Fiber Optics Communications

Week 8 Optical Modulators

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Topics of Previous Lecture (Week-7)

Optical Modulation Schemes

- Line coding and pulse shaping
- Types of digital optical modulation schemes
- Amplitude shift keying (ASK)
- Phase shift Keying (PSK)
- Deferential Phase shift keying (DPSK)
- Quadrature Phase shift keying (QPSK)
- Frequency shift keying (FSK)
- Polarization Shift Keying (PolSK)

Week-8: Lecture Learning Outcomes

1. Explain the basic concept and purpose of optical modulators in communication systems
2. Distinguish between direct modulation and external modulation techniques
3. Identify the advantages and limitations of direct versus external modulators
4. Define key performance parameters of external modulators such as extinction ratio, insertion loss, and bandwidth.
5. Explain the working principle of electro-optic modulators
6. Describe the structure and operation of the Mach-Zehnder interferometer as an amplitude modulator.
7. Explain the principle of electro-absorption modulation and its operating mechanism.

Week-8: Optical Modulation Schemes

Outline

- Introduction to Optical Modulators
- Direct and External Optical Modulation Techniques
- External Modulators Important Parameters
- Electro-Optic Modulators
- Mach-Zehnder Amplitude Modulator
- Electro-Absorption Optical Modulators

Introduction to Optical Modulators

- Optical modulation is categorized into direct modulation and external modulation**.**
- **Direct modulation** modifies the light source's driving current.
- **External modulation** uses a separate device to modulate a continuous-wave (CW) light source.

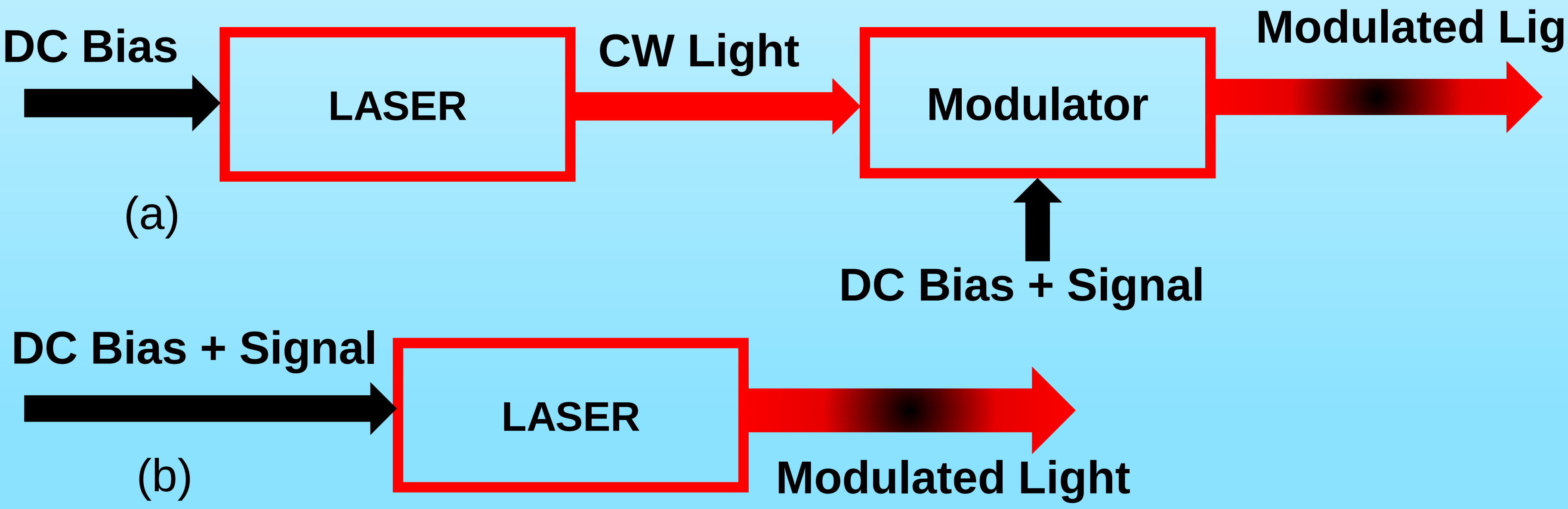


Figure 1: (a) External Modulation (b) Direct Modulation

Direct Modulation vs. External Modulation

- **Direct Intensity Modulation:**
  - ✓ Through modulation of the laser current
  - ✓ More compact (no additional external device required) and low cost
  - ✓ Small extinction ratio
  - ✓ High chirp (Introduce spurious frequency modulation of light)
  - ✓ Slow response or Low Bandwidth
- **External Intensity Modulation:**
  - ✓ Requires an external device (voltage driven), less compact, high cost
  - ✓ High extinction ratio
  - ✓ Negligible chirp
  - ✓ Faster response or Higher Bandwidth
  - ✓ Various external modulations solutions available

Common Types of External Modulators

- **Electro-Optic Modulators (EOM):**
  - ✓ Modulation based on refractive variation or change under an applied electric field
  - ✓ Amplitude modulation achieved through interference of two phase-modulated beams in a **Mach–Zehnder modulator**
  - ✓ Can be realized in multiple electro-optic materials such as piezoelectric ($LiNbO_3$ (Lithium Niobate)), semiconductor compounds (GaAs, InP, SiGe), and electro-optic polymers

- **Electro-Absorption Modulators (EAM):**
  - ✓ Amplitude modulation achieved directly by varying material absorption
  - ✓ Requires bulk or quantum well (QW) semiconductor materials

External Modulators Important Parameters

- **Extinction ratio:** Ratio of the ON state and the OFF state output light
- **On-off voltage (V_π):** The required applied voltage to turn off the input light at the output of the modulator with a specific extinction ratio**.**
- **Frequency response:** The variation of modulated light amplitude with input signal frequency (f), compared to DC response.
- **Modulation Bandwidth:** The input RF frequency at which the frequency response drops by 3 dB from the DC level
- **Optical bandwidth:** The range of optical signal wavelength on which the modulator is operating

External Modulators Important Parameters

- **Chirp:** instantaneous frequency deviation or spurious frequency (wavelength) modulation of the output light of the modulator with respect to the unmodulated light
- **Optical insertion loss:** The insertion loss of the external modulator in the ON state
- **Electrical (RF) insertion loss:** input reflection coefficient as the function of frequency of the harmonic modulating signal, measured at the modulator’s electrical port

Performance Comparisons of EOM and EAM

- **Electro-Optic Modulators (EOM):**
  - ✓ Better system properties such as low chirp and high extinction ratio
  - ✓ Large in size:
    - ❖ **Piezoelectric-EOM:** Not integrable at all with LASER source
    - ❖ **Semiconductor-EOM:** hardly integrable with LASER source
  - ✓ Possess good frequency response and large optical bandwidth
  - ✓ Large on-off voltage [1] $\rightarrow (V_\pi \geq 5\ \mathrm{V})$
- **Electro-Absorption Modulators (EAM):**
  - ✓ Worse system properties such as high chirp and insertion loss
  - ✓ Small in size and integrable with LASER source
  - ✓ Good frequency response and high speed
  - ✓ Smaller on-off voltage $\rightarrow (V_\pi \leq 2\ \mathrm{V})$

Electro-Optic Modulators (EOM)

Electro-Optic Modulators (EOM)

- An applied electric field changes the material’s refractive index
- The Electric field induced refractive index variation modulates the phase of the optical signal
- Several materials can be utilized to realize EOM:
  - ✓ **Piezoelectric/Ferroelectric crystals** such as lithium niobate and lithium tantalate
  - ✓ **Semiconductors** such as GaAs, InP, and GaN
  - ✓ **Electro-optic polymers** such as Polycarbonate and Polyimides
- Semiconductors materials which are in be bulk or quantum well (QW) structure are suitable for EOM

Electro-Optic Modulators (EOM)

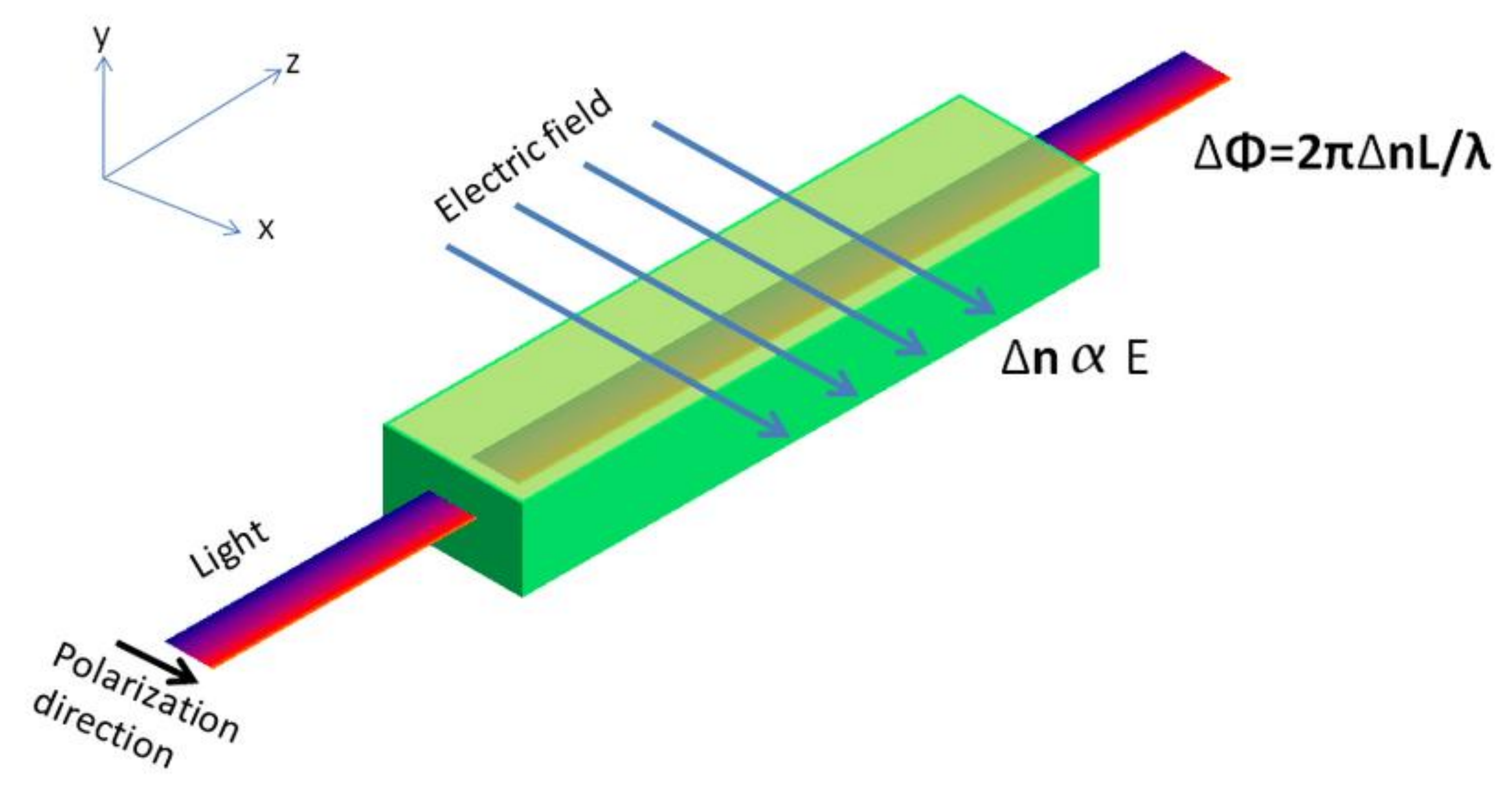


Figure 2: Operation of electro-optic modulator using Pockels effect

Source: I. E. Araci, "Low-loss, high performance hybrid photonics devices enabled by ion-exchanged glass waveguides," ResearchGate, 2010. https://www.researchgate.net/profile/Ismail-Araci-2/publication/253566147/figure/fig33/AS:648598333173770@1531649301593/Ilustration-of-the-electro-optic-effect-in-an-electro-optic-polymer-Refractive-index.png

Electro-Optic Modulators (EOM)

- Electro-optic materials can be categorized in to two based on their properties of the refractive variation as the function of the applied electric field as:

- **Pockels Materials:**
  - ✓ **Pockels Effect:** Refractive index (n) change linearly with the applied electric field (E)

$$\rightarrow \Delta n \propto E$$

- **Kerr Materials:**
  - ✓ **Kerr Effect:** Refractive index (n) change in proportion to the square or quadratic of the applied electric field (E)

$$\rightarrow \Delta n \propto E^2$$

Electro-Optic Modulators (EOM)

- The applied electric field dependent refractive index $(n(E))$ of electro-optic materials can be expanded using Taylor series about the refractive index n at E=0 as:

$$n(E) \approx n + a_1 E + a_2 E^2 + \ldots \qquad (1)$$

- The coefficient a_1 and a_2 in the above equation are related to electro optic coefficients of the material $(r \text{ and } \xi)$ as :

$$a_1 = -\frac{1}{2} r n^3 \qquad (2)$$

$$a_2 = -\frac{1}{2} \xi n^3 \qquad (3)$$

$$\text{Where} \rightarrow a_m \approx 0, \ \text{for } m > 2$$

Electro-Optic Modulators (EOM)

- Substituting Eq (2) and Eq (3) in Eq (1), We have :

$$E(n) \approx n - \frac{1}{2} r n^3 E - \frac{1}{2} \xi n^3 E^2 \qquad (4)$$

Pockels Effect

Kerr Effect

- From Eq (4), We have :

Pockels Electro-Optic Material

$$\xi = 0$$

$$E(n) \approx n - \frac{1}{2} r n^3 E \qquad (5)$$

Kerr Electro-Optic Material

$$r = 0$$

$$E(n) \approx n - \frac{1}{2} \xi n^3 E^2 \qquad (6)$$

Electro-Optic Modulators (EOM)

- Pockels materials are widely used to realize EOM
- Based on the direction of the applied field/voltage EOM can be further divided as:

- **Transverse EOM:**
  - ✓ The electric field or voltage is applied perpendicular to the direction of light propagation
  - ✓ Offers high speed and efficient modulation

- **Longitudinal EOM:**
  - ✓ The electric field or voltage is applied parallel to the direction of light propagation
  - ✓ Not as fast as transverse EOM

Electro-Optic Modulators (EOM)

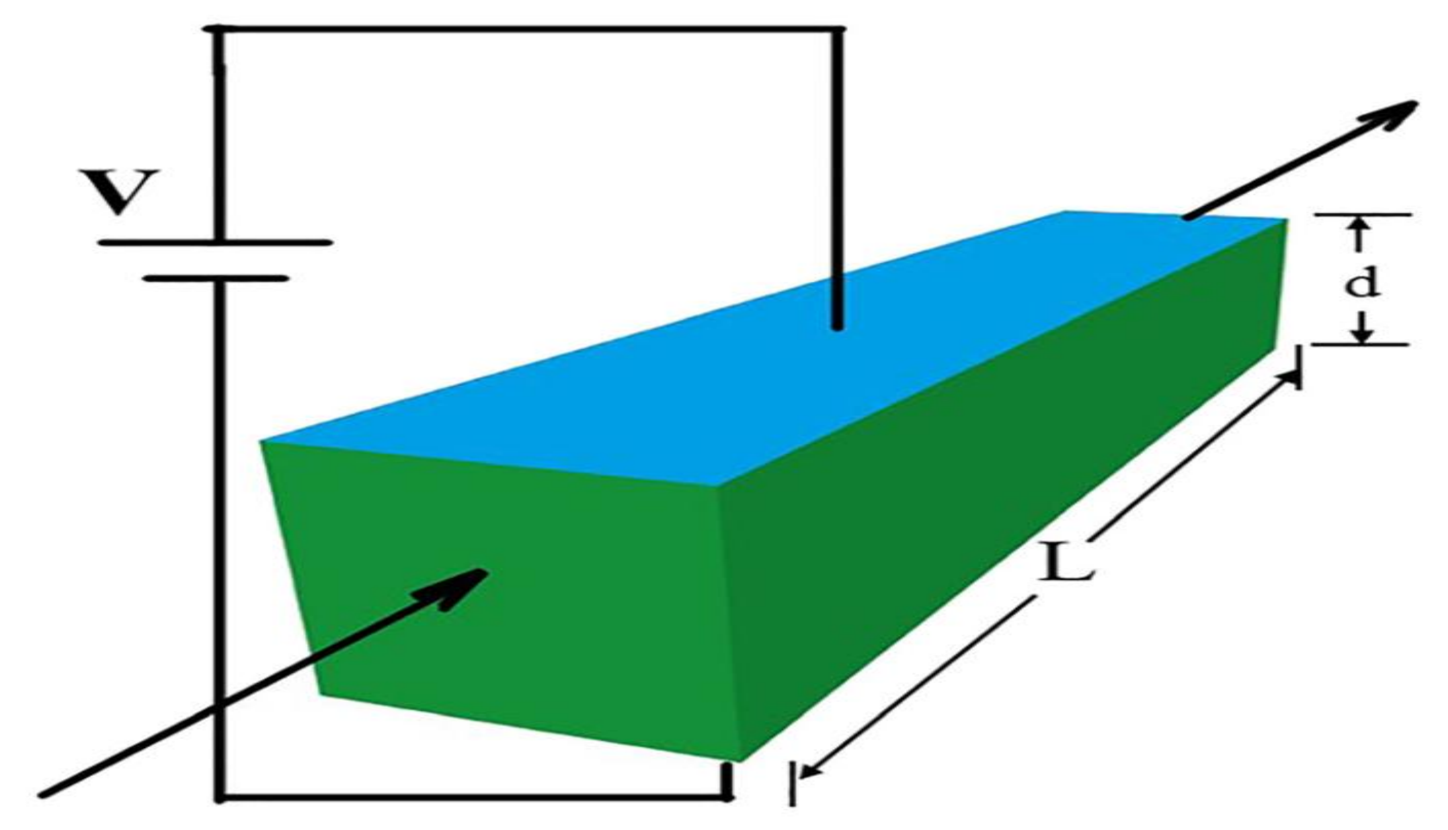


Figure 3: Transverse Pockels electro-optic modulator

Source: D. Chauhan, Z. Sbeah, R. P. Dwivedi, J.-Michel Nunzi, and S. Thakur, “An investigation and analysis of plasmonic modulators: a review,” Journal of optical communications, DE GRUYTER, 2022. https://www.researchgate.net/profile/Diksha-Chauhan/publication/360304912/figure/fig5/AS:11431281118674028@1675846976554/Transverse-configuration_W640.jpg

Applied Field is given by [2]

$$E = \frac{V}{d} \qquad (7)$$

Electro-Optic Modulators (EOM)

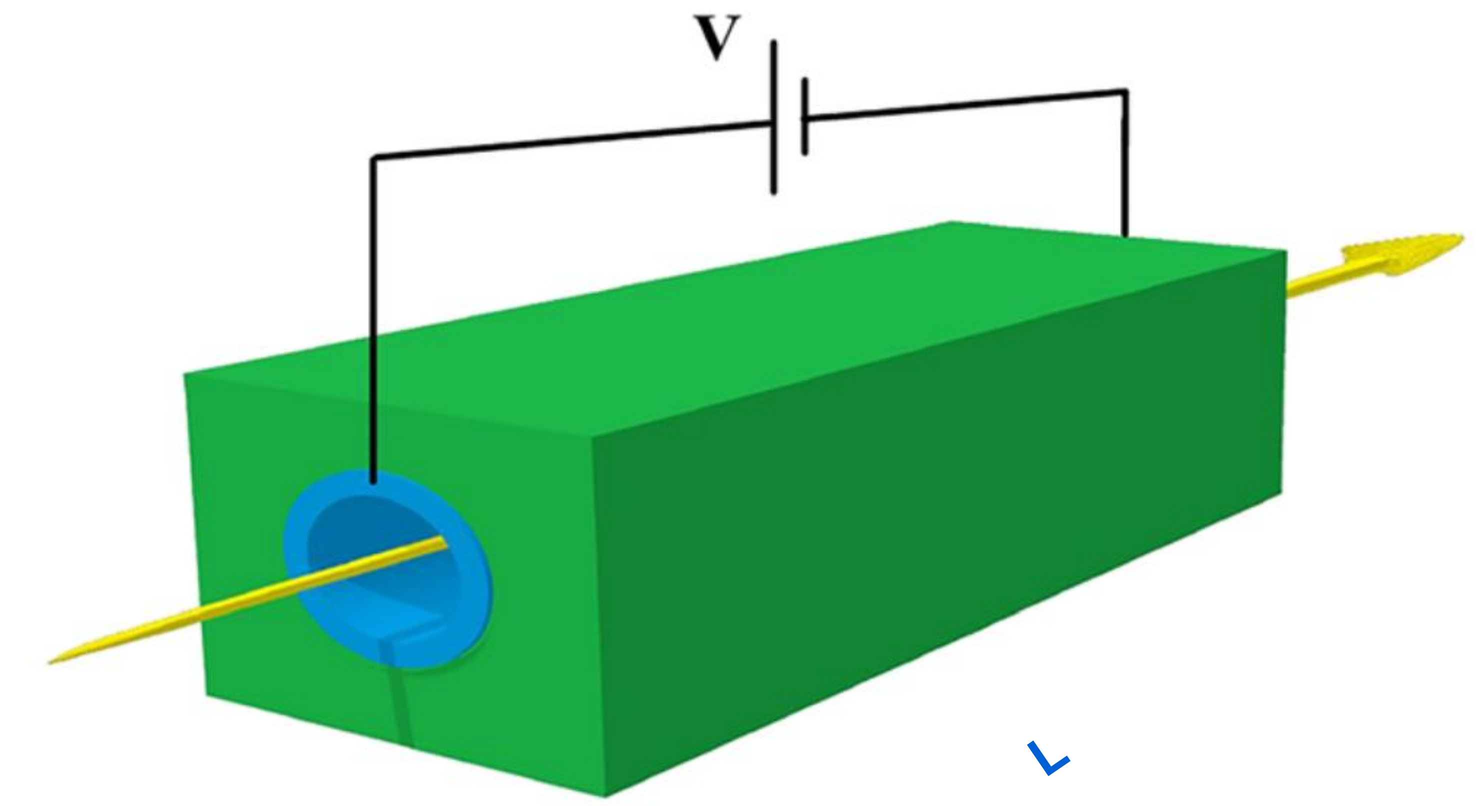


Figure 4: Longitudinal Pockels electro-optic modulator

Source: D. Chauhan, Z. Sbeah, R. P. Dwivedi, J.-Michel Nunzi, and S. Thakur, “An investigation and analysis of plasmonic modulators: a review,” Journal of optical communications, DE GRUYTER, 2022. https://www.researchgate.net/profile/Diksha-Chauhan/publication/360304912/figure/fig4/AS:11431281118702435@1675846976075/Longitudinal-modulator_W640.jpg

Applied Field is given by [2]

$$E = \frac{V}{L} \tag{8}$$

Electro-Optic Phase Modulation

- The phase shift of the output signal of the modulator can be written in the following form:

$$\phi = \beta(E)L = n(E)kL \qquad (9)$$

Where:

$\beta(E)$ Electric field dependent propagation constant of Pockels electro-optic material

k Free space propagation constant

ϕ Phase shift

- Substituting Eq (5) in Eq (9) since it is Pockels material, we have;

$$\phi = n(E)kL = \left(n - \frac{1}{2}rn^3E\right)kL = knL - \frac{1}{2}krn^3EL \qquad (10)$$

Electro-Optic Phase Modulation

- Eq (10) can be written in the form:

$$\phi = knL - \frac{1}{2}krn^3EL = \phi_0 - \frac{1}{2}krn^3EL \qquad (11)$$

Where:

ϕ_0 Phase shift with out applied electric field

- Substituting $k = \frac{2\pi}{\lambda}$ and $E = \frac{V}{d}$ in Eq (11): :

$$\phi = \phi_0 - \pi\frac{rn^3VL}{\lambda d} \qquad (12)$$

Where:

V Is the applied voltage in transverse configuration

Electro-Optic Phase Modulation

- The on-off driving voltage (V_π), the voltage required to have 180 degrees or $\pi\ rad$ phase shift is given by:

$$V_\pi = \frac{\lambda d}{r n^3 L} \qquad (13)$$

- From Eq (12), It is possible to reduce the on-off voltage (V_π) by increasing L but it will reduce the bandwidth too.
- From Eq (12) and Eq (13):

$$\phi = \phi_0 - \pi V \frac{r n^3 L}{\lambda d} = \phi_0 - \pi V \left(\frac{1}{V_\pi} \right) = \phi_0 - \pi \frac{V}{V_\pi} \qquad (14)$$

- When $V = V_\pi$, the electric field induced phase shift be come $\pi\ rad$

Electro-Optic Phase Modulation

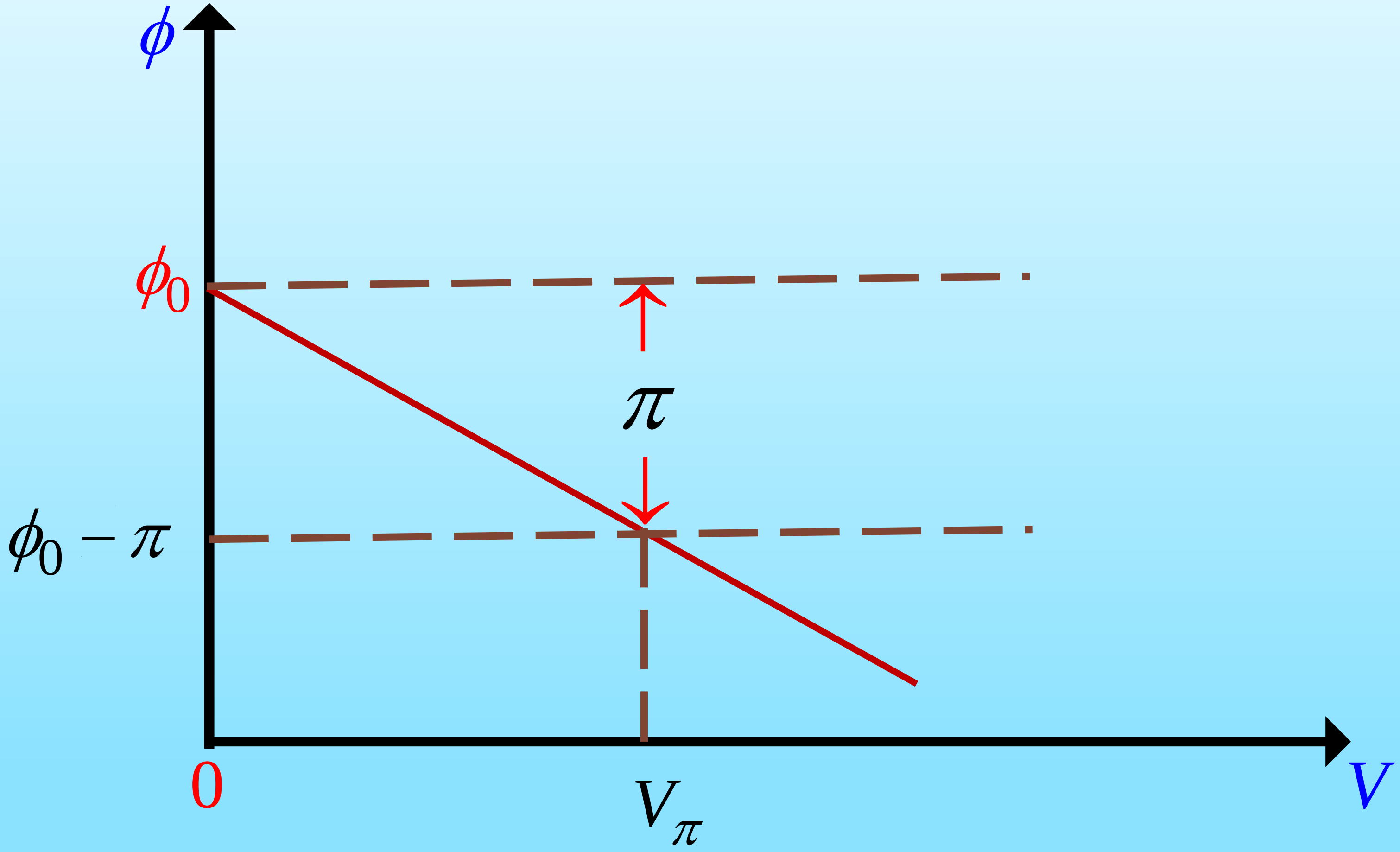


Figure 5: applied voltage Vs phase change

Electro-Optic Phase Modulation

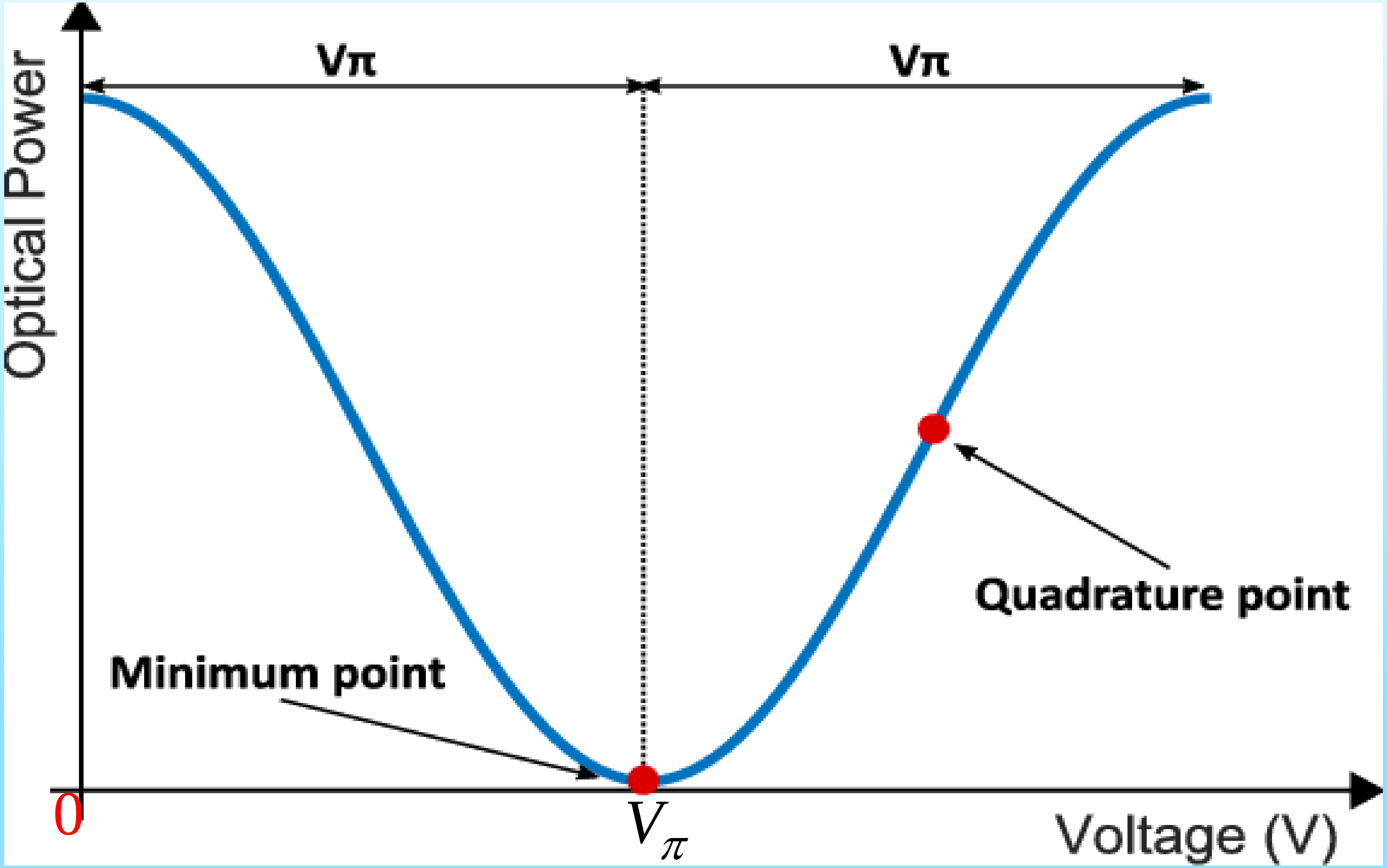


Figure 6: applied voltage Vs Optical power

Source: P. Rito et al., "A monolithically integrated segmented driver and modulator in 0.25 µm SiGe:C BiCMOS with 13 dB extinction ratio at 28 Gb/s," 2016 IEEE MTT-S International Microwave Symposium (IMS), San Francisco, CA, USA, 2016. https://www.researchgate.net/profile/D-Petousi/publication/306117417/figure/fig3/AS:646816102096897@1531224384522/MZM-transfer-function-and-operating-points.png

Mach-Zehnder Amplitude Modulator

- Mach–Zehnder amplitude modulators use interference between two optical paths to control light intensity through electro-optic effects [3]
- The optical beam is split in two beams
- Each optical beam experiences electro-optic phase modulation, and the two beams are later recombined to produce an amplitude modulated output
- Phase modulation is zero at zero applied signal, increases with increasing signal amplitude
- Interferometric amplitude modulator exploiting two phase modulator arms
- At zero applied signal, zero phase modulation obtained and the two beams recombine constructively $\Rightarrow$ ON State
- At ON-OFF voltage the total phase difference between the two beams is 180 degrees since the two beams recombine destructively $\Rightarrow$ OFF State

Mach-Zehnder Amplitude Modulator

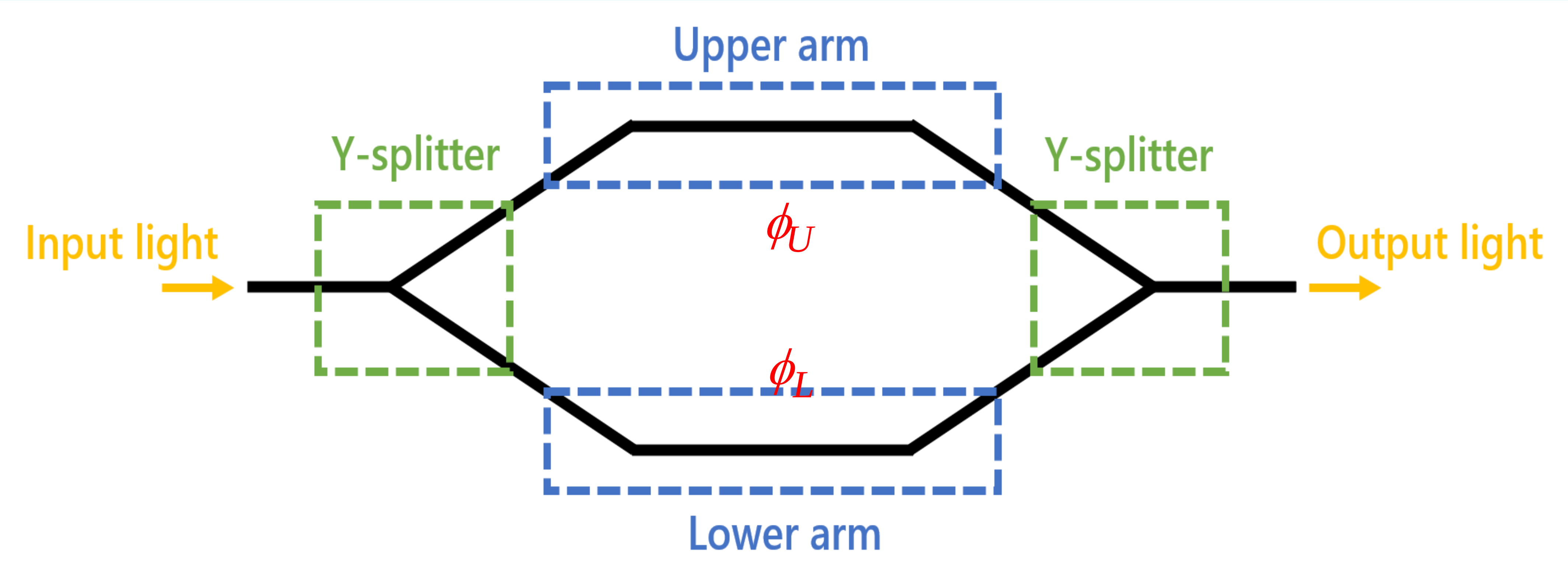
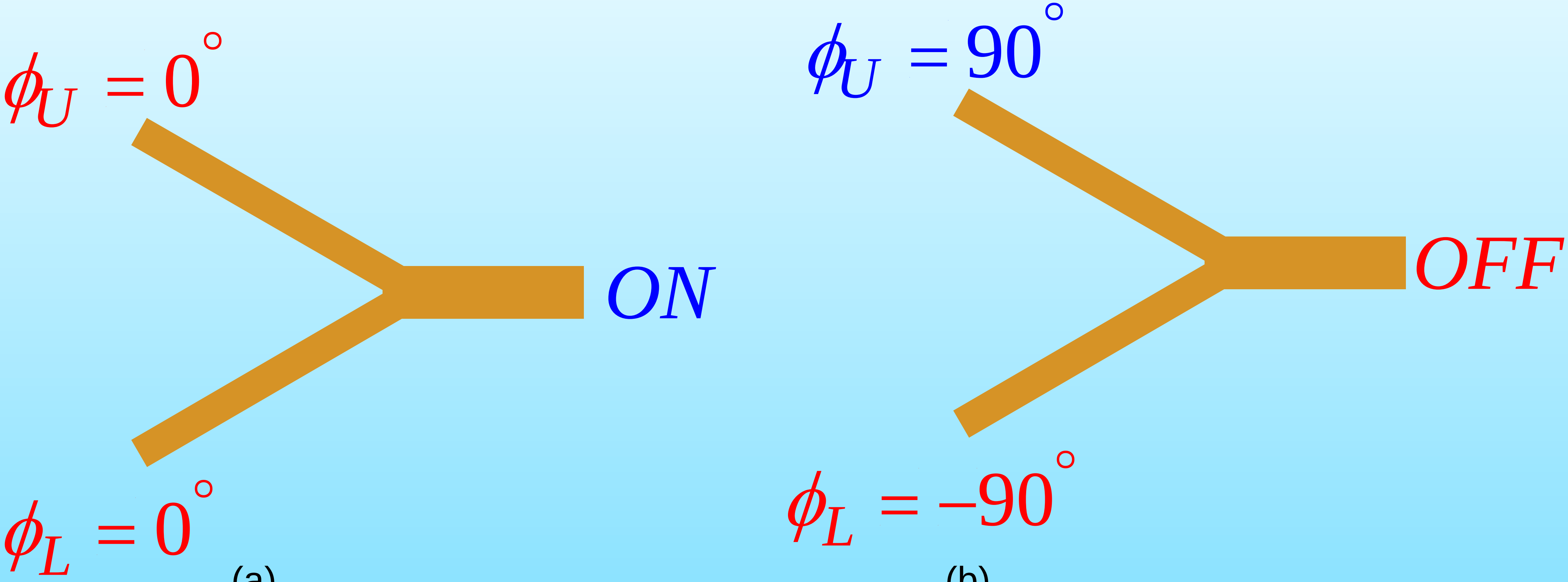


Figure 7: Mach-Zehnder Amplitude Modulator

Source: “Mach-Zehnder interferometer,” Luceda Academy, 2025.
https://academy.lucedaphotonics.com/_images/mzi_schematic_siepic.png

Mach-Zehnder Amplitude Modulator

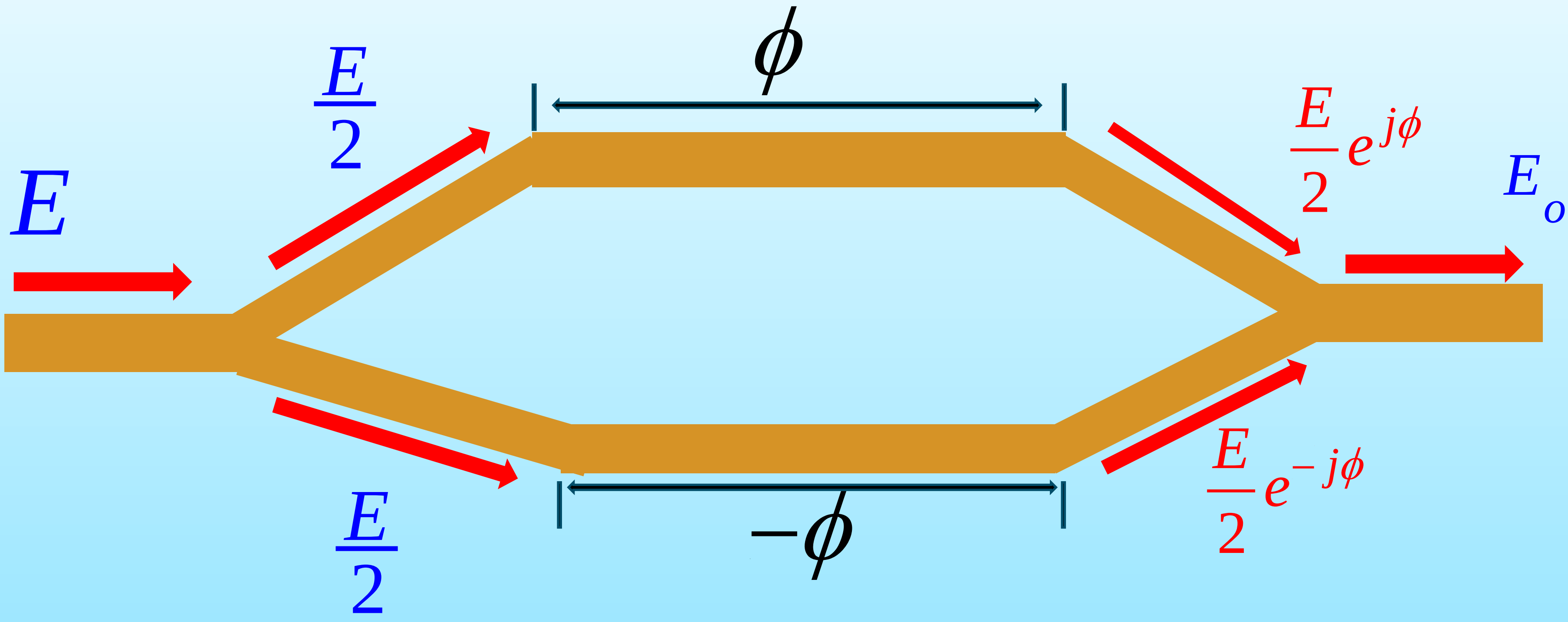


(a)

(b)

Figure 8: (a) Constructive interference (b) Destructive interference

Mach-Zehnder Amplitude Modulator



$$E_{out} = \frac{E}{2}e^{j\phi} + \frac{E}{2}e^{-j\phi}$$
$$= E\cos(\phi)$$

Figure 9: Operation of Mach-Zehnder Amplitude Modulator

- At the output of the modulator we have

$$E_{out} = E\cos(\phi) = 0,\ \text{for}\ \phi = 90^\circ \rightarrow OFF\ \text{State}$$

$$E_{out} = E\cos(\phi) = E,\ \text{for}\ \phi = 0^\circ \rightarrow ON\ \text{State}$$

Electro-Absorption Modulator (EAM)

Electro-Absorption Modulator (EAM)

- EAMs modulate light by changing semiconductor absorption as the function of an applied electric field.
- An external electric field modifies the bandgap energy and shifts the absorption spectrum
- The Change in absorption coefficient as a function of applied electric field arise from a phenomena called **Franz-Keldysh Effect**
- Without an external electric field, the photon energy is insufficient to excite an electron from the valence band to the conduction band
- When an electric field is applied, the energy bands tilt, allowing electrons to tunnel from the valence band to the conduction band

Electro-Absorption Modulator (EAM)

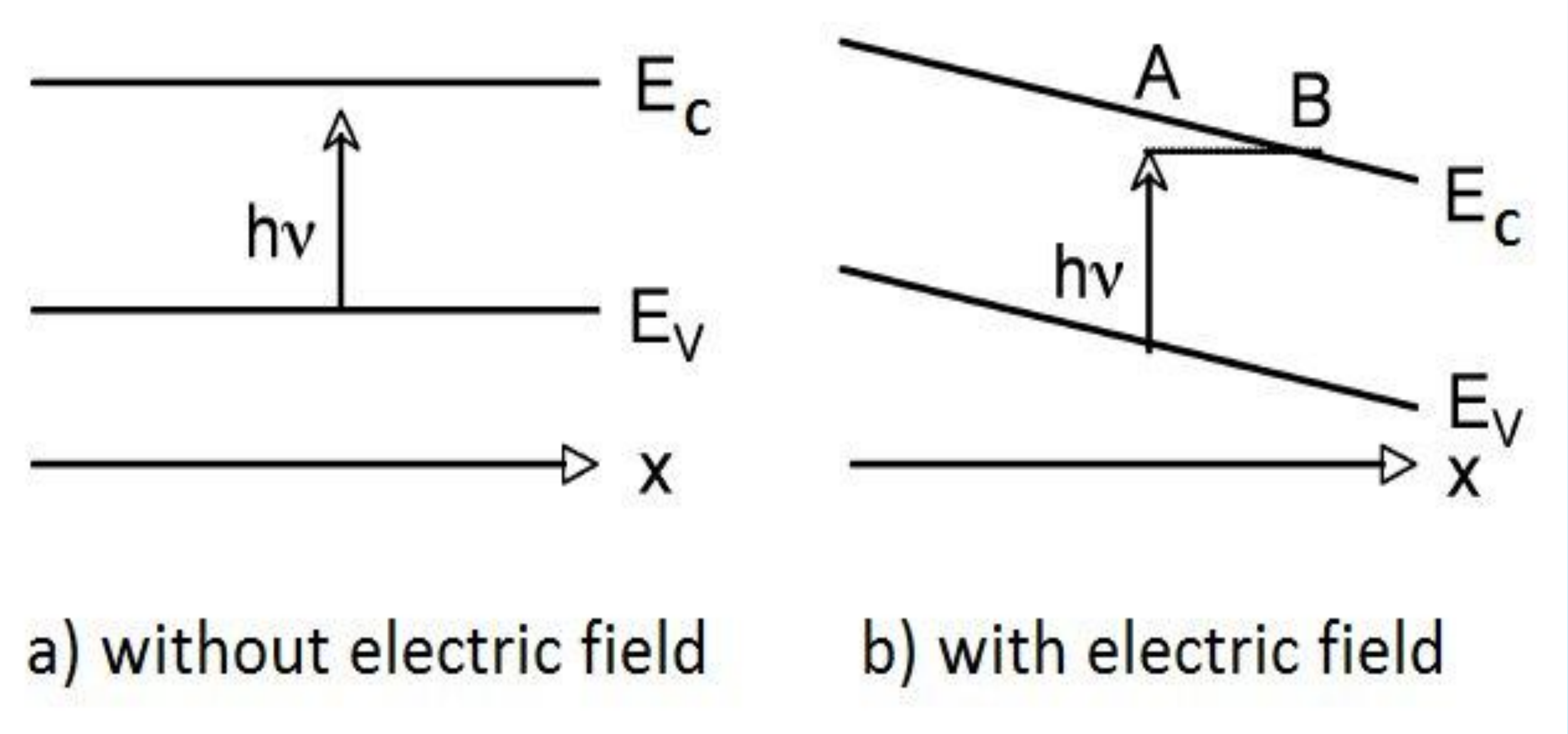


Figure 10: Illustration of the Franz-Keldysh Effect in a Semiconductor

Source: A. Aji, K. Sabo, P. Priyadarshini, “External Optical Modulator (EOM),” technical report, ResearchGate, 2017. https://www.researchgate.net/profile/Asem-Aji-2/publication/323486182/figure/fig4/AS:599375730454529@1519913718839/Franz-Keldysh-effect-1_W640.jpg

Electro-Absorption Modulator (EAM)

- EAM is small and can be integrated with the laser on the same substrate

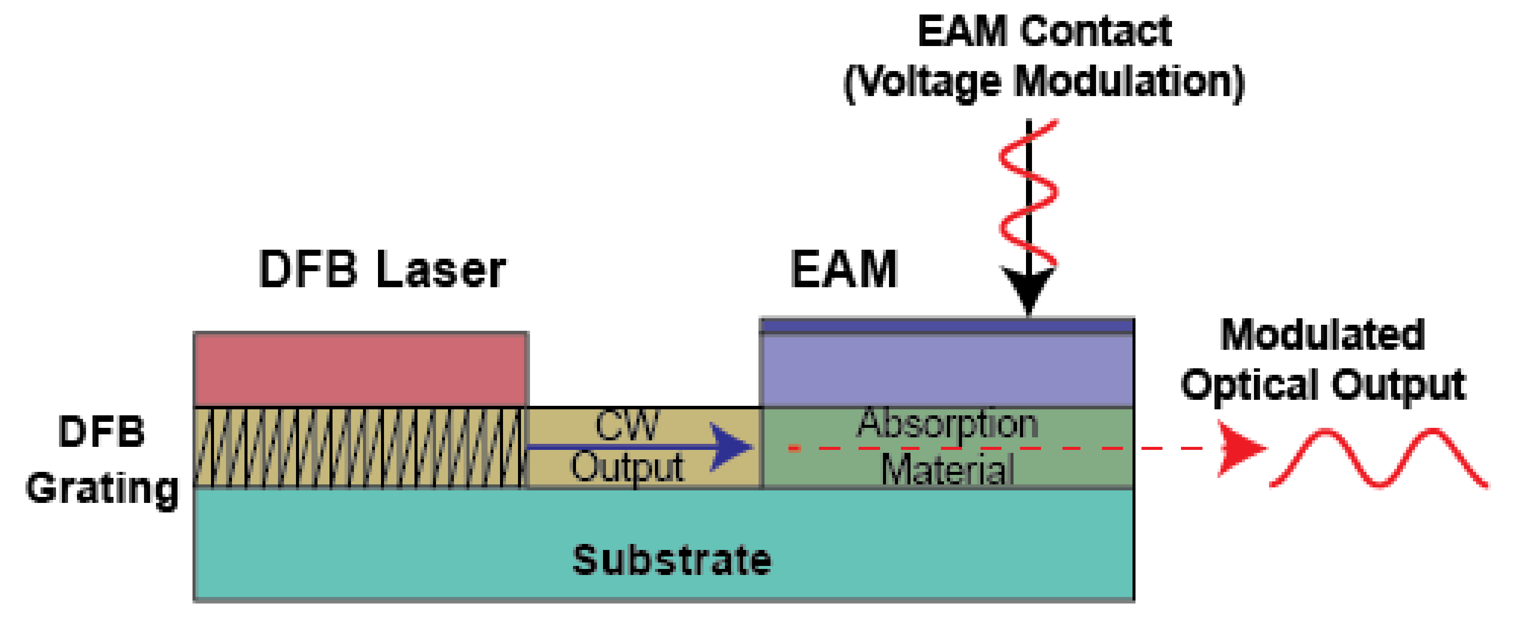


Figure 11: EAM integrated into a DFB Laser Chip

Source: "Modulation Basics," Wavelength Electronics,2025.
https://www.teamwavelength.com/download/eam-1.png

Summary

- **Types of optical signal modulation techniques:**
  - ✓ **Direct Modulation:** through modifying the light source's driving current
  - ✓ **External Modulation:** requires separate device
- **Types of external optical modulators:**
  - ✓ **EOM:** through variation of refractive index as a function of applied field
  - ✓ **EAM:** through variation of material absorption as a function of applied field
- **Widely used electro-optic amplitude modulator :**
  - ✓ **Mach-Zehnder Amplitude Modulator :** optical amplitude modulation through formation of an optical interferometer

References

[1] Giovanni Ghione,*‘’ Semiconductor Devices for High-Speed Optoelectronics”, CAMBRIDGE UNIVERSITY PRESS*, Pp.357, 2009.

[2] D. Chauhan, Z. Sbeah, R. P. Dwivedi, J.-Michel Nunzi, and S. Thakur, *“An investigation and analysis of plasmonic modulators: a review,”* Journal of optical communications, DE GRUYTER, 2022. .

[3] S.O. Kasap, *“Optoelectronics and Photonics: Principles and Practices,”* Pearson Education Limited, 2nd ed., Pp.487, 2013.

Thank You !