International Journal of the Physical Sciences Vol. 6(35), pp. 7926 - 7934, 23 December, 2011
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS11.1498
ISSN 1992 - 1950 ©2011 Academic Journals

Full Length Research Paper

New-generation optical access system based on the thin film filter technology

O. Ozoliņš*, V. Bobrovs, Ģ. Ivanovs and I. Ļašuks

Telecommunications Institute, Riga Technical University, 12 Āzenes Str., Rīga, LV-1048, LATVIA.

Accepted 30 November, 2011

Dense wavelength division multiplexing-direct scheme with two thin film filters (full width half maximum bandwidth 100 and 200 GHz) for broadband access has been realized to evaluate the minimal channel interval for each thin film filter needed for a satisfactory bit error ratio. From the results, the minimal channel interval has been established for both thin film filters that ensure reliable data transmission and higher spectral efficiency of the whole system. It was found that for the dense wavelength division multiplexing-direct system for broadband access with 200 GHz thin film filter, a satisfactory performance is achieved with a 100 GHz channel interval at the 10 Gbit/s data transmission speed and the spectral efficiency was raised from 0.05 to 0.1 bit/s/Hz.

Key words: Dense wavelength division multiplexing (DWDM), thin film filters (TFF).

INTRODUCTION

The number of consumers of the optical fiber technology has grown rapidly due to benefits of broadband connections (Miyazawa and Harai, 2010). A passive optical network (PON) offers a multiple network topology that allows the fundamentally unlimited bandwidth of optical fiber to be employed (Shea and Mitchell, 2007). Service providers are pushing optical fiber deeper into their networks for inhabited locality broadband access (Ļašuks et al., 2010; Piehler, 2011). This trend has lead to Gigabit Passive Optical Network (G-PON) and Gigabit Ethernet-PON (GE-PON) commercialization (Miyazawa and Harai, 2010).

Still, the amount of data to transmit increases and global internet protocol (IP) data quadruple from 2009 to 2014 and the annual global IP traffic will exceed half a Zettabyte in four years (Cisco Systems, 2010). The services and applications offered are becoming increasingly bandwidth intensive due to broadband up-take (Shea and Mitchell, 2007). Due to enormous amount of data to transmit, telecom providers are forced to adjust their employed optical fiber access systems to manage these challenges (Haro and Horche, 2008; Ozoliņš et al., 2010). From an application viewpoint, bandwidth guaranteed services that can guarantee quality of service (QoS) for applications that require real-time capabilities and several Gbit/s class speeds: digital cinema, 3Dvideo and online game, will be required in addition to conventional bandwidth shared services (Miyazawa and Harai, 2010). Moreover, currently employed optical access systems are built to operate within standard specifications and it is quite challenging for new-generation access systems, since degrading effects can change with temperature, aging and component drift (Ļašuks et al., 2010; Pan et al., 2010). Under this assumption, new concept for optical access architecture will be needed.

The novel concept is a dense wavelength division multiplexing (DWDM)-direct (Miyazawa and Harai, 2010) in which multiple wavelengths are directly connected to each optical network unit (ONU). The DWDM-direct system for broadband access could be one promising solution to the high capacity access network with high spectral efficiency, good flexibility and enhanced security (Wang et al., 2007). This concept has the potential to significantly reduce system power consumption and promises great network flexibility for expected and

---

*Corresponding author. E-mail: oskars.ozolins@rtu.lv. Tel: +371 28682855.

Abbreviations: **DWDM,** Dense wavelength division multiplexing; **TFF,** thin film filters; **SSMF,** standard single mode fiber.

unexpected user demands by offering rate extendibility as well as user and service multiplexing (Kimura et al., 2010). Also, there will be multiple wavelengths assignment requests for each ONU in new-generation optical access rather than just one wavelength an in next generation wavelength division multiplexing (WDM)-PON (Miyazawa and Harai, 2010; Shea and Mitchell, 2007). Due to this optical band-pass, filters are required at ONU to perform wavelength separation.

Thin film filters (TFF) have been employed in a variety of fields (Shen et al., 2009). TFF were the first band-pass filter type to be widely utilized in WDM systems in the 1990s. These devices were appropriate for employment in WDM optical systems, because it was relatively mature: optical interference thin films have been produced since the 1930 (Venghaus, 2006). As a TFF technology provides low optical loss, high optical isolation and polarization independence has been extensively employed in optical transmission systems in the last 20 years (Sumriddetchkajorn and Chaitavon, 2007). In addition, realization of TFF with 200 GHz and later 100 GHz full width half maximum (FWHM) bandwidth for DWDM systems channel separation has spurred technology to be applied to several network applications and more recently as de-multiplexers for access networks (Venghaus, 2006; Willey, 2001).

The research on optical communications in the past years was partly directed towards increasing the total capacity of a single optical fiber (Ivanovs et al., 2010). Our proposed approach for increasing the transmission capacity is to reduce the channel spacing of a DWDM-direct system for broadband access to the minimum, while keeping the employed optical band-pass filter technologies. We have measured the complex transfer functions of TFFs with 100 GHz and 200 GHz FWHM bandwidth, and evaluated the minimal channel spacing of 2.5 Gbit/s and 10 Gbit/s DWDM-direct systems for broadband access with optical filters of the kind over 20 km of a standard single mode fiber (SSMF). Subsequently, for the DWDM-direct system for broadband access with 100 GHz TFF, a satisfactory performance is achieved with a 75 GHz channel interval at the 10 Gbit/s data transmission speed and the spectral efficiency was raised from 0.1 to 0.1333 bit/s/Hz. These results provide benefits which are obtained from optical band-pass filter parameter estimation to take them into consideration for realization of high speed spectrally efficient DWDM-direct system for broadband access.

BAND-PASS THIN-FILM FILTERS

One of the most common passive devices for multiplexing/de-multiplexing (mux/de-mux) of optical signals in the systems based on WDM is the TFF due to its design flexibility and technological maturity for achieving low loss, high isolation and wide bandwidth performances (Dutta et al., 2003). A TFF can be made to have excellent wavelength stability, which makes this device an appropriate passive component (Venghaus, 2006). Particularly, a TFF device is presently in a 1 × 2 port configuration, when one filter is inserted between a dual-fiber optic collimator and a single-fiber optic collimator (Sumriddetchkajorn and Chaitavon, 2007).

A band-pass TFF device consists of one or more coupled thin-film Fabry-Perot filters. A filter of the kind contains a thin-film etalon surrounded by all-dielectric thin-film reflectors. In a Fabry-Perot filter, only a small portion of light penetrates the first reflector, while at resonant wavelengths, the light intensity increases in the spacer layer until a substantial proportion of the input light is transmitted (Venghaus, 2006). Mux/de-mux devices for DWDM applications have to pass very stringent environmental tests: high humidity, high temperature and various mechanical tests; the lifetime of such an optical device is expected to be at least 25 years (Dutta et al., 2003).

A typical single-cavity layered TFF structure contains quarter-wave layers and half-wave layers. All the layers composing of the TFF structure are made of materials with high and low refractive index (Dutta et al., 2003; Macleod, 2001). The most commonly used low-index material is SiO_2, and as high-index materials TiO_2 and Ta_2O_5 are typically used because of their high refractive index, low absorption and stability at 1550 nm (Macleod, 2001; Arabshahi and Asmari, 2010). The thickness of the spacer layer determines the central wavelength of a filter, while alternating reflector layers determine its reflectivity (Dutta et al., 2003).

A TFF is feasible to employ in modular architectures that start with a few channels, but can later be expanded as the need for a greater bandwidth arises. The transmission of a filter at non-resonant wavelengths as well as the pass-band width is determined by the number of periods in the reflectors. As the reflectors are made with higher reflectivity, the transmission at non-resonant wavelengths is suppressed, whereas the resonant transmission is preserved as mentioned earlier, narrowing the filter (Venghaus, 2006). The numbers of layers vary depending on the particular performance requirements. When a light beam with components of different wavelength is launched into the device, portion of the light with the frequency component matching the resonant frequency of the cavity is transmitted, and the rest of the light beam is reflected by the filter.

The properties of a single-cavity TFF are similar to those of a single-cavity etalon filter with narrow bandwidth and limited isolation (Dutta et al., 2003). TFF can be designed and built to have nearly square pass-band characteristics, which makes them useful as optical band-pass filters (Venghaus, 2006). It is known that the pass-band of a TFF can be flattened to impart a square shape by cascading multiple spacers in the structure (Dutta et al., 2003). The familiar square shape of an optical band

-pass filter is achieved by inducing a very strong resonance: the light is trapped within the filter for an appreciable time, especially near the band edges, to achieve constructive interference and eventual transmission through the multi-cavity structure (Venghaus, 2006). It is clear that better filtering performance can be obtained by increasing spacers in the filter design. However, in practice, this will result in the enlarged number of the layers and additional difficulties in the film deposition. To maintain isolation, a filter with higher cavity count may have steeper edges, increasing the chromatic dispersion (CD) but still pushing it from the channel center. Another approach is to give up some of the filter “squareness”, trading the transmission penalty for that of CD (Dutta et al., 2003; Venghaus, 2006). Different delay for the wavelength components of a pulse can lead to its broadening and distortion. Due to this, strong CD in optical band-pass filters is a limiting effect in DWDM applications.

COMPLEX TRANSFER FUNCTION MEASUREMENT

Agilent Technologies 86038B photonic dispersion and loss analyzer was used to perform TFF passive device parameters measurements. As a result, numerous parameters were obtained: attenuation, group delay (GD), chromatic dispersion and differential group delay (DGD) as functions of wavelength for 200 MHz and 100 GHz TFF passive devices. This equipment employs the modulation phase shift (MPS) method. In the conventional MPS method, light from a sinusoidal source is intensity modulated before being launched into the device under test (Peucheret, 2004). The signal is detected and the envelope amplitude and phase is measured relative to the radio frequency (RF) source (Hui and O’Sullivan, 2009).

Modulation phase shift measurement scheme is as shown in Figure 1. Light from a tunable laser is sinusoidally amplitude modulated (typically in the 100 MHz to 1.25 GHz range) in a Mach-Zehnder modulator (MZM). Polarization controller is employed to alter signal polarization state for differential group delay (DGD) measurements. After propagating through the device under test (DUT), the transmitted signal is detected by a PIN photodiode. A RF network analyzer is used to provide a modulating signal of frequency f_m and to measure electrical phase difference between input and output signals (Agilent Technologies, 2006; Peucheret, 2004).

In practice, the wavelength is swept and the change in the group delay $\Delta\tau$ for each wavelength increment is calculated from the measured change in the phase according to Equation 1:

$$\Delta\tau_{(\Delta\lambda)} = \frac{\Delta\phi}{360^o}\cdot\frac{1}{f_m} \tag{1}$$

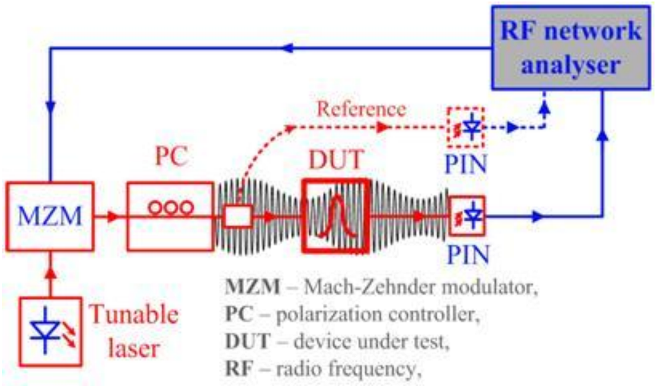

Figure 1. Modulation phase shift method measurement scheme.

where $\Delta\phi$ is the phase change in degrees produced by a small wavelength step, f_m is the modulation frequency in Hz, and the subscript $\Delta\lambda$ indicates that the change in group delay being measured was produced in response to an incremental change in wavelength (Agilent Technologies, 2006; Hui and O’Sullivan, 2009).

The attribute called dispersion is defined by:

$$D = \frac{\Delta\tau}{\Delta\lambda} \tag{2}$$

where $\Delta\tau$ is the change in group delay in seconds corresponding to a change in wavelength $\Delta\lambda$ in meters. In practice, the dispersion is expressed in units of picoseconds per nanometer (ps/nm). Combining equation 1 and 2, we obtain:

$$\Delta\phi = 360^o \cdot D \cdot f_m \cdot \Delta\lambda \tag{3}$$

Equation 3 shows that the amount of phase change measured in response to a wavelength step is the product of device dispersion, modulation frequency and wavelength step. This equation provides several key insights into the capabilities of the MPS measurement method. The DGD at each wavelength is calculated using the minimum to maximum phase change in the same formula used to calculate group delay, but in this case the stimulus is polarization rather than wavelength (Agilent Technologies, 2006; Hui and O’Sullivan, 2009).

Figure 2 shows measured attenuation, GD, CD and DGD as function of wavelength for TFF with 200 GHz FWHM bandwidth. The insertion loss for 200 GHz TFF is 0.53 dB, while its bandwidth at -1 dB level is 137.5 GHz and its bandwidth at -20 dB level is equal to 225 GHz. The group delay variation is limited to 6 ps in the pass-band and the dispersion at the center wavelength is equal to 0 ps/nm. The maximum dispersion in the bandwidth at -3 dB level is found to be within the range of -30 to 40 ps/nm.

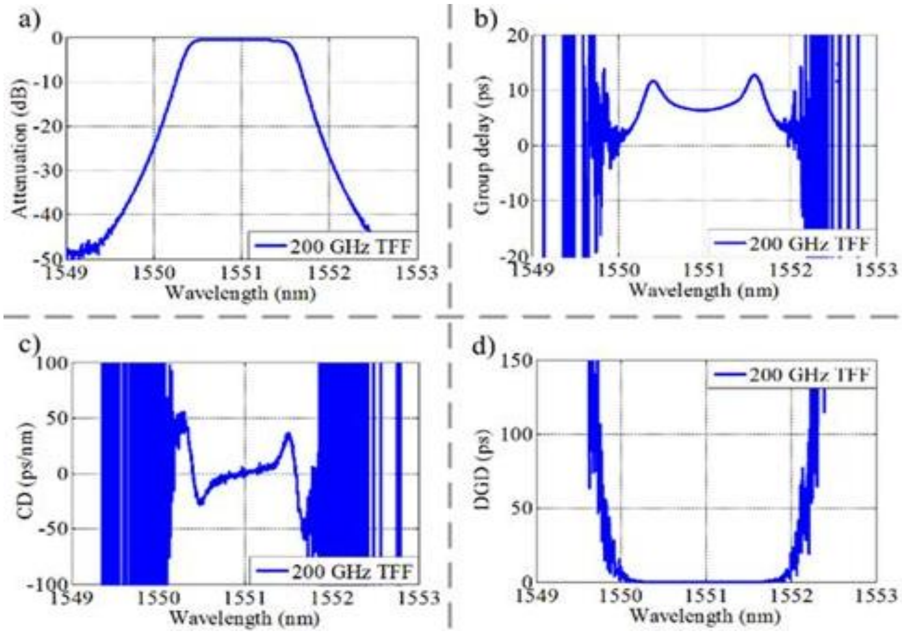

Figure 2. Measured attenuation (a), group delay (b), chromatic dispersion (c) and differential group delay (d) as function of wavelength for 200 GHz TFF device.

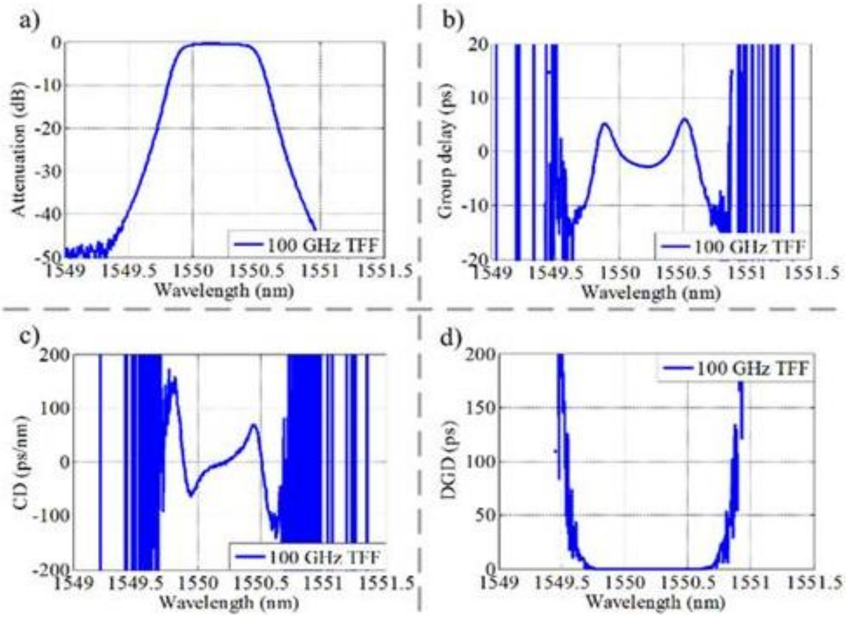

Figure 3. Measured attenuation (a), group delay (b), chromatic dispersion (c) and differential group delay (d) as function of wavelength for 100 GHz TFF device.

Figure 3 shows the measured attenuation, GD, CD and DGD as a function of wavelength for TFF with 100 GHz FWHM bandwidth. The insertion loss for 100 GHz TFF is 0.45 dB, while its bandwidth at -1 dB level is 68.75 GHz and its bandwidth at -20 dB level is equal to 118.75 GHz. The group delay variation is limited to 9 ps in the pass-band and the dispersion at the center wavelength is equal to 0 ps/nm. The maximum dispersion in the bandwidth at -3 dB level is found to be within the range of -65 to 70 ps/nm. Results show that DGD value for both TFF passive devices increases at the edges of the optical filter amplitude transfer function which could be a

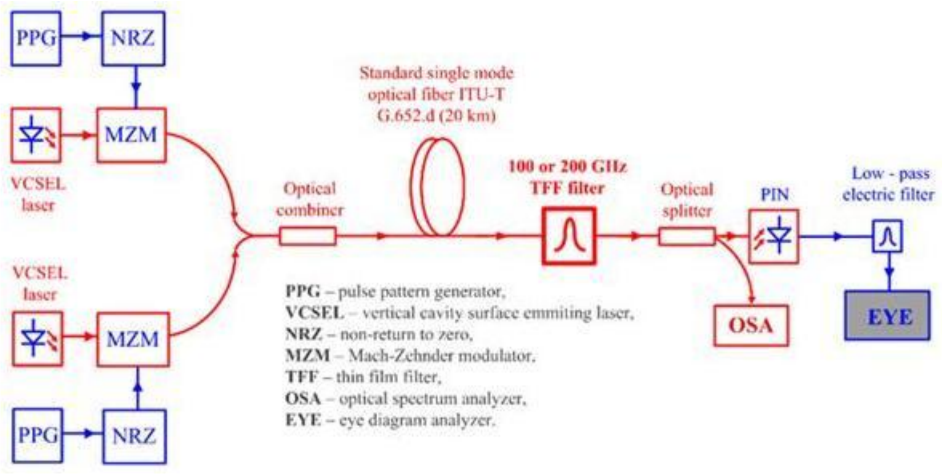

Figure 4. DWDM-direct measurement scheme.

degradation factor for optical signal transmitted through device.

DWDM-DIRECT SYSTEM MEASUREMENT

The realization of the spectrally efficient data transmission via optical systems is also dependent on the optical band-pass filter performance (Peucheret, 2004). Therefore, detailed research into the TFF influence on the optical signals in DWDM-direct has been done. The DWDM-direct scheme with two TFF (200 and 100 GHz FWHM bandwidth) for broadband access was worked out to evaluate the minimal channel interval at which the bit error ratio (BER) is sufficiently low ($< 10^{-12}$). The evaluation was performed using eye diagrams and measured optical power spectral densities of the received signal.

The realized DWDM-direct scheme has two channels and consists of three parts: a transmitter, an optical fiber and a receiver. In turn, the transmitter (Figure 4) consists of a pseudo-random data source with 2^{31}-1 bit sequence (Anritsu MU181020A), a non-return-to-zero (NRZ) code former (Anritsu MU181020A), a tunable continuous wavelength (CW) laser source (Agilent 81989A, 81949A) and an Avanex $LiNbO_3$-based external MZM. The data source produces a pseudo-random electrical signal which contains the information to be transmitted via optical fiber. Then a code former is used to form an NRZ code from the incoming pseudo-random bit sequence. This code format has long been dominant in the fiber optics transmission systems, because of relatively low electrical bandwidth for transmitters and receivers and insensitivity to the laser phase noise (Ozoliņš et al., 2010). The optical pulses are obtained by modulating CW laser irradiation in MZM with the previously mentioned bit sequence. After optical modulation, the formed optical pulses are sent directly to a 20 km SSMF (G.652.d) which is a typical length of access systems. The utilized fiber has a large core effective area of 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. The receiver block consists of an optical filter (100 or 200 GHz TFF), a PIN photodiode, and a Bessel-Thomson's electrical filter (4 poles, 7.5 GHz -3dB bandwidth, Anritsu MP1026A) (Ozoliņš et al., 2010).

In this research, we have measured the eye diagrams and optical power spectrum densities to determine the minimal channel interval for DWDM-direct systems for broadband access with 100 and 200 GHz TFF passive optical devices. A high-frequency oscilloscope Anritsu MP1026A was used to perform the eye diagram measurements, and the optical spectrum analyzer ADVANTEST Q8384 was employed to obtain spectral densities of the optical power.

The BER evaluation is a straightforward and 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 ($< 10^{-12}$). Therefore, the International Telecommunications Union (ITU) has created the eye diagram masks for different bit rates with definite BER values (Ozoliņš et al., 2010).

Figure 5 shows the eye diagrams and optical power spectral densities of a 2.5 Gbit/s DWDM-direct system realized with 200 GHz TFF after 20 km of SSMF for different channel intervals from 75 to 175 GHz with 25 GHz (0.2 nm in a wavelength range) step. The step value was chosen to fit DWDM wavelength grid defined in ITU-T G.694.1 recommendation. Both signal detection in the 2.5 Gbit/s DWDM system, 200 GHz TFF, was observed with a 75 GHz channel interval. To reduce undesirable

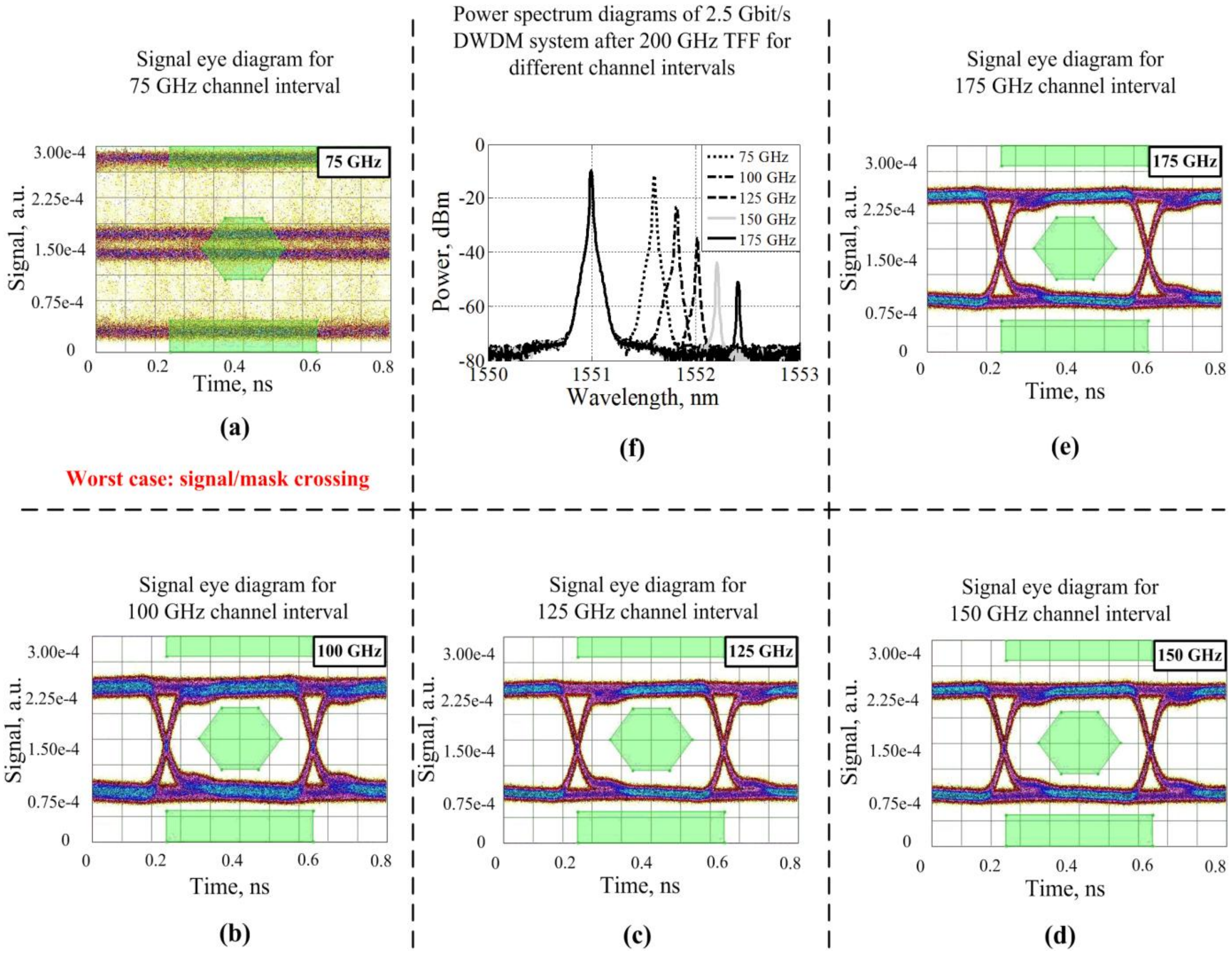

Figure 5. Eye diagrams (a toe) and optical power spectral densities (f) of 2.5 Gbit/s DWDM-direct system realized with a 200 GHz TFF after 20 km of SSMF for different channel intervals (shown in insets).

interaction between adjacent signals, the channel interval was increased, which gave lower BER values for the detected signal. As a result, the adjacent channel was suppressed more efficiently, because the steepness of a 200 GHz TFF device is very good and the adjacent channel's isolation is approximately 40 dB. As can be seen from the results (Figure 5b), a 100 GHz channel interval is sufficient to ensure the appropriate BER value for adequate system's performance. The results for greater channel intervals (125, 150 and 175 GHz, Figure 5c to e) are also shown to demonstrate DWDM-direct (200 GHz TFF) system's stability in the spectral range employed for transmission.

The eye diagrams and optical power spectral densities of a 10 Gbit/s DWDM-direct system (200 GHz TFF) for broadband access after 20 km of SSMF for the same channel intervals as in the previous case are as shown in Figure 6. Similar to the aforementioned, a 100 GHz channel interval is sufficient to ensure the appropriate BER value for normal performance of the system at 10 Gbit/s transmission speed; the spectral efficiency is in this case improved from 0.05 to 0.1 bit/s/Hz. Due to a higher modulation frequency, the optical power spectral density is broader, which results in shorter optical pulses and stronger influence of CD on the signal quality. This leads to greater degradation of the optical signal, which emerges as a larger standard deviation and jitter for "0" and "1" levels in eye diagram.

Figures 7 and 8 show the eye diagrams and optical power spectral densities of 2.5 and 10 Gbit/s DWDM systems realized with 100 GHz TFF (amplitude transfer function is as shown in Figure 3b) after 20 km of SSMF for different channel intervals from 50 to 150 GHz with 25 GHz (0.2 nm in wavelength range) step. As can be seen from Figures 7 and 8, a 75 GHz channel interval is sufficient to ensure an appropriate BER value for a

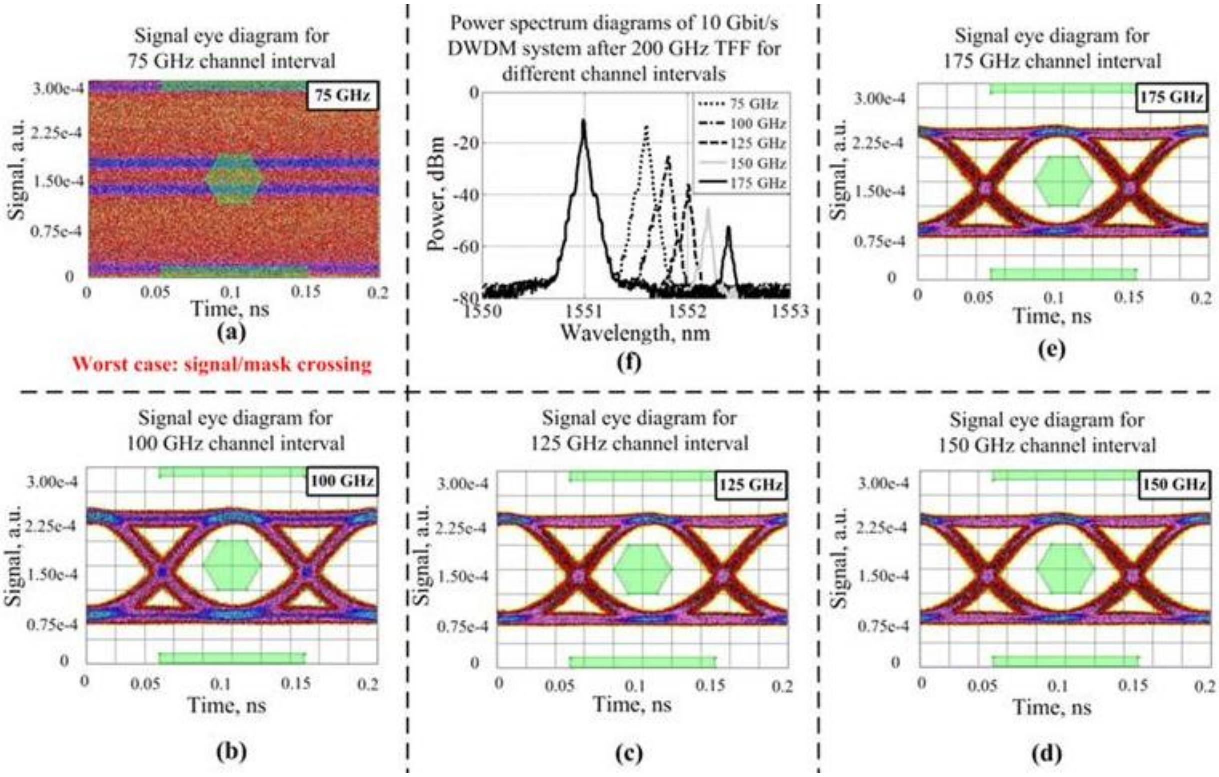

Figure 6. Eye diagrams (a–e) and optical power spectral densities (f) of 10 Gbit/s DWDM-direct system realized with a 200 GHz TFF after 20 km of SSMF for different channel intervals (shown in insets).

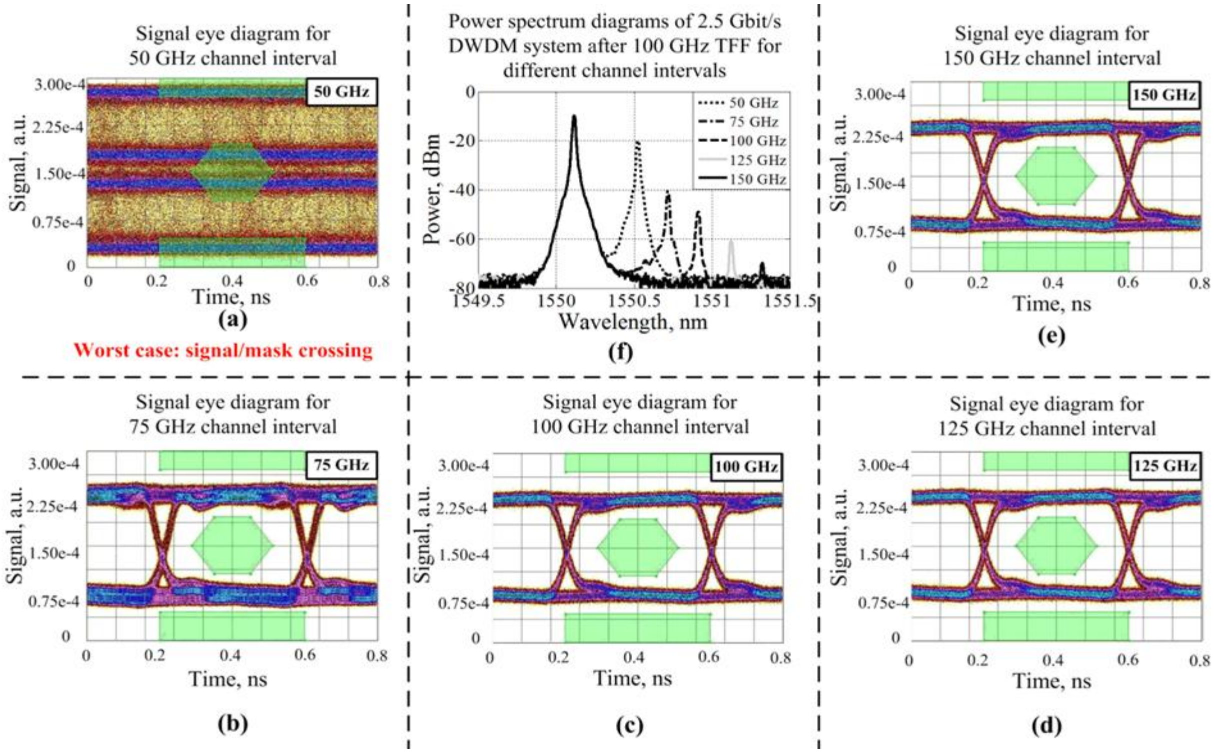

Figure 7. Eye diagrams (a to e) and optical power spectral densities (f) of 2.5 Gbit/s DWDM-direct system realized with a 100 GHz TFF after 20 km of SSMF for different channel intervals (shown in insets).

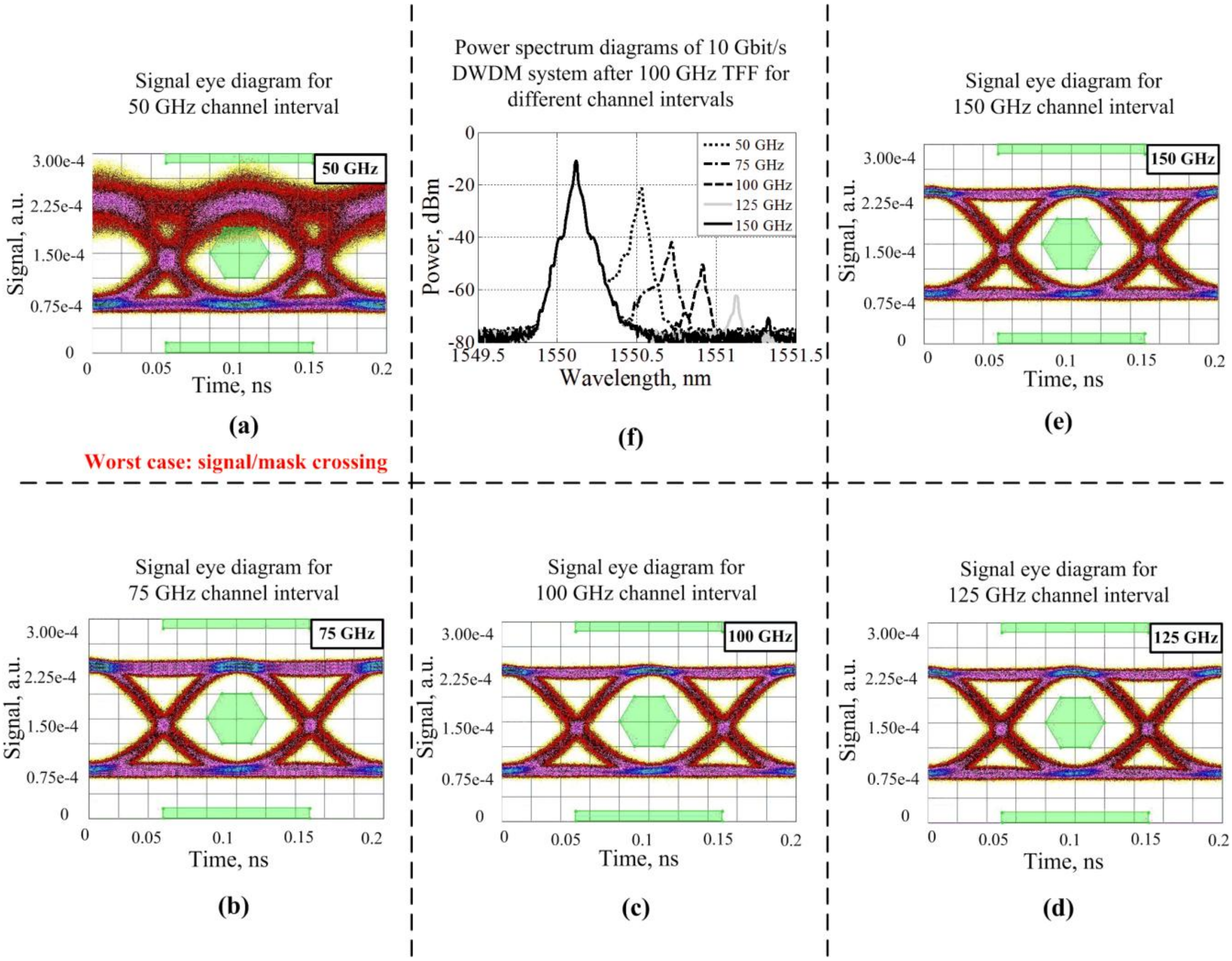

Figure 8. Eye diagrams (a to e) and optical power spectral densities (f) of 10 Gbit/s DWDM-direct system realized with a 100 GHz TFF after 20 km of SSMF for different channel intervals (shown in insets).

DWDM (200 GHz TFF) system's performance. Figures 7a and 8a clearly show that a 50 GHz channel interval is insufficient to suppress the adjacent channel’s power level (that is, both signals are detected). To ensure appropriate signal detection, the channel interval was raised to 75 GHz, owing to which the power level of adjacent channel was suppressed (Figures 7f and 8f). Since there is no signal and mask crossing, the signal quality corresponds to the BER limit defined by ITU. Thus, the spectral efficiency of 10 Gbit/s DWDM-direct systems with 100 GHz TFF has risen from 0.1 to 0.1333 bit/s/Hz.

Conclusions

We have realized a DWDM-direct system for broadband access that includes TFFs with 100 and 200 GHz FWHM bandwidth. From the measurement results, we found the minimal channel interval for each of the optical filters to ensure reliable data transmission, and therefore were able to increase the spectral efficiency of the whole DWDM-direct system for broadband access.

In 2.5 Gbit/s and 10 Gbit/s DWDM-direct systems with 200 GHz TFF, the detection of both signals was observed for a 75 GHz channel interval. To achieve single-channel detection (with ITU-defined BER < 10^{-12}) and suppression of the adjacent channel’s power level, channel interval was increased to 100 GHz. In the same DWDM systems with 100 GHz TFF, an undesirable both signal detection was observed for a 50 GHz channel interval. To avoid it, the channel interval was increased to 75 GHz, which proved to be sufficient to ensure appropriate BER value for the system's performance. As a result, the spectral efficiency of the 10 Gbit/s DWDM system with 200 GHz TFF was raised from 0.05 to 0.1 bit/s/Hz, and the 10 Gbit/s DWDM system with 100 GHz TFF from 0.1 to 0.1333 bit/s/Hz.

ACKNOWLEDGEMENTS

This work has been supported by the European Regional Development Fund within the project Nr. 2010/0270/2DP/2.1.1.1.0/10/APIA/VIAA/002 and by the European Social Fund within the project “Support for the implementation of doctoral studies at the Riga Technical University”.

REFERENCES

Agilent Technologies (2006). Agilent 86038B Photonic Dispersion and Loss Analyzer. (2nd ed-n) Germany: Agilent Technologies Manufacturing GmbH, p. 350.

Arabshahi H, Asmari M (2010). Optimum designing of thin film filter layers of SiO_2 and SnTe based on optical particle swarm opimizer. Int. J. Phys. Sci., 5(01) 057-061.

Cisco Systems (2010). Cisco visual networking index – forecast and methodology 2009–2014.White pp. 11–17.

Dutta AK, Dutta NK, Fujiwara M (2003). WDM TECHNOLOGIES: Passive Optical Components. USA: Academic Press, p. 551.

Haro J, Horche PR (2008). Evolution of PMD with the temperature on installed fiber. Optical Fiber Technol., 3(14): 203–213.

Hui R, O’Sullivan M (2009). Fiber Optic Measurement Techniques. London: Elsevier Academic Press, p. 630.

Ivanovs Ģ, Bobrovs V, Ozoliņš O, Poriņš J (2010). Realization of HDWDM Transmission System.Int. J. Phys. Sci., 5(5): 452–458.

Kimura H, Iiyama N, Sakai Y, Kumozaki K (2010). A WDM-Based Future Optical Access Network and Support Technologies for Adapting the User Demands Diversity. IEICE Transactions on Communications. E93-B(2): 246-254.

Ļašuks I, Ščemeļevs A, Ivanovs Ģ. (2010). A hybrid TDM/WDM-PON system with FWM-generated source of multiwavelength optical signals. Latv.J. Phys. Tec. Sci., 47(5): 3-14.

Macleod HA (2001). Thin-Film Optical Filters. (3rd ed-n) Bristol: J.W. Arrowsmith Ltd. Institute of Physics Publishing, p. 641.

Miyazawa T, Harai H (2010). Optical access architecture designs based on WDM-direct toward new generation networks. IEICE Transactions on Communications, E93-B(2): 236-245.

Ozoliņš O, Bobrovs V, Ivanovs Ģ (2010). Efficient wavelength filters for DWDM systems. Latv. J. Phys. Tec. Sci., 47(6) 13-24.

Pan C, Yu Z, Willner AE (2010). Optical performance monitoring for the next generation optical communication networks. Optical Fiber Technology. 16(1): 20–45.

Peucheret C (2004). Fibre and component induced limitations in high capacity optical networks. Doctoral Thesis. pp. 11–8.

Piehler D (2011). Next-generation components for optical access networks. Proc. Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference, 6(10): 1 - 3.

Shea DP, Mitchell JE (2007). Long-Reach Optical Access Technologies. IEEE Network, 21(5): 5-11.

Shen W, Sun X, Zhang Y, Luo Z, Liu X, Gu P (2009). Narrow band filters in both transmission and reflection with metal/dielectric thin films. Optics Communications, 282(2): 242–246.

Sumriddetchkajorn S, Chaitavon K (2007). 1*N add–drop filter structures using one dense wavelength division multiplexing thin-film filter.Optics Communications. 280(1): 33–38.

Venghaus H (2006). Wavelength filters in fibre optics. Berlin: Springer, p. 454.

Wang X, Wada N, Miyazaki T, Cincotti G, Kitayama K (2007). Hybrid WDM/OCDMA for Next Generation Access Network.in Proc. SPIE The International Society for Optical engineering. 6783(10): 28-41.

Willey RR (2001). Achieving narrow bandpass filters which meet the requirements for DWDM. Thin Solid Films. 398–399(1): 1–9.