6. Optical components

Optical Communication Systems and Networks
BIBLIOGRAPHY

- Optical Networks. A practical perspective

- External electro-optic modulators

- Optical passive components: couplers, combiners, isolators, filters, multiplexers, ...
Introduction to optical networks

- **Unidirectional transmission**

- **Bidirectional transmission**
  The same fiber used to carry out traffic in both propagation directions

**Advantages:**
It is achieved an optimization of optical fiber bandwidth and cost savings outside plant

**Disadvantages:**
- a) Special components (circulator) are needed for separating the transmission directions
- b) Most EDFAs have internal insulators that prevent bidirectional transmission
- c) Crosstalk from nonlinear effects
- d) Complex implementation of restoration and protection schemes

Setting up lighpaths along fiber optic links and nodes supporting traffic from a variety of client layer: ATM, IP, ... In the optical layer, comprises:

- Optical transmission medium
- OLT, optical line terminal equipment
  OADM, optical add / drop multiplexer for inserting or removing optical channels
- OXC, optical Crossconnect
Optical transmission medium

Parameters to consider when choosing an optical fiber

- Core and cladding diameters (µm)
- Attenuation coefficient (dB/km)
- Dispersion coefficient D (ps/km·nm)
- Differential Dispersion coefficient (ps/km·nm²)
- PMD parameter (ps/km¹/²)
- Minimum dispersion wavelength (µm)
- Cutoff wavelength (µm)
- Nonlinear refractive index
- Modal field diameter / effective area (µm)

Band descriptors defined by ITU to operate in minimum loss spectral region

<table>
<thead>
<tr>
<th>Band</th>
<th>Descriptor</th>
<th>Spectral range (nm)</th>
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<tbody>
<tr>
<td>O</td>
<td>Original</td>
<td>1260 – 1360</td>
</tr>
<tr>
<td>E</td>
<td>Extended</td>
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<tr>
<td>S</td>
<td>Short</td>
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<td>C</td>
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<tr>
<td>L</td>
<td>Long</td>
<td>1565 – 1625</td>
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<tr>
<td>U</td>
<td>Ultra-long</td>
<td>1625 - 1675</td>
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</tbody>
</table>
Optical transmission medium

**Standard Single Mode Fiber, SSMF**
- Represents 95% of installed outside plant (> 100 million km)
- Standardized by ITU-G.652 recommendation
- Used for transmission within the spectral range 1260 - 1675 nm, except E and S bands
- Presents high dispersion between 1530 - 1675 nm spectral region
  
  It requires dispersion compensation for long distances

**Main applications:**
- Operation at 1310 nm in CATV and MAN networks
- Operation at 1550nm over long distances

**Typical Dispersion profile**

![Dispersion profile graph](image.png)
Optical transmission medium

Dispersion Shifted Fiber, DSF

- By a geometric modification of the refractive index profile the minimum dispersion wavelength is shifted from 2nd to 3rd communications window
- Loss slightly higher than SSMF (0.25 dB / km @ 1550 nm)
- Not suitable for WDM since D = 0 ps/km·nm and small $A_{\text{eff}}$ increases nonlinear effects considerably
- For example, the effective area is typically lower than 40 µm$^2$
- Suitable for single-channel systems.

Typical Dispersion profile

![Dispersion Profile Graph](image-url)
Optical transmission medium

Non-Zero Dispersion Fiber, NZDSF

- Low dispersion D in 3rd window but not negligible
- Dispersion can be positive or negative, and sign to get a zero total dispersion using the concept of dispersion management
- Standardized by ITU-G.652 recommendation

Applications:

- high-speed communications and long distances networks
- Not suitable for transmission at 1310 nm
- Available for DWDM technology

Typical Dispersion profile
OLTs take care of multiplexing and demultiplexing multiple wavelengths (or optical channels) on the same fiber.

- They are used in point-to-point or in the terminal stage of the link.
- They are built from relatively simple elements, mainly composed by multiplexer devices, wavelength converters (transponder/repeaters) and optical amplifiers.

**Optical Node: OLT function**

- SDH
- Router IP
- O/E/O (transponder)
- OC S
- 
- 
- 
- 
- Signals managed in electrical domain
- Signals managed in optical domain

**Client protocols**

**Tema 6: Redes WDM**

**Optical line terminal equipment, OLT**

**Optical Communication Systems and Networks**
Optical line terminal equipment, OLT

- OTL presents adaptation functions: the wavelength conversion according to standards set by the International Telecommunications Union (ITU)

- Transponders may add additional overhead for purposes of network management

- The adaptation function is typically done through an optical-to-electrical-to-optical (O/E/O) conversion
  - the adaptation can be enabled only in the incoming direction

- The signal coming out of a transponder is multiplexed with other signals at different wavelengths using a wavelength multiplexer

- It exists technological options to implement mux/demux: Fabry-Perot filters, arrayed waveguide gratings, dielectric thin-film filters, or fiber Bragg gratings

- OLT can be terminated with an optical supervisory channel (OSC) on a separate wavelength to monitor the performance of amplifiers
Optical line terminal equipment, OLT

Optical Multiplexers

- The function of the multiplexer is to couple two or more wavelengths in the same optical fiber

  (the demultiplexer is responsible for performing the inverse operation, to separate the various wavelengths comprising the WDM signal from an optical fiber)

- Multiplexer requirements:
  - Low insertion losses
  - Independent losses of the polarization state
  - Steep skirts (reduce crosstalk)
  - Flat passbands (prevent a reduction in bandwidth in cascaded stages) and insensitive to temperature variations
  - Inexpensive devices

- Technological options considered for the implementation of multiplexers are considering in the following devices.
Optical line terminal equipment, OLT

**Fabry – Perot filters**

- FP filter is a dielectric resonant cavity (*etalon*), formed by two highly reflective mirrors placed parallel to each other.
- It has been used for WDM applications although there are better filters nowadays.

\[
E_{out} = E_{in} \cdot t_1 t_2 e^{-j\beta l} + t_1 t_2 r_1 r_2 e^{-j3\beta l} + \ldots
\]

The electric field at the output is the sum of successive transmitted fields:

\[
E_{out} = E_{in} \cdot t_1 t_2 e^{-j\beta l} (1 + r_1 r_2 e^{-2j\beta l} + r_1^2 r_2^2 e^{-4j\beta l} + \ldots)
\]
Optical line terminal equipment, OLT

Considering the associated periodic Transfer Function $T(f)$:

$$T(f) = \left| \frac{E_{out}}{E_{in}} \right|^2 = \frac{(1 - A - R)^2}{(1 - R)^2 + 4R\sin^2(\frac{\pi f}{FSR})}$$

Where $R = |r_i|^2$, $A$ takes into account intracavity losses (defined in power) and it is defined as:

$$A = 1 - (R + T)$$

The period is defined through the parameter FSR or free spectral range:

$$FSR = \frac{c}{2nl}$$
Optical line terminal equipment, OLT

There are several parameters to evaluate the performance or quality of a FP-filter (assuming mirrors reflectivity is near $R\approx 1$):

1) $\text{FWHM}$: Full-width at half maximum

$$FWHM = \frac{c}{2\pi n l} \arcsin \left( \frac{1 - R}{2\sqrt{R}} \right)$$

2) Finesse, $F$

$$F = \frac{FSR}{FWHM} \approx \frac{\pi \sqrt{R}}{1 - R}$$

- **Channel selection**

It must be satisfied $B < FSR$, otherwise crosstalk!
Filters based on Bragg gratings

- These devices are based on the effect Bragg effect acting as selective wavelength reflective mirrors
- They are built by inserting a diffraction grating in the fiber (Bragg grating)
  - A pattern is written in the core of the according to a prestablished periodic variation of the refractive index
  - When light propagates through this pattern, the wavelength satisfying Bragg condition reflects while the remaining wavelengths continue their propagation along the fiber

Bragg condition

\[ \lambda_B = 2n_0 \Lambda_B \]
Optical line terminal equipment, OLT

- Filters based on Bragg gratings
- They are usually combined with optical circulators to operate as optical add-drop multiplexers
- Although insertion loss is negligible, it increases up to ~3 dB when they are configured as OADM due to the inclusion of circulators
- Channel spacing of 100 GHz and 50 are achieved, keeping a low adjacent channel crosstalk

Other advantages:
- Easy coupling to other fibers
- Insensitivity to polarization loss
- Reduced cost
- Active control of temperature not required

- In the design of an OADM, it is important to consider the pass-band narrowing after propagating along a OADM cascaded stages (crosstalk and losses)
- OADM device manipulates only the extracted signals without affecting those which traversing the node, thereby reducing undesirable effects.
Dropping a channel in a WDM system

- The reflection spectrum is obtained as the Fourier transform of the index distribution
- The bandwidth is inversely proportional to the length of the grating (a few millimeters long provides a bandwidth ~1 nm)

Add/Drop function based on Bragg fiber gratings (Also available a coupler-based solution replacing 2nd circulator)
Thin Film Multicavity Filters

- A multilayer dielectric thin film filter (TFF) is based on a Fabry-Perot interferometer consisting of multiple cavities surrounded by multiple reflective dielectric thin film layers.

- This device acts as a bandpass filter where a particular wavelength passes through and the rest are reflected is determined by the length of each cavity.

- The filter response is determined by the number of cavities: as the number increases the top of the passband becomes flatter and the skirts become steeper.
Optical line terminal equipment, OLT

Implementation as a multiplexer / demultiplexer:

- Presence of lenses with graded refractive index for confining and directing at a certain angle the signal to the next filter
- Each filter allows a specific range of wavelength of light to pass through to reflect the rest to the next filter in the cascade arrangement

Main features:
- Efficient configuration: access only to channels to be removed and inserted without affecting the rest of the wavelengths passing through
- Flat Passbands and very steep skirts
- Stability to temperature variations
- Low losses
- Insensitive to the signal polarization
- Each extracted wavelength from the WDM signal is injected into a separate fiber
- Passive nature makes them especially useful in distribution network (cost saving)
Optical line terminal equipment, OLT

Arrayed waveguide gratings, AWGs

- It consists of two couplers interconnected by an array of waveguides.
- Two copies of the same signal but shifted in phase by different amounts are added together.
- AWGs can be used as an $n \times 1$ wavelength multiplexers: an $n$-input, 1-output device where the $n$ inputs are signals at different wavelengths that are combined onto the single output.
- Demultiplexing is performed by the inverse of this function ($1 \times n$ wavelengths).
Fixed Optical crossconnect. Static wavelength switch routes signals from an input port to an output port on basis a predesigned assignment.
Introduction to optical components

- Passive optical devices act on signals propagating through them. Among the various functions they perform are not included the generation, transmission, amplification and optical detection.

- Matrix formalism is used for describing polarization phenomena and applications. There are several methods:
  - For devices which are not affected by the polarization state of the signal (not alter the state of polarization with respect to the signal input):
    - **Scattering matrix**: relates outgoing fields with incoming electrical fields
    - **Transfer matrix**: relates incoming and outgoing fields of an even number of ports on the left side of the optical component with the incoming and outgoing fields of an even number of ports on its right
  - **Jones Matrix** describes the change or modification of the optical signal polarization state when an optical signal goes through an optical device
    - It is used in polarizers, polarization rotators, wave retarders, isolators, or polarization splitters and combiners

- It is very common the use of parameters expressed in dB from manufacturers datasheets which provide information about the power distribution among different ports.
Optical Communication Systems and Networks

**System of coupled linear differential equations**

\[
\frac{dE_1}{dz} = -j\beta_1 E_1 + c_{12} E_2 \\
\frac{dE_2}{dz} = -j\beta_2 E_2 + c_{21} E_1
\]

where \( c_{ij} = \text{coupling coefficient} \)

**Power definition**

\[
P_1(z) = |E_1(z)|^2 = P_1(0)(1 - k) \\
P_2(z) = |E_2(z)|^2 = P_1(0)k
\]

where \( k = \text{sen}^2(cL) \) is the coupling ratio

\[
\begin{pmatrix}
E_1(z) \\
E_2(z)
\end{pmatrix} =
\begin{pmatrix}
\cos(cz) & j\text{sen}(cz) \\
j\text{sen}(cz) & \cos(cz)
\end{pmatrix}
\begin{pmatrix}
E_1(0) \\
E_2(0)
\end{pmatrix}
\]

\[
\begin{pmatrix}
E_1(z) \\
E_2(z)
\end{pmatrix} =
\begin{pmatrix}
\sqrt{1-k} & j\sqrt{k} \\
j\sqrt{k} & \sqrt{1-k}
\end{pmatrix}
\begin{pmatrix}
E_1(0) \\
E_2(0)
\end{pmatrix}
\]
Optical passive Components:
COUPLERS/COMBINERS

Incoming energy from $M=2$ input waveguides is distributed into $N=2$ output waveguides

$$P_1(0) \quad P_1(L) = P_3$$

$$P_2(0) \quad P_2(L) = P_4$$

OPTICAL COUPLER
$M=2 \times N=2$

Optical coupler response

$$\frac{P_1(z)}{P_1(0)}$$

$$\frac{P_2(z)}{P_2(0)}$$

Normalized distance
Optical passive Components: COUPLERS/COMBINERS

There are different technological options to implement combiners. The most usual are:

- Based on optical fibers
  - Fusion
  - Polishing

- Based on integrated optics
  - Deposition
  - Ionic-exchange

Operation principle: evanescent field or modal interference coupling
Optical passive Components: COUPLERS/COMBINERS

Insertion Loss: loss experimented by the signal when it propagates according to a particular configuration input-output ports

\[ L_I = L_i(dB) = 10\log \left( \frac{P_1}{P_3} \right) \]

Coupling parameter: provides information about how power is distributed among output ports

\[ k = \frac{P_4}{P_3 + P_4} \]

Excess Loss: ratio of total power at all output ports with respect to the input power.

\[ L_E = \Gamma(dB) = 10\log(\gamma) = 10\log \left( \frac{P_1}{P_3 + P_4} \right) \]

Directivity represents the power fraction at the input port which is back-propagated to other input ports

\[ D(dB) = 10\log \left( \frac{P_2}{P_1} \right) \]
Optical passive Components: COUPLERS/COMBINERS

Directional Coupler M x N

M Inputs

Inputs (i, i')

MxN

Outputs (k, k')

N outputs

Input power is distributed equally through all output ports (excess loss negligible)

Output power = Input power/N – excess loss

\[ L_{I_{ik}}(dB) = -10 \log \frac{P_k}{P_i} \]

Uniformity

\[ U = L_{I_{\text{max}}} - L_{I_{\text{min}}} \]

\[ L_{E_i}(dB) = 10 \log \gamma_i = -10 \log \frac{\sum_{j=1}^{N} P_{ij}}{P_i} \]

\[ D_{ii'}(dB) = -10 \log \frac{P_{i'}}{P_i} \]

Coupler N x N

N x N coupler built from \(\log_2 N\) stages of elemental 2x2 couplers

\[ L_i = L_{\text{dis}} + L_E \]

Distribution loss

Optical Communication Systems and Networks
Optical passive Components:
MULTIPLEXERS/DEMULTIPLEXERS

MULTIPLEXOR

λ₁ → λ₁ + λ₂
λ₂ → λ₁ + λ₂

DEMULTIPLEXOR

λ₁ + λ₂ → λ₁
λ₁ + λ₂ → λ₂

Multiplex/demultiplex functions can be also performed by filter technology (FP-Fabry-Perot Filters, AWG-Arrayed Waveguide Gratings, TFMF-Thin Film multilayer Filters)
Passive components acting on polarization state

Polarizers:

Allows the propagation of the linear polarization component of the electric field aligned in the direction of its transmitting axis, blocking the propagation of the orthogonal component.

Technological options:

1. Absorption or selective loss
2. Selective reflection in isotropic materials
3. Selective refraction in birefringent materials

In practice, the orthogonal polarization is not completely suppressed and the passing polarization component (parallel to the optical axis) suffers losses, unlike an ideal polarizer.

Operating parameters:

**Insertion Loss:**

\[ L_i(dB) = 10 \log_{10} \left( \frac{P_{in \parallel}}{P_{out \parallel}} \right) \]

**Extinction ratio:**

\[ R_{ext}(dB) = 10 \log_{10} \left( \frac{P_{out \parallel}}{P_{out \perp}} \right) \]
Passive components acting on polarization state

Wave retarder:

Introduces a relative phase shift $\Gamma$ (phase retardation) between the horizontal and vertical states of the electric field.

They are implemented by using bulk optics (anisotropic media): birefringent films with a thickness $d$ with a particular refractive index $n_h$ for horizontal polarization (slow axis), and a different refractive index $n_v$ for vertical polarization (fast axis). Then:

$$\Gamma = \frac{2\pi d}{\lambda} (n_h - n_v)$$

Transmittance = $\sin^2 \frac{\Gamma}{2}$

Quarter wave retarder

When $\Gamma = \pi/2$, the initial linearly polarized signal (at 45° with respect to x axes) is transformed to a left-hand circular polarization.

Half-wave retarder

When $\Gamma = \pi$, the initial linearly polarized wave forming 45° with x axis is converted to another linearly polarized wave forming -45° with x axis (polarization rotation 90°).
Passive components acting on polarization state

**Wave retarder:**

Introduces a relative phase shift $\Gamma$ (phase retardation) between the horizontal and vertical states of the electric field.

They are implemented by using bulk optics (anisotropic media): birefringent films with a thickness $d$ with a particular refractive index $n_h$ for horizontal polarization (slow axis), and a different refractive index $n_v$ for vertical polarization (fast axis). Then:

$$\Gamma = \frac{2\pi d}{\lambda} (n_h - n_v)$$

**Transmittance**

$$\text{Transmittance} = \sin^2 \frac{\Gamma}{2}$$

**Application:** Intensity control $\rightarrow$ wave retarder + 2 polarizers (crossed config.)
Passive components acting on polarization state

**Polarization Rotators:**

A polarization rotator produces a rotation of the polarization plane of a linearly polarized wave by a fixed angle \( \theta \), maintaining the linearly polarized property.

It is required materials in which a magnetic field \( B \) produces the rotation of the polarization direction of linearly polarized wave. This property is called **Faraday effect**.

\[
\theta = V B d
\]

where \( V \) is the Verdet constant and its value depends on the material used (\( n \), refractive index and \( \gamma \) magneto-optical rotation coefficient) and wavelength:

\[
V = -\frac{\pi \gamma}{\lambda n}
\]

**Materials with Faraday effect:**

- Terbium gallium garnet (TGG), terbium aluminum garnet (TbAlG), and yttrium iron garnet (YIG).
- Bismuth garnets (GdB\text{Bi}G and TbBiIG) are used in 1550 nm
Passive components acting on polarization state

**Optical Isolator:**

Transmits light in only one direction, preventing reflected light from returning back to the source.

![Diagram of an Optical isolator](image)

**Insertion Loss**, considers the power loss when light propagation is in the direction (1→2):

$$L_i(dB) = 10 \log_{10} \left( \frac{P_{in(1)}}{P_{out(2)}} \right)$$

**Isolation ratio**, provides the ratio between the power transmitted through port 1 when optical power is introduced in port 2:

$$I(dB) = 10 \log_{10} \left( \frac{P_{in(2)}}{P_{out(1)}} \right)$$
Passive components acting on polarization state

Optical Isolator:

- **Transmitted wave**
  - Incident wave
  - Polarizer A
  - Faraday Rotator
  - Polarizer B
  - Transmitted wave

- **Reflected wave**
  - Incident wave
  - Polarizer A
  - Faraday Rotator
  - Polarizer B
  - Reflected wave

- **Blocking transmitted signal**
  - Incident wave
  - Polarizer A
  - Faraday Rotator
  - Polarizer B
  - Blocking transmitted signal
Optical passive Components:

**OPTICAL ATTENUATORS**

- Reduce the power level at their entrance
- Allow to adjust properly power levels at the optical devices input ports for a correct performance
- Can provide a fixed or variable attenuation

**Fixed attenuator**

**Variable attenuator**

**Fixed/variable attenuators by transversal or longitudinal displacement**
Optical passive Components: OPTICAL CIRCULATORS

Circulators allow adding and dropping optical channels in a WDM signal, processing optical headers and selective optical processing functions when they are combined with other optical devices.

The signal injected into the port 1 goes directly to the port 2. When a signal is introduced in 2, it exits through the port 3. And a signal comes through 1 when it has been previously introduced in port 3.

Adding or dropping channels in WDM systems

Wavelengths at the input $\lambda_1 \lambda_2 \lambda_3 \lambda_4$

Bragg grating tuned at $\lambda_3$

Wavelengths at the output $\lambda_1 \lambda_2 \lambda_3 \lambda_4$

Dropped wavelength: $\lambda_3$
EXTERNAL MODULATORS

Optical sources directly modulated at high frequencies in systems based on intensity modulation (IM) can introduce chirp when semiconductor laser diodes are used as transmitter, increasing the dispersion effects, and then, limiting the maximum bit rate.

- Solution: EXTERNAL MODULATION

After biasing semiconductor lasers by a constant current, the continuous wave emission (CW) is injected into an external device (external modulator) which superimposes a copy of the electrical information signal, providing the optical signal modulated at the output. This will eliminate or reduce the chirp to negligible values.
EXTERNAL MODULATORS

• There are two main techniques to implement external modulators with features such as fast response, simplicity and compacticity required in optical systems:

1) Electro-optic Modulators
   Intensity and phase modulation are achieved
   Based on ferro-electric crystals like lithium niobate (LiNbO3)
   Currently, the use of polymers is being investigated for this purpose

2) Electro-absorption Modulators
   Operation based on intensity modulation and usually built in semiconductor technology
EXTERNAL MODULATORS: Electro-optic effect

- EO effect is responsible for the refractive index change in electro-optic materials by applying an external field (Pockels effect).

- External modulators take advantage of this effect to modulate the optical carrier in phase or intensity.

- Crystals used in modulators are anisotropic, in which refractive index depends on the polarization direction of the electric field (optical signal).

- To produce an intense effect, the access to $r_{33}$ coefficient, the greatest element in the electro-optic tensor, is required. This is achieved when the electric field polarization is parallel to the crystal’s optical axis:

$$n(E) = n_0 \pm \frac{1}{2} n_0^3 r_{33} E$$

- $n_0$ = refractive index in absence of electric field
- $n(E)$ = refractive index when electric field is applied
- $r_{33}$ = electro-optic effect
- $E$ = Applied electric field component according to the optical axis
EXTERNAL MODULATORS: Electro-optic effect

$$\vec{E}_i(\omega) = E_{oi} \exp[-j\omega n/c]$$

LiNbO$_3$ crystal (anisotropic crystal)

$$n(E) = n_0 \pm \frac{1}{2} n_0^3 r_{33} E$$

With typical values of LiNbO$_3$

$$n_0 \approx 2.2 \quad r_{33} \approx 30 \ pm/V$$
EXTERNAL MODULATORS: Electro-optic effect

The incident wave must be polarized.

\[ V = \frac{\lambda}{r_{33}n_0^3 L} \]

Values in the range \( \sim 2-5 \) V
EXTERNAL MODULATORS: Electro-optic effect

TRANSVERSAL CONFIGURATION

LONGITUDINAL CONFIGURATION
Applications: Electro-optic modulator for intensity modulation (Polarization configuration)

Optical intensity modulator based on Pockels cell between crossed polarizers

Optical Transmittance

Output polarizer

Oriented at 45 degrees with respect to the optical axis

Voltage, V

Transmittance (V)

V_{bias}

V_{\pi}
Applications: Electro-optic modulator for intensity modulation (Interferometer configuration)

Intensity modulator based on Mach-Zehnder Interferometer

- Guide configurations allow reduced values of $d/L$ ($d \sim 10 \, \mu m$, $L \sim 10 \, cm \rightarrow d/L \sim 10^{-3}$), providing reduced control voltages $V_{\pi} \sim 1-2 \, V$.
- The commercial electro-modulators allow modulation bandwidths of $\sim 40 \, GHz$.
Example: Use of Mach-Zehnder configuration in a RZ-coding intensity modulation

- When a MZM Mach-Zehnder modulator is driven by a voltage:

\[ V_m(t) = V_{bias} + V_{RF}(t) = V_{bias} + V_{RF} \cos(2\pi ft + \phi_m) \]

where \( V_{bias} \) is the DC voltage, \( V_{RF} \) is the amplitude of the RF signal, \( f \) is the modulation frequency and \( \phi_m \) the phase shift.

- The transmittance can be expressed as:

\[ T(t) \propto \cos^2 \left( \frac{\pi V_m(t)}{2V_\pi} + \frac{\theta}{2} \right) = \cos^2 \left( \frac{\pi V_{bias}}{2V_\pi} + \frac{\pi V_{RF}(t)}{2V_\pi} + \frac{\theta}{2} \right) \]

where \( \theta \) is the MZM phase shift in absence of exciting voltage and \( V_\pi \) is the \( \pi \)-phase voltage.

- Then:
  - If \( V_{bias} = V_{max} \Rightarrow \) the MZM is biased to offer maximum optical transmission
  - If \( V_{bias} = V_{min} \Rightarrow \) the MZM is biased to offer minimum optical transmission
  - MZM interferometer can be also driven in a balanced performance.
Example: Return to zero implementation for different duty cycles

RZ – 50%

RZ – 33%

RZ – 67%
Example: Return to zero implementation for different duty cycles

- Techniques to generate RZ coding signal:
  - Directly modulated diode laser by an electrical RZ signal (intensity)
  - Generating an optical pulse train modulated by a no return to zero data signal
Return to zero schemes

RZ pulse of three duty cycles for a bit sequence: 1001101

- **RZ – 50%**
  - The red bar indicates the full-width at half maximum and duty cycle
  - $\pi$ and 0 indicate phase shift in RZ CS-RZ-67%.

- **RZ – 33%**

- **RZ – 67%**

Frequency with regard to the optical carrier [GHz]
Power [dBm]
MAIN OPTICAL SWITCHING TECHNOLOGIES

- Bulk opto-mechanical switches
- Micro-electro-mechanical (MEMs) switches
- Bubble-based waveguide switches
- Electro-optical switches
- Thermo-optic switches
OPTICAL COMPONENTS: Micro-electro-mechanical switch (MEM)

- 2D MEMS: switching takes places in a 2D silicon substrate, where rows of micromirrors can be fold up or down (by electromagnetic, electrostatic or piezoelectric method) to deflect incident beams
- 3D MEMS: steering mirrors allow switching in 3D. It is obtained a drastically increase of the number of ports, providing more compact devices (from 256 to over 1000 ports)
- **Advantages**: fast response, high integration and number of ports
OPTICAL COMPONENTS: Bubble-based waveguide switch

- Under normal conditions, light propagates straight on crossover points, without interruption.
- Switching is performed as a result of the bubble formation after heating the crossover point by termo-electric actuators.
  - The light beam is reflected towards the corresponding waveguide to the desired output port.
OPTICAL COMPONENTS:
Switch based on integrated Mach-Zehnder interferometers
(Electro-optic control)

- In directional coupler configuration, the coupling ratio varies by changing electro-optically the refractive index

- **Advantage:** Fast response (typically, less than 1 ns) and high level of integration

- **Disadvantages:** Usually have a relatively high loss and PDL
OPTICAL COMPONENTS:
Switch based on integrated Mach-Zehnder interferometers
(Thermo-optic control)

- In directional coupler configuration, the coupling ratio varies by changing thermo-optically the refractive index

- **Main disadvantage:** Quite slow response (milliseconds)
Comparison of different optical switching technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Size</th>
<th>Loss (dB)</th>
<th>Crosstalk (dB)</th>
<th>PDL (dB)</th>
<th>Switching time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk-mechanical</td>
<td>8 x 8</td>
<td>3</td>
<td>55</td>
<td>0,2</td>
<td>10 ms</td>
</tr>
<tr>
<td>2D-MEMs</td>
<td>32x32</td>
<td>5</td>
<td>55</td>
<td>0,2</td>
<td>10 ms</td>
</tr>
<tr>
<td>3D-MEMs</td>
<td>1000x1000</td>
<td>5</td>
<td>55</td>
<td>0,5</td>
<td>10 ms</td>
</tr>
<tr>
<td>Bubble-based</td>
<td>32x32</td>
<td>7,5</td>
<td>50</td>
<td>0,3</td>
<td>10 ms</td>
</tr>
<tr>
<td>Thermo-optic</td>
<td>8x8</td>
<td>8</td>
<td>40</td>
<td>Low</td>
<td>3 ms</td>
</tr>
<tr>
<td>Electro-optic</td>
<td>4x4</td>
<td>8</td>
<td>35</td>
<td>1</td>
<td>10 ps</td>
</tr>
</tbody>
</table>