

Chapter 2

Fiber Optical Transmission Systems

Abstract In this chapter the basic concepts of fiber optical transmission systems are explained. The chapter starts with the presentation of the generic setup of a wavelength division multiplexing optical long-haul system. Afterwards the most important components are introduced, which are transmitters, optical amplifiers, fibers, optical cross-connects and receivers. At this point only the general properties of the components are outlined. The mathematical equations describing the various transmission effects are given in [Chap. 3](#).

2.1 Generic Setup

The generic setup of a typical optical transmission system is shown in [Fig. 2.1](#), and it is described briefly in the following. In this book long-haul transmission systems with a typical (transparent) reach of more than 1,000 km are investigated. In these systems single mode fibers are currently the transmission medium of choice.

Such optical fibers have a total usable bandwidth of several terahertz. This is why wavelength division multiplexing (WDM) is commonly employed to utilize this enormous capacity. A typical transmission system consists of an array of lasers with different wavelengths to generate the optical carriers. Each laser is modulated by an external modulator (e.g. a Mach–Zehnder modulator) to impress the data signal. Most commercially available transmission systems have a channel bit rate of 43 Gb/s (e.g. [\[1, 2\]](#)), and the next generation of optical transmission system operating at a line rate of 112 Gb/s (including FEC and Ethernet protocol overheads) is already available from some system vendors. As modulation format initially non-return-to-zero (NRZ) on–off keying (OOK) has been employed for line rates up to 10.7 Gb/s [\[3\]](#). The following first generation of 43 Gb/s (per channel) transmission systems has been designed to use

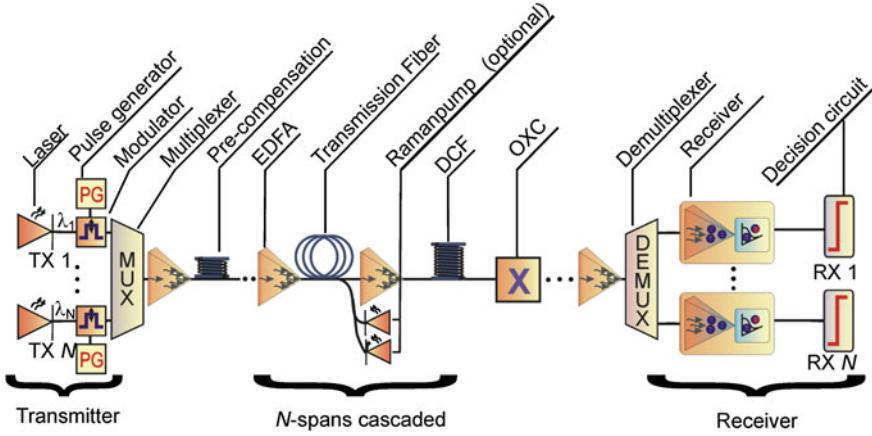


Fig. 2.1 Generic setup of a fiber optical wavelength division multiplexing transmission system

return-to-zero (RZ) OOK. Soon a duobinary implementation followed due to the higher tolerance to accumulated chromatic dispersion. Further improvements led to the use of differential phase shift keying (DPSK) with interferometric detection and to the current version using quadrature phase shift keying (QPSK) and polarization multiplexing (polmux) with coherent reception. QPSK polmux transmits a QPSK signal on each of the two orthogonal polarization axes, thus doubling the spectral efficiency. For long distance 112 Gb/s line rate systems coherent QPSK polmux transmission is widely adopted as the modulation format of choice [4].

To combine the different wavelengths for transmission on a single mode fiber a multiplexer (typically an arrayed waveguide grating, AWG, with fixed channel spacing) is employed [5]. After the multiplexer an optical amplifier (erbium doped fiber amplifier, EDFA) is deployed to increase the signal launch power. Potentially a dispersion pre-compensation fiber may be used. To improve the performance—especially in long fiber links—contra-directional (in some cases combined with co-directional) Raman pumping may be utilized in the transmission fiber. Along the transmission line the signal is periodically amplified (approximately every 80–100 km). In most of today's systems the accumulated group-velocity dispersion (GVD) is compensated after each span by a lumped dispersion compensating fiber (DCF). An alternative to DCFs are chirped fiber Bragg gratings (FBG). They have the advantage of a lower insertion loss which is also independent of the amount of dispersion to be compensated. A major disadvantage is the inherent phase ripple originating from the production process, which can lead to significant signal distortions, if several FBGs are concatenated [6].

At a node, where several different routes interconnect, an optical cross-connect (OXC) may be deployed. An OXC allows to switch from one fiber to another dynamically. It is also possible to route individual wavelengths in different directions [5].

At the receiver, the different wavelengths need to be demultiplexed. This can be achieved by optical band pass filters (e.g. dielectric multicavity thin-film filters [7]) or an AWG. For the widely employed NRZ-OOK format the received signal is directly detected by a photo diode, which generates the electrical base band signal. Finally, the binary data stream is restored by a decision circuit. Novel modulation formats with coherent detection make use of an additional laser at the receiver to generate a local oscillator signal. This signal is mixed with the incoming signal using a so called 90°-hybrid. In polmux systems additionally a separation of the two polarization axes is needed, which is usually performed by a polarization splitter. After conversion into the electrical domain typically an electrical equalizer is employed (compare also Sect. 2.8). The equalizer is used to compensate for distortions along the transmission line (especially linear effects such as accumulated dispersion and polarization mode dispersion). Additionally the mismatch in phase and frequency between the transmitter laser and the local oscillator at the receiver must be compensated. This is also achieved by digital signal processors.

In the following paragraphs the various components mentioned above (compare also Fig. 2.1) are explained in more detail.

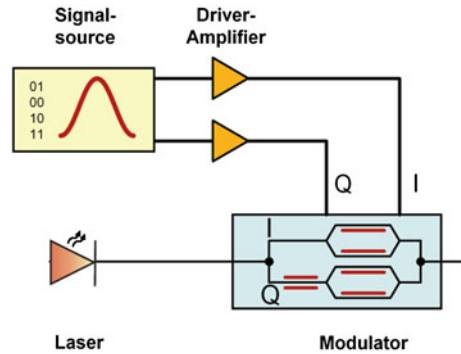
2.2 Transmitters

In fiber optical transmission systems transmitters consist of a light source used as the optical carrier and a modulator to impress the data signal onto this carrier.

In optical long-haul transmission networks mainly coherent continuous-wave (CW) lasers are used. Semiconductor lasers are by far the most popular light source for optical communication systems [5]. Semiconductor lasers are compact and usually only a few hundred micrometers in size. As they are essentially based on pn-junctions they can be fabricated in large volumes using highly advanced integrated semiconductor technology. Frequently used are DFB (distributed feedback) lasers, which are made of InGaAsP (indium gallium arsenide phosphide) for the required wavelength range. Today (wavelength) tunable lasers are highly desirable to relax inventory and sparing issues, which are rather expensive. They are also one of the key enablers of reconfigurable optical networks as they allow to choose the transmit wavelength arbitrarily at the source of a lightpath. DFB lasers can be tuned by varying the forward-bias current, which changes the refractive index. However, changing the bias current also changes the output power of the device and makes this technique unsuitable. This is why distributed Bragg reflector (DBR) lasers are typically used, if tuning is desired. In DBR lasers a separate current in the Bragg region can be used to tune the wavelength.

Lasers are usually not directly modulated to suppress the chirping of the emission wavelength, which is especially detrimental at higher bit rates (>2.5 Gb/s) [5]. Instead, external modulators are used e.g. optical Mach-Zehnder modulators

Fig. 2.2 Transmitter setup with an optical IQ modulator



(MZM). MZMs can be implemented in Lithium Niobate (LiNbO_3), Gallium Arsenide (GaAs) or Indium Phosphide (InP). These modulators and the underlying electronics allow to directly generate signals of up to 40 GSamples/s. Field experiments have already shown 107 Gb/s ETDM transmission with NRZ-OOK directly driving an MZM [8]. Signals with significantly higher data rates (up to more than 1 Tb/s) are usually generated by optical time domain multiplexing (OTDM). Different optical signals of lower bit rates are interleaved in this process to generate a data signal of the desired higher modulation frequency.

If QPSK or even higher order modulation formats are to be transmitted, the modulator setup is getting more complicated [9]. In Fig. 2.2 the setup of a QPSK transmitter based on an optical IQ modulator is shown. Typically a nested Mach-Zehnder structure (IQ modulator) is used with a 90° -phase shift between the upper and lower branches allowing to modulate the real and imaginary parts of the signal independently. Such a device is available in an integrated form. For polmux transmission two of these IQ modulators are used. In this case the orthogonal carriers are provided from a laser source, which is split into two orthogonal polarizations by a polarization beam splitter (PBS).

As already mentioned above, the high bandwidth of the fiber can be utilized efficiently by employing a multitude of transmitters using different wavelengths. This transmission scheme is called wavelength division multiplexing (WDM). With the help of a multiplexer the different wavelengths are combined and transmitted over the same transmission fiber. Often an arrayed waveguide grating (AWG) is utilized as a multiplexer [5]. An AWG is a generalization of the Mach-Zehnder interferometer. It consists of two multiport couplers interconnected by an array of waveguides. In this array several copies of the same signal, but shifted in phase by different amounts, are superimposed. The AWG can be used as an $n \times 1$ wavelength multiplexer as well as a $1 \times n$ wavelength demultiplexer. The main drawback of AWGs is their relatively high cost and lack of scalability.

In today's commercially available transmission (e.g. [1, 2]) systems up to 160 channels can be transmitted simultaneously.

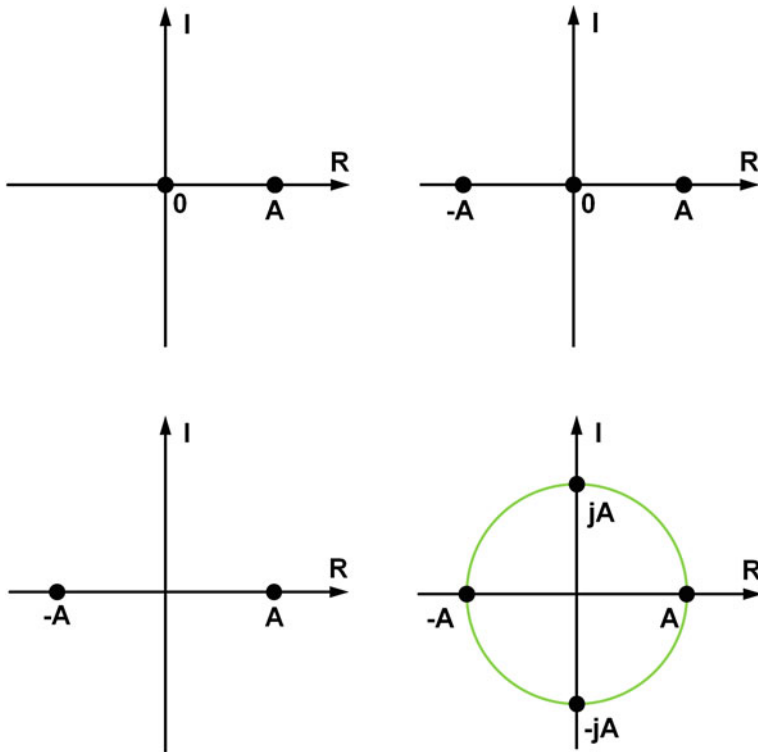


Fig. 2.3 Constellation diagrams of OOK, duobinary, DPSK and DQPSK modulation formats (from left to right and top to bottom)

2.3 Modulation Formats

The most commonly used modulation scheme in optical communications has been on-off keying (OOK) over years [10]. This means that the optical power is modulated according to the binary data input signal. Two main types of line codes are usually employed: return to zero (RZ) and non-return to zero (NRZ) formats. In RZ formats, the signal amplitude returns to zero at the boundaries of each bit slot, even if consecutive marks are sent whereas in NRZ format the signal amplitude remains on the high level in the case of consecutive marks.

The input data signal may be additionally pre-processed to generate more complex signal forms such as duobinary [9]. The duobinary modulation format is a pseudo three level modulation format. Apart from the mark signal in the unipolar complex plane also a signal with 180° phase shift is admissible (leading to the symbols -1 , 0 , 1 also shown in Fig. 2.3, top right).

Duobinary modulation is a special partial-response code. It can be generated from a binary NRZ signal by delay-and-add coding or low pass filtering (Fig. 2.4).

Fig. 2.4 Duobinary transmitter with single-arm MZ modulator. This setup avoids symmetry requirements of the MZ modulator

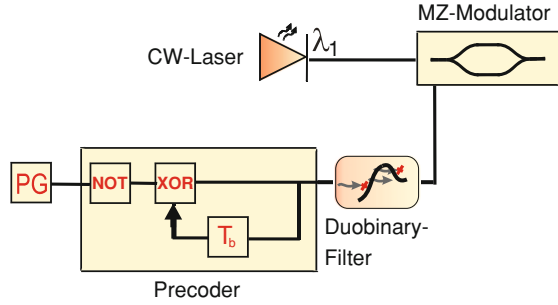
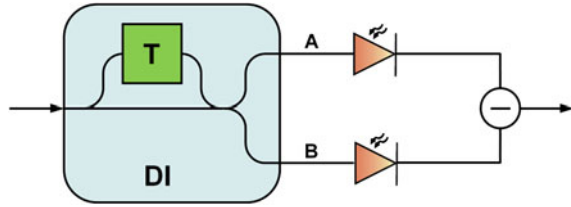


Fig. 2.5 Schematic setup of a balanced receiver using an optical delay line interferometer



The receiver setup can remain unmodified compared to standard direct detection systems. The main advantages of duobinary modulation are that the signal is more robust against accumulated chromatic dispersion induced signal distortions and that it shows a narrower spectrum compared to NRZ-OOK. Furthermore, a more complex setup is needed only at the transmitter. This is why duobinary modulation has been deployed in some 43 Gb/s transmission systems.

Recently, phase modulation formats and higher order modulation have become more widely studied [9, 10]. At first the focus has been primarily on differential phase shift keying (DPSK). DPSK encodes information on the binary phase change between adjacent bits. A mark is encoded onto a π phase change, whereas a zero is represented by the absence of a phase change. The main advantage compared to NRZ-OOK is a 3 dB receiver sensitivity improvement, which can be intuitively understood from the increased symbol spacing for DPSK compared to OOK for fixed average optical power [9]. This signal format furthermore shows better behavior regarding signal distortions due to fiber nonlinearities especially excellent resilience to cross-phase modulation, which is a key requirement for DWDM system implementation. DPSK, however, cannot be directly received using square-law detection of a photodiode. This is why—if direct detection is desired—a delay line interferometer (DI) is inserted in the optical path at the receiver to convert the differential phase modulation into intensity modulation (Fig. 2.5). DPSK has also been employed in some commercial 43 Gb/s transmission systems (e.g. [1]).

Currently, multilevel modulation formats (with a capacity of more than one bit per symbol) are state-of-the-art. Especially DQPSK has been widely studied (e.g. [9, 11, 12]). DQPSK transmits the four phase shifts $0, +\pi/2, -\pi/2, \pi$ at a symbol

rate of half the bit rate. As already mentioned above DQPSK is most conveniently implemented by two nested MZMs. DQPSK has the advantage that the spectrum is compressed in frequency by a factor of two compared to DPSK. This is beneficial for achieving a higher spectral efficiency in WDM systems, but also for increased tolerance to chromatic dispersion as well as a higher robustness concerning polarization mode dispersion (PMD). At the receiver the DQPSK signal can be detected by two balanced receivers using optical DIs.

The most recent version of optical long-haul transmission systems uses 43 Gb/s coherent polmux QPSK transmission, and this modulation format is also widely chosen for next generation optical transmission systems with line rates of 112 Gb/s [4]. Compared to the previously outlined modulation formats, which use only a single polarization axis, the spectral efficiency is doubled in polmux transmission by utilizing two orthogonal polarization axes. To enable access to both polarization axes the incoming signal is split into its orthogonal parts by a polarization splitter before the receiver. These two signals are coherently detected by mixing with a local oscillator in so called 90°-hybrids. This makes available both amplitude and phase information. The detailed configuration will be shown in Sect. 2.7.

In contrast to all previously described modulation formats, in coherent polmux transmission, digital signal processing is used extensively at the receiver (compare also Sect. 2.8). This requires information on both the amplitude and the phase of the incoming signals. Both are only available, if coherent detection is employed. Because it is hard to design an optical phase-locked loop the difference between the local oscillators at the receiver and the transmitter with respect to (carrier) frequency and phase have to be compensated in the electrical domain. Furthermore, the digital signal processing must compensate for the mixing of the orthogonal polarization components induced by PMD. As a benefit (linear) degradation effects can be compensated more easily by electrical equalization.

For the upcoming generation of optical transmission systems higher-order modulation formats attract increasing interest [10, 13]. 16-QAM modulation may become the format of choice for transmission systems with 224 Gb/s (compare e.g. [13]). For even higher bit rates more sophisticated higher level modulation formats may be used in the future.

Also orthogonal frequency division multiplexing (OFDM) has been widely studied in the recent years. OFDM has the advantage of being very tolerant to linear signal distortions such as chromatic dispersion and PMD. Furthermore, in combination with coherent detection electronic equalization can be implemented easily. Also adaptation to the desired reach is possible because the signal constellation and use of subcarriers can be changed electronically. On the other hand OFDM requires a relatively high resolution of DAC and especially ADC converters, which may be difficult to realize at the required high bandwidth [14]. So far, however, no commercial realization for long-haul transmission at high bitrates is foreseeable. A short introduction into optical OFDM is given in e.g. [15]. A good overview and comparison between OFDM and QPSK modulation can be found in e.g. [16].

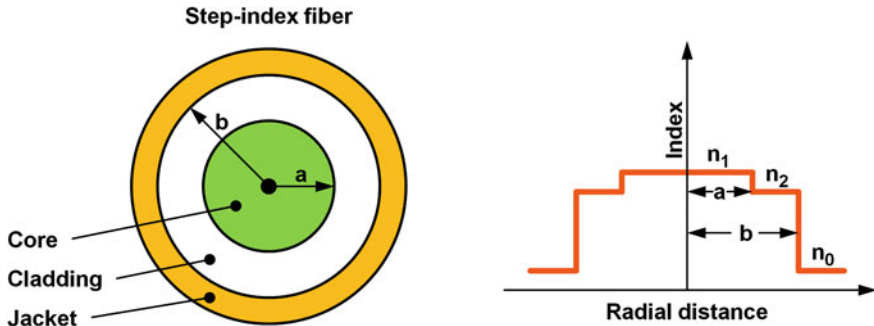


Fig. 2.6 Cross-section and refractive index profile of a single mode step-index fiber (adapted from [18])

2.4 Fiber Properties

In today's long and ultra-long haul networks solely single mode fibers (SMF) are used [17]. These fibers guide a single transmission mode only (but two orthogonal polarizations). Single mode glass fibers consist of a cylindrical core of silica glass surrounded by a cladding whose refractive index is lower than that of the core (Fig. 2.6, left). As the refractive index changes abruptly from the cladding to the core (Fig. 2.6, right) they are called step-index fibers. The diameter of a single mode fiber core ($2 \cdot a$) is approximately 8–10 μm and the cladding diameter ($2 \cdot b$) is typically 125 μm .

In Fig. 2.7 the spectral characteristics of dispersion and attenuation are plotted. There are two operational windows, which are normally used for optical communications. The windows are centered on 1,550 nm (usually used for long-haul communications) and 1,300 nm (usually used for metro networks) and are separated by OH^- absorption peaks. In today's transmission systems, usually the C- and L-bands (conventional- and long-band, compare Fig. 2.7) are used, which allow a total number of up to 160 channels using a channel spacing of 0.4 nm (50 GHz) in dense wavelength division multiplexing (DWDM) configuration. To utilize an even larger spectral bandwidth, new fiber types have been developed, which do not show the OH^- absorption peak and are usually referred to as "AllWave" fibers.

The reasons for using the C- (1,530–1,565 nm) and L-bands (1,565–1,625 nm) are the low attenuation of the transmission fiber in this wavelength region and the availability of optical amplifiers, so called Erbium-doped fiber amplifiers (EDFA, also compare the following section). In combination with gain flattening filters, EDFAs offer a flat gain spectrum over the whole C- and L-bands. Additionally the S- and U-bands may be used in future optical networks. In this case, a combination of Raman amplification, which is available in all bands and other lumped rare-earth doped amplifiers, may be employed.

Apart from the attenuation of the fiber, the spectral characteristics of the dispersion are important. These characteristics are measured by the dispersion

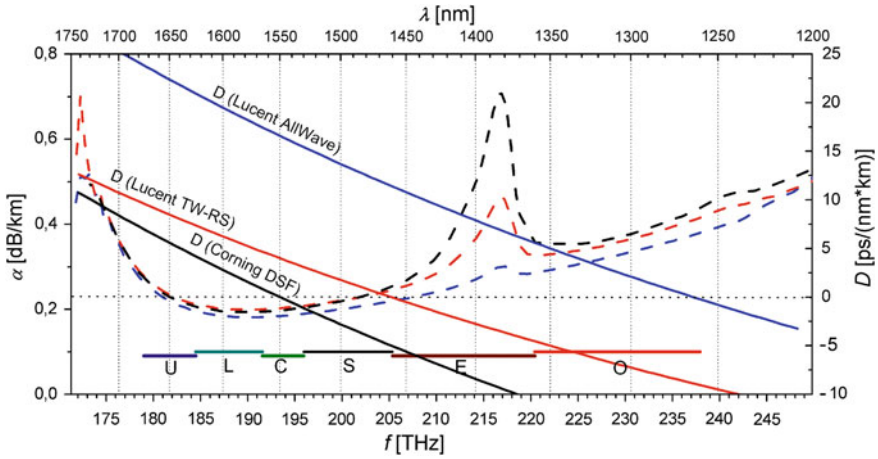


Fig. 2.7 Spectral characteristics of the dispersion (*solid lines, right axis*) and attenuation (*dashed lines, left axis*) as well as transmission band nomenclature

parameter D [ps/(nm · km)]. From the dispersion point of view four different fiber types can be distinguished: standard single mode fibers (SSMF), non-zero dispersion shifted fibers (NZDSF), dispersion shifted fibers (DSF) and dispersion compensating fibers (DCF). An overview of the fiber parameters is given in Table A1 in the appendix. The SSMF has $D \approx 0$ at 1,300 nm and a dispersion value of $D \approx 17$ ps/(nm · km) in the C-band. This is why (accumulated) dispersion compensation is needed, which can be done optically e.g. by the use of DCF. DCFs have a high negative dispersion value in the C-band. In contrast to that DSFs have $D \approx 0$ in the C-band. This offers the advantage that no dispersion compensation is needed. In WDM systems, though, large impairments occur due to nearly perfect phase matching of the different channels, which leads to strongly increased non-linear effects (especially four-wave mixing) in the fiber. Consequently, NZDSF fibers have been developed, which attempt to create a compromise between both fiber types. They offer a relatively low local dispersion of $D \approx 4$ ps/(nm · km) in the C-band. Thus they suppress the nonlinear effects more effectively than DSFs, and they offer a performance advantage over SSMFs in terms of less accumulated dispersion.

Furthermore, the dispersion slope parameter S [ps/(nm² · km)] is used to model the spectral tilt of the dispersion. It is extremely important to additionally compensate for the slope of the dispersion, if DWDM systems with a high channel count are used, which cover a larger bandwidth and operate at high channel bit rates (≥ 10 Gb/s). Otherwise, the edge channels of the spectrum may still encounter a considerable amount of degradation due to uncompensated dispersion stemming from imperfect matching of transmission fiber and DCF slope values. In high bit rate systems of 40 Gb/s or more also the temperature dependence of chromatic dispersion becomes noticeable. The fiber cables are normally buried 0.6–1.2 m

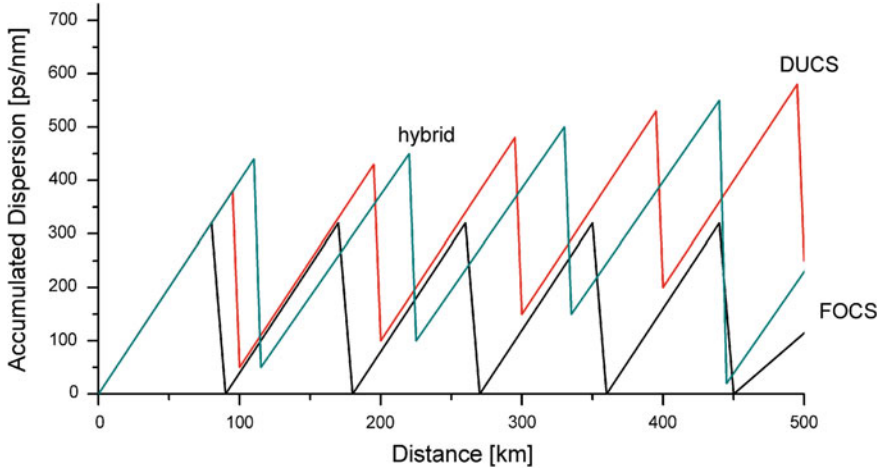


Fig. 2.8 Visualization of different dispersion compensation schemes

below the surface. In this depth the cable temperature can vary by several degrees over the year [19].

For the suppression of the nonlinear effects, the dispersion compensation scheme plays an important role. Several different dispersion compensation schemes exist in today's transmission systems.

First, there is the full-inline optimized post-compensation scheme (FOCS), where the accumulated dispersion is returned to (approximately) zero after each span. A major disadvantage of FOCS is that after each span the same phase conditions are restored leading to a strong accumulation of especially nonlinear fiber effects. This is why the distributed under-compensation scheme (DUCS) is commonly employed. In this scheme after each span some residual dispersion remains, which is advantageous for suppressing nonlinear fiber effects. Recently, a combination of DUCS and selective over-compensation has been suggested (hybrid dispersion compensation, compare Fig. 2.8). Hybrid compensation offers the advantage of some residual dispersion after each span while not accumulating a very high amount of residual dispersion, which needs to be compensated in front of the receiver.

Also pre-compensation is likely to be employed in WDM transmission systems with NRZ-OOK channels. Dispersion pre-compensation means that a certain amount of dispersion is compensated already at the beginning of the transmission system before the first transmission fiber. More information can be found in e.g. [20], where also design rules for the right amount of pre-compensation have been presented.

In today's high data rate transmission systems using coherent detection, the dispersion can be compensated electronically on a channel-by-channel basis to obtain the maximal system performance making it possible to build transmission systems without in-line dispersion compensation. However, as often legacy systems are upgraded, most systems are very likely to contain inline DCF modules for a long time in the future.

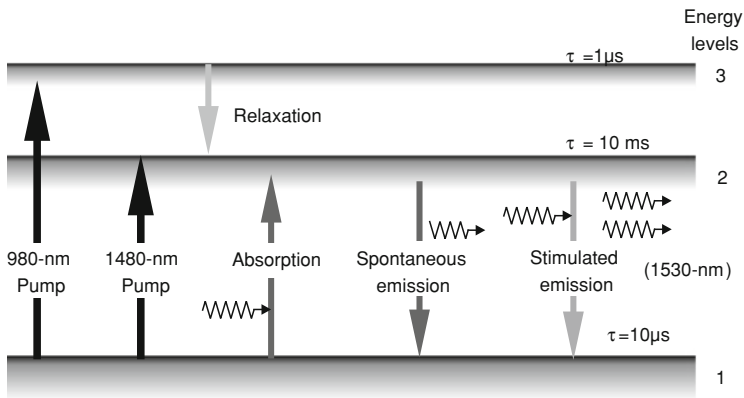


Fig. 2.9 Visualization of EDFA energy levels and working principle (adapted from [21])

2.5 Amplifiers

As in an optical communication system the optical signal is attenuated by the optical fiber and other components such as multiplexers and couplers, it has to be reamplified after some distance. Instead also so-called regenerators may be deployed, which receive the signal and retransmit it again. Today mostly optical amplification with Erbium-doped fiber amplifiers (EDFA) is used as it allows amplifying the entire WDM spectrum simultaneously [21]. Usually every 80–120 km an EDFA is deployed. The Erbium-doped fiber (EDF) in these amplifiers has a length of a few meters. In the EDF electrons are raised to a higher energy level by optical pumping with a lower wavelength laser (compare Fig. 2.9). The electrons fall back to their original level, stimulated by incoming signal photons. During this process, they emit a duplicate of the original photon. EDFAs work similar to lasers but without a feedback cavity. However, apart from the stimulated emission of photons there is also spontaneous emission, which adds noise to the signal. This noise is referred to as amplified spontaneous emission noise (ASE) because the photons generated by spontaneous emission are amplified along the rest of the EDF. In modern WDM systems EDFAs with several stages are widely used. The first stage of the EDFA has a low noise figure because it needs to provide a low output power only. The second stage of the EDFA, the booster, is used afterwards to generate a high output power signal. The noise performance of the whole amplifier is dominated by the first stage. Thus the 2-stage amplification produces a high-performance amplifier with low noise and high output power. Between the two amplifier stages a loss element can be placed with negligible impact on the performance. Typically a DCF module is connected at this point, and also a gain flattening filter is inserted [5].

An alternative to lumped amplification using EDFAs is distributed amplification using the Raman effect [22]. To utilize this nonlinear effect, Raman pumps with

lower wavelengths than the signal are fed into the fiber. Normally, contra-directional pumping is employed. As a result of the Raman effect, power is transferred from the lower wavelengths to the higher ones. The efficiency of Raman amplification (on standard transmission fibers and limited pump powers) is significantly lower than the gain, which can be obtained by EDFAs. That is why mostly a combination of Raman amplification and EDFAs is used. The greatest advantage of Raman amplifiers is that they work in every waveband. Furthermore, the OSNR is improved by Raman amplification because the minimum signal power along the transmission line is increased. Today the most popular use of Raman amplifiers is to complement EDFAs by providing additional gain in a distributed manner in long-haul transmission systems with some extra long fiber spans.

2.6 Optical Cross Connects

To enable dynamic reconfiguration of the transmission system along the transmission path optical cross connects (OXCs) may be deployed. In the literature OXCs exist in opaque and transparent configurations. In this book OXCs are used only in the all-optical configuration leaving the signal in the optical domain as it passes through the node.

Transparent OXCs are replacements for manual fiber patch panels. There are two main applications: protection switching to another lightpath in the case of a network failure (or planned maintenance) and provisioning of new lightpaths. Many optical technologies are available to realize optical switches [5]. OXCs can be based on micro-electro-mechanical systems (MEMS), on thermo-optical silica based systems, on electro-optics lithium niobate systems or on liquid crystals to enumerate only a few possible realizations.

The simplest realization of a MEMS based switch uses 2D mirrors. In one state, the mirror remains flat in line with the substrate and in the other state the mirror pops up to a vertical position and the light beam is deflected (Fig. 2.10).

Thermo-optical silica based switches are essentially 2×2 integrated-optic Mach-Zehnder interferometers. By varying the refractive index in one arm, the relative phase difference between the two arms is changed, leading to a switching from one output port to the other. Electro-optical switches can also be built in the Mach-Zehnder configuration, however, this time the electro-optical effect is used to change the relative phase.

Liquid crystals allow rotating the polarization of the incoming light based on an applied external voltage. In a configuration with a polarization beam splitter and a polarization beam combiner in this way the signal can be switched from one port to the other (for more details see e.g. [5]). Furthermore, the liquid crystal can be used as a variable optical attenuator (VOA) to control the output power of the signal.

To allow switching on a wavelength granularity level a (wavelength) demultiplexer is deployed in front of the OXC to split the incoming signal in its individual wavelengths. Afterwards the same switch architectures as described above

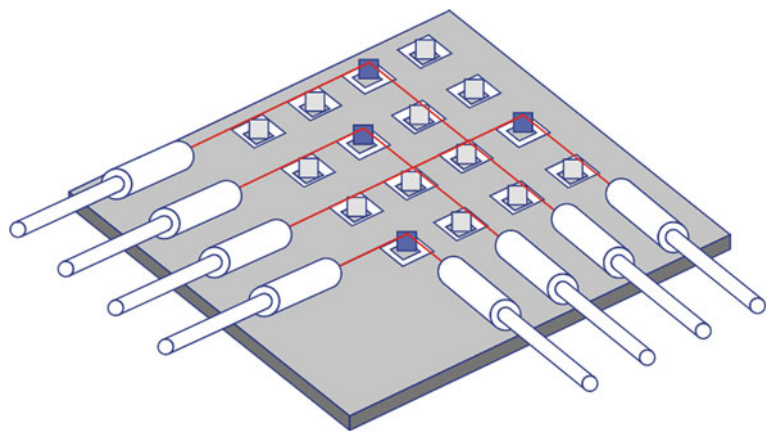
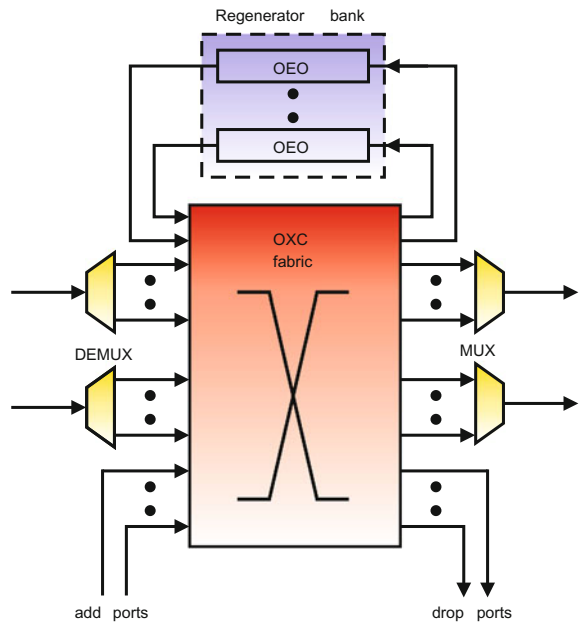


Fig. 2.10 4×4 MEMS matrix switch using free-space paths and 2D- movable mirror elements [23]

Fig. 2.11 Optical cross connect with optional optical-electrical-optical regeneration



may be utilized. On the output of the OXC a multiplexer is used to combine the different wavelengths again.

Optical cross connects can also be combined with an optical-electrical-optical (OEO) regenerator bank (Fig. 2.11). In this way some channels, which are highly degraded e.g. because of a long transparent path length, may be passed to a regenerator to recover the signal.

2.7 Receivers

At the receiver the optical WDM signal is demultiplexed. For this purpose an identical arrayed waveguide grating (AWG) may be used as for the multiplexer. After demultiplexing the signal has to be converted from the optical to the electrical domain.

In the case of intensity modulated signals, the power of each WDM channel can be directly fed to a photodiode (direct detection), which converts the optical signal into an electrical one. Direct detection can only recover the intensity of the electric field due to the square transfer function of the photodiode. This has the advantage that no phase-, frequency- or polarization control is necessary. On the contrary the information encoded in the optical phase can only be obtained when employing additional components (e.g. delay line interferometers).

Photodetectors are made of semiconductor materials (more details can be found in e.g. [5, 24]). Photons incident on such a semiconductor are absorbed by electrons in the valence band. As a result, these electrons acquire higher energy and are excited in the conduction band (if the band gap is chosen correctly), leaving behind a “hole” in the valence band. When an external voltage is applied to the semiconductor, these electron–hole pairs give rise to an electrical current (the photocurrent). In practice it is necessary to sweep the generated conduction band electrons rapidly out of the semiconductor before they can recombine with holes in the valence band. This is best achieved by using a semiconductor pn-junction instead of a homogeneous slab semiconductor. To improve the efficiency of the photodiode, a very lightly doped intrinsic (*i*-type) semiconductor is introduced between the p-type and n-type semiconductors. Such a photodiode is called pin photodiode. Typically pin photodiodes for the C- and L-bands are built from indium gallium arsenide (InGaAs) for the intrinsic zone and indium phosphide (InP) for the p- and n-zones (so called double heterostructures).

As photodiodes can only detect the optical intensity, in the case of phase modulated signals direct detection is not possible. A different receiver structure has to be used to recover the phase information. A possible realization with a delay line interferometer (DI) has already been depicted in Fig. 2.5. A DI can be used to convert the differential phase modulation into intensity modulation.

If in the electrical domain both amplitude and phase information are needed (e.g. because digital signal processing and equalization are desired), coherent reception must be employed. The setup of a coherent receiver for a polmux QPSK system is shown in Fig. 2.12. A local oscillator (LO) laser is used to provide a local reference signal. Two fundamental principles are distinguished: homodyne and heterodyne detection. In the former case of homodyne detection, the carrier frequencies of the LO and the signal laser are (almost) identical and the optical data signal is directly converted to the electrical baseband signal. One of the main challenges, though, is to synchronize the carrier frequencies and phases of the signal laser at the transmitter and the LO at the receiver. In the case of heterodyne detection, the frequencies of the signal laser and the LO are chosen to be different

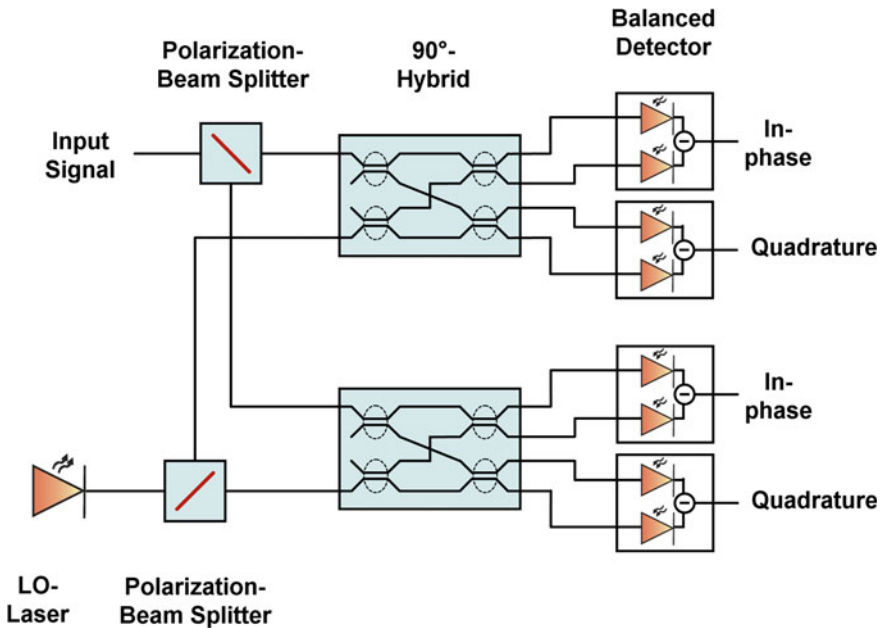


Fig. 2.12 Setup of coherent receiver for polmux QPSK signals

leading to an electrical signal at an intermediate frequency (IF). The advantage of heterodyne detection is that it permits simpler demodulation schemes and enables carrier synchronization with an electrical phase locked loop. On the other hand, the occupied electrical bandwidth is more than twice as high as for homodyne detection.

The mixing of the LO laser and the input signal is usually achieved by a so-called 90° -hybrid. It enables detection of the in-phase and quadrature components of an optical signal. Different realization options can be found in [25].

In principle single-ended detection by a photodiode would be possible at the upper and lower outputs of the 90° -hybrid. To not waste half of the power, however, a balanced detector is usually applied and the difference of both photodiodes is passed onwards.

For polmux operation additional care has to be taken to the demultiplexing of the two orthogonal polarization components. For this purpose polarization beam splitters are used to split up the LO laser and the input signal into parallel and orthogonal components. For each of these two polarization components an identical setup of 90° -hybrid and balanced detector is used leading to four output signals (two in-phase and two quadrature signals). In the electrical domain the four outputs are analog-to-digital converted. Afterwards, polarization demultiplexing and compensation of degradation effects is accomplished by adaptive digital signal processing.

2.8 Electrical Signal Processing

Digital (electrical) signal processing (DSP) has been emerging as a practical solution for long-haul optical communications for some years (compare e.g. [26 or 27]). Historically optical communications have operated at the very limits of electronic technology, preventing the application of digital signal processing which has become prevalent in many other fields such as e.g. wireless communications.

The first generation of electronic signal processing in optical communications emerged in the late 1980s and introduced forward error correction (FEC) to the digital (binary) data sequence. The first FEC codes (in optical communications) have been applied in 1988 by Grover [28]. Over the next years FEC has been standardized for use in optical transmission by the ITU-T with a 7% out-of-band overhead. Current codes (e.g. RS(1901, 1855)) yield a net coding gain of 8.7 dB at an output BER = 10^{-13} .

The second generation of electronic signal processing used some limited analog functions such as feed-forward equalizers (FFE) or decision directed equalizers (DDE). As in these days direct detection has been prevalent, the signal processing has been very limited due to the loss of phase information. In the third generation the main improvement has been the introduction of analog-to-digital converters (ADCs). DSPs replaced the analog signal processing and the clock and data recovery circuitry [26]. Maximum likelihood sequence estimation (MLSE) has been studied intensively in this period (compare e.g. [29]).

In the fourth generation electronic pre-distortion (EPD) of the signal at the transmitter side has been proposed. In contrast to the MLSE approach the complexity has been reduced and allowed precompensation of the chromatic dispersion and also nonlinear (single channel) effects (compare e.g. [30]). The main drawback of such a system is the limited robustness to interchannel crosstalk stemming from nonlinear effects such as four-wave mixing (FWM) and especially cross-phase modulation (XPM) and the limited flexibility inherent with predistortion (e.g. exact knowledge of the length of the transmission line and the dispersion parameters is required).

Current DSP systems operate on the electrical signals obtained from the outputs of a coherent receiver as shown in Fig. 2.12 and are implemented in application specific integrated circuits (ASICs). DSP are used for the compensation of (linear) transmission impairments and polarization demultiplexing [31]. One of the main challenges is that the algorithms have to be as simple as possible to enable high-speed real time processing. The adaptation speed is usually of less concern as the fiber channel varies rather slowly (compared to e.g. wireless communication systems) making blind adaptation attractive. The first step in the DSP is usually the compensation of the accumulated chromatic dispersion (CD) using e.g. a finite impulse response (FIR) filter structure. Another possibility is the implementation with infinite impulse response (IIR) filters, where the required tap number is lower than for FIR filters. However, the feedback of the IIR equalizers makes this approach hard to implement in high-speed electronics with parallelized signal

processing [27]. Ideally the dispersion estimation can be performed automatically allowing an optimum channel-by-channel compensation of the actual accumulated dispersion. An example of a possible realization is given in [32]. The next task is timing recovery to correct for the timing phase and frequency offset between the transmitter and receiver clocks. The phase error can be derived e.g. with the help of the Gardner algorithm [33]. The correction of the timing phase and frequency is performed either in the digital domain with the help of an interpolator or directly in an ADC. Afterwards polarization demultiplexing is performed. For this problem the fiber optic channel can be seen as a special case of the more general multiple-input-multiple-output (MIMO) systems. The constant modulus algorithm (CMA) is a popular choice for the approximate acquisition [34]. It is often followed by a least-mean squares (LMS) algorithm for tracking purposes. However, the LMS is decision directed requiring prior correction of the carrier phase and frequency offset. These offsets stem from the mixing with the local oscillator and are identical in both polarizations. The consequence is a rotating constellation diagram. A typical implementation of the phase offset estimation is based on the Viterbi-and-Viterbi algorithm [35]. The LO-phase recovery should have a rather low bandwidth in order to minimize the noise influence which is even worsened by the rapid XPM-induced phase fluctuations. Further improvements to the standard implementation using the Viterbi-and-Viterbi algorithm processing the two polarization planes independently can be gained by a joint-polarization (JP) algorithm [36]. These improvements lead to a significant increase of the ASE-noise tolerance.

Concluding one can say that digital signal processing has become a central element in state-of-the-art coherent optical communication systems. It will be interesting to see whether electrical signal processing will keep pace with the increasing data rates of optical communications and even more complex signal processing will be an integral part of future transmission systems.

References

1. Nokia Siemens Networks. SURPASS hiT 7500—Brochure, http://www.nokiasiemensnetworks.com/sites/default/files/document/hiT_7500_0.pdf
2. Alcatel-Lucent. 1625 LambdaXtreme Transport—Brochure, Release 8.1 (2009)
3. Gnauck, A.H., Tkach, R.W., Chraplyvy, A.R., Li, T.: High-capacity optical transmission systems. *IEEE/OSA J. Lightw. Technol.* **26**(9), 1032–1045 (2008). May
4. Birk, M., Gerard, P., Curto, R., Nelson, L., Zhou, X., Magill, P., Schmidt, T.J., Malouin, C., Zhang, B., Ibragimov, E., Khatana, S., Glavanovic, M., Lofland, R., Marcoccia, R., Saunders, R., Nicholl, G., Nowell, M., Forghieri, F.: Coherent 100 Gb/s PM-QPSK field trial. *IEEE Comm. Mag.* **48**(7), 52–60 (2010). July
5. Ramaswami, R., Sivarajan, K.N., Sasaki, G.H.: Optical networks—a practical perspective, 3rd edn. Morgan Kaufmann, Burlington (2010)
6. Kaminow, I., Li, T.: Optical fiber an telecommunications IV B. Academic Press, San Diego (2002)
7. Vossen, J.L., Kern, W.: Thin Film Processes. Academic Press, NY (1978)

8. Jansen, S. L., Derksen, R. H., Schubert, C., Zhou, X., Birk, M., Weiske, C. -J., Bohn, M., van den Borne, D., Krummrich, P. M., Möller, M., Horst, F., Offrein, B. J., de Waardt H., Khoe, G. D., Kirstädter, A., 107-Gb/s full-ETDM transmission over field installed fiber using vestigial sideband modulation, Optical Fiber Communication Conference (OFC), OWE3, March 2007
9. Winzer, P.J., Essiambre, R.-J.: Advanced modulation formats for high-capacity optical transport networks. *IEEE/OSA J Lightw. Technol.* **24**(12), 4711–4728 (December 2006)
10. Seimetz, M.: Higher-order modulation for optical fiber transmission. Springer, Berlin (2009)
11. Griffin, R. A., Carter, A. C.: Optical differential quadrature phase shift key (oOQPSK) for high capacity optical transmission. Optical Fiber Communication Conference (OFC), WX6, March 2002
12. Griffin, R. A., Johnstone, R. I., Walker, R. G., Hall, J., Wadsworth, S. D., Berry, K., Carter, A. C., Wale, M. J., Hughes, J., Jerram, P. A., Parsons, N. J.: 10 Gb/s optical differential quadrature phase shift key (DQPSK) transmission using GaAs/AlGaAs integration, Optical Fiber Communication Conference (OFC), FD6, March 2002
13. Alfiad, M., Kuschnerov, M., Jansen, S., Wuth, T., van den Borne, D., de Waardt, H.: Transmission of 11 x 224 Gb/s POLMUX-RZ-16QAM over 1500 km of LongLine and pure-silica SMF, European Conference on Optical Communication (ECOC), We.8.C.2, Torino, September 2010
14. Pachnicke, S., Özdür, S., Griesser, H., Fürst, C., Krummrich, P.: Sensitivity to signal quantization of 43 Gb/s and 107 Gb/s optical 16-QAM OFDM transmission with coherent detection. *Elsevier J. Opt. Fiber Technol.* **15**(5), 414–419 (2009)
15. Lowery, A.: Adaptation of orthogonal frequency division multiplexing (OFDM) to compensate impairments in optical transmission systems, European Conference on Optical Communication (ECOC). Tutorial, Berlin, (2007)
16. Jansen, S.L., Spinnler, B., Morita, I., Randel, S., Tanaka, H.: 100GbE: QPSK versus OFDM. *Elsevier J. Opt. Fiber Technol.* **15**(5), 407–413 (2009)
17. Kao, K.C., Hockham, G.A.: Dielectric-fibre surface waveguides for optical frequencies. *IEE Proc.* **113**(7), 1151–1158 (1966)
18. Agrawal, G.P.: *Fiber optic. comm. sys.* Wiley, New York (1992)
19. Vorbeck, S., Leppla, R.: Dispersion and dispersion slope tolerance of 160-Gb/s systems, considering the temperature dependence of chromatic dispersion. *IEEE Photon Technol. Lett.* **15**(10), 1470–1472 (2003)
20. Lehmann, G., Meissner, E.: Dispersion management for the transmission of mixed data rates of 40 Gb/s and 10 Gb/s in the same fiber. *Proc. SPIE* **4906**, 253–260 (2002)
21. Desurvire, E.: *Erbium doped fiber amplifiers—principles and applications.* Wiley, New York (1994)
22. Islam, M.N.: *Raman amplifiers for telecommunications 2: sub-systems and systems.* Springer, Berlin (2003)
23. Hoffmann, M.: *Micro-opto-electro-mechanical systems on silicon for optical communications systems.* Habilitation, Dortmund (2002)
24. Voges, E., Petermann, K.: *Optische Kommunikationstechnik.* Springer, Berlin (2002)
25. Seimetz, M., Weinert, C.M.: Options, feasibility and availability of 2 x 4 90°-hybrids for coherent optical systems. *IEEE/OSA J. Lightw. Technol.* **24**(3), 1317–1322 (2006)
26. Savory, S.J.: Electronic signal processing in optical communications. In: *Proc. of SPIE Vol. 7136, SPIE Asia-Pacific Optical Communications Conference (APOC 2008).* Hangzhou, China (2008)
27. Kuschnerov, M., Hauske, F.N., Piyawanno, K., Spinnler, B., Alfiad, M.S., Napoli, A., Lankl, B.: DSP for coherent single-carrier receivers. *IEEE/OSA J. Lightw. Technol.* **27**(16), 3614–3622 (2009)
28. Grover, W.D.: Forward error correction in dispersion-limited lightwave systems. *IEEE/OSA J. Lightw. Technol.* **6**(5), 643–645 (1988)

29. Kupfer, T., Dorschky, C., Ene, M., Langenbach, S.: Measurement of the performance of 16-States MLSE digital equalizer with different optical modulation formats, Optical Fiber Communication Conference (OFC), PDP13, Anaheim, USA, March 2008
30. Killey, R. I., Watts, P. M., Glick, M., Bayvel, P.: Electronic dispersion compensation by signal predistortion. In: Optical Fiber Communication Conference (OFC), OWB3, Anaheim, USA, March 2006
31. Fludger, C.R.S., Duthel, T., van den Borne, D., Schulien, C., Schmidt, E.-D., Wuth, T., Geyer, J., De Man, E., Khoe, G.-D., de Waardt, H.: Coherent equalization and POLMUX-RZ-DQPSK for robust 100-GE transmission. *IEEE/OSA J. Lightw. Technol.* **26**(1), 64–72 (2008)
32. Kuschnerov, M., Hauske, F. N., Piyawanno, K., Spinnler, B., Napoli, A., Lankl, B.: Adaptive chromatic dispersion equalization for no-dispersion managed coherent systems. In: Optical Fiber Communication Conference (OFC), OMT1, San Diego, USA, March 2009
33. Gardner, F.M.: A BPSK/QPSK timing-error detector for sampled receivers. *IEEE Trans. Commun.* **34**(5), 423–429 (1986)
34. Savory, S.J.: Digital filters for coherent optical receivers. *OSA Opt. Exp.* **16**(2), 804–817 (2008)
35. Viterbi, A.J., Viterbi, A.M.: Nonlinear estimation of PSK-modulated carrier phase with applications to burst digital transmission. *IEEE Trans. Inf. Theory* **29**(4), 543–551 (1983)
36. Kuschnerov, M., van den Borne, D., Piyawanno, K., Hauske, F. N., Fludger, C. R. S., Duthel, T., Wuth, T., Geyer, J. C., Schulien, C., Spinnler, B., Schmidt, E. -D., Lankl, B.: Joint-polarization carrier phase estimation for XPM-limited coherent polarization-multiplexed QPSK transmission with OOK-neighbors. In: European Conference on Optical Communication (ECOC), Mo.4.D.2, Brussels, September 2008



<http://www.springer.com/978-3-642-21054-9>

Fiber-Optic Transmission Networks
Efficient Design and Dynamic Operation
Pachnicke, S.
2012, X, 166 p., Hardcover
ISBN: 978-3-642-21054-9