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OPPORTUNITIES FOR THE OUT OF THE 1550 nm WINDOW TRANSMISSION

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Abstract. In this paper, opportunities for transmission in the 850 nm and 1310 nm windows are reviewed. In particular, the mentioned windows can be utilized for the data centre related transmission.

Keywords: optical communication, optical fibre, optical amplifier

MOŻLIWOŚCI WYKORZYSTANIA TRANSMISJI POZA PASMEM 1550 nm

Streszczenie. W artykule dokonano analizy możliwości wykorzystania okien transmisyjnych 850 nm i 1310 nm. Rozważane okna można wykorzystać do realizacji transmisji dla potrzeb centrów danych.

Słowa kluczowe: komunikacja optyczna, światłowód, wzmacniacz optyczny

Introduction

The ever growing number of information and communication network users like Internet, development of bandwidth hungry applications, e.g. high quality video streaming as well as increased quality requirements, e.g. low latency is driving development of the telecommunication networks. The optical fibre is the only one physical medium that can provide high transmission capacity, while maintaining very long transmission distances, up to trans continental ones. The importance of the optical fibre to the development of civilization, has been recognized by awarding Charles K. Kao in 2009 Nobel Prize in physics for “for ground breaking achievements concerning the transmission of light in fibres for optical communication” [4].

The potential of optical fibre transmission had been very quickly recognized and it has been widely adopted for the signal transmission. For the very long time, the key application area was high capacity (whatever did it mean at the given moment in time) over long distances, where the high cost of the transmission system was shared among many users. Recently, we observe rapid increase of data rates used in the computer inert and intra board communication as well as growth of the data storage and processing centres. In such application areas, copper cable transmission cannot handle high data rates transmission over the required distances. However, such demand can be fulfilled by the optical fibre transmission. One could say, that sarcastically the optical fibre transmission is covering shorter and shorter distances.

Due to the lowest attenuation of 0.2 dB/km and excellent amplification technology, namely erbium doped fibre amplifier (EDFA) the 1550 nm transmission window is a window of choice to realize optical fibre transmission. The other transmission windows like 850 nm or 1310 nm seemed to be until recently almost entirely forgotten. However, the rise of new application areas like inter- and intra-data centre transmission that put attention on the features like low cost and high energy efficiency, give prospect for efficient utilization of other transmission windows.

The high data rate ultrashort data links, called data interconnect, currently operate at the data rates 25 Gbit/s with the foreseen increase to 50 Gbit/s and even 100 Gbit/s over the distances up to a few hundred meters to cover the data centre area. The key requirements of the data interconnects are small footprint, limited energy consumption and overall low component cost. Such data interconnects can be realized in the 850 nm transmission window. The 1310 nm transmission window can be used to realize high data rate transmission over the distances up to few dozen kilometres, leveraging a key standard single mode fibre (SSMF) advantage at 1310 nm, namely low value of chromatic dispersion, which translates into the simplified system design (lack of dispersion compensation) as well as straightforward system installation, which is one of the most sought features of the data communication equipment. Table 1 shows comparison of the key transmission window characteristics.

Table 1. Optical fibre transmission window comparison

	1550 nm	1310 nm	850 nm
λ number	Over 100	Up to several	A few
Single data rate	400 Gbit/s	50 Gbit/s	25 Gbit/s
Range	>1000 km	< 50 km	< 1 km
Optical amplifier	EDFA	SOA	none
Total capacity	Tbit/s	100 Gbit/s	100 Gbit/s
Fibre	SSMF	SSMF	MM
Attenuation	0.2 dB/km	0.4 dB/km	4 dB/km

1. 850 nm data interconnects

The fibre of choice for the 850 nm window is a multi-mode fibre (MMF). Except the high attenuation at 850 nm around 4 dB/km, the multi-mode fibres transmission is affected by the modal and chromatic dispersion, which limits the available transmission bandwidth to about 4.7 GHz·km for the newest generation of MMF. However, for the ultra-short links, e.g. of 100 m, the fibre bandwidth increases to 47 GHz and even higher for meter range distances. Further, the core diameter of MMF fibres is 50 μ m. Such large core diameter allows easy coupling with the emitting lasers and receiving photo-detectors.

The vertical-cavity emitting lasers (VCSELs) at 850 nm are characterized by surface light emission, the modulation bandwidth up to 25 GHz, coupled output power of a few milliwatt and driving current of a few milliamper [5]. Figure 1 shows the spectrum and light-intensity-voltage characteristics of the 850 nm VCSEL. The high modulation bandwidth and low energy consumption, while maintaining desired optical power allows realization of the cost-effective transmission systems with a few dozen Gbit/s data rate over up to a few hundred meter distances based on MMF and VCSEL [19]. The system simplicity (direct modulation and detection) and limited power consumption translate into low transmission cost, which is a key feature required for the data interconnects, which number can exceed a few dozen thousand in a single data centre.

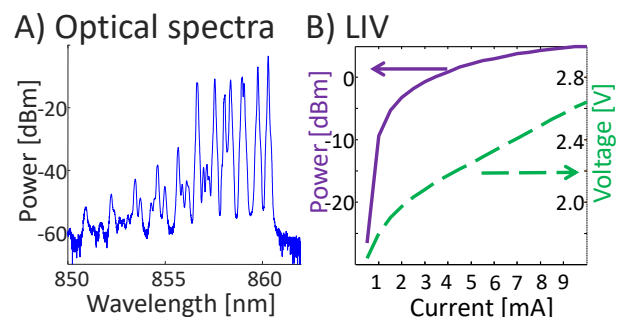


Fig. 1. 850 nm VCSEL spectral and LIV characteristics

Figure 2 shows the exemplary eye diagram of the 850 nm VCSEL operated at various data rates for the amplitude binary on-off keying (OOK) modulation. Up to the 35 Gbit/s the eye is almost not distorted, while distortions can be observed for higher data rates. The data rate related distortions are due to the limited bandwidth of the utilized components like VCSEL and photo-receiver, which show bandwidth of about 22 GHz. Nevertheless, as we can see up to the data rate of 50 Gbit/s the eye diagram is widely open in the middle, indicating proper transmission and signal reception. The shown eye diagrams were captured in so called back-to-back (b2b) configuration, i.e. directly connecting transmitter to the receiver, as such the transmission distance was in the range of a few meters as the length of the pigtailed attached to the components. It is important to note, that such a distance perfectly covers the distance required to connect components within a 19" standard rack of height up to 2 m.

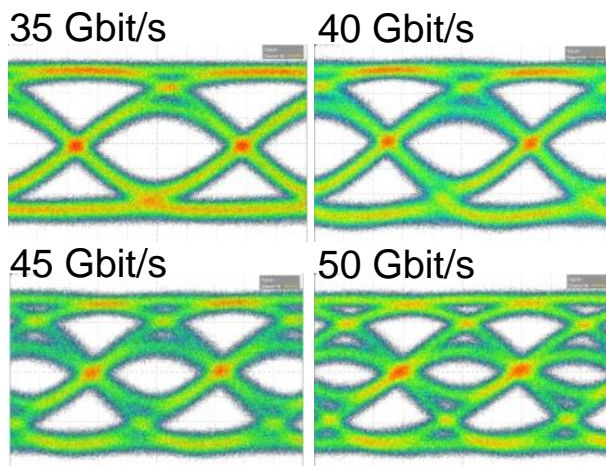


Fig. 2. 850 nm VCSEL eye diagrams at various data rates

Data interconnect transmission capabilities, in terms of the achievable data rate will not only be affected by the limited bandwidth of the VCSEL and photo-detectors but more importantly as the distance grows by transmission properties of the MMF.

To overcome limitations related to the MMF chromatic dispersion, single mode (SM) VCSELs have been developed [7]. The single mode VCSELs are characterized by the limited optical spectrum width, since preferably only one wavelength mode occurs. In such a way, the influence of the chromatic dispersion is significantly limited. SM VCSELs offer potential to cover much higher distances than the multi mode (MM) VCSELs, which is critical to cover inter-rack/room/building distances in the data center, without switching to another more complex and expensive transmission technology. Obviously, the SM VCSEL modulation bandwidth must stay in the range of a few dozen GHz.

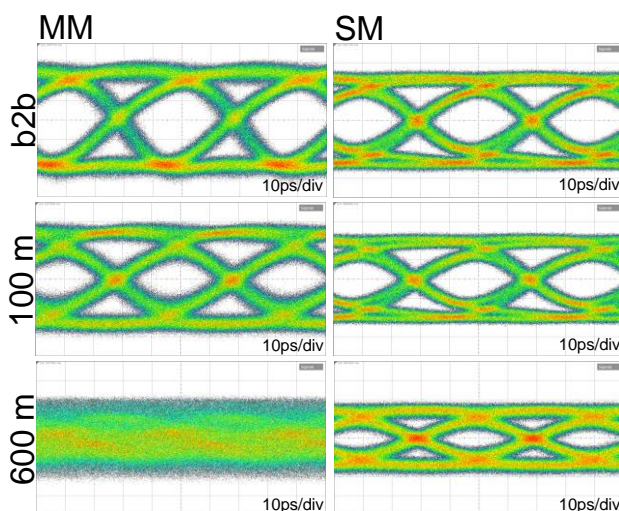


Fig. 3. 25 Gbit/s 850 nm MM and SM VCSEL eye diagrams at different distances

Figure 3 presents the eye diagrams at 25 Gbit/s captured at the various MMF lengths with MM and SM VCSELs. As we can see for b2b configuration (a few meter transmission) both SM and MM VCSEL signal are basically the same and show excellent system operation. With the increased transmission distance the signal distortion becomes visible. For the 100 m transmission, the MM VCSEL eye diagram is slightly closed compared to b2b, while at 600 m it is completely distorted. For the SM VCSEL the eye diagram remains widely open up to 600 m, proving that much longer transmission distances can be bridged with such type of VCSELs.

The realized transmission systems with MM VCSELs included transmission up to 54 Gbit/s with the OOK modulation over the distances up to 1 km [1] and 2.4 km [17]. Further, the MM and SM VCSEL can be utilized in transmission with advanced modulation formats. Advanced modulation formats, in opposition to the binary modulation, allow to transmit more than one bit in one symbol, e.g. 2 bits for four level pulse-amplitude modulation (PAM-4) modulation. Therefore the spectrum utilization is significantly improved from 1 bit/s/Hz to 2 and more bit/s/Hz. That allows to overcome bandwidth limitations of the existing components and increase the achievable data rates. The drawback of the proposed solution is more complex structure of the transmitter and receiver. Further the required, signal-to-noise ratio is much higher than for binary modulation.

The performed work on the advanced modulation format transmission includes transmission with the PAM-4 modulation, again showing superior SM over MM VCSEL performance [16]. Even higher spectral efficiency was achieved with the carrier less amplitude-phase (CAP) modulation, which was utilized in many applications with the very limited system bandwidth [25]. A variant of CAP modulation, namely multi-CAP was used in [14] to demonstrate the record at the time of publishing transmission of 107 Gbit/s. In multi-CAP transmission, the system bandwidth is divided into the sub-bands, in which one of the individual CAP signals are transmitted with the highest possible modulation order. In such a way, sub-bands with the excellent transmission properties transmit signals with high data rate, while the sub-bands with the limited transmission performance are utilized for the lower data rate signals. Further, the sub-band can be turned on-off adjusting to the varying traffic and therefore the variable data rate and energy efficient transmission can be realized [13].

To allow characterization and in general work with the newest VCSEL generations, a probe station had been designed and built. The probe station is based on the micrometric XYZ stages and allows connection of the electrical signals through the high bandwidth electrical probe as well as couple the optical signal into the fibre. The VCSEL chips can be observed through the side cameras. That simplifies the systems connections and adjustment. On Fig. 4., the photograph of the probe station is shown. The developed probe station can be used not only for the VCSEL testing but also for testing of other components like photo-detectors or even electronics circuits.

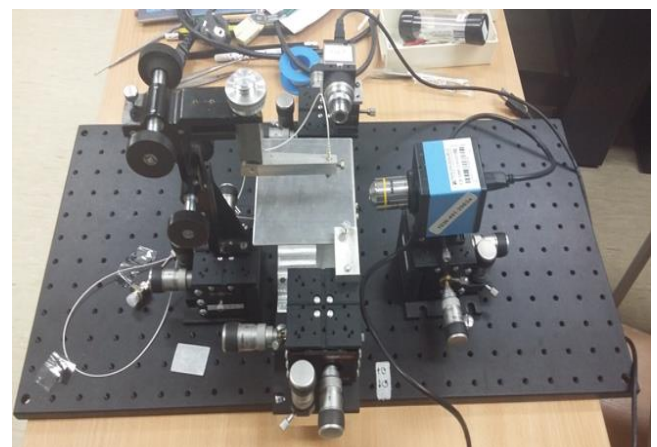


Fig. 4. Probe station used to test the bare (chip level) VCSELs

2. 1310 nm transmission

The 1310 nm transmission window (1260 nm – 1360 nm) was considered in the early years of optical fibre communication, namely mid 1970s as the key transmission band. That is reflected in the alternative 1310 nm window name O-band, where O stands for original. Fibre technology improvements resulted in conquering other bands like C-band (1550 nm), where C stand for conventional. For the very long time, the 1310 nm band has been utilized just for the upstream traffic in the passive optical networks (PON). In PON networks the downstream traffic to the user is realized in the 1550 nm band. Such wavelength band division comes from availability of the low cost and low loss 1310/1550 nm band splitters and combiners. The downstream PON data rates are up to 10 Gbit/s. In mid 2000s, work on the 100G and more Ethernet standard started, where one of the solutions is to transmit 100G and 400G Ethernet streams using multi-wavelength technology in the 1310 nm window. That is still bellow multi-terabit/s capacity of the 1550 nm band.

The key features of the 1310 nm transmission window are attenuation of about 0.3 dB/km – 0.4 dB/km, presence of the zero-dispersion wavelength and therefore limited chromatic dispersion as well as pronounced presence of the non-linear effects due to the low dispersion value. The higher than in the 1550 nm wavelength band losses (0.2 dB/km) must be compensated otherwise only very short unrepeated transmission can be realized. Three amplification technologies have been demonstrated for applications in the 1310 nm domain, namely semiconductor optical amplifier (SOA), praseodymium doped fibre amplifier (PDFA) and Raman amplifier. Recently, a bismuth doped fibre amplifier with the 25 dB gain, 3 dB saturation power of about 15 dBm and noise figure (NF) of about 5 dB has been demonstrated [18]. SOA and PDFA demonstrate moderate gain, high noise figure and moderate saturation power [2]. Progress in the high power quantum dot lasers allows realization of the 1310 nm Raman amplifier with the gain over 15–18 dB and very low noise figure [3, 12]. The 1310 nm Raman amplifier has been tested in the various transmission experiments, e.g. [10] outperforming SOA. Table 2 summarizes key transmission properties of the 1310 nm window amplifier technologies.

Table 2. 1310 nm optical amplifier comparison

	SOA	PDFA	Raman	BiDFA
Gain [dB]	25	25	18	25
Psat [dBm]	10	10	15	15
NF [dB]	>6	>6	4	5

Chromatic dispersion affects transmitted signals by limiting the available transmission range for the given data rate or limiting the data rate for the given transmission distance. The chromatic dispersion limits for SSMF are specified in ITU-T Recommendation G.652 [15]. The zero dispersion wavelength, a wavelength where no chromatic dispersion occurs must be between 1300 nm and 1324 nm. Figure 5 shows the chromatic dispersion limits for SSMF as specified in the ITU-T Recommendation G.652. The very low value of chromatic dispersion allows realization of the transmission systems without any form of the chromatic dispersion compensation. That just not only simplifies system design, but more importantly makes the installation straightforward, without necessity of dispersion measurements and compensation. These features are highly desirable in the data centre environment, where a large number of such systems must be installed. Further, the limited influence of the chromatic dispersion is a decisive advantage for the analog radio-over-fibre systems [6], where the signals are transmitted in the fibre in such a form than they can be directly emitted by the radio antenna just after the optical-to-electrical conversion. Such systems are of great importance for the development of the newest generation of mobile networks, namely 5G, in particular for the ultra-high carrier frequencies, which are needed to realize ultra-broadband and therefore high data rate radio transmission. The targeted here data rates are in the range of a few Gbit/s to the user.

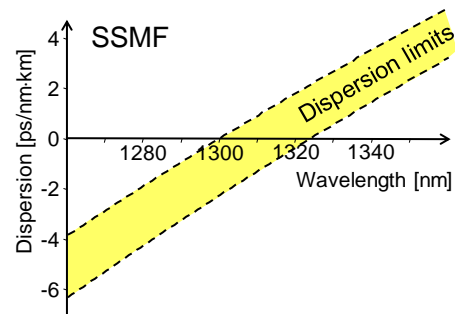


Fig. 5. SSMF chromatic dispersion limits at 1310 nm

However, looking at the Fig. 5, we can notice that at the edges of the O-band, namely 1260 nm and 1360 nm chromatic dispersion of a few ps/nm·km can be expected. Such high value of dispersion can influence high data rate transmission of 50 Gbit/s and more, even for distances of a few dozen kilometres. That dispersion value can not be neglected and can be a source of severe performance limitations that can be omitted by the chromatic dispersion management in the fibre infrastructure [24].

Low value of chromatic dispersion can lead to pronounced nonlinear effect interactions like cross-phase modulation and in particular four-wave mixing (FWM). In FWM effect three co-propagating wave interacts with each other and a new wave is generated. A new FWM wave can appear at the data signal frequency, which will be a source of cross-talk. FWM can be effectively suppressed by lowering the signal power, transmission in the region with non-zero chromatic dispersion as well as large channel spacing. The conducted studies have shown that the channels spacing of about 250 GHz allows to effectively suppress FWM, while maintaining relatively high signal power in the range of 0 dBm for the 1310 nm band dense wavelength division multiplexed systems [8]. Obviously, spectral efficiency is not that high as in the 1550 nm band with the standard channels spacing of 50 GHz, nevertheless it is sufficient to realize transmission of a several and even few dozen channel with overall capacity in the order of Tbit/s.

Several research works have been devoted to that topic. In [20] $n \times 25$ Gbit/s transmission in the 1310 nm band has been investigated, while [21] demonstrates up to 400 Gbit/s transmission with eight wavelength channels and data rates of 40 Gbit/s and 50 Gbit/s. Further, a single data channel transmission at 112 Gbit/s has been demonstrated in [9]. The polarization and wavelength multiplexing concept has been further expanded towards 1 Tbit/s transmission in [11].

One of the features of the 1310 nm band is feasibility of the parallel to the 1550 nm band utilization. The capacity of the optical fibre can be increased by the multi core or a few mode transmission. In such special fibre new spatial channels (multiple cores and/or multiple modes) are created. Obviously, the inter core and inter mode cross-talks must be compensated to achieve desired performance. Recognized alternative to that is utilization of the parallel to the 1550 nm wavelength bands like the 1310 nm or 1650 nm (U-band) [26]. That solution has advantage that the already existing fibre infrastructure can be used to carry additional data channels, postponing or even omitting necessity of the very expensive new fibre installation. Obviously, appropriate band multiplexers and demultiplexers must be inserted into the transmission line as well as suitable amplification technology must be used, with the most promising candidates of BiDFA and Raman amplifier. Due to the development of the all-optical signal processing techniques, the 1310 nm signals can be all-optically without any optical-electrical-optical conversion converted into the 1550 nm wavelength domain. Such an ultra-wide data wavelength conversion utilizing non-linear polarization rotation in the semiconductor optical amplifier has been demonstrated in [22]. In such a way, transparent all-bands optical networks can be realized. In other applications, the 1310 nm components were used for 1550 nm signal processing [20].

3. Conclusions

Optical fibre transmission technologies are conquering new application areas. In particular, the growth of optical transmission is observed in the data center infrastructure. The diverse advantages of the optical fibre transmission are ultra-high data rates and energy efficiency, which cannot be fulfilled by the metal wire techniques. New transmission solution are tailored to the application needs. Here, the window of opportunity for the unutilized so far band has opened. The 850 nm window can be successfully applied to realize high data rate transmission at the ultra-short distances utilizing VCSELs and MMF. The 1310 nm window can be used to support intra data center transmission of high capacity over distances up to a few dozen kilometers.

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