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INVESTIGATION INTO THE POTENTIALITIES OF QUASI-RECTANGULAR OPTICAL FILTERS IN HDWDM SYSTEMS

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Currently, many research topics in the field of optical transmission systems (mostly grounded on novel modulation techniques) are focused on increasing the total data transmission speed of an individual optical fiber. 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. We have developed an experimental 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.*

1. INTRODUCTION

The annual global internet protocol (IP) traffic will exceed half a Zettabyte in four years. At just under 44 Exabytes per month, the annual run rate of traffic in the late 2012 will be 522 Exabytes per year. 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 level through 2012, increasing at a compound annual growth rate (CAGR) of 46 percent [1] (see Fig. 1).

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. This approach reduces the cost per transmitted information bit in a fully loaded and optimized transmission system [2–4].

High performance optical filters make the groundwork for realization of high-speed high-density WDM (HDWDM) transmission systems [5]. 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 [2, 6].

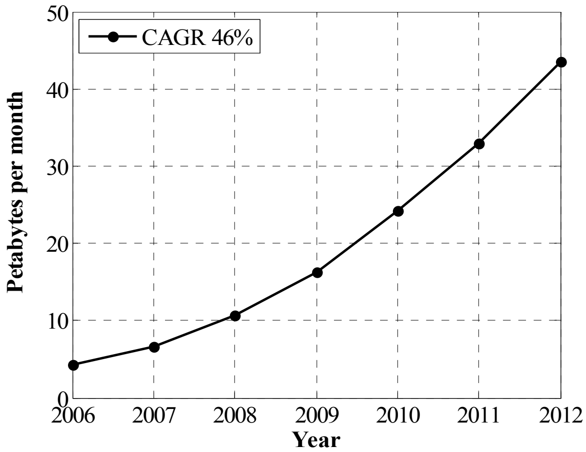

Fig. 1. Global IP Traffic Forecast (2006–2012) [1].

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-haul HDWDM systems a signal waveform distortion can be generated by linear chromatic dispersion, polarization mode dispersion, fiber nonlinearity, or their combination. In high-speed (more than 2.5 Gbit/s) time division multiplexing (TDM) optical systems, because of the short optical pulses and wide optical spectrum, the effect of complex dispersion dominates in a system's performance degradation [7].

In multi-wavelength WDM transmission systems the inter-channel crosstalk originated by fiber nonlinearity, such as cross-phase modulation (XPM) and four-wave mixing (FWM), is a limiting factor. To maximize the WDM network capacity, in the system's design and optimization it is necessary to take into account all 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 [4, 8].

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 specific 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 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.

2. SELECTION OF THE HDWDM SYSTEM'S MAIN COMPONENTS AND PERFORMANCE 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 the 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 execution becomes more complex with the increasing channel data rate, thus raising the requirements to electrical and optical components of the optical transmitter. A conventional optical transmitter employs the amplitude/intensity modulation (AM, IM) of 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 performed by direct or external modulation of the laser diode. For realization of transmission systems with channel data rates larger than 2.5 Gbit/s the external modulation is a better solution, because the impact of laser internal chirp on the optical signal can be reduced efficiently; on the other hand, the complexity of optical transmitter increases. The external modulation of laser light is performed in an external modulator (e.g. a Mach–Zehnder's). The external modulator is driven by the electrical signal with corresponding data rate. Depending on this driving signal, different transmission speeds can be reached.

The distributed feedback laser (DFB) represents the most important and most widely used single-mode laser type for the 1550 nm region. DFB lasers are obtained by implementation of a Bragg's grating structure inside the cavity between the reflecting surfaces of a Fabry-Perot (FP) laser [9].

External modulation can be reached with a $LiNbO_3$-based MZM. The operational principles of such 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. This variation 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 the MZM lower and upper arms. If no electrical field is applied, both signals arrive at the same time (in-phase) at the MZM output and interfere constructively. If otherwise, the 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 fulfilled with DFB lasers, whose main characteristics 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) [10].

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). To compensate losses in the fiber and optical components, optical amplifiers (crucial components in an optical transmission system) should be used. Despite the minimum attenuation at 1.55 μm, fiber losses significantly limit the transmission performance with increased transmission distance. Optical amplification can be realized using rare-earth (erbium, holmium, thulium and samarium) doped fiber amplifiers. These amplifiers provide optical amplification in the 0.5–3.5 μm region. 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 amplification at ~ 1.55 μm. The EDFAs present the state-of-the-art technology in conventional optical transmission systems and can be used as in-line amplifiers (placed every 30–80 km), power boosters (amplifiers at the transmitter side) or pre-amplifiers (amplifiers before the receiver) independently of the channel bit rate in the system.

The role of such an optical receiver is to detect the transmitted signal by the opto-electrical transformation of the signal received by a photo-diode (e.g. PIN or APD). Then additional electrical equalization is performed together with electric 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. They should also provide comparison of experimental and numerical data to verify 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 ($< 10^{-9}$). Therefore the International Telecommunication Union has created the eye diagram masks for different bit rates with a definite BER value.

The optical-signal-to-noise ratio (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. This effect can be suppressed placing an optical filter placed before the optical receiver.

Depending on the amplifier infrastructure used in a transmission system, the OSNR 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. In practice, the OSNR can be found by measuring the signal power as the difference between the total power of the signal peak and the background noise; this latter, in turn, is determined by measuring the noise contributions on either side of the signal peak. However, in practice it is difficult to separate measurements of the signal and noise power, because the latter in an optical channel is included in the signal power. The determination of this parameter in a HDWDM system can be made by interpolating it between the adjacent channels [11]. Nowadays, the modern optical spectrum analyzers can perform such measurements automatically, simultaneously for the signal spectrum and the OSNR.

3. OPTICAL FILTERS FOR WDM APPLICATIONS AND DESCRIPTION OF A QUASI-RECTANGULAR OPTICAL FILTER

The wavelength filters in optical transmission systems are a special subgroup of physical components defined in such a way that they select or modify parts of the signal spectrum. In fact, the optical wavelength filters are defined as referred to the modifications that they induce in the frequency spectrum. In electronic systems, filters play a crucial role in numerous signal processing applications. In turn, optical filters play an equally crucial role in the optical domain [12, 13].

We will restrict our considerations to the application of optical filters in optical transmission systems. Most of today's network concepts are based on WDM, which means that WDM filters are mainly needed in order to route and select specific wavelength channels [12].

The filters in optical WDM transmission systems are classified into band-pass filters, low-pass filters, high-pass filters, and notch filters [13].

The band-pass filters (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 is generally broadband, and can often be described as quasi-white noise having a constant level in the power spectrum. By applying a band-pass filter to selection of the wavelength channel, the useful information is retained and most of the noise is filtered, resulting in improvement of the OSN ratio. A band-pass optical filter can also be used to select a particular channel in a WDM application from several channels that are transmitted in a common WDM transmission system [12, 13].

Although different kinds of filters are required in an optical WDM transmission system, the band-pass filters are by far the most important since they are prerequisite for add and drop, multiplex, as well as interleave and routing functionalities which are essentials for a WDM network [2, 13].

Physically, WDM filters rely on different principles of operation and on different materials. The diffraction gratings are based on the interference of multiple optical signals originating from the same source but with different phase shifts. The key property of a grating is its ability to simultaneously diffract all incoming wavelengths, so that it is possible to construct simple wavelength division multiplexers or high-performance tunable band-pass filters with a narrow bandwidth [12].

The primary characteristic of such a filter is its spectral profile. The ideal spectral shape of a band-pass filter has an almost rectangular function, providing a perfect transmission, without distortion, of the whole signal within the filter bandwidth, and cutting undesired signals out of the band. In our measurements we exploited a high-performance Anritsu Xtract tunable optical band-pass filter. With a flat top and sharp edges, such a filter has quasi-rectangular characteristic (see Fig. 2) and allows clean extraction of HDWDM channels without any corruption of data. One of the modifications of Anritsu Xtract optical filter offers a variable bandwidth as an option. Without altering the remarkable optical features of the filter, this capability enables perfect adaptation of the filter bandwidth to the transmission speed of the signal.

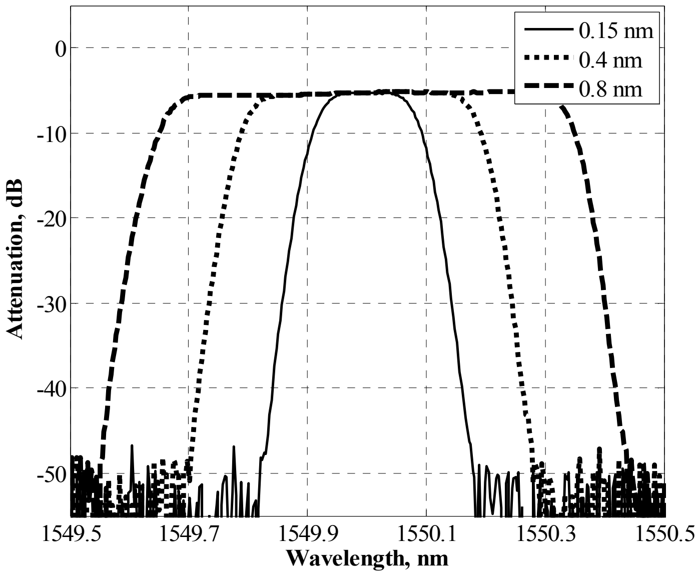

Fig. 2. The measured amplitude responses of the Anritsu Xtract tunable optical band-pass filter at different FWHM values.

Another 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 of the Xtract allows a centering accuracy better than ± 15 pm (< 2 GHz), which is sufficient to considerably reduce the filter effect in the test results.

The Anritsu Xtract tunable optical band-pass filter covers all transmission bands of a standard single-mode optical fiber. The filter operates in the range of 1450–1650 nm, covering the E, S, C, L bands and partially the U band. The ready for next generation DWDM Transport Systems Xtract is suitable for systems with a very high channel density and a moderate data transmission speed. 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.

To test DWDM systems in the design phase, at manufacturing, final quail-fication or commissioning, an optical band-pass filter is needed to extract a single channel and test the transmission quality on this individual carrier. Since the trend in DWDM networks is to densify the channel spacing and to increase the modulation rate, isolating one channel without altering the data transmission is not a simple task.

4. REALIZATION OF EXPERIMENTAL HDWDM TRANSMISSION SYSTEM

The execution and field implementation of 2.5 and 10 Gbit/s single-channel transmission systems will be the first step towards deployment of 2.5 and 10 Gbit/s HDWDM systems. Accordingly, optimization of the component characteristics and system settings in the mentioned systems is required. To deliver sufficient rules for a future system design it would be necessary to consider not merely characteristics of single transmission components (e.g. fibers, amplifiers, modulators), but also the interaction of different components and their interplay with different transmission limitations.

The exemplary transmission line setup used in investigations of the optimum system settings for 2.5 and 10 Gbit/s single-channel propagation is illustrated in Fig. 3 for 193 THz transmission. To evaluate the output signal characteristics, an optical direct-detection receiver was used with an electrical fourth-order Bessel–Thomson electrical filter having a 3 db bandwidth of 7.5 GHz. The transmission line is formed by a 40 km long span. In practice, this span length is preferred by most network providers since it allows a compromise between the system's costs and its performance.

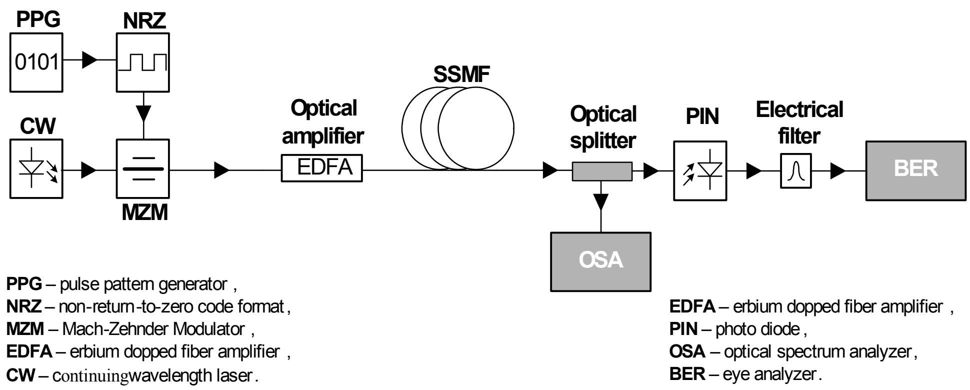

Fig. 3. Transmission setup used in investigations of optimum system settings for 10 Gbit/s single-channel propagation.

For the performance evaluation and optimization of the experimental single-channel system it is necessary to analyze the optical and electrical signal quality before MZM, after MZM and after SSMF (Figs. 4, 5). The choice of arbitrary units used on the Y-axis in the eye diagrams was purposeful – to make them more general in the cases when the plotted electrical quantity is current or voltage.

Comparing the output diagrams of Fig. 5 it can be seen that despite the fact that the signal at the output after 40 km is 15 dB lower than at the input, the system is highly efficient, the BER is greater than 10^{-9}, and the eye-pattern is not crossed with ITU mask.

To compensate the power losses caused by attenuation in the optical elements after upgrading a single-channel system to a WDM level it is necessary to raise the output power of optical amplifier. After that, the system's nonlinearities can significantly impair the quality of transmitted signals; therefore optical filters should be applied. Possible positions of an optical filter are after MZM or after EDFA amplifier. In our measurements we exploited a high-performance Anritsu Xtract tunable optical band-pass filter (described in Ch. 3), owing to which the EDFA output power was increased from 1 mW to 40 mW. The results are presented in Figs. 6 and 7.

2.5 Gbit/s single channel fiber optical system

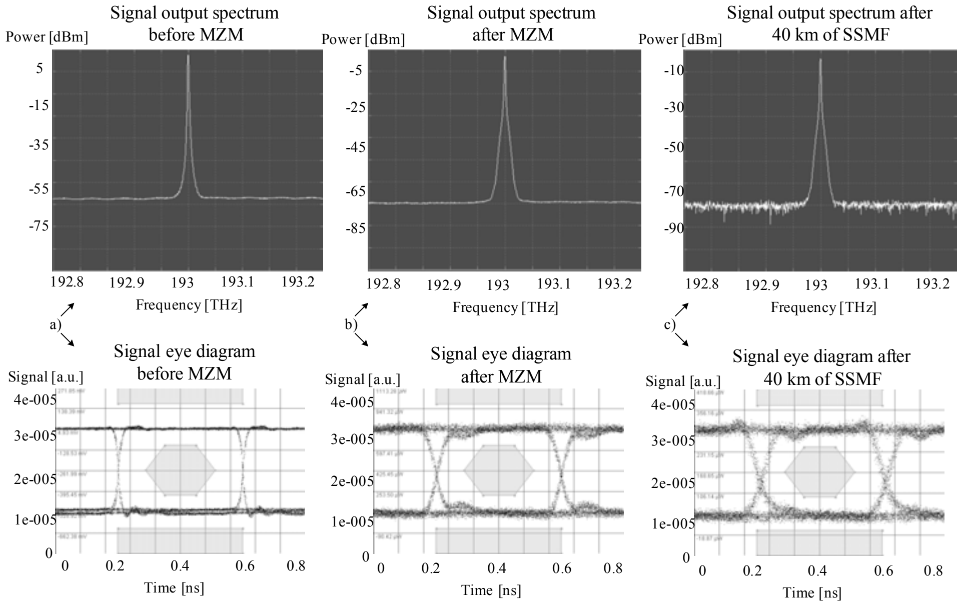

Fig. 4. Output optical signal spectra and eye-patterns
with ITU defined mask for 2.5 Gbit/s systems:
a) before MZM, *b*) after MZM, *c*) after 40 km of SSMF.

10 Gbit/s Single Channel Fiber Optical System

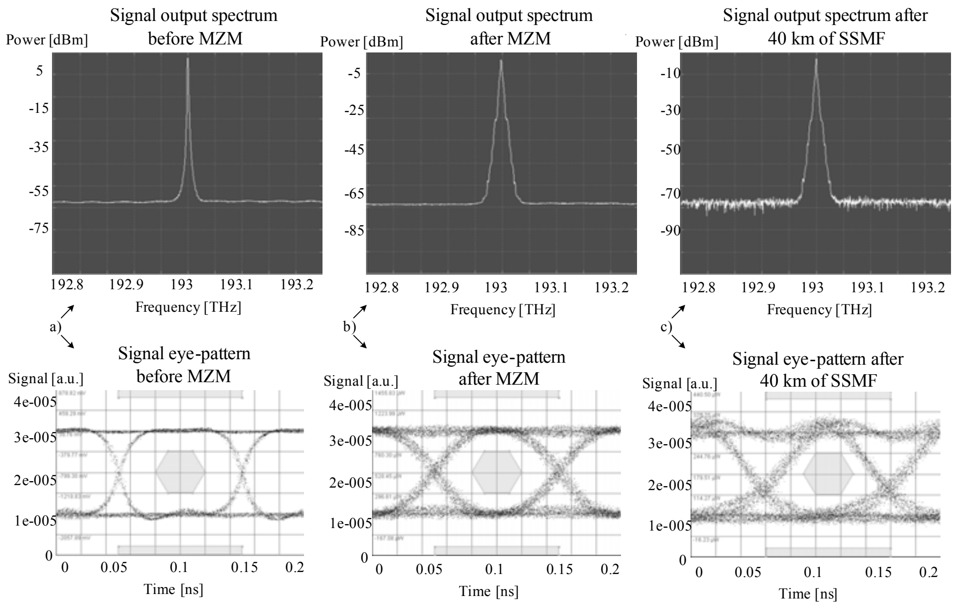

Fig. 5. Output optical signal spectra and eye-patterns
with ITU defined mask for 10 Gbit/s systems:
a) before MZM, *b*) after MZM, *c*) after 40 km of SSMF.

2. 5 Gbit/s Single Channel Fiber Optical System with Quasi -rectangular Optical Filter inside

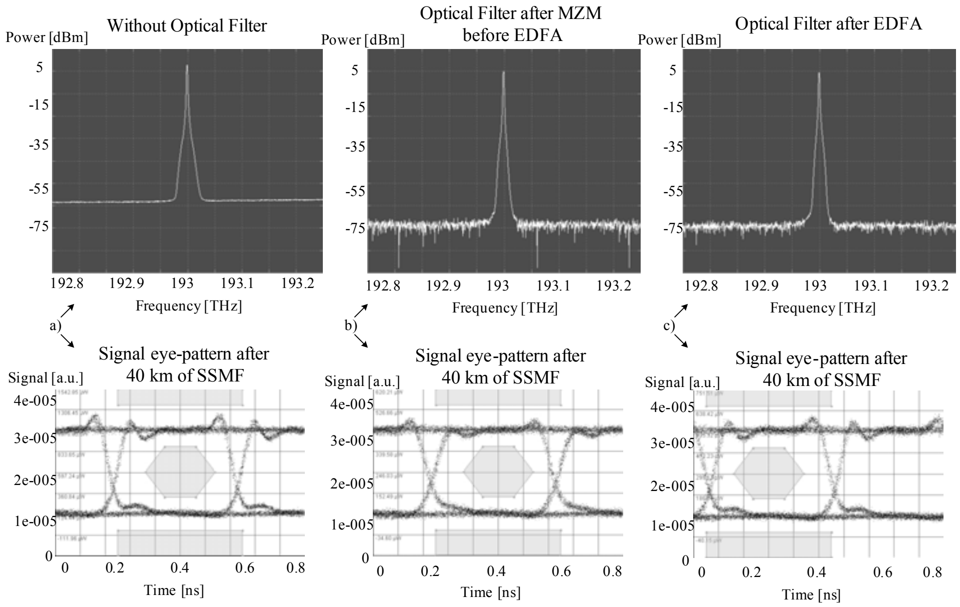

Fig. 6. Output optical signal spectra and eye-patterns with ITU defined mask for 2.5 Gbit/s systems: *a*) without optical filter, *b*) with quasi-rectangular optical filter after MZM, *c*) with quasi-rectangular optical filter after EDFA.

10 Gbit/s Single Channel Fiber Optical System with Quasi -rectangular Optical Filter inside

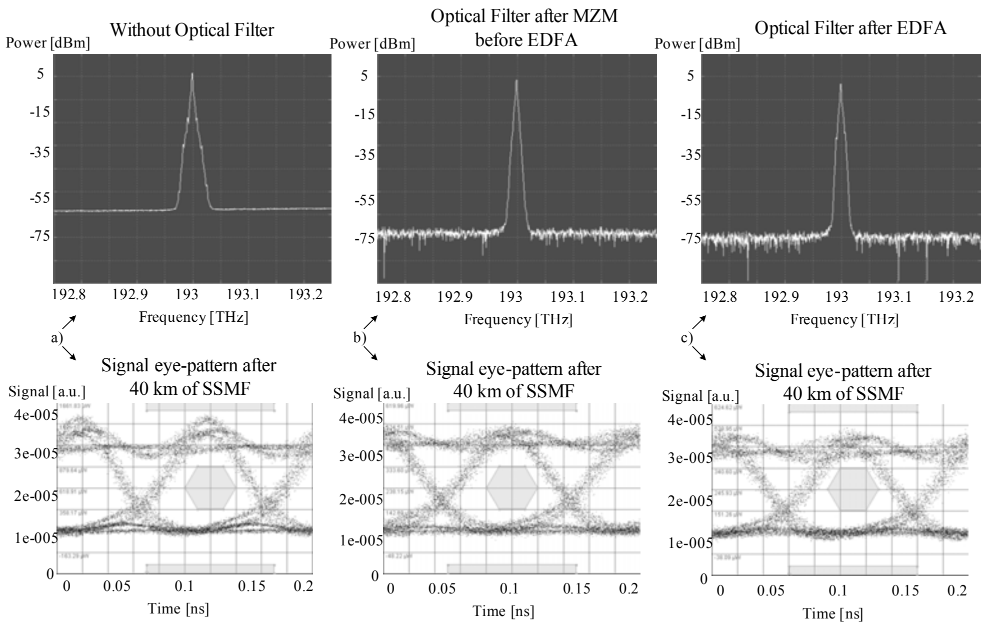

Fig. 7. Output optical signal spectra and eye-patterns with ITU defined mask for 10 Gbit/s systems: *a*) without optical filter, *b*) with quasi-rectangular optical filter after MZM, *c*) with quasi-rectangular optical filter after EDFA.

As we can see from the measurement results shown in the previous figures, the optimal single-channel optical transmission is realized for a distance of 40 km using the EDFA amplification technique, which is the first step for development of HDWDM transmission system. The next step in this direction is introduction of an additional optical signal into operating fiber optical transmission system. To obtain such a signal it is necessary to place one more transmitter with optical multiplexer (in our case executed with an optical 3dB coupler) at the beginning of optical fiber, and a receiver with optical de-multiplexer (in our case having a tunable quasi-rectangular optical filter) at its end.

The completed experimental HDWDM transmission system (see Fig. 8) consists of two optical channels with wavelength tuneable in a wide range (1525–1565 nm). To perform the BER and OSNR measurements for each channel of the HDWDM transmission system it was necessary to separate them with a tunable quasi-rectangular optical filter. Such a filter is executed with FWHM parameter and central wavelength adjustable with a very high precision in the 3rd optical window (~1550 nm). In our measurements we used a filter having different FWHM values, with better results obtained at the FWHM value reduced to 0.15 nm (see Fig. 2).

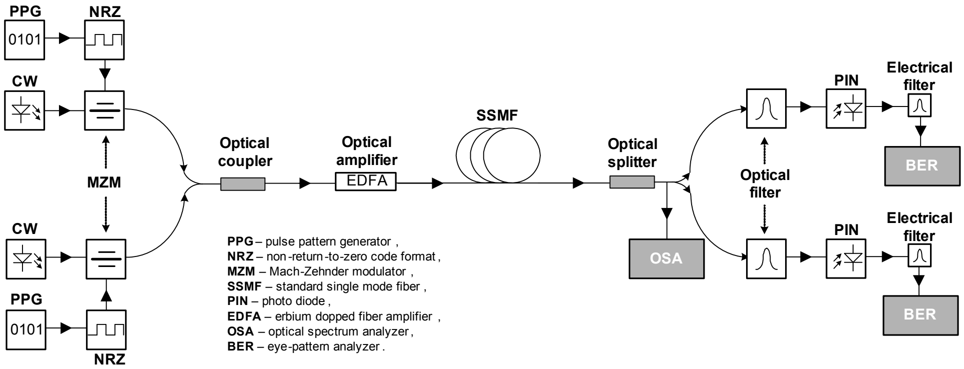

Fig. 8. The setup used for investigation of HDWDM transmission.

As a result, we have designed a HDWDM transmission system with a variable data transmission speed up to 12.5 Gbit/s, the channel interval up to 12.5 GHz and optical power up to 23 dBm. In Fig. 9 one can see 2.5 Gbit/s HWDM transmission systems with 18.75 GHz and 25 GHz channel interval. As is seen from the results, reducing channel interval to 18.75 GHz gives rise to Kerr's effect, which degrades a 2.5 Gbit/s HDWDM system. The signal eye-pattern overlaps with the mask (see Fig. 9*c*), which means that the signal quality does not ensure a 10^{-9} BER value. To obtain a system with an appropriate BER we should reduce the data transmission speed or increase the channel interval. As can be seen from Fig. 9, the 25 GHz channel interval ensures a good signal quality, and the signal eye-pattern in this case does not overlap with the mask.

To reach an appropriate signal quality at a 10 Gbit/s data transmission speed we need to increase still more the channel interval. From the simulation results we can conclude that the channel interval is to be 37.5 GHz to ensure the sought-for 10 Gbit/s HDWDM transmission. The corresponding measurement results are shown in Fig. 10. As can be seen from these results, the 37.5 GHz channel interval ensures appropriate signal quality, and the signal eye-pattern does not overlap with the mask at the end of a 10 Gbit/s HDWDM system.

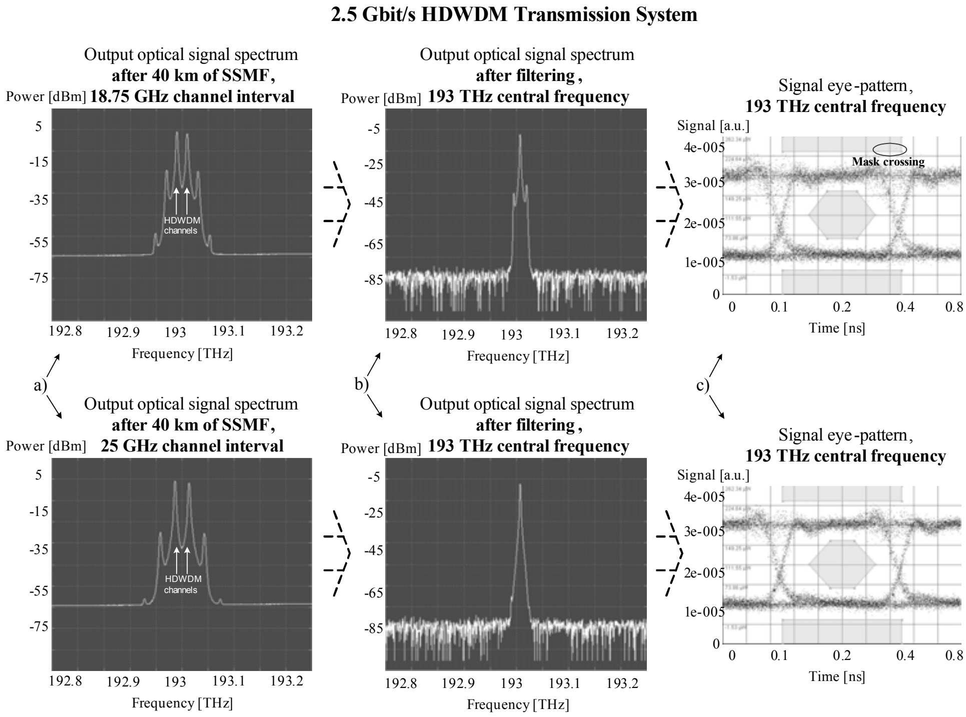

Fig. 9. Output optical signal spectra and eye-patterns with ITU defined masks for a 2.5 Gbit/s system: *a*) common optical spectra, *b*) signal optical spectrum after filtering, *c*) eye-pattern.

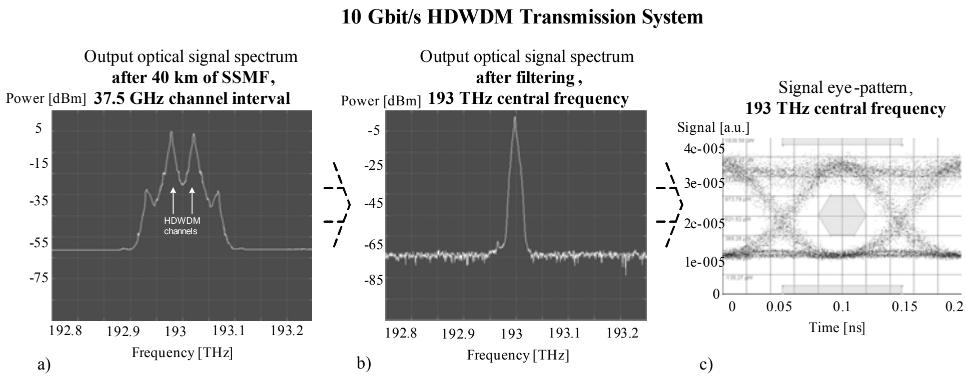

Fig. 10. Output optical signal spectra and eye-patterns with ITU defined masks for 10 Gbit/s system: *a*) common optical spectra, *b*) signal optical spectrum after filtering, *c*) eye-pattern.

5. CONCLUSIONS

We have evaluated experimentally the developed HDWDM transmission system and reached the minimum channel interval for reliable data transmission. Our investigation of the least allowed channel spacing in HDWDM systems will provide recommendations for the next generation WDM transmission systems.

The main conclusions from our experiments are therefore as follows.

- In our experimental system the quality of optical and electrical signals can be evaluated and optimized for each channel in several its places: before and after the MZ modulator and before and after SSMF. Due to ITU standards, the optical signal quality in the experimental system after transmission through 40 km SSMF is ensured with an appropriate BER value of 10^{-9}.
- For channel separation in a HDWDM system the optical filter is required which would have parameters close to ideal – the rectangular amplitude transfer function and the linear phase transfer function, providing the least BER values and minimal influence on the optical signal parameters. We have applied a quasi-rectangular optical filter with close to ideal parameters: the alterable FWHM value (from 0.15 to 0.7 nm) and the tunable central wavelength with high precision of $\pm$ 15 pm in a wide range (from 1450 to 1650 nm) covering the E, S, C, L bands and, partially, the U band of the optical fiber transmission windows.
- In the measurements, different optical filter FWHM values (from 0.15 nm to 0.7 nm) were used. The best results were obtained for 0.15 nm, when the eye pattern was opened wider. For evaluation of the signal quality a visual method was employed, in which the eye pattern was evaluated visually in the electric signal analyzer varying the quasi-rectangular optical filter FWHM value.
- At reducing the channel interval to 18.75 GHz the Kerr effects (self – phase modulation, cross – phase modulation and four-wave mixing) degrade the 2.5 Gbit/s HDWDM system. The signal eye-pattern overlaps with the mask (see Fig.9*c*), which means that the signal quality does not ensure in this case the BER value of 10^{-9}. From the measurement results it follows that the 25 GHz channel interval ensures a good signal quality and that the signal eye-pattern does not overlap with the mask.
- At 10 Gbit/s HDWDM transmission the channel interval should be 37.5 GHz to ensure the signal quality with the BER value of 10^{-9}, which fits well the previous simulation results.

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KVAZI-TAISNSTŪRA OPTISKĀ FILTRA IESPĒJU IZPĒTE HDWDM SISTĒMĀS

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K o p s a v i l k u m s

Liela daļa no pētījumiem optiskajās pārraides sistēmās koncentrējas uz individuālas optiskās šķiedras pārraides ātruma palielināšanu. Vairākums no šiem pētījumiem ir balstīti uz inovatīvām modulācijas metodēm. Alternatīva, bet ekvivalenta pieeja ir WDM sakaru sistēmas kanālu intervāla samazināšana līdz minimāli atļautajam, saglabājot nemainīgu datu pārraides ātrumu konkrētam kanālam. Publikācijā ir parādīts eksperimentāls HDWDM pārraides sistēmas makets ar kvazi-taisnstūra filtrēšanas tehniku. Mērījumu rezultāti liecina, ka 2,5 Gbit/s HDWDM pārraides sistēmu ir iespējams realizēt ar 25 GHz kanālu intervālu, savukārt, 10 Gbit/s HDWDM pārraides sistēmā kanālu intervāls starp blakus esošajiem kanāliem jāizvēlas ne mazāks kā 37,5 GHz.

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