10 Optical Multi-Channel Systems (OTDM / OWDM)

WDM Tb/s-Link
(20Gb/s x2x80=3.6Tb/s)
Goals of the chapter:

- In order to avoid the electronic bottle-neck in single wavelength fiber transmission, the available optical transmission spectrum of 20-40 THz is multiplexed in the optical domain.
- Optical multiplexing is realized either in the time domain by ultra-short pulse transmission (OTDM) or in the wavelength domain by using a large number of carrier wave length in the same fiber (OWDM).
- What are the key devices for OTDM and OWDM.

Methods for the Solution:

- OTDM and OWDM are simple in concept, but they require a number of key optoelectronic elements in order to become feasible.
- OTDM critical: short pulse generation by mode-locked lasers, all-optical demultiplexing and channel-clock extraction by ultra-fast optical nonlinearities.
- OWDM critical: precise and stable optical frequency generation by single frequency lasers, optical demultiplexing by precise multi-wavelength bandpass filters, low cost components due to the large component number required.
10 Optical Multi-Channel Systems (OTDM / OWDM)

Introduction:
Electronically multiplexed systems just make marginal use of the fiber THz-bandwidth, therefore broadband systems use optical time-and frequency multiplexing.

In optical multi-channel-systems the bandwidth of the optical fiber is used efficiently by

1) optical time domain multiplex (OTDM)
2) optical wavelength domain multiplex (OWDM)

and subsequent transmission of the aggregated signal trough one single fiber. At the receiving end the data streams are demultiplexed, which is in both system the challenging part.

OTDM: (Optical Time Division Multiplex)
• The optical multiplex-operation of different data channels occurs in the time domain into non-overlapping (*) bit-time slots $T$.
  There is total overlap in the optical frequency domain $\omega$ (because only one transmission frequency $\omega_0$, resp. wavelength $\lambda_0$ exists).
  (*) no crosstalk in the time domain

OWDM: (Optical Wavelength Division Multiplex)
• The optical multiplex-operation of different data channels occurs in the frequency domain into non-overlapping (**) frequency-bands $B_{ch}$. There id total signal overlap in the time domain $t$ (because N transmission wavelengths $\lambda_1 - \lambda_N$ exist which are unrelated in time).
  (**) no crosstalk in the frequency domain

It is the goal to transfer the MUX / DEMUX-Operations into the optical format, to avoid electrical signal representation (electronic bottle neck ~100 Gb/s), for accessing the optical band width $B_{opt} ~10-20$ THz of fibers and optical nonlinear effects.

As the analysis of optical multi-channel reaches considerably into system and network technology, we just consider basic principles and the implication with respect to the necessary key devices.
### System overview:

<table>
<thead>
<tr>
<th>System</th>
<th>Multiplex, electrical carriers</th>
<th>Multiplex, optical channels</th>
<th>Application</th>
<th>Advantages</th>
<th>Drawbacks</th>
<th>Key components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opt. Time Division Multiplex, OTDM</td>
<td>$N_e$ channels, ETDM baseband</td>
<td>$N_{opt}$ time-channels, OTDM 1 wavelength, $\lambda_0$</td>
<td>Long (short) distance</td>
<td>System simplicity</td>
<td>Challenges in device functions Switching, dispersion</td>
<td>Mode-locked lasers All-optical DEMUX Dispersion comp.</td>
</tr>
<tr>
<td>Opt. Wavelength Division Multiplex, OWDM</td>
<td>$N_e$ channels, ETDM baseband</td>
<td>$N_{opt}$ wavelength-channels, OWDM $N_{opt}$ wavelengths, $\lambda_1 - \lambda_{N_{opt}}$</td>
<td>Long distance, LANs</td>
<td>Simple components</td>
<td>High component count Difficult wavelength conversion</td>
<td>Optical DEMUX, narrowband filters Single frequency sources</td>
</tr>
<tr>
<td>Subcarrier Multiplex, SCM</td>
<td>$N_e$ electrical carriers $f_{1e} - f_{Ne}$</td>
<td>1 optical carrier $N_{opt}=1$ 1 wavelength, $\lambda_0$</td>
<td>Short distance distribution, eg. Video</td>
<td>Simple electronic extendibility</td>
<td>Large signal dynamic and high linearity</td>
<td>Broadband E/O modulator</td>
</tr>
</tbody>
</table>

Practically often hybrids of OTDM and WDM are implemented.

### 10.1 Optical Time-Multiplex (OTDM) Transmission

At the begin of the fiberoptic data transmission the electrical digital channel signals have been **electrically up-multiplexed to the maximal aggregated data rate** following a predefined data hierarchy ([Lit.[3]]). This aggregated electrical signal was converted electro-optically into the optical domain only for the transmission.

For demultiplexing, the transmitted optical signal is converted into the electrical domain and demultiplexed in the electrical domain.

#### 10.1.1 Concepts of OTDM-Systems

To avoid the electronic bottle-neck, OTDM-systems realize the MUX-, DEMUX- and gain-function at the front end by **optical signal processing**. Goal is the increase of the aggregate rate $B_{tot}=N_{opt}B_{ch}$ into the Tb/s-range (T~1ps). $N_{opt}$=number of time-channels, $B_{ch}$=channel rate.
Schematic Representation of a All-optical OTDM-systems:

![Diagram of OTDM-systems](image)

Opt. MUX (N_{opt}:1) (passive couplers) Opt. DEMUX (1:N_{opt}) (opt. nonlinearity)

\[ B_{ch}/\text{channel} \quad B_{tot}=N_{opt}B_{ch}/\text{channel} \quad B_{ch}/\text{channel} \]

Requirements of all-optical devices for OTDM:

- **Pulse-Sources** → *optical pulse width* (\(\Delta t<T\sim 1/B_{tot}\)) (critical)
- **Multiplexer** → *passive optical couplers* (∼300 Gb/s – 1 Tb/s)
- **Modulator driver** → *electronic* (\(B_{ch}=1/(N_{opt}T)\) ∼40 Gb/s)
- **Modulator** → *optoelectronic* (∼40 Gb/s)
- **Photodetector** → *optoelectronic* (∼40 Gb/s)
- **Pre-Amplifier** → *optical* (\(B_{tot}\sim 5\) THz)
- **Clock-Extraction** → *optical* (\(B_{tot}\sim 300-600\) GHz) (critical)
- **Threshold-Gate** → *electronic* (∼40 Gb/s)
- **Demultiplexer** → *optical* (\(B_{tot}\sim 500\) Gb/s – 1 Tb/s) (critical)
10.1.1.1 Ultrafast Optical DEMUX-Function

Optical nonlinear processes in SC and glasses (absorption, stimulated emission, nonlinear polarization effects, etc.) often display bandwidth, resp. time constants >100 THz, resp. ~10fs.

In comparison to current electronic transistors, which are approaching switching speed of 2-5 ps, all-optical devices, which must be based on an optical nonlinearity have the potential to improve the switching speed of all-optical logic devices by a factor of 10 – 100x.

Generic principle of operation of an all-optical switch (AND-gate between signal and channel clock):

An intense optical control signal \( P_c \) induces a nonlinear change mostly in the refractive index \( \Delta n(P_c) \), but also changes in the optical gain \( \Delta g(P_c) \), etc. are feasible.

Ultrafast index \( \Delta n \) changes are caused eg. by:

a) opt. Kerr-Effect in WG (non-resonant)

\[ \Delta n = k P_c \quad k = \text{Kerr coefficient} \]

\[ \Delta g \cong \Delta n_e(P_c) \]

\[ \Delta n = \alpha \Delta n_e(P_c) \]

\( \Delta n_e \)=electron density \( \alpha = \text{line width enhancement factor} \)

For photon energies \( h \omega_c > E_g \) of the control signal \( P_c(t) \) is smaller than the bandgap \( E_g \) of the nonlinear material then no carriers are generated (eg. glasses, but not necessarily SC), \( \rightarrow \) non-resonant excitation.

Otherwise carriers are generated by absorption, which can have large lifetimes (eg. SC) and lead to a slow decay of the refractive index change \( \rightarrow \) resonant excitation.

Fast refractive index changes \( \Delta n \) mean fast changes of the phase \( \Delta \phi \), which can be used in a interferometric configuration to switch the transmission \( T(\Delta \phi) \) between on- and off-states on a sub-ps time scale \( (T(0) \leftrightarrow T(\Delta \phi(P_c(t)))) \).
Example: a) All-optical SOA-Mach-Zehnder-Interferometer Switch and b) Fiber-MZI-Switch:

Principle of operation Fiber MZI-Switch: (L₁ and L₂ are designed that the interferometer does not transmit with control signal $P_C=0$)
- The strong control signal pulse $P_C$ with wavelength $\lambda_C \neq \lambda_S$ is coupled into arm 1 of the MZ-interferometer and changes the refractive index ($\Delta n$) and the phase ($\Delta \phi_1$)
- The induced phase difference between arm 1 and 2 $\Delta \phi = \Delta \phi_1 - \Delta \phi_2 - \pi$ for the data signal $P_S$ at wavelength $\lambda_S$ switches the MZ-interferometer during the duration $\Delta t$ of $P_C$ from the off- ($T=0$) to the on-transmission state ($T(\Delta t=\pi)=1$)

a) MZI-SOA-Switch:

$$\Delta \phi (P_C) = 2\pi L \Delta n / \lambda = 2\pi L / \lambda \alpha \Delta n_c (P_C)$$

optically induced carrier- and refractive-index change in SOAs

b) Fiber-MZI-Switch

$$\Delta \phi (P_C) = 2\pi L \Delta n / \lambda = 2\pi L / \lambda kP_C$$

Optical Kerr-effect in SiO₂

MZ-Interferometer Transmission:

$$T(P_C(t)) = \frac{P_{out}}{P_{in}} = T_0 \sin^2 \left( \frac{2\pi}{\lambda} L k P_C(t) \right)$$

Transmission $T(P_C)$
Time diagram of the all-optical MZ-interferometer switch:

b) Fiber-MZI-Switch

a) MZI-SOA-Switch:

Remarks:

1) control- and data signals $P_C$ and $P_S$ have different wavelengths $\lambda_C$ and $\lambda_S$

2) The $\lambda_C$-filter at the output removes the control signal

3) the interferometer, that is $L_1$ and $L_2$ are designed that there is a built-in phase shift $\Delta \phi = \pi$ for $P_C=0$
10.1.1.2 Dispersion compensation for ultra fast OTDM-Systems

For optical signal in the RZ-format with aggregated data rates $>100$ Gb/s require pulse width $T$ in the order of $0.3 – 3$ ps and RMS-values of the time-jitter $\delta t$ of the pulses $\delta t < 0.1 – 0.3$ps.

For such short pulses we have to compensate dispersion already after a few 10 km for 1. and 2. order even for dispersion-shifted fibers (predistortion of equalization). If the fiber length is known, then precise dispersion compensation is possible (eg. by fibers of opposite dispersion properties).

10.1.1.3 Optical Broadband-Amplifiers

Fibers have an available bandwidth of 15 and 25 THz, -on the other hand the bandwidth of SOAs and EDFAs is typically ~15 and 6 THz at a gain of about 20-30 dB. In chap.6 we demonstrated that with increasing gain $G$, the optical –3dB-bandwidth is reduced.

Possibilities to increase the bandwidth are:

- Bandwidth equalization by passive filters
- Broadband Raman-amplifiers in fibers
10.1.1.4 Optical Pulse Generation by Mode-Locked Lasers

For ODTM-systems very short light pulses with a duration \( T < 1/B_{\text{tot}} \) (~ps) are required. The unmodulated pulse trains from \( N \) mode-locked laser with a repetition rate \( f_{\text{rep}} = B_{\text{ch}} \) has to be modulated and then \( N \)-times multiplexed, such that \( B_{\text{tot}} = NB_{\text{ch}} \).

Because conventional diode lasers and also modulators have bandwidth of less than 40 GHz, resp 80 GHz, it is impossible to generate ps-pulses – not to mention that also a driving electronic for such short pulses is not feasible today.

**Active Mode-Locking of Diode Lasers:**

**Operation Principle:**

Mode-locking is a technique where a longitudinal multimode laser, with a mode separation \( \Delta \omega = 1/T \), is modulated by an external source with a frequency \( f_{\text{mode-lock}} = \Delta \omega / 2\pi \). \( T = 2L/v_{\text{gr}} \) is equal to the round-trip time of a pulse in the FP-resonator of length \( L \).

Mode-locking results in a phase-synchronization of the laser-modes, which produces a pulse with the width \( \Delta t \approx 1/(N_{\text{mode}} \Delta \omega) \). \( N_{\text{mode}} \) is the number of synchronized longitudinal laser modes in the spectrum.

The mode-locked laser emits an unmodulated pulse-train with the repetition rate \( f_{\text{rep}} = 1/T = v_{gr}/(2L) \) equal to the inverse of the round-trip time \( T \) of the cavity. \( f_{\text{rep}} \) must be identical to the channel rate \( B_c \).
InGaAsP/InP Mode-Locked Laser Diode at 1.55 \( \mu \)m:

- Pulse width \( \Delta t \approx 2.5 \) ps
  - @ \( f_{\text{rep}} = 10 \) GHz

Example: 1.28 Tbit/s OTDM-Network-Demonstrator:

1. Setup for the generation of 10 GHz clock light
   - Laser
   - Channel

2. Setup for the generation of 1.28 Tbit/s signal
   - Clock light
   - 1:2 opt. Pol. MUX
   - Transmission Fiber
   - 70 km

3. Setup for the demultiplexing of 1.28 Tbit/s OTDM signal to 10 Gbit/s
   - 10 GHz Clock-Extraction
   - Nicht-linearer Fiber-DEMUX

Example: 1.28 Tb/s OTDM-Network-Demonstrator:
10.2 Optical Wavelength-Multiplex (OWDM) Systems

10.2.1 System concept and requirements

Although OTDM-systems make use of the fiber bandwidth up to the Tb/s-range, dispersion and the DEMUX-operation in the time domain at full aggregated date rate represent a difficult challenge. An alternative to the above mentioned drawbacks of OTDM is OWDM, where each electrical data channel i is modulated onto its optical carrier wave with a wavelength \( \lambda_i \). Therefore one subdivides the optical transmission band \( B_{\text{opt}} \sim 20 \text{ THz} \), resp. \( \Delta \lambda_{\text{opt}} \sim 200 \text{nm} \), into \( N_{\text{opt}} \sim (100-1000) \) bands \( (B_{\text{ch}}=B_{\text{opt}}/N_{\text{opt}}) \). To extract a particular channel at the receiver, the DEMUX has to filter one particular channel at the desired wavelength \( \lambda_i \) by a narrow band optical filter \( \Delta f_{\text{filter}} \sim B_{\text{ch}} \) and direct it to the photodetector.

Critical requirements of a OWDM-system are the generation of the extremely stable carrier frequency \( \omega_i \) with \( \Delta \omega_i \ll B_e \) and the precise and narrowband wavelength filtering, as well as the system complexity and the high number of optical components for large channel numbers.

On the other hand the electronic signal processing is relatively simple for OWDM-systems, which is an advantage for optical information distribution in broadcast-networks or LANs.

10.2.2 Point-to-point OWDM-Systems

The simplest OWDM-network is the point-to-point link, - after the optical DEMUX the signal distribution is carried out in the electrical domain. Signal distribution in the optical domain is considerably more difficult because it requires the function of optical wavelength conversion.

Critical components / requirements:

- fixed \( \lambda \)-MUX \( (N_{\text{opt}}:1), \text{DEMUX} \ (1:N_{\text{opt}}) \) with high channel selectivity and high out of band damping, small channel separation \( \Delta \lambda \sim 1 – 0.1 \text{nm} \) (!), low losses and high thermal stability
- \( N_{\text{opt}} \) single frequency DFB-Laser sources with fixed and stable wavelengths \( \lambda_i \) ; \( 1<i<N_{\text{opt}} \)
**OWDM System-Concept (Example):**

Channel wavelength slot $\Delta \lambda_j = \Delta \lambda_{\text{opt}} / N_{\text{opt}}$  
DMUX = $\lambda$-Filter with $N_{\text{opt}}$ channels

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**Advantages:**
- relative low data rate per optical channel with modest requirements for dispersion and electronic speed
- data format and timing of the channels are independent of each other

**Drawbacks:**
- Challenging requirements for the wavelength MUX and DEMUX with respect to wavelength control, filter characteristics ($\Delta \lambda \sim 0.5$-1.2 nm), cross talk and thermal stability
- large component count
- highly stable optical frequency generation and small oscillator bandwidth (~MHz)
- high total operational power ($N_{\text{opt}} \times P_{\text{op,channel}}$; typ. 200 x 1mW/ch=200mW) in the fiber can result in optical nonlinearities
10.2.3 Broadcast-OWDM-Systems

Broadcast Systems are used for the broad and efficient (large number M of receivers / clients) **unidirectional distribution** of information, generated by a potential small number of N transmitters (M>>N). The optical distribution is realized by a passive or active **Star-Coupler** (Broadcast-Star).

**System Concept (example):**

![System Concept Diagram](image)

N sources with fixed wavelength $\lambda_i$  

M tuneable wavelength filters ($\lambda_1, \lambda_2, ..., \lambda_N$) with photoreceivers

The star-coupler is a combination of a N-wavelength MUX and a non-wavelength selective M-power splitter. At the star-output one can „see“ all wavelength $\lambda_i$, i=1-N from its inputs. Each receiver needs a **tuneable optical filter** at its input.

**Advantages:**
- compared to optical bus-structures the power losses in star-structures are advantageous, because the power losses increase only with the power of $\log_2 M$ instead with M as for bus-structures.

**Drawbacks:**
- tuneable narrowband single-frequency filters are technologically difficult to realize and are expensive
System critical components:
- \( \lambda \)-star coupler
- \( \lambda \)-filter (tuneable)
- \( \lambda \)-sources, fixed single-frequency DFB-laser

10.2.4 LANs (\( \lambda \)-Add-Drops)

Functional Goal: non-blocking, reconfigurable, bi-directional interconnection of \( N \) transmitters with \( M \) receivers

System Concept (example):

System critical components:
- \( \lambda \)-stars
- \( \lambda \)-filter (fixed)
- \( \lambda \)-tuneable DBR-laser diodes
All these examples of OWDM-networks make use of the following generic important and technologically challenging functions:

- star coupler, combiners / splitters
- wavelength MUX
- fixed and tuneable optical narrow-band filters
- fixed and tuneable single-frequency lasers
- wavelength DEMUX

10.3 Realization of OWDM-key-components

Similar to the OTDM-systems, also OWDM-systems require some absolutely performance critical components, which we will describe just in their functionality but not the underlaying physical mechanisms.

The functional requirements for these components are particular high if:

- **small channel separation** $\Delta \lambda_{\text{ch}} = (\lambda_i - \lambda_{i-1})$, ~ 1.2 – 0.5nm
- **large channel number** $N$ (100 – 1000)
- **high temperature stability**
- **tuneability by preferably electrical signals**
- **Integrated devices for low costs**
- **cost efficiency with respect to packaging, fiber-coupling, volume, etc.**
10.3.1 Star-Couplers

**Function:** Distribution of any input-power $P_{in,i}$ at input-port $i$ to all $N$ output-ports as $P_{out,k} = k_{loss}P_{in,i}/N$, $k=1-N$. The distribution should be independent of wavelength.

- **Passive, hybrid Fiber-Star-coupler:** (wavelength independent)
  - Each input is connected to each output.
  - Multimode-Mixing-Region:
    - (flame molded fiber bundle)

- **Passive, integrated planar wave-guide star-coupler with optical directional couplers:** (wavelength dependent)
  - 2-D matrix of elementary 1:1-couplers (2-input-2-output splitter)
  - Technology:
    - Planar glass or SC-waveguides (or fibers)

- **Passive, integrated planar star coupler:** (wavelength independent)
10.3.2 Wavelength-MUX /DMUX

**Function:** Distribution of the multi-wavelength input-power $\sum P_{in,\lambda_i}$ with the individual wavelengths $\lambda_i$ to the N different outputs $i$. $P_{out,i} = k_{loss} P_{in,\lambda_i}$, where each output has a particular assigned wavelength $\lambda_i$. This is the $\lambda$-Demultiplex function, the inverse is the $\lambda$-Multiplex.

Diffraction-grating -Demultiplexer:

**Operation principle:**
Spatial separation of the input multi-wavelength power spectrum by a **diffraction grating** into the individual wavelength components. The individual wavelength components are focused into different output ports.

Integrated, planar Array-Waveguide-Demultiplexer:

**Operation principle:**
Spatial separation similar to the diffraction grating, but the angular phase differences are realized by propagation differences in the individual waveguides of different length in the waveguide-array.
Waveguide analog of a diffraction grating.
Integrated, planar Mach-Zehnder-Interferometer - Multiplexer:

![Diagram](Bild Agraw. P.283)

**Operation principle:**
Spatial separation by an array of different Mach-Zehnder interferometers with different filter characteristics.

**Problems:**
- relative high losses (optical amplification may be necessary)
- wavelength control of the device design and device stability is critical for the desired narrow-band filter characteristic
- controlling the parasitic cross-talk between the different wavelength channels is non-trivial

### 10.3.3 Single Wavelength Laser-Diodes with Wavelength Tuning

Single frequency diodes, where tuning of the oscillation wavelength $\lambda$ is electronically and fast, are important components for:

- **Signal Generators in OWDM-based LAN-systems**
- **Local Oscillators in coherent optical homo- and heterodyne-systems**

Referring to chap.6 we repeat that tuneable DBR- or DFB-diode lasers are built from three generic components:

1) an optical amplifier (SOA)
2) a Bragg-grating filter for single frequency selection
3) a phase control part for controlling the phase in the resonator by current injection and subsequent index change
3-Section DBR InGaAsP-Laser Diode: Due to the considerable device complexity these laser diodes are rather expensive (typ. a few kCHF) and demanding in the fabrication process.

Tunable Optical Filters
Tunable filters have a similar functions as $\lambda$-DEMUX by filtering a specified power $P_{out} = k_{loss} P_{in,\lambda_i}$ at the wavelength $\lambda$ from a total multi-wavelength input spectrum $P_{in} = \sum P_{in,\lambda_i}$. 
From the large number of possible realizations, usually based on a type of passive high Q Fabry-Perot-resonator (see chap.6), we will consider just a special case:

**Mechanically tuneable Fabry-Perot-filter (FP):**

By changing the mirror separation $L$ (eg. by piezo-electric effects) of a FP-filter we modify the multiple resonances $\omega_{res,i}$ of the FP-resonator. If the reflection coefficients $r_1$, $r_2$ of both mirrors are very high, we get a filter with a very narrow bandwidth $\Delta\omega$ and a high suppression of off-resonance frequencies. A drawback are the multiple undesired resonances of the FP.

**Schematic filter construction and basic filter-characteristics:**

Definitions:

- $\phi = \omega L n / c$
- $\omega_{res,i} = i \pi c / (L n) = $ resonance frequency
- $\Delta\omega_L = \pi c / (n L) =$ separation of FP-Resonances
- $\Delta\omega = \Delta\omega_L / \{ \pi \sqrt{r_1 r_2} / (1 - r_1 r_2) \} = $ filter bandwidth (function of $r$)
- Finess:
  - $F = \Delta\omega_L / \Delta\omega = \pi \sqrt{r_1 r_2} / (1 - r_1 r_2)$
- Free Spectral Range:
  - $FSR = \lambda^2 / (2 n L) = \Delta\lambda_L$

**Challenges:**
- relative high insertion losses
- absolute wavelength control (wavelength reference source), slow scanning (due to the high filter $Q$)
- high out-of-band attenuation, cross-talk effects
- Multiple transmission bands (pre-filters)
Limitations of WDM-Systems

Despite their simplicity OWDM systems have a number of nonidealities limiting their performance with respect to bandwidth usage, resp. number of transmitted channels or economic boundaries.

Crosstalk between channels of different wavelengths

Optical filters have, in analogy to their electrical counterparts, the following limitations:
- finite transmission attenuation, caused by waveguide losses, fiber-waveguide coupling, absorption, etc.
- finite out-of-band attenuation, resulting in crosstalk in the non-wavelength selective photodetector of the receiver
- finite transition width between the transmission band and the stop-band, dictating the minimal channel wavelength separation (limited usage of the available fiber bandwidth)
- Temperature stability and manufacturing tolerances of the filter characteristics
- (polarization sensitivity)
- (wavelength stability of the laser source)
- availability of broadband optical amplifiers

Fiber-Nonlinearity

Depending on the transmission distance, typical input power per wavelength-channel \( P_{\text{in},\lambda_i} \) in the fiber is \(~1\text{mW at } \lambda_i \). With a modest number of a 100 channel the total fiber power can be as high as a 100mW in a fiber core of \(~6\mu \text{m diameter} \). The power density in the order of several MW/cm\(^2\) generates very large optical field strengths. These fields produce in combination with the very long interaction length \( L_{\text{fiber}} \) of the fibers nonlinear effects in the polarization \( P \), resp. in the susceptibility \( \chi (\vec{E}) \).

These nonlinear effects, depending of their origin can cause channel-crosstalk, distortion of the signal spectra or of the waveform of the digital signals. Physical effects of these polarization nonlinearities are:
- Intensity \( (I_{\text{opt}}) \) dependent refractive index \( n(I_{\text{opt}}) \) (Kerr-effect)
- Generation of new optical frequencies as mixing products of the polarization nonlinearity (self-phase modulation, four-wave mixing, etc.)
10.3.5 OWDM, ODWDM (optical dense wavelength division multiplex)

10.92 Tbps OWDM, 273 x 40 Gbps channels

Although OWDM-systems have complex requirements for wavelength stability and wavelength conversion, their development is further advanced than comparable OTDM systems due to the less challenging electronic and all-optical DEMUX-function.

Abbreviations:
LD=laser diode
AWG=Array waveguide MUX
LN-MOD=Lithium-Niobate modulator
PBS=polarizing beam splitter
TDFA=Terbium doped fiber amplifier
PC=power control
EDFA=Erbium doped fiber amplifier
ETDM=Electronic TDM

Remark:
Each 40 Gbps channel uses only a bandwidth of ~0.5nm/ch corresponding to 65 GHz.
Summary:

- Optical TDM- and WDM-Systems eliminate successfully the „electronic bottle-neck“ at 40-100 Gb/s and push the aggregated data rates as hybrid OTDM / OWDM toward 10 Tb/s.
- OWDM is currently more advanced toward a practical implementation than OTDM. All-optical components for ps-processing are currently still a topic of research.
- OWDM-Systems allow, beyond simple point-to-point links, interesting signal distribution concepts.
- Optical coherent systems allow in OWDM-systems a more optimal SNR to be achieved than simple intensity modulation. These systems come close to the inherent quantum-limit, but are very demanding in terms of component performance and stability.