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100 Gigabit-per-second: Ultra-high transmission bitrate for next generation optical transport networks

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Abstract

Modern telecommunication networks have to provide enormous data transport capacity in order to enable the dramatic annual internet traffic growth rates. As an illustration, today some internet exchange nodes partly exhibit annual peak traffic growth rates of more than 200% due to strongly emerging data and broadband video services. This explosion of internet data and video traffic can only be assured by the implementation of the most advanced optical metro and core transport network technologies. It is likely that next generation telecommunication transport networks will be based on 100 Gigabit/s Ethernet (100 GbE) interconnections. Here we will report on the technical challenges and achievements associated with the development of ultra-high speed components and systems for serial 100 Gbit/s optical transmission. ***To cite this article: G. Veith et al., C. R. Physique 9 (2008).***

Résumé

Un débit binaire de 100 Gigabit/s pour la prochaine génération de réseaux de télécommunications optiques. Les réseaux de télécommunications modernes doivent disposer d'énormes capacités de transport de données pour pouvoir accompagner les taux de croissances annuels toujours vertigineux du trafic Internet. Aujourd'hui, notamment, certains nœuds d'échange Internet peuvent présenter une croissance annuelle de leur trafic pic de plus de 200 % en raison de l'émergence soutenue de services de données de vidéo large-bande. Cette explosion du trafic de données internet et de la vidéo n'est rendue possible que grâce à l'implémentation des technologies les plus avancées de réseaux optiques métropolitains et de cœur. Il est d'ailleurs probable que la future génération de réseaux de transport sera basée sur des interconnections 100 Gigabit/s Ethernet (100 GbE). Dans cet article, nous décrivons les défis techniques ainsi que les principales réalisations associés au développement de composants et de systèmes à ultra-haut débit, permettant de la transmission optique en série à 100 Gb/s. ***Pour citer cet article : G. Veith et al., C. R. Physique 9 (2008).***

Keywords: High speed optical transmission; Optical fibers; Optical transport networks

Mots-clés : Transmission optique haut débit ; Fibre optique ; Réseaux de transport optiques

1. Introduction

Today's telecommunication networks have to provide enormous transport capacity in order to enable the dramatic growth of mainly internet based data and video traffic. As an illustration, Fig. 1 shows the average and peak traffic

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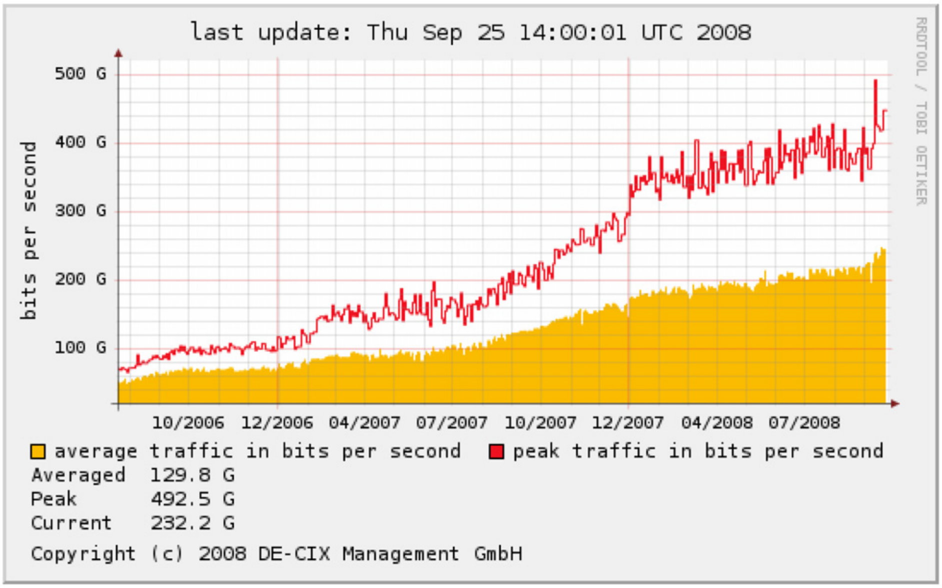

Fig. 1. Average and peak traffic evolution of Frankfurt Internet Exchange node (DE-CIX).

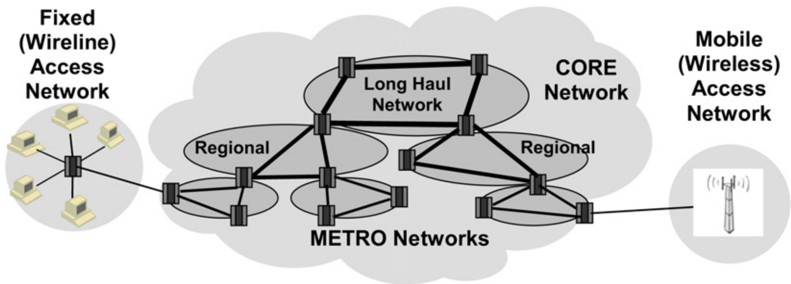

Fig. 2. Structure of modern communication networks including wireline/wireless access networks and wireline metro/regional/core networks.

evolution of the German Internet exchange node in Frankfurt (DE-CIX) from the end of 2006 to mid 2008 [1]. During 2007, an annual average traffic growth rate of >100% and a peak traffic growth rate of more than 200% has been observed, due to strongly emerging internet data and broadband video services and an increasing number of internet users.

Although not all network parts exhibit a similar high growth rate as the DE-CIX node shown if Fig. 1, currently the average traffic growth rate over all wireline/wireless network segments is estimated to be >50% during the coming years. The explosion of data and broadband video services in the wireline and wireless access networks aggregates strongly in the metro and core segment and can only be assured by the implementation of most advanced optical transport technologies in fiber based core networks (Fig. 2).

Fig. 3 illustrates, – as an example –, how advanced access technologies (e.g. DSL: digital subscriber lines) can lead to multiterabit/s transport capacity in the core network. Assuming 100 DSL users (3 Mbit/s each) per access point (AP) and 100 APs per access network, the peak aggregated traffic in the metro network (100 Central Offices/COs, connected to a metro switch/MS) could reach around 3 Terabit/s, leading to an overall peak traffic of 30 Terabit-per-second (Tbit/s) in the long-haul core network to be routed via optical cross connects (OXCs).

It is likely that the strong increase of IP data traffic expected in the wireline core network during the next decade cannot be provided by conventional transport technologies.

Fig. 4 shows the evolution of optical transport technologies and standards during the last decades. Previous generations of optical transmission systems for metro/core networks have been based mainly on the SDH (Synchronous Digital Hierarchy), SONET (Synchronous Optical Network), and OTH (Optical Transport Hierarchy) standards [2],

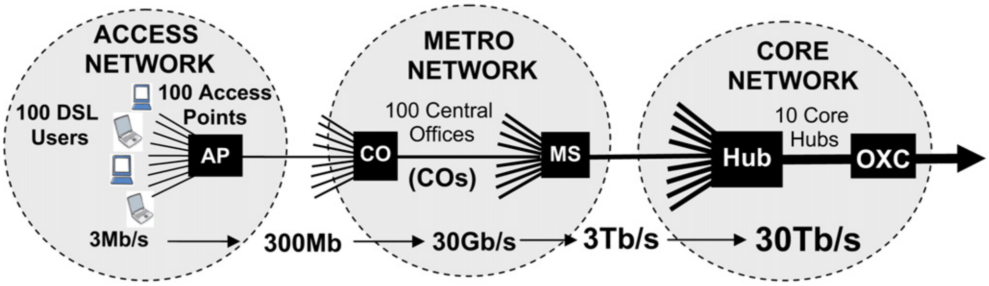

Fig. 3. Expected traffic aggregation within metro/core networks (abbreviations explained in the text).

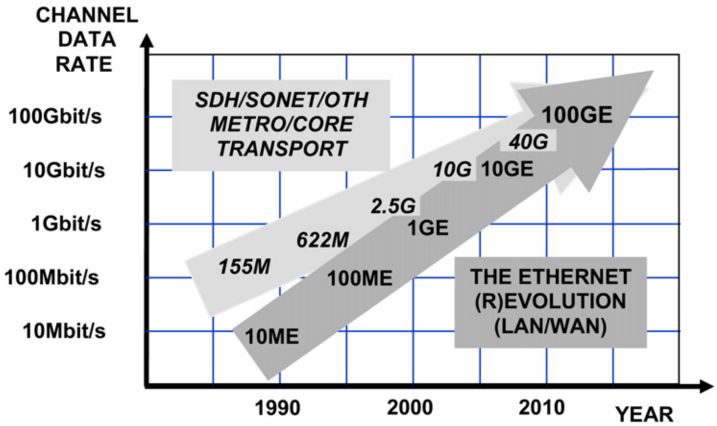

Fig. 4. Evolution of optical transport technologies (SDH/SONET/OTH, Ethernet) (M/G = Mega-/Gigabit-per-second, ME/GE = Mega-/Gigabit Ethernet).

exhibiting a fourfold increase of channel bitrate every 4–5 years. For example, the optical transmission bitrates have been increased stepwise from 155 Mbit/s in the late 1980s, to 10 Gbit/s around year 2000. Currently first 40 Gbit/s OTH systems are under operation or implementation in the metro and core area. SONET/SDH was originally developed to transport multiple data signals in combination with pulse-code modulated voice traffic. However, depending on the data and voice traffic mix that must be carried, there can be a large amount of wasted bandwidth left over, due to the fixed sizes of concatenated containers.

Ethernet, originally defined for efficient Local Area Network (LAN) data exchange, during recent years has been more and more established as the most flexible packet transport standard also for metro and for Wide Area Network (WAN) applications. The data transport speed of recent Ethernet standards has been stepwise increased much more progressively than the classical optical transport standards, i.e. approximately by a factor of 10 each 5 years. The standard for 10 Gigabit/s Ethernet (10 GbE) over fiber has been launched in 2003 (IEEE 802.3ae). It is likely that next generation telecommunication transport networks will be based predominantly on 100 Gigabit/s Ethernet (100 GbE) interconnections. Therefore, international standardization bodies, e.g. the Institute of Electrical and Electronics Engineers (IEEE), and the International Telecommunications Union (ITU-T Telecommunication Standardization Sector), are currently preparing a novel flexible and high capacity standard for next generation transport networks, based on 40–100 Gigabit/s Ethernet. It is expected that first 100 GbE standards will emerge by end of year 2010.

Here we will report on the technical challenges and achievements associated with the development of ultra-high speed 100 Gbit/s optical transmission technologies and systems.

2. High speed optical transmission technologies

Modern metro and core transport networks are based on the unique transmission properties of single mode fiber. Fig. 5 illustrates the main transmission parameters of modern single mode fibers. Due to the availability of efficient

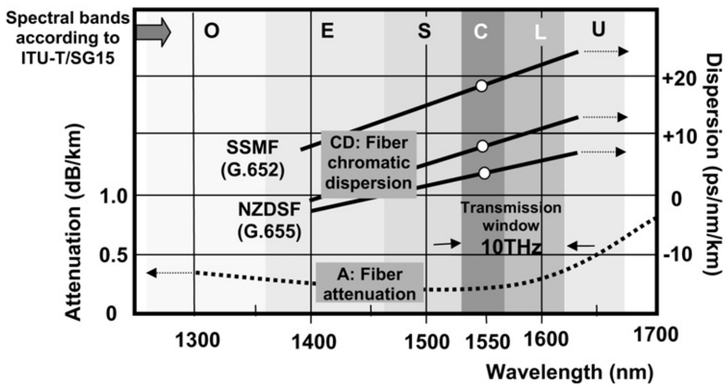

Fig. 5. Main transmission parameters (attenuation, chromatic dispersion) of modern single-mode fibers (SSMF, NZDSF). (Abbreviations explained in the text.)

Table 1
Limitations of (uncompensated) fiber propagation due to chromatic dispersion.

Fiber type (ref. C-band/1550 nm) (ps/nm/km)	Limitation 10 Gbit/s NRZ-OOK (km)	Limitation 40 Gbit/s NRZ-OOK (km)	Limitation 100 Gbit/s NRZ-OOK (km)
SSMF: $D = 17$	58	3.6	0.6
NZDSF (Type 1): $D = 8$	124	7.7	1.24
NZDSF (Type 2): $D \approx 4$	248	15.4	2.5

Erbium-Doped-Fiber-Amplifiers (EDFA, [3]) in the spectral wavelength range 1530–1620 nm, today's optical networks are operated mainly within the so-called C-band (1530–1565 nm) and L-band (1565–1620 nm) as specified by ITU-T Study Group 15 (SG15), offering a total transmission bandwidth of around 10 THz. Both transmission windows (C/L band) provide sufficient spectral range for the parallel transmission of 40 or 80 dense-wavelength-division-multiplexed (DWDM) high speed channels (10 Gb/s, 40 Gbit/s, 100 Gbit/s) applying channel spacings of 100 GHz or 50 GHz, respectively. Modern commercially available transmission fibers like standard Single-Mode Fiber (SSMF, ITU-T rec. G.652) and Non-Zero Dispersion Shifted Fibers (NZDSF, ITU-T rec. G.655) exhibit typical losses of 0.2–0.35 dB/km in the C/L band. Optical amplifiers (EDFAs) offer an efficient compensation of transmission losses simultaneously for all DWDM channels within the C and L-band (20–30 dB gain per amplifier stage) enabling long-haul multi-Terabit/s repeatered transmission over several thousand fiber kilometers. The chromatic dispersion (CD) characterizes the wavelength dependent light propagation speed of optical fibers, causing length dependent signal broadening in terms of ps/nm/km. After a certain propagation distance the optical signal (one bit) has reached a critical temporal width leading to strong intersymbol interference (ISI) with the neighbouring signals. The fiber dispersion D represents a major limitation of fiber transmission distance specifically at high data rates and must be fully compensated in long-haul fiber links [4]. Table 1 illustrates the bitrate dependent transmission distance limitation of SSMF (G.652) and of NZDSF (G.655, Type 1 or 2) without optical dispersion compensation (Ref. 1550 nm/C-band) assuming an optical-signal-to-noise (OSNR) system penalty of 1 dB. If no appropriate dispersion compensation fibers (DCF) are applied the maximum transmission distance of 100 Gbit/s NRZ-OOK (non-return-to-zero on-off-keying) signals in the C-band will be only around 600 m. Correspondingly, 10 Gbit/s (40 Gbit/s) signals can be transmitted over 58 km (3.6 km) of uncompensated standard SMF. Therefore, modern high speed DWDM transmission systems are operated with dispersion compensation units (DCUs) or by using transmission links with periodical positive/negative dispersion (D+/D−) fibers, respectively. Special dispersion slope compensation fibers (DSCF) are enabling an efficient dispersion management of all DWDM channels within a transmission window, including the impact of signal distortions due to nonlinear optical effects.

In contrast to the chromatic dispersion (CD) the polarization mode dispersion (PMD) represents a statistically varying fiber parameter describing the dependence of the optical signal propagation velocity on the state of polarization (SOP) along the fiber [5]. PMD can be characterized by the Differential Group Delay (DGD) defining the difference in propagation time (in psec) between the slowest and fastest signal polarization state at a given frequency. The PMD

Table 2
Limitations of fiber propagation length due to polarization mode dispersion (PMD).

Fiber type PMD coefficient (ps/nm/km$^{1/2}$)	Limitation 10 Gbit/s NRZ-OOK (km)	Limitation 40 Gbit/s NRZ-OOK (km)	Limitation 100 Gbit/s NRZ-OOK (km)
Old fiber: PMD = 0.5	400	25	4
Modern fiber: PMD = 0.1	10,000	625	100
Advanced fiber: PMD = 0.05	40,000	2500	400

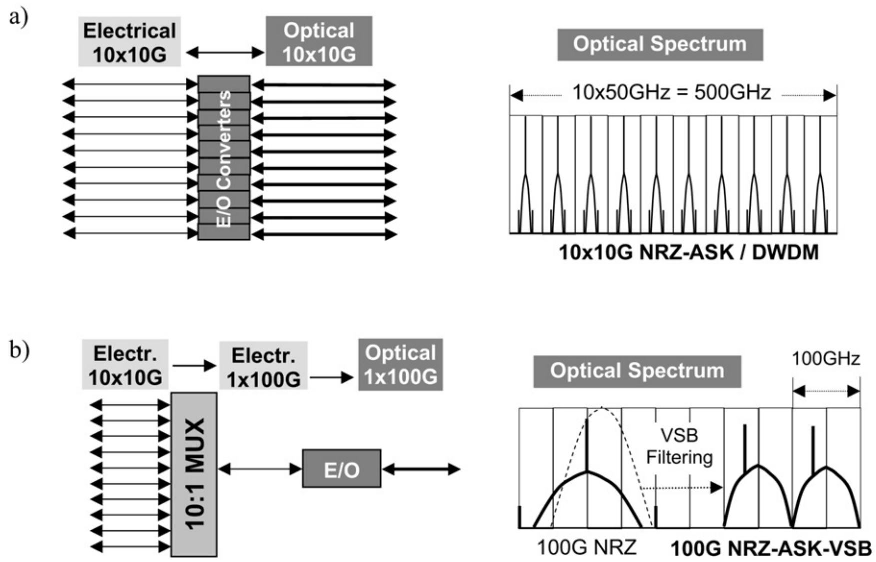

Fig. 6. Multiplexing configurations and optical spectra of parallel and serial 100 Gbit/s modulation formats: (a) Parallel 10 ×10 Gbit/s NRZ-ASK DWDM, (b) Serial 100 Gbit/s NRZ-ASK (100 Gbaud symbol rate).

characteristics of optical single mode fibers is typically described by an average DGD value per square-root distance (ps/km$^{1/2}$). All DWDM channels of an optical link exhibit individual specific PMD characteristics (i.e. independent from neighbour channels) which has to be mitigated individually. Table 2 illustrates the typical PMD coefficients of older and of modern/advanced single mode fibers with the associated PMD dependent fiber propagation distance limitations for different data rates (10/40/100 Gbit/s NRZ-OOK). As shown in the table PMD might represent a serious transmission limitation for 100 Gbit/s signals, specifically over older fiber infrastructure.

The PMD distortions of DWDM channels can be mitigated to a certain extent by PMD compensators [5]. Otherwise, only fiber links with appropriately low PMD have to be selected for high bitrate transmission.

However, at serial channel data rates of 100 Gbit/s with Non-Return-to-Zero Amplitude-Shift-Key (NRZ-ASK) Modulation and with full 100 Gbaud symbol rate also modern fibers exhibit a transmission length limitation of around 100–400 km; i.e. for long-haul, transmission will be required an efficient PMD mitigation per channel. Otherwise 100 Gbit/s channels have to be transmitted with lower symbol rates, e.g. by Differential Quaternary-Phase-Shift-Key (D-QPSK) modulation (50 Gbaud) [6] or by Polarisation-Multiplexed Quarternary-Phase-Shift-Key (PM-QPSK) modulation (25 Gbaud) [7], respectively. 100 Gbit/s data can also be transmitted over 10 × 10 Gbit/s parallel DWDM channels each exhibiting a symbol rate of 10 Gbaud, enabling a transmission of an aggregated capacity of 100 Gbit/s over several thousand kilometers of modern fibers without PMD mitigation.

Fig. 6 illustrates the transmitter/receiver (Tx/Rx) configurations and the optical spectra of parallel or serial 100 Gbit/s modulation formats.

Fig. 6(a) shows the Tx/Rx configuration and associated optical signal spectra of parallel 10 × 10 Gbit/s DWDM channels. Due to the low symbol rate (10 Gbaud) the individual data channels exhibit higher chromatic dispersion and PMD tolerance. However, the overall 10 × 10 Gbit/s channel ensemble requires a spectral range of 500 GHz within the standard DWDM transmission platform (50 GHz channel grid), i.e. the overall spectral efficiency (effective

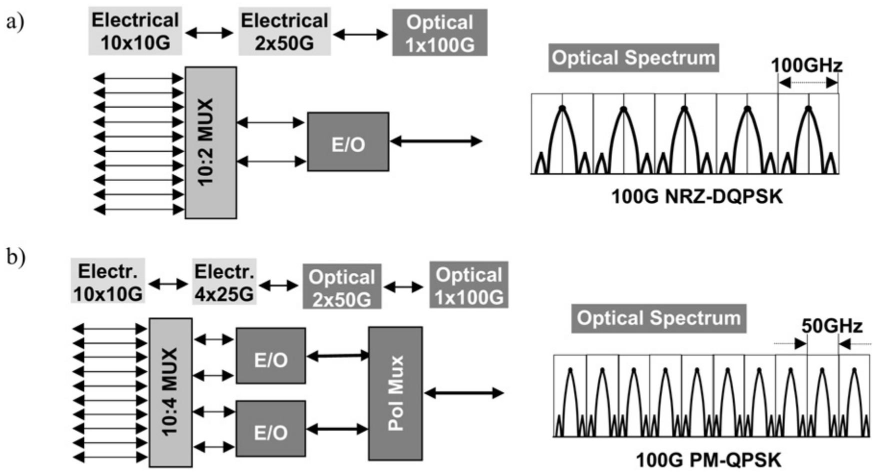

Fig. 7. Multiplexing configurations and optical spectra of serial multilevel 100 Gbit/s modulation formats: (a) 100 Gbit/s NRZ-DQPSK (50 Gbaud), (b) 100 Gbit/s PM-QPSK (25 Gbaud).

bitrate per frequency range) is relatively low (0.2 bit/s/Hz). In addition, the parallel 10 ×10 Gbit/s = 100 Gbit/s transmission approach exhibits disadvantages with respect to 100 Gbit/s networking and will presumably also be more expensive w.r.t. the serial 100 Gbit/s approach (10 Tx/Rx vs. 1 Tx/Rx per 100 Gbit/s).

Fig. 6(b) illustrates the Tx/Rx configuration and associated optical signal spectra of serial 100 Gbit/s NRZ-ASK modulation ("serial" means 100 Gbit/s transport over one wavelength channel): The serial 100 Gbit/s data channel exhibits reduced CD/PMD tolerance due to the high symbol rate (100 Gbaud). The serial 100 Gbit/s NRZ-ASK channel requires a spectral range of around 200 GHz [8], which is not compliant with the 100 GHz channel grid of standard long-haul DWDM transmission platform. However by using a so-called vestigial-side-band (VSB) filtering of the signal (i.e. using only one side band of the spectrum) the 100 Gbit/s serial channel can be transmitted also over a 100 GHz channel grid, enabling a spectral efficiency of 1 bit/s/Hz (see optical spectrum on right side of Fig. 6(b)) [9,10]. The serial 100 Gbit/s approach represents, in principle, a low cost system concept (only one Tx/Rx required per 100 Gbit/s channel). However, the generation and detection of the 100 Gbaud signals requires novel ultra-fast electronic and opto-electronic components (e.g. electronic mux/demux, optical modulator/detector) which are not yet commercially available. Advanced components and DWDM system transmission experiments with 100 Gbit/s VSB-NRZ modulation format will be presented in the following section.

Fig. 7 shows two promising options for serial 100 Gbit/s transmission enabling higher CD and PMD tolerance by the use of lower symbol rate and multilevel modulation formats.

Fig. 7(a) shows the Tx/Rx configuration and associated optical signal spectra of 100 Gbit/s NRZ-DQPSK. The 100 Gbit/s NRZ-DQPSK signal exhibits a symbol rate of 50 Gbaud enabling a transmission over a standard 100 GHz DWDM grid with a spectral efficiency of 1 bit/s/Hz [6]. Due to the lower symbol rate NRZ-DQPSK enables the use of 50 GHz electronical and optical components which are partly commercially available as advanced versions of existing 43 Gbit/s system solutions. However, the overall 100 Gbit/s NRZ-DQPSK transmitter and receiver subsystems have to process simultaneously two tributary 50 Gbit/s channels and are more complex as compared to the 100 Gbaud Tx/Rx.

Fig. 7(b) shows the Tx/Rx configuration and associated optical signal spectra of 100 Gbit/s PM-QPSK. Due to the QPSK modulation combined with Polarization-Multiplexing (PM) the 100 Gbit/s signal exhibits only a relatively low symbol rate of 25 Gbaud enabling a transmission over a standard 50 GHz DWDM channel grid associated with a high spectral efficiency of 2 bit/s/Hz [10]. 25 Gbaud symbol rate is accessible by today's standard high speed electronic and optical components. However, the multilevel modulation and polarization-multiplexing/demultiplexing of 100 Gbit/s channels requires relatively complex Tx/Rx subsystems and digital signal processing (DSP) circuits in the receiver.

Multilevel modulation formats exhibit higher CD/PMD tolerance and enable higher spectral efficiency as compared to NRZ-ASK, but require more complex Tx/Rx optoelectronic subsystems. Fig. 8 shows, as an example, the basic configurations and bit/symbol structure of different serial 100 Gbit/s transmitters, including NRZ-ASK (100 Gbaud),

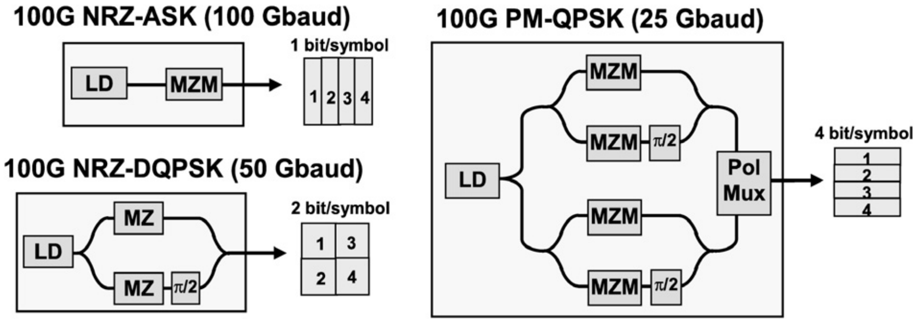

Fig. 8. Serial 100 Gbit/s transmitter configurations: NRZ-ASK (100 Gbaud), NRZ-DQPSK (50 Gbaud), Polarization-Multiplexing (PM) QPSK (25 Gbaud). (Abbreviations explained in text.)

NRZ-DQPSK (50 Gbaud), and PM-QPSK (25 Gbaud). All serial modulation formats are based on one wavelength channel provided by one laser diode (LD).

100 Gbit/s NRZ-ASK requires only one ultra-fast (100 GHz) Mach–Zehnder modulator (MZM) processing one bit/symbol, i.e. 100 Gbaud symbol rate. 100 Gbit/s NRZ Differential Quarternary-Phase-Shift-Key (DQPSK) needs to split up the laser diode light into two operational paths, each of them is to be phase-modulated by a separate MZM at 50 Gbaud symbol rate (2 bit/symbol). Thus, the NRZ-DQPSK transmitter needs to integrate one laser diode, optical waveguide splitters/combiners, two MZMs and one $\pi/2$ phase shifter.

The 100 Gbit/s PM-QPSK transmitter includes waveguide splitters for 4 operational optical paths and 4 MZ phase modulators each operating at 25 Gbaud (4 bit/symbol). In addition a polarization multiplexer (Pol Mux) is required for coupling two states of polarization (SOPs) into one fiber. Thus, this serial 100 Gbit/s transmitter approach uses electronic and optical components operating at moderate speed at the expense of higher Tx integration complexity, in comparison to Tx options operating at higher symbol rates (50 Gbaud, 100 Gbaud).

3. Serial 100 Gbit/s optical transmission system experiments

During recent years, research on 100 Gbit/s based transport technologies has gained worldwide strong interest and several 100 Gbit/s record transmission experiments have been reported. Here we will summarize the main high capacity transmission results achieved so far with the above mentioned serial 100 Gbit/s modulation formats. One major drawback associated with the increase of the channel bitrate is due to the related loss of receiver sensitivity. Due to a limitation of the optical amplifier (EDFA) output power, the average total DWDM signal channel power has to remain constant when an upgrade of the channel data rate is performed. This has as consequence that the number of photons per bit is reduced inverse proportionally to the increase of data rate. For example, doubling of the channel bitrate corresponds to a 3 dB-reduction of receiver sensitivity, measured in terms of optical-signal-to-noise-ratio (OSNR). In order to gain additional receiver sensitivity high bitrate optical transmission systems are operated today usually with so-called forward-error-correction (FEC) codes enabling around 6–8 dB of OSNR gain at the expense of 7–14% of coding bitrate overhead [11]. Therefore, most of the record 100 Gbit/s research transmission experiments have been conducted with effective data rates of 107–114 Gbit/s.

100 Gbit/s transmission based on 100 Gbaud symbol rate (1 bit/symbol) requires ultra-fast electronic and opto-electronic components. First full-rate 100 Gbit/s electrical-time-division-multiplexing (ETDM) transmitter/receiver (Tx/Rx) subsystems have been reported in [8]. 100 Gbit/s multiplexing and demultiplexing have been achieved by novel ultra-high speed electronic circuits realized with the latest generation of ultra-fast Silicon–Germanium Hetero-Bipolar-Transistor (SiGe-HBT) technology. For electro-optical (E/O) conversion and opto-electrical conversion (O/E) of the high speed 100 Gbit/s signal at the Tx/Rx side advanced versions of optical Mach–Zehnder modulators (MZMs) and Indium-Phosphide (InP) based photodiodes [12] have been used. On the basis of these first 100 Gbit/s ETDM Tx/Rx subsystems 8×107 Gbit/s NRZ-ASK-VSB DWDM transmission over 480 km Standard SMF has been demonstrated successfully [9]. Fig. 9(a) shows the eye diagram of the 107 Gbit/s NRZ-ASK signal. Due to the use of vestigial-side-band (VSB) filtering of the 107 Gbit/s transmission channels (see optical spectrum in Fig. 9(b)) has been achieved experimentally a spectral efficiency of 1 bit/s/Hz enabling a transmission over standard ITU-T 100 GHz channel grid.

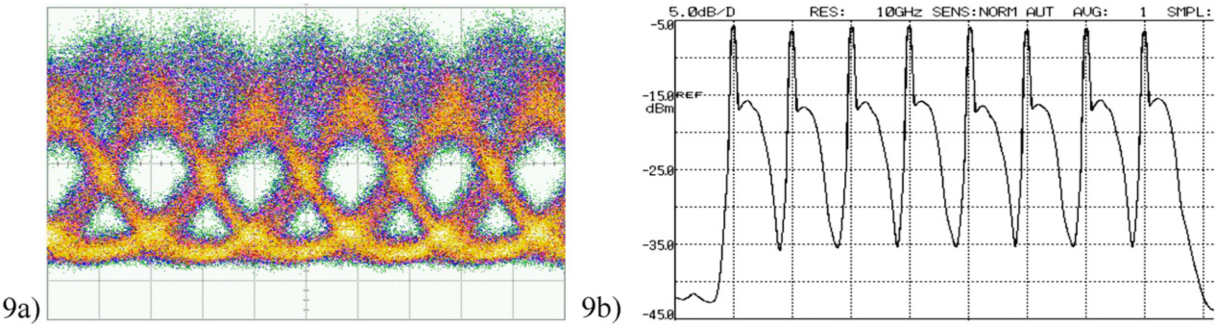

Fig. 9. 107 Gbit/s NRZ-ASK eye diagram (a) and 8 ×107 Gbit/s NRZ/VSB DWDM spectrum.

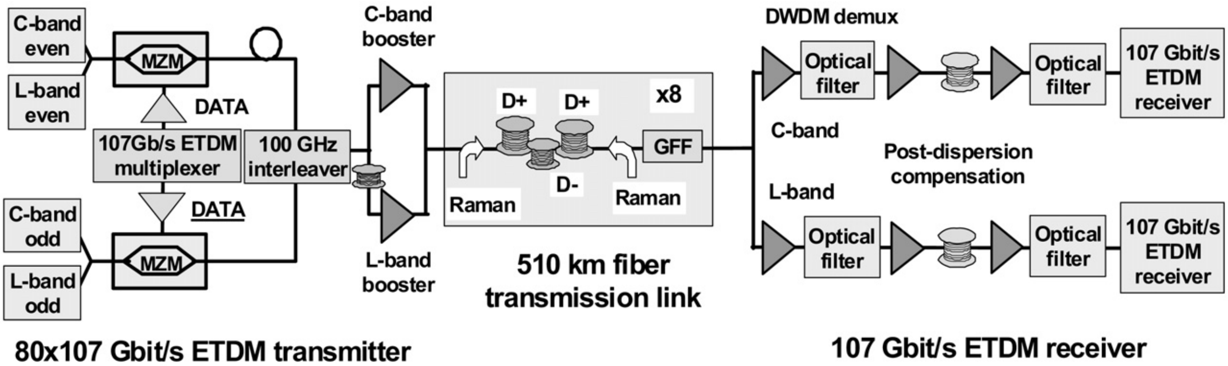

Fig. 10. Setup for 80 × 107 Gbit/s DWDM transmission experiment over 510 km fiber. (Abbreviations explained in the text.)

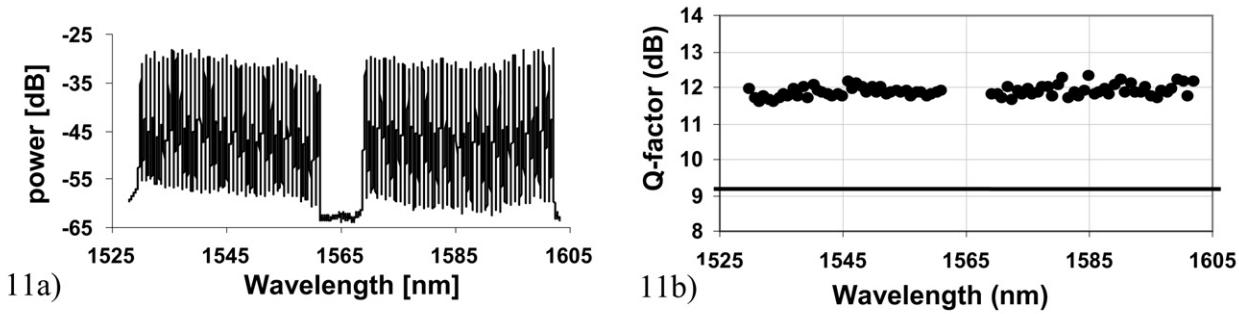

Fig. 11. 80 × 107 Gbit/s NRZ-ASK DWDM channel spectrum (a) and associated Q-factor measurement after 510 km fiber transmission link.

By this VSB-filtering approach a record multiterabit/s transmission capacity of 8 Tbit/s over 510 km fiber has been achieved on the basis of 80 × 107 Gbaud channels using the C- and L-transmission bands and Raman amplifiers [10].

The system setup for this record experiment is shown in Fig. 10: 2 ×40 decorrelated 107 Gbit/s NRZ-ASK-VSB channels within C- and L-band are combined by a 100 GHz DWDM interleaver and transmitted simultaneously over a fully dispersion compensated 510 km fiber link consisting of eight dispersion managed spans composed of D+ D− D+ UltraWave^{TM} fiber. To compensate for the fiber losses each span was forward and backward Raman pumped, providing a forward Raman gain of 4 dB and a backward Raman gain of 14 dB, respectively. After each span a gain flattening filter (GFF) was placed. The overall DGD of the 510 km fiber link was measured to be only 0.8 ps, so that no PMD compensator was required for this experiment.

Fig. 11 shows the 80 × 107 Gbit/s NRZ/VSB DWDM channel spectrum (Fig. 11(a)) and the associated Q-factor measurement after 510 km transmission for all channels (Fig. 11(b)). All Q-factors of the 80 × 107 Gbit/s DWDM channels are measured to be about 2.5 dB above the FEC correction limit of 9.2 dB indicating sufficient system margin for error-free transmission over 510 km fiber.

The above results indicate that serial 100 Gbit/s transmission with 1 bit/symbol (i.e. 100 Gbaud symbol rate) is feasible with advanced electronic and opto-electronic components and subsystems. By applying VSB filtering 107 Gbit/s NRZ-ASK signals can be transmitted over standard ITU-T 100 GHz channel grids, i.e. this approach offers an option for upgrading the capacity and spectral efficiency of existing DWDM transmission platforms.

High capacity and high spectral efficiency DWDM transmission experiments have been reported recently using different serial multilevel 100 Gbit/s modulation formats, including e.g. 10×107-Gbit/s NRZ-DQPSK DWDM transmission over 1200 km fiber with 1 bit/s/Hz spectral efficiency [6], and 164×111 Gbit/s (16.4 Tbit/s) PM-QPSK transmission over 2550 km fiber using a coherent receiver [7]. These alternative serial 100 Gbit/s modulation formats enable higher transmission reach length as compared to the NRZ-ASK, due to the lower symbol rate (53 Gbaud, 28 Gbaud) and associated higher CD/PMD tolerance. In the PM-QPSK transmission experiment a spectral efficiency of 2 bit/s/Hz and a record capacity-distance product of 41.8 Petabit/s-km, respectively, have been achieved [7].

By a simultaneous coherent detection of the 25 Gbaud PM-QPSK signals in combination with digital signal processing (DSP) receivers a full compensation/mitigation of CD/PMD induced signal distortions can be achieved, enabling a long-haul serial 100 Gbit/s transmission without dispersion compensation fibers (DCF) and without PMD mitigators. Since the PM-QPSK modulation approach enables a densely-spaced (50 GHz grid DWDM) transmission of serial 100 Gbit/s channels over long distances this approach is currently considered as promising system option for next generation 100 GbE based transport systems.

A similar high spectral efficiency and CD/PMD tolerance is presumably also achievable by optical orthogonal-frequency-division-multiplexing (O-OFDM) based on serial 100 Gbit/s transmission via many orthogonal subcarriers each with relatively low effective symbol rate (e.g. <100 Mbaud) [13].

4. Summary

Next generation optical metro and core networks are expected to be based on 100 Gigabit/s Ethernet (100 GbE) transport in order to provide the flexible transmission capacity upgrade as required by the strong growth of aggregated internet/data traffic. Serial 100 Gbit/s transmission technologies are currently under investigation including different optical modulation formats with 25–100 Gbaud symbol rates. Multiterabit/s overall DWDM transmission capacity over long-haul fiber links have been demonstrated with several promising serial 100 Gbit/s modulation formats, e.g. by NRZ-ASK-VSB, NRZ-DQPSK, PM-QPSK, or O-OFDM, respectively, achieving spectral efficiencies of 1 bit/s/Hz or beyond. Some of these offer promising options for the realization of next generation 100 GbE based optical transport systems.

List of abbreviations

ASK	Amplitude-Shift-Keying
CD	Chromatic Dispersion
DCF	Dispersion Compensating Fiber
DCU	Dispersion Compensating Unit
DGD	Differential Group Delay
DQPSK	Differential-Quarternary-Phase-Shift-Keying
DWDM	Dense-Wavelength-Division-Multiplexing
EDFA	Erbium-Doped-Fiber
ETDM	Electrical-Time-Domain-Multiplexing
FEC	Forward-Error-Correction
Gbaud	Gigasymbol-per-second
GbE	Gigabit/s Ethernet
Gbit/s	Gigabit-per-second
GFF	Gain-Flattening-Fiber
IEEE	Institute of Electrical and Electronics Engineers
ITU-T	Intern. Telecommunication Union, Telecommunication Standardization Bureau

LAN Local Area Network
LD Laser Diode
MZM Mach-Zehnder-Modulator
NRZ Non-Return-to-Zero
NZDSF Non-Zero-Dispersion-Compensation-Fiber
OFDM Orthogonal-Frequency-Division-Multiplexing
OIF Optical-Internet-Forum
OOK On-Off Keying
OSNR Optical-Signal-to-Noise-Ratio
OTH Optical Transport Hierarchy
PMD Polarization-Mode-Dispersion
SDH Synchronous-Digital-Hierarchy
SONET Synchronous Optical Network
SOP State of Polarization
SSMF Standard Single Mode Fiber
WAN Wide Area Networks
VSB Vestigial Side Band

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