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Escola Tècnica Superior d'Enginyeria de Telecomunicació de Barcelona

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

FIBER-OPTIC COMMUNICATIONS

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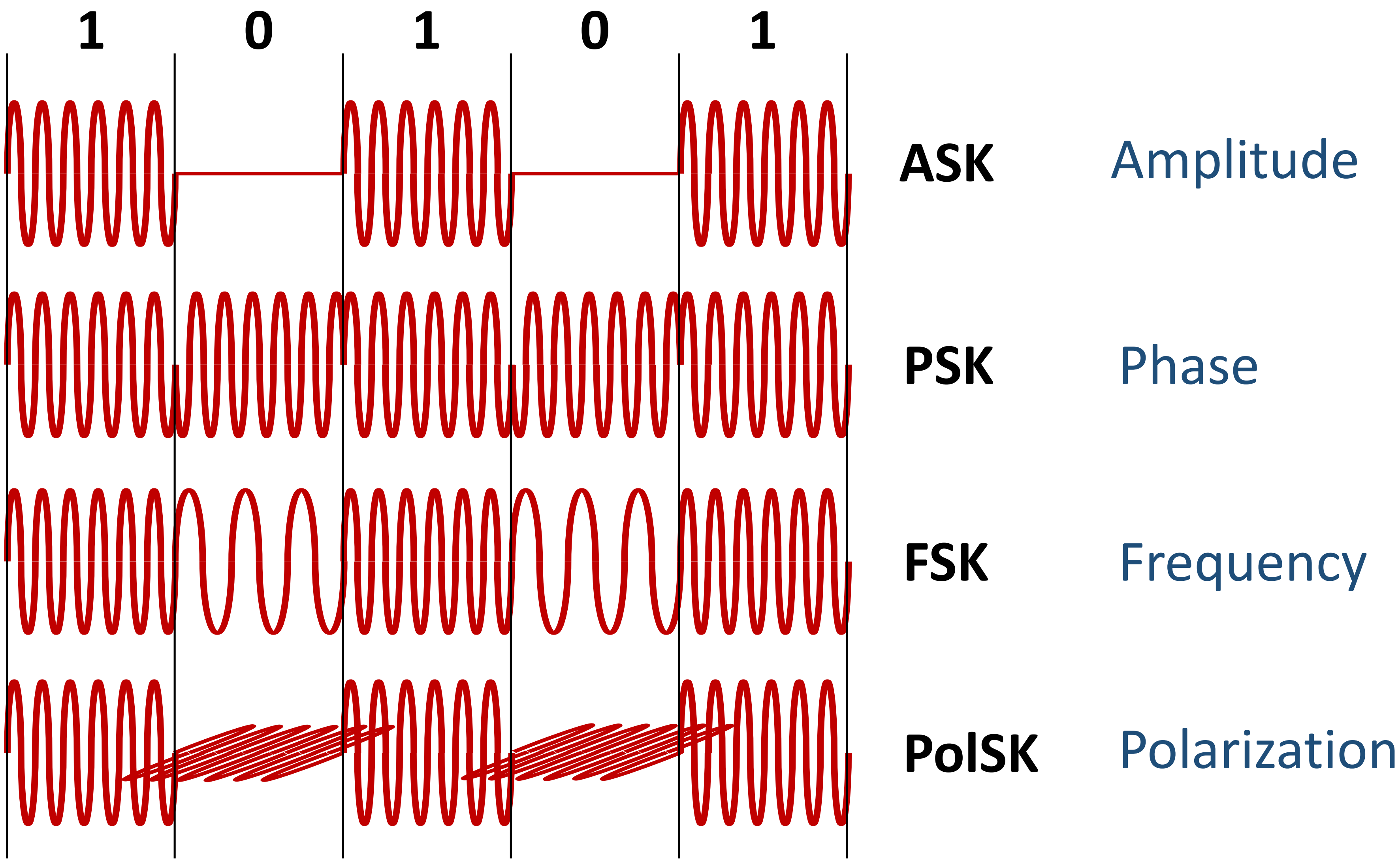
INTRODUCTION

MODULATION OF LIGHT PROPERTIES



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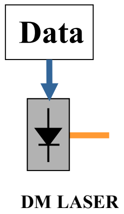
Modulation/ Detection Schemes

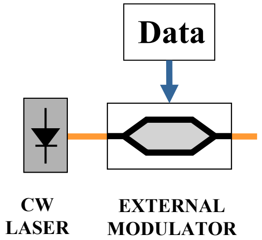
Modulation

Direct

- Intensity
- Frequency
- Phase



External

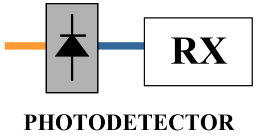


- EAM
  - Intensity
- ERM
  - Phase
  - Polarization
- Mach-Zehnder
  - Intensity
  - Phase

Detection

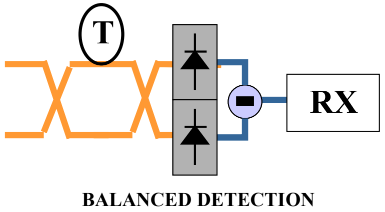
Direct

- Intensity



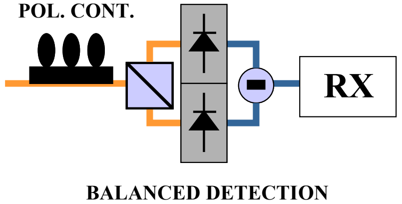
Differential

- Phase
- Frequency
- Polarization



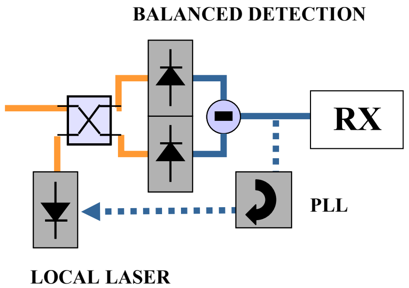
Polarization

- Polarization



Synchronous

- Intensity
- Phase
- Frequency
- Polarization



DESIRABLE CHARACTERISTICS

- ✓ HIGH MODULATION SPEED (EO BANDWIDTH)
- ✓ NO FREQUENCY CHIRP
- ✓ LINEAR LIGHT-CURRENT RESPONSE
- ✓ WORKING TEMPERATURE AND STABILITY
- ✓ LOW INSERTION LOSS
- ✓ SMALL DRIVING CURRENT
- ✓ POLARIZATION INDEPENDENCY
- ✓ SMALL SIZE AND CONSUMPTION (INTEGRATION)
- ✓ REDUCED COST

ELECTRO-ABSOPTION MODULATOR

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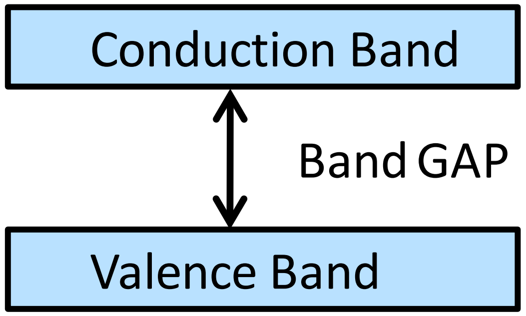
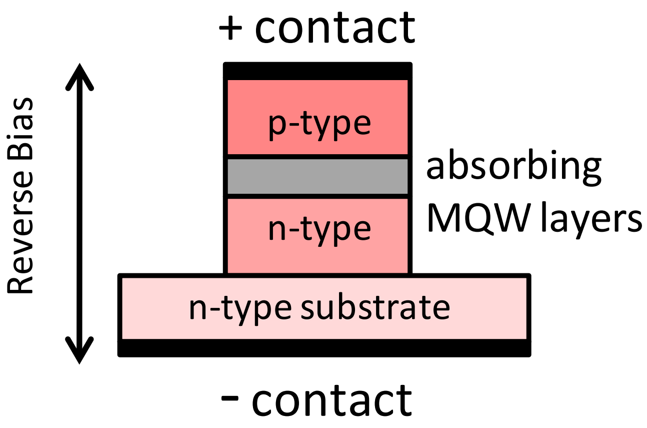
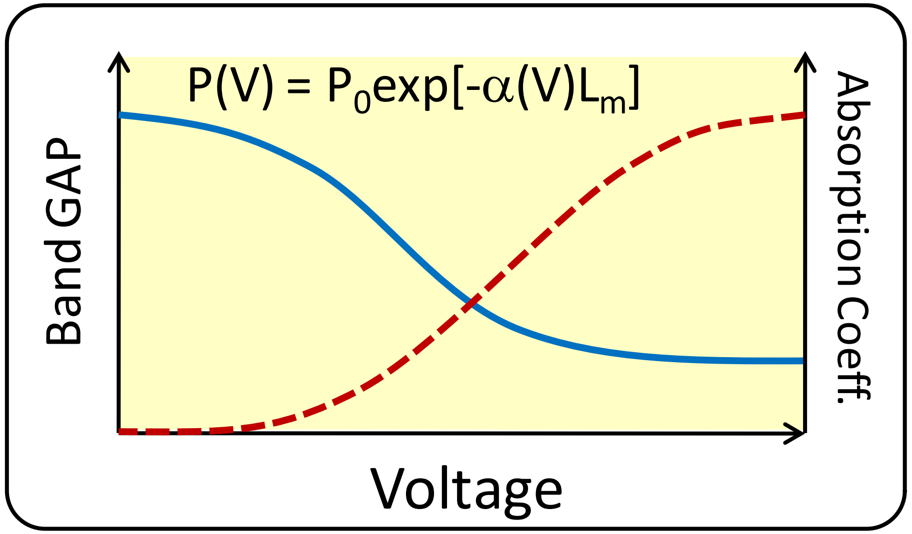
Electro-Absorption Modulators (EAM)

Semiconductors Electro-absorption → Franz-Keldysh Effect   Agrawal, "Components and Devices", pg. 225.





InGaAsP



EO Bandwidth → 30-50 GHz

Temporal Response → 10 ps (40 Gb/s → 25 ps)

Extinction Ratio → 15 dB

Wavelength Range → 20 nm (1550 nm)

Insertion Loss → 5 dB

Residual Chirp → Kramers-Kronig Relation

Temperature Sensitivity → Very high

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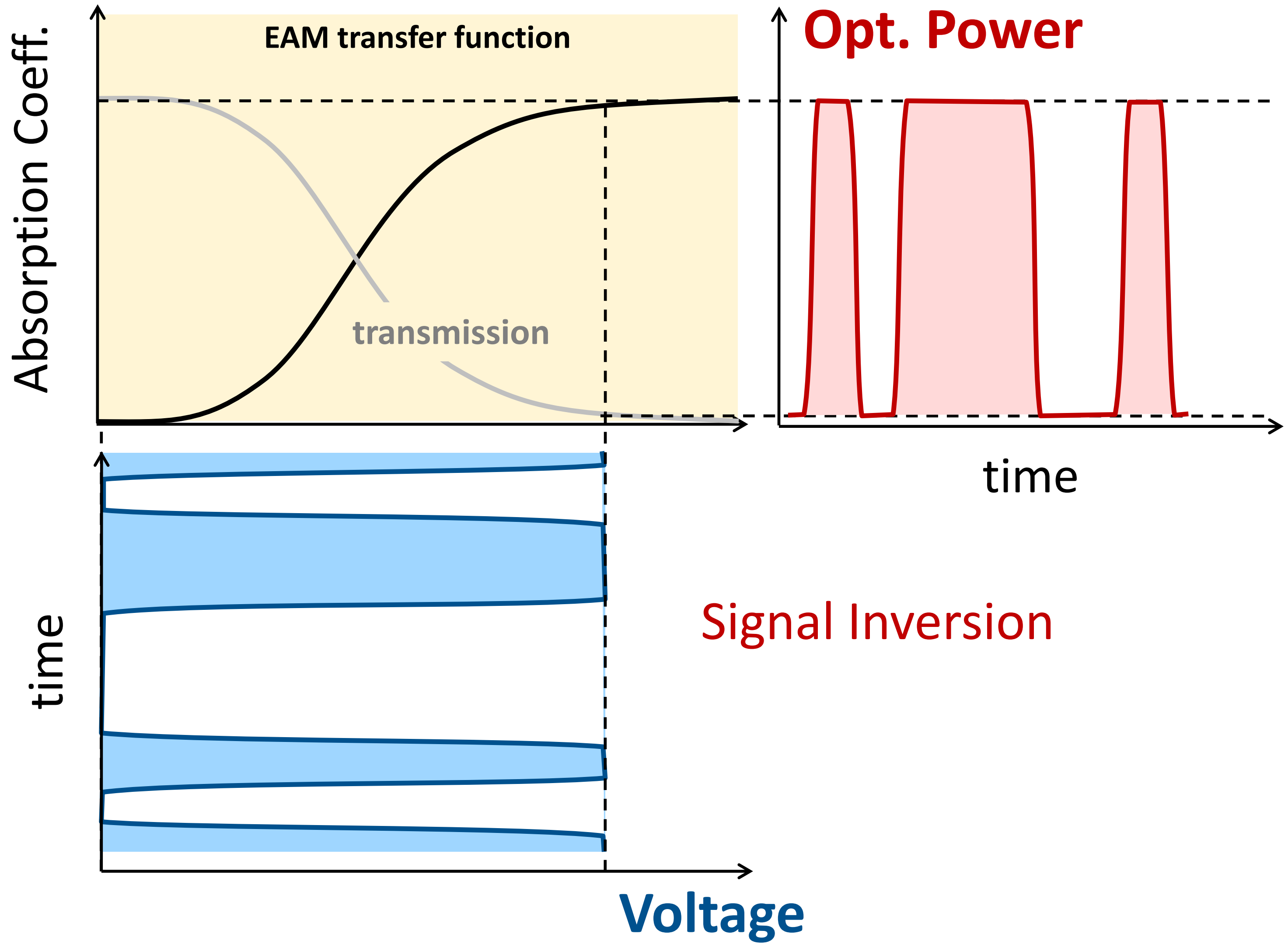
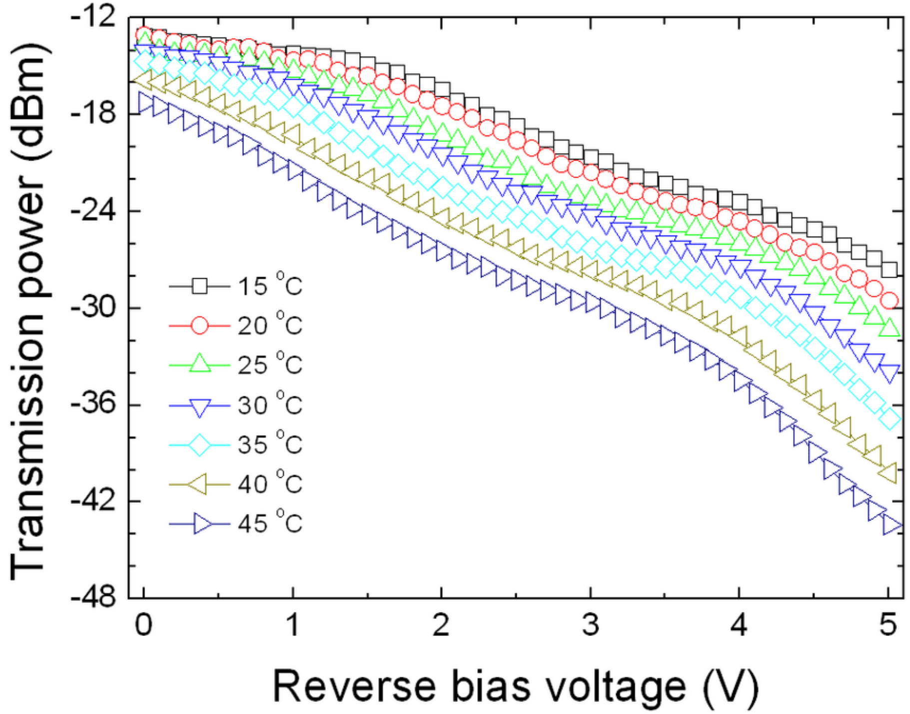
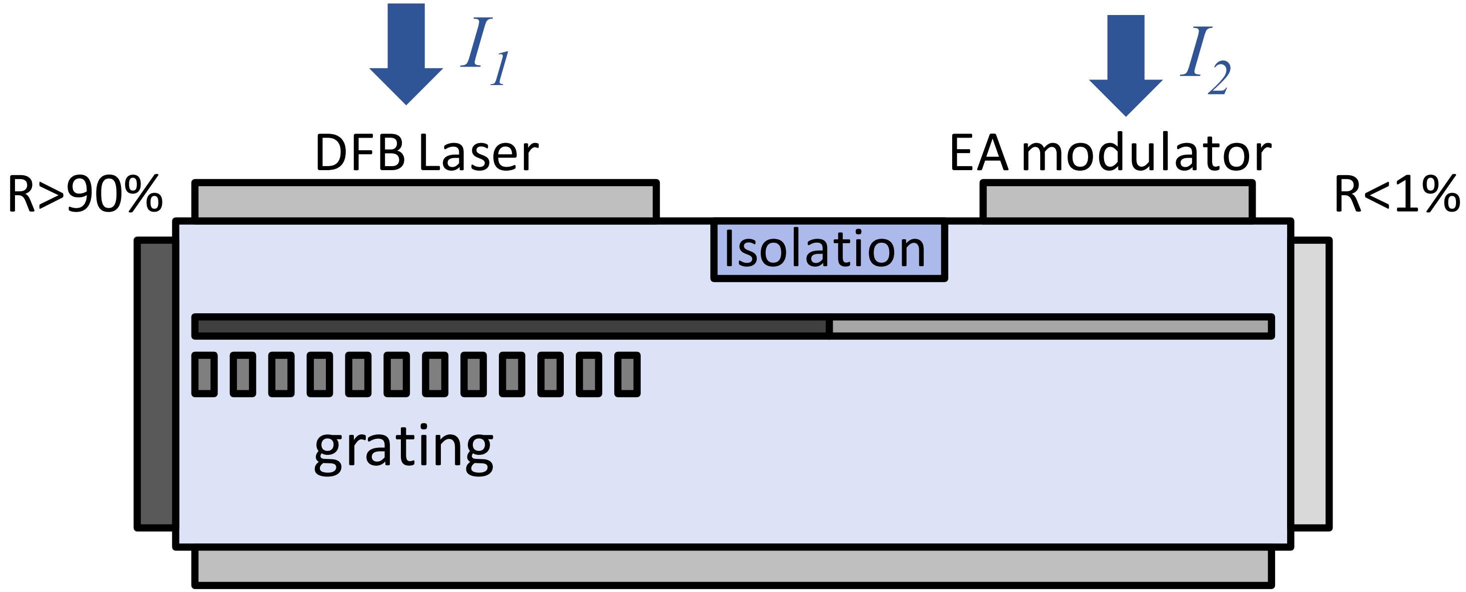
INTENSITY MODULATION USING AN EAM

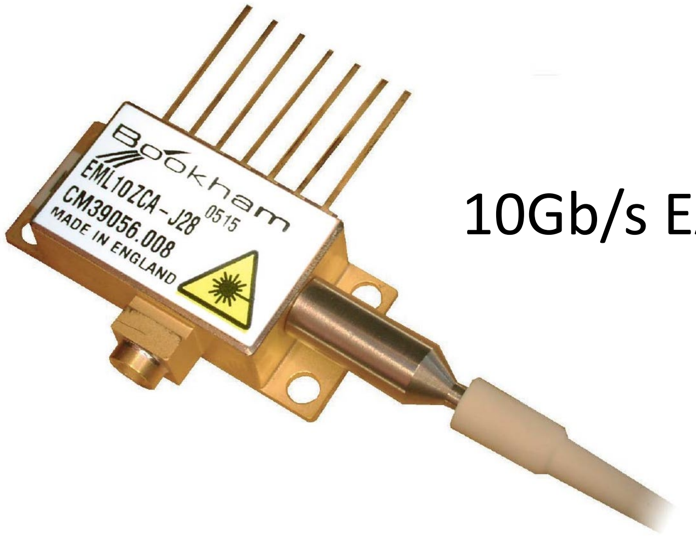


Temperature Dependence
https://doi.org/10.3938/jkps.53.1538



DFB Laser-EAM Integration





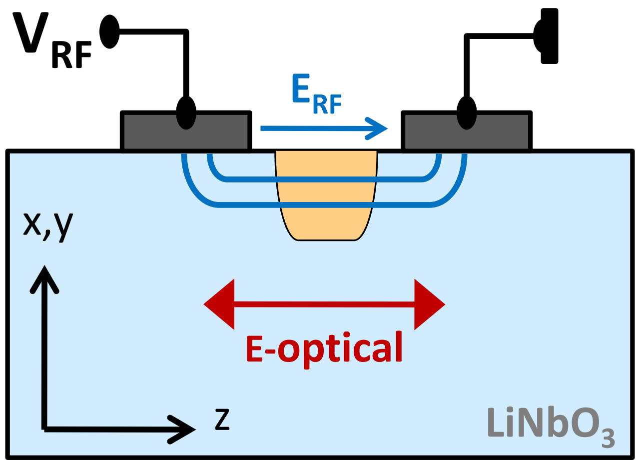
10Gb/s EA Modulator and DFB Laser

MACH-ZEHNDER MODULATOR

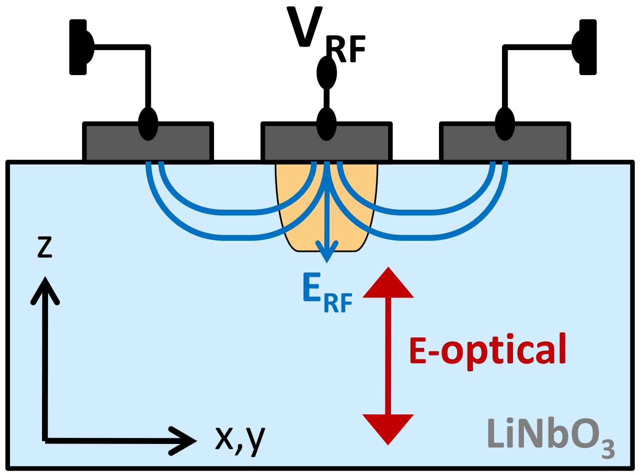
MACH-ZEHNDER MODULATORS (MZM)

Crystals Electro-refraction → Pockels Effect

Agrawal, "Components and Devices", pg. 227.

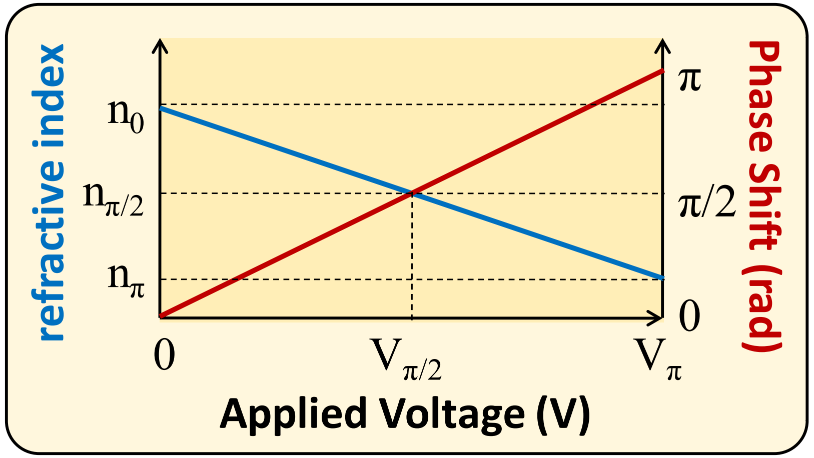


x,y-cut



z-cut

Phase Modulation



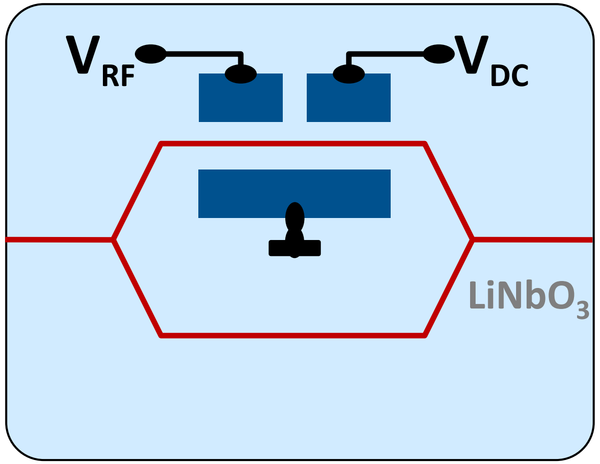
Phase Shift

$$\Delta\phi = \pi \frac{V_{RF}}{V_{\pi}}$$

V_{π} : Required driving voltage for a π radians phase shift

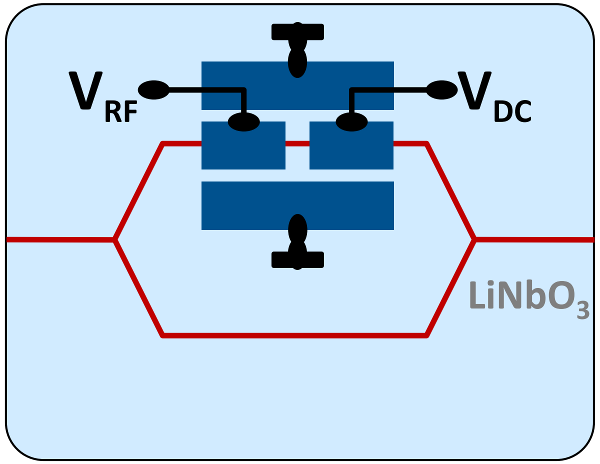
Mach-Zehnder Structures

unbalanced drive



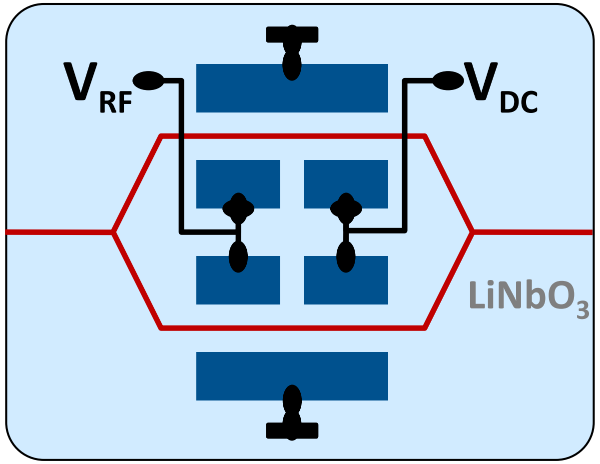
x,y-cut

unbalanced drive



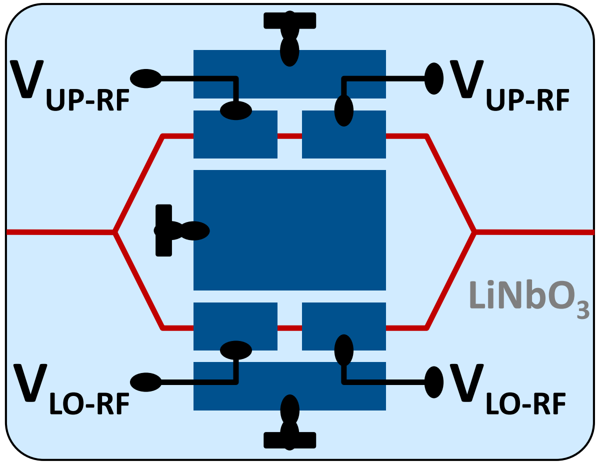
z-cut

balanced drive



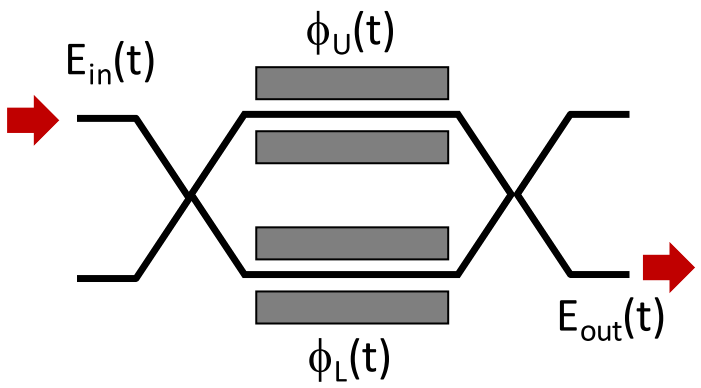
x,y-cut

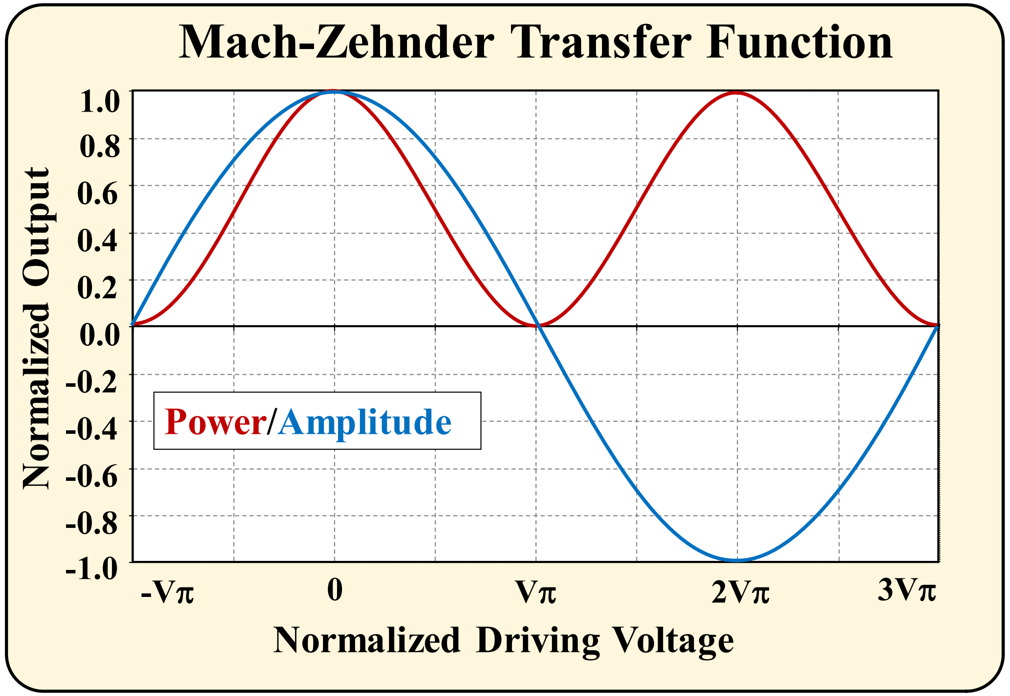
differential drive



z-cut

MACH-ZEHNDER TRANSFER FUCNTION





$$E_{in}(t) = E_0 e^{j\omega t}$$

$$E_{out}(t) = E_0 \cos\left(\frac{\phi_U(t) - \phi_L(t)}{2}\right) e^{j\frac{\phi_U(t)+\phi_L(t)}{2}} e^{j\omega t}$$

$$P_{out}(t) = P_0 \cos^2\left(\frac{\phi_U(t) - \phi_L(t)}{2}\right) = P_0 \cos^2\left(\pi\frac{V_U(t) - V_L(t)}{2V_\pi}\right)$$

$$\phi_{out}(t) = \frac{\phi_U(t) + \phi_L(t)}{2} = \pi\frac{V_U(t) + V_L(t)}{2V_\pi}$$

Driving Voltage $V_U(t) - V_L(t)$

$$\phi_U(t) = \pi\frac{V_U(t)}{V_\pi}$$

$$\phi_L(t) = \pi\frac{V_L(t)}{V_\pi}$$

Proof

$$\begin{pmatrix} E_{out,1} \\ E_{out,2} \end{pmatrix} = \underbrace{\frac{1}{\sqrt{2}}\begin{pmatrix} 1 & j \\ j & 1 \end{pmatrix}}_{coupler} \underbrace{\begin{pmatrix} e^{j\phi_U} & 0 \\ 0 & e^{j\phi_L} \end{pmatrix}}_{delay} \underbrace{\frac{1}{\sqrt{2}}\begin{pmatrix} 1 & j \\ j & 1 \end{pmatrix}}_{coupler} \begin{pmatrix} E_{in,1} \\ E_{in,2} \end{pmatrix} = \frac{1}{2}\begin{pmatrix} e^{j\phi_U} - e^{j\phi_L} & j\left(e^{j\phi_U} + e^{j\phi_L}\right) \\ j\left(e^{j\phi_U} + e^{j\phi_L}\right) & e^{j\phi_L} - e^{j\phi_U} \end{pmatrix} \begin{pmatrix} E_{in,1} \\ E_{in,2} \end{pmatrix} \xrightarrow[E_{in,2}=0]{E_{in,1}=E_0\, e^{j\omega t}} \frac{E_0}{2}\begin{pmatrix} e^{j\phi_U} - e^{j\phi_L} \\ j\left(e^{j\phi_U} + e^{j\phi_L}\right) \end{pmatrix} e^{j\omega t}$$

$$E_{out,1}(t) = \frac{E_0}{2} e^{j\frac{\phi_U+\phi_L}{2}} \underbrace{\left(e^{j\frac{\phi_U-\phi_L}{2}} - e^{-j\frac{\phi_U-\phi_L}{2}}\right)}_{j2\sin\left(\frac{\phi_U-\phi_L}{2}\right)} e^{j\omega t} = E_0 \sin\left(\frac{\phi_U-\phi_L}{2}\right) e^{j\frac{\phi_U+\phi_L+\pi}{2}} e^{j\omega t}$$

$$P_{out,1}(t) = P_0 \sin^2\left(\frac{\phi_U(t)-\phi_L(t)}{2}\right) = P_0 \sin^2\left(\pi\frac{V_U(t)-V_L(t)}{2V_\pi}\right)$$

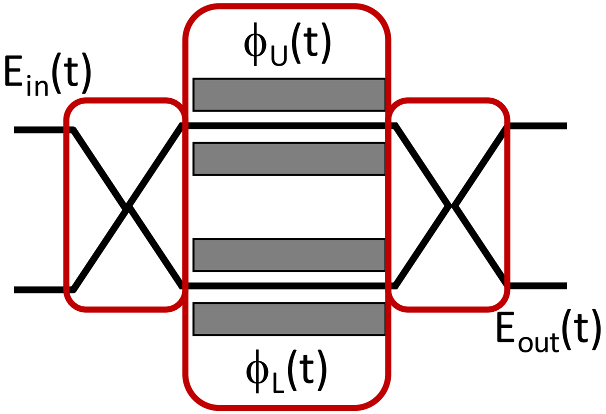
$$\phi_{out,1}(t) = \frac{\phi_U(t)+\phi_L(t)}{2} + \frac{\pi}{2} = \frac{\pi}{2}\left(\frac{V_U(t)+V_L(t)}{V_\pi} + 1\right)$$

$$E_{out,2}(t) = \frac{E_0}{2} e^{j\frac{\phi_U+\phi_L}{2}} \underbrace{\left(e^{j\frac{\phi_U-\phi_L}{2}} + e^{-j\frac{\phi_U-\phi_L}{2}}\right)}_{2\cos\left(\frac{\phi_U-\phi_L}{2}\right)} e^{j\frac{\pi}{2}} e^{j\omega t} = E_0 \cos\left(\frac{\phi_U-\phi_L}{2}\right) e^{j\frac{\phi_U+\phi_L+\pi}{2}} e^{j\omega t}$$

$$P_{out,2}(t) = P_0 \cos^2\left(\frac{\phi_U(t)-\phi_L(t)}{2}\right) = P_0 \cos^2\left(\pi\frac{V_U(t)-V_L(t)}{2V_\pi}\right)$$

$$\phi_{out,2}(t) = \phi_{out,1}(t)$$

Complementary outputs



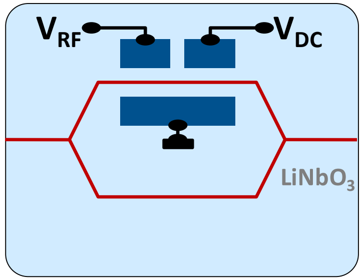
Push-Pull Operation (Chirp-free)

$$\phi_{out}(t) = \frac{\phi_U(t) + \phi_L(t)}{2} = \pi \frac{V_U(t) + V_L(t)}{2V_\pi} \xrightarrow{V_U(t) = -V_L(t)} 0$$

Frequency Chirp (transient chirp)

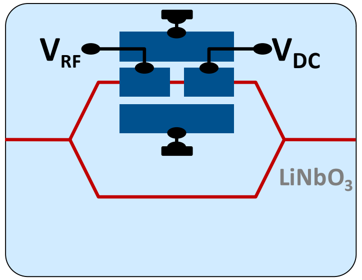
Chirp parameter $$\alpha \equiv -2P(t)\frac{\frac{\partial \phi(t)}{\partial t}}{\frac{\partial P(t)}{\partial t}}$$

unbalanced drive

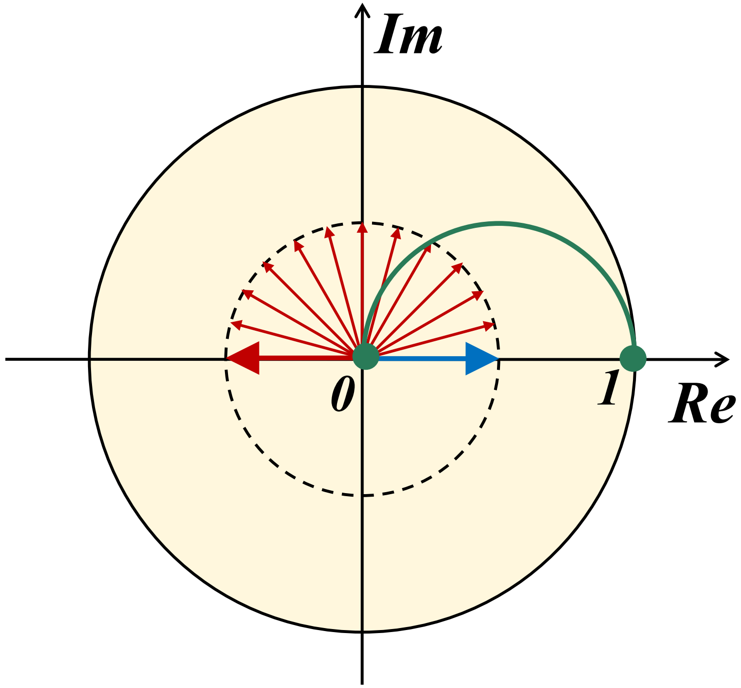


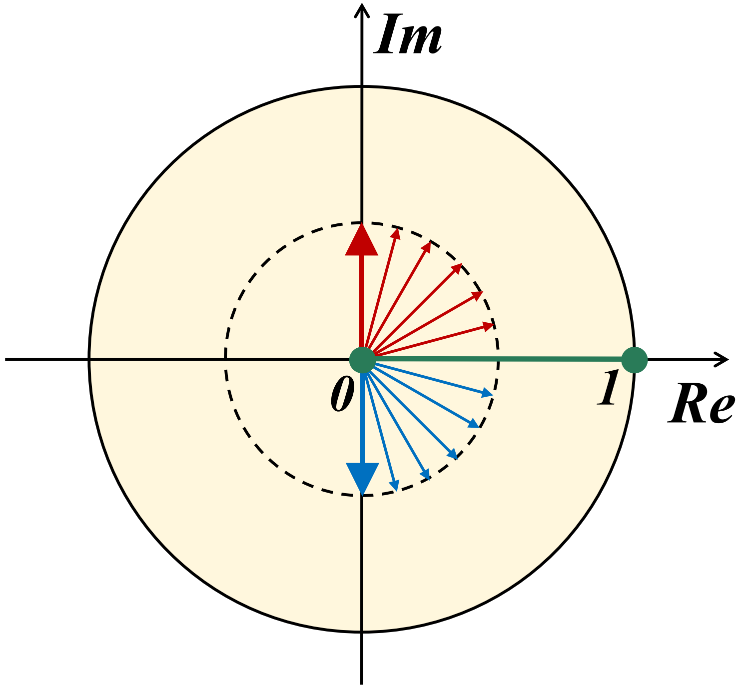
x,y-cut

unbalanced drive

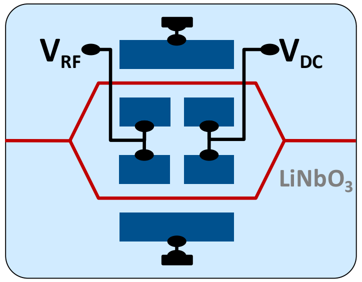


z-cut



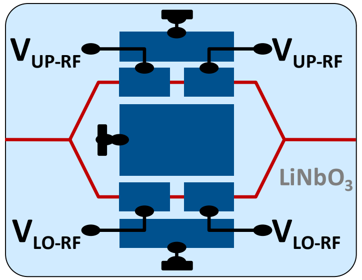


balanced drive



x,y-cut

differential drive



z-cut

Extinction Ratio

ε_i : coupler-i offset parameter

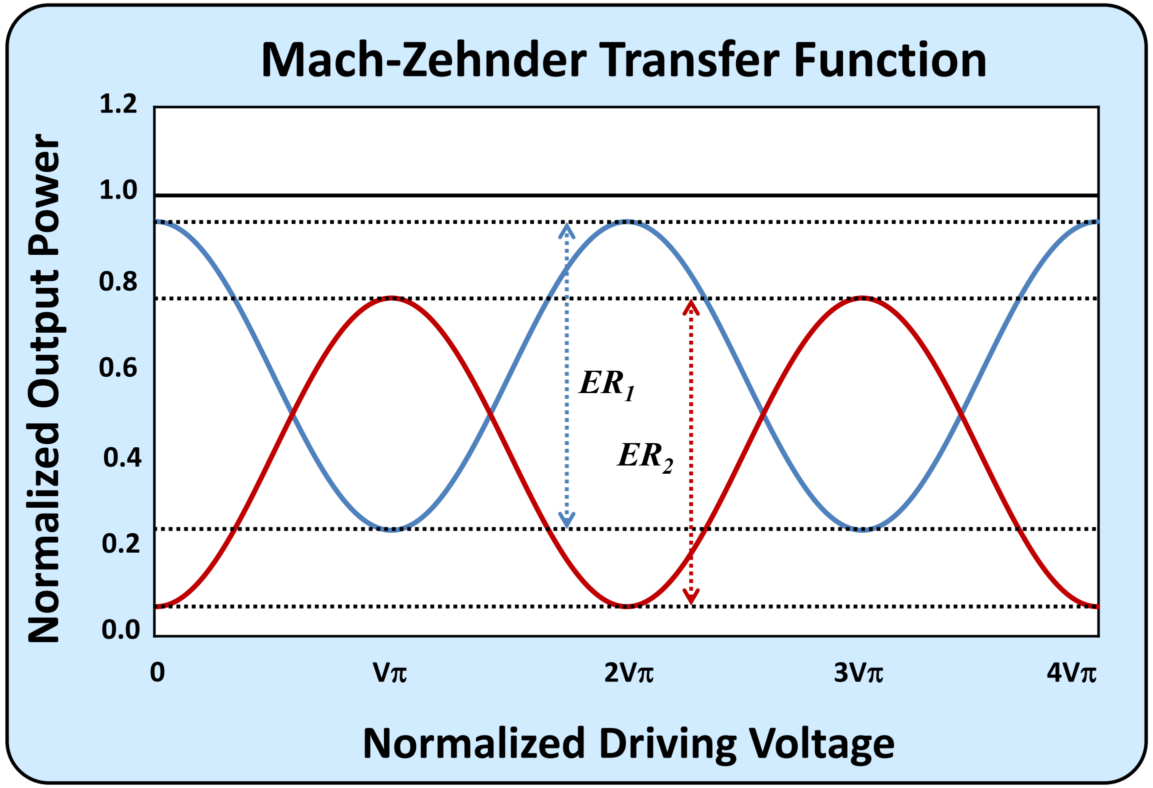
$$\begin{pmatrix} E_{out,1} \\ E_{out,2} \end{pmatrix} = \underbrace{\frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{1+\varepsilon_2} & j\sqrt{1-\varepsilon_2} \\ j\sqrt{1-\varepsilon_2} & \sqrt{1+\varepsilon_2} \end{pmatrix}}_{coupler\_2} \underbrace{\begin{pmatrix} e^{j\phi_U} & 0 \\ 0 & e^{j\phi_L} \end{pmatrix}}_{delay} \underbrace{\frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{1+\varepsilon_1} & j\sqrt{1-\varepsilon_1} \\ j\sqrt{1-\varepsilon_1} & \sqrt{1+\varepsilon_1} \end{pmatrix}}_{coupler\_1} \begin{pmatrix} E_0\, e^{j\omega t} \\ 0 \end{pmatrix}$$

$$\frac{\left|E_{out,2}(t)\right|^2}{E_0^2} = \frac{1}{2}(1-\varepsilon_1\varepsilon_2) + \frac{1}{2}\sqrt{(1-\varepsilon_1^2)(1-\varepsilon_2^2)}\cos(\phi_U - \phi_L)$$

$$ER_2 = \frac{1-\varepsilon_1\varepsilon_2 + \sqrt{(1-\varepsilon_1^2)(1-\varepsilon_2^2)}}{1-\varepsilon_1\varepsilon_2 - \sqrt{(1-\varepsilon_1^2)(1-\varepsilon_2^2)}}$$

$$\frac{\left|E_{out,1}(t)\right|^2}{E_0^2} = \frac{1}{2}(1+\varepsilon_1\varepsilon_2) - \frac{1}{2}\sqrt{(1-\varepsilon_1^2)(1-\varepsilon_2^2)}\cos(\phi_U - \phi_L)$$

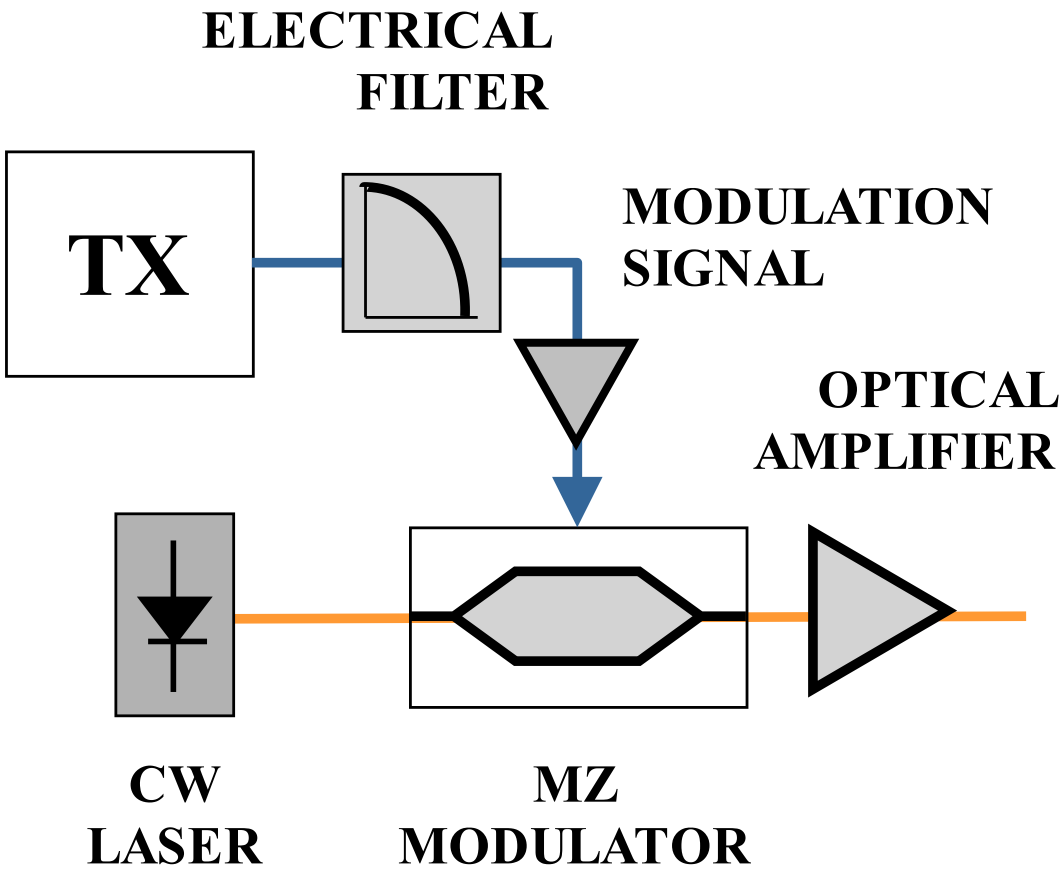
$$ER_1 = \frac{1+\varepsilon_1\varepsilon_2 + \sqrt{(1-\varepsilon_1^2)(1-\varepsilon_2^2)}}{1+\varepsilon_1\varepsilon_2 - \sqrt{(1-\varepsilon_1^2)(1-\varepsilon_2^2)}}$$



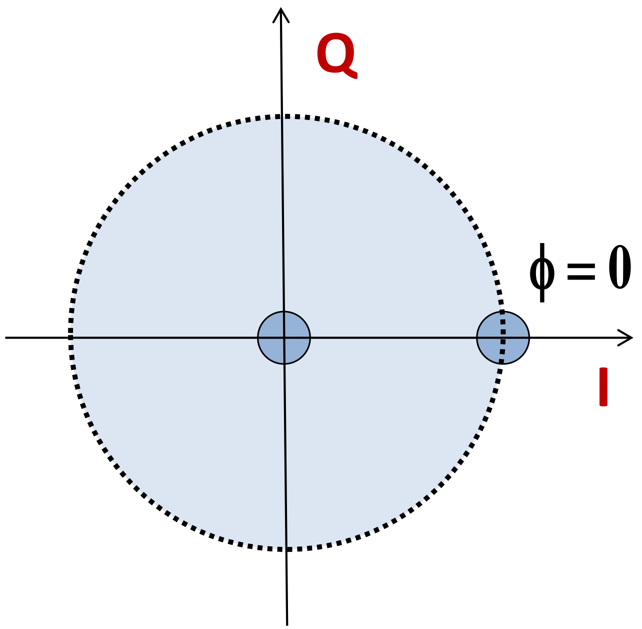
INTENSITY MODULATION (IM)

Intensity Modulation Transmitter

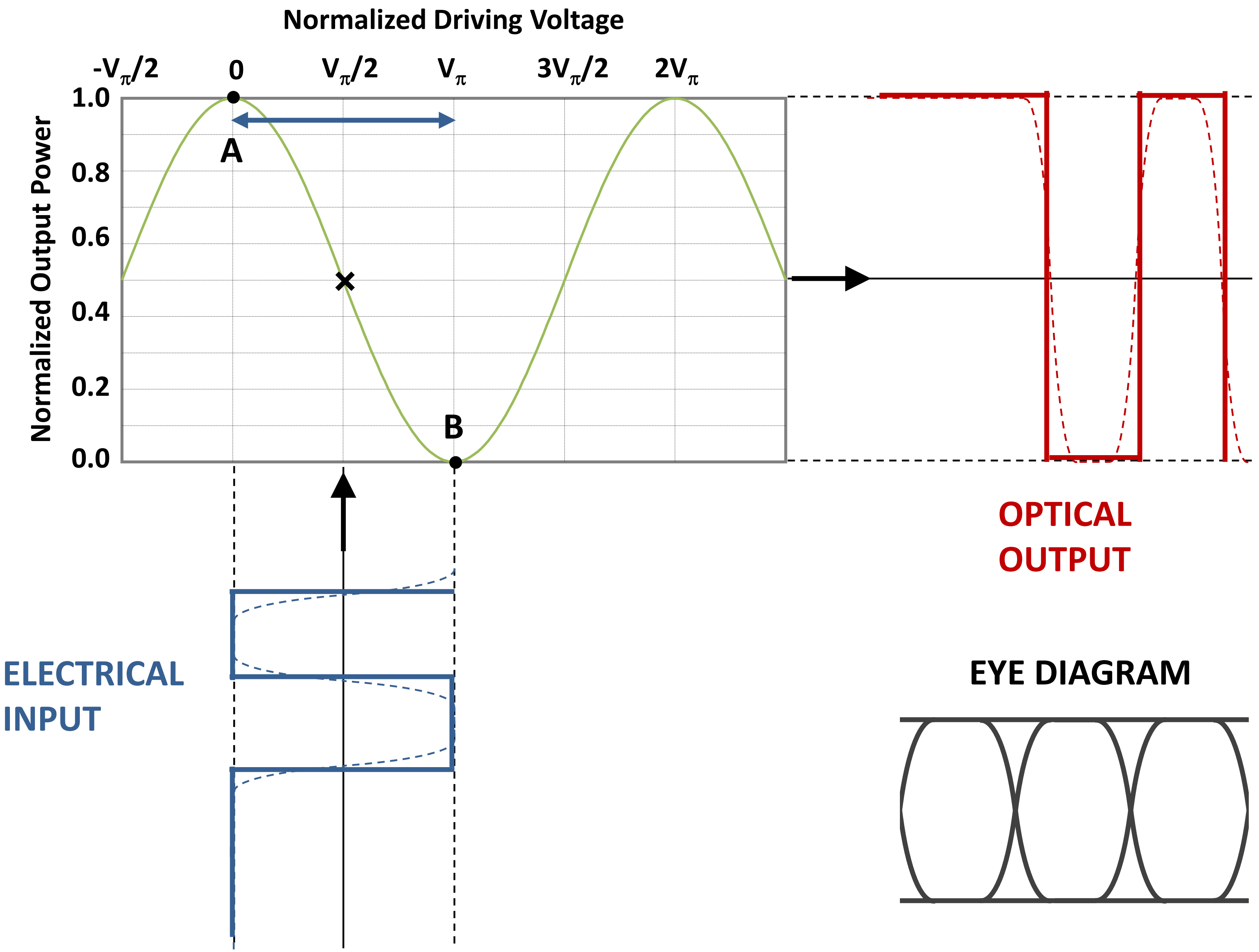
Also known as On-Off Keying (OOK)



phasorial diagram

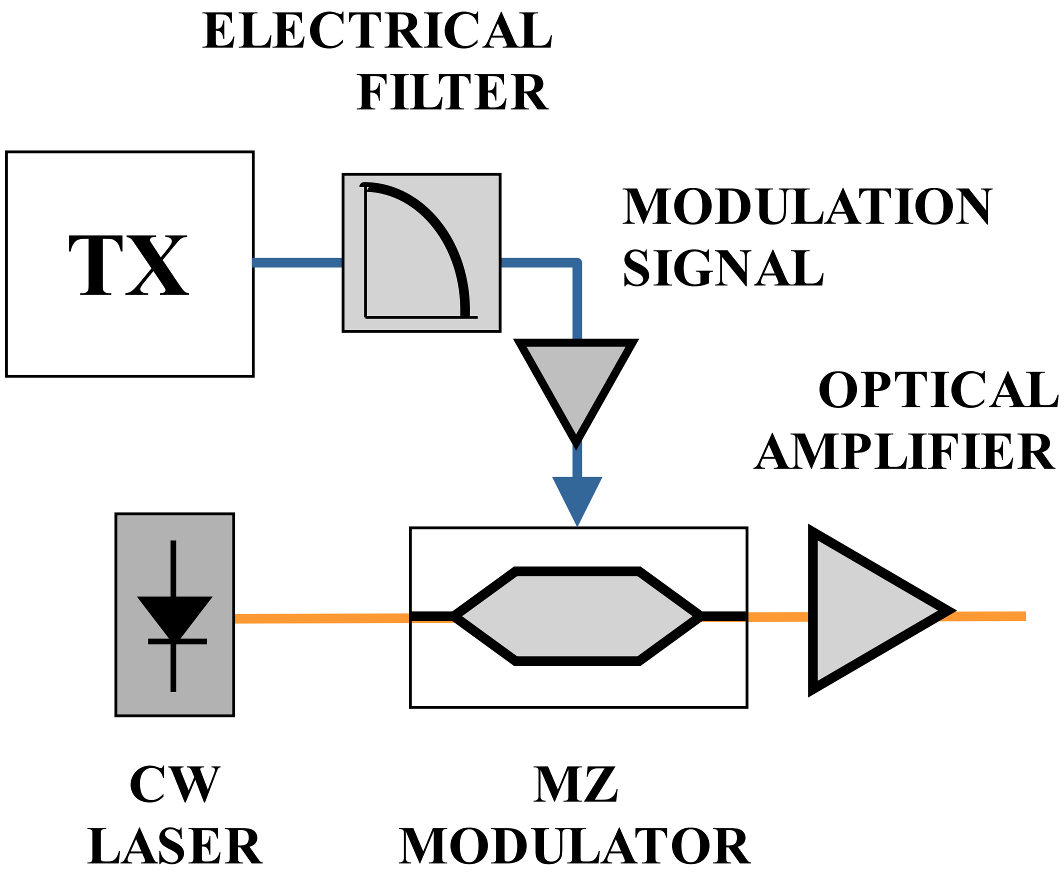


Non Return to Zero (NRZ)

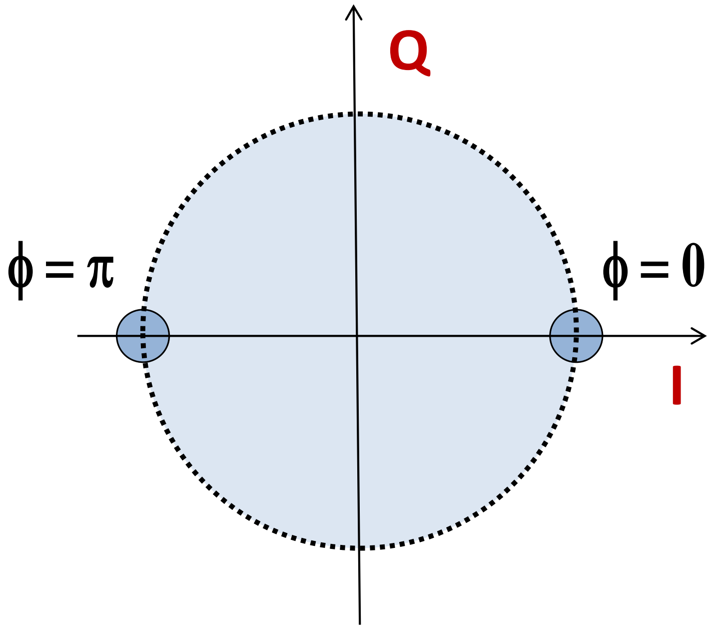


PHASE MODULATION (PM)

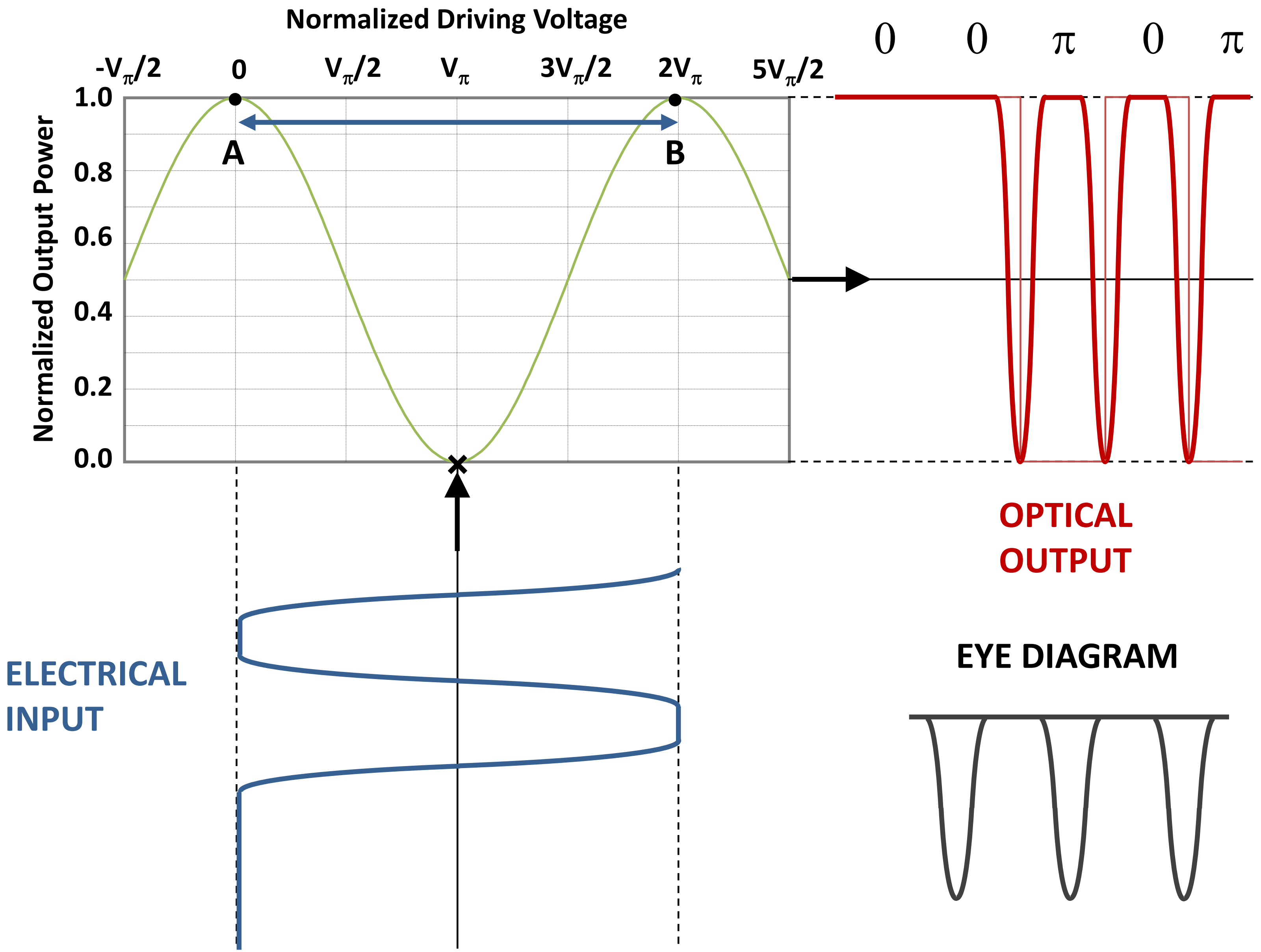
Binary Phase-Shift Keying (BPSK) Transmitter



phasorial diagram

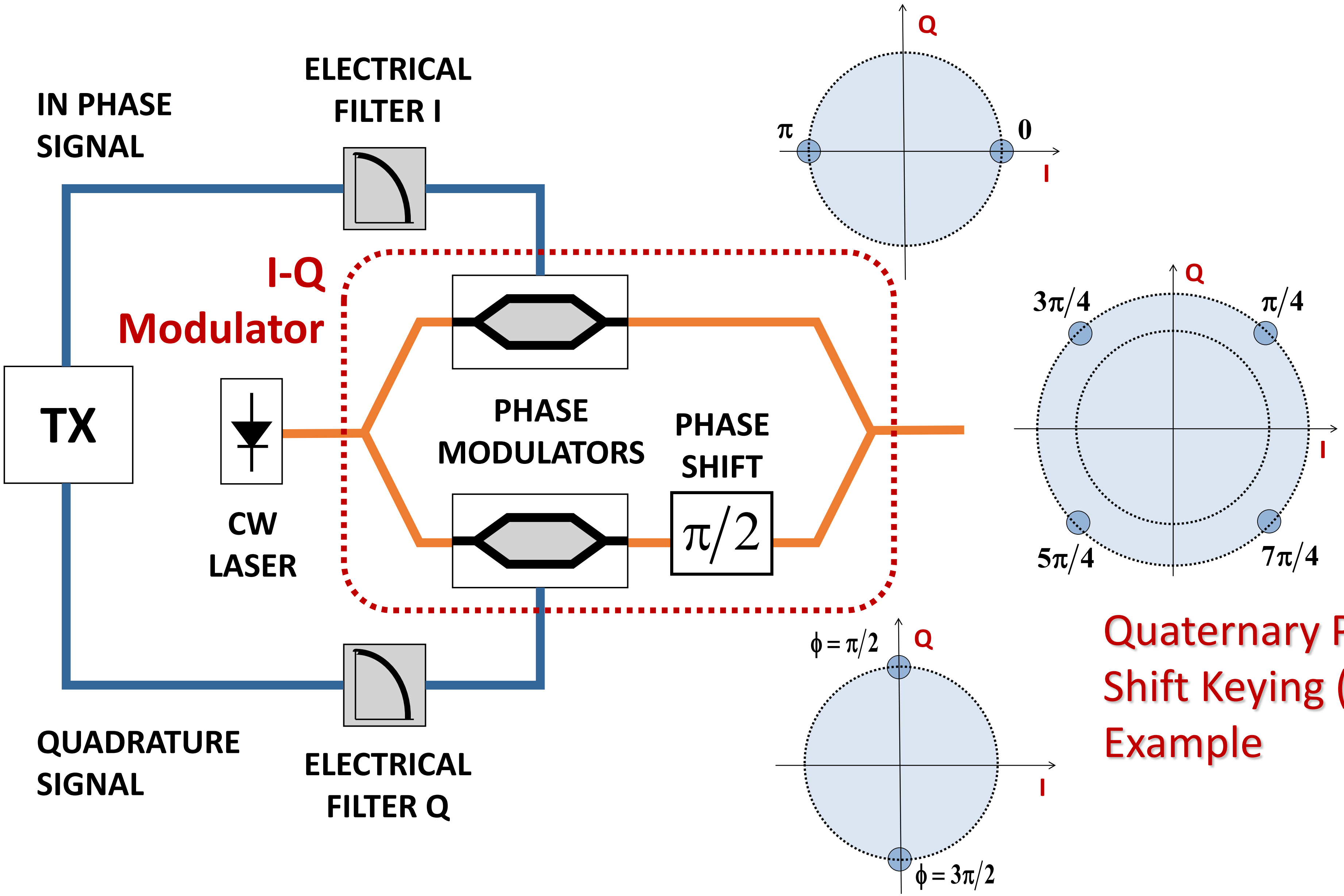


Non Return to Zero (NRZ)



IQ MODULATOR

IN-PHASE/QUADRAT. MODULATOR (IQM)



Quaternary Phase-Shift Keying (QPSK) Example

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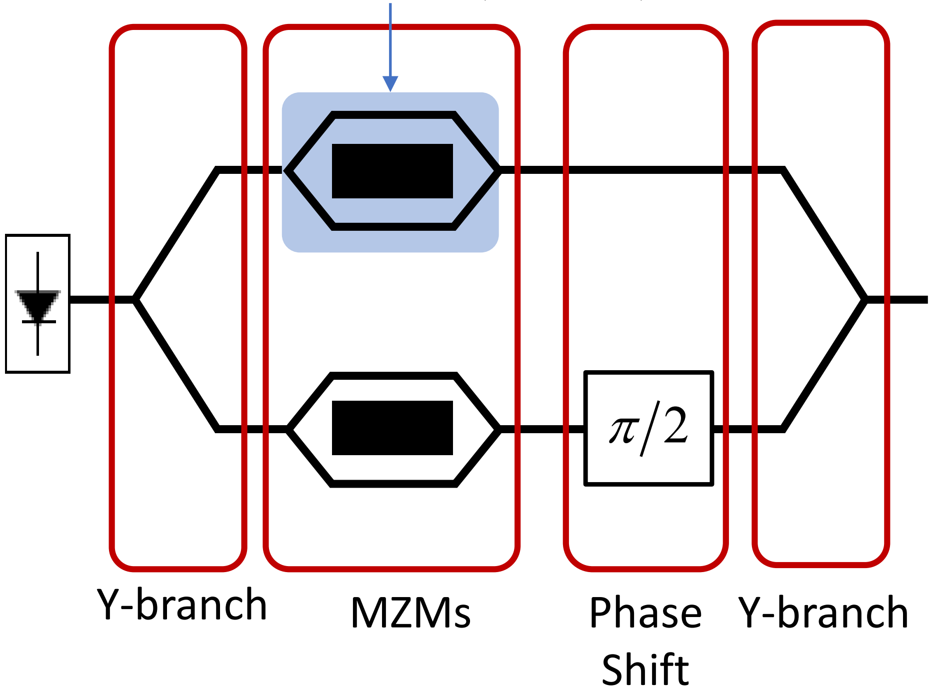
$$E_{out}^{MZM} = \cos\left(\pi \frac{V(t)}{2V_\pi}\right) E_{in}^{MZM}$$

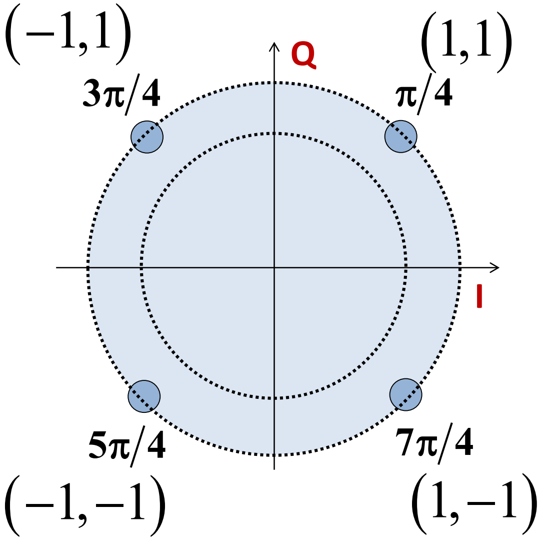


$$s(t) = s_I(t) + j s_Q(t) = |A(t)| e^{j\phi(t)}$$

$$\begin{cases} |A(t)| = \sqrt{s_I^2(t) + s_Q^2(t)} \\ \phi(t) = \arctan\{s_I(t)/s_Q(t)\} \end{cases}$$

$$E_{out}^{IQM} = \frac{1}{2}\left\{ \overbrace{\cos\underbrace{\left(\pi \frac{V_I(t)}{2V_\pi}\right)}_{\phi_I(t)}}^{s_I(t)} + j \overbrace{\cos\underbrace{\left(\pi \frac{V_Q(t)}{2V_\pi}\right)}_{\phi_Q(t)}}^{s_Q(t)} \right\} E_{in}$$

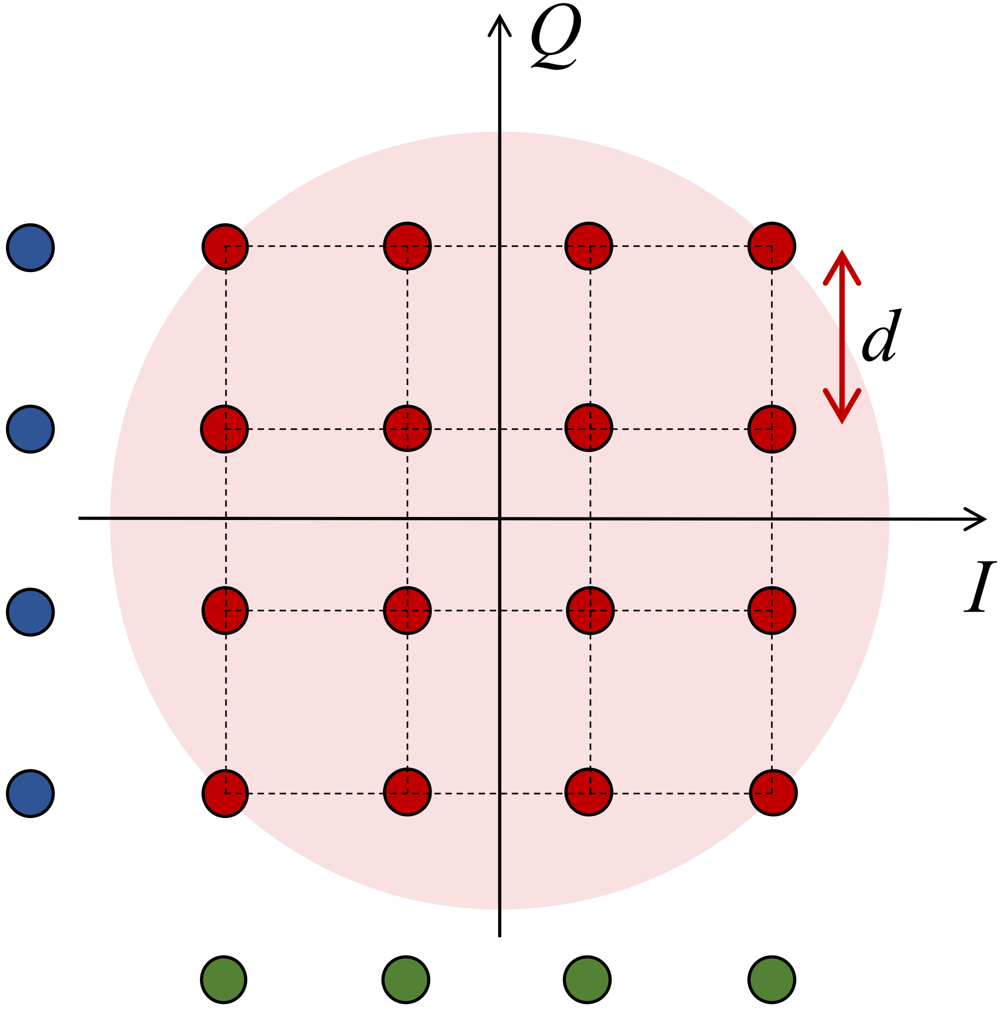
QPSK
$$\begin{cases} s_{I,Q}(kT_S) = \{1, -1\} \\ \phi_{I,Q}(kT_S) = \{0, \pi\} \\ V_{I,Q}(kT_S) = \{0, 2V_\pi\} \end{cases}$$



$$E_{out}^{IQM} = \underbrace{\frac{1}{\sqrt{2}}\begin{pmatrix}1 & 1\end{pmatrix}}_{Y-branch\_OUT} \underbrace{\begin{pmatrix}1 & 0 \\ 0 & j\end{pmatrix}}_{phase\_shift} \underbrace{\begin{pmatrix} \cos\left(\pi \frac{V_I(t)}{2V_\pi}\right) & 0 \\ 0 & \cos\left(\pi \frac{V_Q(t)}{2V_\pi}\right) \end{pmatrix}}_{MZMs} \underbrace{\frac{1}{\sqrt{2}}\begin{pmatrix}1 \\ 1\end{pmatrix}}_{Y-branch\_IN} E_{in}$$

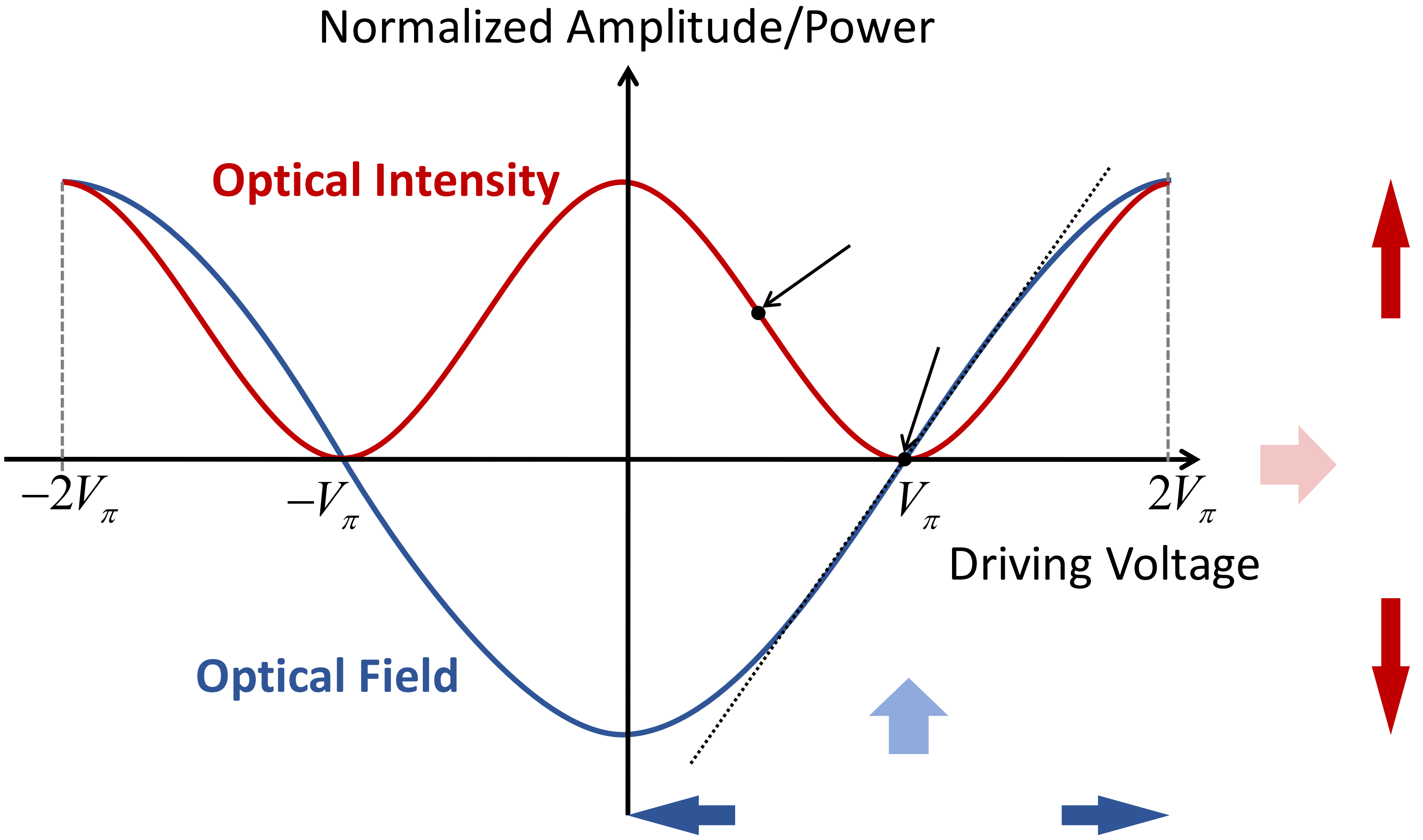
QAM Modulation

Quadrature Amplitude Modulation (QAM)



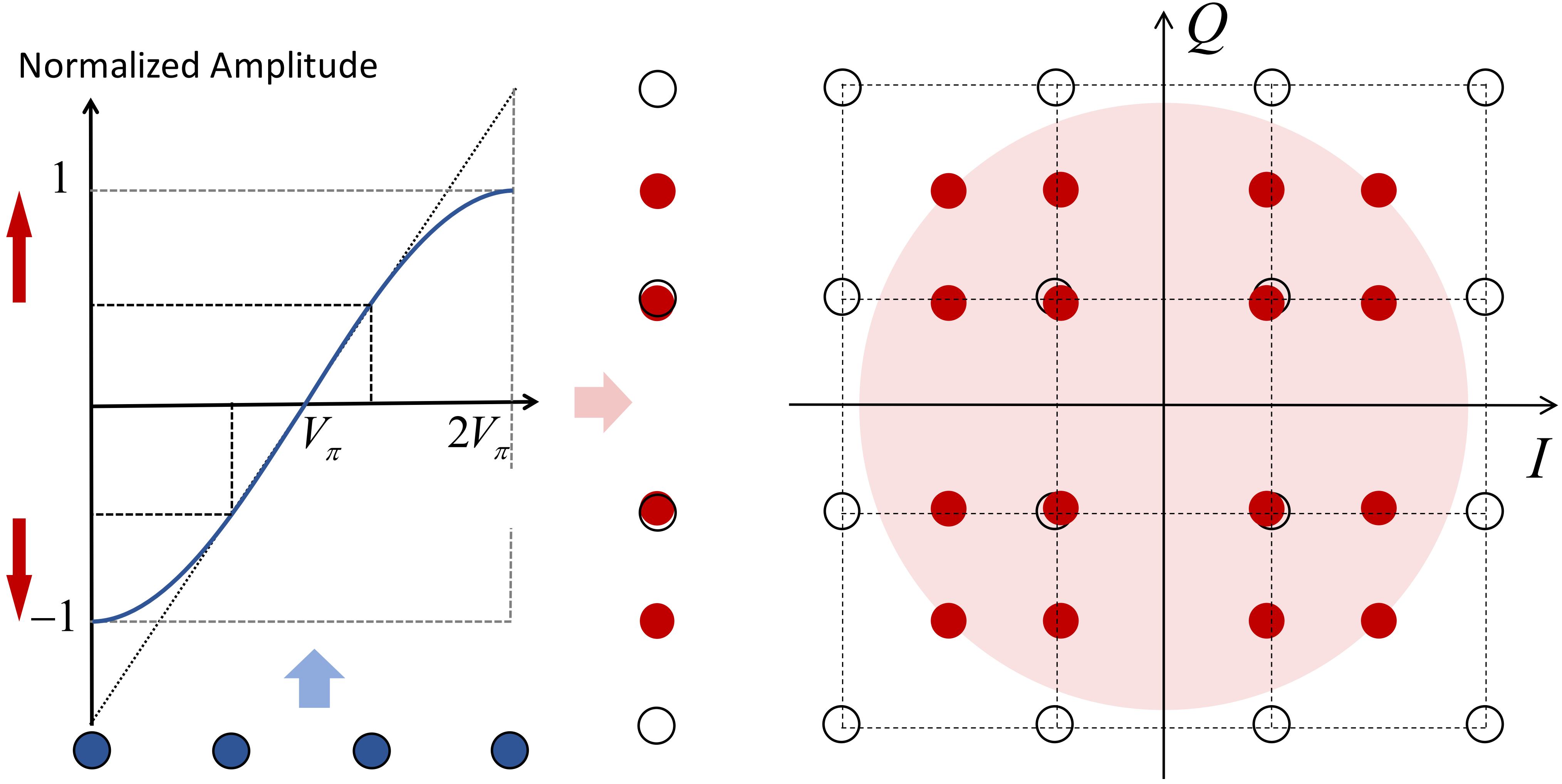
QAM Modulation

MZM (Nonlinear) Transfer Function



Full Swing → Huge Distortion

QAM Modulation



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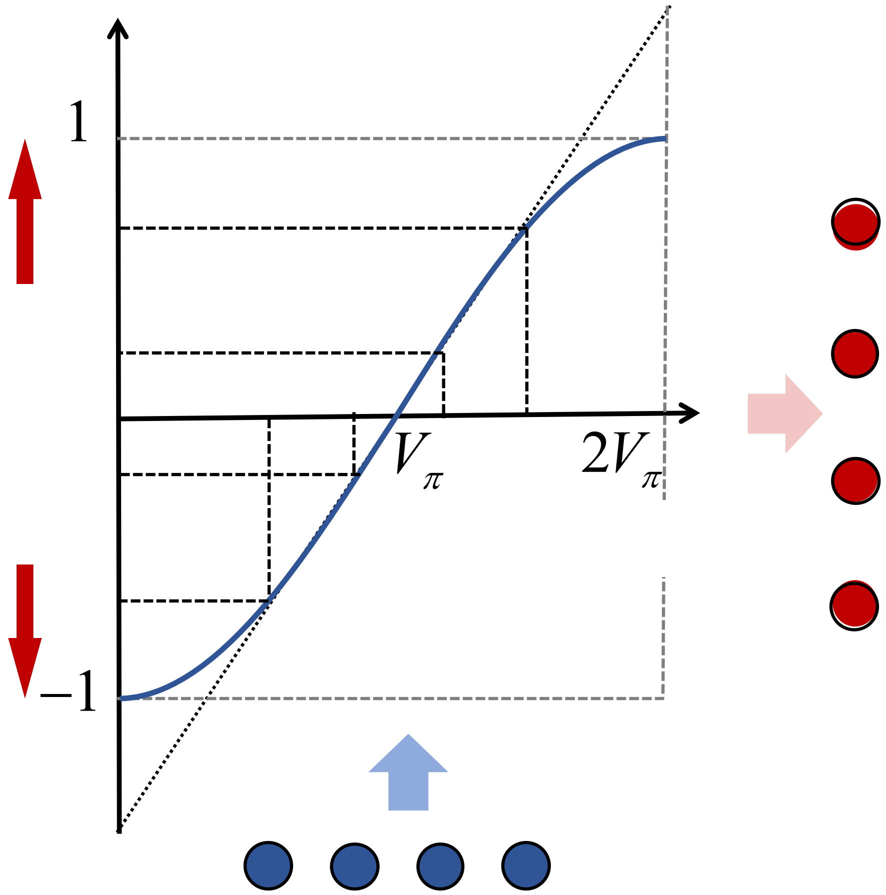
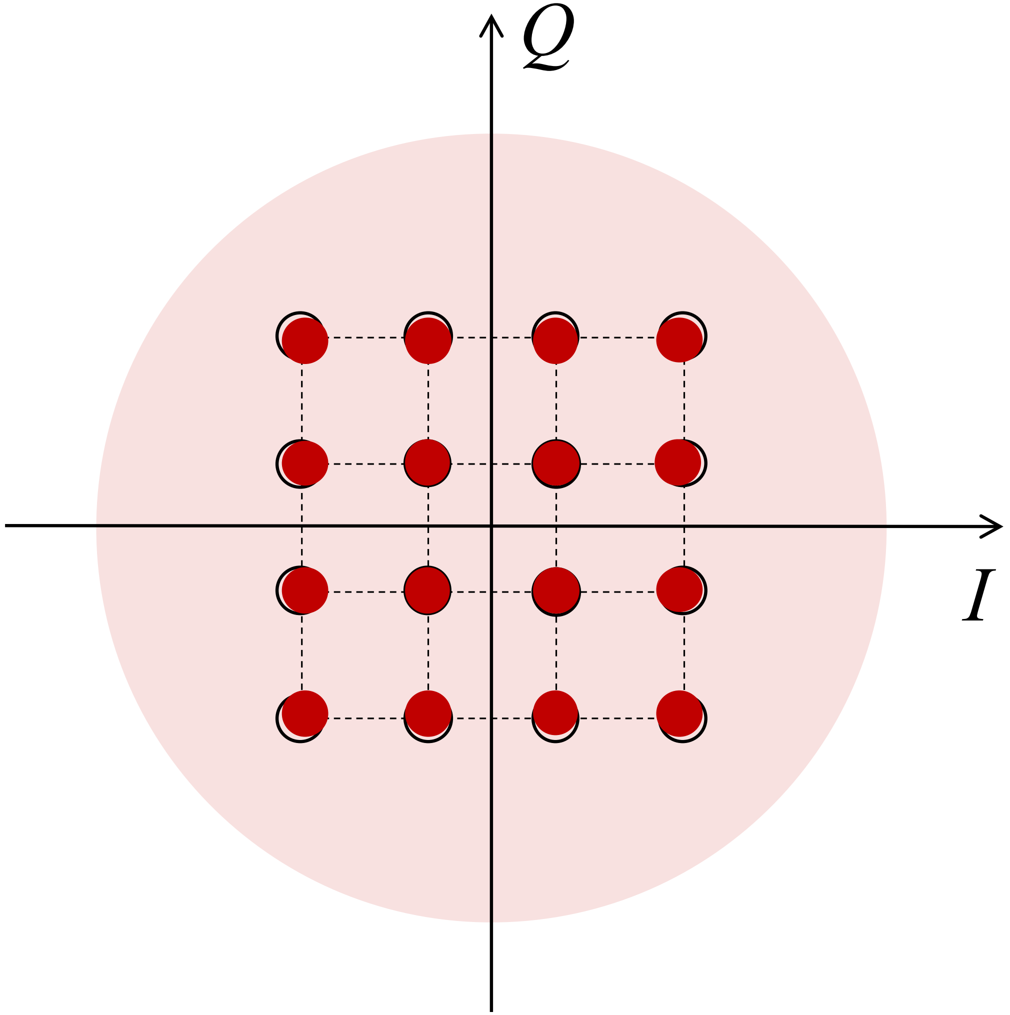
QAM Modulation

Reduced Swing → Small Distortion





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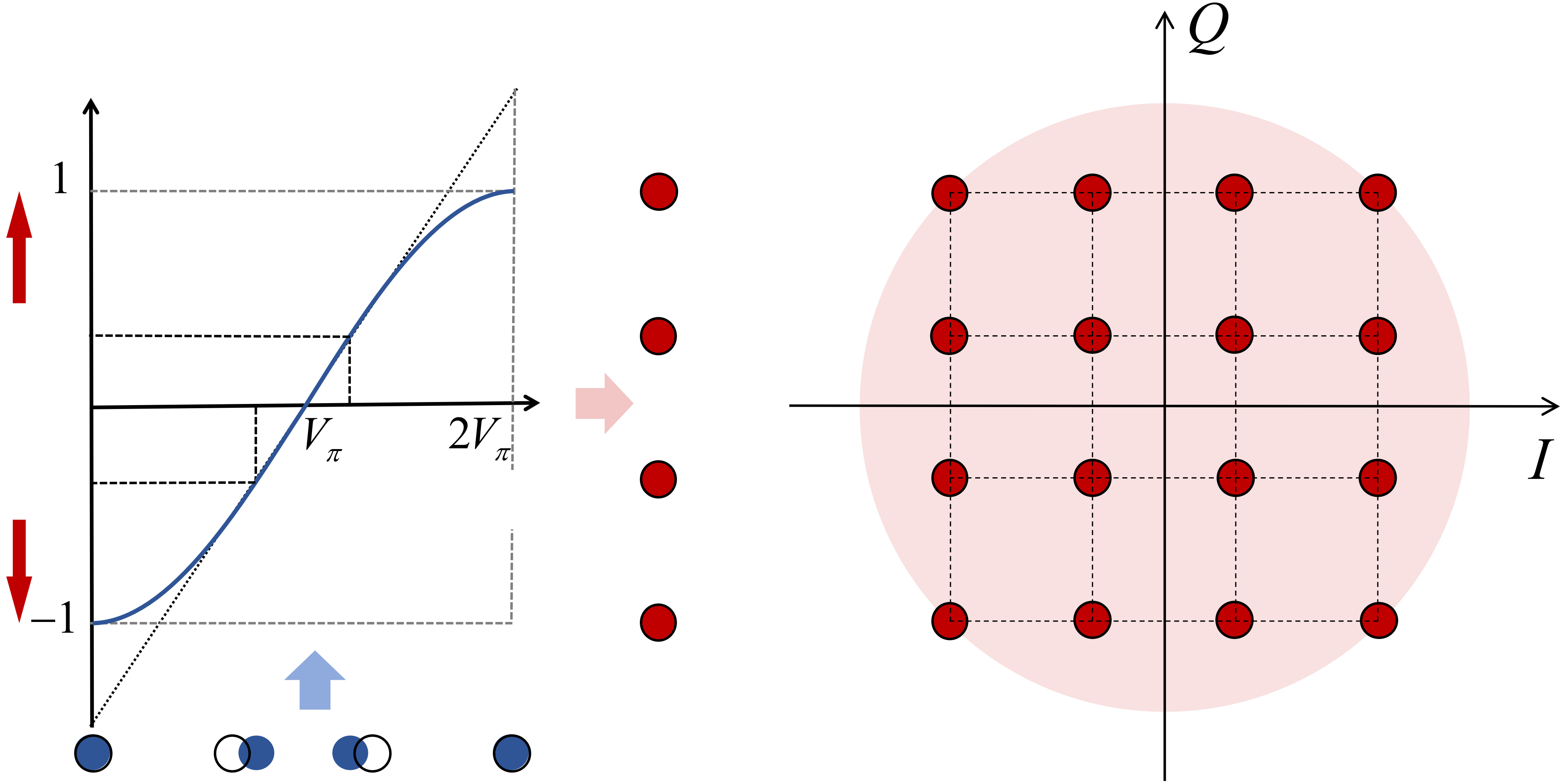
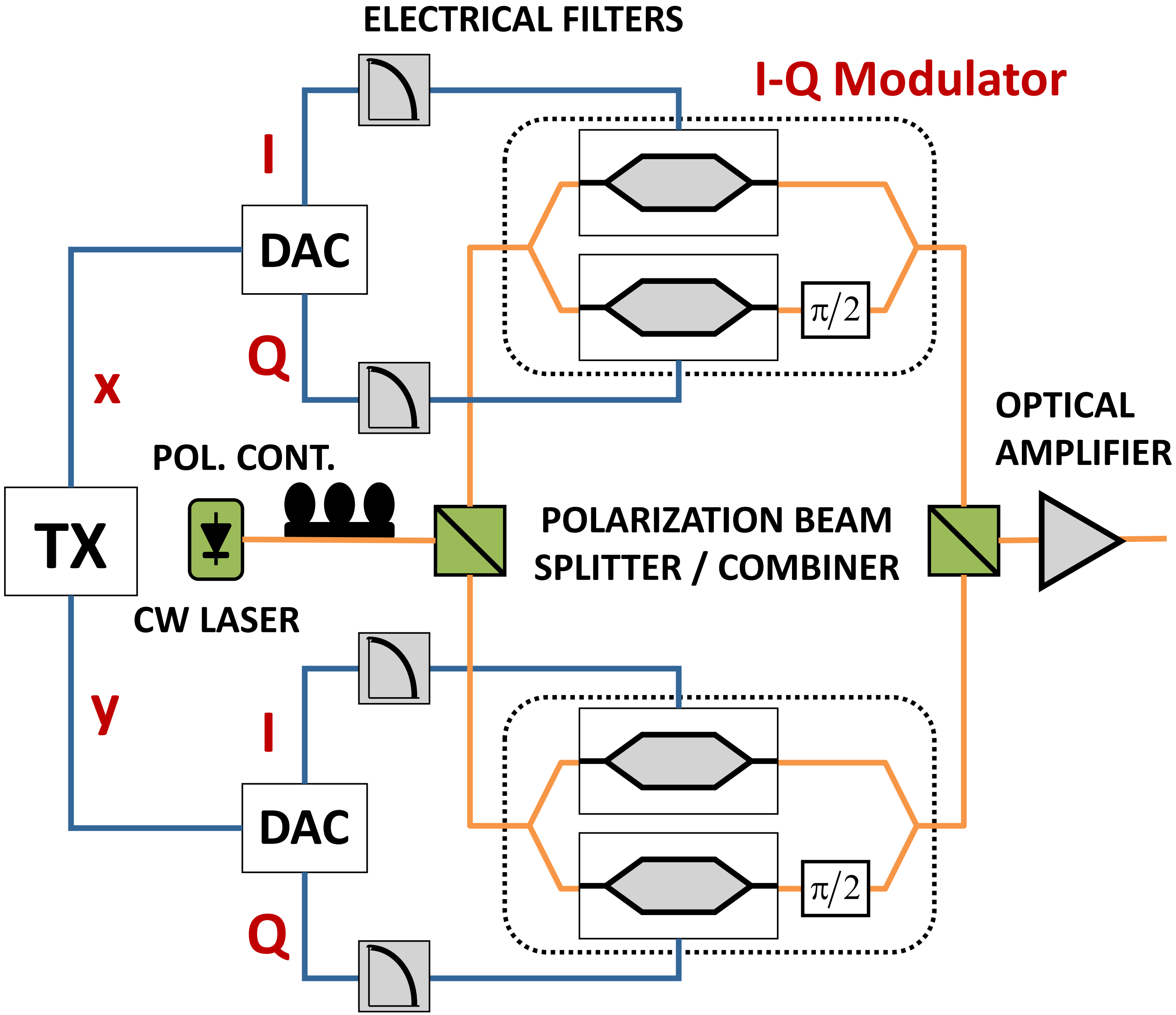
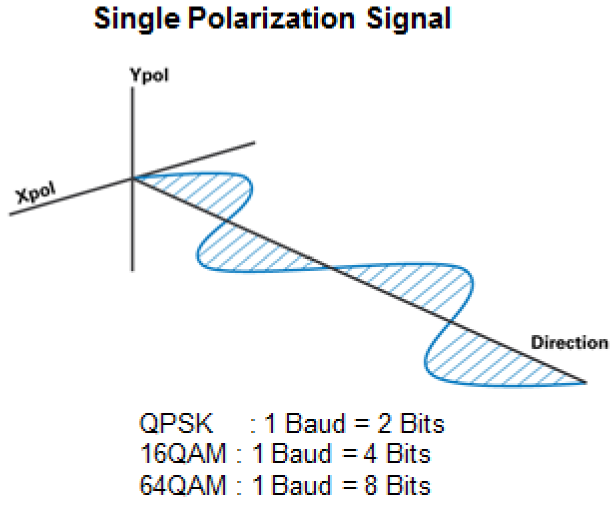
QAM Modulation

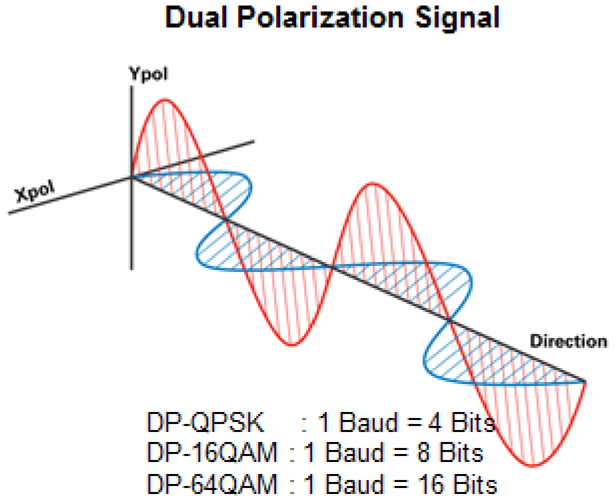
Predistortion → Full Swing

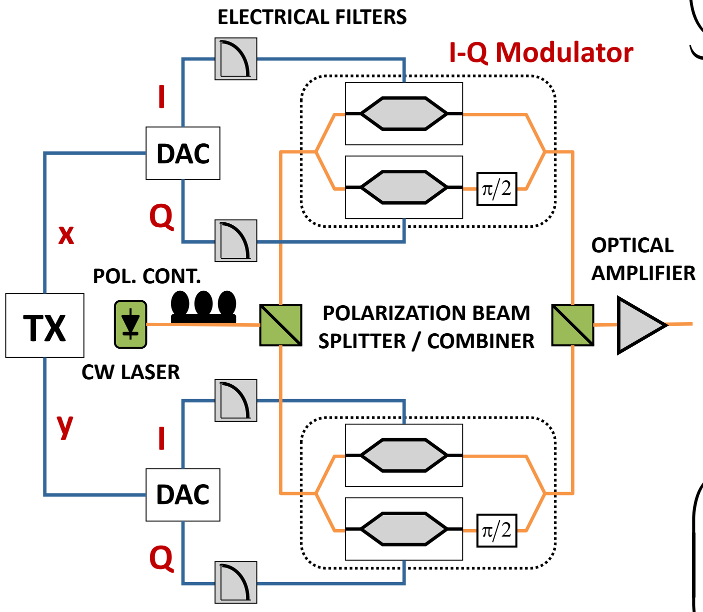


Polarization Multiplexing (PM)









$$\underbrace{\begin{pmatrix}E_{out-x}(t)\\E_{out-y}(t)\end{pmatrix}}_{E_{out}(t)} = \frac{1}{2}\begin{pmatrix} s_{I-x}(t)+js_{Q-x}(t) & 0 \\ 0 & s_{I-y}(t)+js_{Q-y}(t)\end{pmatrix}\underbrace{\begin{pmatrix}E_{in-x}(t)\\E_{in-y}(t)\end{pmatrix}}_{E_{in}(t)}$$

Linear 45º Polarization

$$E_{in}(t)=\frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix}A_L e^{j\omega_c t}$$

$$\underbrace{\begin{pmatrix}E_{out-x}(t)\\E_{out-y}(t)\end{pmatrix}}_{E_{out}(t)} = \frac{A_L}{2\sqrt{2}}\begin{pmatrix} s_{I-x}(t)+js_{Q-x}(t) \\ s_{I-y}(t)+js_{Q-y}(t)\end{pmatrix}e^{j\omega_c t} = \frac{A_L}{2\sqrt{2}}\begin{pmatrix}\overbrace{\left|A_x(t)\right|e^{j\phi_x(t)}}^{A_x(t)}\\ \underbrace{\left|A_y(t)\right|e^{j\phi_y(t)}}_{A_y(t)}\end{pmatrix}e^{j\omega_c t}$$

Arbitrary Rotation ➡

$$\begin{pmatrix}\sqrt{\alpha}\cdot e^{j\theta} & \sqrt{1-\alpha}\\ \sqrt{1-\alpha} & -\sqrt{\alpha}\cdot e^{-j\theta}\end{pmatrix}\begin{pmatrix}A_x(t)\\A_y(t)\end{pmatrix}=\begin{pmatrix}A_x(t)\sqrt{\alpha}e^{j\theta}+A_y(t)\sqrt{1-\alpha}\\ A_x(t)\sqrt{1-\alpha}-A_y(t)\sqrt{\alpha}e^{-j\theta}\end{pmatrix}$$

Mixed Information