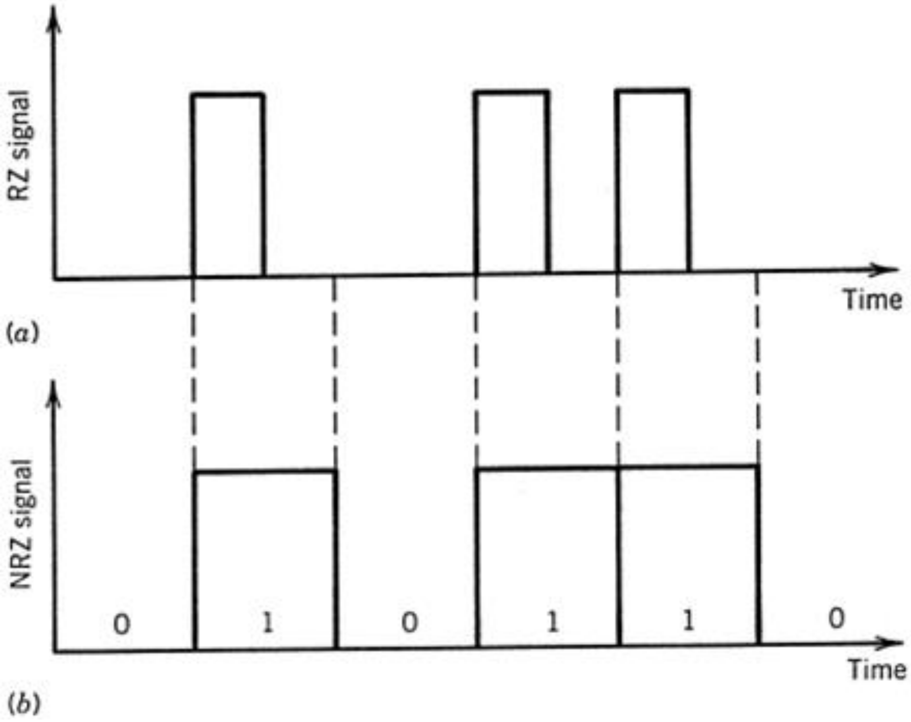
ASK Modulation Format

also known as IM OOK (intensity modulation-on-off key) format

In ASK format, just amplitude is modulated by stream of “1” and “0”

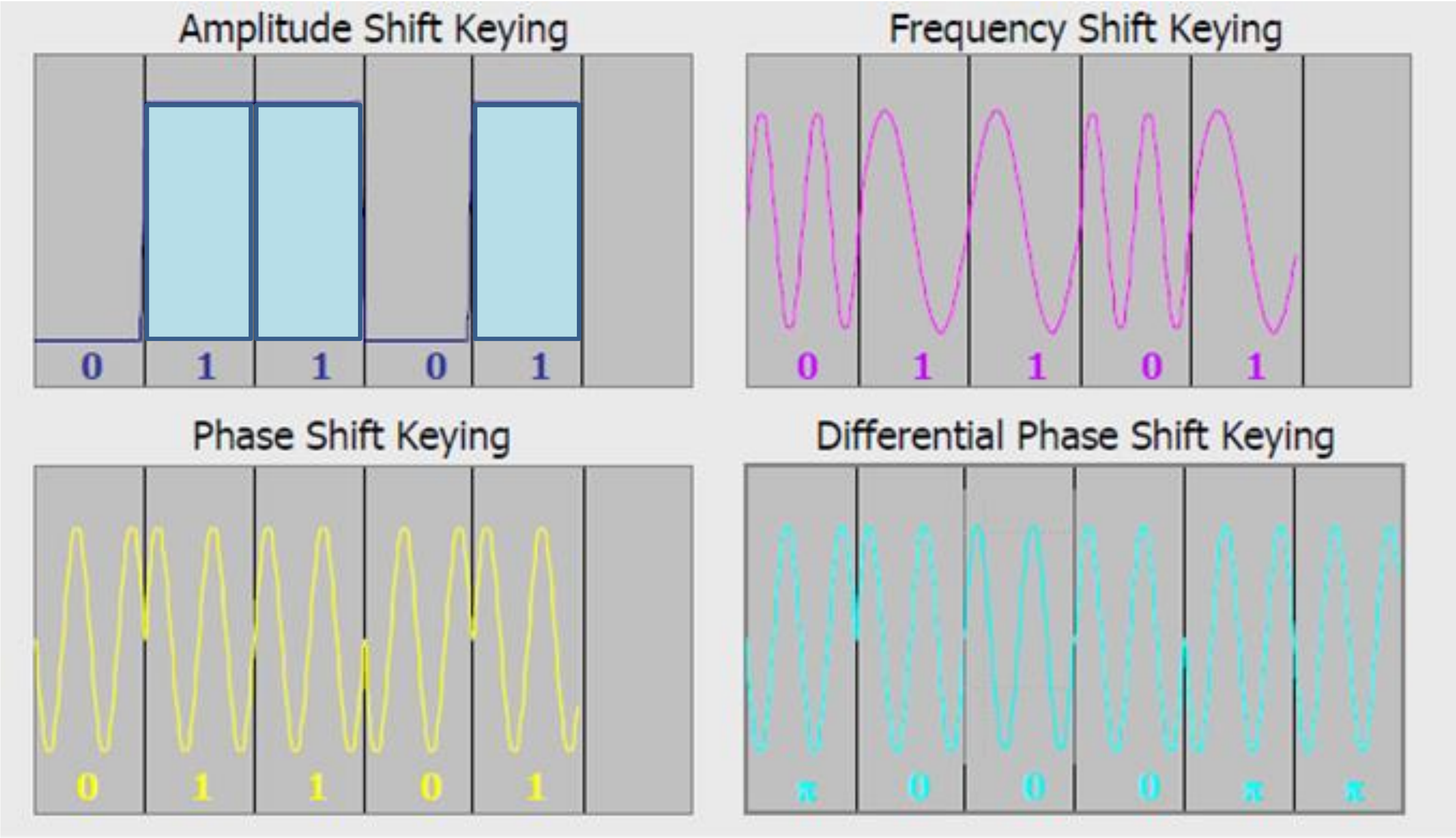
$$A(t) = A_0 \sum_n b_n s(t - nT) = \sqrt{P_0} \sum_n b_n s(t - nT)$$

A_0- max amplitude of the pulse
P_0- max optical power of the pulse
b_n= either “1” or “0”
s(t)- individual signal pulse shape, which is ideally rectangular
-T time slot **(T=1/B; B is bit rate)**



The pulse can occupy the entire slot T or just part of it , so we have NRZ- non return to zero) or RZ (return to zero) formats

Other Binary Modulation Formats

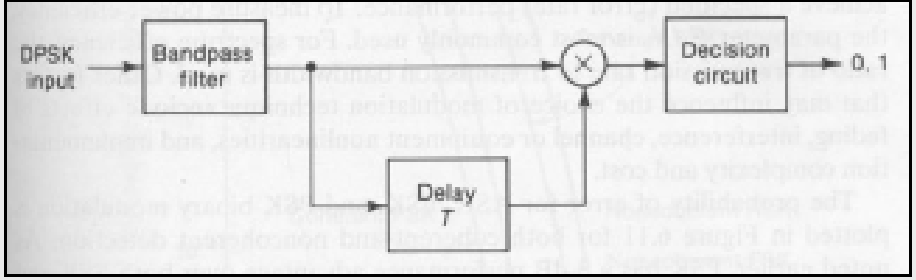


DPSK

Instead of coding bits, code the bit difference

- No bit difference could be encoded as a 1
  - $0 \rightarrow 0 = 1$
  - $1 \rightarrow 1 = 1$
- Bit difference could be encoded as a 0
  - $0 \rightarrow 1 = 0$
  - $1 \rightarrow 0 = 0$
- Need an initial reference bit to begin the sequence
  - Data: _ 0 1 1 0 1 _
  - Diff Encoded: 0 1 1 1 0 0 _
  - Phase: 0 π π π 0 0 _
  - 1-bit delay: _ 0 π π π 0 0
  - Superposition: _ 0 1 1 0 1 _

Phase Shift Keying requires coherent detection
→ a phase reference must be available.
DPSK does not require coherent detection!
(The time delay T will be equal to one bit period T_{bit}.)



Multilevel Modulation Formats

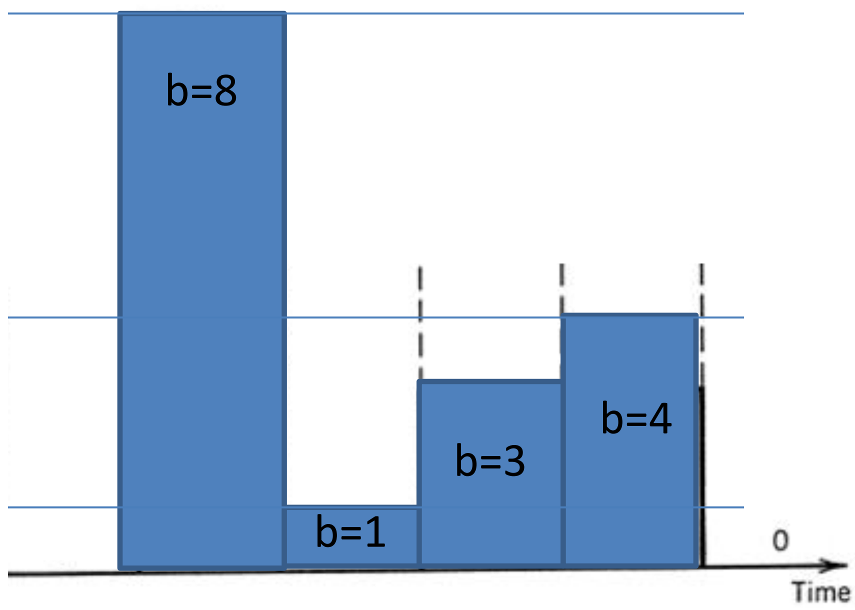
Pulse Amplitude Modulation (PAM)

In PAM format, just amplitude is modulated by stream symbols takin any of M values ($M=2^m$)

$$A(t) = \sum_n b_n s(t - nT_s) = \sum_n b_n s(t - nT_s)$$

b_n= symbol not bit any more
s(t)- individual signal pulse shape, which is ideally rectangular
-T_s time slot **($T_s=1/B_{sym}$; B_{sym} is symbol rate)**
Now, bit B rate is calculated as

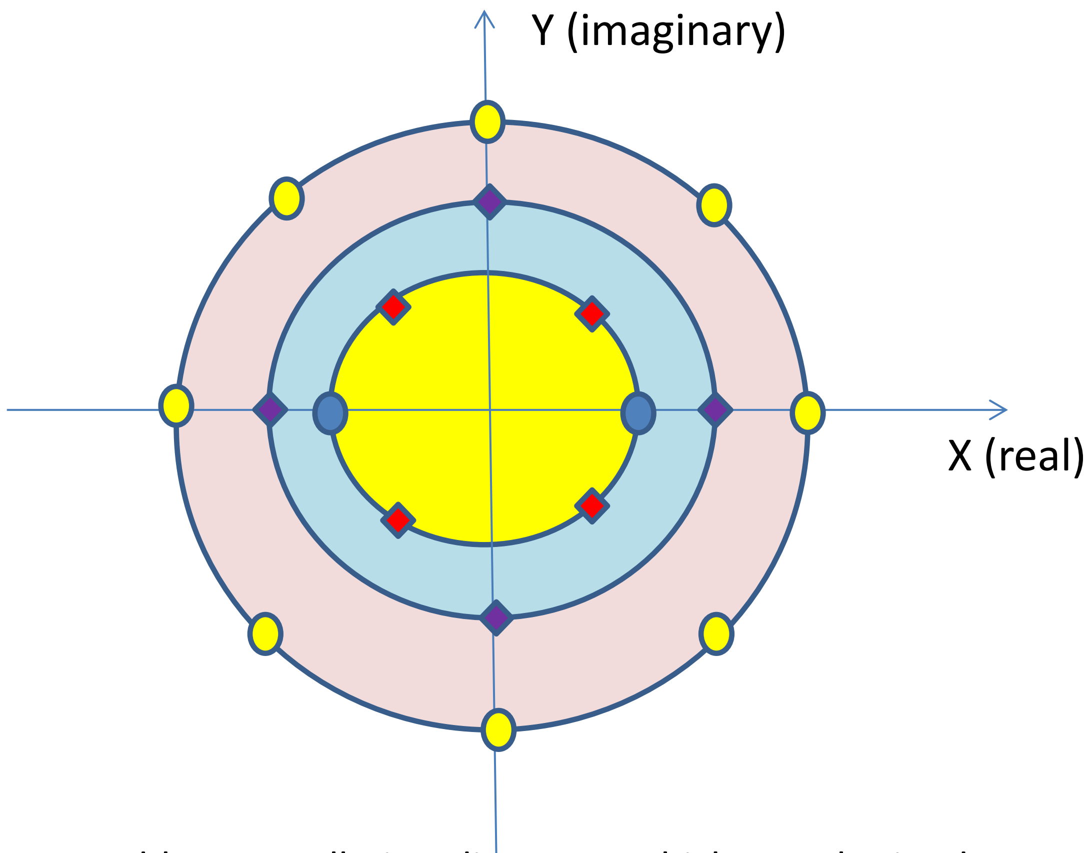
B= $\mathbf{B_{sym}\log_2 M}$



Multilevel Modulation Formats

use both amplitude and phase; complex form represantation

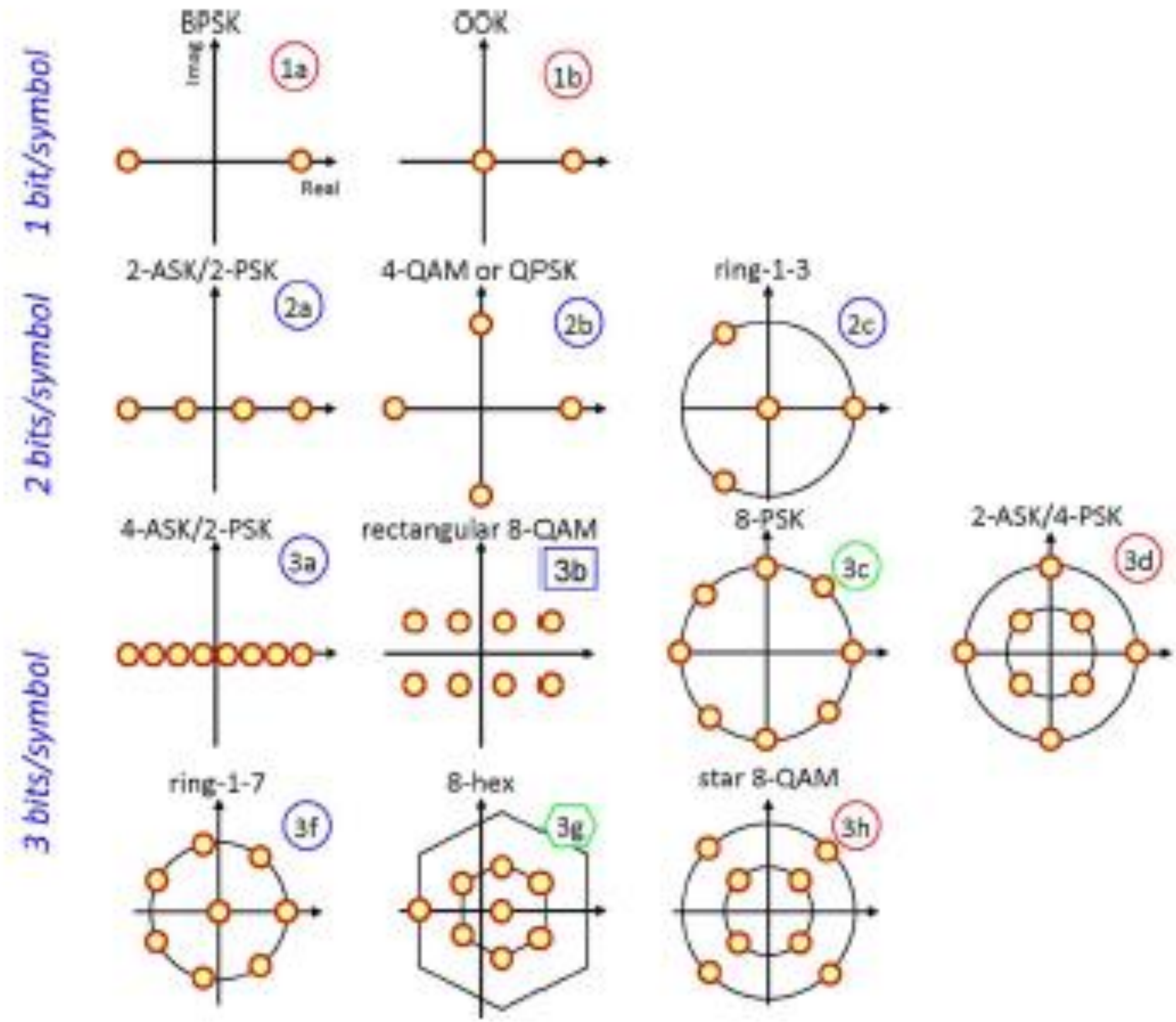
- ASK
- BPSK
- **QPSK**
- **M-QAM**
  - **(8-QAM)** +
  - **8PSK**



Multilevel modulation formats are represented by constellation diagrams, which are obtained as complex representation of combination of phase and amplitude states. Digital stream of “1” and “0” is represented as complex phasors obtained as complex sum of **in phase (x-axis)** and and **in quadrature (y-axis)** components. There may be a number of constellation point in a diagram, depending of what kind of multilevel modulation format is chosen.

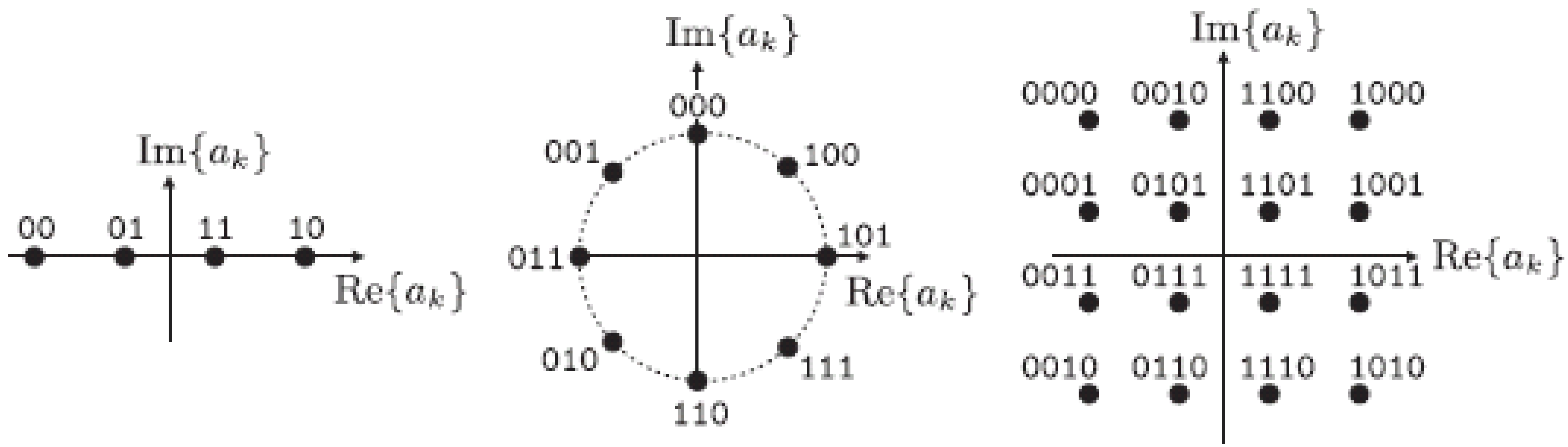
The mail point is that a stream of multiple bits is represented by a single state in constellation diagram

Multilevel Modulation Format Examples



constellations with $M = 2$, $M = 4$, and $M = 8$ points.

Multilevel Modulation Formats
(Mapping Rules)



(a) 4-ASK (b) 8-PSK (c) 16-QAM

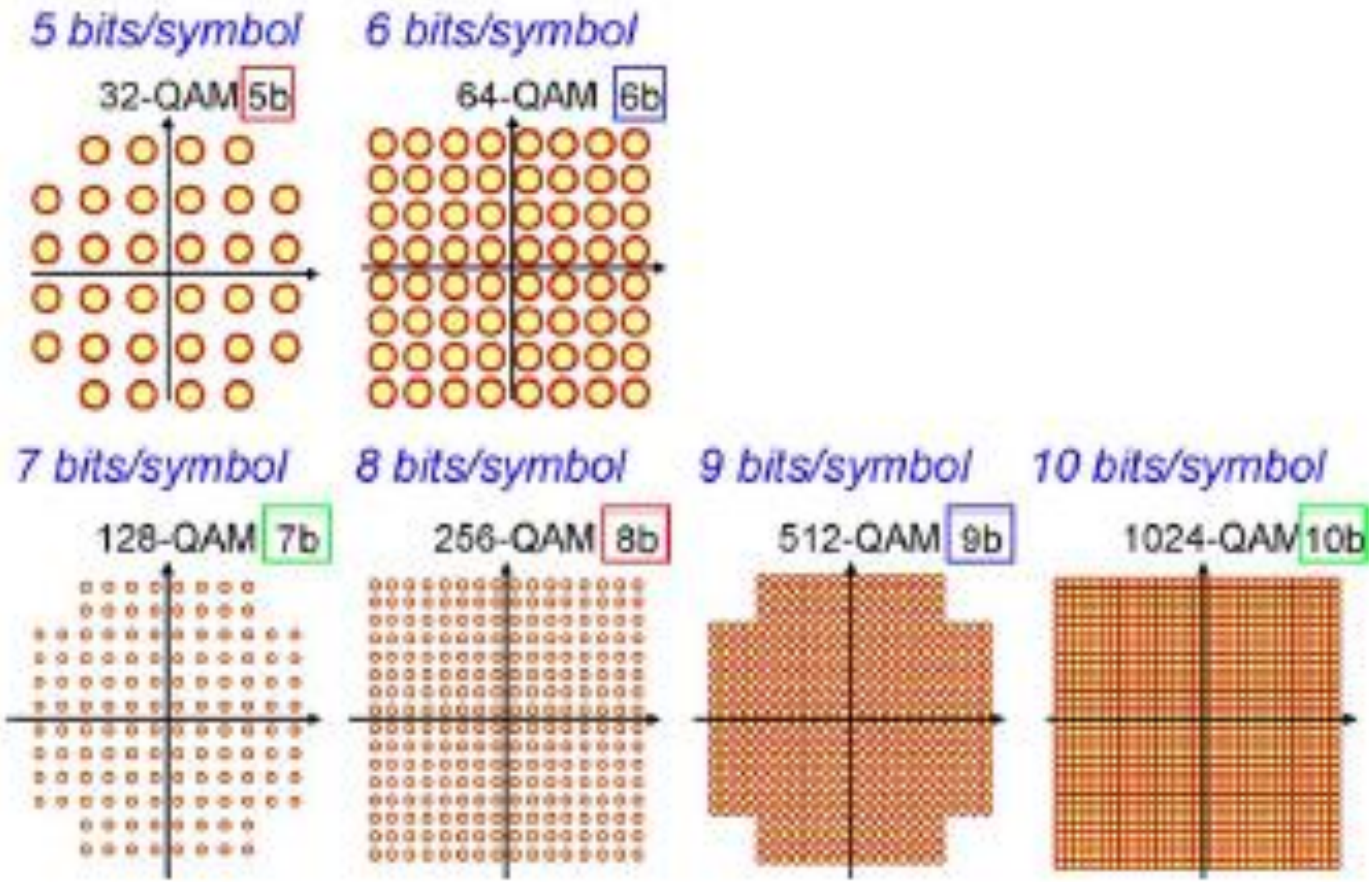
M-QAM mapping rules

Different mapping rules can be used to map binary sequence to corresponding constellation points including: natural mapping, Gray mapping, and anti-Gray mapping. In the Gray mapping rule, the neighboring signal constellation points differ in only one bit position.

Table 5.1 8-PSK/8-QAM Gray Mapping Rule.

Input bits ($c_2c_1c_0$)	ϕ_k	8-PSK		8-QAM	
		I_k	Q_k	I_k	Q_k
000	0	1	0	$1+\sqrt{3}$	**0**
001	$\pi/4$	$\sqrt{2}/2$	$\sqrt{2}/2$	1	**1**
011	$\pi/2$	0	1	0	**$1+\sqrt{3}$**
010	$3\pi/4$	$-\sqrt{2}/2$	$\sqrt{2}/2$	-1	**1**
110	π	-1	0	$-(1+\sqrt{3})$	**0**
111	$5\pi/4$	$-\sqrt{2}/2$	$-\sqrt{2}/2$	-1	**-1**
101	$3\pi/2$	0	-1	0	**$-(1+\sqrt{3})$**
100	**$7\pi/4$**	**$\sqrt{2}/2$**	**$\sqrt{2}/2$**	**1**	**-1**

Multilevel Modulation Formats



QAM constellations with 32, 64, 128, 256, 512, and 1024 points.

Multilevel Modulation Formats

We can use the complex envelope representation of the signal $s(t)$ to represent multilevel modulation signals, so we have:

$$\tilde{s}(t) = s_I(t) + js_Q(t) \tag{5.28}$$

where $s_I(t)$ and $s_Q(t)$ represent **in-phase and quadrature components**, respectively. The standard form can also be represented by cylindrical (polar) coordinates in a form

$$s(t) = a(t)\cos\left[2\pi f_c t + \phi(t)\right];$$

$$a(t) = \left[s_I^2(t) + s_Q^2(t)\right]^{1/2}, \ \phi(\mathrm{t}) = \tan^{-1}\left[\frac{s_Q(t)}{s_I(t)}\right] \tag{5.30}$$

If amplitude and phase are used simultaneously, the corresponding modulation scheme is known as quadrature amplitude modulation (QAM).

M-QAM representation
8-QAM>> 2 amplitudes, 4 phases (M=2 x 4=8)

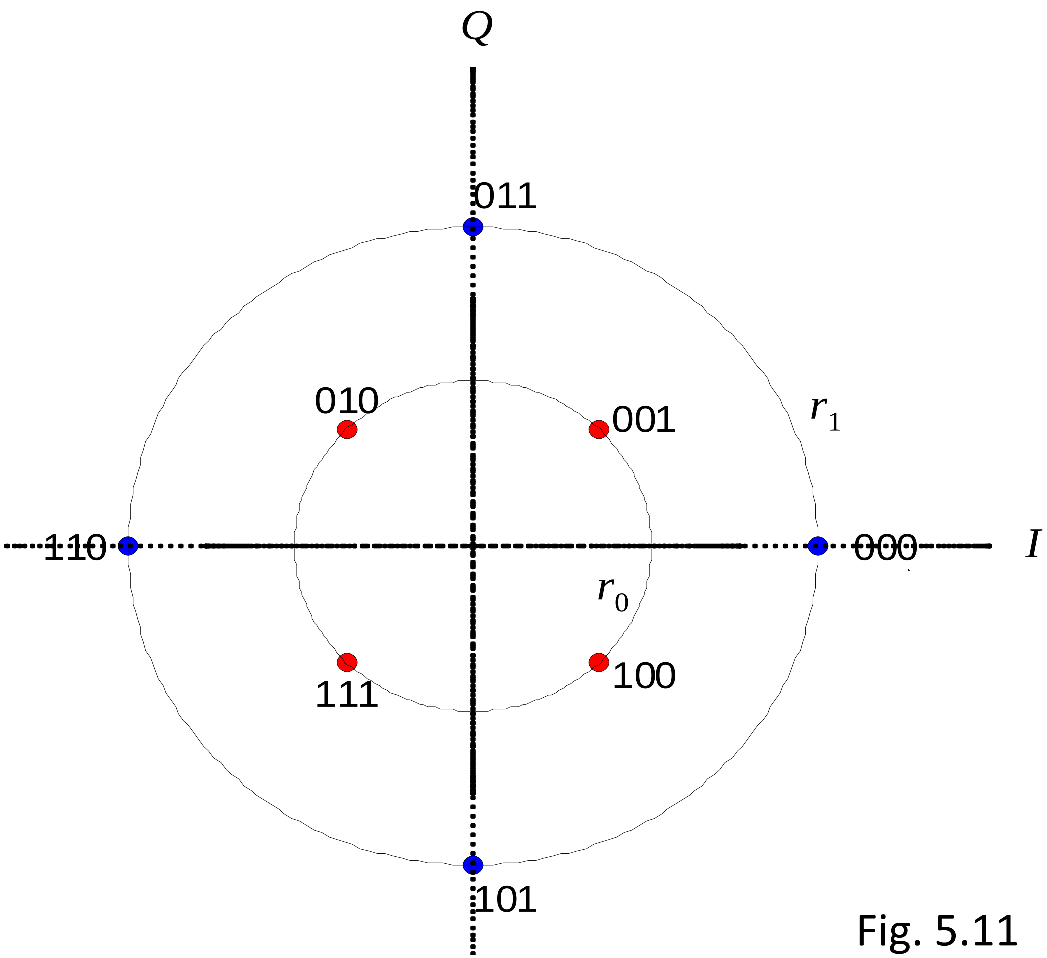


Fig. 5.11

M-QAM representation
8-QAM=8-PSK>> 1 amplitude, 8 phases (M=1 x 8=8)

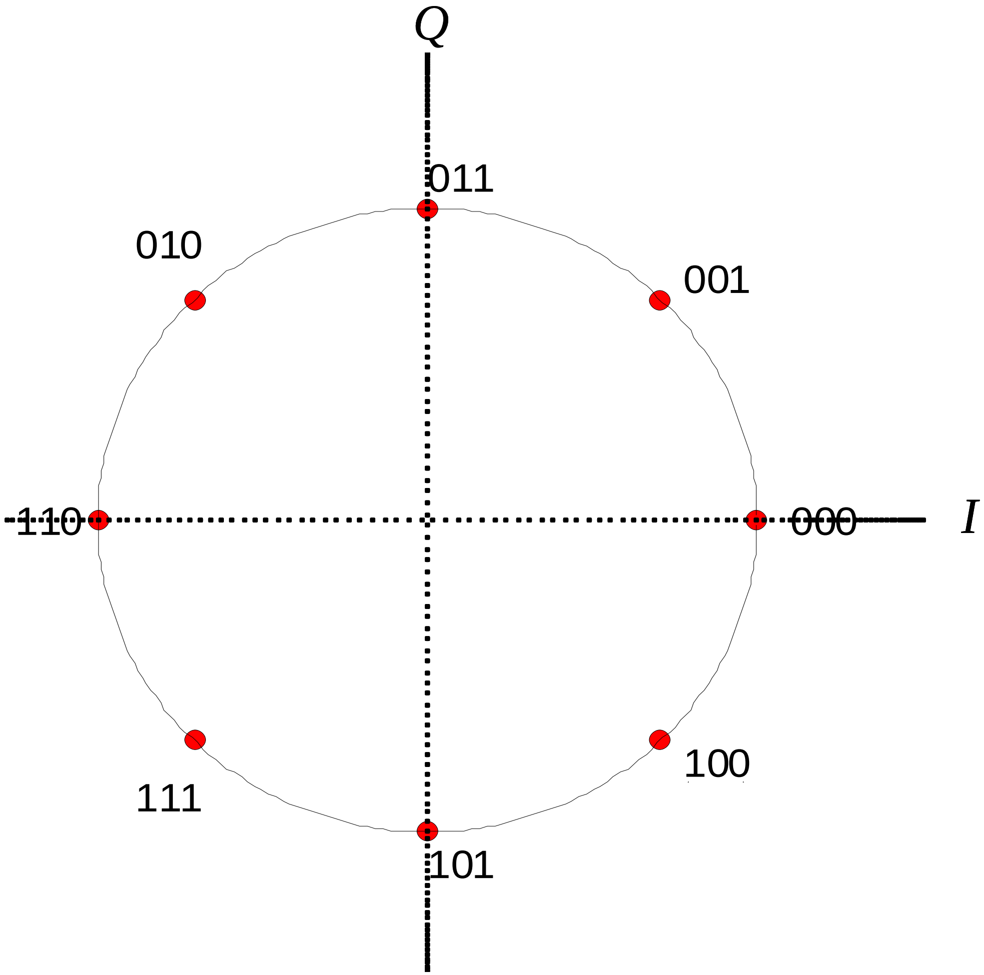


Fig. 5.11

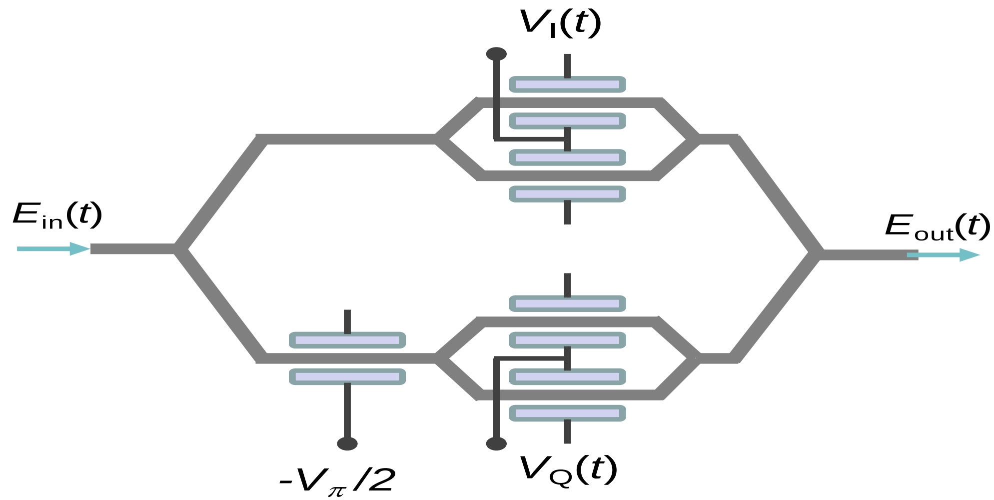


Figure 5.17 The operation principle of the I/Q modulator.

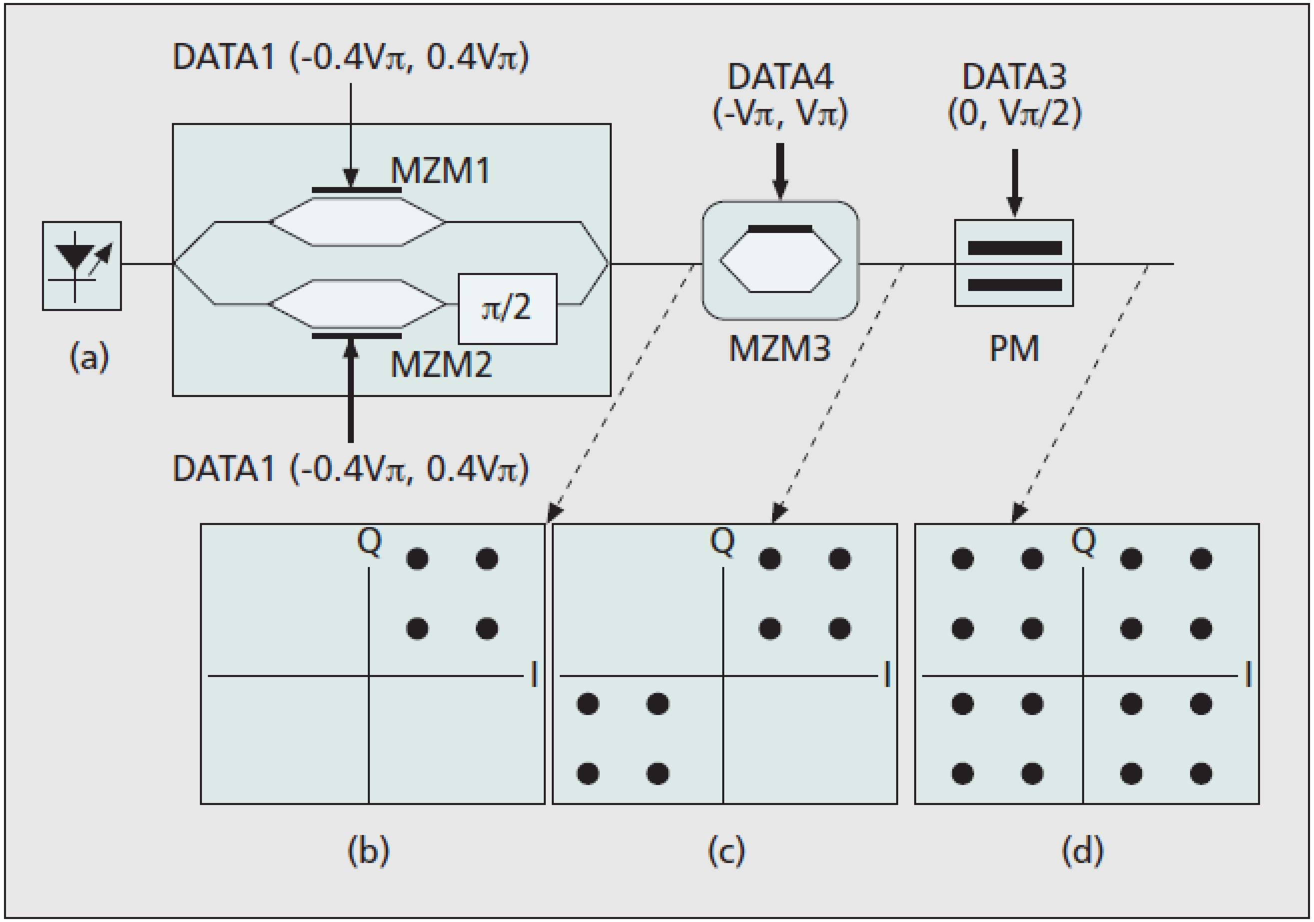
By using two MZM modules and one PM, which introduces the π/2 phase shift, we can implement the I/Q modulator in the way shown in Figure 5.17. It can be shown that output E_{out} and input E_{in} electrical fields of the I/Q modulator are related as

$$\begin{aligned}\frac{E_{out}(t)}{E_{in}} &= \frac{1}{2}\cos\left[\frac{1}{2}\frac{\pi V_I(t)}{V_\pi}\right] + j\frac{1}{2}\cos\left[\frac{1}{2}\frac{\pi V_Q(t)}{V_\pi}\right] \\ &= \frac{1}{2}\cos[\Phi_I(t)/2] + j\frac{1}{2}\cos[\Phi_Q(t)/2], \quad \Phi_{I(Q)}(t) = \pi V_{I(Q)}(t)/V_\pi\end{aligned} \tag{5.63}$$

where V_I and V_Q are the in-phase and quadrature RF modulating signals.

M-QAM Realization

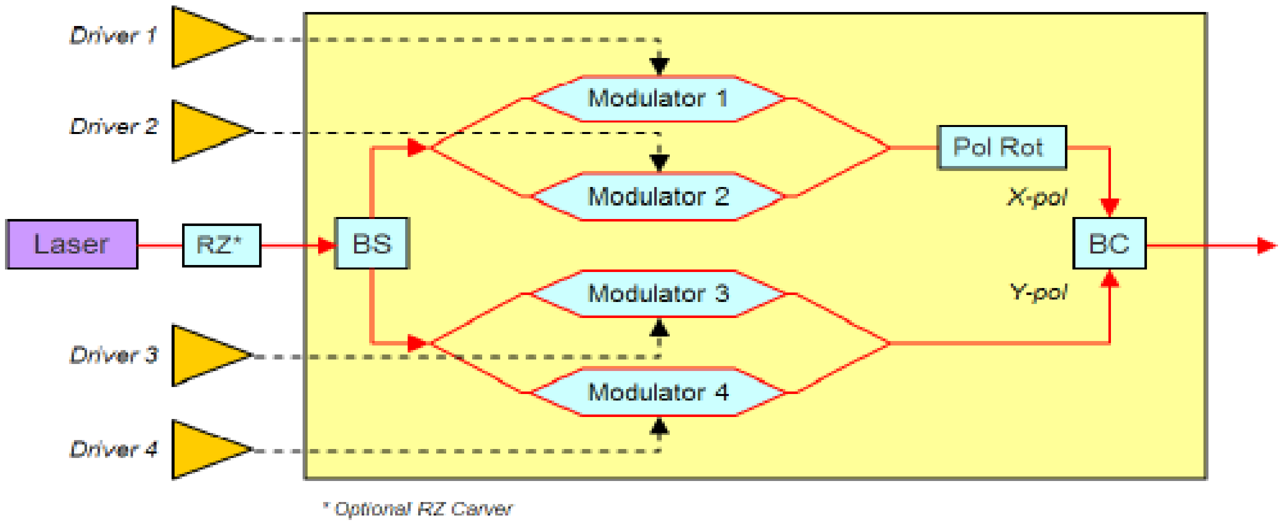
Serial/Parallel Combination of MZM and PM



Source: ***Jianjun Yu, Xiang Zhou, IEEE Comun. Magazine, March 2010***

100 G Standard: DP-QPSK Spec

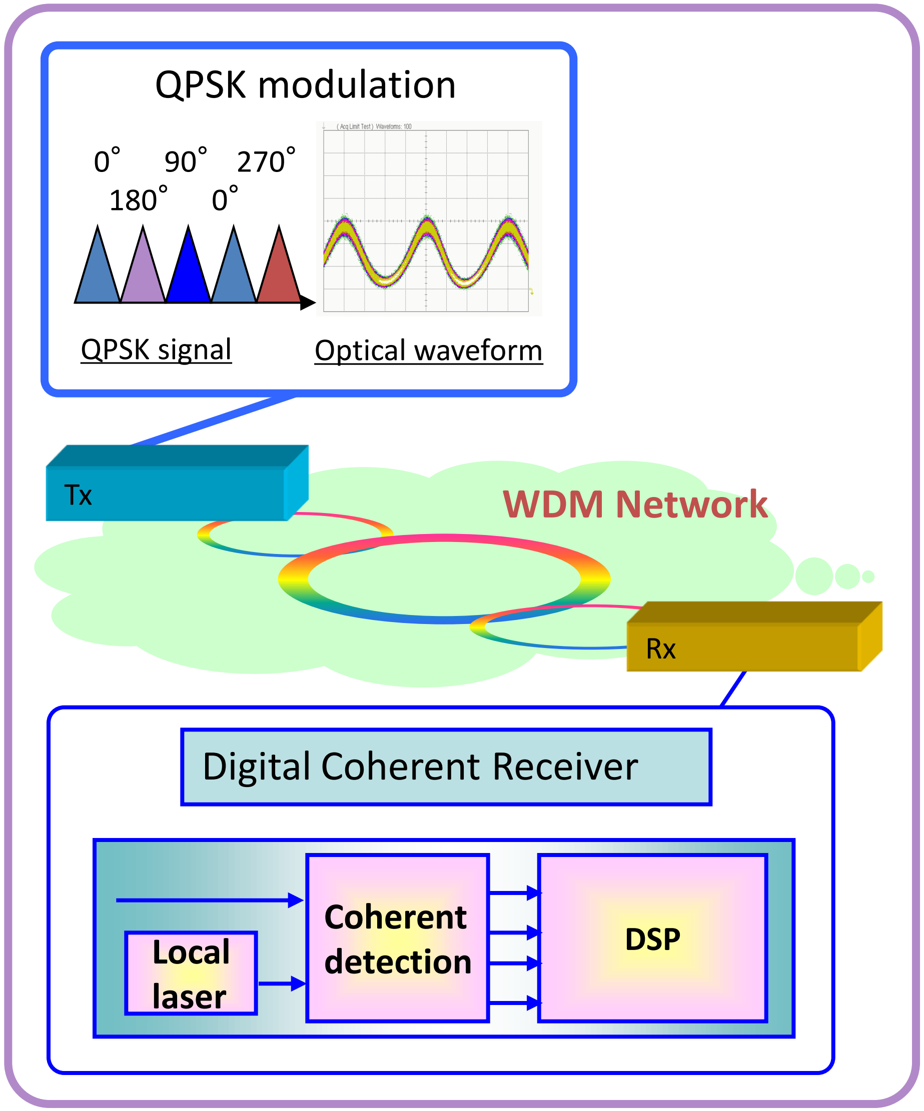
Integrated Photonic Modulator



- Current photonic transmitter module composition
  - Modulators and other optical components integrated
  - Integrated drivers on separate module(s)
  - Transmit laser using OIF ITLA*
- Future possibility of further integration
- Modulation Scheme independent

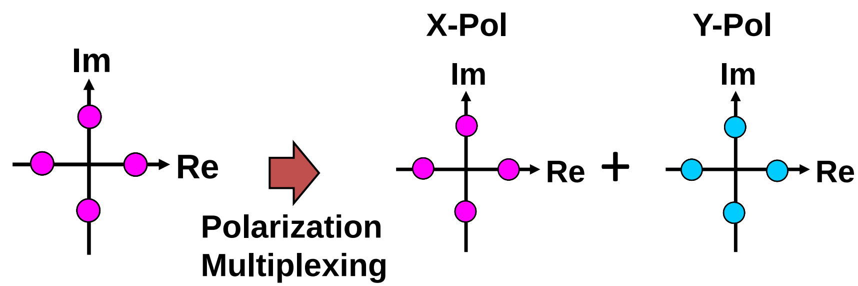
Source: OIF 2010

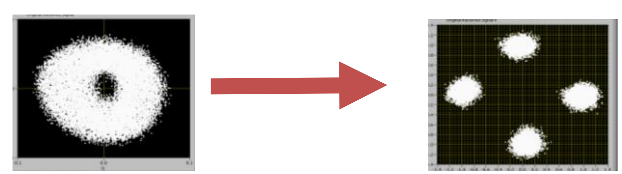
100+G Transmission with Coherent and DSP Technology



- Waveform distortion due to chromatic dispersion and polarization mode dispersion can be compensated utilizing digital signal processing
- Multi-level code modulation with polarization multiplexing technology is applied to achieve lower baud-rate, and to be relaxed electrical device performance.

$$P(t) \approx P_L + 2\sqrt{P_L P_S(t)}\cos\left[\Delta\omega(t)t + \Delta\varphi(t)\right]$$





Signal at Rx

After Signal Processing

Source material: M. Cvijetic *"Coherent and nonlinear Ligtwave Communications",* Artech House, Boston-London 1996

OFDM (Orthogonal Frequency Division Multiplexing)

The OFDM signal is in essence a sum of orthogonal subcarriers where each of them can be modulated independently by a specific modulation format, such QPSK or M-QAM. The key is the subcarrier arrangement since **subcariers are orthogonal to each other by keeping a precise distance among the frequencies of subcarriers in and an aggregate OFDM signal**.

The orthogonality is achieved by generating subcarriers with the following properties:

(i) each subcarrier should be represented by rectangular shape in time domain,

(ii) if the duration of the digital symbol is T_s, each subcarrier should perform only a specified integer number of periods (cycles) within duration T_s, and

(iii) the difference in the number of cycles between adjacent subcarriers (or the difference Δf in frequencies f_{k+1} and f_k of neighboring subcarriers) should differ by one, which is $\Delta f = f_{k+1} - f_k = 1/T_s$.

OFDM (Orthogonal Frequency Division Multiplexing)

The signal $s(t)$ that takes OFDM form in the interval from $-T_s/2$ to $T_s/2$ can be represented as

$$s(t) = s_{rec}(t) \sum_{k=-N_{SC}/2}^{N_{SC}/2-1} X_{k+N_{SC}/2} \exp\left(j2\pi kt/T_s\right) \qquad (5.103)$$

where N_{SC} is to total number of subcarriers,

$s_{rec}(t)$ represent rectangular shape of the pulse with the duration from $-T_s/2$ to $T_s/2$,

and X_n represents complex valued symbol at the k-th subcarrier (mostly in QPSK and M-QAM format).

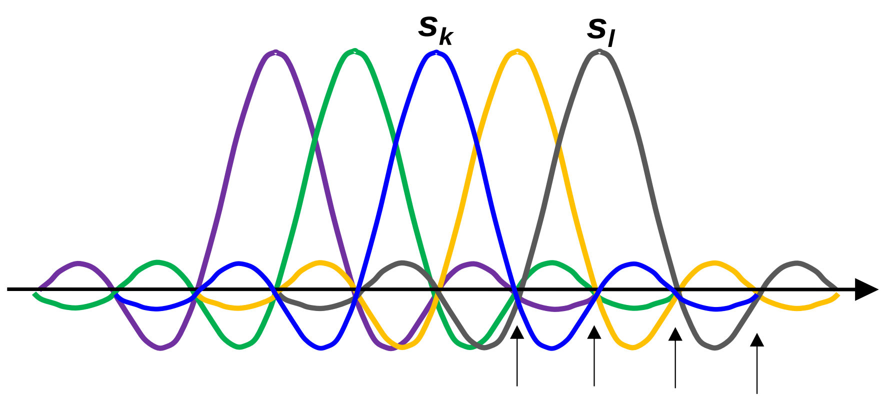
OFDM (Orthogonal Frequency Division Multiplexing)-cont.

We can conclude that the OFDM form is produced by using **QPSK or M-QAM constellation points as projections along the set of basis functions represented by subcarriers**. The Fourier transform of this signal can be expressed as

$$S(f) = FT\{s(t)\} = \frac{\sin(f\pi T_s)}{f\pi T_s} \sum_{k=-N_{SC}/2}^{N_{SC}/2-1} X_{k+N_{SC}/2} \delta(f - k/T_s) = \sum_{k=-N_{SC}/2}^{N_{SC}/2-1} X_{k+N_{SC}/2} \frac{\sin[(f - k/T_s)\pi T_s]}{(f/T_s)\pi T_s} \tag{5.107}$$

where functions $\delta(f\text{-}k/T_s)$ represent Dirac pulses located at the subcarrier frequencies, which in convolution with subcarrier rectangular pulses produce $\sin x/x$ functional shape.

The principle of orthogonally between subcarriers can be described as a feature where just given subcarrier out of a number of overlapping subcarriers has a nonzero value at the points $1/T_s$, which is illustrated in Figure 1. **The overlapping spectra of individual subcarriers that satisfy the Nyquist criterion guarantee intersymbol interference (ISI) free detection with the high spectral efficiency.** We should notice that the pulse shape of the OFDM subcarrier is observed in the frequency domain, rather than in the time domain.



OFDM (Orthogonal Frequency Division Multiplexing)-cont.

- The input serial stream of M-QAM (or QPSK) data, obtained by encoding the binary data stream and binary-to-QAM mapping, is then converted into N_{SC} parallel streams, which are multiplied with corresponding subcarrier basis functions to generate the OFDM waveform.

- The real and imaginary parts of this OFDM signal are converted to analog form and used to modulate optical signal. Just opposite happens at the receiver side after photodetection process is done, by performing downconversion in frequency equal to k/T_s for the subcarrier k.

- However, if there is any frequency offset caused by conditions in the optical channel, the original orthogonality between subcarriers will be violated, thus **causing a crosstalk known as inter-carrier interference (ICI).**

- The generation and detection of OFDM signals described above is related to continuous time (analog) domain. It is much easier to use DSP and perform a number of functions in discrete time (digital) domain.

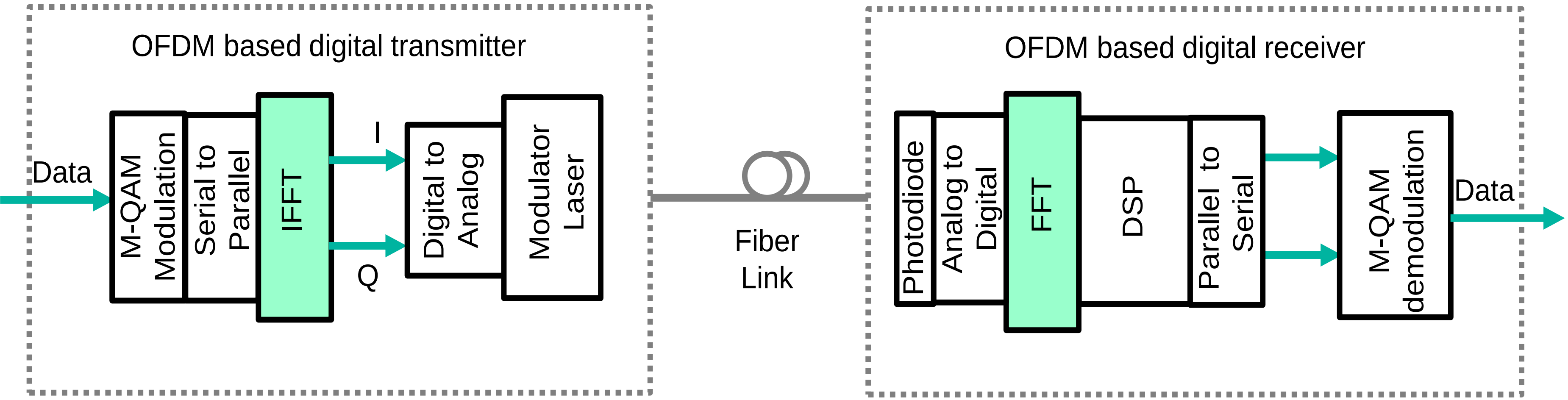
OFDM (Orthogonal Frequency Division Multiplexing)-cont.

If the signal from Equation (**) is sampled with an interval $T_{sam}=T_s/N_{sam}$, where $N_{sam} = 2^n$ is an integer for n>1, the samples defined by points m can be expressed as

$$s(mT) = \sum_{k=-N_{SC}/2}^{N_{SC}/2-1} X_{k+N_{SC}/2} \exp\left(j2\pi kmT/T_s\right) = \sum_{k=-N_{SC}/2}^{N_{SC}/2-1} X_{k+N_{SC}/2} \exp\left(j2\pi km/N_{SC}\right)$$

This equation defines the **inverse discrete Fourier transform of an input QAM sequence**, which can be efficiently implemented by the inverse fast Fourier transform (IFFT). After the IFFT calculation, digital to analog conversion (DAC) is performed. **By the reverse logic, the fast Fourier transform (FFT) is applied in optical receiver after and analog to digital conversion (ADC) process.**

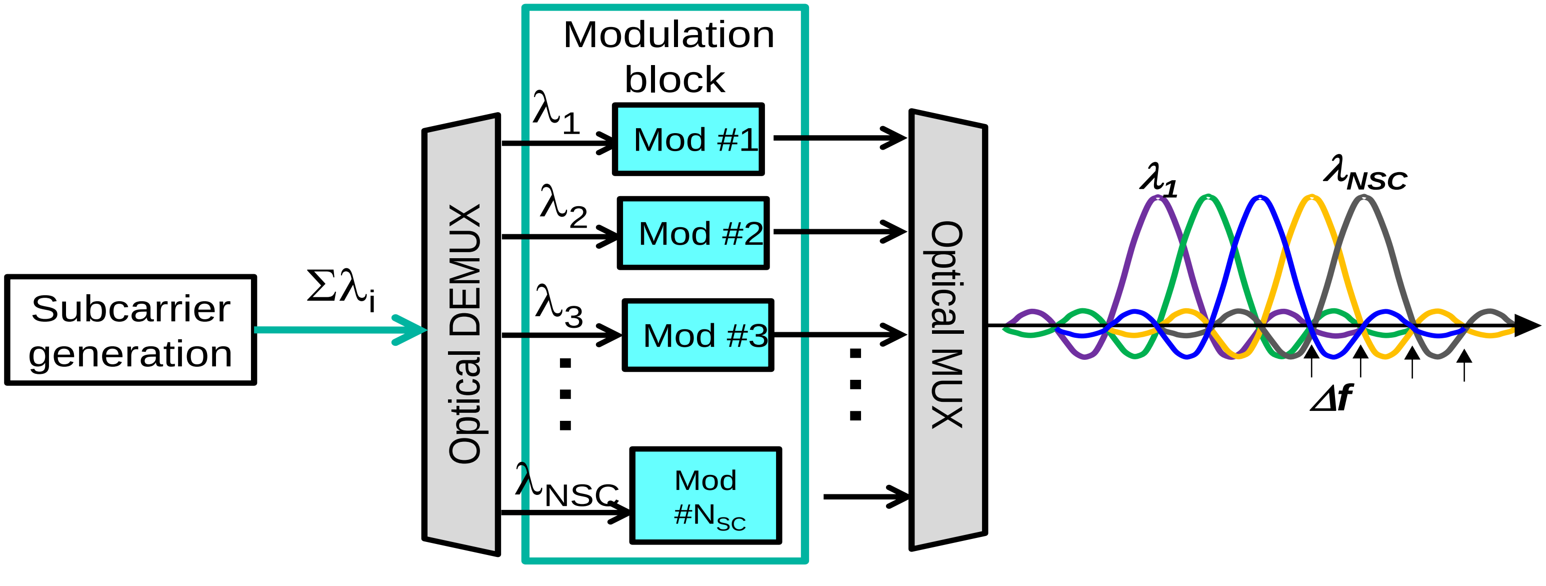
OFDM (Orthogonal Frequency Division Multiplexing)-cont.



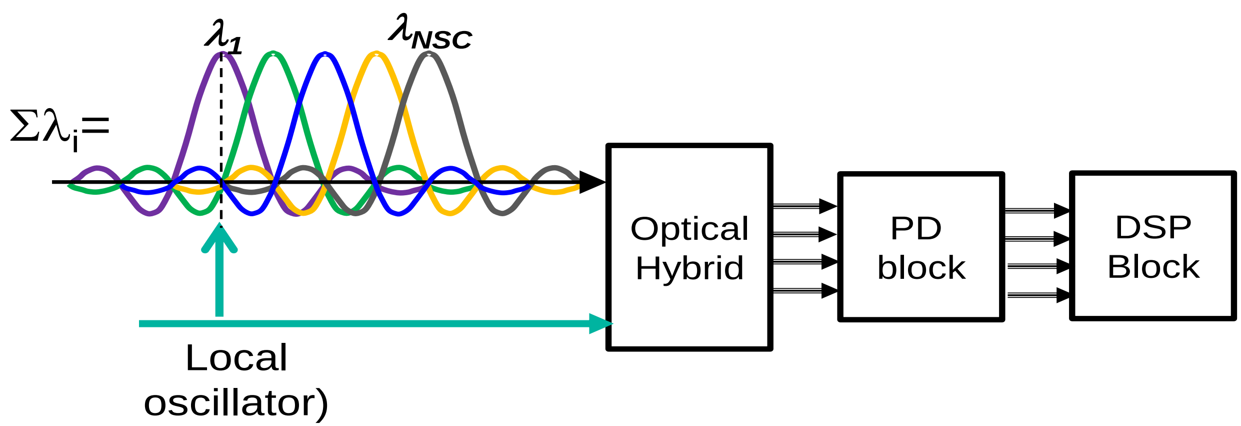
- The OFDM is very efficient in dealing with dispersion effects (both chromatic and PMD).
- In order to increase OFDM efficiency with respect to dispersion compensation, every OFDM symbol is accompanied with **a guard interval, which is chosen to be longer than the pulse widening due to dispersion impact**.
- The guard interval thus prevents dispersion **spreading related to a specific symbol to interfere with the neighbouring symbols, which would cause ISI**.
- The guard interval is conventionally designed in such way that **a specific OFDM symbol is cyclically extended in the guard time in order to keep the orthogonally** of the subcarrier components and prevent ICI.

O-OFDM

The data rate of the formed superchannel can be increased adding optically generated subcarr. (so they go from 1 to N_{SC}). Each subcarrier is modulated independently in the modulator block by using I-Q capable M-ary devices, mainly based on Mach-Zehnder modulators.



(a)



(b)