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Full Length Research Paper

Realization of HDWDM transmission system

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Currently, many research topics in the field of optical transmission systems are focused on increasing the total data transmission speed of an individual optical fiber. Most of them are grounded on novel modulation techniques. An alternative but equally valid approach to increasing the data transmission is to decrease the WDM channel spacing to high-dense dimensions, while keeping the existing data transmission speed for an exact channel. The authors have developed an experimental and theoretical HDWDM transmission system based on the quasi-rectangular optical filter technique. The results indicate that for 2.5 Gbit/s HDWDM transmission the suitable channel interval should be greater than 25 GHz and for the 10 Gbit/s HDWDM solution not less than 37.5 GHz between adjacent channels.

Key words: wavelength division multiplexing (WDM), high-density wavelength division multiplexing (HDWDM), optical filtering.

INTRODUCTION

The annual global internet protocol (IP) traffic will exceed half a Zettabyte in four years. Driven by high-definition video and high-speed broadband penetration, the consumer of IP traffic will bolster the overall IP growth rate so that it sustains a steady growth rate through 2012, growing at a compound annual growth rate of 46% (Cisco Systems, 2008). Due to these rapidly growing capacity requirements for long-haul transmission, the optical wavelength division multiplexing (WDM) systems are advancing into high data transmission rate and narrow channel spacing to utilize the available bandwidth more effectively.

To increase the spectral efficiency is important for building efficient WDM transmission systems, since this allows the optical infrastructure to be shared among many wavelengths. Often it is necessary to made for the possibility to create a WDM system that would be suitable for already existing standard single-mode fibers at comparatively different distances and, therefore, would be compatible with the existing fiber optic transmission system (FOTS). This approach reduces the cost per transmitted information bit in a fully loaded and optimized transmission system (Agrawal, 2001; Belai et al., 2006; Bobrovs and Ivanovs, 2008; Bobrovs et al., 2006).

Forging ahead into the high data transmission rate and narrow channel spacing, the optical network developers and designers should take into account the degradation effects in optical transmission systems. These effects can be categorized by the random noise and waveform distortion. For long-span high density WDM (HDWDM) systems, signal waveform distortion can be generated by linear chromatic dispersion, fiber nonlinearity, or their combination. In high-speed time division multiplexing (TDM) optical systems, because of the short optical pulses and wide optical spectrum, the effect of chromatic dispersion dominates in the system performance. In multiwavelength WDM optical systems the inter-channel crosstalk originated by fiber nonlinearity, such as cross-phase modulation (XPM) and four-wave mixing (FWM), is a limiting factor (Agrawal, 2001).

To maximize the WDM network capacity, the system's design and optimization have to take into account all the contributing factors – the channel data rate, transmission distance, signal optical power, fiber linear and nonlinear effects, and, of course, the channel interval. In a HDWDM system the last factor is the most important for a high-quality solution. In order to maximize the system capacity and to minimize the performance degradation caused by transmission impairments, the system investigation and optimization are very important (Bobrovs and Ivanovs, 2008).

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Abbreviations: WDM, Wavelength division multiplexing; **HDWDM,** high-density wavelength division multiplexing; **MZM,** Mach-Zehnder modulator; **DFB,** distributed feedback; **OSNR,** optical-signal-to-noise ratio; **SMF,** single mode fibre.

High performance optical filters are groundwork for realization of high- speed HDWDM transmission systems where coherent crosstalk between adjacent channels becomes the main source of degradation: adjacent channels interfere with each other upon detection and the resulting beating gives rise to signal distortions, provided that the beat frequencies lie within the bandwidth of the detection electronics. High channel spacing and data transmission rate set strict requirements for HDWDM filter characteristics, so any imperfections in their parameters, such as amplitude and phase responses, could become critical. The low channel isolation from adjacent channels is one of these imperfections in optical filter parameters (Agrawal, 2001; Ozoliņš and Ivanovs, 2009).

Currently, much research in optical communications is focused on increasing the total bit rate of an individual optical fiber. Most of the research works are grounded on novel modulation schemes for concrete wavelengths. An alternative; though equally valid, approach to increasing the transmission capacity is to scale the WDM channel spacing to high-dense dimensions while keeping the existing bit rate. Our investigation of the minimum allowed channel spacing in HDWDM systems will provide recommendations for future WDM solutions. The experimental and simulation results indicate that for 2.5 Gbit/s HDWDM transmission the suitable channel interval should be wider than 25 GHz and for the 10 Gbit/s HDWDM solution not narrower than 37.5 GHz between adjacent channels.

HDWDM main components and evaluation criteria

The complexity of a system's design in optical communications can be seen as the result of a large number of components with different parameters and operational states. The description of the interaction between the optical signal and transmission disturbances is a multi-dimensional issue, whose solution depends on the relation between different system parameters. The right approach to the optimization of system settings and derivation of design rules must take into account the interaction of effects which take place in each component. In this section, the system components needed for realization of an HDWDM transmission system are described.

The role and realization of an optical transmitter become important with increased channel data rates in the system. While the optical transmitters at lower channel data rates are less complex and easier to realize by direct modulation of a laser diode, the realization becomes more complex with the increasing channel data rate, thus raising the requirements on electrical and optical components of the optical transmitter. The conventional optical transmitter employs the amplitude/intensity modulation (AM, IM) of the laser light (better known as on-off keying (OOK)), because different signal levels for marks and spaces are characterized by the presence of optical power. The amplitude modulation can be realized by direct or external modulation of the laser diode. For the realization of transmission systems with channel data rates larger than 2.5 Gbit/s, the external modulation presents a better solution, because the impact of laser internal chirp on optical signal can be reduced efficiently, but, on the other hand, the complexity of optical transmitters increases. External modulation can be realized with a $LiNbO_3$-based Mach-Zehnder modulator (MZM). The operational principles of MZMs are based on the electro-optic effect, which is characterized by variation in the applied electrical field causing changes of the refractive index in the modulator arms. The variation of the refractive index in the modulator arms induces a change of material propagation constant β, resulting in different phases in both modulator arms. The input optical signal is divided by a 3-dB coupler into two equal parts; in lower and upper arm of the MZM. The external modulator is driven by an electrical signal with corresponding data rate. Depending on the electrical driving signal, different transmission speeds can be realized. If no electrical field is applied, both signals arrive at the same time (in-phase) at the MZM output and interfere constructively. If an electrical filed is applied, signals in different arms are shifted in phase relative to each other. Depending on the phase difference between the MZM arms, the signals can interfere constructively or destructively, resulting in an amplitude modulation of the modulator input signal. In this signal generation method, the laser source acts as a continuous wave (CW) pump. In conventional systems, the CW pumps are realized with distributed feedback laser (DFB) lasers. (DFB) represents the most important and most widely used single mode laser type for the 1550 nm region. DFB lasers are realized by the implementation of a Bragg's grating structure inside the cavity between the reflecting surfaces of a laser (Voges and Peteramann, 2002). The main characteristics of the DFB lasers are high side-mode suppression ratios (> 50 dB) enabling stable single-mode operation, a small spectral line width (0.8...50 MHz) and large output optical power (10...40 mW) (Funabashi et al., 2001).

After the MZM, such a signal is sent directly to a transmission medium, where optical pulses are propagating over different distances of standard single- mode fiber (SSMF). For compensation of losses in the fiber and optical components it is necessary to use optical signal amplification technique. The optical amplifiers represent one of the crucial components in an optical transmission system. Despite the minimum attenuation at 1550 nm, fiber losses significantly limit the transmission performance with increased transmission distance. Optical amplification can be realized using different amplifier concepts and mechanisms, e.g. semiconductor optical amplifiers (SOA), rare-earth (erbium, holmium, thulium, samarium) doped fiber amplifiers, or, more recently, Raman amplifiers. All these amplifier types are based upon different physical mechanisms resulting in different device characteristics and implementation areas. The rare-earth-doped fiber amplifiers provide optical amplification in the wavelength region from 500 to 3500 nm.

The most important representative of these amplifier types is the erbium-doped fiber amplifier (EDFA), which is widely used today in optical transmission systems since it provides efficient optical amplification in the 1550 nm region. The EDFAs present the state-of-the-art technology in conventional optical transmission systems and they can be used as in-line amplifiers (placed every 30 - 80 km), power boosters (amplifiers at the transmitter side) or pre-amplifiers (amplifiers in front of the receiver) independently of the channel bit rate in the system.

After transmission through optical fiber multiwavelength optical signal need to be separated in individual channels. This realized with implementation of band-pass filters (BPFs). BPFs transmit optical power within a definite wavelength window only and reflect or absorb the rest. In the case of a single-channel transmission the role of an optical band-pass filter is to separate the channel information from the noise which has been added, e.g., by optical amplifiers. This noise generally is broadband and can often be described as quasi-white noise: it has a constant level in the power spectrum. By applying a band-pass filter to select the wavelength channel, the useful information is retained and most of the noise is filtered resulting in an improvement of the optical-signal-to-noise ratio (OSNR).

A band-pass optical filter can also be used to select a particular channel in a HDWDM application from several channels that are transmitted in a common HDWDM transmission system (Azadeh, 2009; Venghaus, 2006). The role of an optical receiver is to detect the transmitted signal by the opto-electrical trans-formation of the signal received by photo-diode (e.g. PIN or APD). Furthermore, additional electrical equalization is performed together with electrical signal amplification enabling further signal-processing (e.g. clock-recovery) and performance evaluation (e.g. quality measurements).

The right choice of the performance evaluation criteria for characterizing the optical transmission lines is one of the key issues in designing efficient high-speed systems. The evaluation criteria should provide a precise determination and separation of dominant system limitations, making them crucial for suppressing the propagation disturbances. On the other hand, they should provide a comparison of experimental and numerical investigation data, which is useful for verification of the numerical models applied.

The bit error ratio (BER) evaluation is a straightforward and relatively simple method for performance estimation based on counting the errors in the received bit streams. The error counting in a practical system with a transmission speed greater than 1 Gbit/s can be a long process.Especially for realistically low BER values ($< 10^{-9}$). For that reason, the International Telecommunication Union created the eye diagram masks for different bit rates with a definite BER value.

The OSNR is a widely used evaluation criterion for characterizing the system performance in already deployed transmission lines. The optical noise created by transmission media and devices around an optical signal reduces the receiver's ability to correctly detect the signal because of interferences between the signal and the optical noise. This effect can be suppressed if we implement an optical filter before the optical receiver. Depending on the amplifier infrastructure used in a transmission system, the OSNR value is proportional to the number of optical amplifiers and to the gain flatness of a single amplifier. This latter can be an especially critical issue in HDWDM systems, because of the gain non-uniformity in multi-span transmissions. Generally speaking, the OSNR measurements can be realized by measuring the signal power as the difference between the total power of the signal peak and the amount of the background noise; this latter, in turn, is determined by measuring the noise contributions on either side of the signal peak. However, the separation and measurement of the signal and noise power are difficult to realize in practice, because the noise power in an optical channel is included in the signal power. The noise power determination in a HDWDM system can be made by interpolating the noise power between the adjacent channels (Agrawal, 2002). Nowadays, the modern optical spectrum analyzers can perform such measurements automatically, simultaneously for signal spectrum and OSNR.

EXPERIMENTAL AND SIMULATION MODELS

Our experimental transmission system (see Figure 1) employs two optical channels with external intensity modulation (IM) and non-return-to-zero (NRZ) pulse shapes. The laser is always switched on and its light waves are modulated via the electro-optic MZM by data pulse sequence output of a pulse pattern generator (PPG), using the principles of interferometer constructive and destructive interference to present ON and OFF of the light waves.

After the MZ modulator the signal is sent to a single mode fibre (SMF), where optical pulses are propagating over a 40 km without amplification technique. The utilized fiber has a large core effective area 80 μm^2, attenuation α = 0.2 dB/km, nonlinear refractive coefficient $n_k = 2.5 \cdot 10^{-20}$ cm/W and dispersion 16 ps/nm/km at the reference wavelength λ = 1550 nm (Ozoliņš and Ivanovs, 2009). At the fibre end, each channel is optically filtered with Anritsu Xtract tunable optical filter (see Figure 2). Essential parameter of such a filter is its centering on the signal to be extracted. Its position has to be adjusted regarding the signal harmonics. The auto-positioning feature of the Xtract allows a centering accuracy better than ± 15 pm (< 2 GHz), which is sufficient to considerably minimize the filter effect in the test results.

The Anritsu Xtract tunable optical band-pass filter covers all transmission bands of standard single mode optical fiber. The filter operates in the range of 1450 - 1650 nm, covering the E, S, C and

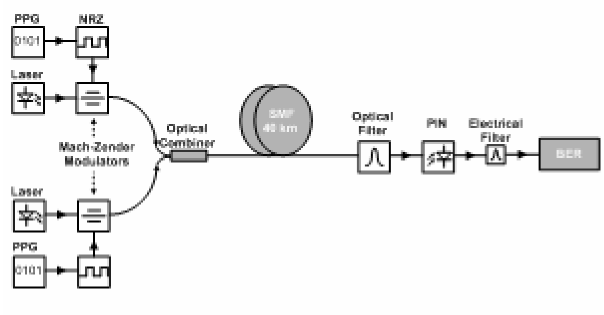

Figure 1. Experimental model of WDM system.

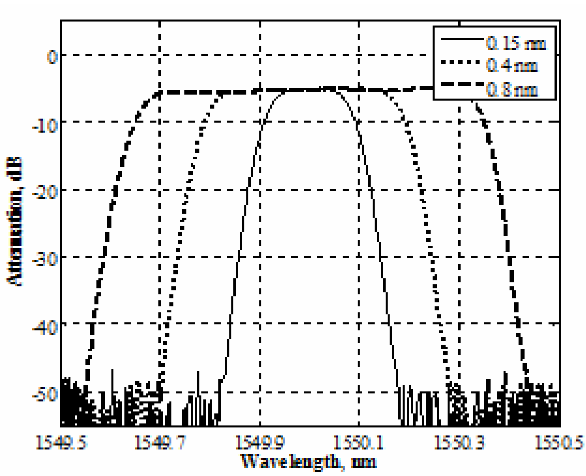

Figure 2. The measured amplitude responses of the Anritsu extract tunable optical band-pass filter at different FWHM (full width half maximum) values.

L bands and partially the U band. The main drawback of this tunable optical band-pass filter is 6 dB insertion losses, which is a limiting factor in realization of high-speed HDWDM transmission systems for moderate distances without optical amplifiers.

Receiver block consists of PIN photodiode (typical sensitivity -17 dBm) and Bessel – Thomson electrical filter (4 poles, 7.5 GHz -3dB bandwidth). In receiver filtered optical signal is converted to electrical one and then electrically filtered. To evaluate the system performance several measurements have been taken. We were interested in observing the optical spectrum at the beginning and at the end of optical link, as well as eye diagrams.

According to experimental model we have created a simulation scheme (see Figure 3) in OptSim 5.0 software with the real parameters of all experimental devices. The accepted method of calculation is based on the solving a complex set of differential equations, taking into account optical and electrical noise as well as linear and nonlinear effects (Belai et al., 2006; Ozoliņš and Ivanovs, 2009). We have used a model where signals are propagating as time domain samples over a selectable bandwidth (in our case, a bandwidth that contains all channels).

The Time Domain Split Step (TDSS) method was employed to simulate linear and nonlinear behavior for both optical and electrical components. The split step method is now used in all commercial simulation tools to perform the integration of a fiber propagation equation that can be written as:

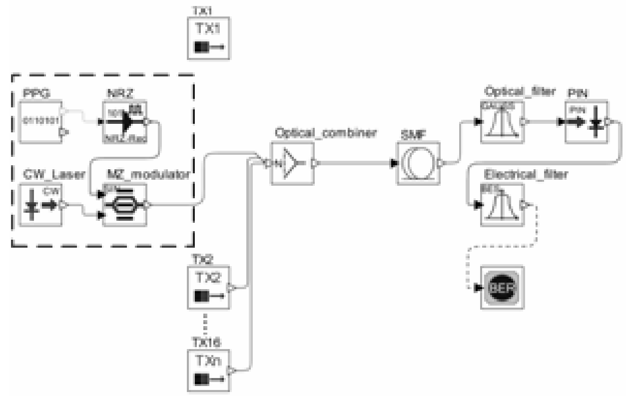

Figure 3. Simulation model of WDM system.

$$\frac{\partial A(t,z)}{\partial z} = \{L + N\} A(t,z) \qquad \text{.................(1)}$$

Here $A(t,z)$ is the optical field, L is the linear operator that stands for dispersion and other linear effects and N is the operator that is responsible for all nonlinear effects. The idea is to calculate the equation over small spans of fiber Δz by including either a linear or a nonlinear operator. For instance, on the first span Δz only linear effects are considered, on the second – only nonlinear, on the third – again only linear ones and so on. Two ways of calculation are possible, frequency domain split step (FDSS) and the above-mentioned time domain split step (TDSS) method. These methods differ in how linear operator L is calculated: FDSS does it in a frequency domain, whereas TDSS – in the time domain, by calculating the convolution product in sampled time. The first method is easy to fulfill, but it may produce severe errors during computation. In our simulation we have employed the second method, TDSS, which, despite its complexity, ensures an effective and time efficient solution (Bobrovs and Ivanovs, 2008; Bobrovs et al., 2006; Ozoliņš and Ivanovs, 2009).

RESULTS AND DISCUSSION

Total transmission capacity can be enhanced by increasing the number of multiplexed HDWDM channels. This can be carried out by reducing the frequency spacing between optical channels. Together with demand for boosting total system capacity, another challenge for service carriers is to find cost-effective solutions for upgrading. These solutions should require minimum renovation to the existing photonic and electronic subsystems.

We have studied experimental system data transmission over two different GHz spaced frequency channels in the frequency range around 193 THz. The channels were shifted till effective eye diagram presented on oscilloscope and the optical signal-to-noise ratio (OSNR) was enough for good system performance. Inter channel interference (ICI) and nonlinear effects become

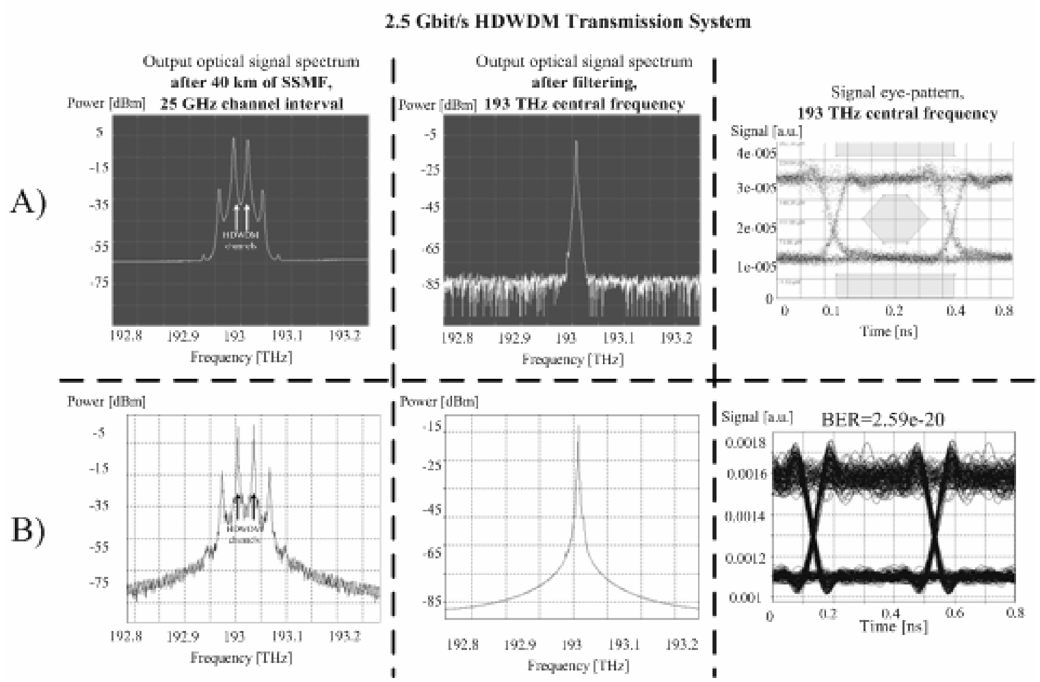

Figure 4. Output optical signal spectra and eye-patterns a) measured, b) calculated.

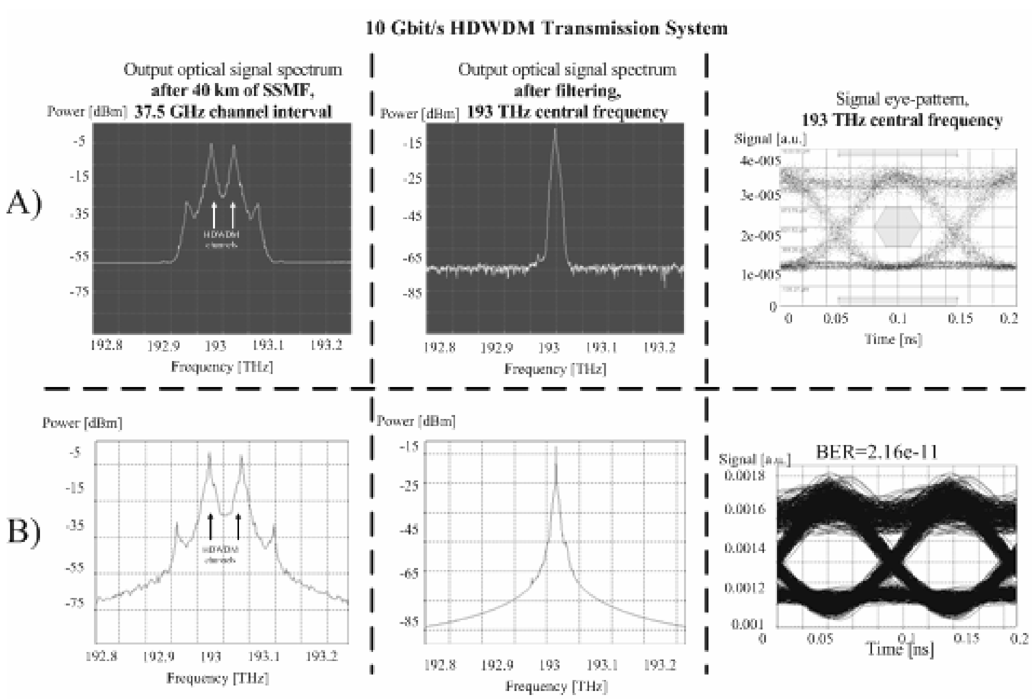

Figure 5. Output optical signal spectra and eye-patterns a) measured, b) calculated.

more and more significant when reducing channel spacing for a given bit rate per channel to increase spectral efficiency in HDWDM systems. A major reason for signal degradation is the nonlinearity of the fiber due to the high power loading at the input and signal optical amplification. For the decreasing the level of nonlinearities we do not use the optical amplification technique at all. Figures 4 and 5 presents measured and calculated

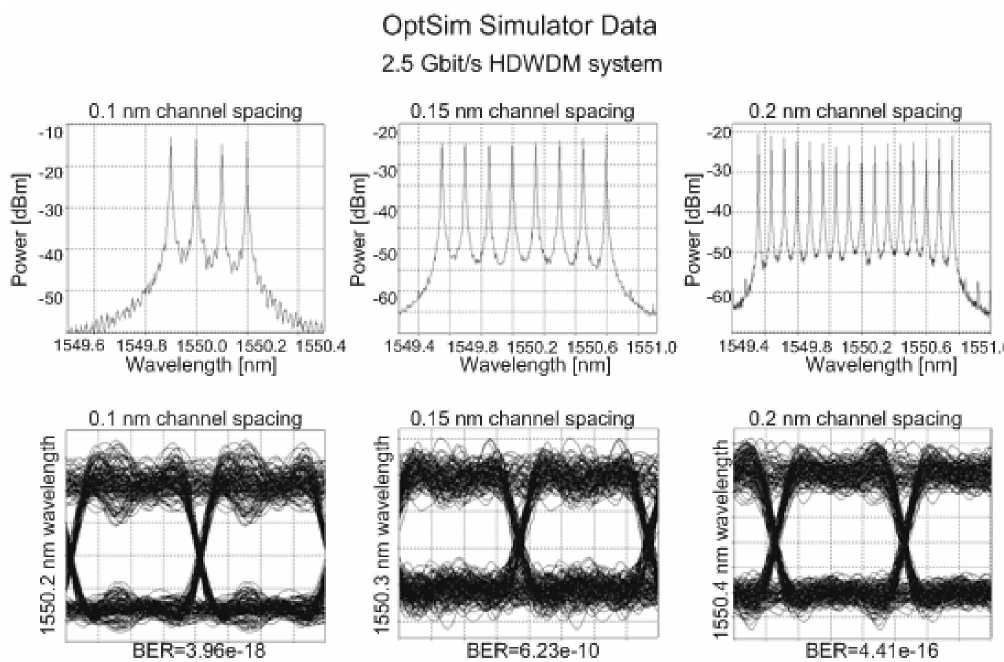

Figure 6. Calculated output diagrams for 2.5 Gbit/s HDWDM systems with different channel spacing and channel count, after 40 km of SMF.

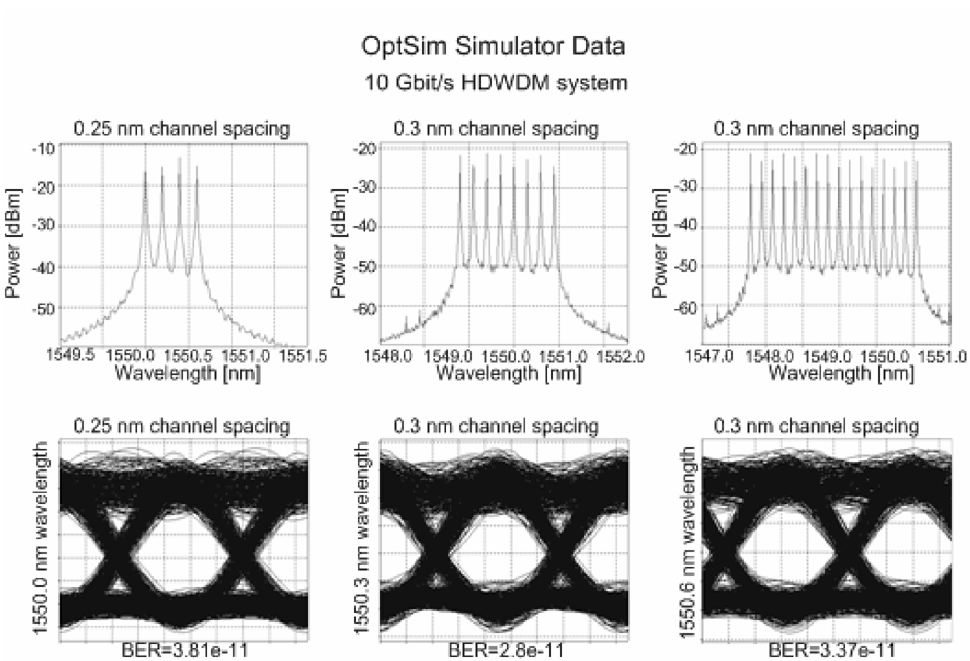

Figure 7. Calculated output diagrams for 10 Gbit/s HDWDM systems with different channel spacing and channel count, after 40 km of SMF.

optical signal quality on output of two channels HDWDM system with different bit rates.

The simulations results do not differ much from experimental model and the optical spectrums of both measurements are not distinct. In that case we can apply more optical channels in theoretical model to reduce the channel spacing and investigate the minimal allowed reduction for HDWDM systems with different bit rates.

Figure 6 shows the spectrum and eye diagrams after photo detection, for a 2.5 Gbit/s bit rate for each channel and different channel spacing. We present only successful transmission and it can be seen that for 4 channel system the minimal channel interval is 0.1 nm or 12.5 GHz respectively. To increase the number of wavelengths till 8 and 16 the channel interval should be 18.75 and 25 GHz accordingly. Only in that case the complex 2.5 Gbit/s HDWDM system transmission will be successful.

The fundamental limitation on the high speed of communications systems over the SMF are the linear chromatic and polarization mode dispersions. For the 10 Gbit/s systems the maximum transmission length, without dispersion compensation technique, would lie somewhere between 40 and 50 km. Figure 7 presents the transmitted 10 Gbit/s HDWDM data signal output eye diagrams and output optical signal spectrums, with different channel intervals. That solution indicates that for 4 channel 10 Gbit/s system the standard 50 GHz wavelength spacing can be reduced and the BER value still sufficient for good system performance. Also, Figure 7 shows that the 8 and 16 channels HDWDM systems works on threshold level until wavelength spacing not less than 37.5 GHz.

Conclusions

HDWDM is a powerful technique for increasing the capacity of fiber optic transmission systems. It may also prove to be a crucial enabling technology for ultra-high capacity on-chip optical interconnects, as well as chip-to-chip optical interconnects in massively parallel different optical systems. It has been shown that the BER and eye-diagram technique is a good means for evaluating the system performance that allows WDM system to be optimized for different parameters.

In contrast to the conventional high speed approach of increasing WDM transmission capacity, we demonstrate the minimal allowed channel spacing in HDWDM systems and provide recommendations for future WDM solutions. Our experimental measurements have shown that the minimal channel interval for 2.5 Gbit/s two channels HDWDM system should be more than 0.2 nm (25 GHz) and for 10 Gbit/s two channels system not less than 0.3 nm (37.5 GHz). Furthermore, our simulation results which where conformed with experimental results at two channels case (see Figures 4 and 5) shows the same results after channel count increment (see Figures 6 and 7). Future optimization of the existing WDM systems will be necessary and the minimal allowed channel spacing is only the first step for dense optical network optimization. Optical service providers probably will choose the favorable solution for current WDM systems and not always 40 Gbit/s signal per wavelength will be the best choice.

ACKNOWLEDGEMENT

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