Module 12 - System Architecture & Design

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Introduction

Optical communication systems use electromagnetic waves ("light" in the near infrared wavelength regime) as the carrier of information. Thus, quite naturally, two media come to mind for transmitting the optical signals: air and glass. Consequently, optical communication systems are implemented in two ways:

- as free-space optical systems (with air as the transmission medium) and
- as fiber optic systems (with fused silica as the material for a waveguide in the form of an optical fiber). We limit the scope of this course to optical glass fibers, excluding plastic optical fibers (POF).

Free-space optical systems are mainly used for two applications:

(1) As permanent back-up links within a larger network in order to protect a specific link from being disabled and to ensure the resilience of the network. Such systems (or networks) where an optical path consists of multiple links using different media (here: free-space and optical fibers) are often called hybrid systems (or hybrid networks).

(2) As temporary links when a communication line is needed only for a limited time (e.g. sports event, disaster recovery).

Typical free-space optical systems operate at data rates in the Mbit/s regime, utilize a single wavelength, and bridge distances of several hundred yards.

Free-space optical systems are not within the scope of this course; we focus on fiber optic systems, specifically those using single-mode fibers operated in the near infrared wavelength regime around 1550 nm.

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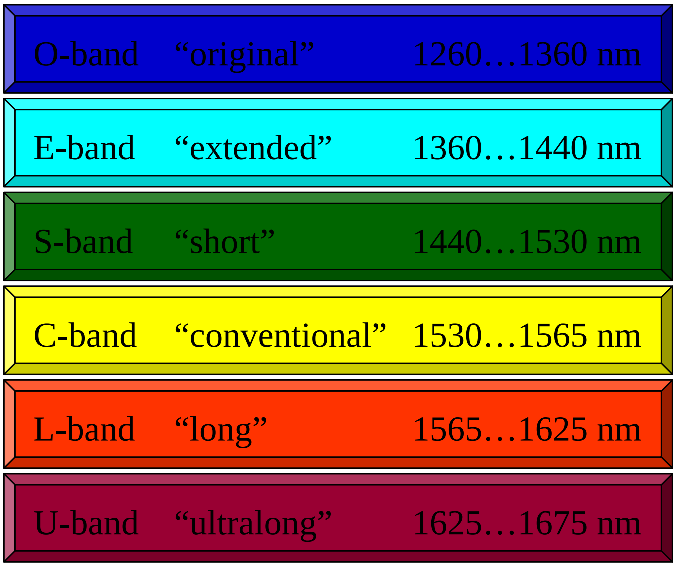
This wavelength regime around 1550 nm is also known as:

(1) *The 3rd optical window* – because it is the third wavelength regime used in optical communications.

The 1st optical window is located around 850 nm, where the first generation of optical communication systems was introduced in the mid 1970s, utilizing GaAs multimode laser diodes, multimode graded index fibers, and Si detectors.

The 2nd optical window is located around 1310 nm, where the second generation of optical communication systems was introduced in the late 1970s / early 1980s, utilizing InGaAsP multimode laser diodes, single-mode step index fibers (SMF), and Ge detectors.

The third generation of optical communication systems operating in *the 3rd optical window* was introduced in the mid 1980s, utilizing single-mode InGaAsP laser diodes, SMF, and InGaAs detectors.



O-band	“original”	1260…1360 nm
E-band	“extended”	1360…1440 nm
S-band	“short”	1440…1530 nm
C-band	“conventional”	1530…1565 nm
L-band	“long”	1565…1625 nm
U-band	“ultralong”	1625…1675 nm

Figure 12.1: ***Wavelength (transmission) bands in modern optical communication systems.***

(2) *The EDFA band* – because if coincides with the wavelength band covered by an erbium-doped fiber amplifier (EDFA).

(3) *The C-band* – where C stands for *conventional* because it is the most commonly used bandwidth regime in modern optical communication systems. Other spectral bands, although not formally standardized, are listed in **Figure 12.1** below by the names by which they are commonly known.

12.1 Telecommunications Network Framework

Network Layers

Before looking into the inner design of a fiber optic transmission system, we like to know where exactly it is located within the larger landscape of a complete telecommunication network. All telecommunications, telecommunication networks, and telecommunication systems are structured in seven *layers* according to the *Open Systems Interconnection (OSI) International Standards Organization (ISO) reference model*. Each layer performs specific functions providing service to the layer above it and receiving service from the layer below it. The seven layers of the OSI reference model as shown in **Figure 12.2**.

7-Application	Allows applications to access network services, e.g. File Transfer Protocol "FTP" and Simple Mail Transfer Protocol "SMTP" operate here.
6-Presentation	Manages data compression, encryption, conversion.
5-Session	Establishes and maintains communication between applications.
4-Transport	Transmits data, e.g. Transmission Control Protocol "TCP" operates at this level.
3-Network	Routes data between nodes, handles network or logical addressing, e.g. Internet Protocol "IP" operates at this level.
2-Datalink	Handles physical addressing, packs data into frames, e.g. Ethernet or Asynchronous Transfer Modus "ATM" operate here.
1-Physical	Transmits data over the network medium, e.g. Synchronous Optical Network "SONET" or "Optical Transport Network "OTN" protocols operate here.

Figure 12.2: *The seven layers of the OSI reference model of a telecommunication system.*

In this stack of layers, fiber optic transmission systems are part of Layer 1, the Physical Layer. Since this abstract structure was developed before optical communications became a commodity, fiber optic components were not explicitly addressed. Originally, Layer 1 referred to electrical data transmission, e.g. in accordance with Plesiochronous and Synchronous Digital Hierarchy (PDH, SDH) protocols. More recently, electrical transmission has been complemented with and/or replaced by optical transmission, and only today are we in the middle of the process of optical network functionalities (e.g. optical add-drop multiplexers and optical cross-connects) being introduced into telecommunication networks. Thus, they are not represented by the OSI reference model to the extent they should be. Often, optical transmission systems, optical network elements and their respective functionalities are referred to as *Layer 0*, the *Optical Layer*.

Now, after some aspects of the framework have been elaborated, we can move forward and look into our fiber optic transmission system in order to understand how it is designed.

An optical transmitter generates an optical signal, which is transmitted over an optical transmission line and received by an optical receiver, as shown in **Figure 12.3**, top. This would describe a unidirectional transmission line. Because in almost all applications the communication is intended to be bidirectional, we need to change the configuration slightly: We will place a transmitter and a receiver at both ends and we will integrate them into one device – which then will be called a transceiver. Two transmission lines are now connecting the transceivers (**Figure 12.3**, bottom), one for each direction. Note: The transmission line, as we define it, is not only a bare fiber, it may consist of transmission fibers and amplifiers (if necessary) and dispersion compensating elements (if necessary) and other network elements if required by the system or network design.

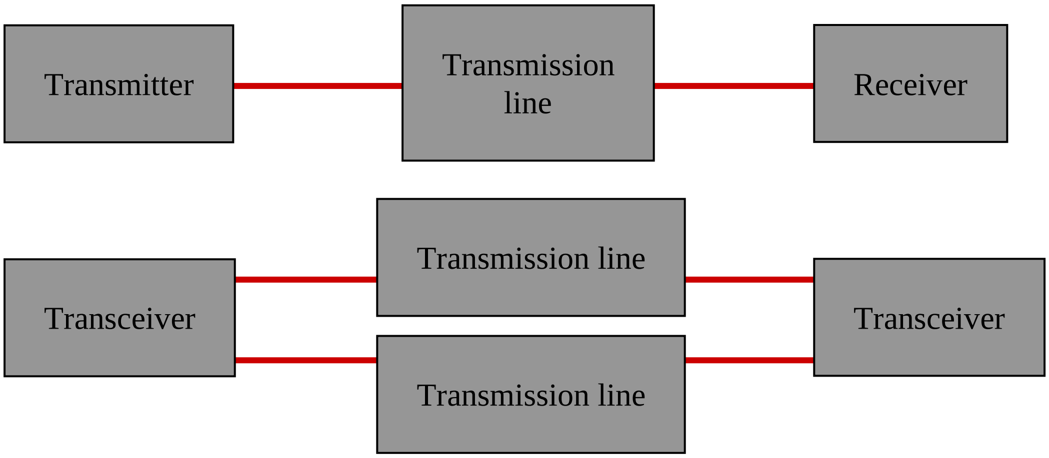


Figure 12.3: ***Unidirectional transmission system (top), bidirectional transmission system (bottom).***

Multiplexing

So far, our system operates at one single wavelength. The transmitter generates an optical signal at an arbitrary wavelength within the third optical window. This signal is transmitted over the transmission line – one signal per fiber – and received. The same is true for the reverse direction. From previous modules, we know the optical fiber as well as the EDFA supports multiple wavelengths. Let us take advantage of this multiwavelength capability of two of the system's

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main building blocks and build a *wavelength division multiplexing (WDM) system*.[1] WDM takes advantage of the fact that electromagnetic waves – the carries of the data stream we want to transmit – at different wavelengths can propagate through a medium in parallel without interfering with each other.

In order to make efficient use of the available bandwidth of the fiber and of the EDFA, the specific wavelengths to be used have been standardized and two wavelength grids have been defined.

For dense WDM (DWDM) the wavelength grid follows ITU-T recommendation G.692. It is centered around 1544.53 nm (194.1 THz) with a standard spacing between DWDM channels of 100 GHz. Note: Indeed, DWDM channels are spaced equidistantly in units of frequency – not in units of wavelength! Channels in-between – at 50 and 25 GHz spacing – are also defined.

Example: If we were to estimate how many DWDM channels could be transmitted within the C-band, we would first calculate the channels spacing in units of wavelength $\Delta\lambda = \frac{c\cdot\Delta f}{f^2} = \frac{3\cdot 10^8\,\frac{m}{s}\cdot 100\,\mathrm{GHz}}{(194.1\,\mathrm{THz})^2} = 0.8\,\mathrm{nm}$ *and then distribute the channels equally across the band* $\frac{\Delta\lambda_{\mathrm{C-band}}}{\Delta\lambda} = \frac{35\,\mathrm{nm}}{0.8\,\mathrm{nm}} \approx 44$ *leading to a channel count of 44 DWDM channels.*

For coarse WDM (CDMA), the wavelength grid follows ITU-T recommendation G.694. The nominal central wavelengths range from 1270 nm through 1610 nm on a 20-nm grid. Note: Here, for CWDM, the channels are spaced equidistantly in units of wavelength – not in units of frequency.

In order to build a DWDM system we first need a DWDM transmitter. Very often, the DWDM transmitter is part of a DWDM transponder. One implementation of a DWDM transponder as used in one of the terminals of a modern DWDM transmission system may look like the example given in **Figure 12.4**. DWDM is a technology specific to Layer 0. In other words, multiple channels at selected wavelengths located at a standardized wavelength grid and multiplexed in the wavelength domain cannot be found in the higher layers. However, at the same time our DWDM system – located in Layer 0, the Optical Layer – serves systems (e.g. SONET, Ethernet) from these higher layers. That means incoming – optical – signals from higher layer equipment do not necessarily match the DWDM channel grid. The incoming channels are said to be “grey,” the higher layer equipment has “grey” interfaces. These optical channels are received by broadband receivers (Rx), converted into the electrical domain, and regenerated (3R) with respect to the power (re-amplifying), the shape (re-shaping), and the timing (re-timing) of the signals. The regenerated electrical signals are fed into DWDM transmitters – well aligned along

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[1] Other “dimensions” of multiplexing are, e.g., time division multiplexing (TDM), code division multiple access (CDMA), or polarization multiplexing (PM)

our DWDM channel grid from λ_1 through λ_N; they are now “colored” and our DWDM transponder is said to have “colored” line interfaces.

A wavelength division multiplexer (WDM multiplexer) combines the N wavelengths: N input fibers each carrying one wavelength and one output fiber carrying N wavelengths. A booster amplifier (EDFA) boosts the power of the combined signal to the desired level.

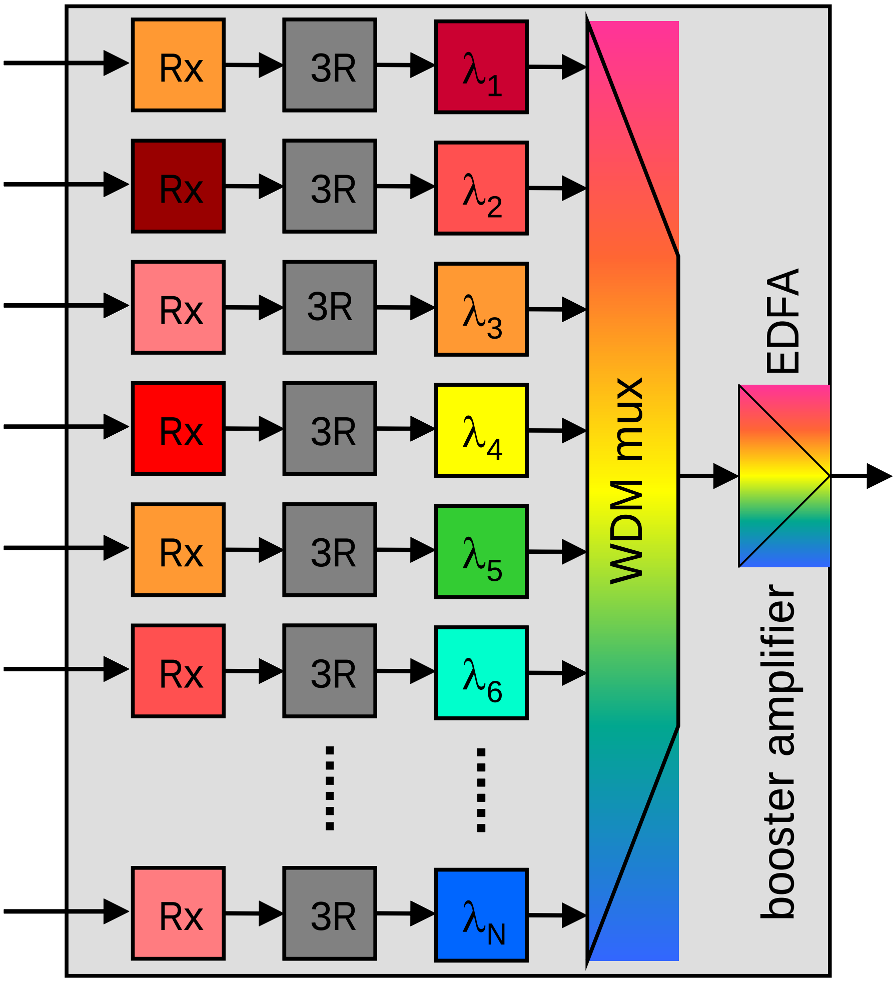

***Figure 12.4**: WDM transponder.*

The transponder not only serves the purpose of wavelength allocation, it is also equipped with long-reach transmitters (designed for long-haul transmission) whereas the client systems possess only short-reach interfaces (designed for rack-to-rack, intra-office, or in-house communication).

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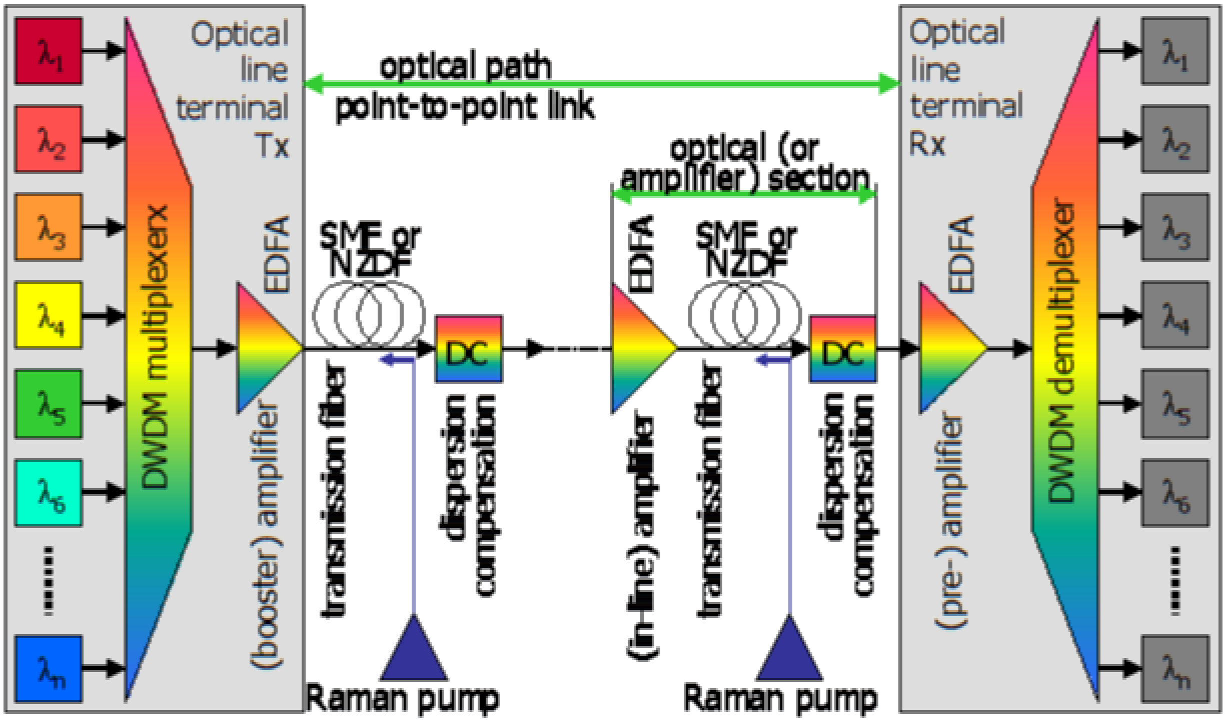

Figure 12.5: *DWDM transmission system consisting of optical line terminals (transmitter Tx and receiver Rx) and optical transmission line.*

Figure 12.5 depicts a complete DWDM transmission system. The optical line terminal at the transmitter (Tx) site houses the colored transmitters, the DWDM multiplexer and the booster amplifier. The DWDM signal, consisting of N wavelength channels, is fed into the transmission line. In our example, the transmission line is a point-to-point link between the respective locations of the optical line terminals. Because this link is transparent (in an optical sense), it is also called the *optical path*. The optical path, in turn, consists of a number of *optical sections*. An optical section typically consists of:

- An optical amplifier (an EDFA) which provides amplification for the DWDM signal (N λ-channels). It compensates for the losses of one section of the optical path and because it is part of the transmission line, it is called an *inline-amplifier*. Moreover, because it provides amplification at the "point" where it is located, it is also called a *lumped amplifier* (in contrast to a *distributed amplifier*, or "Raman amplifier").
- The transmission fiber, which is in the form of an optical cable comprising up to hundreds of single fibers and which bridges the geographical distance between the terminals. Out of the many available fiber types (Table 1), only the standard single-mode fiber (SMF) and the non-zero dispersion fiber (NZDF), is used as transmission fiber for the systems discussed here. The length of the transmission fiber – and thus of the optical section – depends on circumstances given by the installed infrastructure (location of central offices, outdoor cabinets, manholes, etc.) and typically ranges

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from 60 km to 120 km for terrestrial networks. For submarine systems, the sections are shorter; for single point-to-point links, consisting of only one section, they are longer.

- Possibly Raman amplification, which is distributed – not lumped – along the transmission fiber. Current systems do not include Raman amplifiers.
- Dispersion compensation, if needed.

	made of	**utilized wavelength region**	**attenuation**	**core diameter**	**chromatic dispersion**
POF	PMMA	red (650 nm) or infrared	10 dB/km	500…1000 um	0.3 ns/nm/km (material) 0.25 ns/km (modal)
MMF	silica	1st or 2nd window (850 or 1310 nm)	3 / 1 dB/km	62.5 um	-86 ps/nm/km (material) 70 ns/km (modal)
SMF	silica	2nd or 3rd window (1310 or 1550 nm)	0.35 / 0.2 dB/km	9 um	0 or 17 ps/nm/km (chromatic = material + waveguide)
"dry" SMF	silica	2nd to 3rd window (1310 to 1550 nm)	0.35...0.2 dB/km removed H_2O absorption peak at 1400 nm	9 um	0...17 ps/nm/km (chromatic) (depending on wavelength)
DSF	silica	3rd window (1550 nm)	0.2 dB/km	8 um	0...2 ps/nm/km (chromatic)
NZDF	silica	3rd window (1550 nm)	0.2 dB/km	9 um	2…6 ps/nm/km (chromatic)
DM	silica	3rd window (1550 nm)	0.2 dB/km	8 um	-2…-5 ps/nm/km (chromatic)
DCF	silica	3rd window (1550 nm)	0.5 dB/km	6 um	-85 ps/nm/km (chromatic = waveguide + material)

Table 1: *Various fiber types*

Finally, the DWDM signal reaches the receiver terminal. A pre-amplifier increases the signal power, a DWDM demultiplexer separates the DWDM channels, and each wavelength channel is received by a receiver. The electro-optical converters – the photo diodes comprised of the receivers – are not wavelength selective, which means the receivers for all N DWDM channels can be identical.

A convenient way to trace signal and system parameters along the transmission line is to use so-called maps. **Figure 12.6** shows three of such maps.

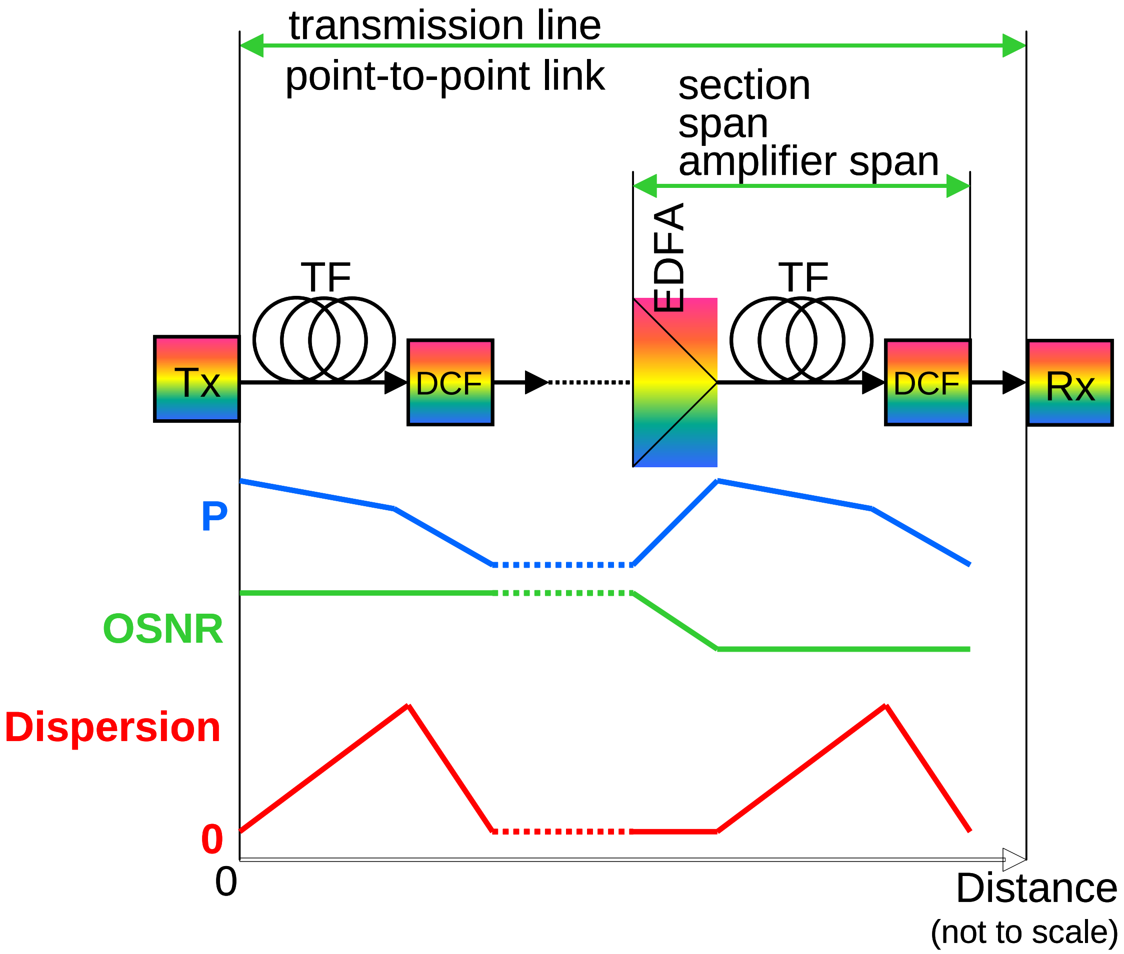

Figure 12.6: *Power (P) map, OSNR map, and dispersion map for a dispersion compensated fiber optic transmission system with lumped (EDFA) amplification.*

The *optical power P* (blue curve, units along the ordinate: mW) fed by the transmitter into the transmission line decreases due to the attenuation of the transmission fiber (α_{TF} = 0.2 dB/km), it decreases slightly faster when it enters the dispersion compensating fiber (DCF) due to the increased attenuation of the DCF (α_{DCF} = 0.5 dB/km), and it gets re-amplified by the EDFA. (Note: Re-amplification takes place over a distance of only a few meters – the length of the erbium-doped fiber insider the EDFA.) Target values for the various elements when designing a system are set by the receiver sensitivity. Typical values are -28 dBm at 2.5 Gbit/s, -16 dBm at 10 bit/s, and -4 dBm at 40 bit/s.

Example: What gain G_{EDFA} in dB is needed in order to fully compensate for the fiber losses within one section if the section consists of 80 km of SMF (D_{SMF} = 16 ps/nm/km) plus a DCF (D_{DCF} = -80 ps/nm/km) which exactly compensated for the transmission fiber's chromatic dispersion?

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$$G_{\mathrm{EDFA}} = L_{\mathrm{SMF}} \cdot \alpha_{\mathrm{SMF}} + L_{\mathrm{DCF}} \cdot \alpha_{\mathrm{DCF}} = L_{\mathrm{SMF}} \cdot \alpha_{\mathrm{SMF}} + \left| \frac{L_{\mathrm{SMF}} \cdot D_{\mathrm{SMF}}}{D_{\mathrm{DFC}}} \right| \cdot \alpha_{\mathrm{DCF}} = 24\ \mathrm{dB}$$

The green curve (units along the ordinate: dB) depicts the evolution of the *optical signal-to-noise ratio OSNR*. Note: only active elements change the OSNR (e.g. due to the amplified spontaneous emission (ASE) of the EDFA), whereas passive elements affect the signal and the noise the same way and the ratio remains unchanged.

The *dispersion* map (red curve, units along the ordinate: psec/nm) shows the accumulated dispersion along the optical path. Here, it increases while the signal propagates through the transmission fiber showing anomalous dispersion and reaches a maximum at the end of the first piece of transmission fiber (e.g. for 80 km of SMF this maximum would be 80 km · 16 psec/nm/km = 1.280 psec/nm). Subsequently, the DCF, showing normal dispersion, compensated for the TF's dispersion and decreases the accumulated dispersion until it reaches zero, meaning the dispersion has been fully compensated. In this example, a post-compensation scheme is applied: the DCF follows the TF. Other schemes are pre-compensation where the order of the fibers is reversed and the TF follows the DCF (rarely used), and alternating compensation where post- and pre-compensated section are aligned along the optical path in an alternating order. (In many cases, this scheme shows superior performance due to the interaction between fiber chromatic dispersion and fiber Kerr nonlinearity. [1,2,3])

12.2 Modulation formats

Fiber optic transmission systems offer various schemes to transmit optical signals (which carry a stream of data containing the information the communicator wants to get across). How does the data stream to be transmitted look? Today's telecommunication is almost exclusively based on digital data where the smallest piece of information, the bit, has two logical states: 0 and 1. In other words, our data stream (or bit stream) consists of a sequence of zeros and ones. The number of bits per unit time is called the bit rate (or data rate) B [bit/s]. Let us remind ourselves how to derive such a binary digital signal from a natural signal, e.g. an acoustic signal in the form of voice.

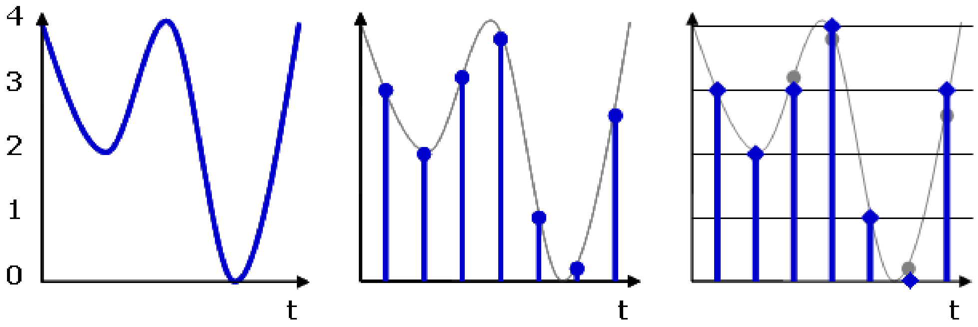

Figure 12.7: *Analog signal (left), time discrete signal (center), time and value discrete signal (right).*

The original – “natural” – signal is time as well as value continuous (**Figure 12.7**, left). After step 1, sampling (Figure 12.7, center), it is still value continuous, but along the time axis it has been discretized and we get a temporally equidistant sequence of values. In order to not loose any information contained in the original signal, we have to obey Nyquist’s theorem and chose the sampling rate f_S to be greater than two times the bandwidth B (see reference 2) of the original signal: $f_S > 2B$. Sampling – obeying Nyqist’s theorem – does not compromise the “quality” of the signal – the original information can be fully recovered at any time without any losses.

We get: 3.00 2.01 3.20 3.80 1.97 0.25 2.65

Next, after step 2, quantization (**Figure 12.7**, right), the signal is both time and value discrete. The quantized values differ from the original values and this difference changes from sample to sample. Thus, it can be regarded as noise and we call it the quantization noise. Quantization noise does compromise the quality of the signal and we want to keep it below a certain threshold depending on the application. The larger the step sizes of the quantization process, the larger the added quantization noise. Or, in other words, the lower the resolution of an analog-to-digital converter (ADC), the larger the added quantization noise.

We get: 3 2 3 4 2 0 3

Finally, in step 3, we binary encode the time and value discrete numbers. In our example, where values only reach from zero to four, a 3-bit encoding is sufficient.

We get: 011010011100010000011

Example: What is the data rate B of a digitized ordinary telephone signal when an ADC with 8-bit resolution is used for quantization?

Knowing the bandwidth B of a traditional phone line is approximately 4 kHz, we estimate: $f_s = 2 \cdot B = 8$ *kHz* $\rightarrow$ *8,000 values per second. Each value will be represented by an 8-bit binary number, thus:* $D = 8\ \text{bit} \cdot 8{,}000\ \text{s}^{-1} = 64\ \text{kbit/s}$.

This bit sequence represents the data signal we are supposed to transmit over our fiber optic DWDM transmission system. It is the – electrical – signal, which is applied to our colored DWDM transmitter, which has been discussed before. The straightforward way to covert the electrical binary digital signal into an optical signal is *on-off-keying (OOK)*. The electrical signal drives an electrical-optical (e-o) converter – usually a laser diode - and the digital “1” is represented by “light on” whereas the digital “0” is represented by “light off” – or vice versa (without losing information we can switch the logical states at any time).

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[2] For our purpose, here, B is equivalent with the highest frequency present in the spectrum of the original signal.

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This – OOK – was just an introductory example. At this point, it is important to take a closer look at the many different schemes of how to represent and transmit digital data by optical signals.

Modulation Schemes

The modulation format (which is sometimes also called the line coding) describes how the data to be transmitted is represented to the transmission line.

The electromagnetic wave, which serves as the carrier of the data, is characterized by its amplitude A_0, its angular frequency ω_0 ($\omega_0 = 2\pi f_0 = 2\pi c/\lambda_0$), its initial phase φ_0, and its state of polarization $\vec{a}_0$:

$$\vec{A} = A_0 \cdot \cos(\omega_0 + \varphi_0) \cdot \vec{a}_0 . \qquad \textit{(Equation 12.1)}$$

Modulation now describes the process of varying one (or more) characteristics of this carrier in accordance with the data signal. Thus, the carrier and its constituting characteristics become time dependent:

$$\vec{A}(t) = A_0(t) \cdot \cos(\omega_0(t) + \varphi_0(t)) \cdot \vec{a}_0(t) . \qquad \textit{(Equation 12.2)}$$

Depending on which characteristic we choose to modulate, we obtain the following basic modulation formats:

- **Amplitude modulation AM:** $\vec{A}(t) = A_0(t) \cdot \cos(\omega_0 + \varphi_0) \cdot \vec{a}_0$.

  AM is also known as amplitude shift keying (ASK) in digital systems or – since the amplitude also determines the intensity of signal – intensity modulation (IM). The specific case where the amplitude is switched between zero and a maximum (representing a logical “0” data bit and a logical “1” data bit, respectively – or vice versa) is called on-off keying (OOK).

- **Frequency modulation FM:** $\vec{A}(t) = A_0 \cdot \cos(\omega_0(t) + \varphi_0) \cdot \vec{a}_0$.

  FM is also known as frequency shift keying (FSK) in digital systems. It is currently not used in commercial DWDM systems.

- **Phase modulation PM:** $\vec{A}(t) = A_0 \cdot \cos(\omega_0 + \varphi_0(t)) \cdot \vec{a}_0$.

  PM is also known as phase shift keying (PSK) in digital systems and like AM it comes in a variety of different implementations:

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Binary PSK (BPSK) switches the initial phase according to the digital data bits between the two states of “0” and “π.” Detecting the data at the receiver end of the transmission line would require a phase reference in the form of a local oscillator (LO, a laser) whose phase is synchronized to the transmitter phase. Since this is hard to implement, a modified scheme is preferred:

Differential phase shift keying DPSK. Instead of encoding the digital data bits [0, 1] directly into a phase state [0, π], the *difference* between two subsequent bits is encoded. E.g., no difference between two subsequent bits could be encoded as a “1”:

$0 \rightarrow 0 = 1$
$1 \rightarrow 1 = 1$
and different subsequent bits could be encoded as a “0”:
$0 \rightarrow 1 = 0$
$1 \rightarrow 0 = 0.$

The process is started with a reference bit (chosen to be 0 by convention) and the first data bit. The resulting bit is compared to the second data bit and so on. This differential encoding is done in the electrical domain prior to the optical (phase) modulation of the carrier. An electro-optic phase modulator (typically implemented as an optical waveguide device in lithium niobate, $LiNbO_3$) modulates the differentially encoded data signal onto the optical carrier. We can choose the convention to have a “0” being represented by zero initial phase and a “1” being represented by π initial phase. The optical data signal to be transmitted now is one with a constant amplitude (intensity), a constant initial frequency, and a constant state of polarization – only the initial phase is switched between the two states of 0° and 180°.

At the receiver end of the transmission line, a Mach-Zehnder type delay interferometer, where the signal passing through one of the two arms is delayed by the duration of one bit, is used to discriminate the phase and to restore the information, see **Figure 12.8**.

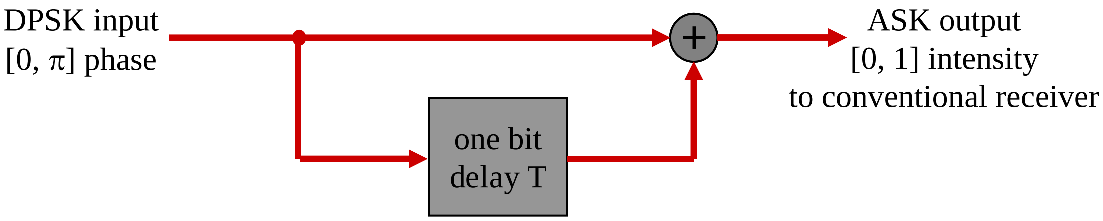
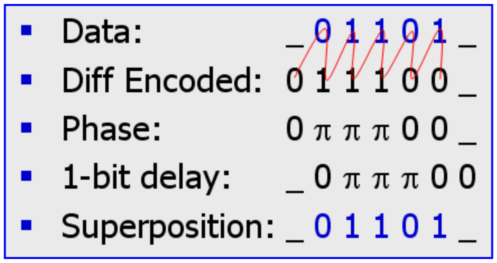


Figure 12.8: ***Mach-Zehnder type delay interferometer used as a phase discriminator for DPSK-to-ASK conversion.***

The delay interferometer eliminates the need for an LO, thus, reducing the complexity of the DPSK receiver significantly.

Example: Show schematically how a ***0 1 1 0 1*** *data sequence is differentially encoded, phase modulated, and recovered.*



- 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 _

The differential encoding process starts with a "0" reference bit (second row) and a "0" data bit (first row) resulting in an encoded "1" bit (second row). This "1" is compared to the second data bit, a "1," resulting in another "1." Applying this algorithm to the entire data sequence leads to a differentially encoded sequence of 0 1 1 1 0 0. By convention, this leads to a phase modulated carrier signal where the optical phase may change from bit slot to bit slot: 0 π π π 0 0. At the receiver end – at the output of the delay interferometer –, interference between subsequent bits takes place and we get the following result:

π phase	*interferes with*	*0 phase*	→ *destructive interference*	→ ***0***
π phase	*interferes with*	*π phase*	→ *constructive interference*	→ ***1***
π phase	*interferes with*	*π phase*	→ *constructive interference*	→ ***1***
0 phase	*interferes with*	*π phase*	→ *destructive interference*	→ ***0***
0 phase	*interferes with*	*0 phase*	→ *constructive interference*	→ ***1***

The column to the right represents exactly the data sequence given at the beginning.

Before we can go into the details of how the various modulation formats are generated, we need to know the definitions of related parameters as shown in **Figure 12.8**.

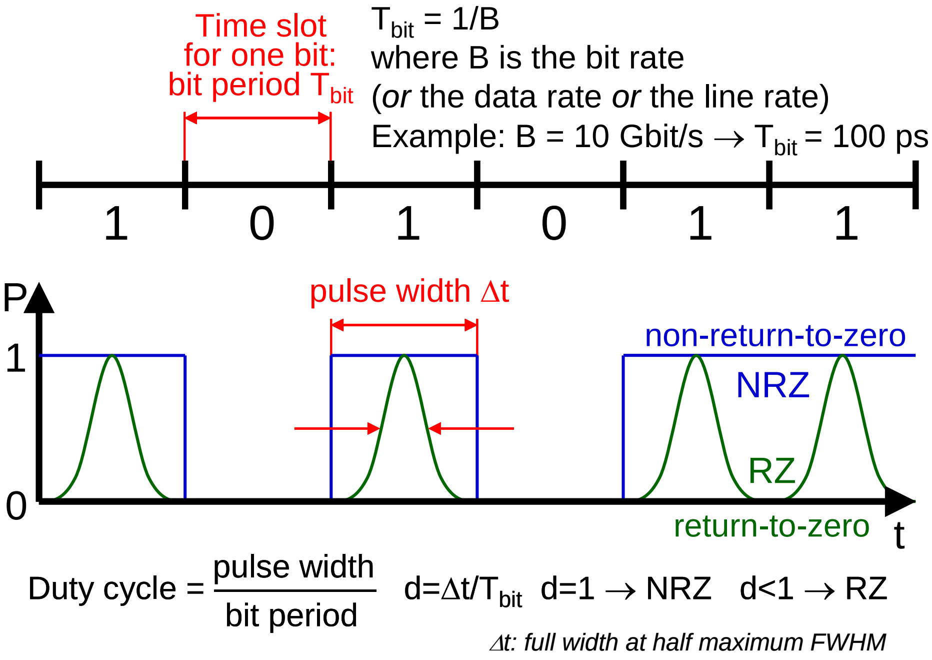


Figure 12.8b: *Definitions of a "time slot" (bit period) and the "duty cycle" for return- (RZ) and non-return-to-zero (NRZ) amplitude modulation (AM).*

One time slot equals one *bit period* T_{bit} and is given by the inverse bit rate B: $T_{bit} = 1/B$.

The width or duration Δt of the optical entity ("pulse") representing a digital "1" depends and the modulation format and, if applicable, the *duty cycle d*.

In case of a non-return-to-zero (NRZ) modulation format, the pulse has an – ideally – rectangular shape and it fills the entire bit slot: $\Delta t = T_{bit}$. The name "NRZ" stems from the fact that for two subsequent digital "1s" the optical power does not return to zero – it stays at the 1-level. The duty cycle d, defined as the ratio of pulse width to bit period ($d = \Delta t/T_{bit}$) equal 1 for NRZ.

In case of a return-to-zero (RZ) modulation format, the pulse is bell-shaped – often following a Gaussian

$$P(t) = P_0 \cdot e^{\left[-2.77\left(t/\Delta t\right)^2\right]} \qquad \textit{(Equation 12.3)}$$

or a soliton (sech^2)

$$P(t) = \mathrm{sech}^2\left(1.76\, t/\Delta t\right) \quad \text{with} \quad \mathrm{sech}(x) = \frac{2}{e^x + e^{-x}} \qquad \textit{(Equation 12.4)}$$

profile – and, contrary to NRZ, does return to zero power between two subsequent pulses. The duty cycle d is smaller than 1 ($d < 1$). Typical numbers for d are 20% for a soliton system and $^1\!/_2$ to $^2\!/_3$ for conventional RZ systems.

Whereas the distinction between RZ and NRZ refers to the representation of the digital data in the optical domain itself, another useful way to categorize transmitters is with respect to how the optical signal has been generated. Two methods are common: direct and external modulation. (Both, the pulse shape and the way it can be generated are shown in **Figure 12.9**.)

Direct modulation (**Figure 12.9**, upper left-hand side) refers to the case where a semiconductor laser is modulated directly via its injection current. The obvious advantage is its simplicity (leading to low-cost transmitters), the disadvantages are the limited speed (applied for bit rates of up to 10 Gbit/s) and frequency chirp it unavoidably generates.

External modulation (**Figure 12.9**, right-hand side) utilizes electro-optic (EO) intensity modulators (waveguide devices with a Mach-Zehnder (MZ) interferometric structure usually implemented in a lithium-niobate ($LiNbO_3$) material system) and their advantageous properties of high speed (up to 100 Gbit/s) and potentially chirp-free operation. They can be used with either format, RZ (lower right-hand side of **Figure 12.9**) as well as NRZ (upper right-hand side of **Figure 12.9**).

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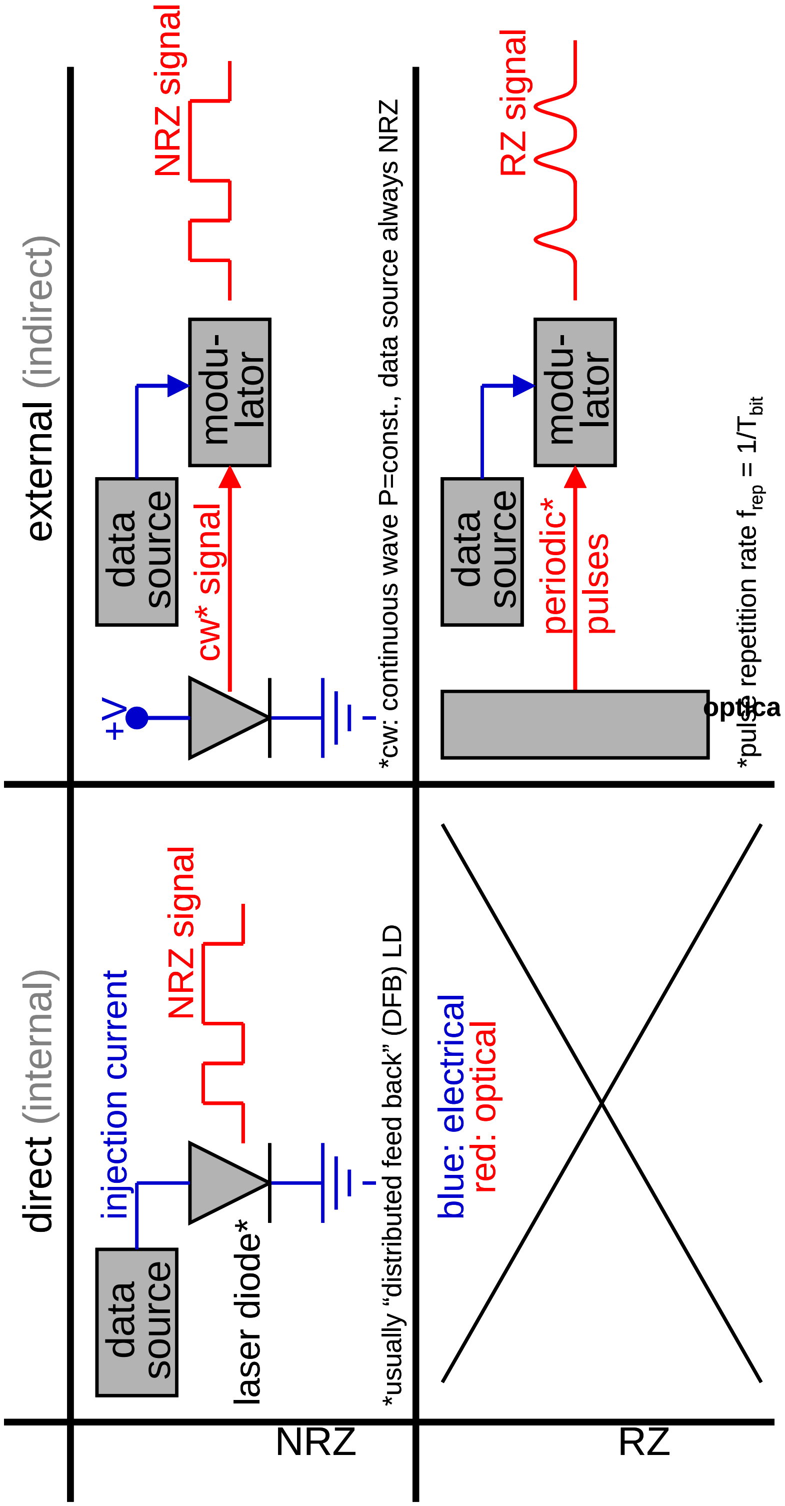

Figure 12.9: *Modulation formats (RZ and NRZ) and schemes of generation (direct and external modulation)*

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Figure 12.10 depicts the generation of an NRZ signal applying external modulation utilizing an electro-optic intensity modulator.

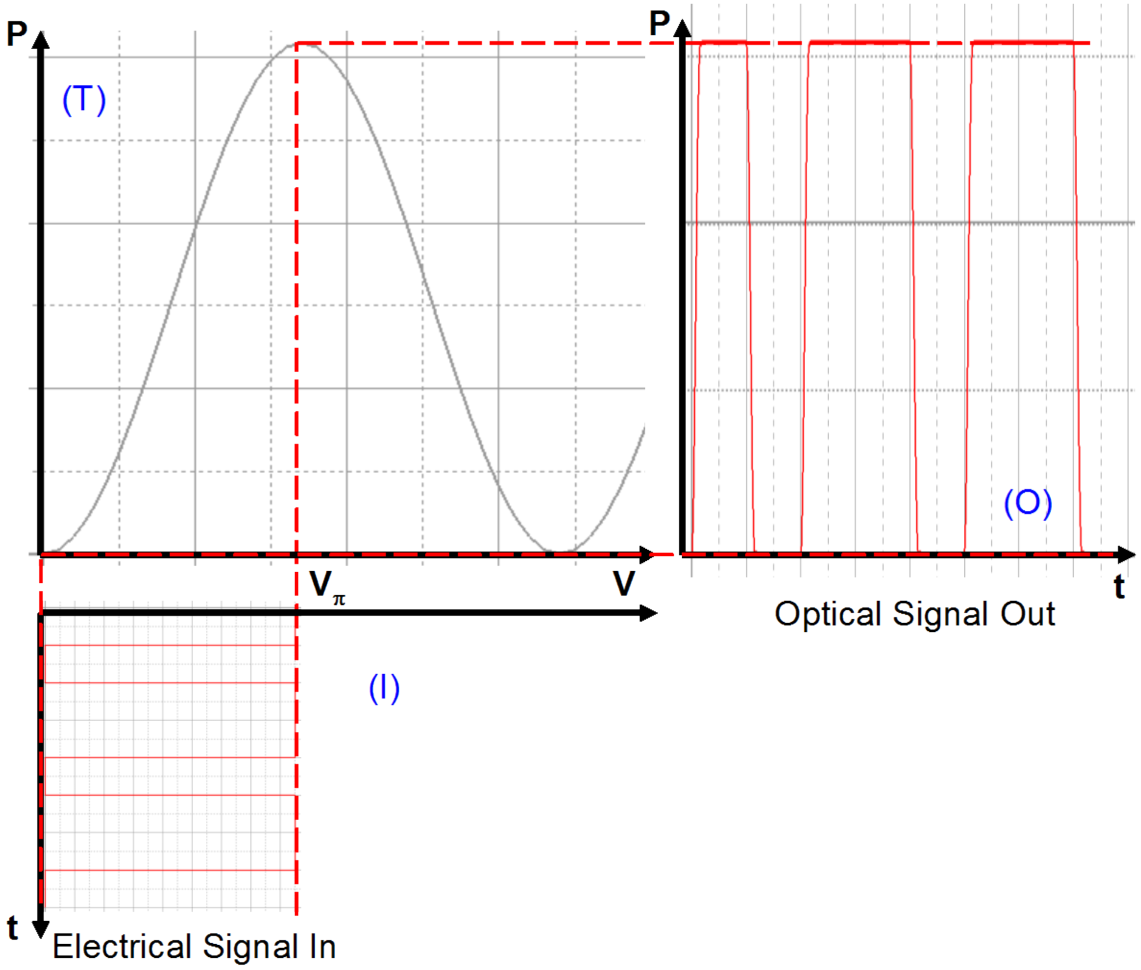

Figure 12.10: ***Generation of an NRZ signal utilizing external modulation I: electrical input (data) signal 1 0 1 1 0 1 1 0, T:*** $\sin^2$ ***transfer function of the external EO MZ modulator with switching voltage*** V_π, ***O: optical output signal.***

Electrical to Optical Signal Transfer

The electrical data signal (V_{data}, which always comes in the form of an NRZ signal) is applied to the electrical control input of the modulator (I). The peak voltage of the data signal is chosen to match the switching voltage V_π of the modulator. An optical continuous wave (cw, $P = P_0 =$ const.) signal is applied to the optical input of the modulator and serves – after modulation took place – as the carrier of the data. Via the $\sin^2$ transfer function of the modulator (grey curve T in **Figure 12.10**), the electrical data is modulated onto the optical carrier:

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$$P_{out}(t) = P_0 \cdot \sin^2\left({\pi}/{2} \cdot \frac{V_{data}(t)}{V_\pi} \right).$$ *(Equation 12.5)*

The dashed red lines depict how the electrical input signal is transferred into the optical output signal. In this – ideal – example the optical carrier is modulated between its maximum and a minimum that equals zero – leading to an infinite *extinction ratio* ε ($\varepsilon = P_{max}/P_{min}$, or, in logarithmic units of dB, $\varepsilon = 10 \cdot \log[P_{max}/P_{min}]$).

In a less ideal case or if we face the requirement to use only the linear portion of the transfer function (both shown in **Figure 12.11**), the extinction ratio adopts values smaller than infinity. (In practical systems, due to imperfections of the modulator itself or of the signals applied to the modulator, ε is always finite.)

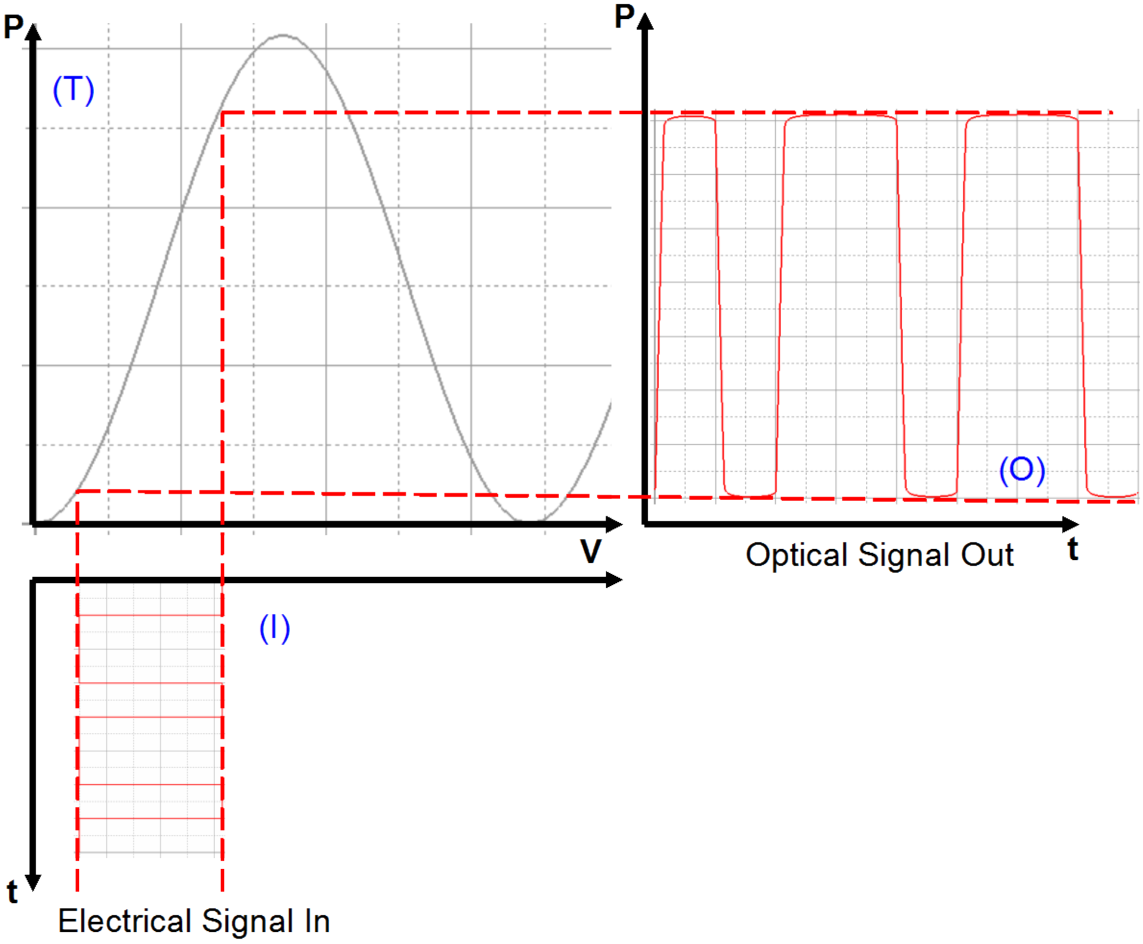

Figure 12.11: *Generation of a more linear NRZ signal with a finite extinction ratio utilizing external modulation.*

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I: electrical input (data) signal 1 0 1 1 0 1 1 0, T: $\sin^2$ *transfer function of the external EO MZ modulator with switching voltage* V_π*, O: optical output signal*

Example: What would the extinction ratio ε *of an optical NRZ signal be if the electrical NRZ data signal applied to the external EO MZ modulator swings between 10% and 80% of* V_π*? (Approximate values taken from* ***Figure 12.11****.)*

$$\varepsilon = \frac{P_{max}}{P_{min}} = \frac{P_{out}(1)}{P_{out}(0)} = \frac{\sin^2\left({}^{\pi}\!/_{2} \cdot \frac{0.8 \cdot V_\pi}{V_\pi} \right)}{\sin^2\left({}^{\pi}\!/_{2} \cdot \frac{0.1 \cdot V_\pi}{V_\pi} \right)} = \frac{0.905}{0.024} \approx 38$$

$$\varepsilon = \frac{P_{max}}{P_{min}} = \frac{P_{out}(1)}{P_{out}(0)} = 10 \cdot \log\left[\frac{\sin^2\left({}^{\pi}\!/_{2} \cdot \frac{0.8 \cdot V_\pi}{V_\pi} \right)}{\sin^2\left({}^{\pi}\!/_{2} \cdot \frac{0.1 \cdot V_\pi}{V_\pi} \right)} \right] \approx 15.8\,\text{dB}$$

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Figure 12.12 depicts the generation of an RZ signal applying external modulation utilizing an electro-optic intensity modulator.

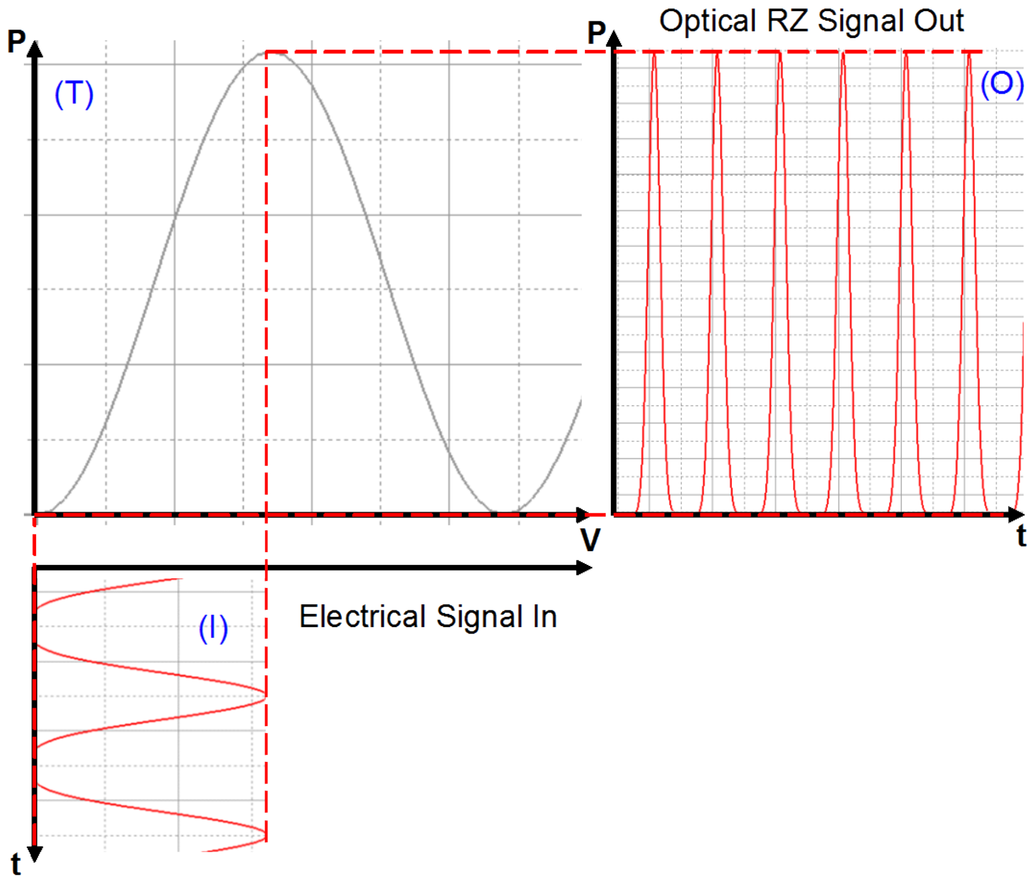

Figure 12.12: *Generation of an RZ signal utilizing external modulation I: electrical input (data) signal 1 0 1 1 0 1 1 0, T: sin2 transfer function of the external EO MZ modulator with switching voltage V_π, O: optical output signal*

The electrical control signal is applied to the electrical control input of the modulator (I). The peak voltage of the harmonic (here: sinusoidal) control signal is chosen to match half of the switching voltage V_π of the modulator. Thus, the total voltage swing equals V_π gain and the modulator *is biased* at $V_\pi/2$. An optical continuous wave (cw, $P = P_0 = \text{const.}$) signal is applied to the optical input of the modulator and serves – after modulation took place – as the carrier of the data in the form of a train of bell-shaped pulses (O). This pulse train is periodic. (Remember: we applied a harmonically oscillating signal to control the modulator, not a data signal!) A subsequent, second modulator to which the periodic pulse stream is incident accomplishes the data modulation, operating in the same mode as the NRZ set-up discussed before. The result is an optical RZ data signal where a digital "1" is represented by a pulse and a digital "0" is represented by the absence of a pulse (or vice versa) – the pulse stream is not periodic any more.

Figure 12.13 depicts the generation of a carrier suppressed RZ signal (CS-RZ) applying external modulation utilizing an electro-optic intensity modulator.

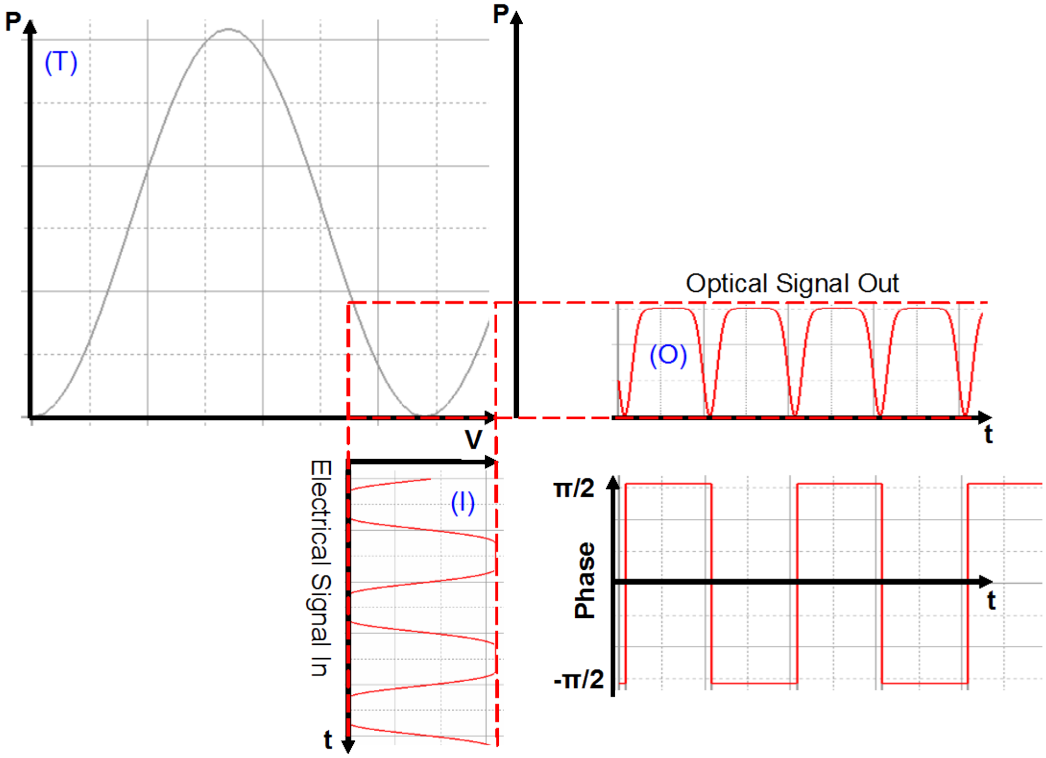

Figure 12.13: *Generation of a CS-RZ signal utilizing external modulation I: electrical input (data) signal 1 0 1 1 0 1 1 0, T: sin2 transfer function of the external EO MZ modulator with switching voltage* V_π, *O: optical output signal*

The electrical control signal is applied to the electrical control input of the modulator (I). The peak voltage of the harmonic control signal is arbitrary chosen. The modulator *is biased* at the minimum of (T), here: $2\cdot V_\pi$. An optical continuous wave (cw, $P = P_0 = \text{const.}$) signal is applied to the optical input of the modulator and serves – after modulation took place – as the carrier of the data in the form of a train of RZ pulses (O). This pulse train is periodic (Remember: we applied a harmonically oscillating signal to control the modulator, not a data signal!) and comprises a phase shift of π between subsequent pulses. In other words, the phase alternates between $+\pi/2$ and $-\pi/2$ (lower, right-hand corner of **Figure 12.13**). A subsequent, second modulator to which the periodic pulse stream is incident accomplishes the data modulation, operating in the same mode as the NRZ set-up discussed before. The result is an optical CS-RZ data signal with an optical spectrum where the original carrier wavelength is no longer present, resulting in a “narrower” spectrum (decreased FWHM compared to the ordinary RZ format discussed before). [4] A digital “1” is still represented by a pulse and a digital “0” is represented by the absence of a pulse (or vice versa) – the pulse stream is not periodic any more.

Figure 12.15 depicts the generation of a DPSK signal applying external modulation utilizing an electro-optic intensity modulator.

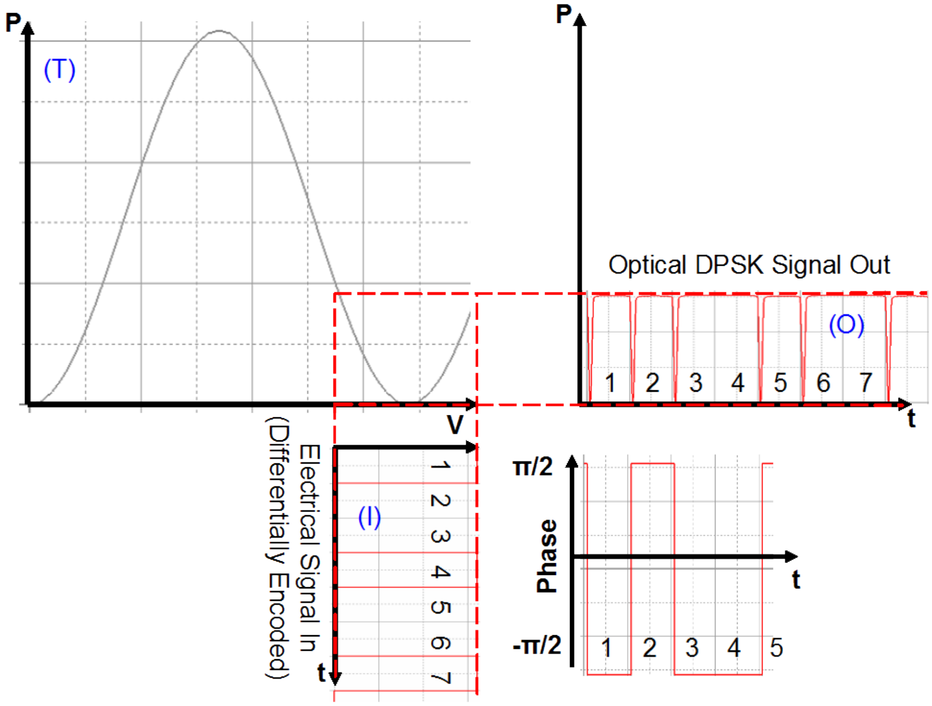

Figure 12.15: *Generation of an RZ signal utilizing external modulation I: electrical input (data) signal 1 0 1 1 0 1 1 0, T: transfer function of the external EO MZ modulator with switching voltage* V_π*, O: optical output signal*

The electrical data signal (differentially encoded, in the form of an NRZ signal) is applied to the electrical control input of the modulator (I). The peak voltage of the data signal is arbitrary chosen. The modulator *is biased* at the minimum of (T), here: $2 \cdot V_\pi$. An optical continuous wave (cw, $P = P_0 =$ const.) signal is applied to the optical input of the modulator and serves – after modulation took place – as the carrier of the data in the form of a DPSK signal (O). The DPSK signal has an almost constant power – except for the “dips” where the voltage of the electrical data signal equals $2 \cdot V_\pi$ and the optical output power becomes zero. The information is encoded in the phase of the optical signal (lower, right-hand corner of **Figure 12.15**), not in the amplitude any more. Thus, it comprises “occasional” phase shifts of π between subsequent bit periods.

12.3 System limitations

Noise Concerns

Noise resulting from the amplified spontaneous emission of the optical amplifiers (OAs) along the optical path limits the number of cascadable OAs and, thus, the number of amplifier sections (see **Figure 12.5**) and subsequently the total length of the optical path – also called the system reach.

As will be seen in Module 15, the noise figure NF_{OA} of an OA is defined by the optical signal-to-noise ratio at the respective in- ($OSNR_{in}$) and output ($OSNR_{out}$) of the device:

$$NF_{OA} = \frac{OSNR_{in}}{OSNR_{out}} = \frac{1}{G_{OA}} \cdot \left[1 + 2 \cdot \eta_{sp} \cdot \left(G_{OA} - 1\right)\right] \qquad \textit{(Equation 12.6)}$$

where G_{OA} is the gain and η_{sp} the inversion factor or spontaneous emission coefficient, which equals 2 (3 dB) in an ideal case. Along the transmission fiber both, ASE and signal are attenuated in the same way. Since the following OA does not distinguish between signal and ASE, they will both be amplified in the same way (by the same G_{OA}) plus additional ASE will be added – thus, decreasing the OSNR. Here, it is worthwhile to emphasize that the signal power level can be restored for every section by off-setting the section loss (transmission fiber attenuation plus attenuation of an dispersion compensating element, if applicable) by the respective OA, the signal quality (the OSNR) constantly decreases due to accumulated ASE (see **Figure 12.5**). Therefore, we need to know NF_{cas} for a cascade of OAs:

$$NF_{cas} = 1 + N_{OA} \cdot 2 \cdot \eta_{sp} \cdot \left(G_{OA} - 1\right) \qquad \textit{(Equation 12.7)}$$

with N_{OA} being the number of in-line OAs and of sections.

We see NF_{cas} increases (and OSNR decreases) with an increasing number of sections. But it also increases with increasing G_{OA} and the required G_{OA} in order to compensate for section losses depends directly on the lengths of section, or, to be precise, on the length of the transmission fiber (and the corresponding dispersion compensating fiber) of the respective section. Thus, the shorter the sections, the lower the total noise figure of the cascade (at the price of more OAs – at higher costs).[3] So the design goal must be to achieve the required distance with a minimum number of OAs while keeping the OSNR at (or below) the level required by the receiver:

$$OSNR_{cas} = \frac{P_{sig}}{\left[1 + N_{OA} \cdot 2 \cdot \eta_{sp} \cdot \left(G_{OA} - 1\right)\right] \cdot h\nu \cdot BW_{opt}} \qquad \textit{(Equation 12.8)}$$

where P_{sig} denotes the signal power into the cascade, h Planck's constant, ν the optical frequency, and BW_{opt} the bandwidth of the optical signal.

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[3] This is the reason why we find shorter sections in trans-oceanic undersea systems than in – shorter – terrestrial systems.

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Chromatic Dispersion

Residual chromatic dispersion resulting from imperfect dispersion compensation limits the total system reach, too. As we learned earlier, chromatic dispersion severely affects the quality of a transmitted optical signal while at the same time we have a very powerful measure to compensate for it: dispersion compensating fiber. Limitations imposed by chromatic dispersion D(λ) stem from a potential mismatch of the slope S = dD(λ)/dλ of the transmission fiber (D_{TF}) and the dispersion compensating fiber (D_{DCF}) as shown in **Figure 12.16**:

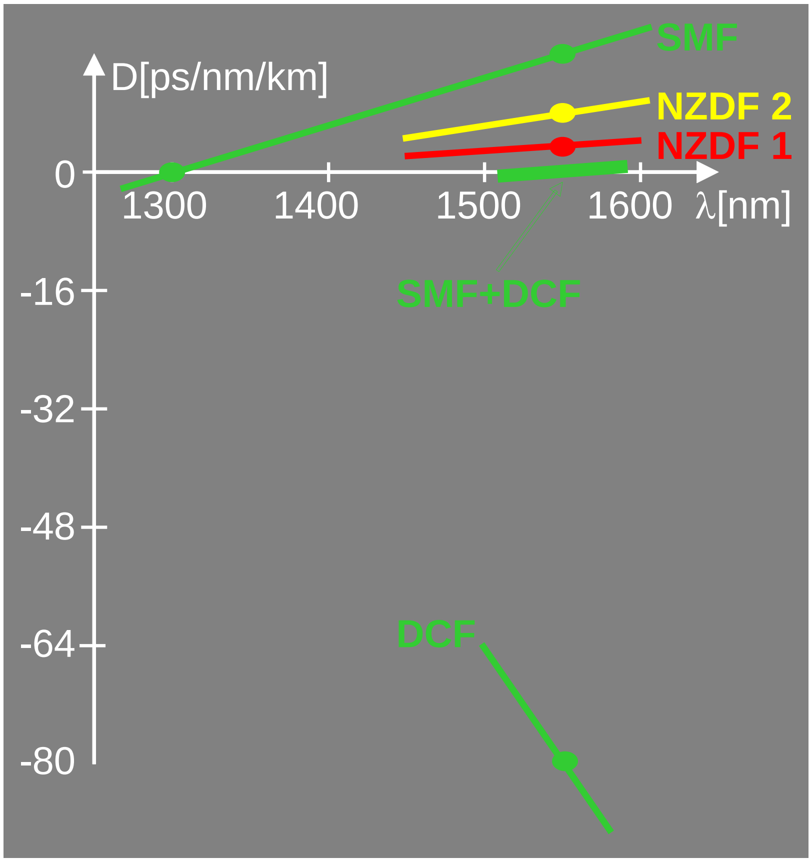

Figure 12.16: ***Chromatic dispersion versus wavelength for standard single-mode fiber (SMF), dispersion compensating fiber (DCF), and a combination of both, constituting a dispersion compensated section. An imperfect match of respective dispersion slopes leads to residual dispersion of the optical path limiting either reach or data rate or both.(Also shown are two types of non-zero dispersion fiber (NZDF).***

The non-zero dispersion slope of the compensated line impacts high-speed DWDM systems in two ways: First, whereas the center wavelength channel of the system might experience a perfect

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compensation of chromatic dispersion with zero residual dispersion left (and the neighboring channels seeing still an “almost” perfect compensation), the outer channels at the lower and higher wavelength boundaries of the C-band might experience a significantly higher residual dispersion. Second, although the chromatic dispersion at the center wavelength of a given signal spectrum of a single DWDM channel might be perfectly compensated for, the spectrum – due to the high bit rate – is of significant width such that the lower and higher wavelength components within the signal spectrum experience a residual dispersion high enough to impact the signal quality and the system performance.

Following established criteria for tolerable pulse broadening due to chromatic dispersion [5], the maximum chromatic dispersion at the center wavelength of a given DWDM channel or for wavelength within the signal spectrum of a given high-speed signal can be derived from

$$B \cdot L \le \frac{c}{4 \cdot \lambda^2 \cdot |D_\lambda| \cdot \Delta f} \qquad \textit{(Equation 12.9)}$$

with B: bit-rate, L: length, c: speed of light, λ: signal wavelength, D_λ: chromatic dispersion at wavelength λ, and Δf: full width at half maximum of the signal spectrum.

Example: What is the maximum bit rate for an RZ signal (Fourier-/transform-limited Gaussian-shaped pulses of d =0.2) for a Tucson to Denver link if the residual dispersion for the respective compensated channel at a center wavelength of 1550 nm is 1 ps/nm/km?

We know the time-bandwidth product of a Fourier-/transform-limited Gaussian-shaped pulse equals 0.44. Thus:

$$\Delta f = 0.44 \cdot {}^{1}\!/_{d} \cdot B = 2.2B.$$

www.maps.google.com provides us with the distance: L = 1,442 km.

Using the above formula, we get:

$$B \le \sqrt{\frac{c}{8.8 \cdot \lambda^2 \cdot |D_\lambda| \cdot L}} = \sqrt{\frac{3 \cdot 10^8\ {}^{m}\!/_{s}}{8.8 \cdot (1550\,\text{nm})^2 \cdot 1\ {}^{ps}\!/_{nm \cdot km} \cdot 1442\,\text{km}}} \approx 3.1\,\text{Gbit/s}$$

Example: A 100 Gbit/s Ethernet signal (100 GE) has been CS-RZ encoded with a FWHM of its signal spectrum of 1.5 times the bit rate. The chromatic dispersion of the transmission line has been perfectly compensated for at the center wavelength with a residual slope of only 0.01 ps/nm^2/km. What is the maximum distance the signal can be transmitted according to the above formula?

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$$\text{Spectral width of the signal}\quad \Delta f = 1.5 \cdot 100\,{}^{\text{Gbit}}\!\!/\!_{\text{s}} = 150\,\text{GHz}$$

$$\text{Conversion to wavelength}\quad \Delta\lambda = \lambda^2 \cdot \frac{\Delta f}{c} = (1550\,\text{nm})^2 \cdot \frac{150\,\text{GHz}}{3 \cdot 10^8\,{}^{\text{m}}\!/\!_{\text{s}}} = 1.2\,\text{nm}$$

$$\text{Calculate dispersion}\quad D = \Delta\lambda \cdot S = 1.2\,\text{nm} \cdot 0.001\,{}^{\text{ps}}\!\!/\!_{\text{nm}^2 \cdot \text{km}} = 0.012\,{}^{\text{ps}}\!\!/\!_{\text{nm} \cdot \text{km}}$$

$$\text{Calculate maximum transmission distance}\quad L \le \frac{c}{4 \cdot \lambda^2 \cdot |D_\lambda| \cdot \Delta f \cdot B} = 173\,\text{km (only!)}$$

Schemes to overcome the problem described before are (i) equalizers to flatten the residual dispersion over wavelength of a dispersion compensated path and (ii) per-channel fine-tuning of the chromatic dispersion (while the coarse part was done by the dispersion compensating fiber's broadband approach). Devices for both applications are mainly based on fiber Bragg gratings and can be adaptive in order to mitigate time-varying chromatic dispersion, e.g., due to temperature changes.

Polarization Mode Dispersion

Polarization mode dispersion (*PMD*), finally, constitutes the third linear limitation of the bit rate-distance product of a fiber-optic transmission system. If the fiber were ideally cylindrical, a transmitted signal would always experience the same time of flight, no matter what its state of polarization (SoP) would be. Unfortunately, that is not the case: Asymmetries due to manufacturing, micro bending, tension, strain, or pressure induce birefringence to the fiber leading to a SoP dependent transit time of the signal. Defining two main polarization axes, this can be described mathematically by the fact that those portion of a signal aligned along the x-axis has a propagation constant different from those aligned along the y-axis (which can also be interpreted as different indexes of refraction):

$$\Delta\beta = |\beta_x - \beta_y| = \frac{\omega \Delta n_{eff}}{c} = \frac{\omega |n_x - n_y|}{c}. \qquad \textit{(Equation 12.10)}$$

The different propagation constants of such a birefringent element will cause a single pulse to split (due to the differential group delay, DGD) while propagating through it (**Figure 12.17**).

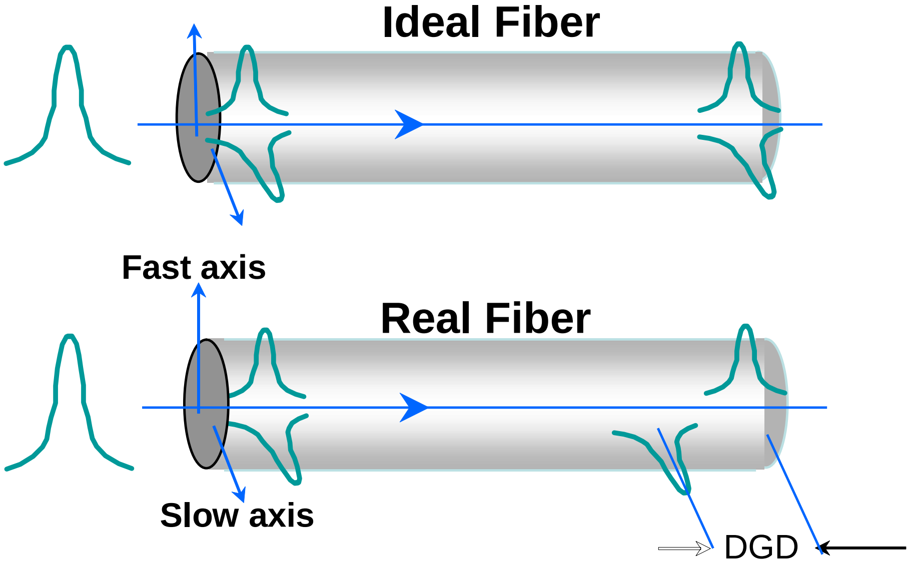

Figure 12.17: ***Pulse splitting due to polarization mode dispersion (PMD).***

Since an optical fiber can be modeled as a concatenation of many of such tiny birefringent elements, the result will not be a split pulse but rather a spread (broadened) pulse (**Figure 12.18**) – as it was the result of chromatic dispersion.

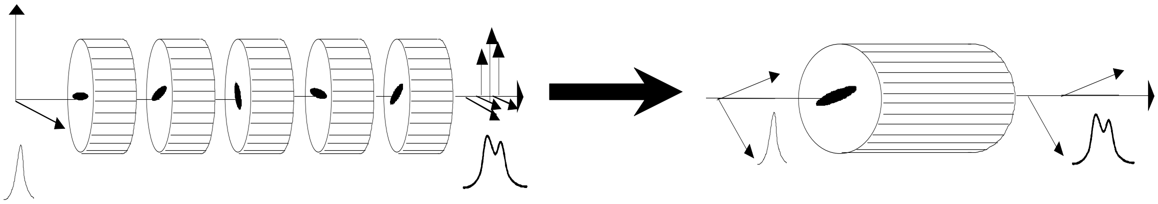

Figure 12.18: Pulse broadening due to polarization mode dispersion (PMD).

Although the PMD coefficient of modern fibers is rather small (typical value: 0.1 ps/√km), it currently constitutes the ultimate limitation for the bit rate-distance product of fiber optics transmission systems.

Example: Over what distance can a 100 GE signal (RZ with d = 0.5) be transmitted if a pulse broadening ΔT not exceeding 10% of the original pulse width is allowed?

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$$\Delta T = PMD \cdot \sqrt{L}$$

$$L = \left(\frac{\Delta T}{PMD}\right)^2 = \left(\frac{0.5\,ps}{0.1\,{ps}\big/{\sqrt{km}}}\right)^2 = 25\,km$$

The final classification of limitations that impact the data transmission characteristics of the fiber optic system is nonlinear optical effects. These effects will be discussed in the graduate level course.

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