Fiber Optics Communications

Week 7 Optical Modulation Schemes

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Topics of Previous Lecture (Week-6)

Optical Sources

- Basic Concepts of Semiconductor Physics
- Reverse and forward biased pn junction semiconductor materials
- Direct and indirect bandgap materials
- Light-Emitting Diodes
- Laser diodes

Week-7: Lecture Learning Outcomes

1. Define optical modulation and explain its role in fiber optic communication
2. Explain the principles of line coding and pulse shaping and their role in digital signal transmission over optical fiber transmission line.
3. Describe key digital modulation techniques, including ASK, PSK, DPSK, QPSK, FSK, and PolSK.
4. Explain the working principles of amplitude, phase, and frequency shift keying in optical communication systems.
5. Compare advantages and limitations of different modulation schemes and coding techniques for optical communication.

Week-7: Optical Modulation Schemes

Outline

- Introduction: What is optical Modulation?
- 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)

Introduction to Optical Modulation

- **Optical modulation:** is the technique of encoding information onto a light wave for transmission in fiber-optic communication systems
- It is an crucial process for transforming the information signal from electrical into optical domain signal to enable long-distance transmission with minimal loss.
- There are several optical modulation techniques, each offering distinct advantages and applications based on the specific requirements of the communication system
- As its fundamental principle, optical modulation works by altering one or more properties of a continuous Lightwave in response to an input signal
- Lightwave systems use the digital format of the information signal to realize digital optical modulations.
- **Direct** and **External optical modulation** techniques are used [1]

Introduction to Optical Modulation

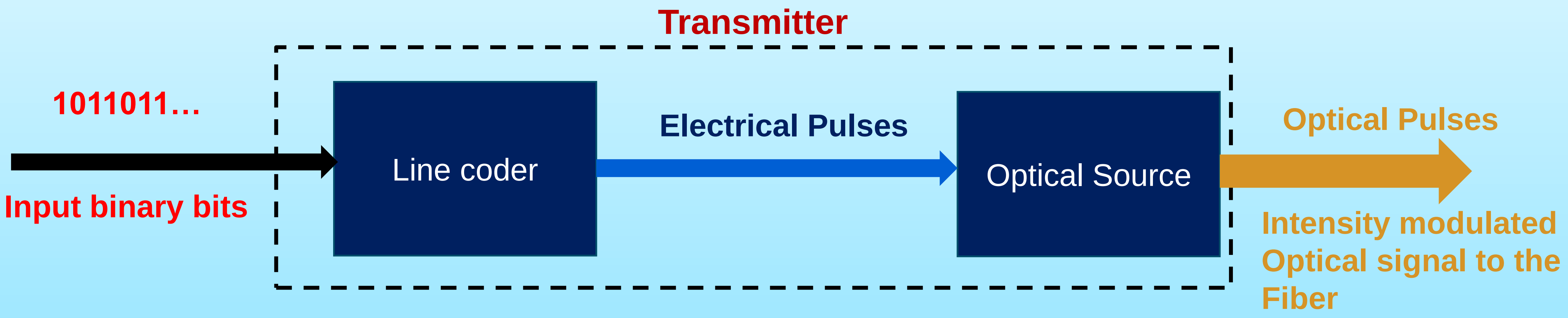


Figure 1: Direct Modulation

Electrical signal

Optical signal

Introduction to Optical Modulation

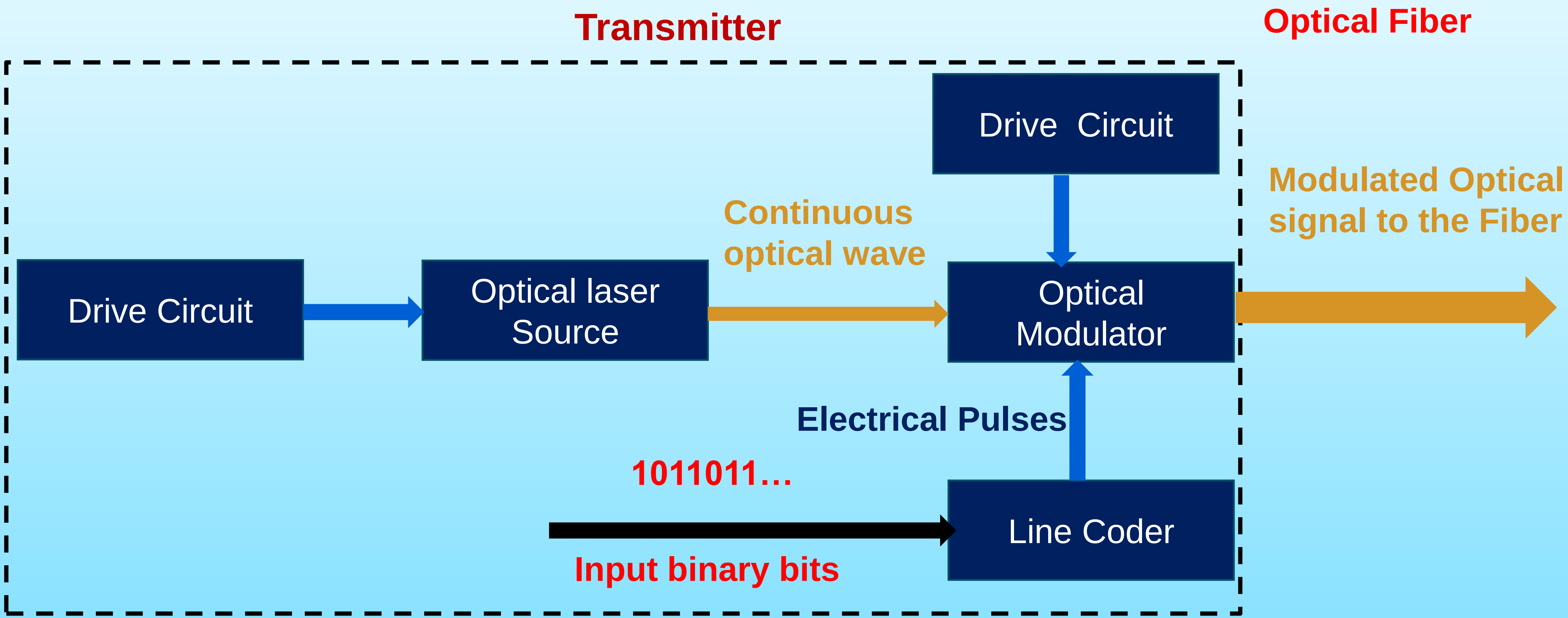


Figure 2 : External Modulation

Introduction to Optical Modulation

- There are four key attributes of light that can be modulated in digital optical modulation
  - **Amplitude (Intensity)**
  - **Phase**
  - **Frequency**
  - **Polarization**
- Based on those modulated properties, Optical modulation schemes can be classified as:
  - **Amplitude Shift Keying (Intensity) Modulation:** The optical signal power or intensity is varied in proportion to the input signal.
  - **Phase Shift Keying Modulation**: The phase of the optical signal is varied to encode information.
  - **Frequency Shift Keying Modulation**: The frequency of the optical signal is varied to encode information.
  - **Polarization Shift Keying Modulation:** Information is encoded in the polarization state of the optical carrier wave (not practical)

Introduction to Optical Modulation

- Mathematically the field of optical carrier wave can be written as:

$$E(t) = \hat{e} A_0 \cos(\omega_0 t - \phi_0) \qquad (1)$$

Where:

A_0	Peak amplitude	ϕ_0	Phase
ω_0	Angular frequency	$\hat{e}$	Polarization state

Amplitude Shift Keying

- Modulating A_0

Phase Shift Keying

- Modulating ϕ_0

Frequency Shift Keying

- Modulating ω_0

Polarization Shift Keying

- Information is encoded in the polarization state $\hat{e}$ of optical carrier wave

Line Coding

- **Line coding:** is the technique of representing digital data using electrical wave forms.
- In fiber optic communication, line coding is used to prepares the data for efficient and reliable transmission.
- Line coding defines the timing, polarity, and level transitions for digital data representation.
- In binary (“0” and “1”) case, the two common types of line coding are:

  - **Unipolar:** bit ‘1’ is represented by a pulse p(t) and bit ‘0’ is sent by transmitting no pulse.
  - **Polar:** bit ‘1’ and bit ‘0’ are represented by p(t) and −p(t), respectively

- Unipolar and polar line coding are the most widely used in optical fiber communication.

Line Coding

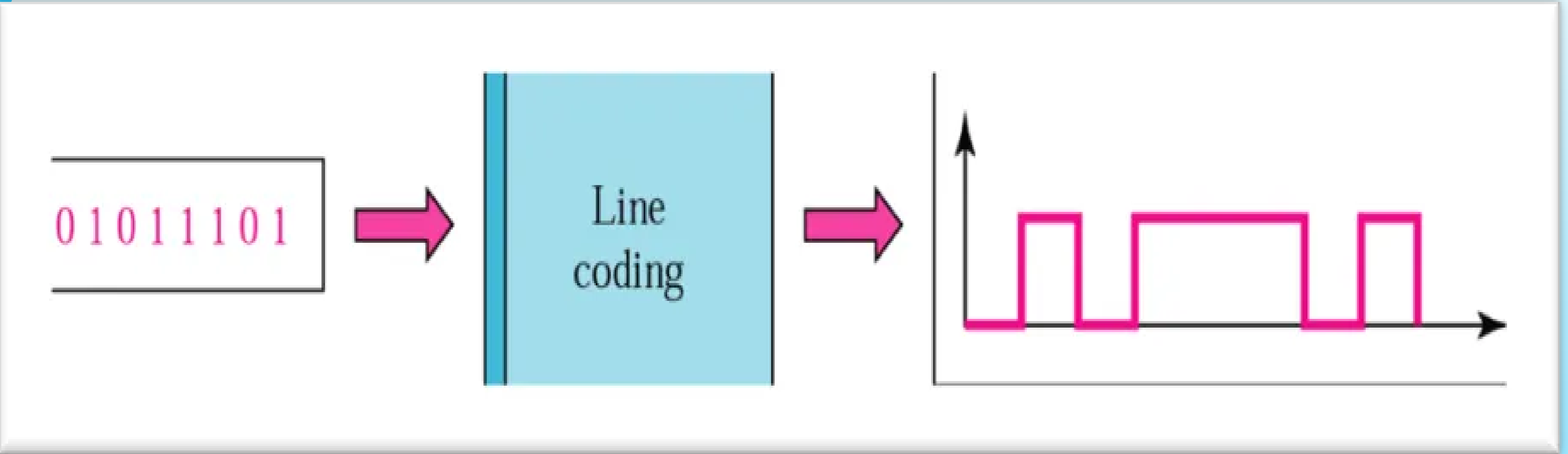


Figure 2 : Line Coding

Source: T. Katale, "Journey of line encoding techniques," Medium, Nov. 24, 2022. https://miro.medium.com/v2/resize:fit:1100/format:webp/1*qhZTfeW3fP7koeLUpw5arA.png

Pulse Shaping

- **Pulse Shaping:** is the selection of the pulse shape (p(t)) to encode the binary bits “1” and “0”
- The widely used pulse shapes (p(t)) are:
    - **Non-Return to Zero (NRZ)**
    - **Return to Zero (RZ)**
- NRZ encodes binary “1” with high signal level and “0” with low signal level
- In NRZ, the signal does not return to zero level if there are two consecutive ‘1’s and ‘0’s in a bit stream
- In RZ, the signal level returns to zero at the middle of each bit period.
- Unipolar and polar NRZ and RZ pulses are the most widely used pulse shapes in fiber optic communications

Pulse Shaping

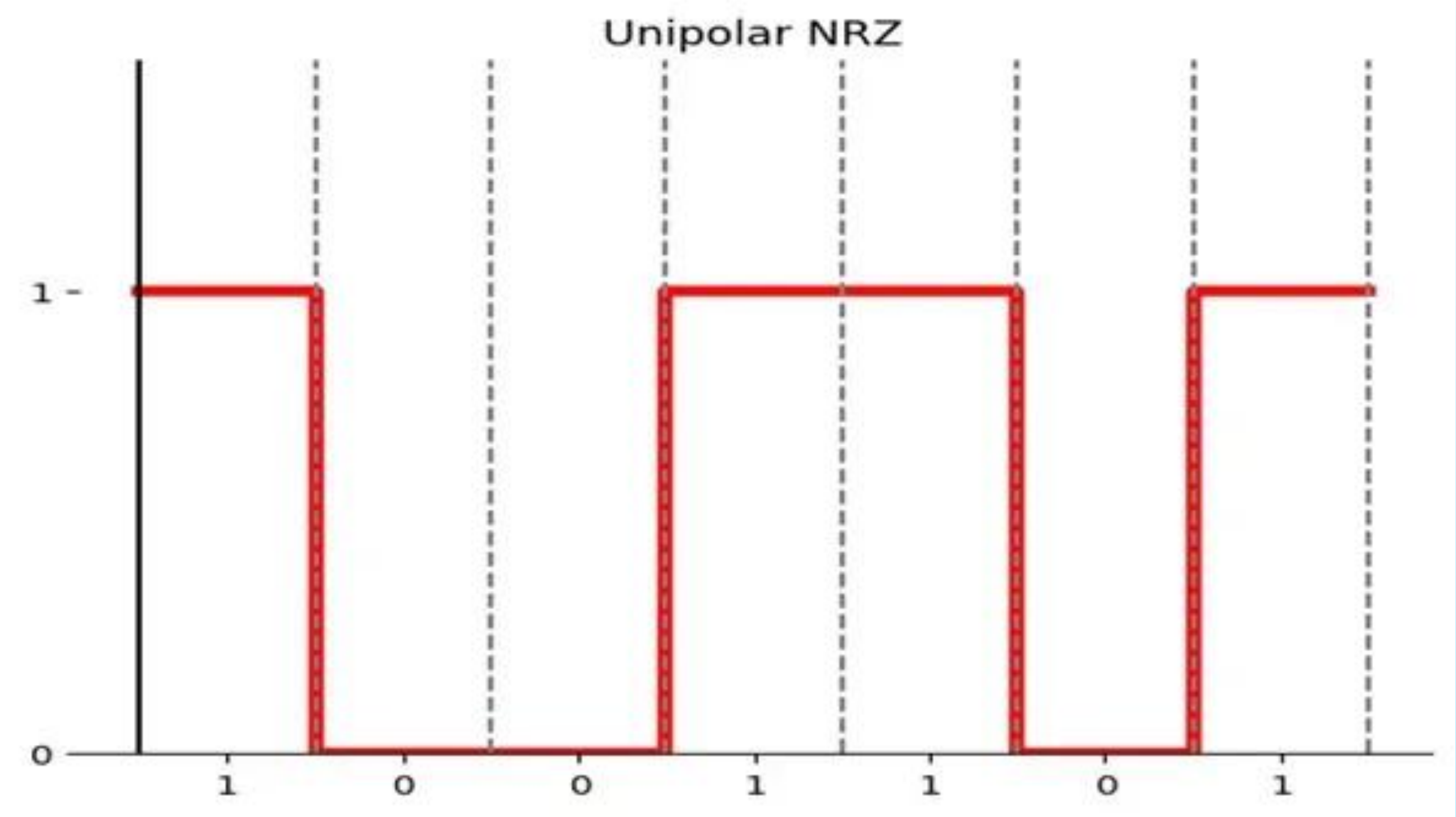


Figure 3 : Unipolar NRZ

Source: T. Katale, "Journey of line encoding techniques," Medium, Nov. 24, 2022.
https://miro.medium.com/v2/resize:fit:1100/format:webp/1*PpVuVbxwqkhUIq_CUsejsg.jpeg

Pulse Shaping

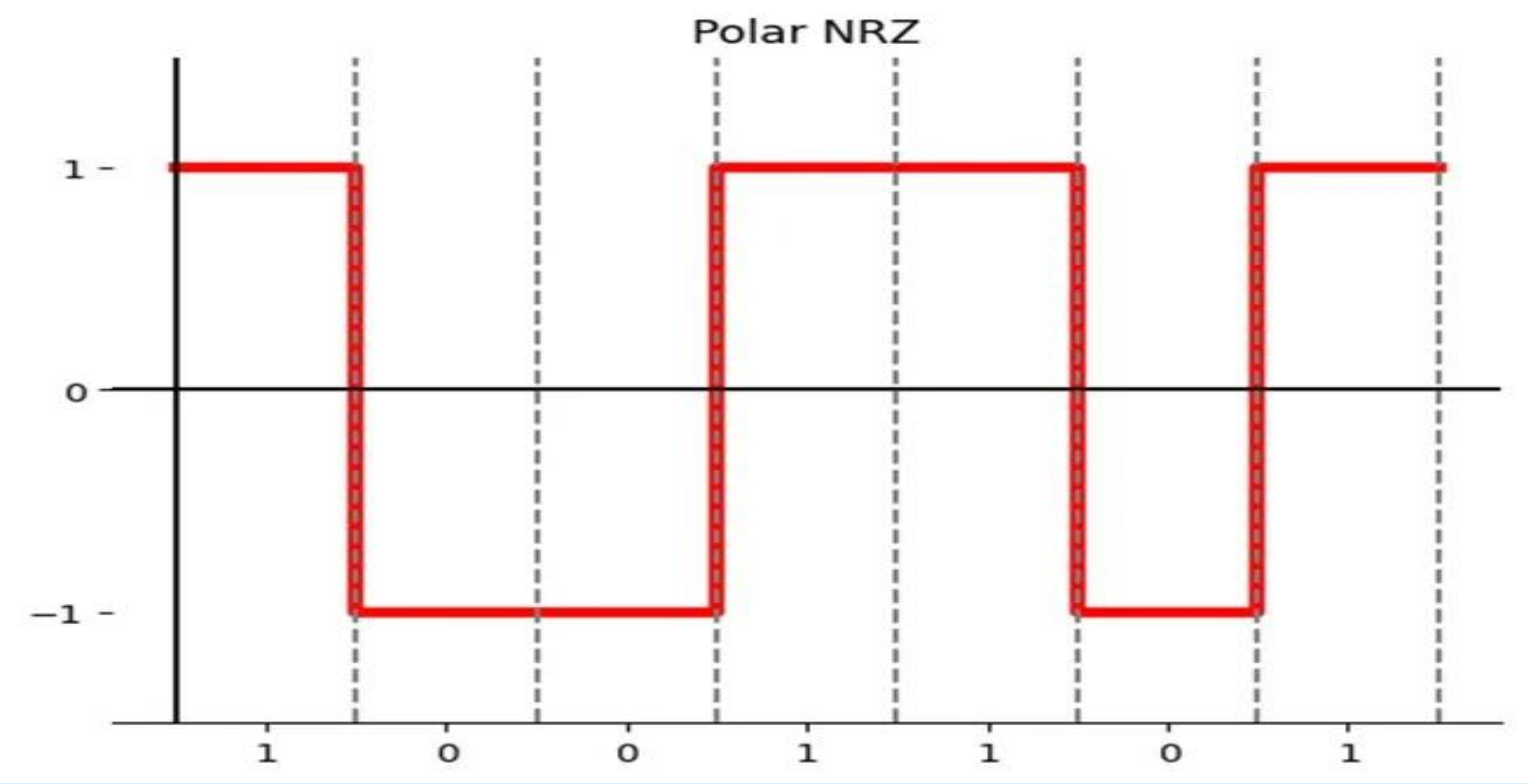


Figure 4 : Polar NRZ

Source: T. Katale, "Journey of line encoding techniques," Medium, Nov. 24, 2022. https://miro.medium.com/v2/resize:fit:1100/format:webp/1*BKCu9MKp8KbzPYbQcItjmg.jpeg

Pulse Shaping

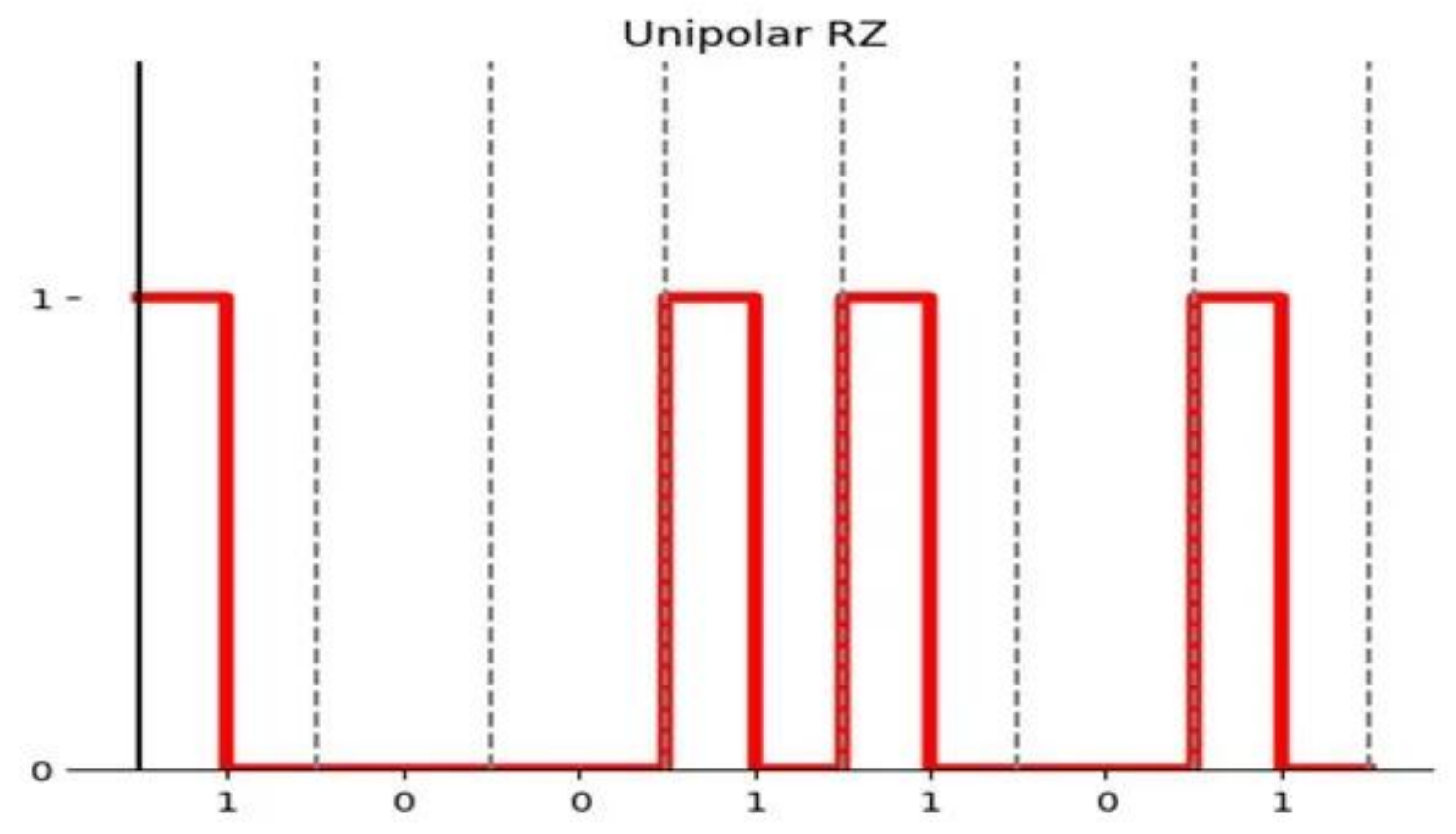


Figure 5 : Unipolar RZ

Source: T. Katale, "Journey of line encoding techniques," Medium, Nov. 24, 2022. https://miro.medium.com/v2/resize:fit:1100/format:webp/1*-dGCSerG553LmGmJ-DjNMA.jpeg

Pulse Shaping

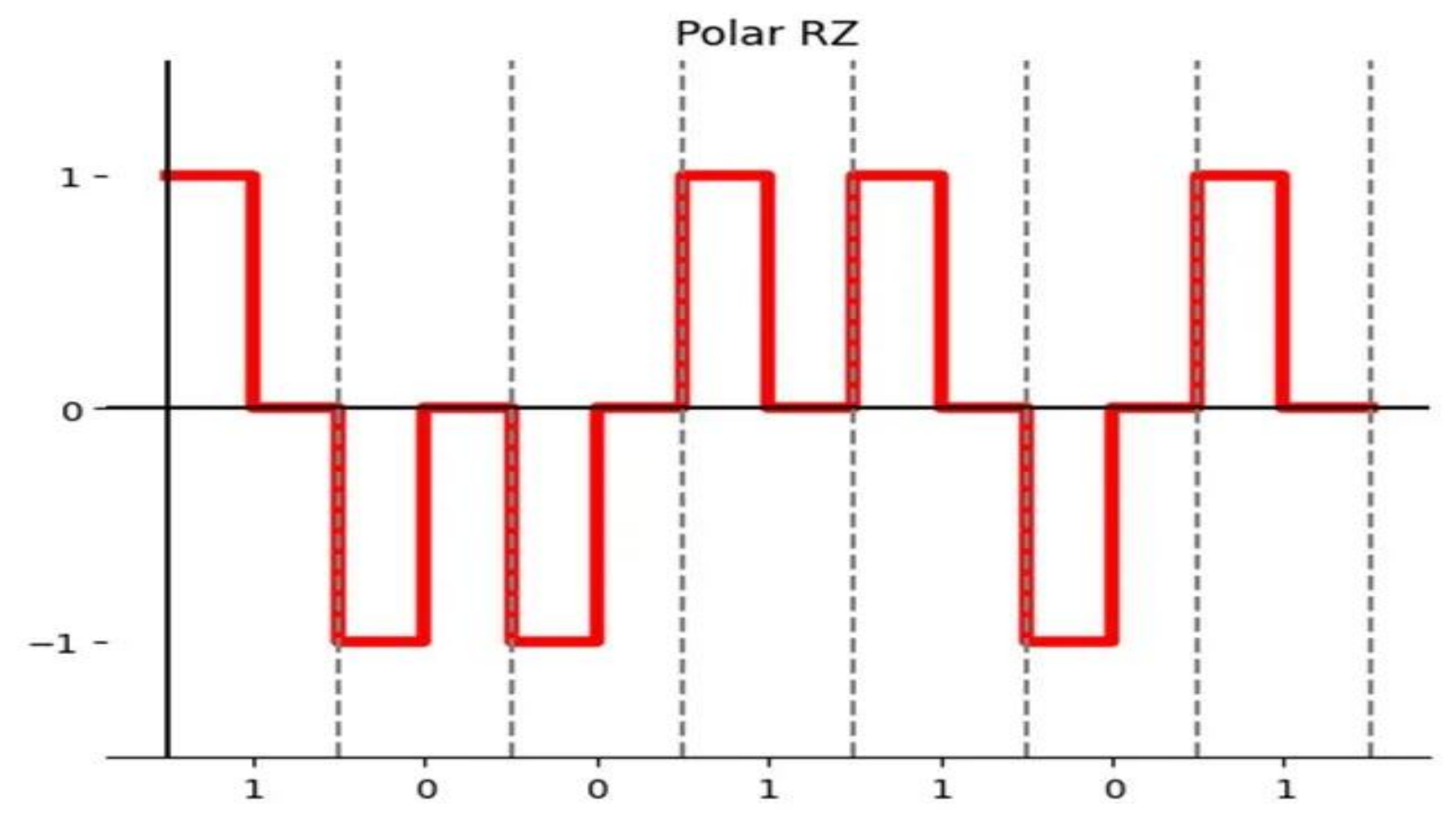


Figure 6 : Polar RZ

Source: T. Katale, "Journey of line encoding techniques," Medium, Nov. 24, 2022. https://miro.medium.com/v2/resize:fit:1100/format:webp/1*ixabKwHch7NuiSDepMPmzw.jpeg

Digital Modulation Schemes

Amplitude Shift Keying (ASK) Modulation

- In ASK also known as On-Off Keying (OOK) modulation, the amplitude of the optical field is used to carry information
- An optical carrier signal $c(t)$ emitted from the laser with can be written as

$$c(t) = A\cos(2\pi f_c t + \phi) \qquad (2)$$

Where:

A Is constant amplitude

f_c Is constant frequency

ϕ Is the phase before modulation

Amplitude Shift Keying (ASK) Modulation

- In ASK the amplitude A is varied in accordance with the digital massage signal m(t) while keeping f_c and ϕ constant as [3]:

$$A(t) = k_a m(t) \qquad (3)$$

Where:

k_a Is amplitude sensitivity

- After modulation the amplitude modulated signal can be written as:

$$\begin{aligned} s(t) &= A(t)\cos(2\pi f_c t + \phi) \\ &= k_a m(t)\cos(2\pi f_c t + \phi) \end{aligned} \qquad (4)$$

Where:

$s(t)$ Is the ASK modulated optical signal

Amplitude Shift Keying (ASK) Modulation

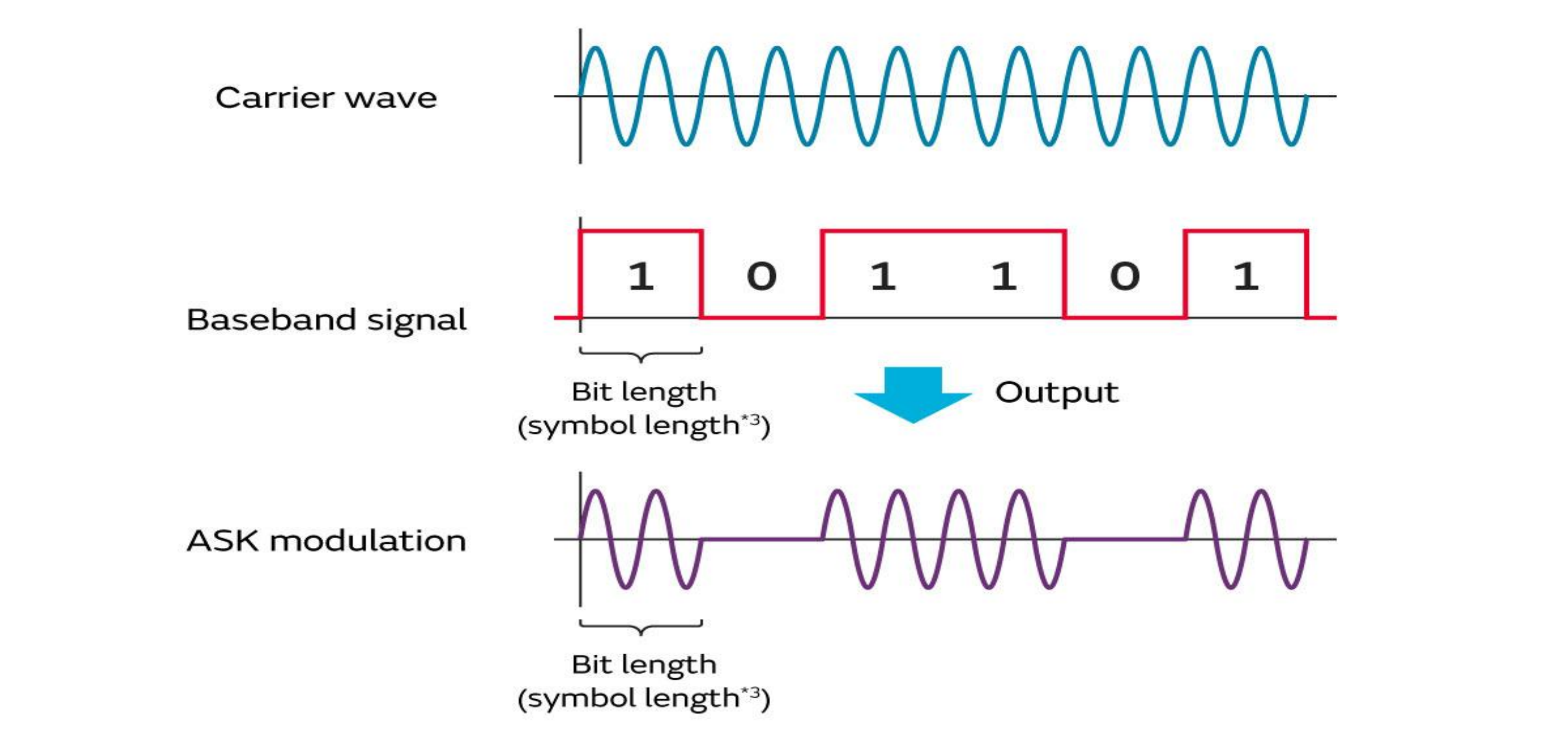


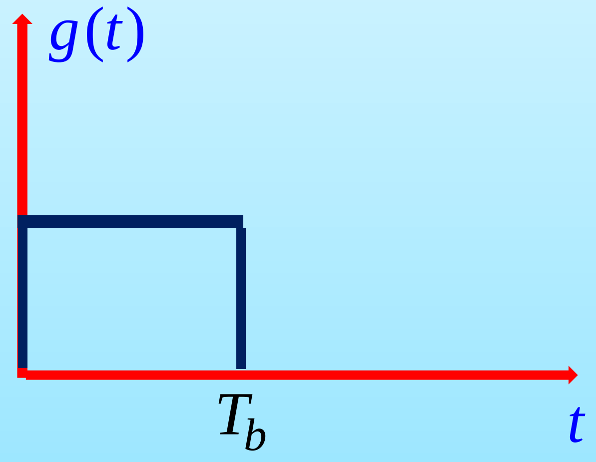
Figure 7 : ASK modulated signal wave

Source: "Digital Modulation – The Basics of Digital Communication," Murata, Jun. 11, 2025. https://article.murata.com/sites/default/files/static/en-global/images/article/basics-of-digital-communication/fig-digitalcommunication2-4-en.jpg

Binary Off-On Keying (OOK) Modulation

- Binary On-Off Keying (OOK) modulation is a basic ASK technique where binary data is transmitted by turning the carrier wave on (for bit “1”) or off (for bit “0”) .
- Considering the previous optical carrier field

$$c(t) = A\cos(2\pi f_c t + \phi) \quad (5)$$



- Only the amplitude A of the carrier wave is varied in accordance the data as:

$$A(t) = \sqrt{P_o}\sum_n b_n g(t - nT_b) \quad (6)$$

Where:

$P_o = A^2$ the peak optical power of the carrier

b_n nth transmitted bit and it is 0 or 1 depend on the bit

$g(t)$ represent the shape of the electrical pulse

T_b single bit duration

Binary Off-On Keying (OOK) Modulation

- The shape of the electrical pulse ($g(t)$) can be in NRZ or RZ format
- Depend on the choice of digital data format (NRZ or RZ), we will have NRZ-OOK or RZ-OOK modulations

NRZ-OOK

- Optical pulse occupies the entire bit duration
- The optical power does not return to zero between consecutive ‘1’ bits
- More affected by dispersion and highly sensitive to pulse broadening
- small pulse broadening causes inter-symbol interference
- Offers good spectral efficiency since the signal bandwidth is smaller than RZ-OOK

Binary Off-On Keying (OOK) Modulation

RZ-OOK

- Optical pulse is shorter than the bit duration
- **Duty Cycle:** the ratio of optical pulse duration and the entire bit duration
- The optical power return to zero after each pulse
- Less sensitive to dispersion effect
- Shorter pulses reduce overlap and improve tolerance to dispersion
- Offers less spectral efficiency since the signal bandwidth is larger than NRZ-OOK

Power Spectrum of NRZ and RZ Pulses

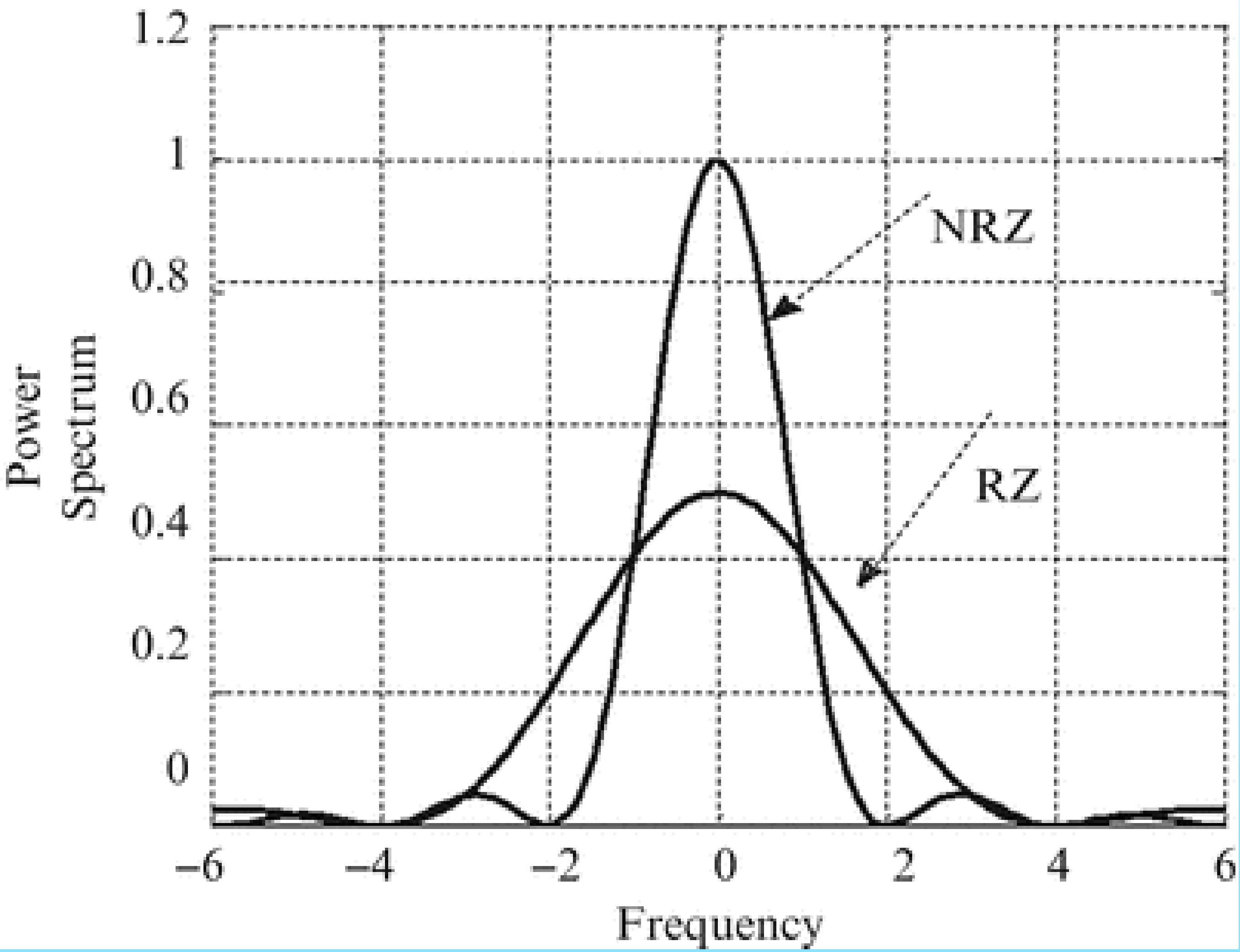


Figure 8 : Power spectrum of NRZ and RZ pulses

Source: S. Faruque, "Introduction to Channel Coding," in Radio Frequency Channel Coding Made Easy, Springer, 2016, pp. 1–16. https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-3-319-21170-1_1/MediaObjects/327036_1_En_1_Fig12_HTML.gif

Phase Shift Keying (PSK) Modulation

- In PSK modulation, the phase of the optical field is used to convey information
- The phase ϕ of the optical carrier $c(t)$ will be varied in accordance with the massage signal $m(t)$ keeping the amplitude and the frequency as constant:

$$\phi(t) = \phi + k_p m(t) \qquad (8)$$

Where:

k_p Is the phase sensitivity

- The PSK modulated optical signal $s(t)$ can be written as:

$$s(t) = A\cos(2\pi f_c t + \phi(t))$$
$$= A\cos(2\pi f_c t + (\phi + k_p m(t))) \qquad (9)$$

- Considering ϕ=0, For binary case (BPSK) modulated optical signal $\phi(t)$ is set to be:

For bit "1"

$\phi(t) = 0$

For bit "0"

$\phi(t) = \pi$

Phase Shift Keying (PSK) Modulation

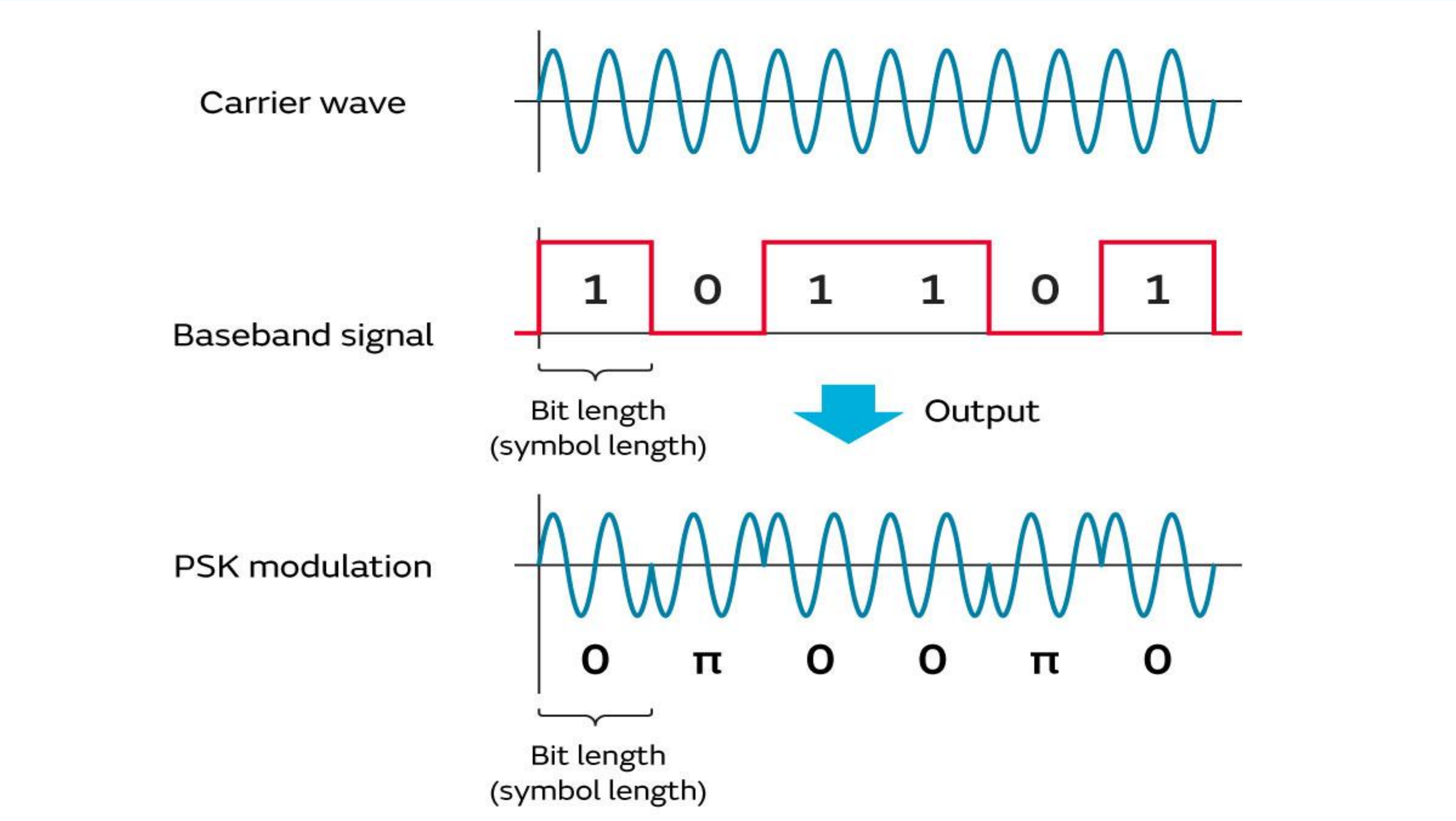


Figure 9 : PSK modulated signal wave

Source: "Digital Modulation – The Basics of Digital Communication," Murata, Jun. 11, 2025. https://article.murata.com/sites/default/files/static/en-global/images/article/basics-of-digital-communication/fig-digitalcommunication2-6-en.jpg

- There are also variants of PSK modulation such as:
  - **Differential Phase Shift Keying (DPSK)**
  - **Quadrature Phase-Shift Keying (QPSK)**

Differential Phase Shift Keying (DPSK)

- It is a widely used modulation scheme in practical fiber optics communications systems:
- The phase difference between two neighboring bits is used to encode information
- Let ϕ_k and ϕ_{k-1} are the phase of kth and k-1th bits respectively, the phase deference $\Delta\phi$ can be given by:

$$\Delta\phi = \phi_k - \phi_{k-1} \qquad (10)$$

- The phase difference $\Delta\phi$ will be exploited to encode the information
- $\Delta\phi$ is changed by 180° when kth bit is 1
- $\Delta\phi$ is changed by 0° (no change) when kth bit is 0

Differential Phase Shift Keying (DPSK)

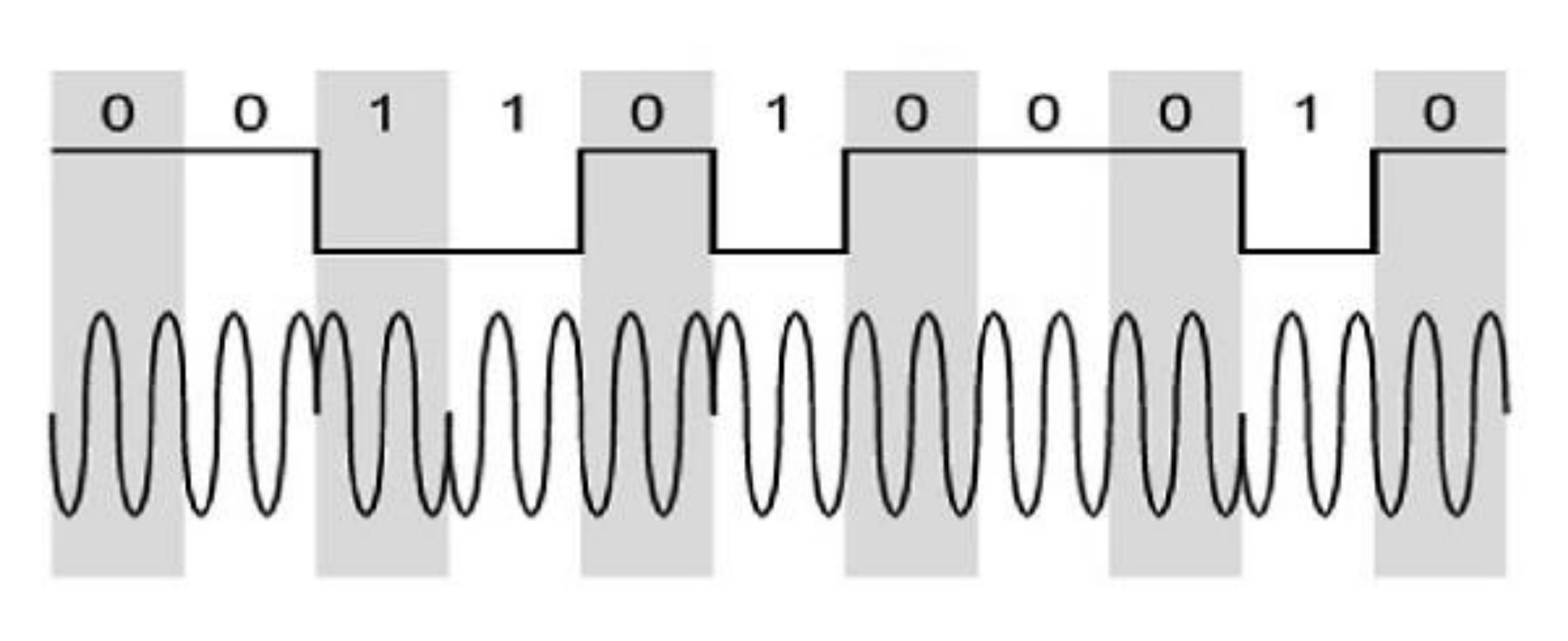


Figure 10 : DPSK modulated signal wave

Source: “Differential Phase Shift Keying,” Tutorials Point.
https://www.tutorialspoint.com/digital_communication/images/model_waveform_of_dpsk.jpg

Quadrature Phase Shift Keying (QPSK)

- In QPSK, The phase modulator encodes two bits at a time into four distinct optical carrier phases
- Typical correspondence of phase values and bit sequences are as follows:

Phase values in rad		Bits
0	$\rightarrow$	00
$\frac{\pi}{2}$	$\rightarrow$	01
π	$\rightarrow$	11
$\frac{3\pi}{2}$	$\rightarrow$	10

- QPSK is spectral efficient compared to BPSK

Frequency Shift Keying (FSK) Modulation

- In FSK modulation, the frequency of the optical field is used to carry information
- The frequency of the optical carrier $c(t)$ will be varied in accordance with the massage signal $m(t)$ keeping the amplitude and the Phase as constant:

$$f(t) = f_c + k_f m(t) \qquad (11)$$

Where:

k_f Is the frequency modulation index

- The FSK modulated optical signal $s(t)$ can be written as:

$$s(t) = A\cos(2\pi f(t)t + \phi)$$

$$= A\cos(2\pi(f_c + k_f m(t))t + \phi) \qquad (12)$$

Frequency Shift Keying (FSK) Modulation

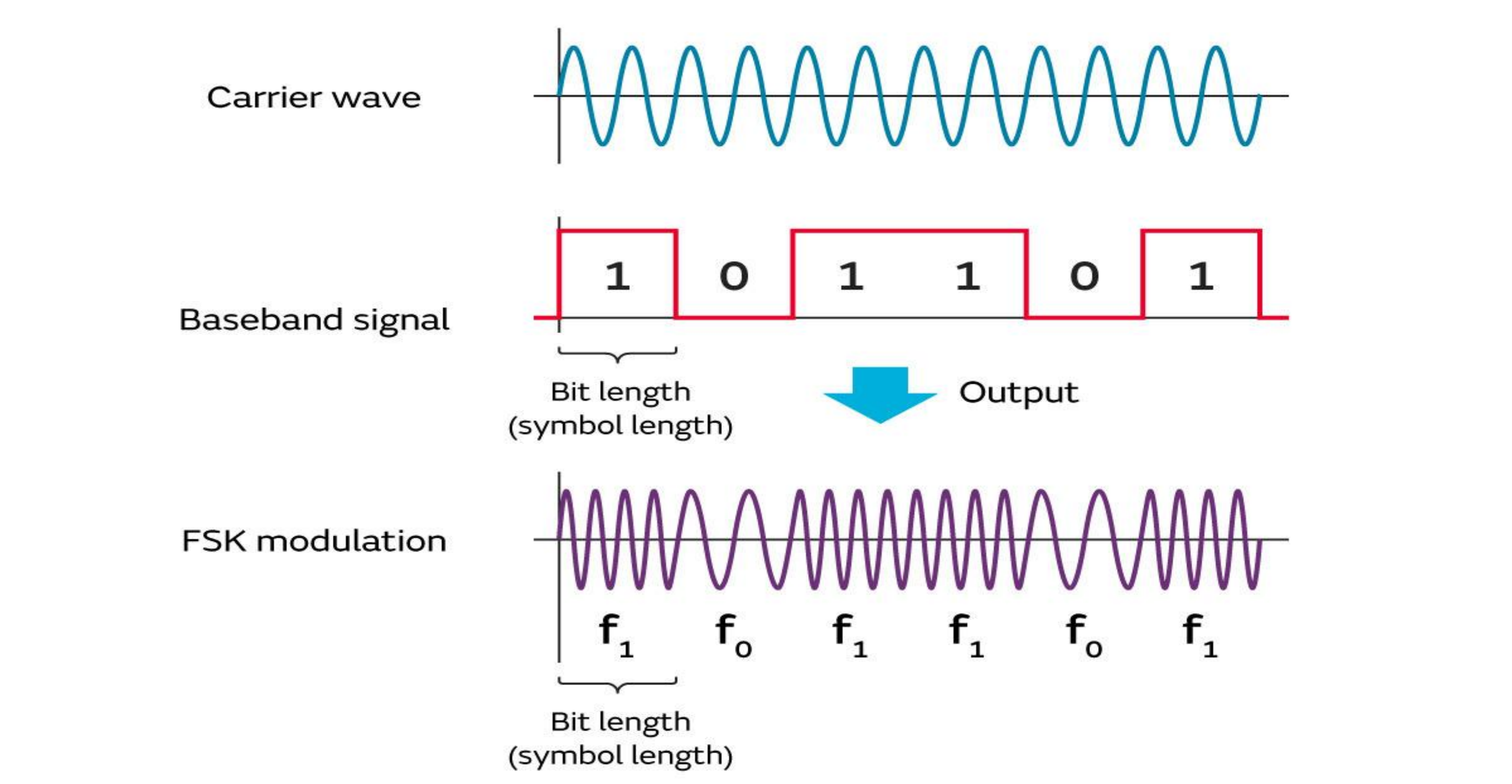


Figure 11 : FSK modulated signal wave

Source: "Digital Modulation – The Basics of Digital Communication," Murata, Jun. 11, 2025. https://article.murata.com/sites/default/files/static/en-global/images/article/basics-of-digital-communication/fig-digitalcommunication2-5-en.jpg

Polarization Shift Keying (PolSK)

- Polarization Shift Keying (PolSK) is a digital modulation technique in which the information (bits) is encoded in the polarization state of the optical carrier wave
- However it is not practical for fiber optic communication due to:
  - Optical fibers do not maintain a stable polarization state during transmission
  - Small mechanical stresses, temperature changes, and bends in the fiber cause random polarization rotation
  - As a result, the polarization state at the receiver can fluctuate unpredictably destroying the information encoded in polarization
  - Requires polarization-sensitive receivers and active polarization controllers, which increase cost and complexity

Summary

- **Optical Modulation:**
  - ✓ encoding information onto a light wave for transmission
- **Optical Modulation Techniques:**
  - ✓ Direct Modulation
  - ✓ External Modulation
- **Line Coding and Pulse shaping:**
  - ✓ Way of representing data bits in the form of electrical wave or pulse
  - ✓ **Common Type of Pulse Shapes:** NRZ and RZ
- **Digital Optical Modulation Schemes:**
  - ✓ ASK (OOK)
  - ✓ PSK: BPSK, DPSK, QPSK
  - ✓ FSK
  - ✓ PolSK (challenging and not practical)

References

[1] Giovanni Ghione,*'' Semiconductor Devices for High-Speed Optoelectronics", CAMBRIDGE UNIVERSITY PRESS*, Pp.356, 2009.

[2] P. J. Winzer and R. J. Essiambre, "*Advanced Optical Modulation Formats*," in Proceedings of the IEEE, vol. 94, no. 5, pp. 952-985, May 2006, doi: 10.1109/JPROC.2006.873438.

[3] Shiva Kumar and M. Jamal Deen, "*Fiber Optic Communication Systems*'', Wiley, Pp.439, 2014.

Thank You !